Experiments in Neutrino Physics

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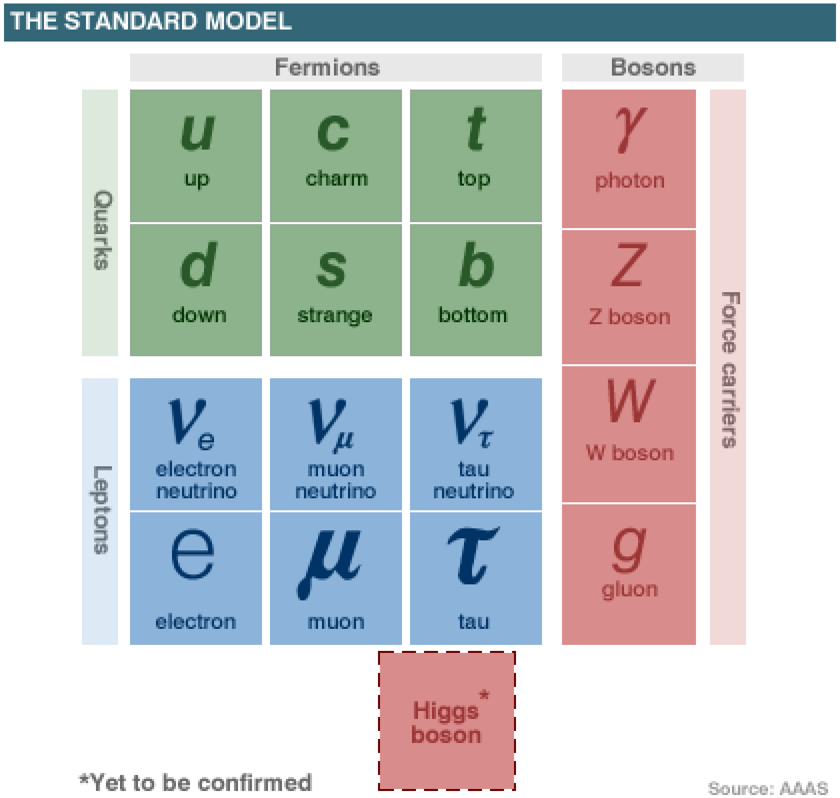
With many thanks to the speakers at Neutrino 2012!

Outline

- Neutrinos, neutrino oscillations
- Neutrino oscillation experiments
  - solar,
  - Atmospheric and ν telescopes
  - reactor,
  - accelerators,
- Some future experiments
- Summary

Neutrinos

Part of the *Standard Model* of particles and their interactions



- Fermions ($s=1/2$), no electric charge,
  - very small mass (< 2 eV/c^2),
  - no (?) magnetic moment ($<\sim 10^{-10}\ \mu_B$),
  - associated to a charged lepton (e, μ, τ).
- Feel only the Weak Interactions ($W^{\pm}$, Z^0).
- Exist as *mixtures* of states with definite mass $\rightarrow$ *Oscilaciones.*

Copiously produced in:
- The Sun, supernovae, AGN's, etc.
- Earth's atmosphere, Earth's interior,
- Nuclear reactors, accelerator beams

In general whenever <u>weak interaction</u> processes occur (ej. β decay of radioactive nuclei)

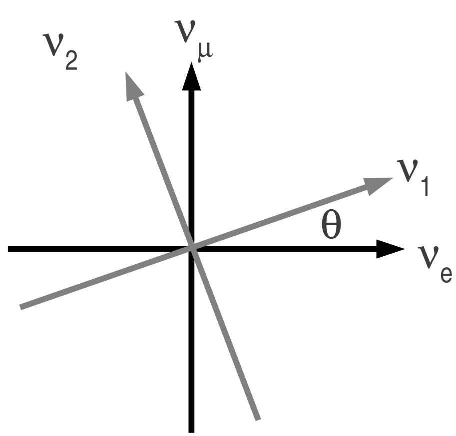
Neutrino oscillations

- If flavor eigenstates are different from mass eigenstates and neutrinos have mass $\Rightarrow$ **interference phenomenon**

Example: *Mixing* of two neutrinos:

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

Mixing Matrix



$$|\nu(t)\rangle = -\sin\theta\, |\nu_1\rangle e^{-iE_1 t} + \cos\theta\, |\nu_2\rangle e^{-iE_2 t}$$

L~*ct*

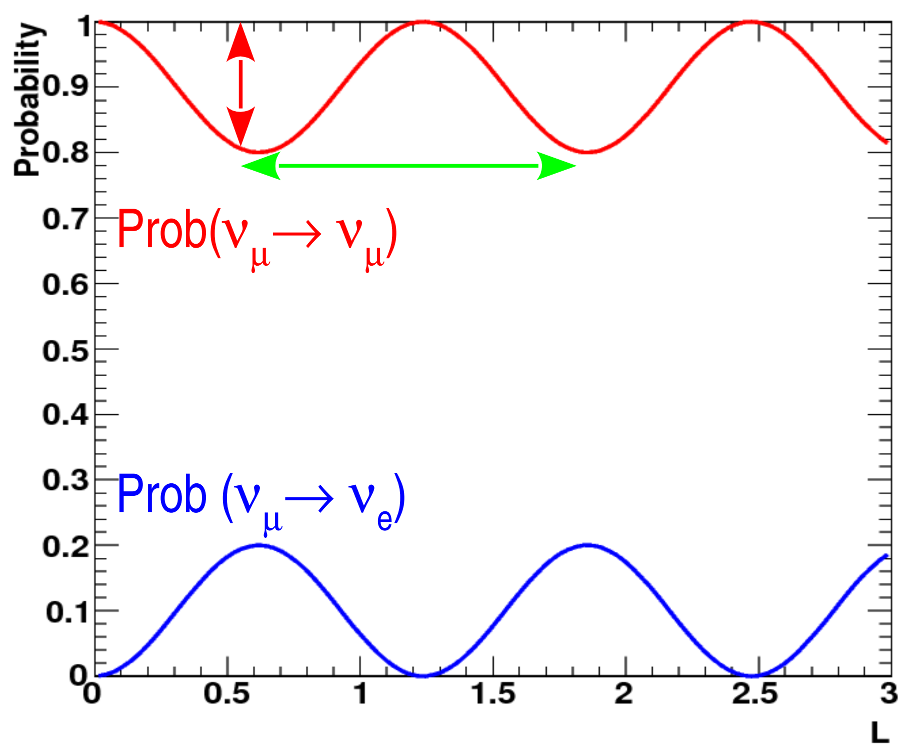
Survival probability
Detected as ν_μ

$$P(\nu_\mu \rightarrow \nu_\mu) = |\langle \nu_\mu | \nu(0) \rangle|^2$$

Oscillation probability
Detected as ν_e

$$P(\nu_\mu \rightarrow \nu_e) = |\langle \nu_e | \nu(0) \rangle|^2$$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_e)$$



Neutrino oscillations, PMNS mixing matrix

We know there are (at least) 3 neutrino flavors. Then the mixing matrix is (at least) 3x3 (Pontecorvo-Maki-Nakagawa-Sakata → PMNS)

Parameterized by 3 angles (θ_{12}, θ_{13} and θ_{23}) + 1 CP-violating phase (δ)

(also 2 more Majorana phases which are not observable in oscillations)

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric sector — Reactor sector — Solar sector

The (vacuum) oscillation probabilities are:

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

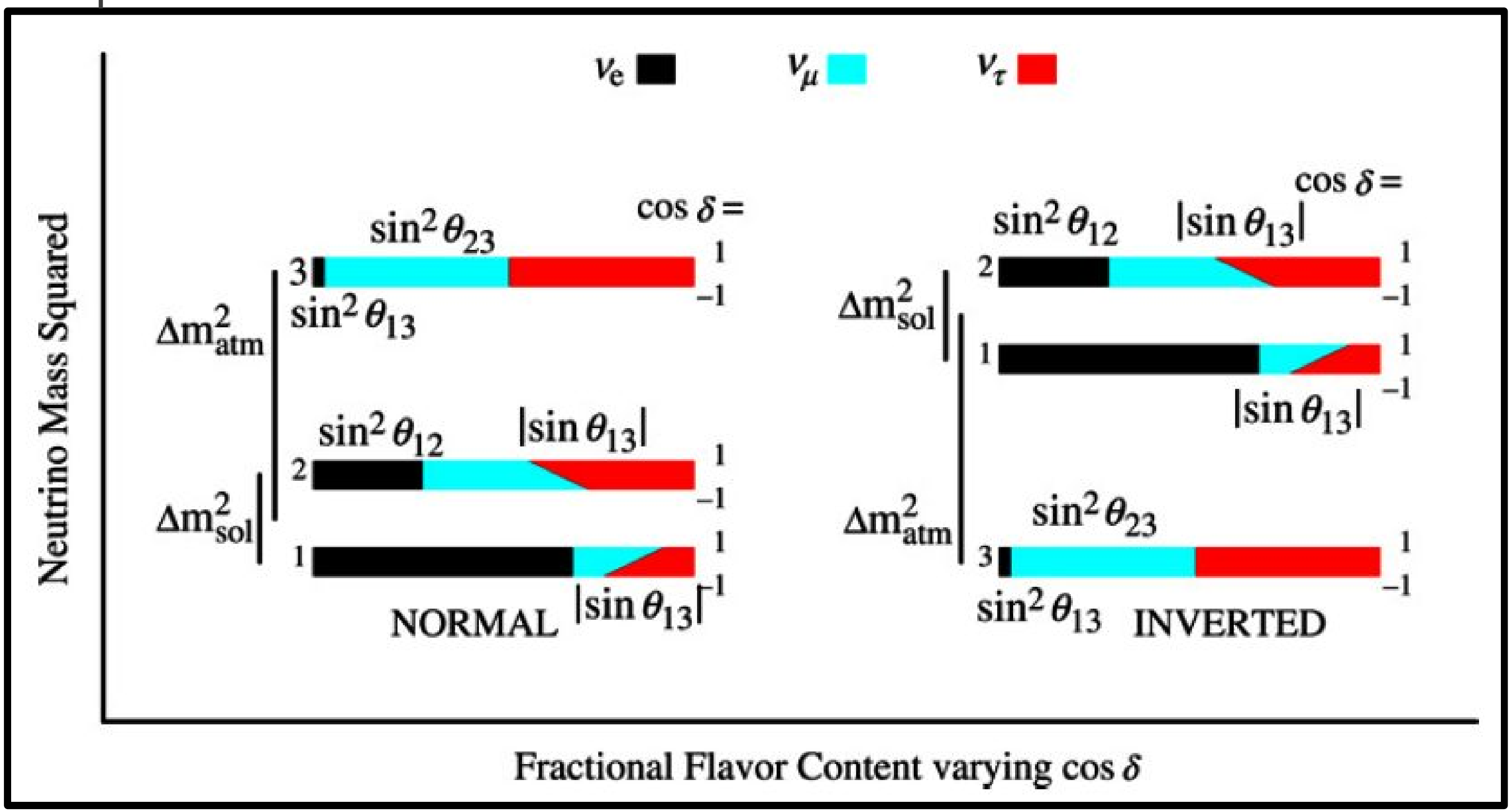
$\Delta m^2_{ij} = m^2_i - m^2_j\,(eV^2)$, $L(Km)$, $E(GeV)$

Neutrino mass hierarchy

Experiments indicate:

$$\Delta m^2_{12} = \Delta m^2_{\odot} \ll \Delta m^2_{atm} = \left|\Delta m^2_{32}\right| \approx \left|\Delta m^2_{13}\right|$$

Two possible hierarchies:



(H. Nunokawa, S.J. Parke, J.W.F. Valle, Prog.Part.Nucl.Phys.60:338-402,2008) $\mathbf{\sin^2 2\theta_{13}=0.1}$

Neutrino oscillations (in vacuum)

Mass hierarchy: $|\Delta m^2_{12}| << |\Delta m^2_{23}| \rightarrow$ approx. decoupling of effects

Atmospheric and accelerator (long baseline):

$P(\nu_\mu \rightarrow \nu_\tau) \approx \cos^4\theta_{13}\ \sin^2\theta_{23} \sin^2(1.27\ \Delta m^2_{23}\ L/E)$ → Super-K, K2K, MINOS, OPERA

$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(1.27\ \Delta m^2_{23}\ L/E)$ → T2K, NOvA

$P(\nu_e \rightarrow \nu_\tau) \approx \sin^2 2\theta_{13} \cos^2\theta_{23} \sin^2(1.27\ \Delta m^2_{23}\ L/E)$ → ?

Reactor neutrinos:

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - P1 - P2$,

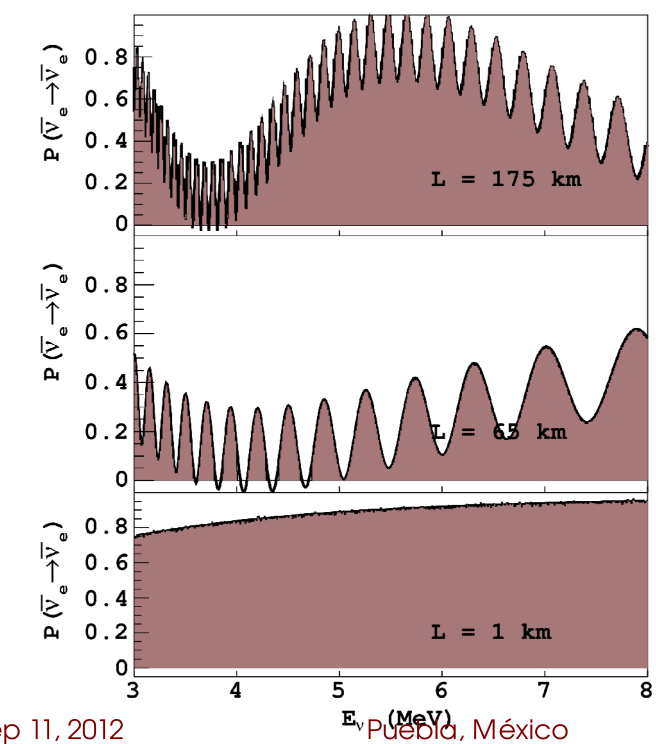
$P1 = \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\ \Delta m^2_{12}\ L/E)$ → Kam-LAND

$P2 = \sin^2 2\theta_{13} \sin^2(1.27\ \Delta m^2_{23}\ L/E)$ → Double-Chooz, Daya-Bay, RENO

$\theta_{13} = (8.8 \pm 3.7)^\circ$

March 2012!

PRL108:171803(2012)

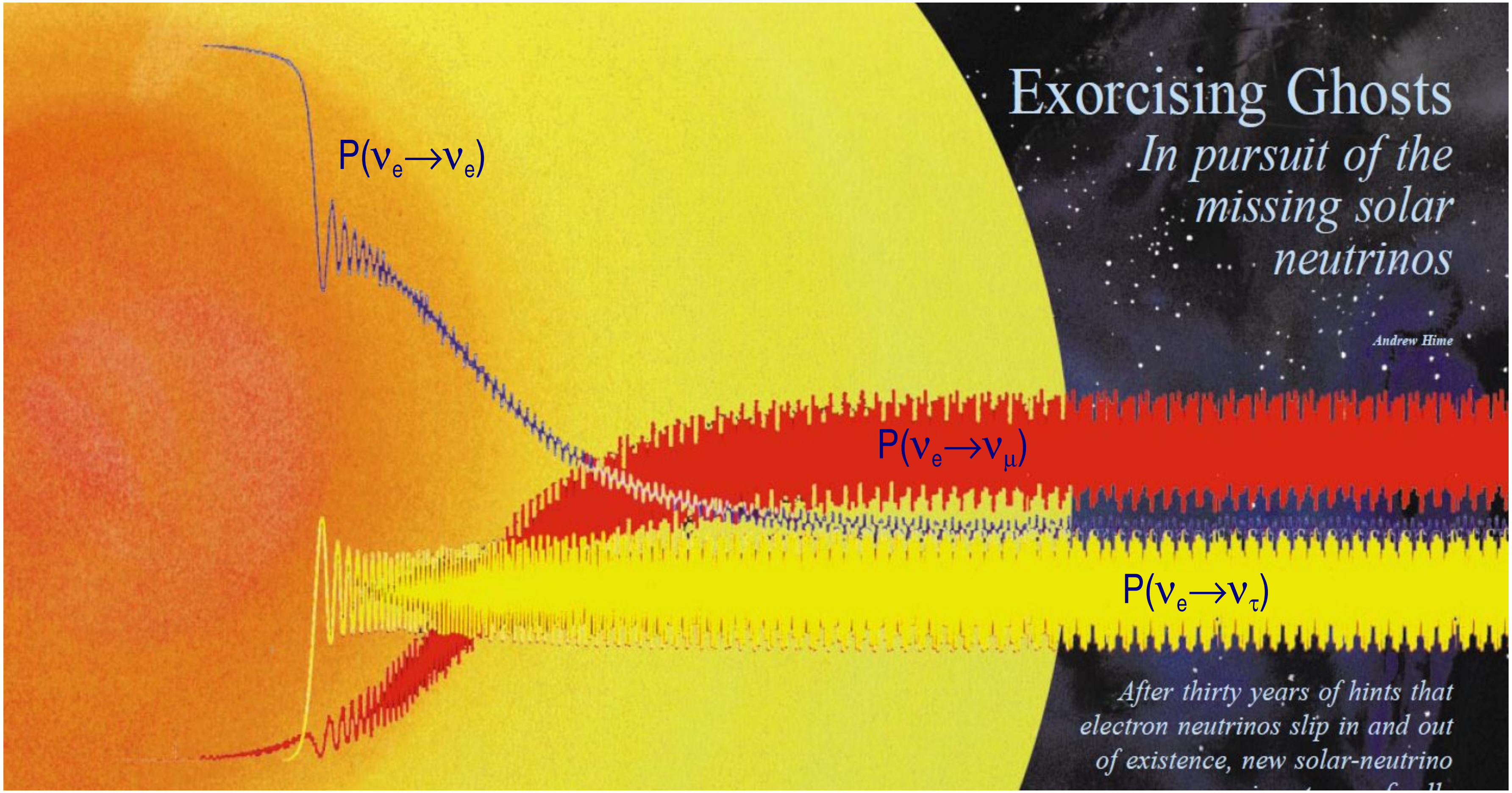


Solar neutrino oscillations, MSW effect

Resonant oscillation effect in solar matter

Depends on matter density profile

$$P_{ee} \approx \frac{1}{2}\cos^4\theta_{13}\left[1+\cos 2\theta_{12}\cos 2\theta_{12}^m(r_0, E_\nu, \Delta m_{12}^2)\right] + \sin^4\theta_{13}$$



Los Alamos Science, 25, 1997 *"Celebrating the Neutrino"*

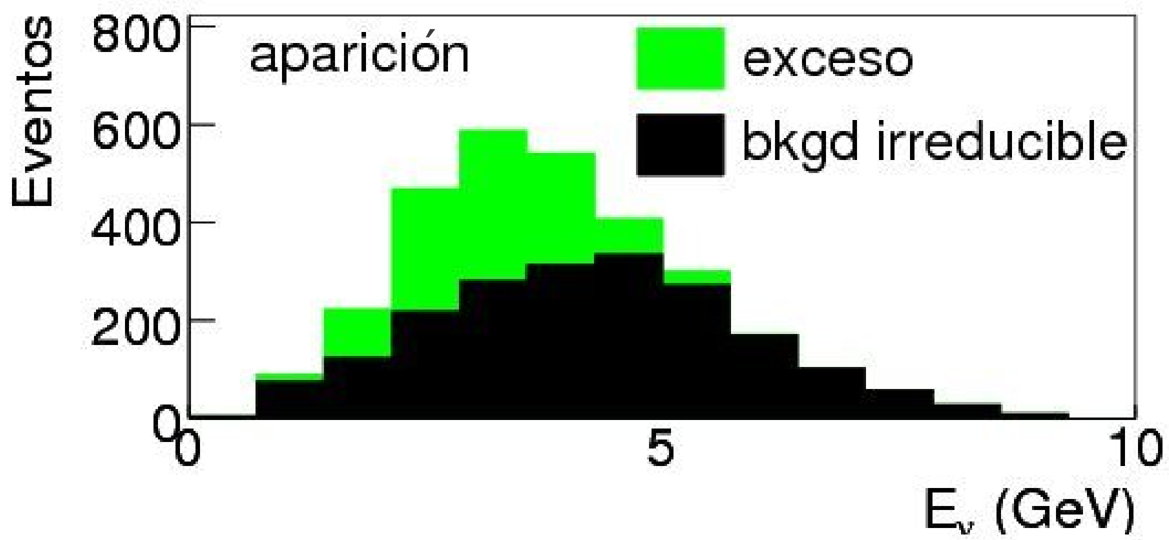
Oscillation experiments

At distance L from the source: $P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 (L/E))$

1. appearance:

Look for ν_β in a beam of ν_α.
Det. must be flavor sensitive

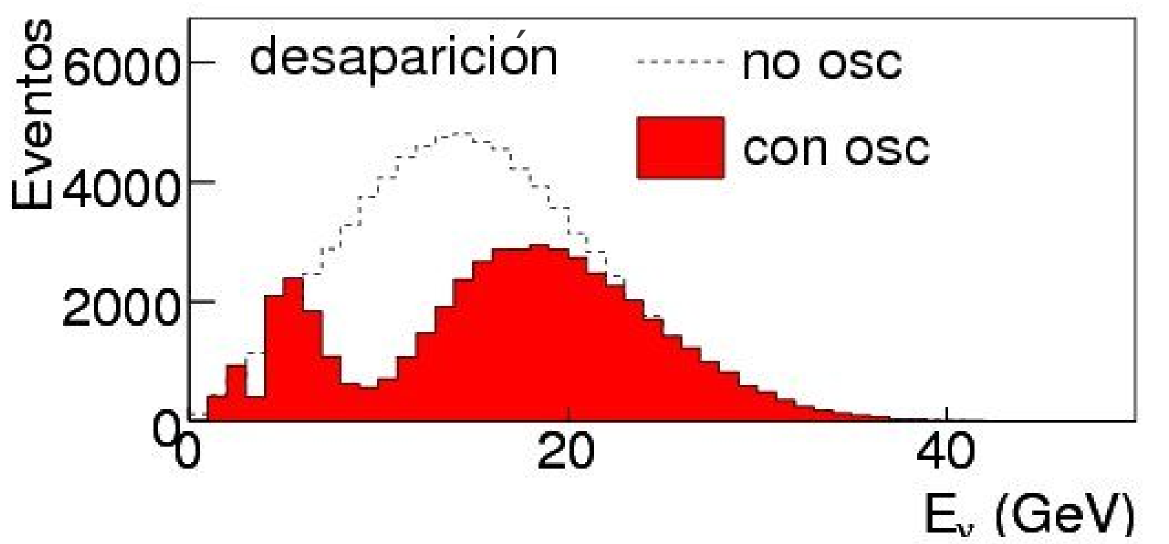
e.g.. searches for ($\nu_\mu \rightarrow \nu_e$)
In accelerator beams.



2. disappearance:

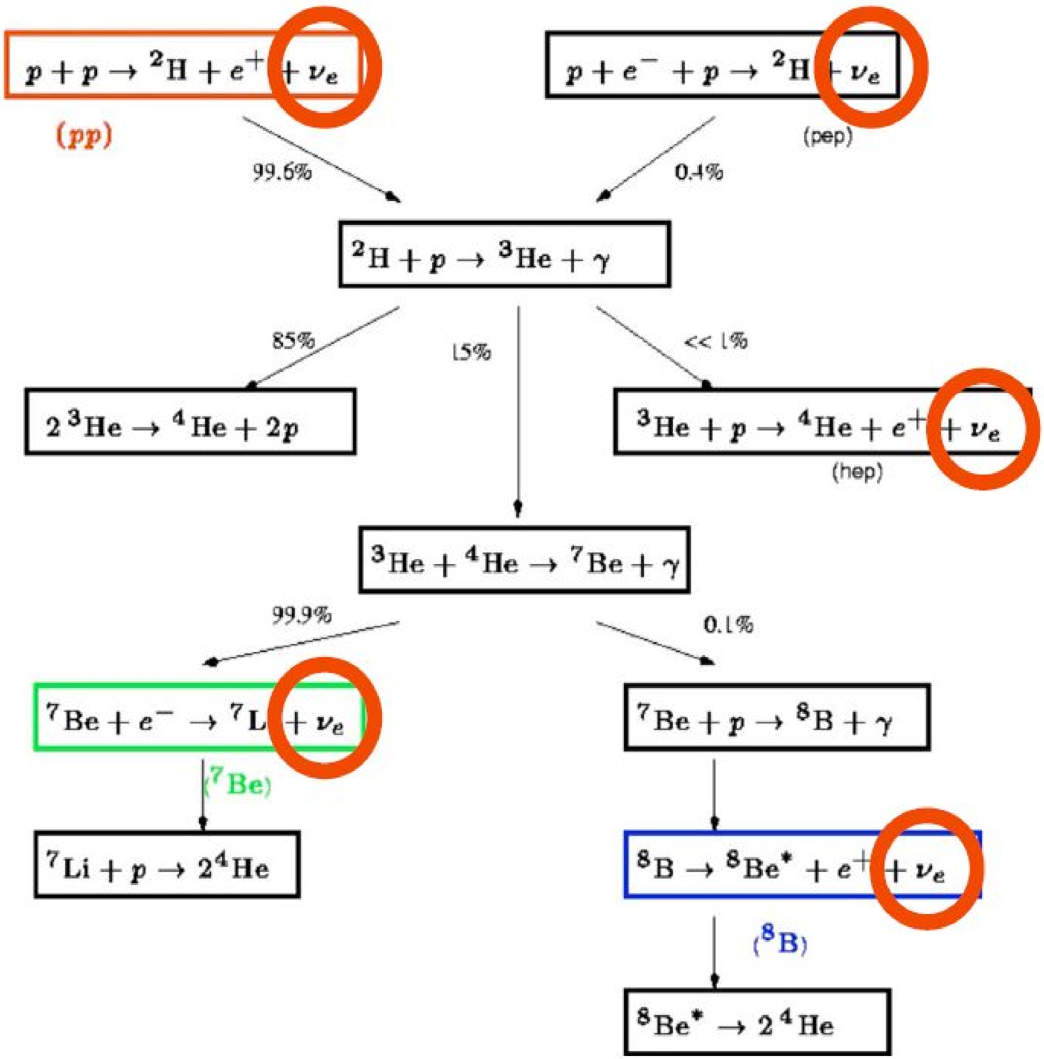
Compare fluxes $\Phi(L)/\Phi(0)$ of neutrinos of flavor ν_α
ratio = $P_{sup}(\nu_\mu \rightarrow \nu_\mu)$,

eg. solar and reactor ν's,
some *LBL* experiments.



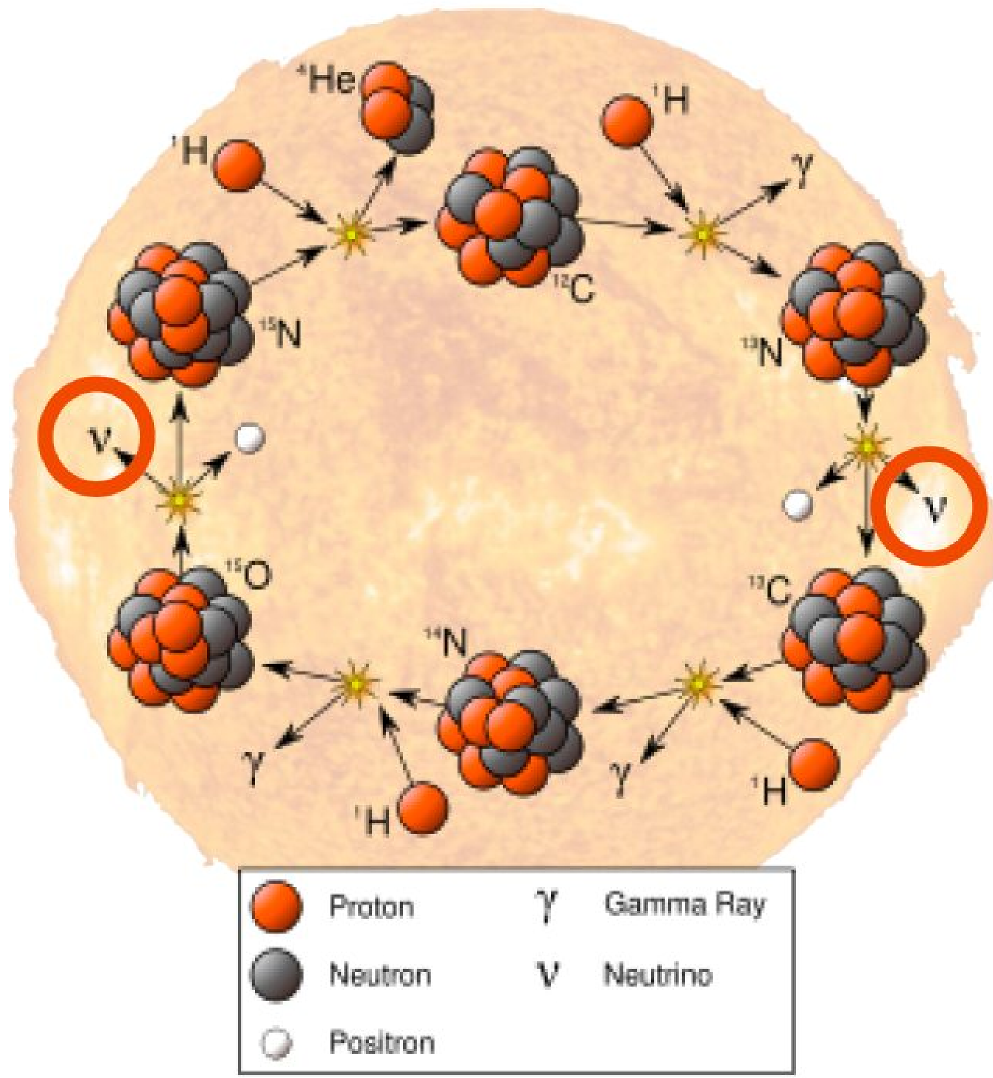
Neutrinos Solares

pp Chain

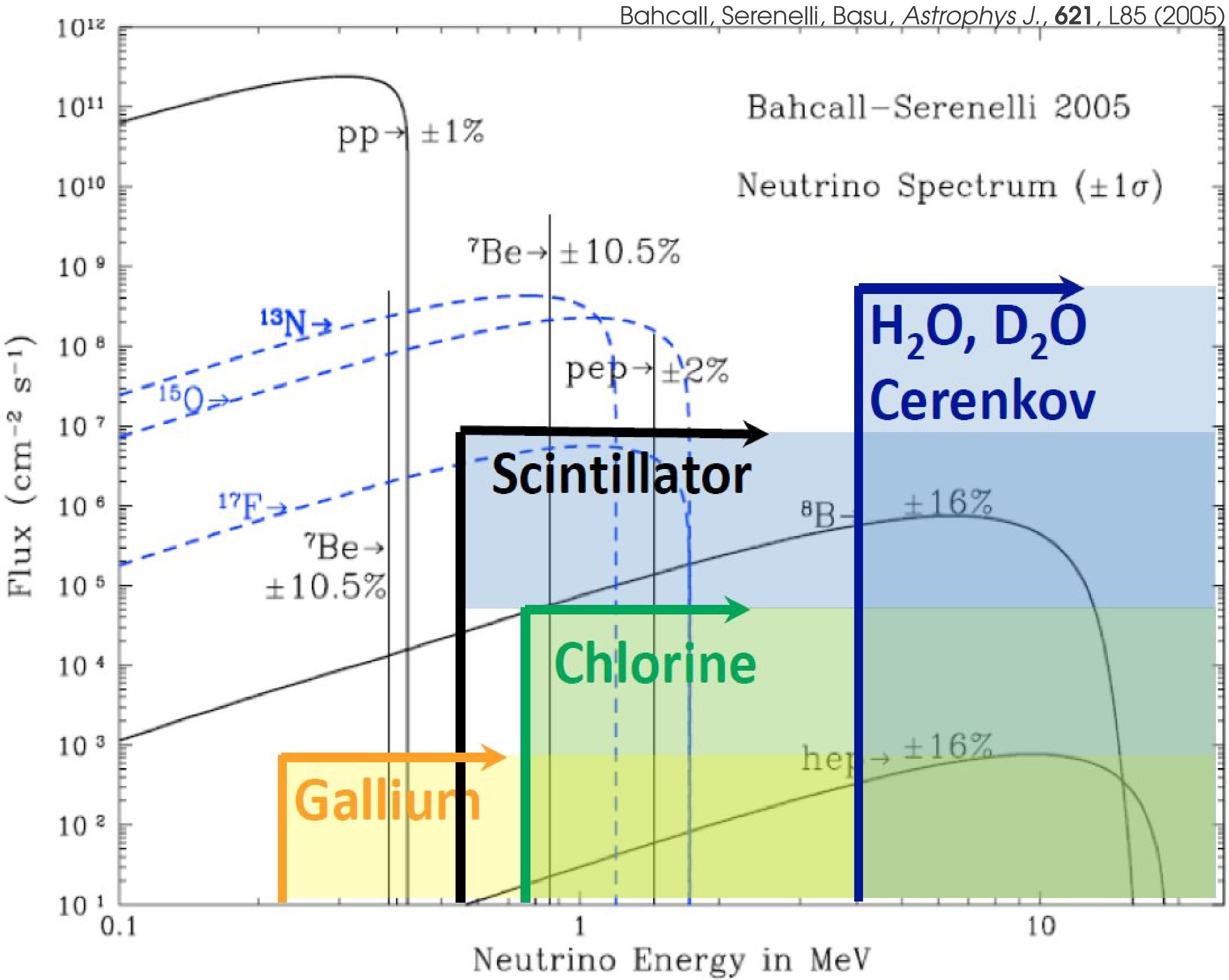


CNO Cycle

(contributes ~1% of solar energy)



Solar neutrino spectrum



Total solar neutrino flux reaching the Earth: $\Phi_{Tot} \sim 65 \times 10^9$ s^{-1} cm^{-2}

Ray Davis experiment (Homestake)

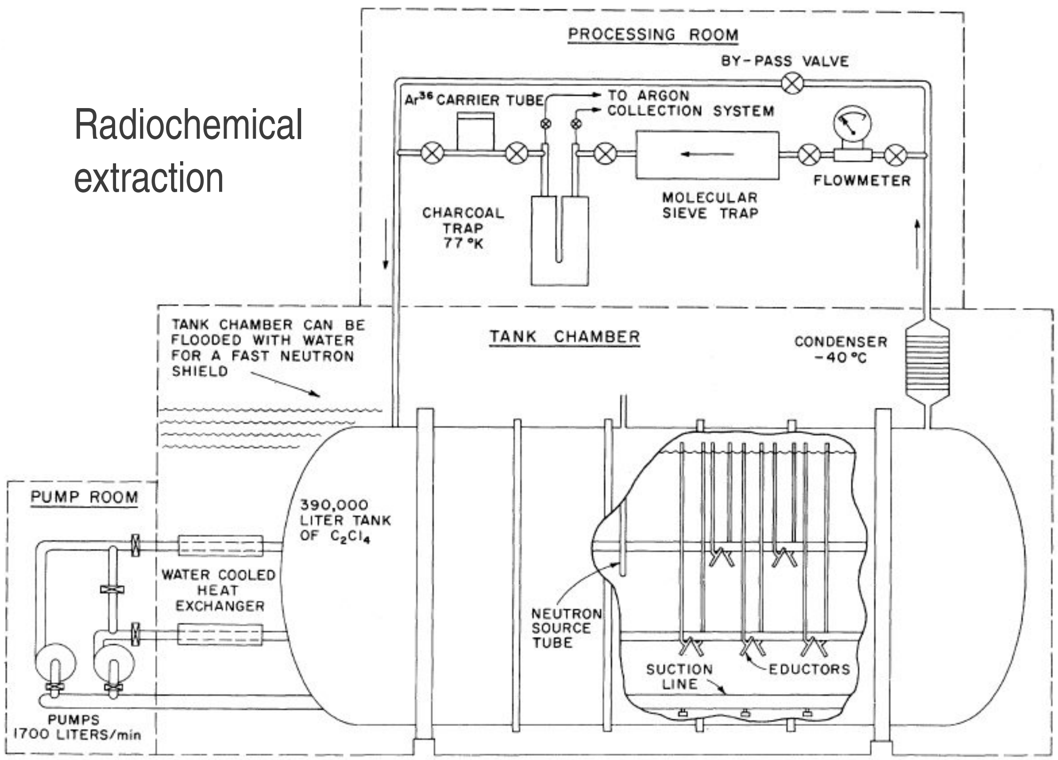
First detection of Solar neutrinos.
Took data from 1967 until 1995

390,000 liters of Tetrachloroethilene (C_2Cl_4)
1,478 m underground (4,400 m.w.e.)

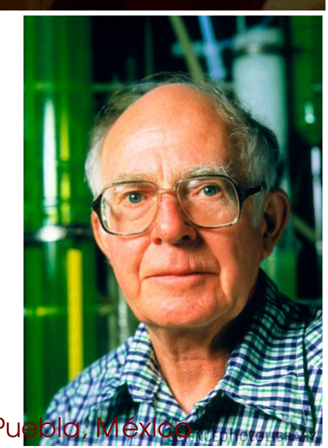
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^+$, ($E_\nu > 0.813$ MeV)

^{37}Ar extracted from medium by He gas purge.
The decays were counted (~0.4/day).

Radiochemical extraction



Ray Davis Jr. received the Nobel Prize in Physics en 2002



Observed ~1/3 of the expected neutrinos according to the SSM.

Radiochemical experiments

Solar ν_e + nucleus $\rightarrow$ unstable nucleus ... watch decay.

1 SNU = 10^{-36} ν-captures/atom/s

Chlorine: $\nu_e + Cl^{37} \rightarrow Ar^{37} + e^{+}$ ($E_\nu > 0.813$ MeV)

100,000 gal. tetrachloroethilene (1968-1995) (Homestake, R. Davis)

Result: 2.56 ± 0.23 SNU (expected SSM: 7.6±1.3)

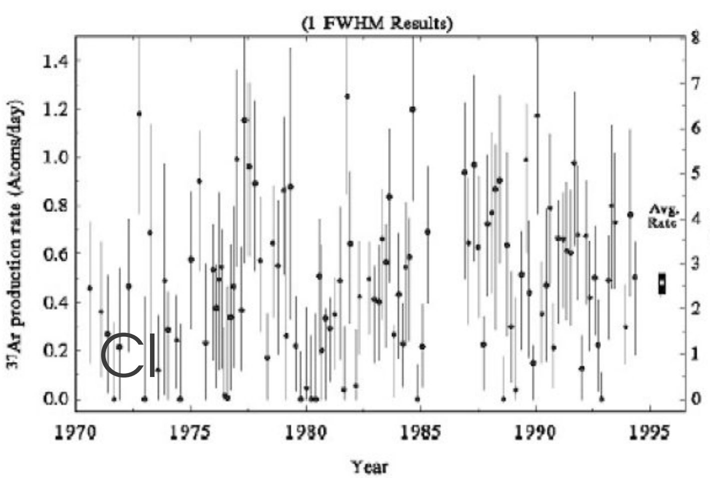
Gallium: $\nu_e + Ga^{71} \rightarrow Ge^{71} + e^{+}$ ($E_\nu > 0.233$ MeV)

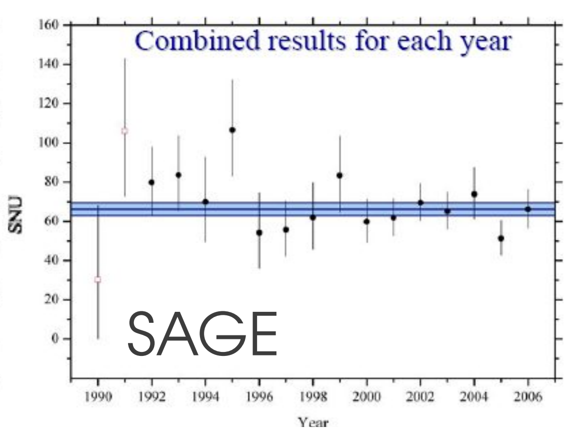
GALLEX (1991-1997), GNO (1998-2003) (Lab. Gran Sasso)

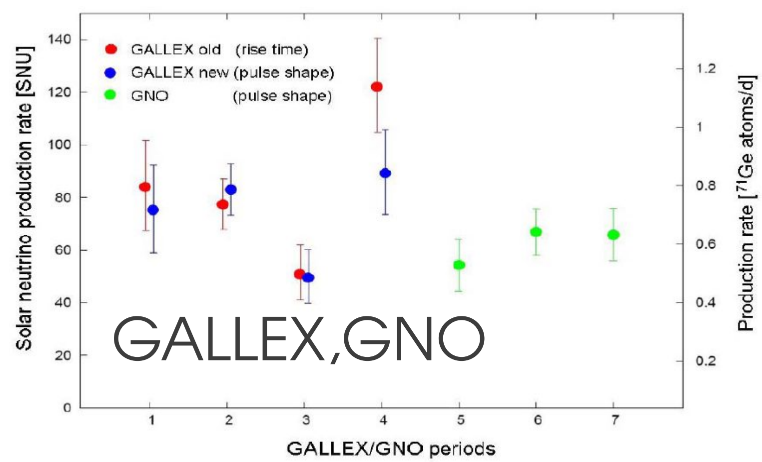
100 ton solution of Ga & Cl in water (30 ton of Ga)

SAGE (1990-2006) ,45.6 ton of metallic Ga (Baskan, Rusia)

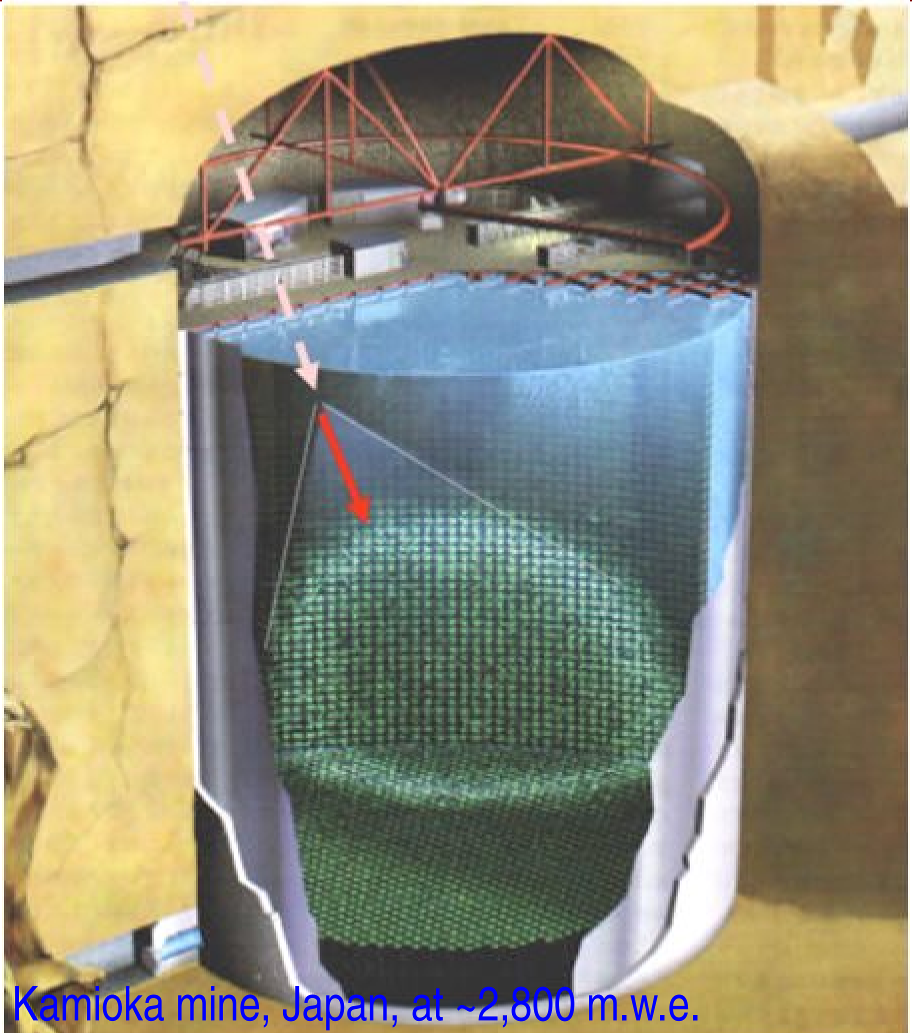
Result: 67.6 ± 3.71 SNU (expected SSM: 128± 9 SNU)



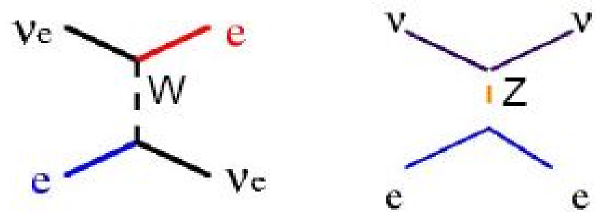


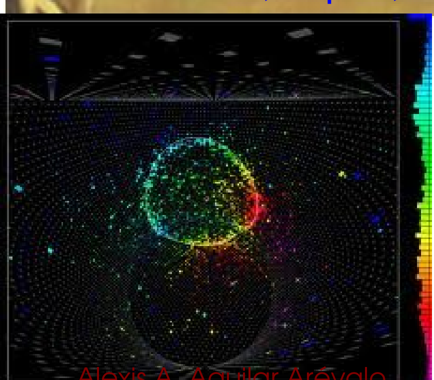


Super Kamiokande

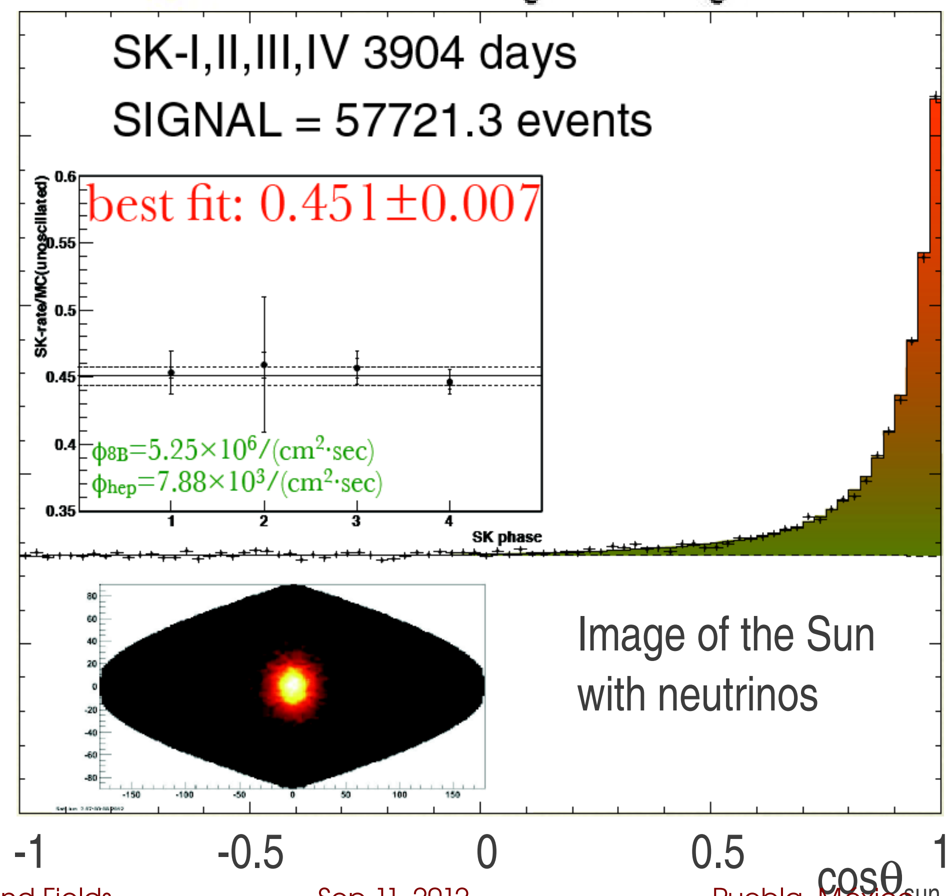


- Cylinder: 41.4 m h x 39.3 m diameter
- Water Cherenkov detector (50 kton H_2O)
- Detects Solar ν's through νe ***Elastic Scattering***:
  $\nu_e + e \rightarrow \nu_e + e$, threshold $E_\nu > 5$ MeV.

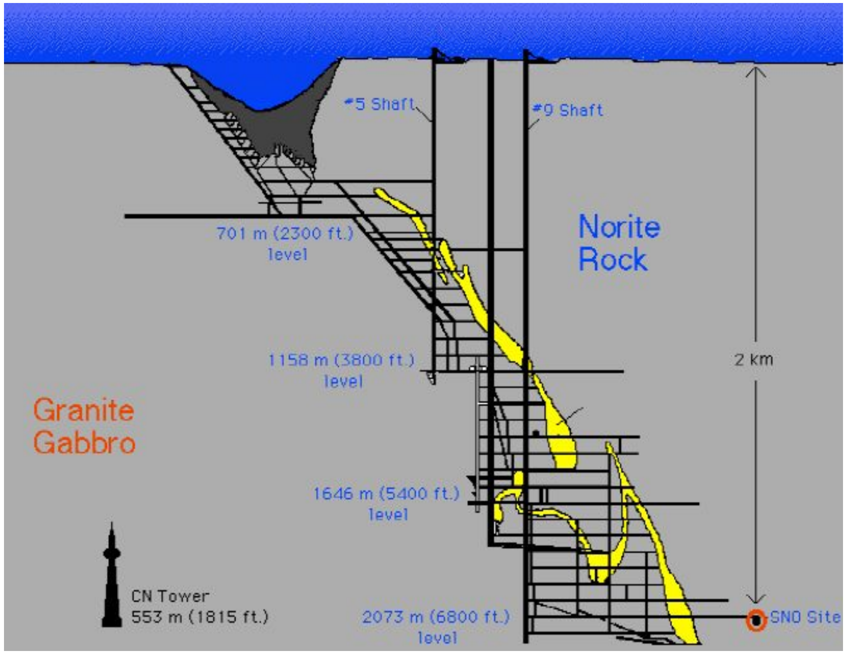




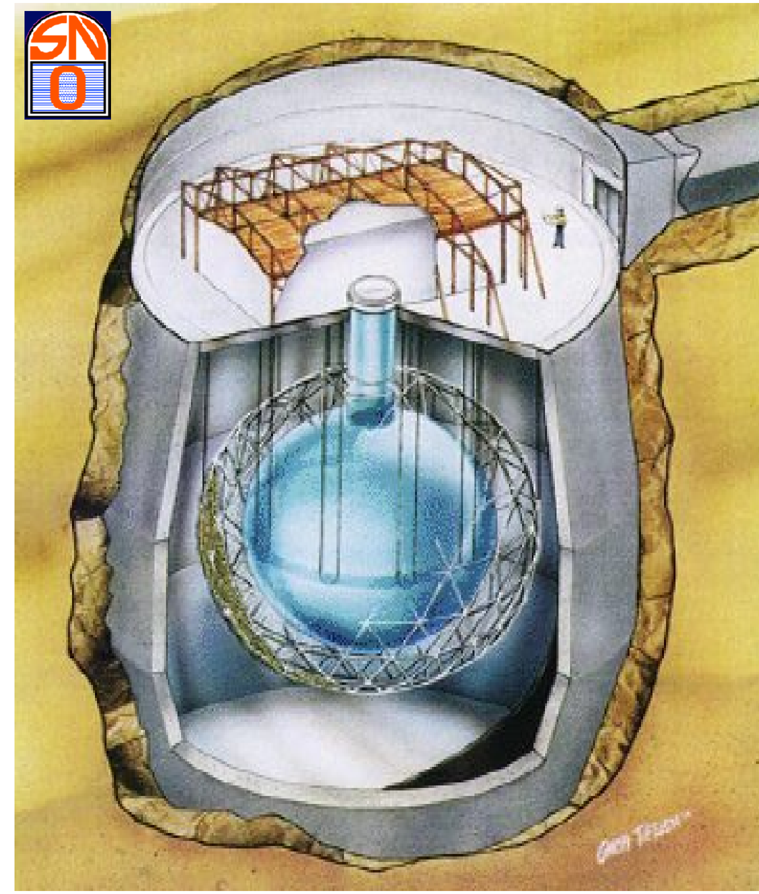
Measures consistently ~45% of the number expected from the SSM.



SNO (Sudbury Neutrino Observatory)



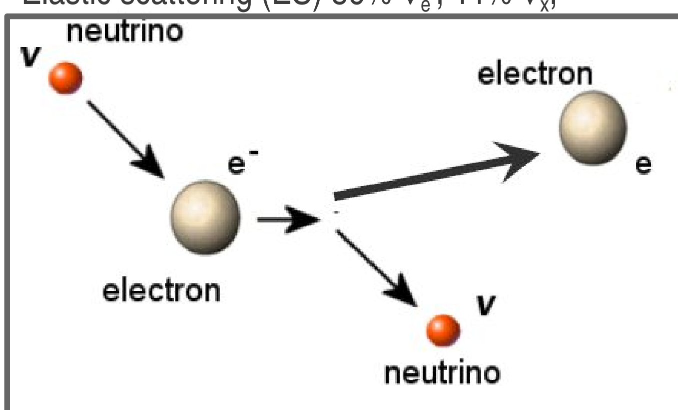
Underground:
2092 m (6010 m.w.e.)



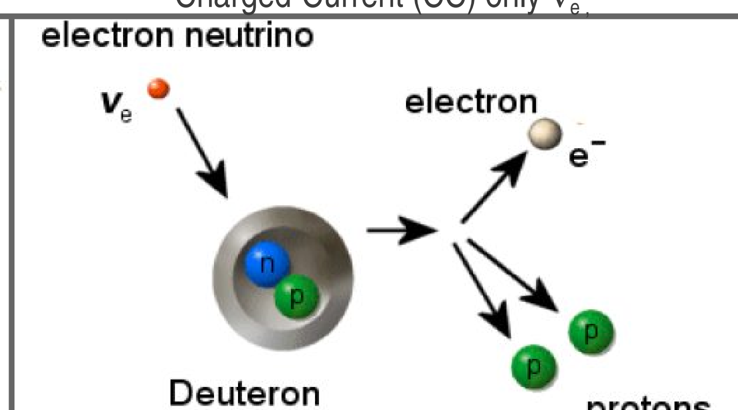
- 1,000 ton of heavy water (D_2O) in acrylic vessel (12 diam)
- PMT Support structure 18 m in diameter
- 1,700/5,300 ton of H_2O, internal/external shield

SNO studied 3 types of reactions:

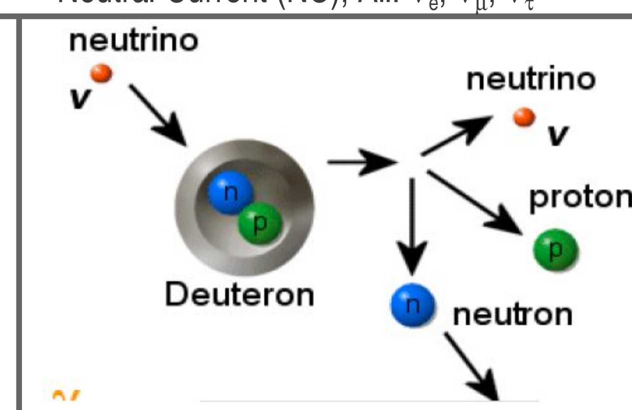
Elastic scattering (ES) 86% ν_e, 14% ν_x,



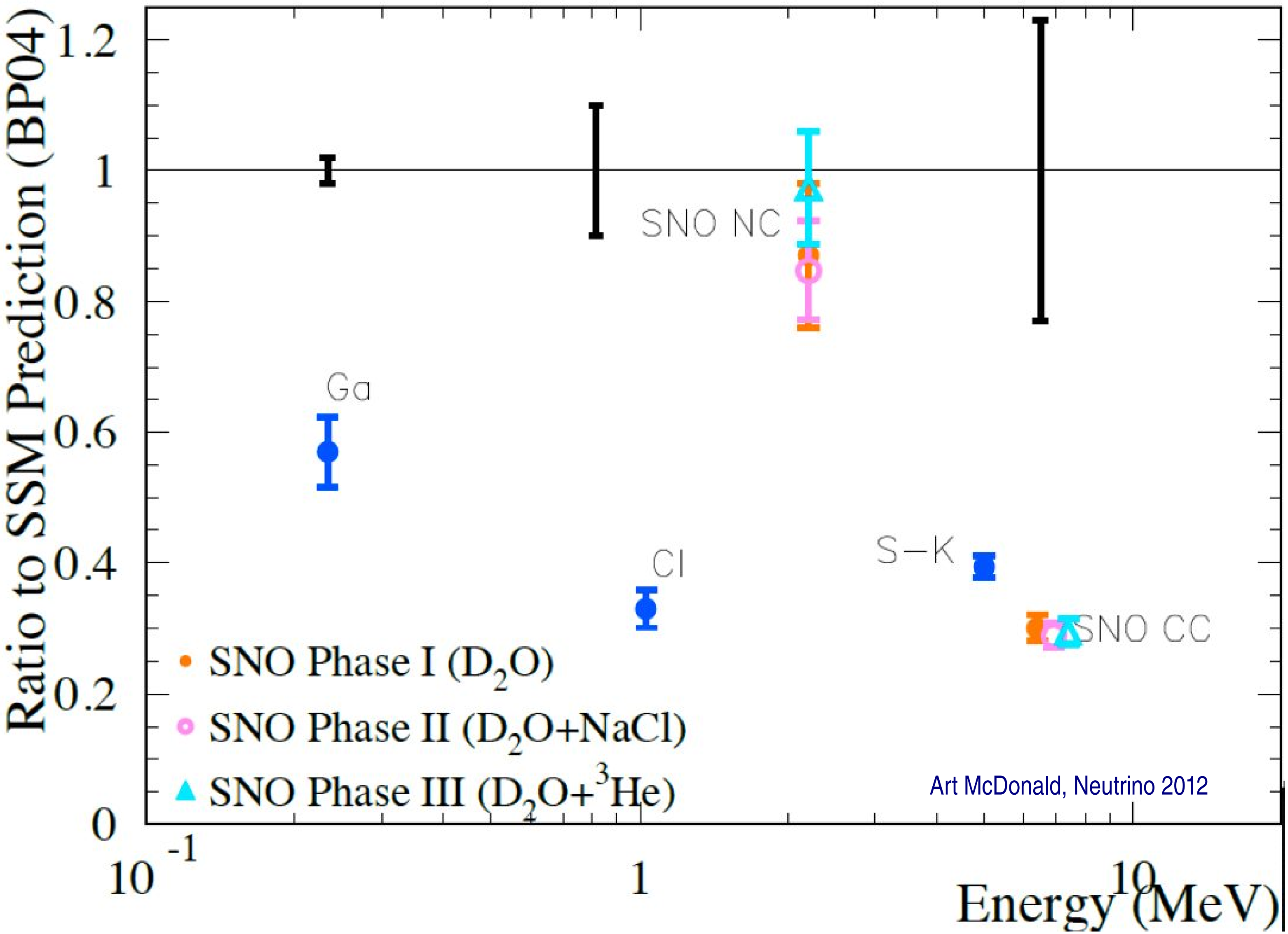
Charged-Current (CC) only ν_e



Neutral-Current (NC), All: ν_e, ν_μ, ν_τ



SNO solved the Solar neutrino problem



$\phi(CC)=\phi(\nu_e)$

$\phi(NC)=\phi(SSM)$

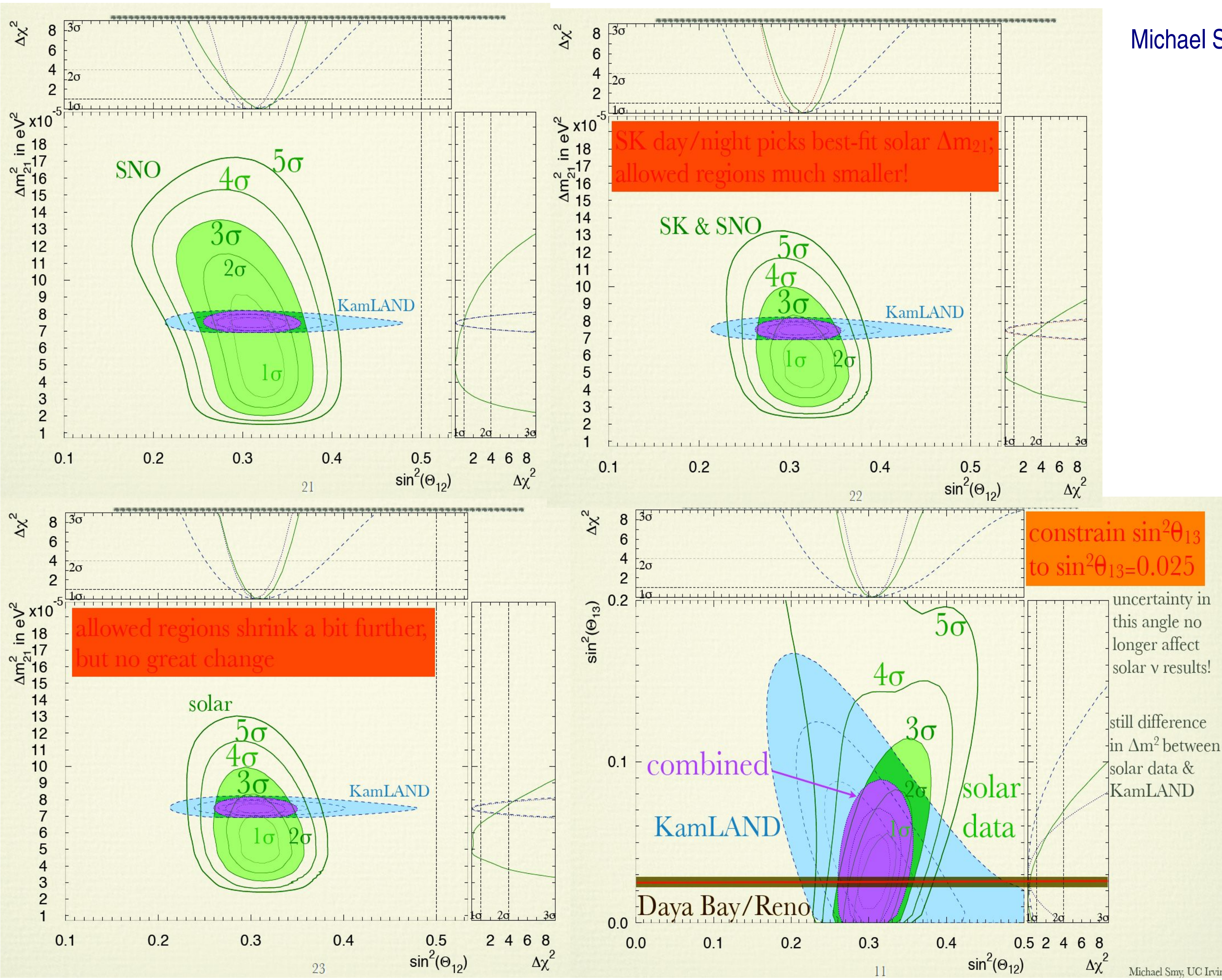
$\phi(\nu_\mu, \nu_\tau)=\phi(NC)-\phi(CC)$

$\Phi_{B8} = (5.25 \pm 0.19) \times 10^6\ cm^{-2}s^{-1}$

$\Phi_{SSM} = (5.05 \pm 1.0) \times 10^6\ cm^{-2}s^{-1}$ (BS05)

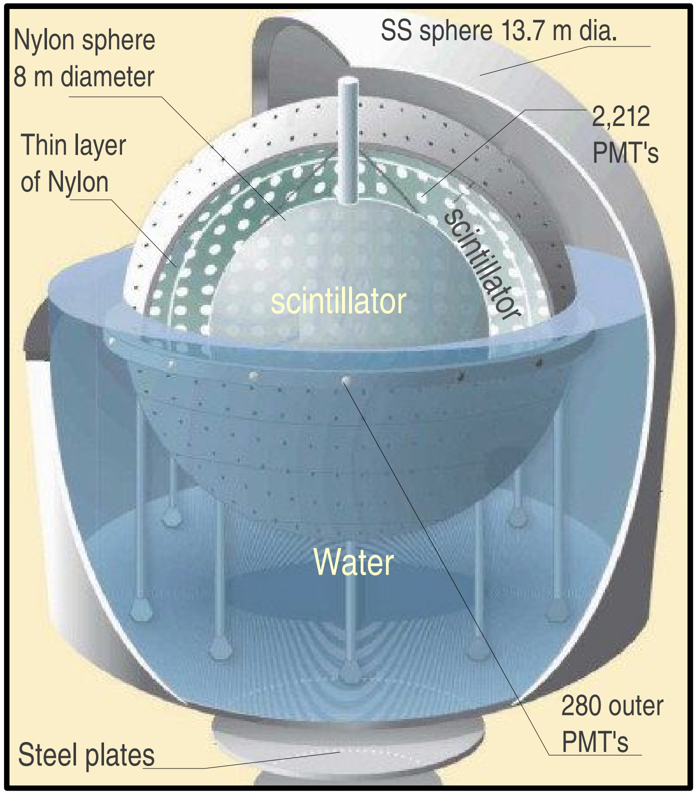
Neutrino oscillations parameters from solar data: Δm^2_{12}, θ_{12} , θ_{13}

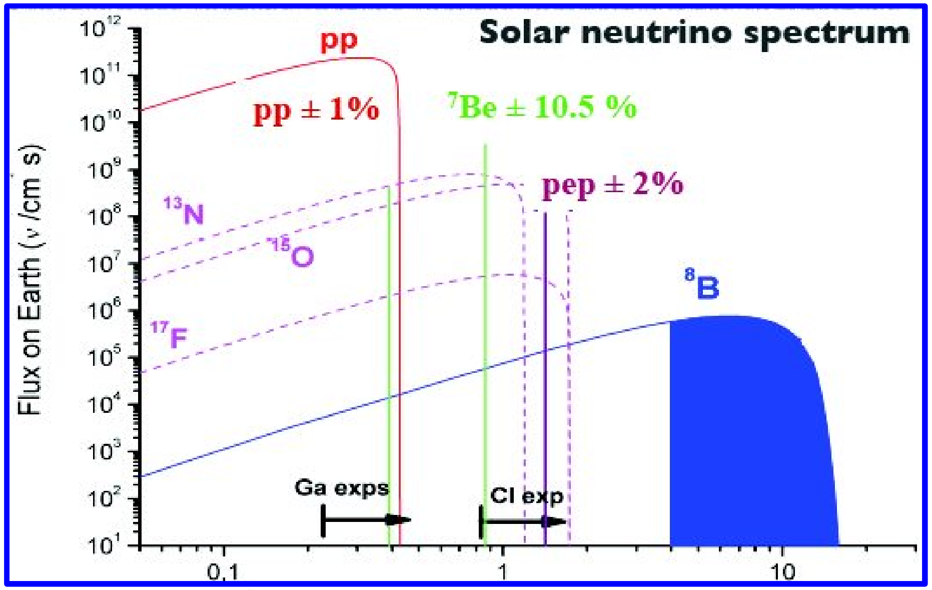
Michael Smy, Neutrino 2012

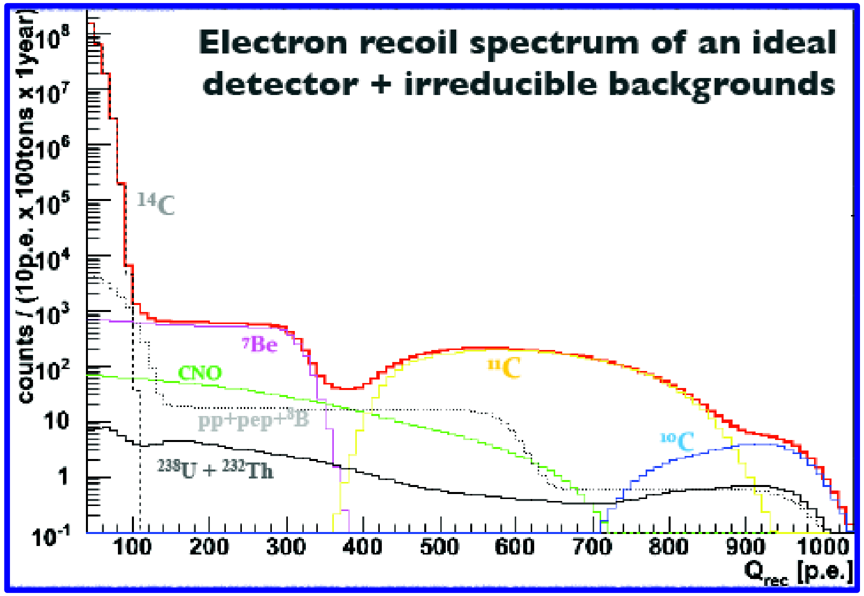


Borexino (Gran Sasso Laboratory, Italy)

- Detects $\nu_x + e^- \rightarrow \nu_x + e^-$ in high purity organic liquid scintillator (~300 ton).
- ***Ultra-low radioactive background*** achieved via ***selection***, ***shielding*** and ***purification.***
- Low threshold (E_ν>250 keV), good energy resolution.
- Main goal: Detect solar ^{7}Be neutrinos in real time.
- First real-time measurement of *pep* neutrinos.



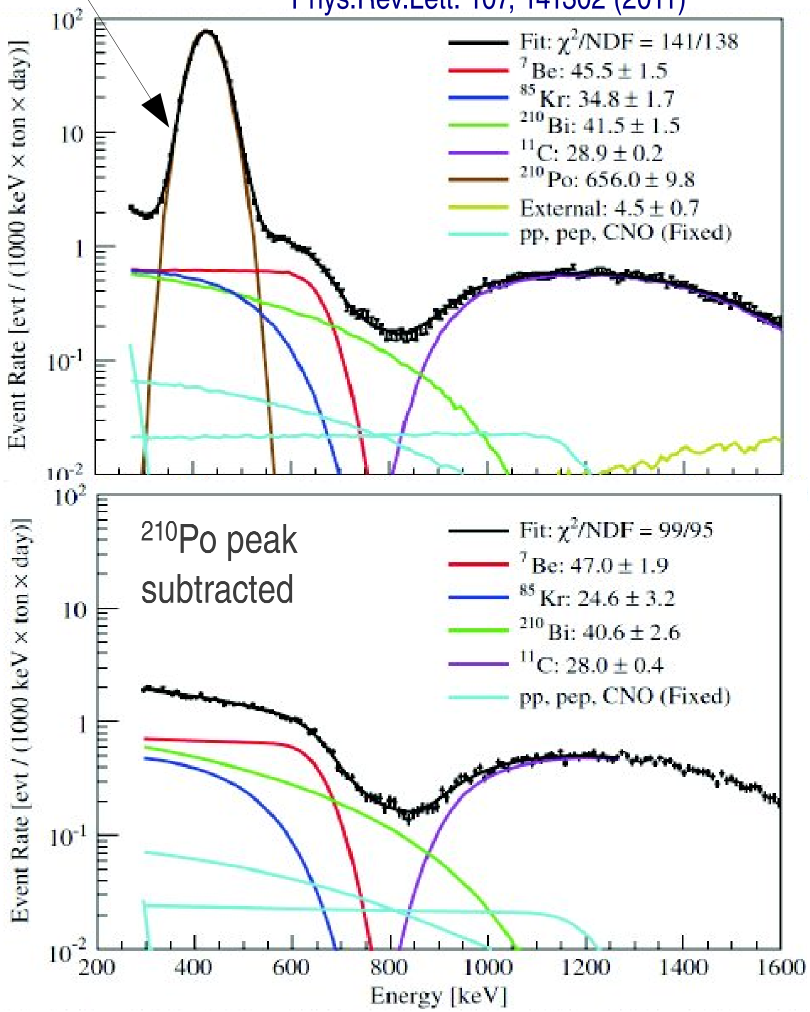




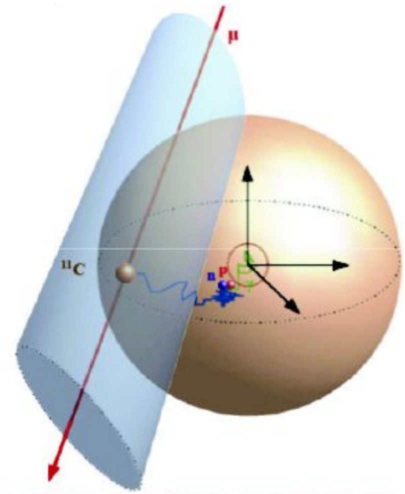
Borexino, ^{7}Be and *pep* neutrinos

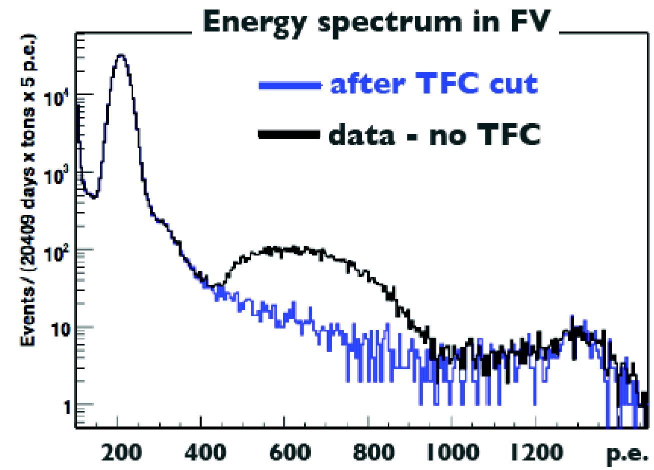
α's from ^{210}Po decays (intrinsic to scintillator)

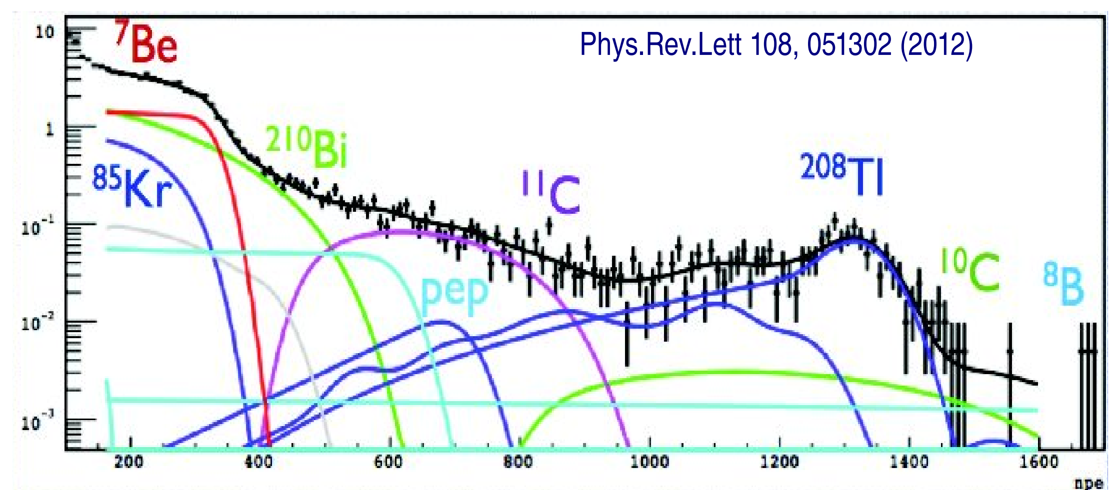
Phys.Rev.Lett. 107, 141302 (2011)



Detection of *pep* neutrinos possible thanks to improvements in bkgd reduction, specially ^{11}C.







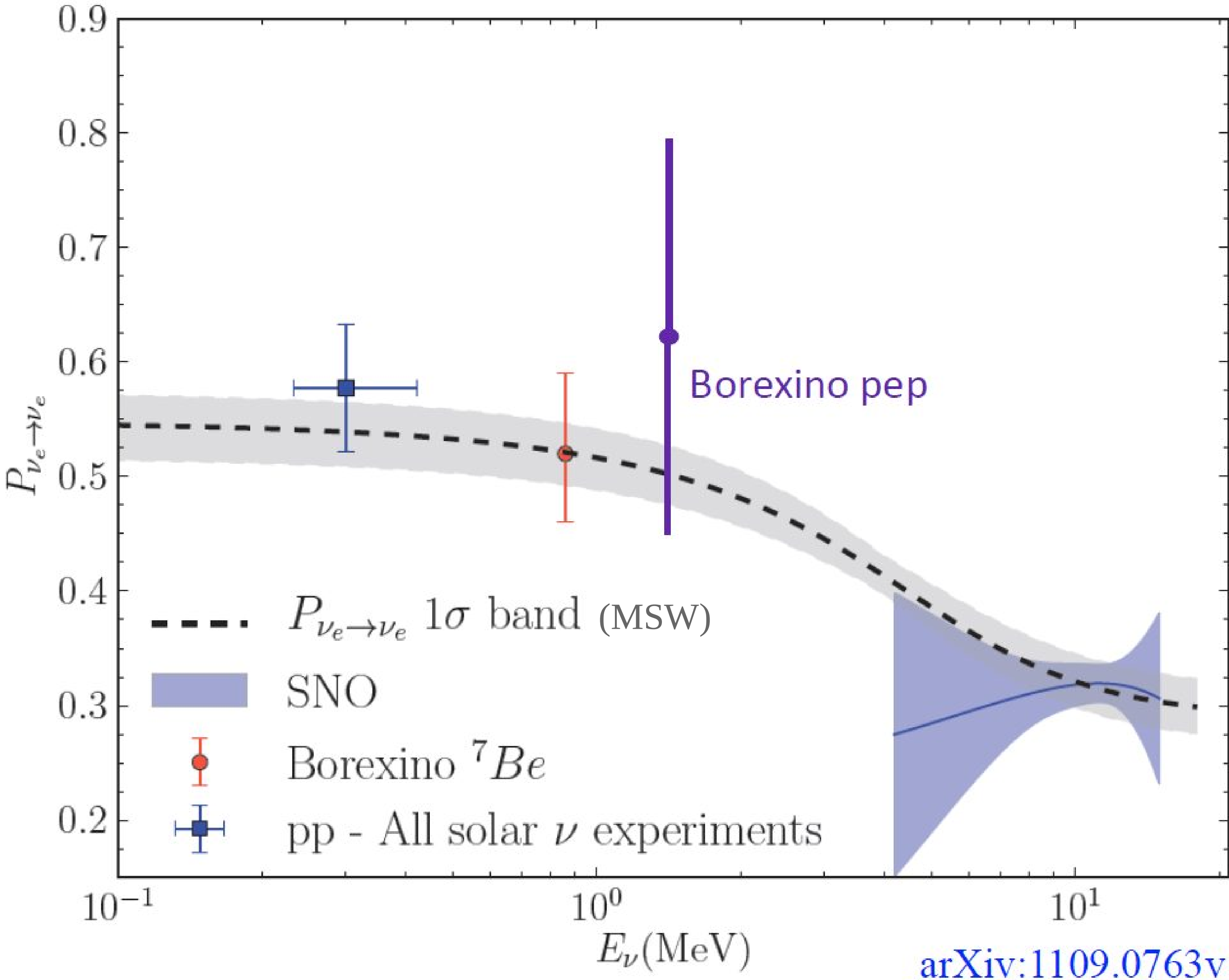
Phys.Rev.Lett 108, 051302 (2012)

R(^{7}Be) = 46 ± 2.1 evts. (100 ton)$^{-1}$ día^{-1}
Φ (^{7}Be) = (4.84 ± 0.24)×10^9 cm^{-2} s^{-1}.

R(*pep*) = 3.1 ± 0.67 evts. (100 ton)$^{-1}$ day^{-1}
Φ(*pep*) = (1.6 ± 0.3)×10^8 cm^{-2} s^{-1}.

Consistent with MSW effect: **$\Delta m^2 = 7.6\times10^{-5}$ eV^2 , $\sin^2\theta = 0.32$**

Survival probability status, 2012



arXiv:1109.0763v1 [nucl-ex]

Atmospheric neutrinos

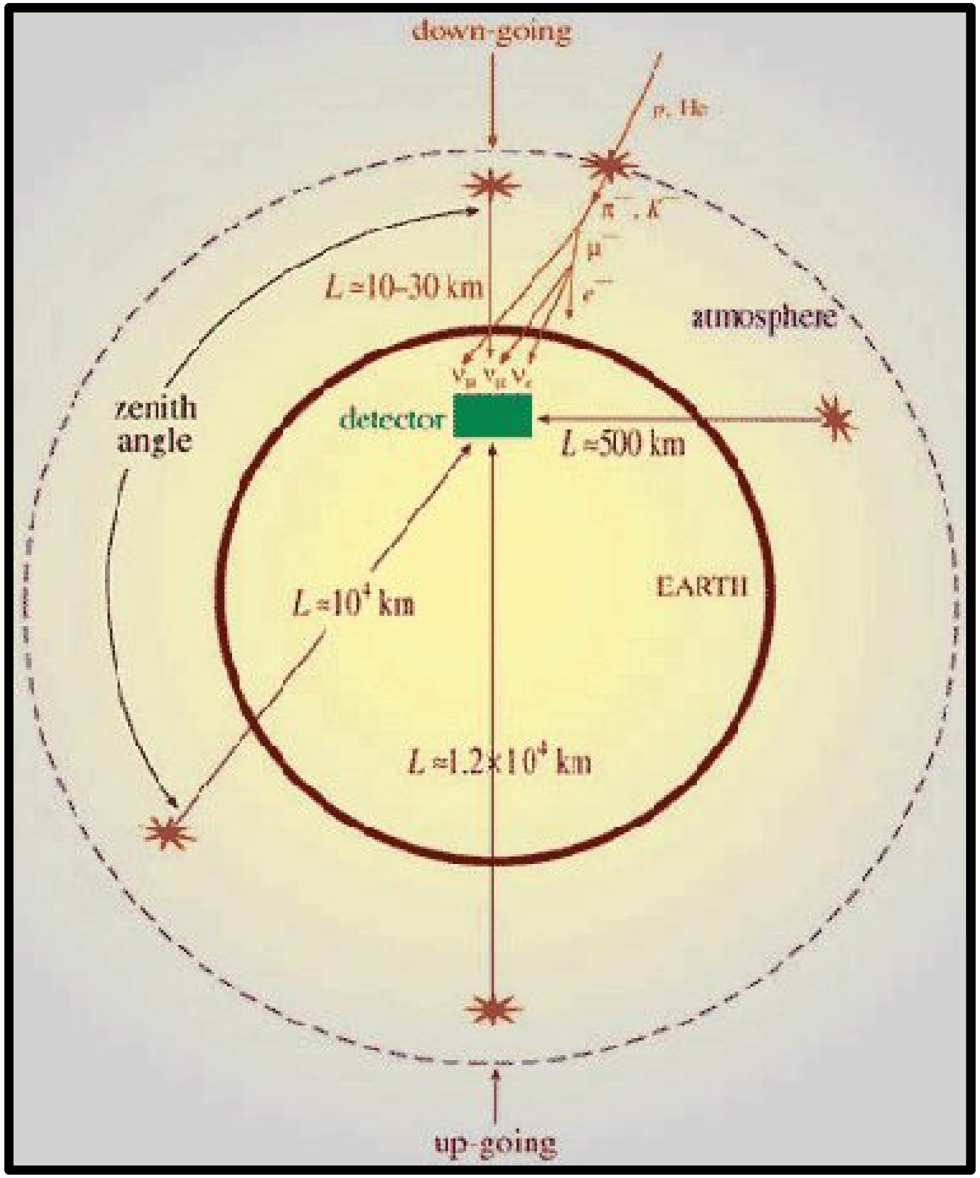
Decay of π, K, μ produced by cosmic rays (protons) interactions with O_2 & N_2 in the upper atmosphere.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu ,$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu ,$$
$$K^+ \rightarrow \mu^+ + \nu_\mu + X ,$$
$$K^- \rightarrow \mu^- + \bar{\nu}_\mu + X ,$$

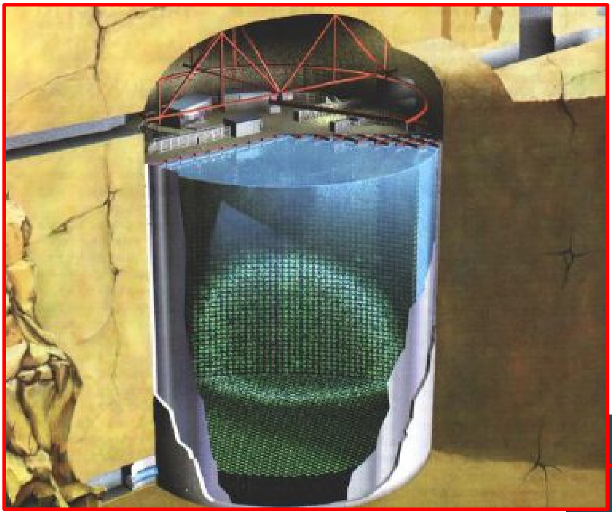
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e ,$$
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

If all μ decayed:

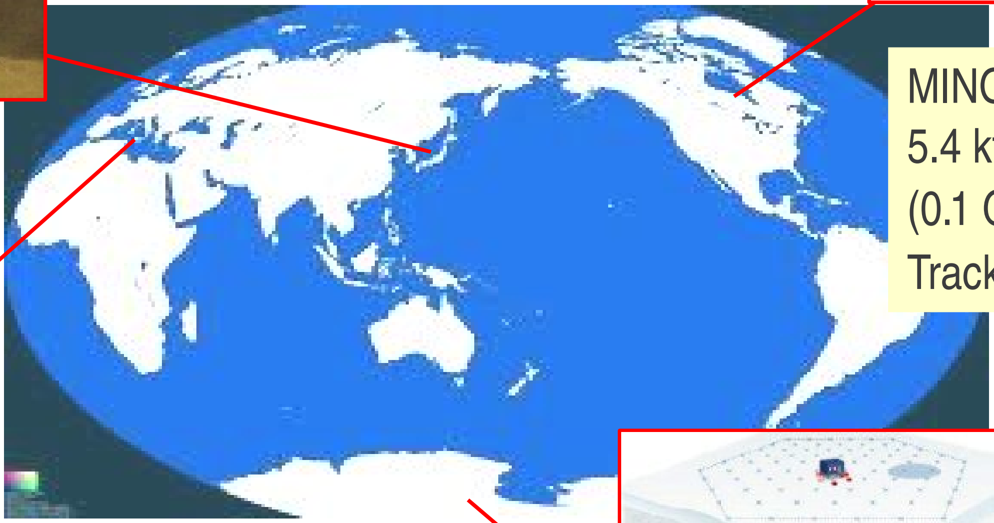
$$\frac{(\nu_\mu + \bar{\nu}_\mu)}{(\nu_e + \bar{\nu}_e)} = 2$$

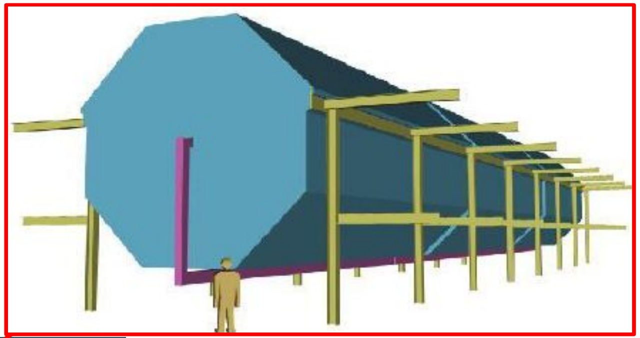


Atmospheric neutrino experiments (2012)

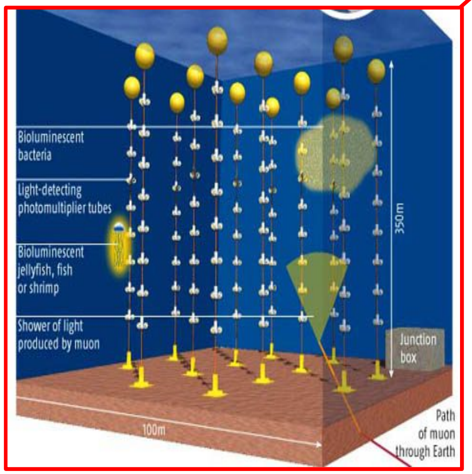


Super-Kamiokande (1996-)
50 kt Water Cherenkov
Low threshold (>4 MeV)
Highly advanced analysis

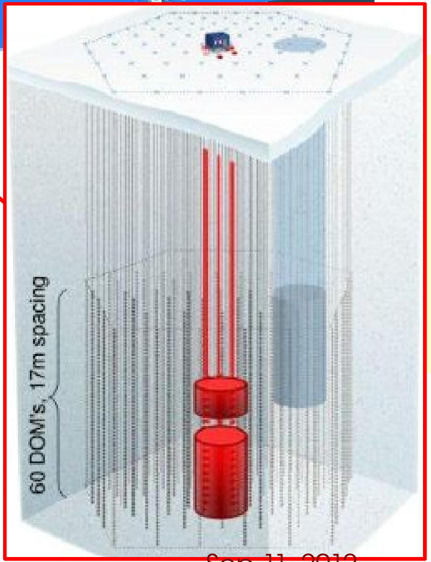




MINOS (Far Detector)
5.4 kt magnetized Iron
(0.1 GeV<E_ν< 250 GeV)
Tracker, magnetic field



ANTARES
20 Mt sea water
(~100 GeV)
10,000 m2 undersea area



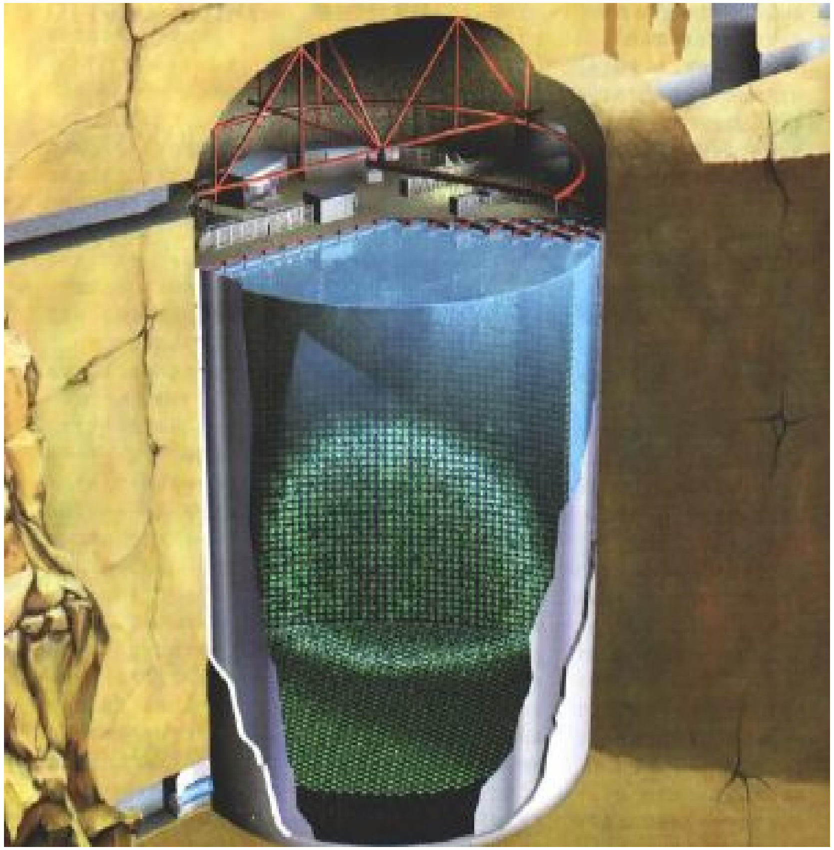
IceCube/DeepCore
(2005-/2010-)
1 Gt / ~1 Mt of ice.
(~100 GeV / 10 GeV)
Gigantic target volume

Atmospheric neutrinos with Super-K

- Detect ν's with ~ 300 MeV < E_ν < 50 GeV.

- Events grouped in various samples:
  - low E_{dep} fully contained (FC).
  - high E_{dep} partially contained (PC).
  - ***e*** -like, or ***μ***-like

- Compare *upward* and *downward* going μ's
  - ↑ μ : traverse the Earth (12,00 km)
  - ↓ μ : traverse the atmosphere (20 km)

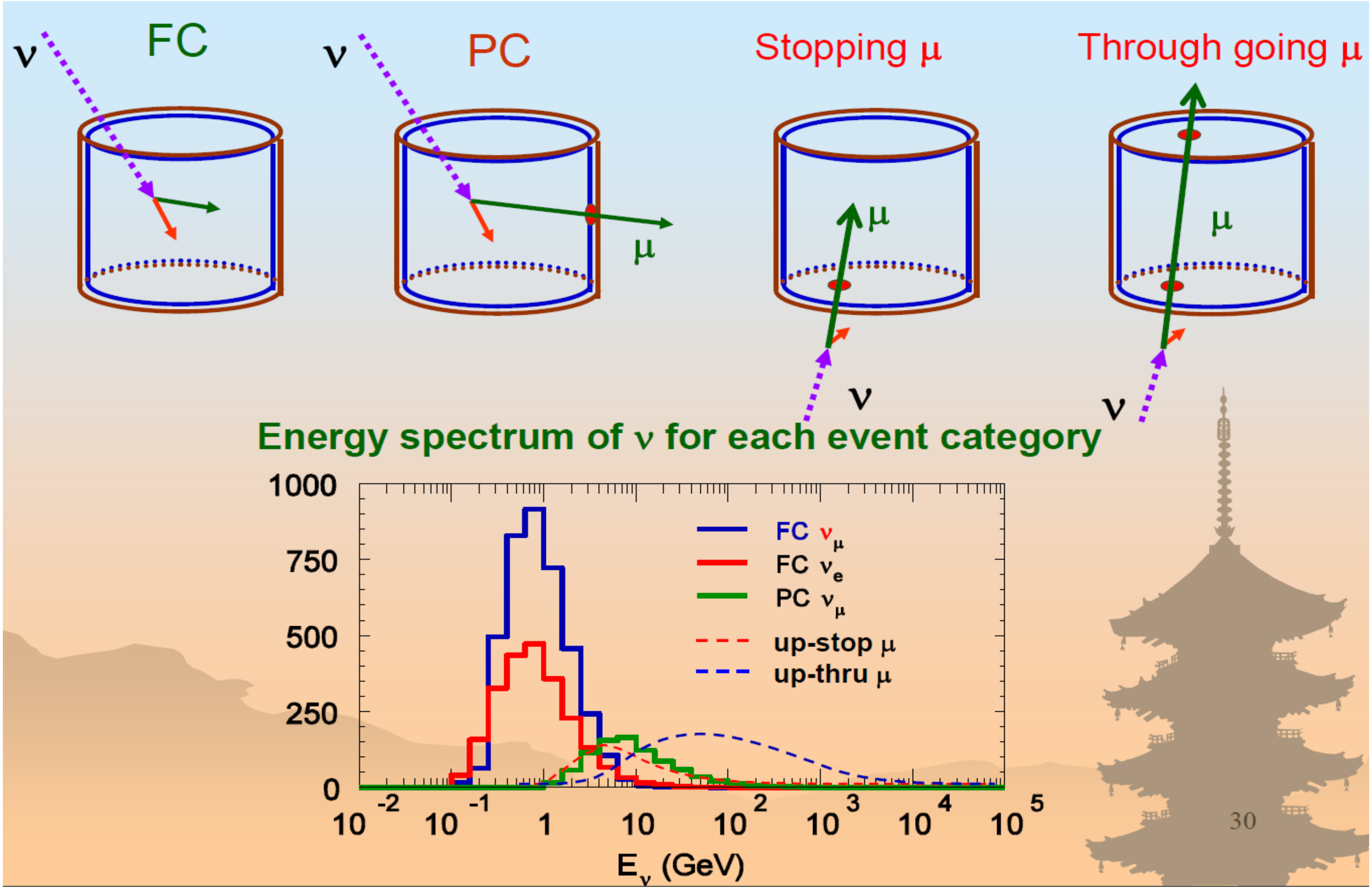


SK's observation in 1998 of atmospheric neutrino disappearance was the first conclusive evidence in favor of neutrino oscillations

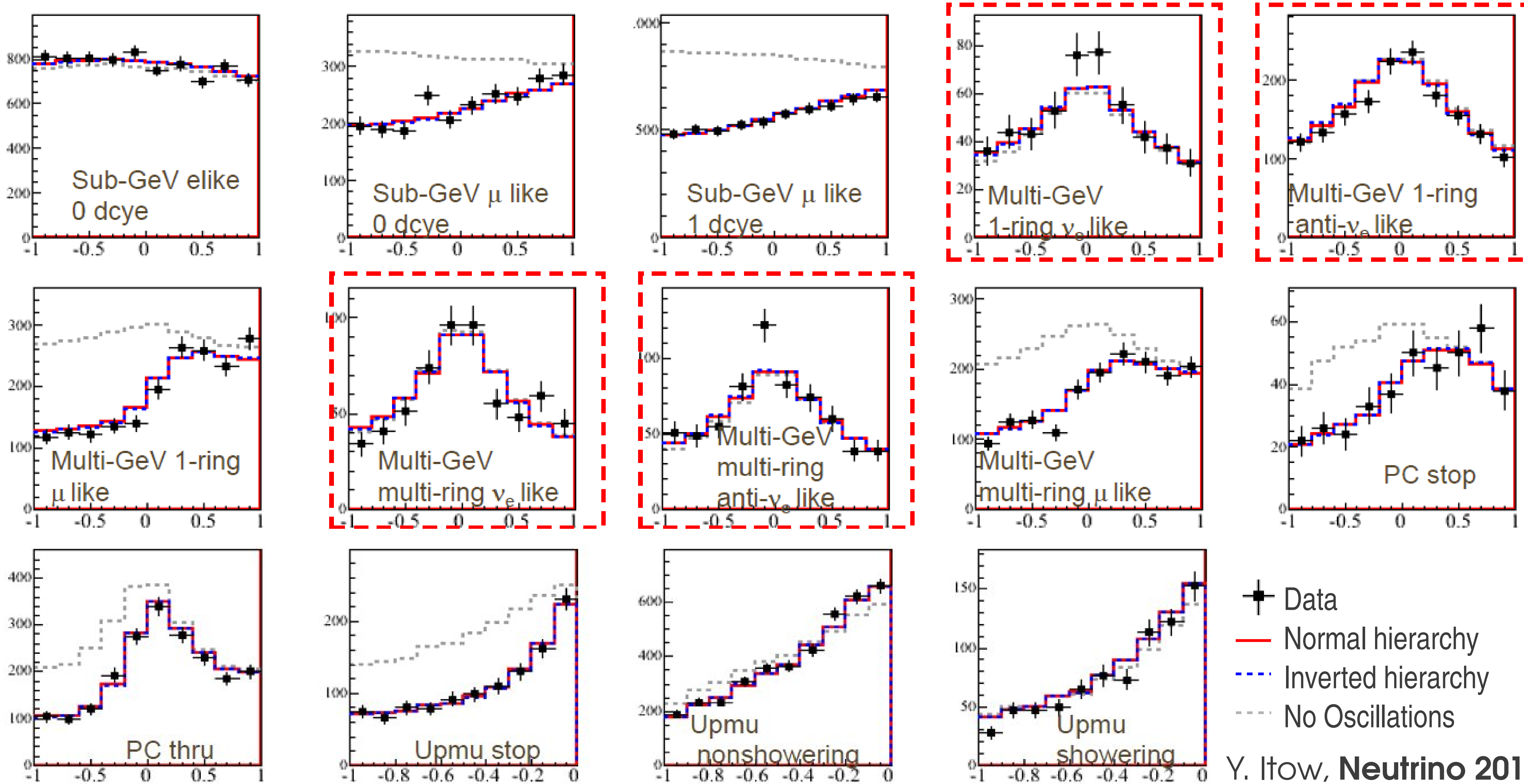
Y.Fukuda *et al.*, Phys. Rev. Lett. 81 (1998) 1562-1567.

Super-K: atmospheric neutrino event categories

Y. Itow, **Neutrino 2012**

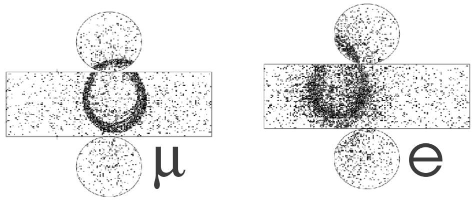


Super-K (I+II+III+IV): atmospheric neutrinos, 3-ν analysis



Y. Itow, **Neutrino 2012**

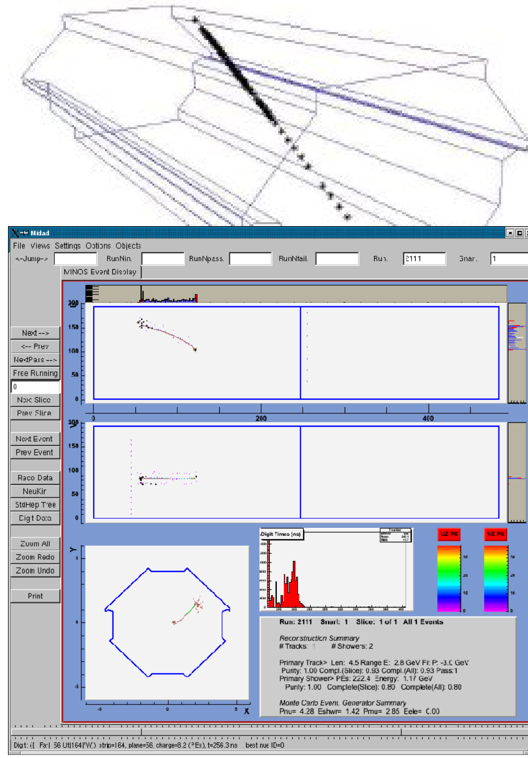
• **Fixed $\sin^2\theta_{13}$ =0.025**

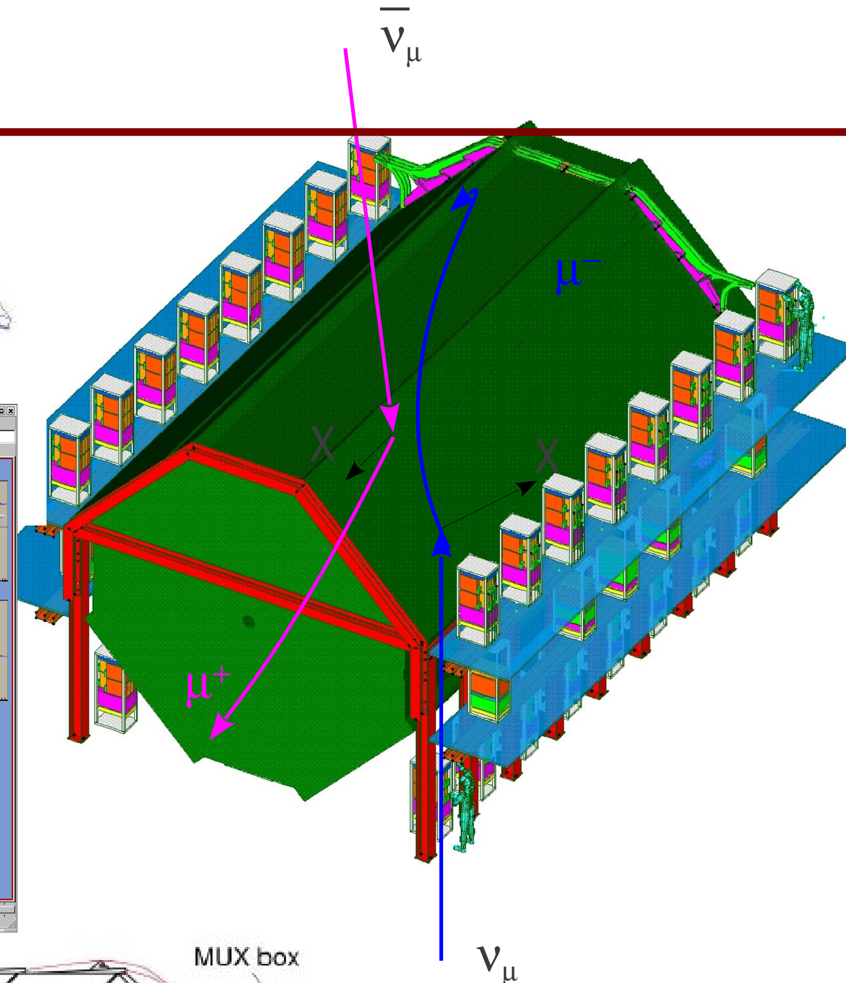


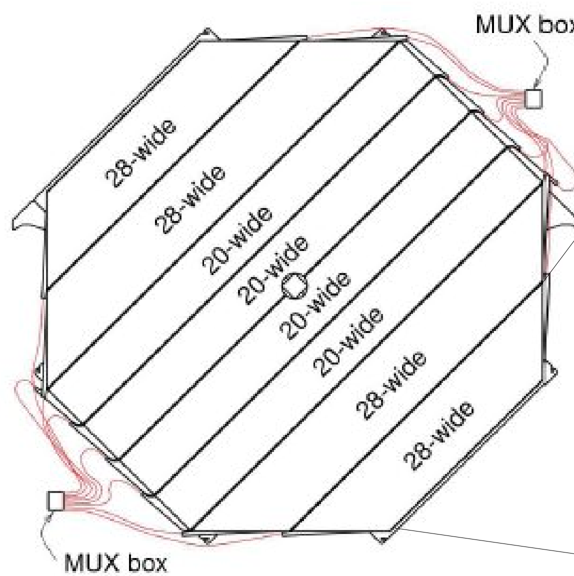
↑ cos θ=-1
↓ cos θ=+1

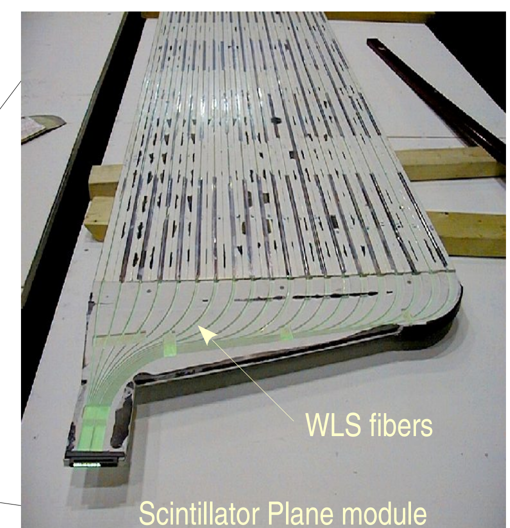
***μ*-like events coming from below are disappearing (oscillate to ν_τ).**

MINOS Far Detector



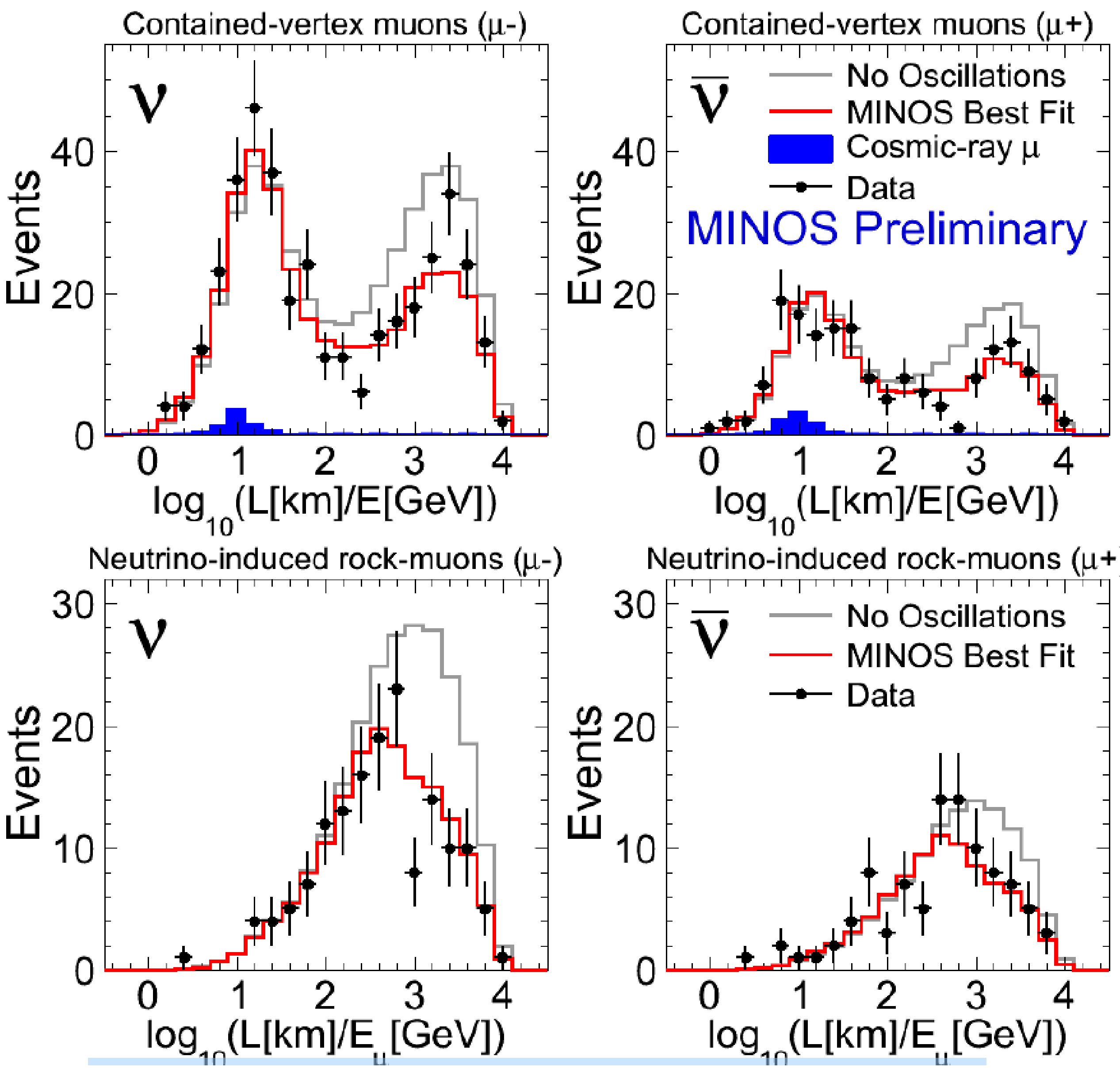






- Magnetized Fe detector (15 kA-turns)
- Can separate $\mu+$ from $\mu-$ tracks
- 486 planes (Fe & plastic scintillator sandwich)
- U/V oriented planes give X-Y position of hits along a track. Plane position gives Z.
- 5,400 ton mass

MINOS: atmospheric neutrinos



37.9 ton-yr

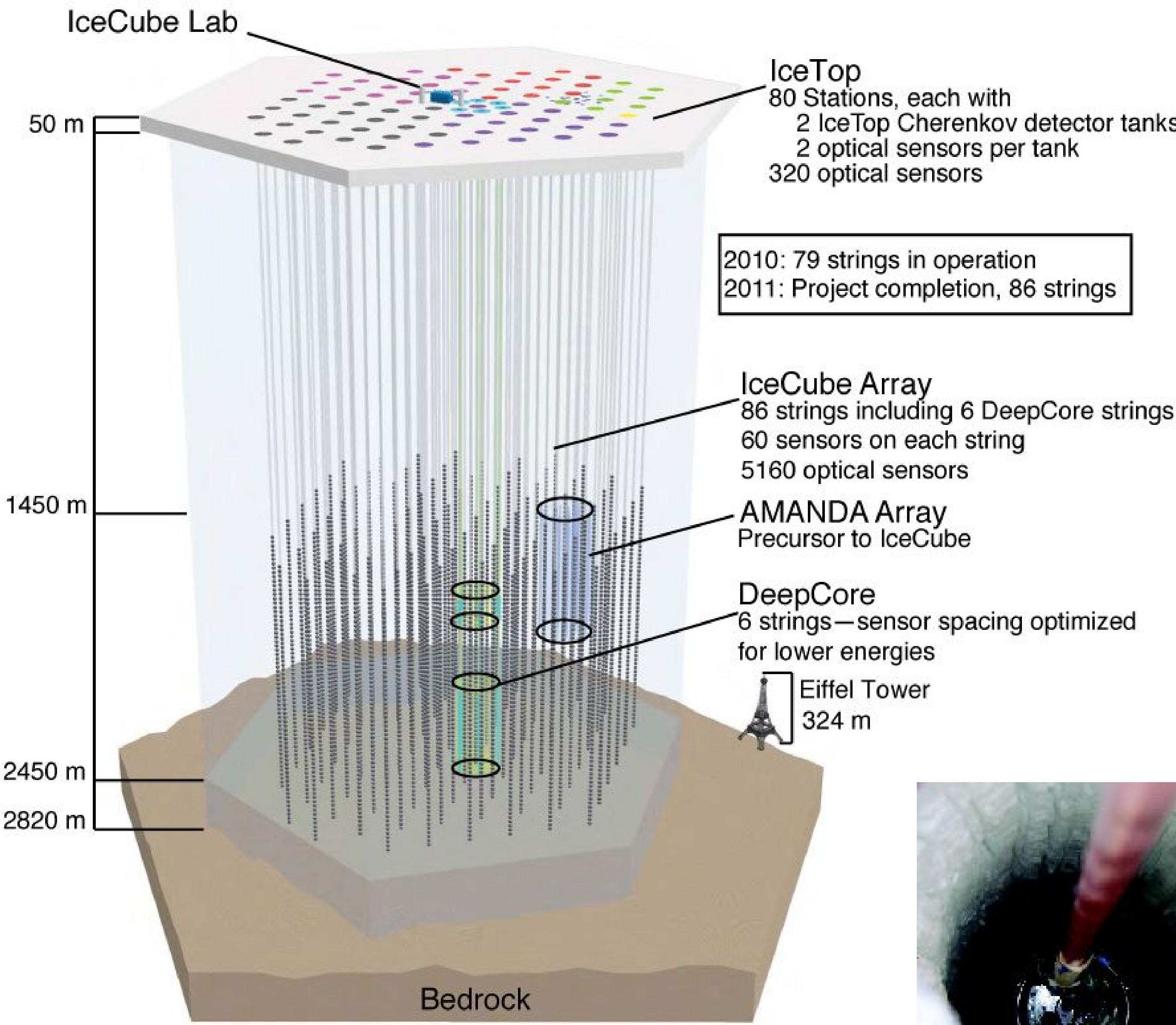
531 ν

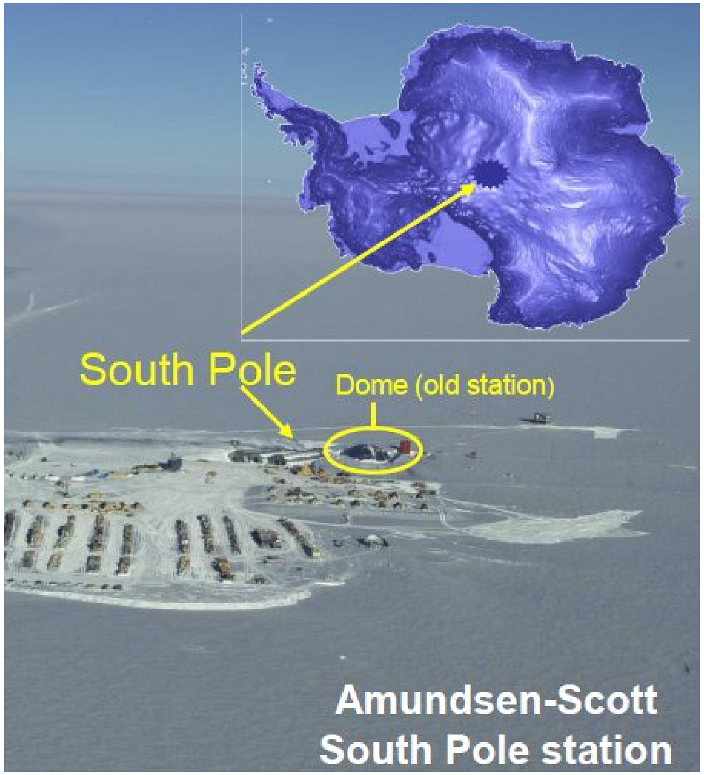
268 $\bar{\nu}$

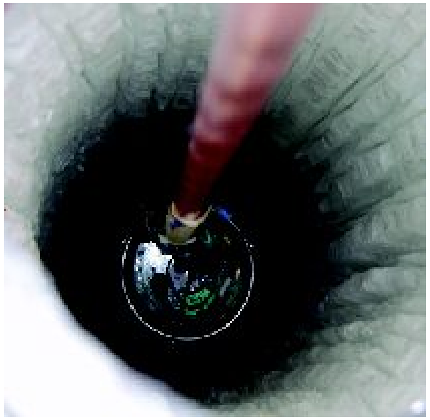
(98% purity)

B. Rebel, Neutrino 2012

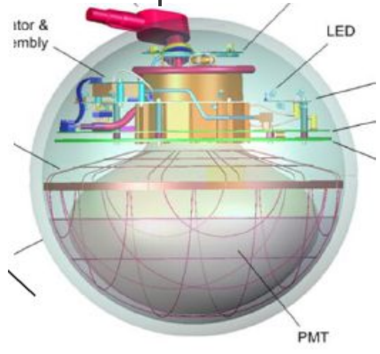
IceCube/DeepCore





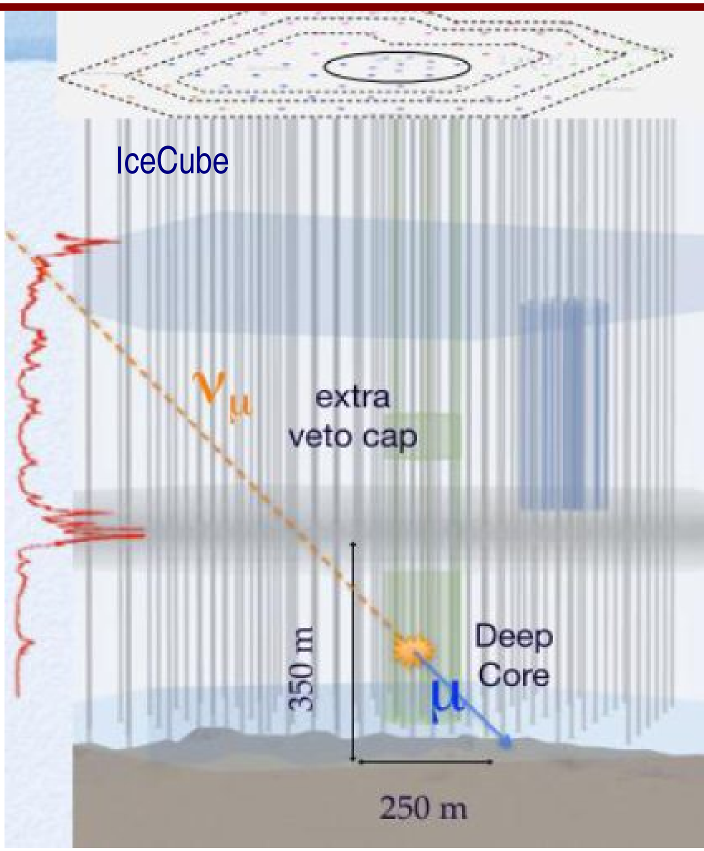


Detector Optical Module

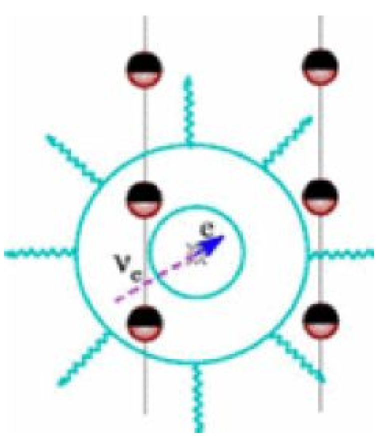


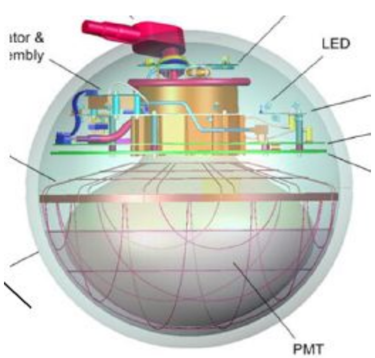
Primary goal: Detect UHE ν's from the cosmos

IceCube/DeepCore: atmospheric neutrinos

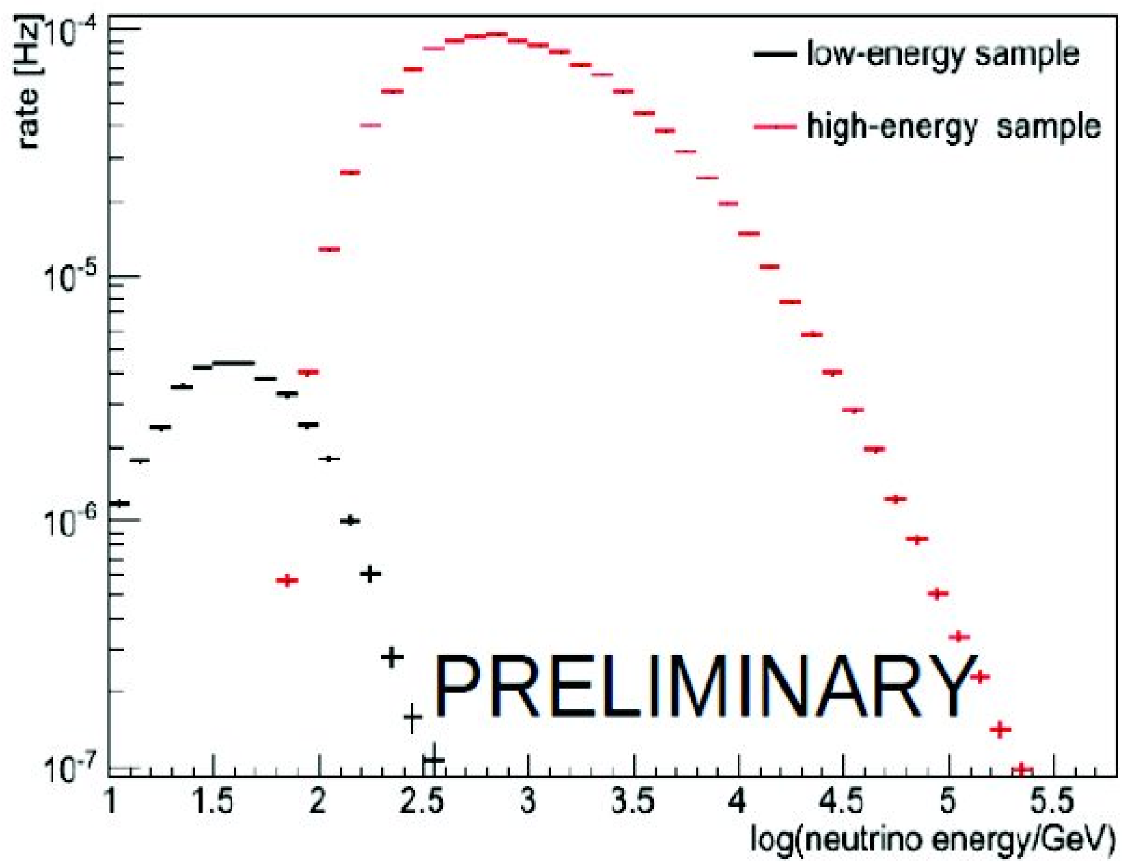


- Inner array of 8 strings within IceCube
- Spaced every 72 m (*vs* 125 m in IceCube).
- Strings instrumented with 60 high efficiency DOM's.
- Allows detection of lower energy ν's (10 – 500 GeV)
- Taking data since June 2012.



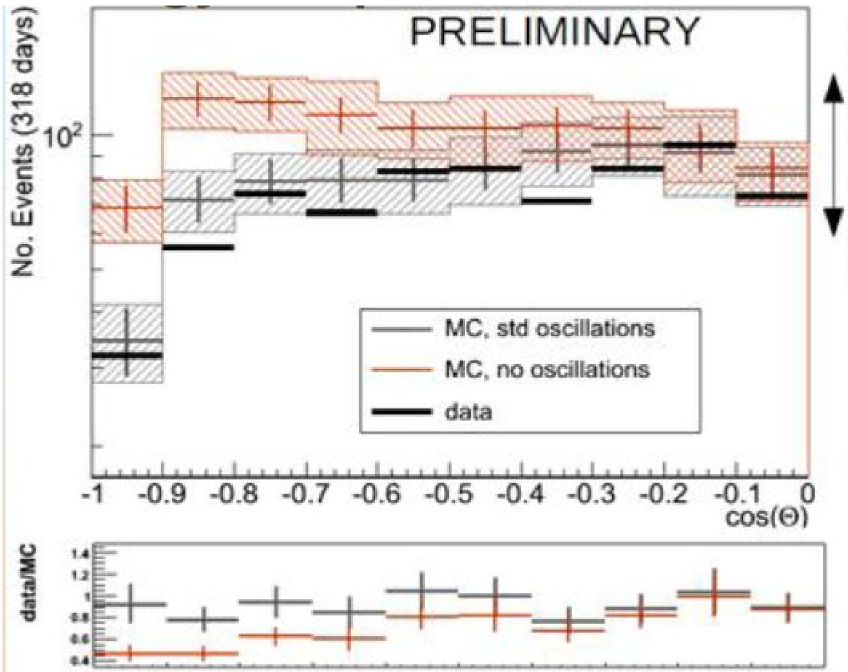


DOM

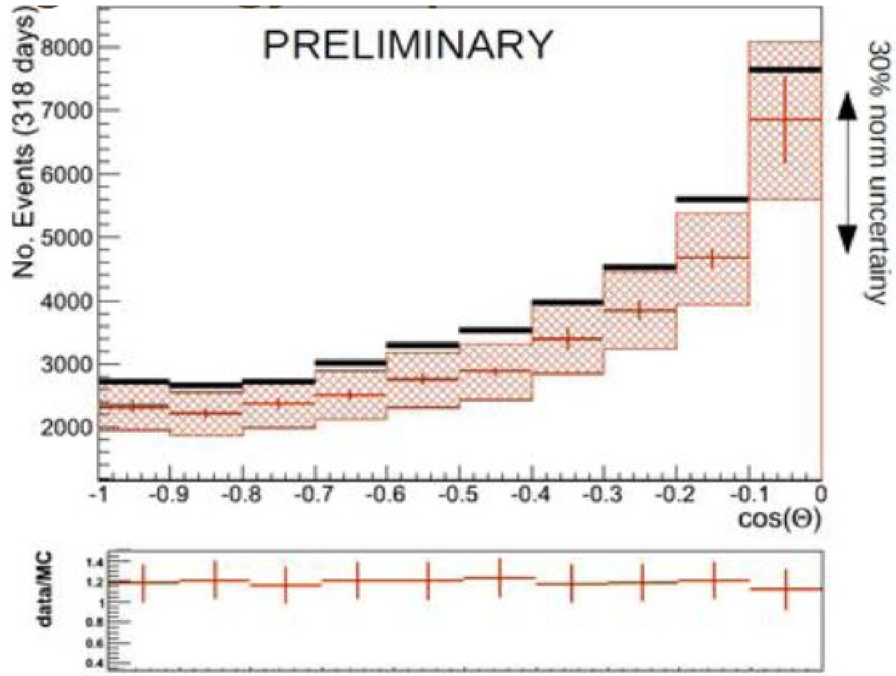


IceCube/DeepCore: atmospheric neutrinos, IC-79

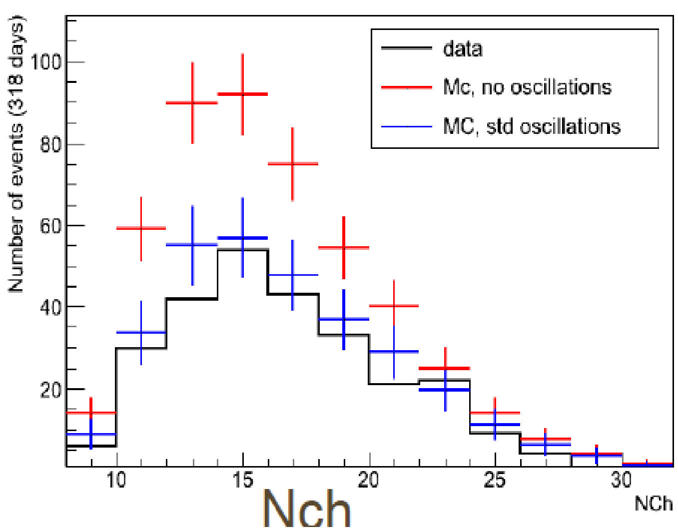
Low energy sample



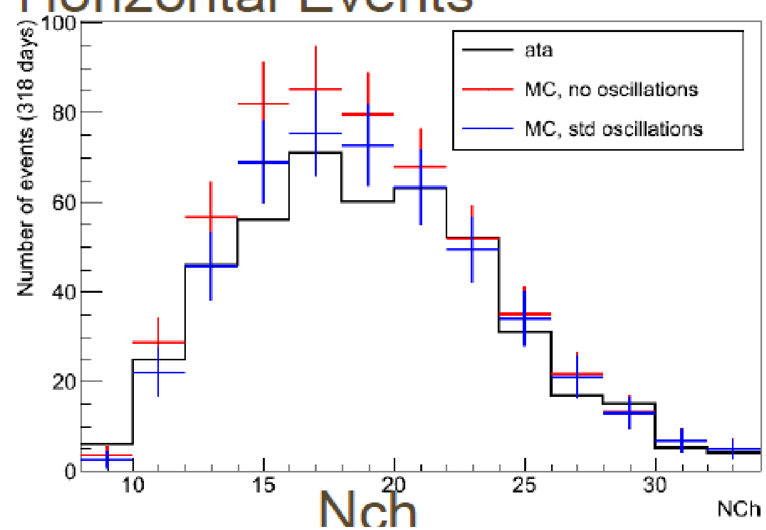
High energy sample



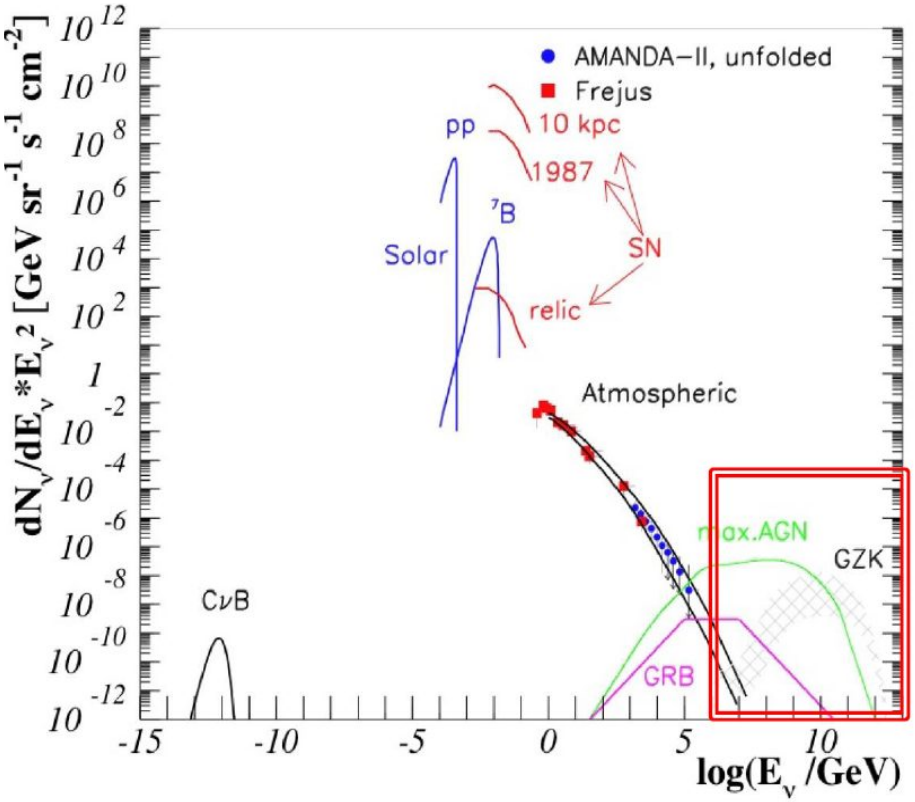
Vertical Events

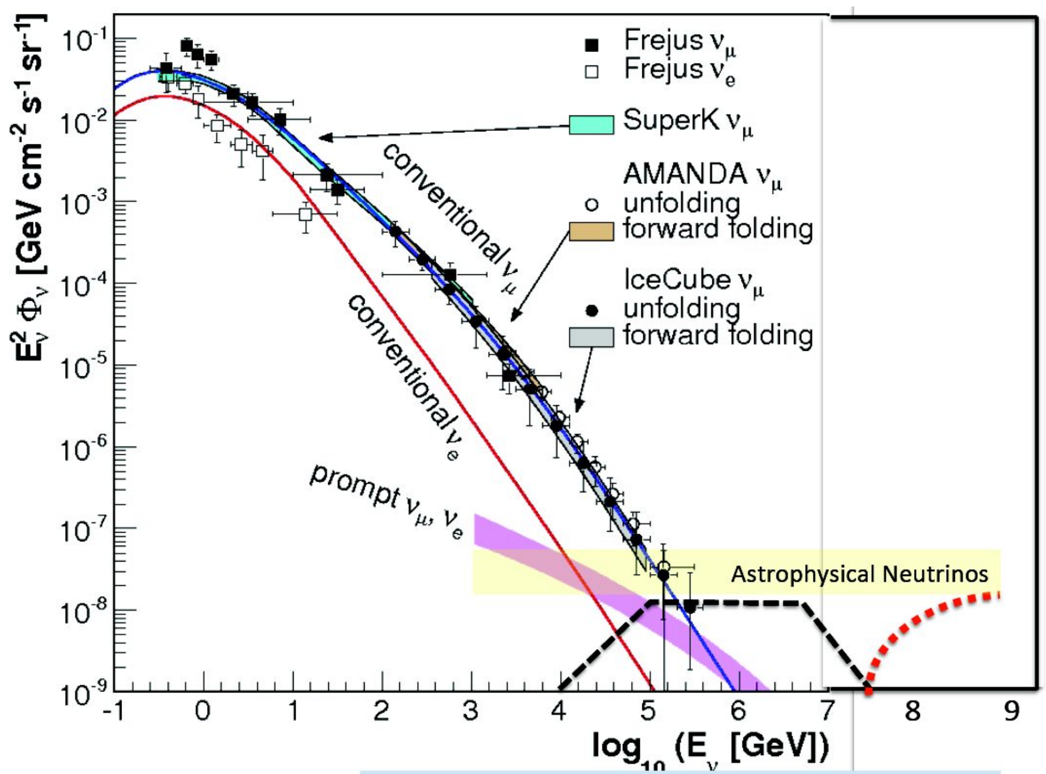


Horizontal Events



Ultra high energy neutrinos (UHE-ν's) (>PeV)





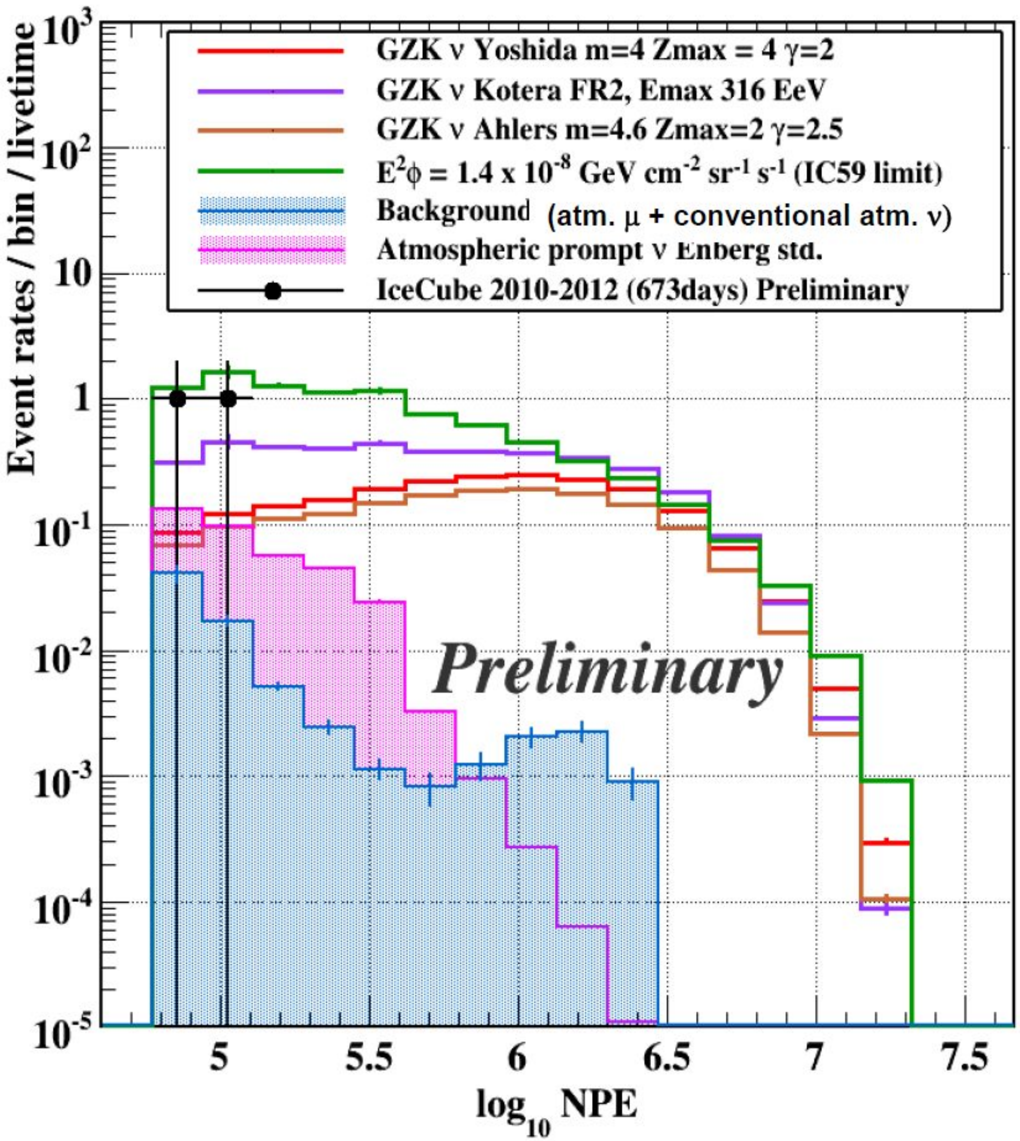
- Higher energies than atmospheric neutrinos which dominate in flux
- UHE cosmic rays "*warrant*" UHE-ν's.
- Expected from a variety of sources: *eg.* AGN's. GRB's, GZK cut-off

Cosmogenic neutrinos: induced by the interactions of cosmic rays with CMB photons

- Produced via the GZK (Greisen-Zatsepin-Kuzimnin) mechanism (**E_ν ~ $10^{8\text{-}10}$ GeV**).

$$p\gamma_{2.7K} \rightarrow \pi^+ + X \rightarrow \mu^+ + \nu \rightarrow e^+ + \nu' s$$

IceCube, search for UHE-ν's (2010-2012 data)



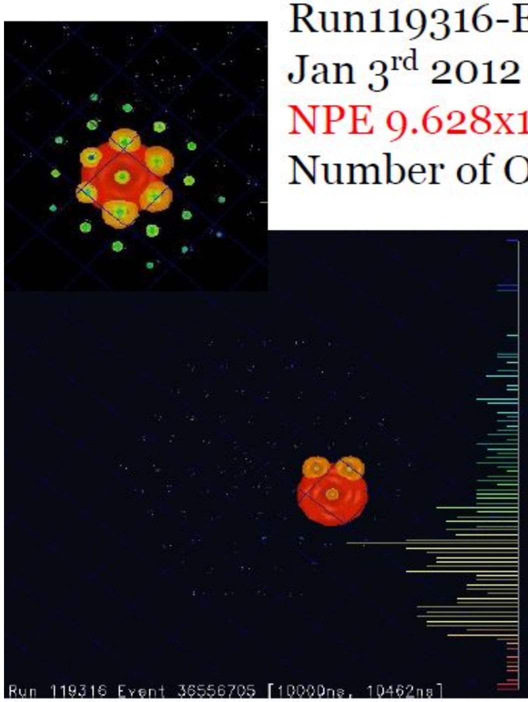
- 2010-2012 search (672.7 days).
- Observes 2 high PE events.
  Energy estimated around 1 – 10 PeV.
- Models predict between 2 and 4 events.
- **No** indication that they are instrumental noise.
- Could be:
  - cosmogenic neutrinos
  - conventional atmospheric neutrinos
  - non-conventional atmospheric neutrinos (prompt)

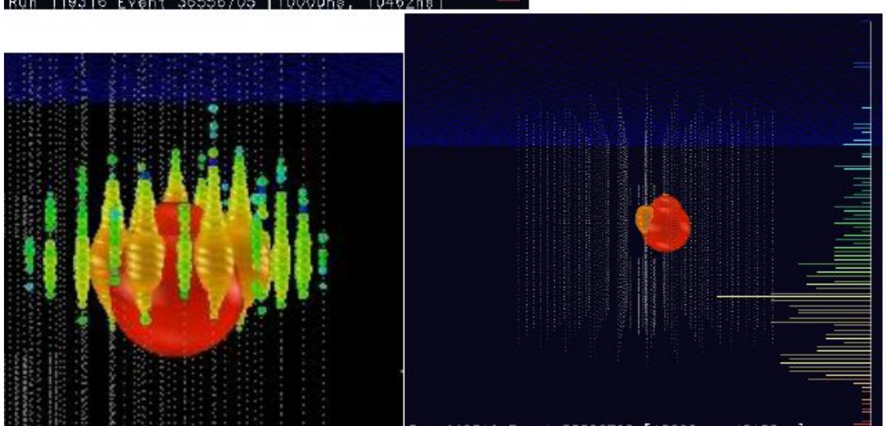
IceCube, search for UHE-ν's (2010-2012 data)

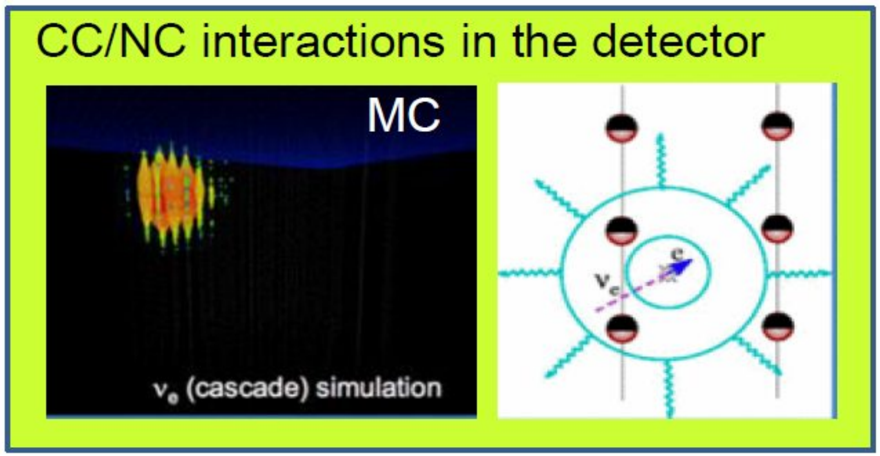
2010-2011 (79 strings) + 2011-2012 (86 strings)

2 events / 672.7 days – expected bkg. (atmos. μ + conventional atmos. ν) 0.14 events
p-value: p=0.0094 (2.36 σ)

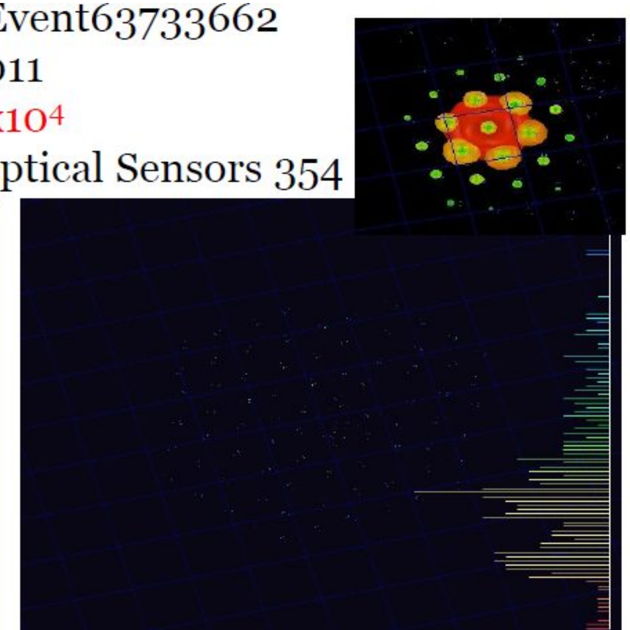
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628×10^4
Number of Optical Sensors 312

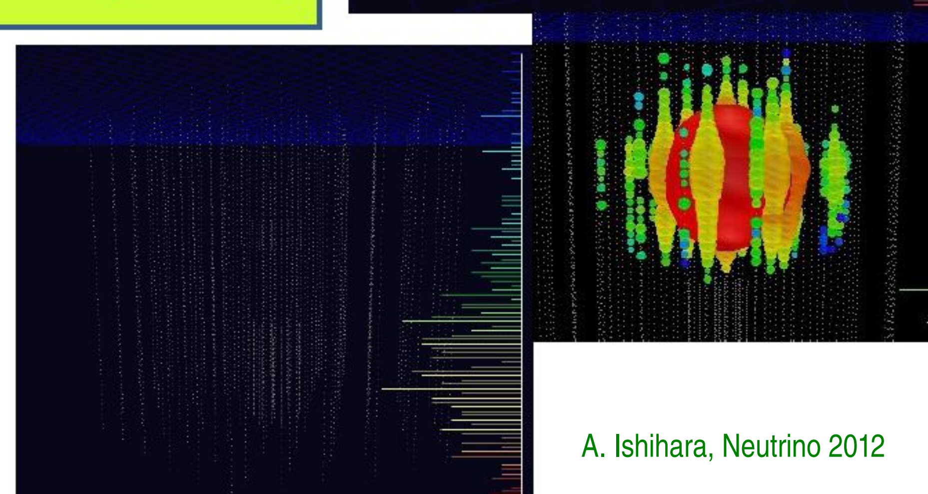






Run118545-Event63733662
August 9th 2011
NPE 6.9928×10^4
Number of Optical Sensors 354





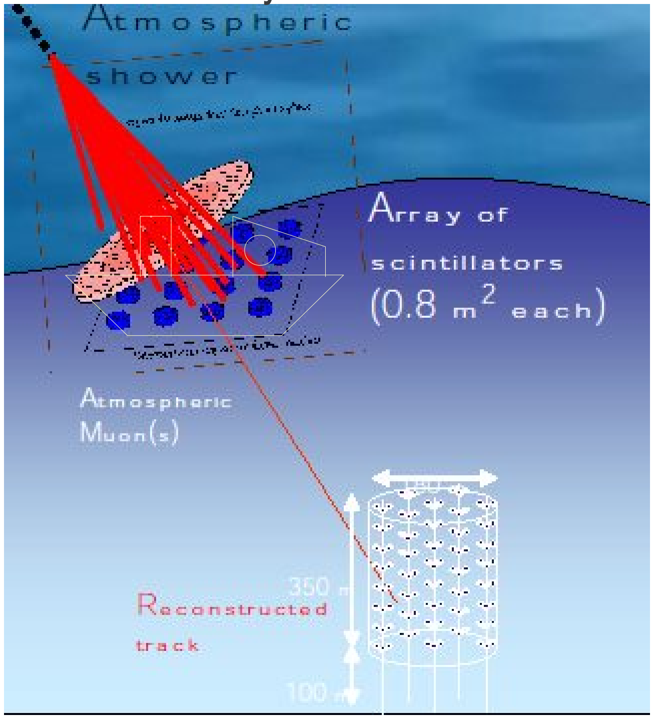
A. Ishihara, Neutrino 2012

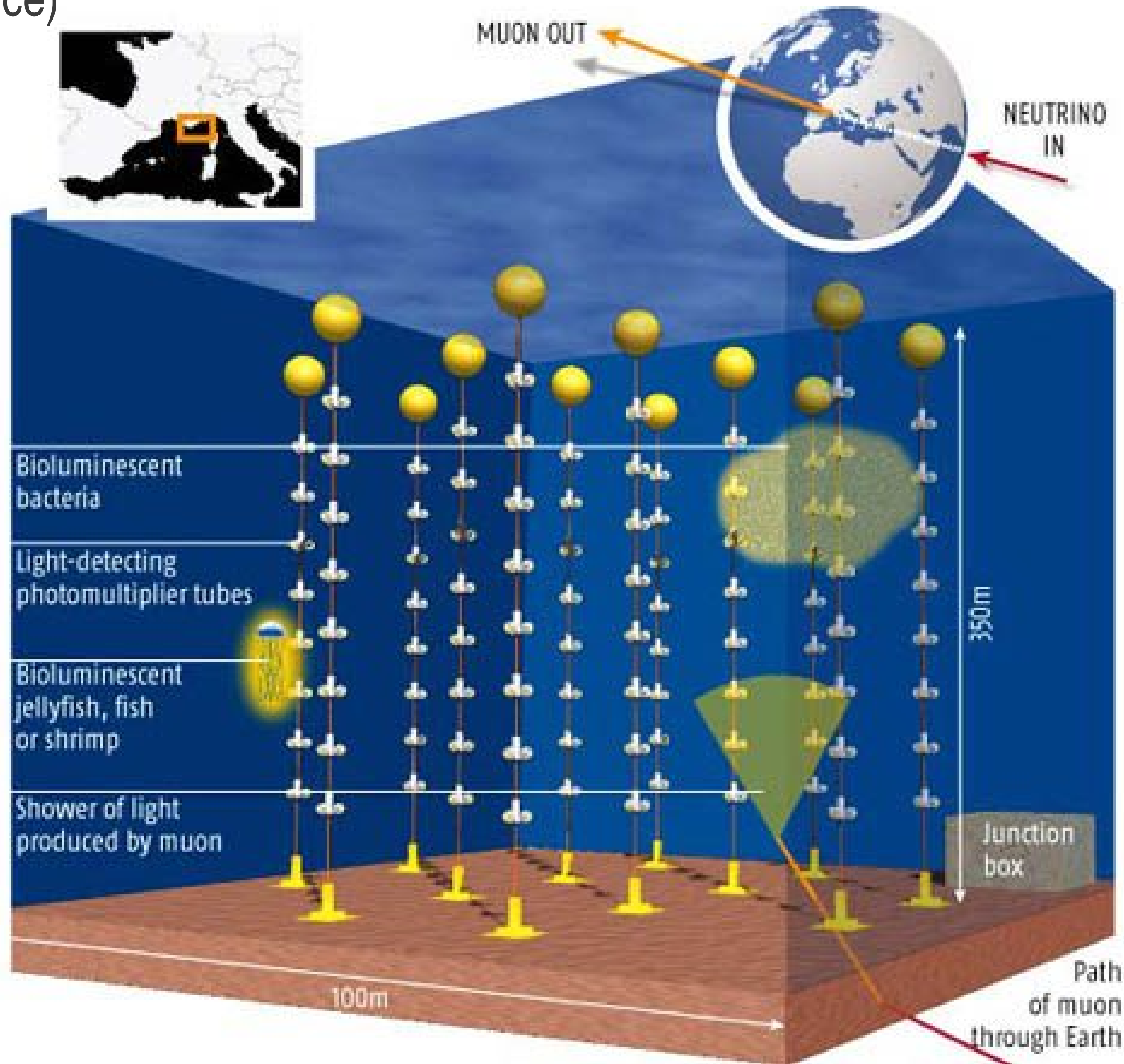
ANTARES (Astronomy with a Neutrino Telescope and Abys RESearch)

- Underwater neutrino telescope in the northern hemisphere
- Mediterranean sea (Toulon, France)
- 10,000 m^2 surface area
- 20 Mton instrumented volume

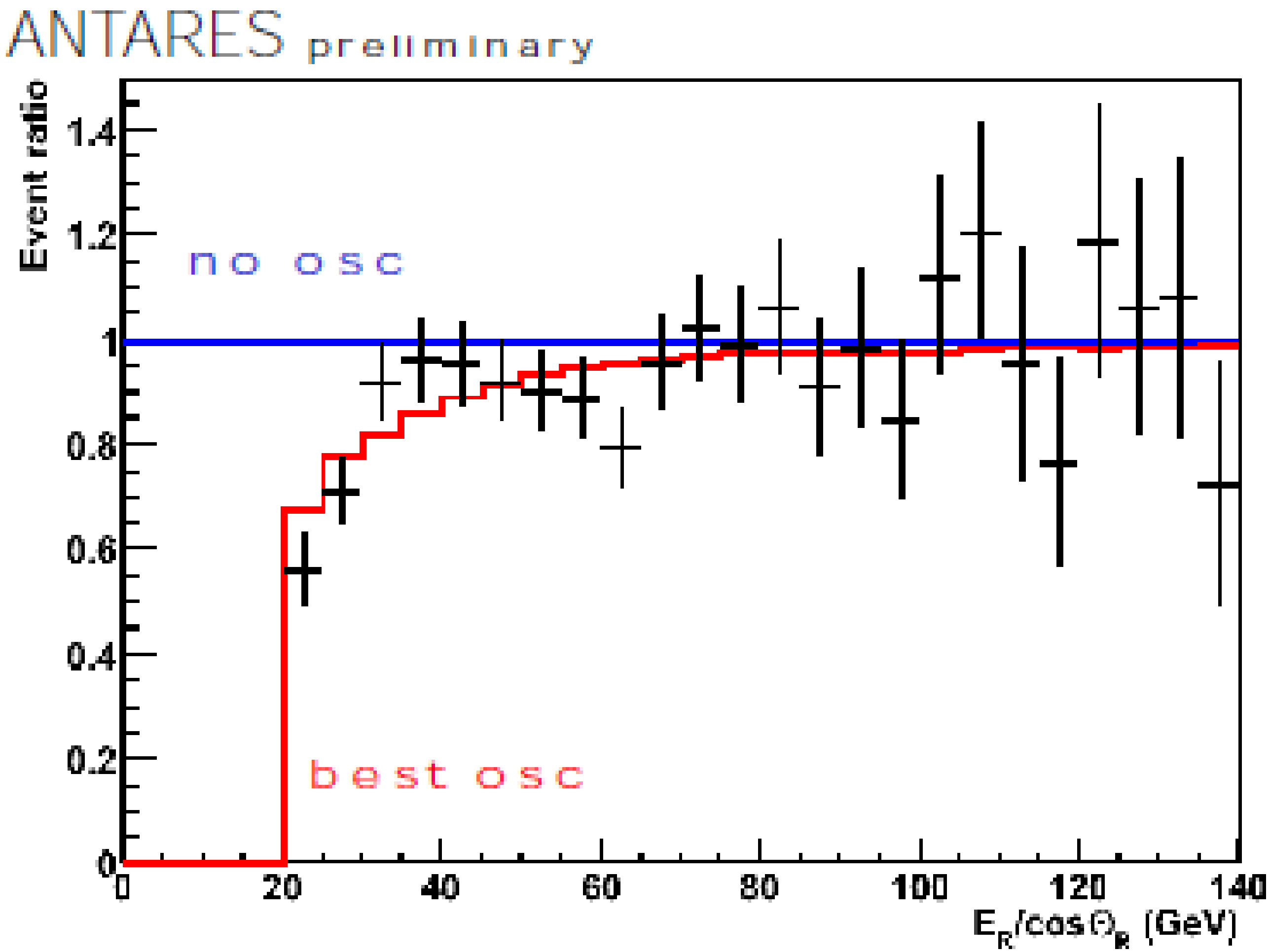
Direccionality:

Scintillator array in a boat

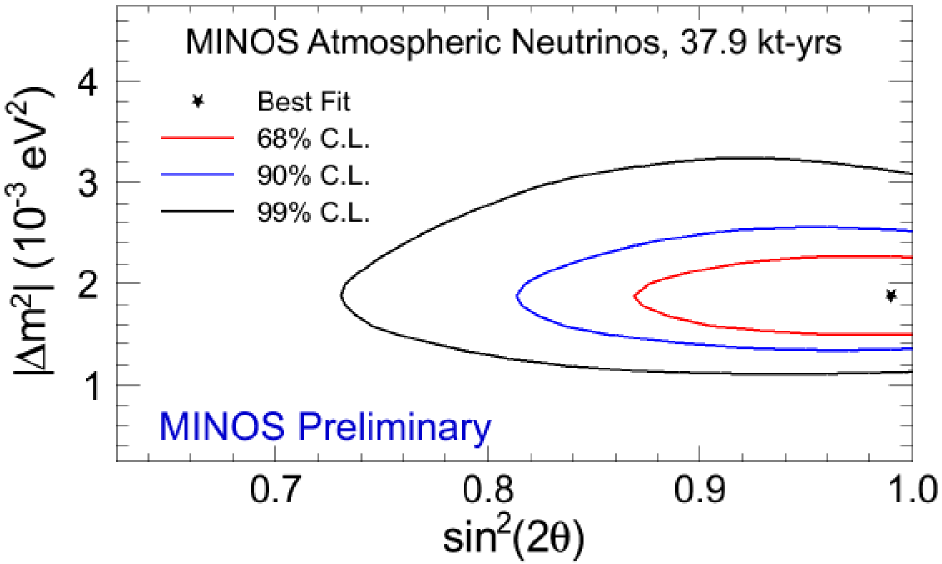


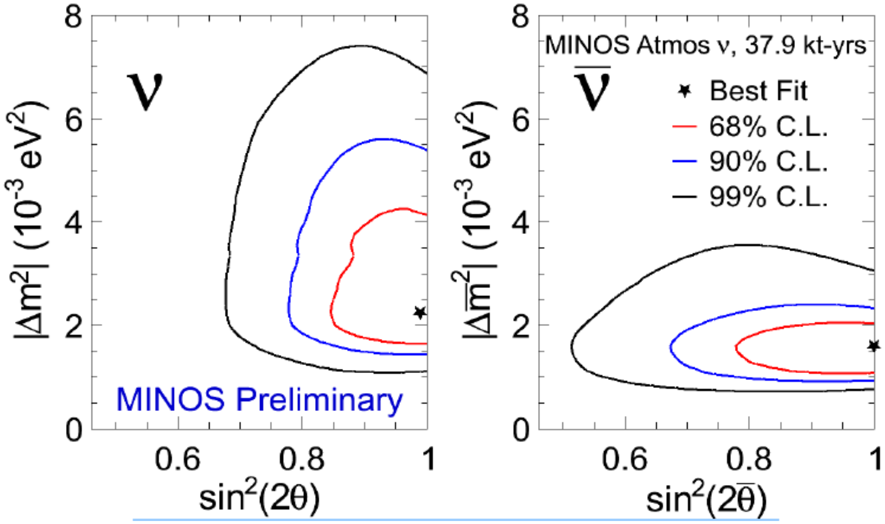


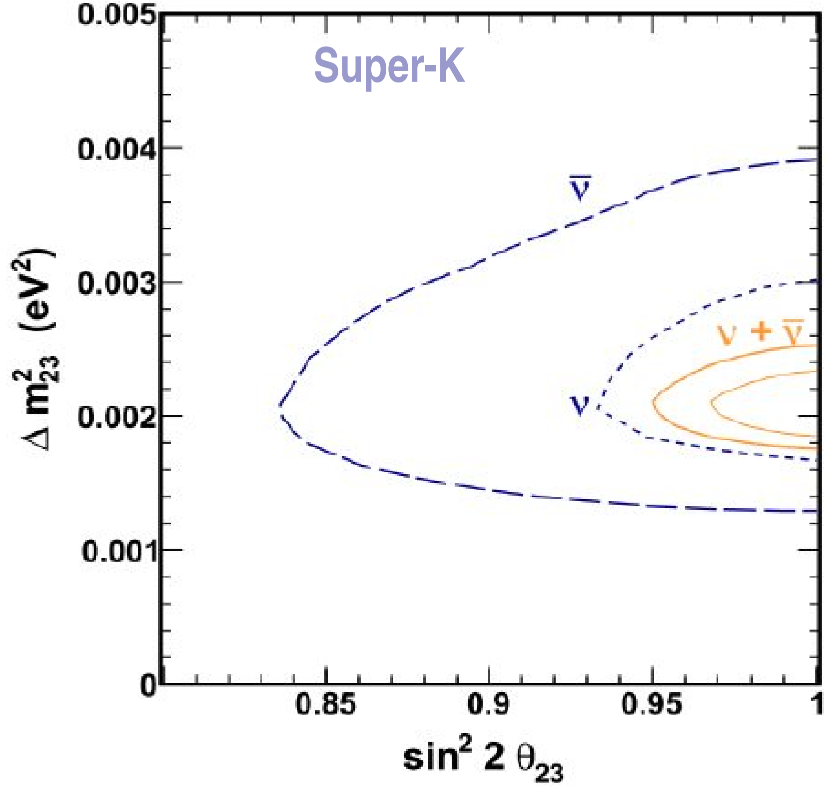
ANTARES, atmospheric neutrino oscillations

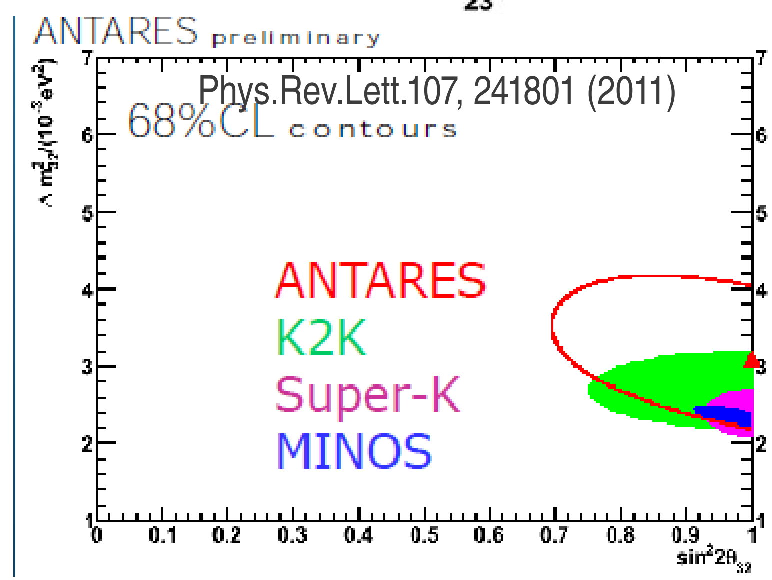


Atmospheric neutrino oscillations









$\Delta m_{23}^2 \sim 2.1\times10^{-3}\ eV^2$

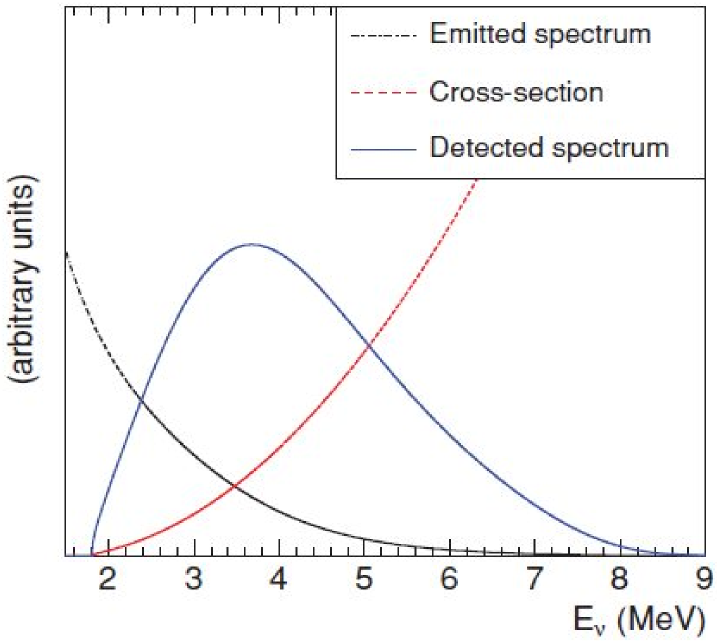
$\sin^2 2\theta_{23} \sim 44°$

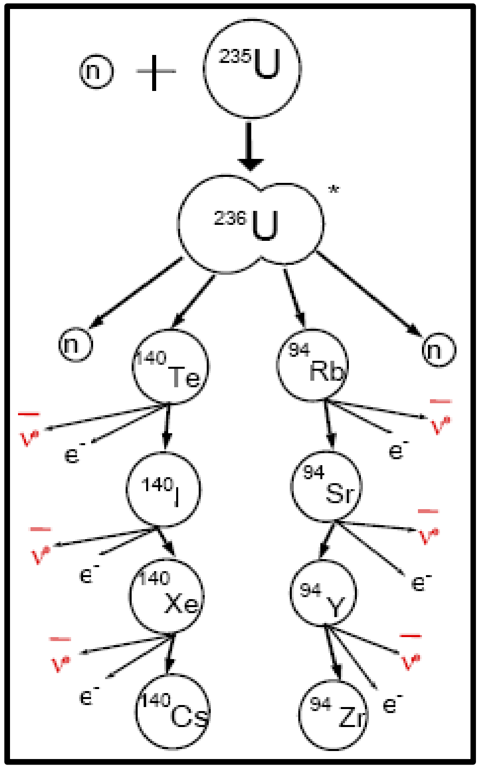
Neutrinos from nuclear reactors

- Intense sources of $\bar{\nu}_e$: ~[6 $\bar{\nu}_e$, 200 MeV] / fission
- Typically: ~ **2×10^{20} $\bar{\nu}_e$*/sec/GW*$_{th}$**

$$R_\nu = \frac{6\,\bar{\nu}/\,fission}{200\,MeV/\,fission} \times \frac{P_{th}(Watts)}{1.6\times10^{-13}\,J/MeV} = 1.875\times10^{20}\left(\frac{P_{th}}{1\;GWatt}\right)\frac{\bar{\nu}}{s}$$

- Neutrino flux depends on:
  1. *Reactor power,*
  2. *Fission rates of U^{235}, U^{238}, Pu^{239}, Pu^{241},*
  3. *E_ν spectra of fission product β decays*

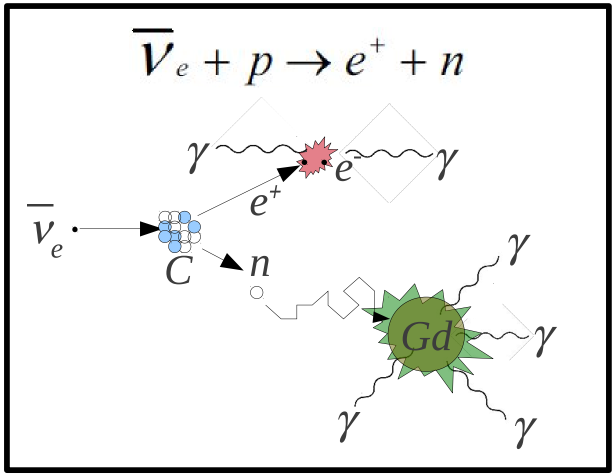




Detected via ***inverse β decay (IBD)***:

➔ Threshold: E_ν>1.8 MeV

➔ Σ_{IBD}~ 10^{-41} (E_ν/10 MeV)^2 cm^2

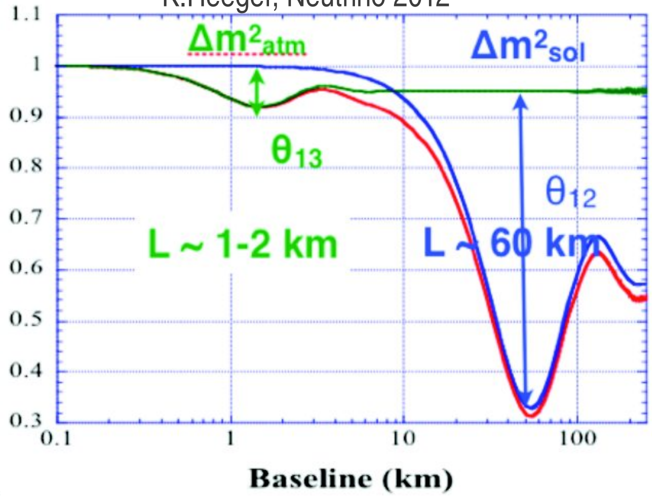


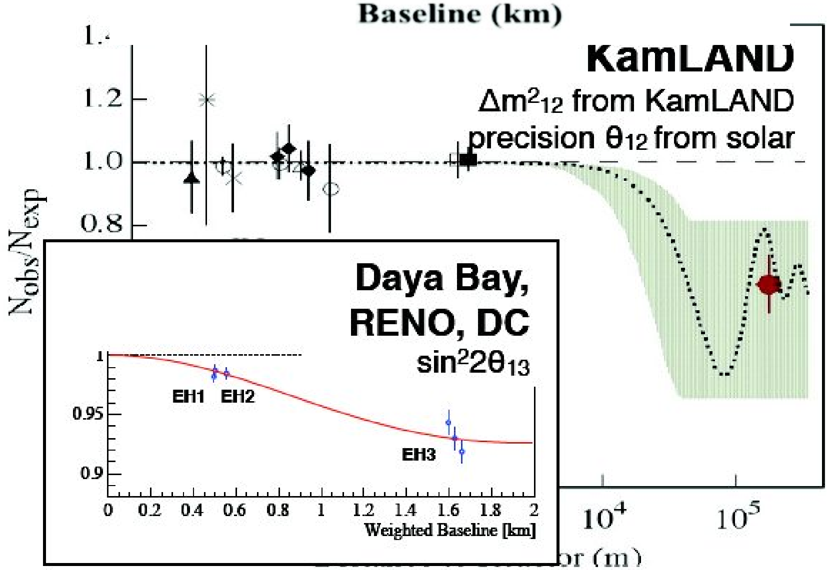
Measuring oscillations with reactor neutrinos

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

Δm_{31} term $\qquad$ Δm_{21} term

K.Heeger, Neutrino 2012





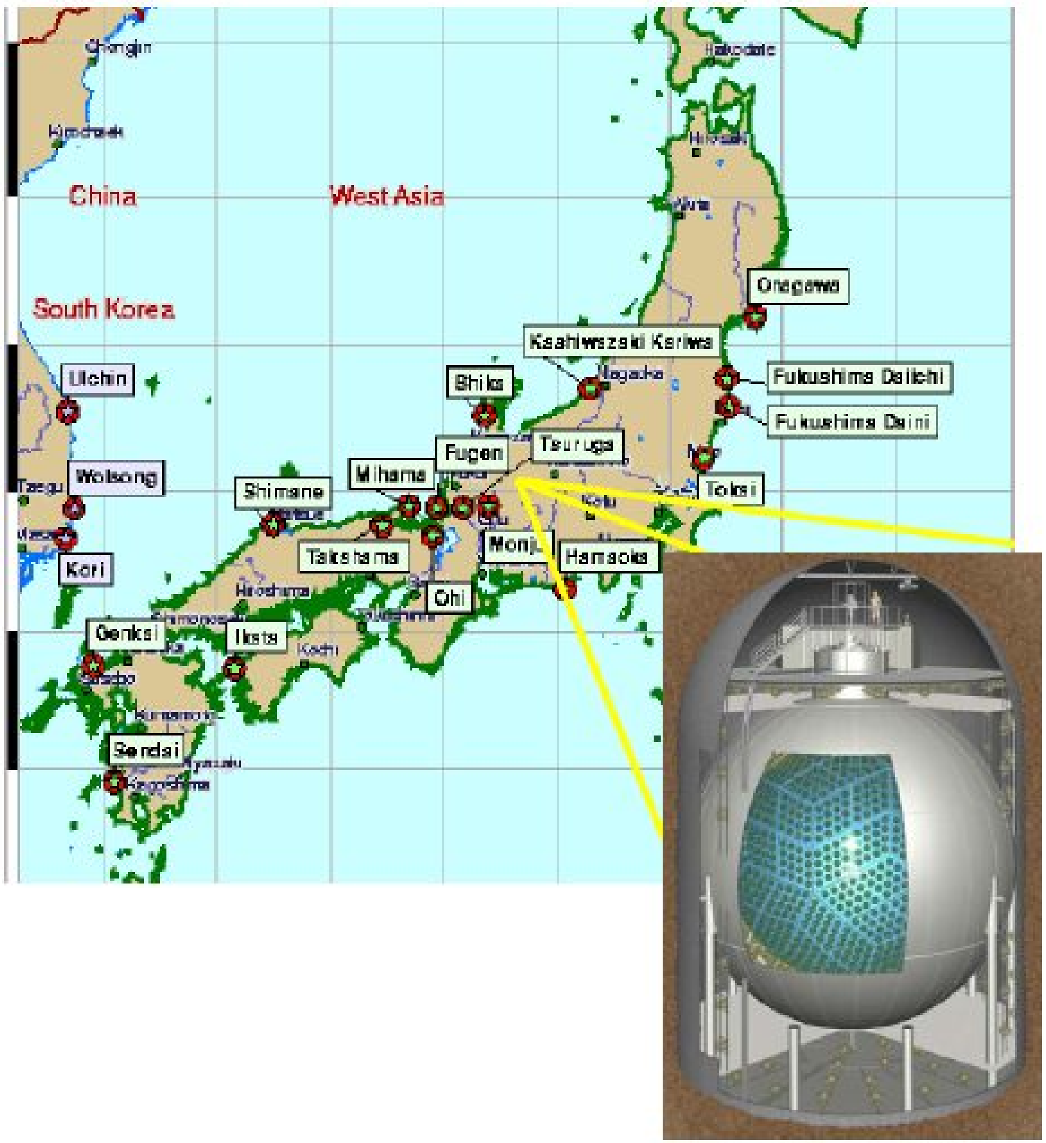
Most previous $\bar{\nu}_e$ disappearance searches with reactor neutrinos were too close to the sources.

KamLAND observed the effect of the Δm_{21} term by placing a detector at ⟨L⟩~150 km from reactors around Japan.

Later, (2011-2012) Double-Chooz, Daya Bay, and RENO reported the observation of the effect of the Δm_{31} term.

KamLAND (**Kam**ioka **L**iquid **An**tineutrino **D**etector)

Detected $\bar{\nu}$'s from *54 reactors around Japan* with <L> = 150 k
Kamioka mine, at 2700 m.w.e. (former site of Kamiokande)

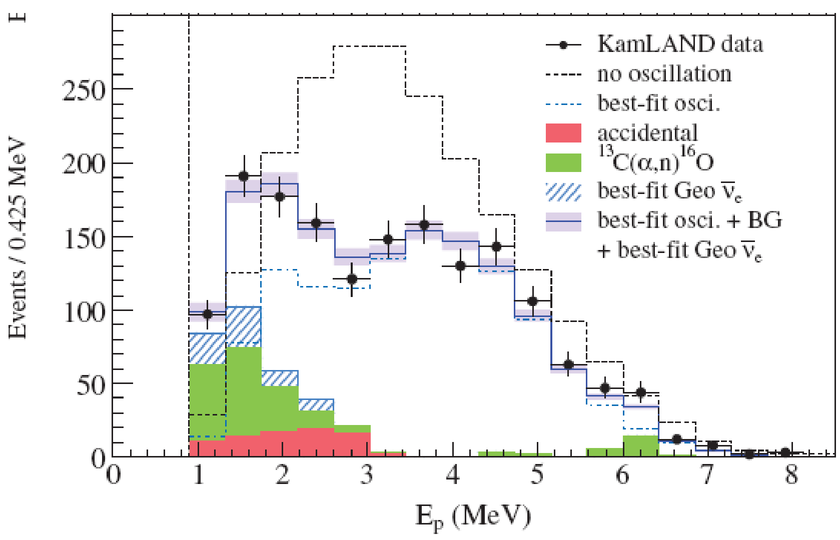


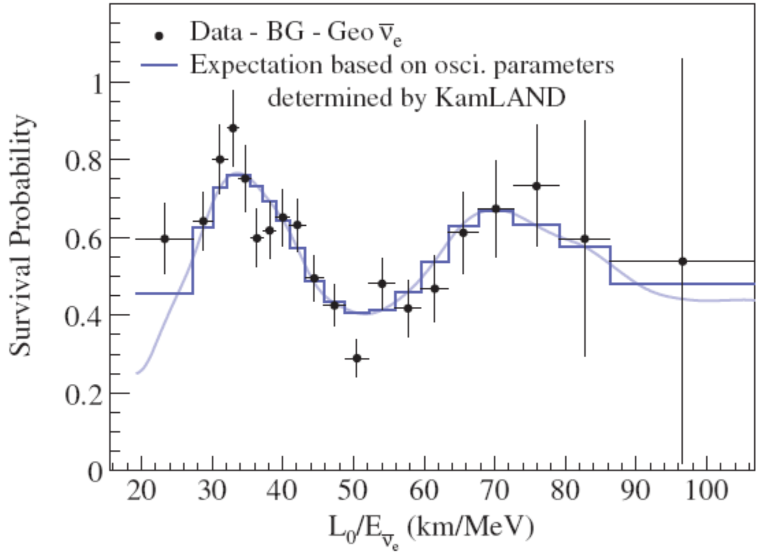
- Balloon 13 m in diameter
- 1 kton of liquid scintillator,
- 2,000 PMTs, 1km underground
- Running since 2001.
- 1st detected Geo-neutrinos.

Since 2011 KamLAND-Zen
Neutrino-less double β decay search

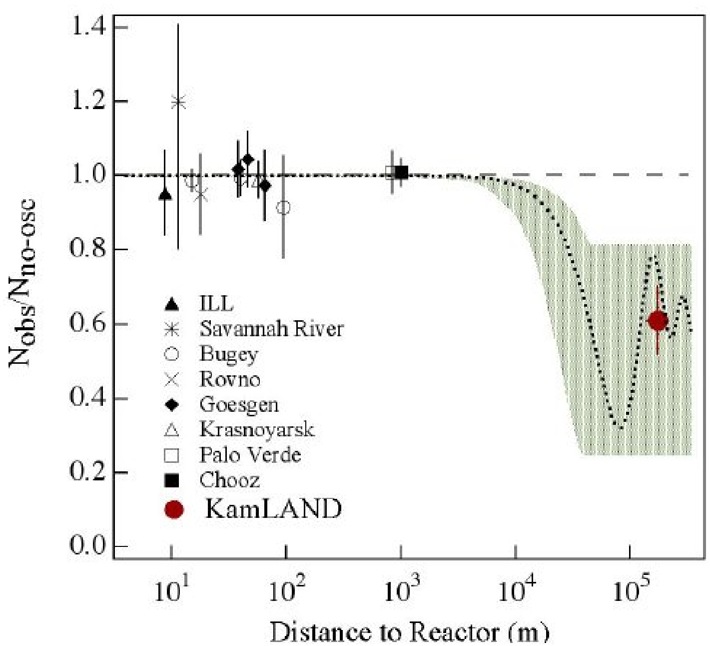
KamLAND (**Kam**ioka **L**iquid **An**tineutrino **D**etector)

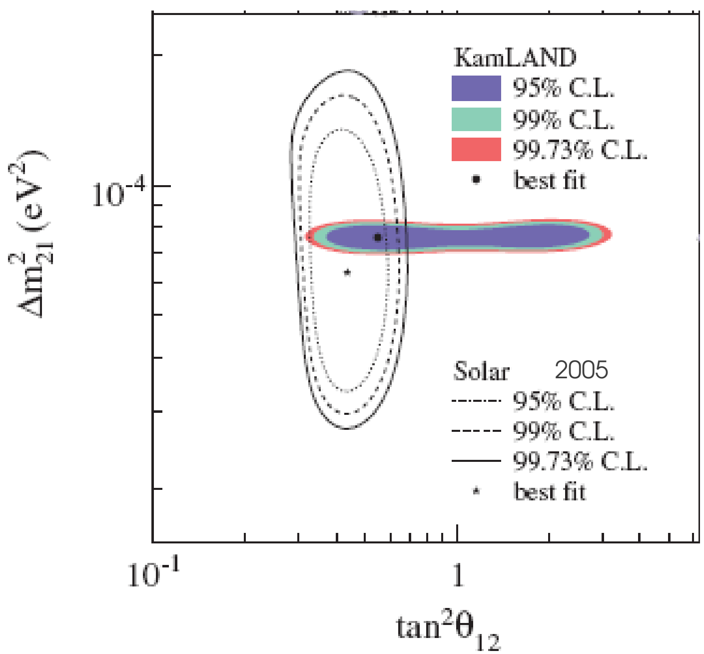
Araki et al. PRL **100**, 221803(2008)



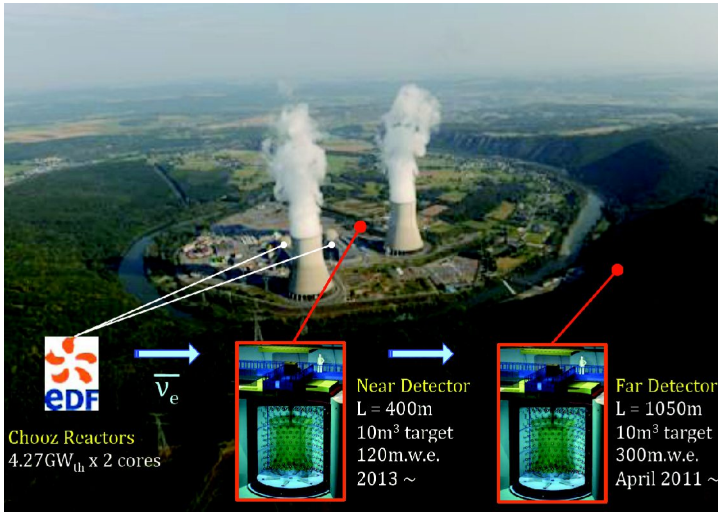


KamLAND favors the LMA solution for solar neutrino oscillations



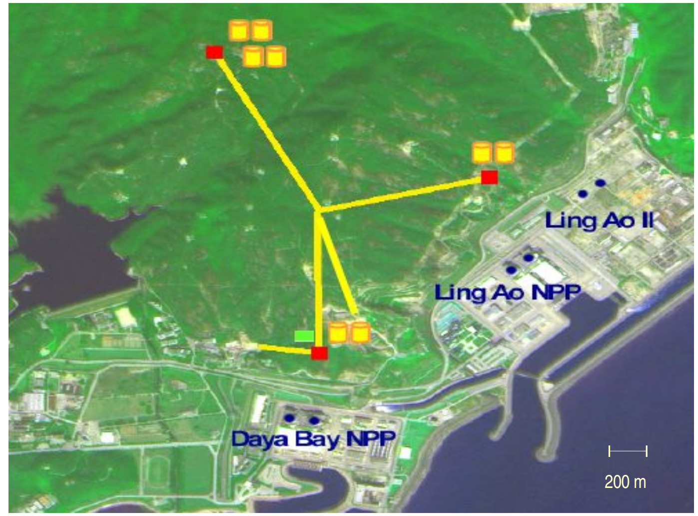


Reactor experiments measuring $\sin^2 2\theta_{13}$



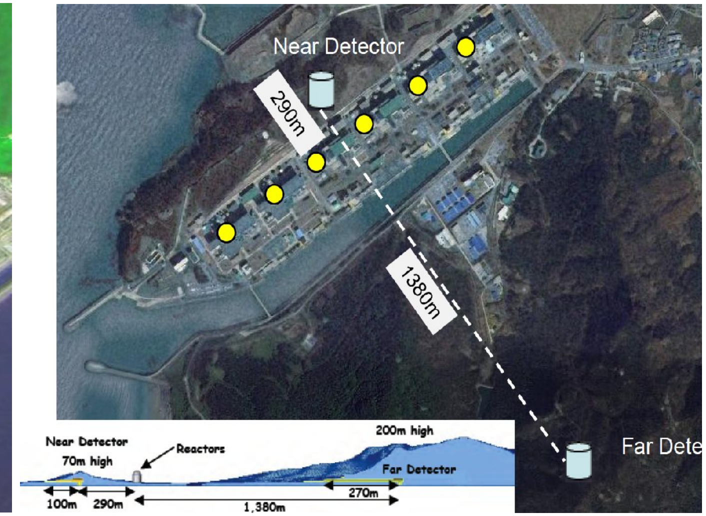
Double-CHOOZ (France)

- Two reactor cores (4.27 GW_{th} each)
- Two identical design detectors:
  Near: @ 400 m (ready >2013)
  Far: @ 1050 m
- 10 m^3 of *LS+GD* per detector



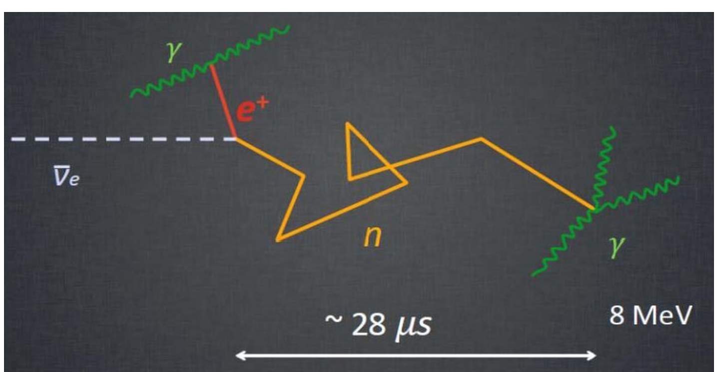
Daya Bay (China)

- 6 reactors in 3 sites (17.4 GW_{th} total power)
- 6 detectors (8 planned), 3 halls:
  Near hall 1: 1 det. (2 planned)
  Near hall 2: 2 det.
  Far hall: 3 det. (4 planned)
  (dist. to cores: 300-2000 m)
- 20 ton of *LS+Gd* per detector



RENO (South Korea)

- 6 reactors along 1.3 km line ($2 \times 2.66\ GW_{th} + 4 \times 2.8\ GW_{th}$)
- Two identical design detectors:
  Near: @ 290 m from line
  Far: @ 1380 m from line
- 16 ton of *LS+Gd* per detector

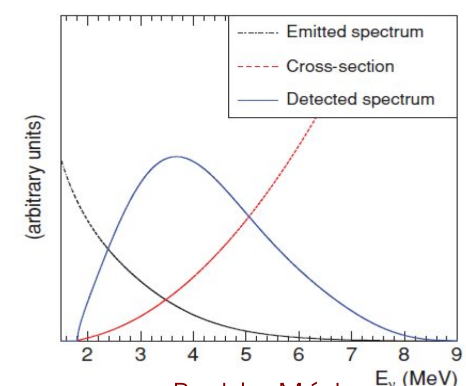


All 3, detect $\bar{\nu}_e$'s via inverse β decay:

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

n + p → d + γ (2.2 MeV)

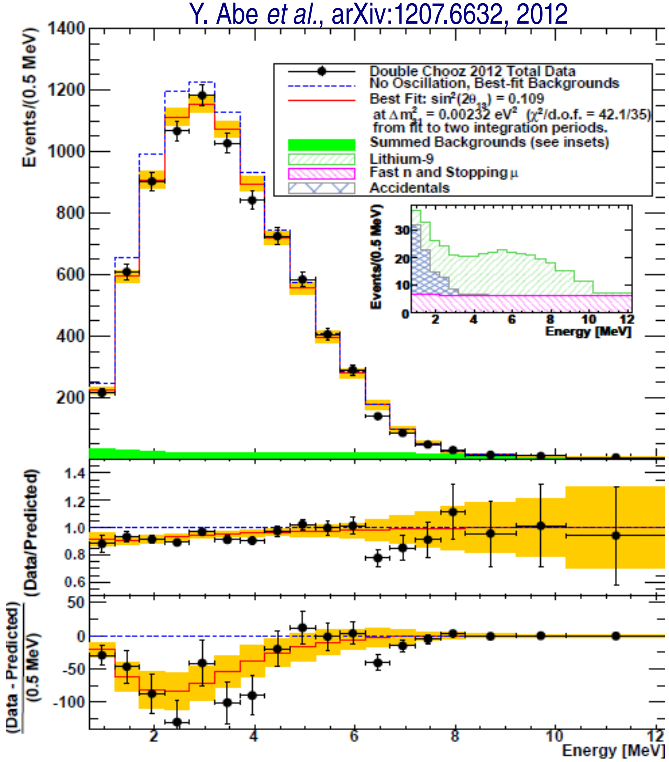
n + Gd → Gd* + γ (8 MeV)



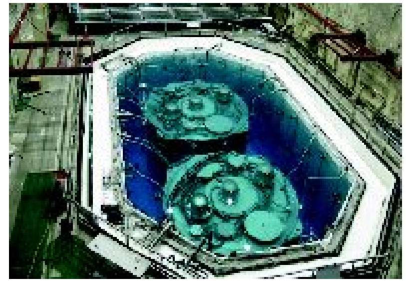
Reactor experiments measuring $\sin^2 2\theta_{13}$ (cont'd)

Double-Chooz (Jul, 2012)

Y. Abe *et al.*, arXiv:1207.6632, 2012

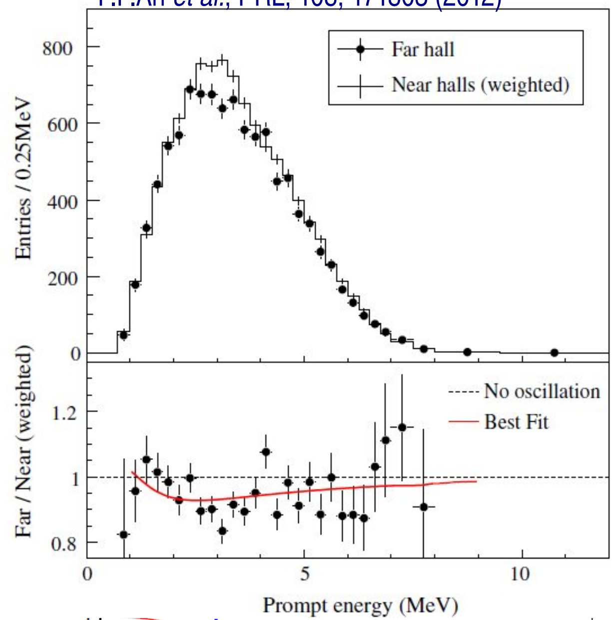


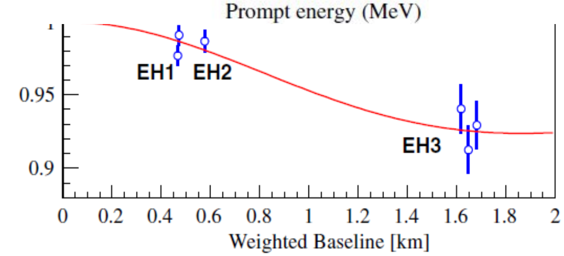
$\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{sys})$



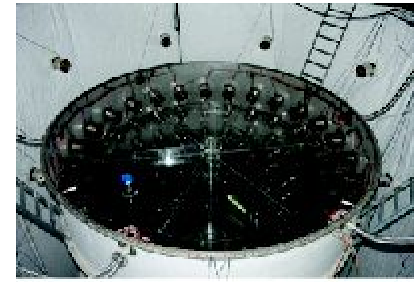
Daya Bay (Mar, 2012)

F.P.An *et al.*, PRL, 108, 171803 (2012)



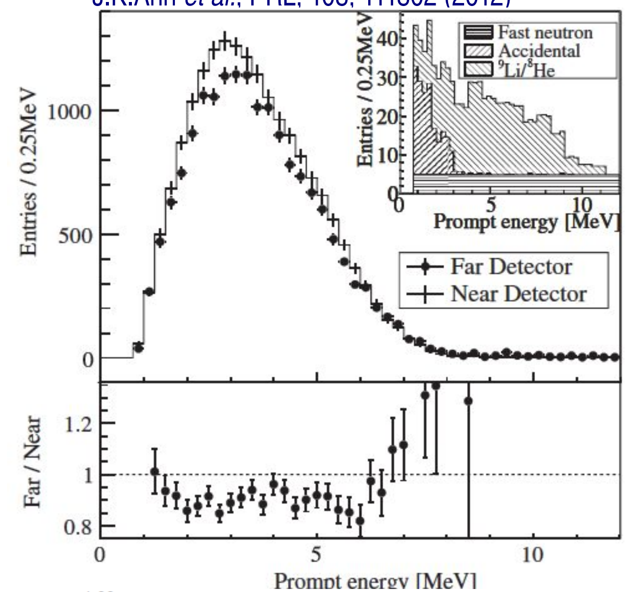


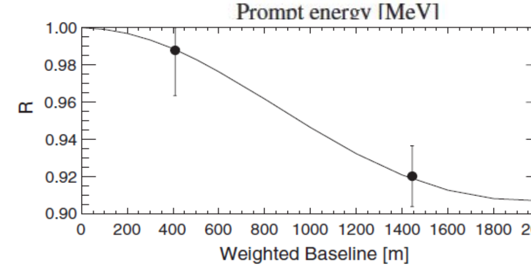
$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{sys})$



RENO (Apr, 2012)

J.K.Ahn *et al.*, PRL, 108, 111802 (2012)



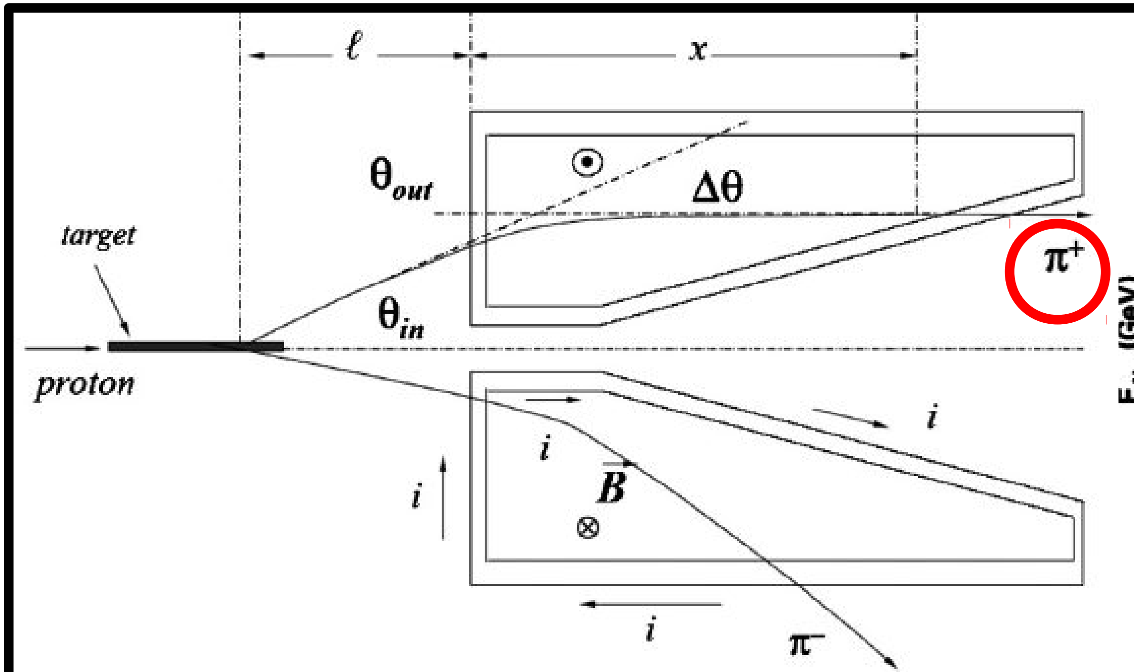


$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{sys})$

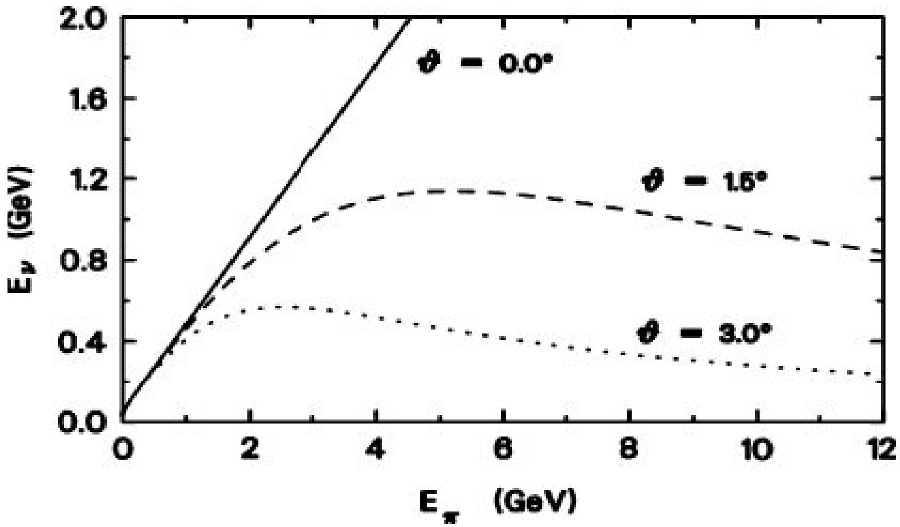
Accelerator neutrino beams

1. Accelerate protons and impact them in a target.
2. Products are focused with *magnetic horns* (Van de Meer, 1961).
3. Focused π's & K's (horn polarity selects charge) decay in a tunnel.
4. All particles, except the ν's, are stopped in an absorber.
5. Figure of merit : # of Protons On Target (P.O.T.)

*LSND, KARMEN: isotropic ν sources -no horns- (decay at rest)



$$E_\nu = 0.43 \times E_\pi / (1 + \gamma_\pi^2 \theta_\pi)$$



(S. Kopp, Phys. Rept. **439**:101-159 (2007))

Accelerator neutrino oscillation searches

Long Baseline: L > a few 100 km ☑ oscillations

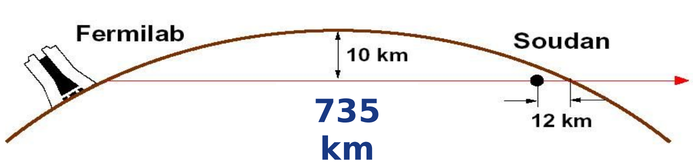
K2K:	KEK – Kaimioka	L/E ~ 1 GeV/250 km, disapp.	$\nu_\mu \to \times$
MINOS:	FNAL – Soudan	L/E ~ 5 GeV/735km, disapp.	$\nu_\mu \to \times$
OPERA:	CERN to LNGS	L/E ~ 17GeV/730 km, appear.	$\nu_\mu \to \nu_\tau$
T2K:	Tokai to Kamioka	L/E ~ 2 GeV/295 km, appear.	$\nu_\mu \to \nu_e$
NOvA:	FNAL – Ash River	L/E ~ 5 GeV/810 km, appear.	$\nu_\mu \to \nu_e$

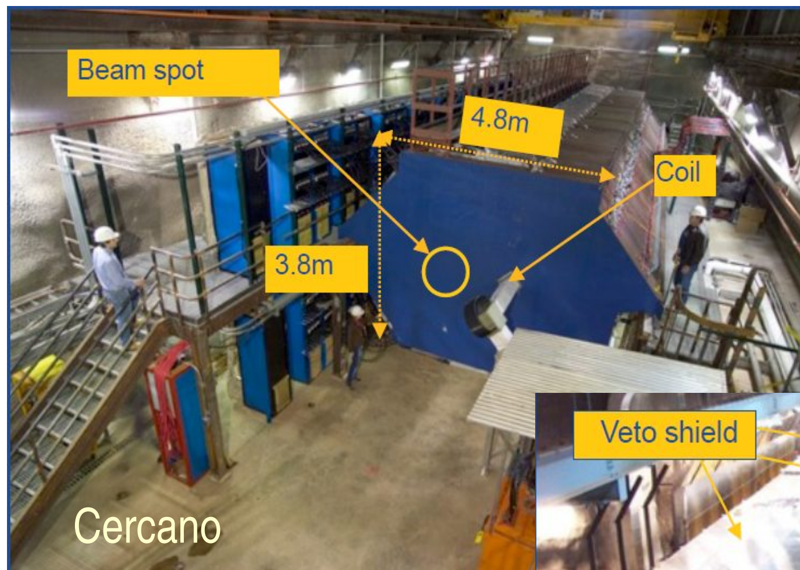
Short baseline: L < a few 100 m ☒ oscillations (?) ☑ anomalies

A) Bubble chambers (GGM, BEBC, FNAL-15ft)
B) electronic detectors: NOMAD, CHORUS, CHARM, CCFR, BNL-E776, BNL-E734, CDHS, KARMEN, MiniBooNE.

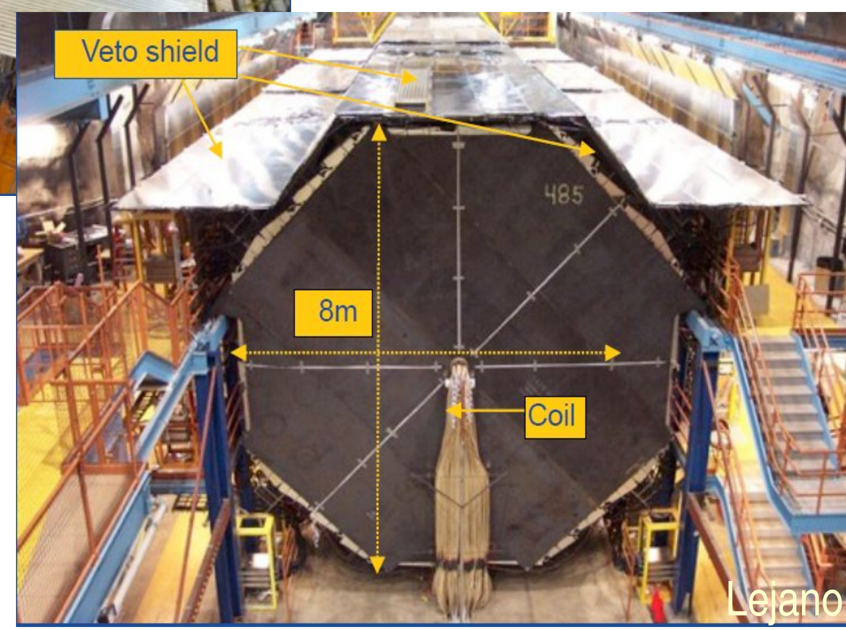
MINOS

Two segmented magnetized iron calorimeters (⇒tracker)
Near detector at ~1 km: FNAL, 980 ton, 107 m underground.
Far detector at ~735 km: Soudan MN, 5.4 kton, 700 m underground.
Measures curvature of μ^- tracks produced in $\nu_\mu + Fe \rightarrow \mu^- + X$





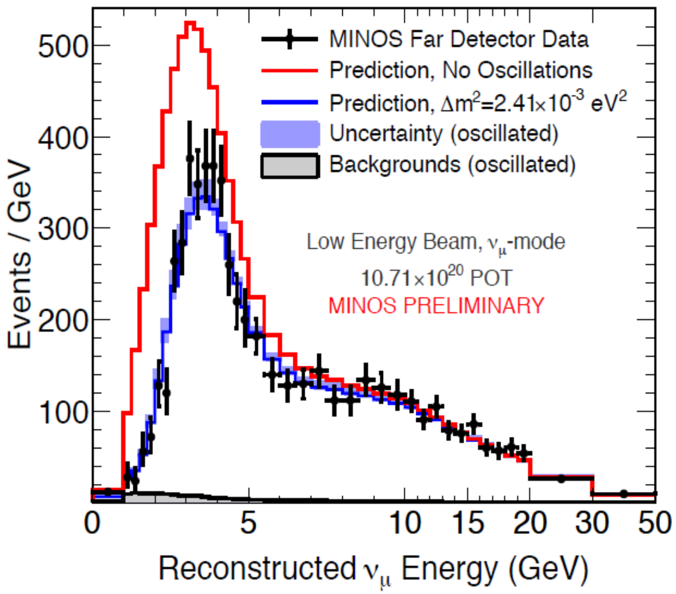
- Can distinguish ν_μ from $\bar{\nu}_\mu$
- 6.4% of CC interactions are $\bar{\nu}_\mu$'s when running a ν_μ beam.

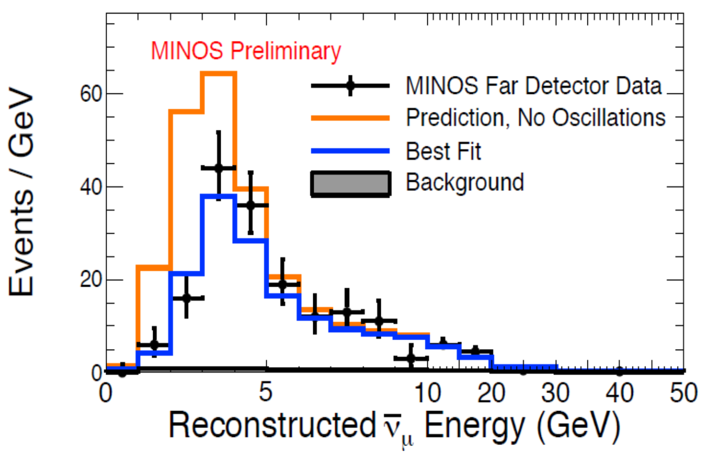


MINOS

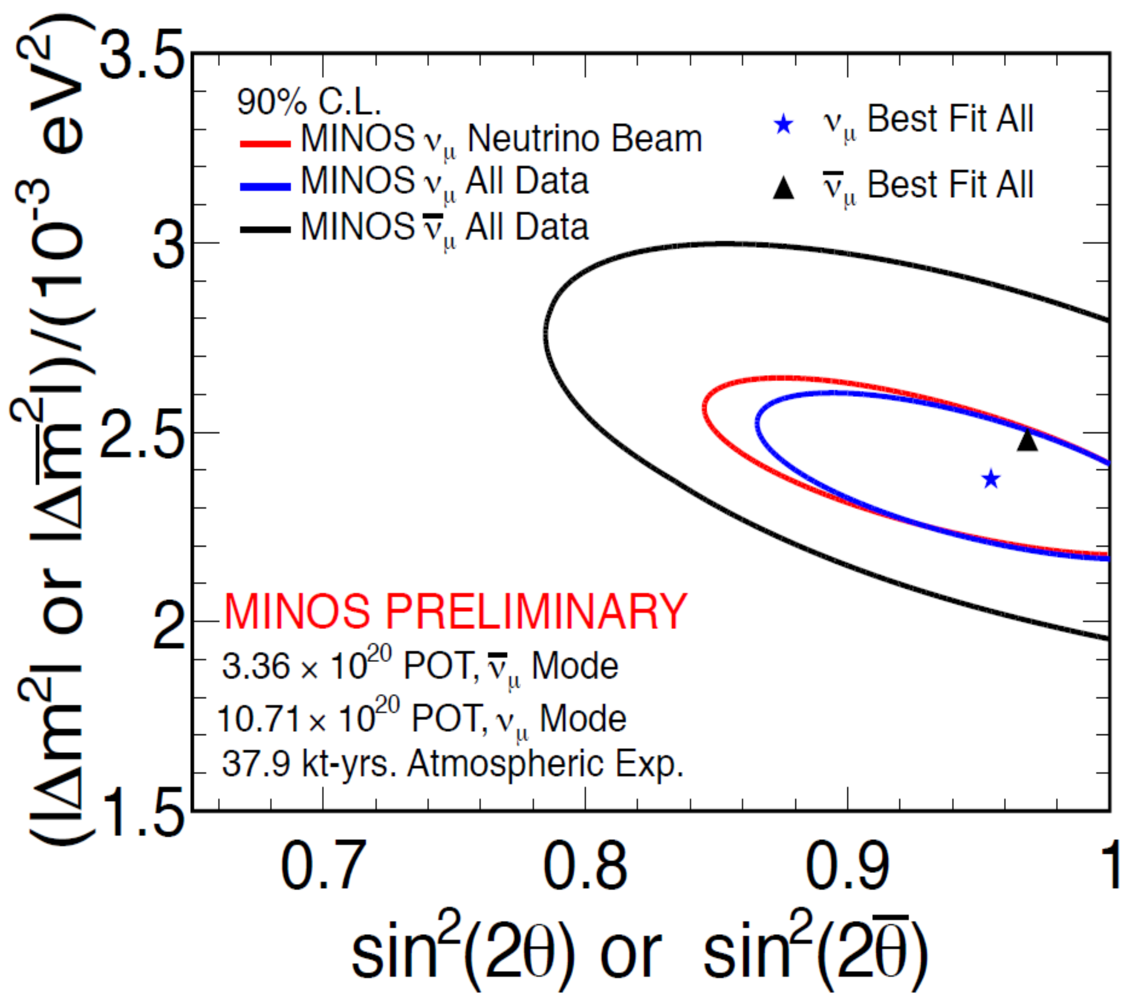
ν_μ and $\bar{\nu}_\mu$ disappearance in beam with $\langle E_\nu \rangle$ ~4-7 GeV

Direct test of $P(\nu_\mu \to \nu_\tau) = P(\bar{\nu}_\mu \to \bar{\nu}_\tau)$.





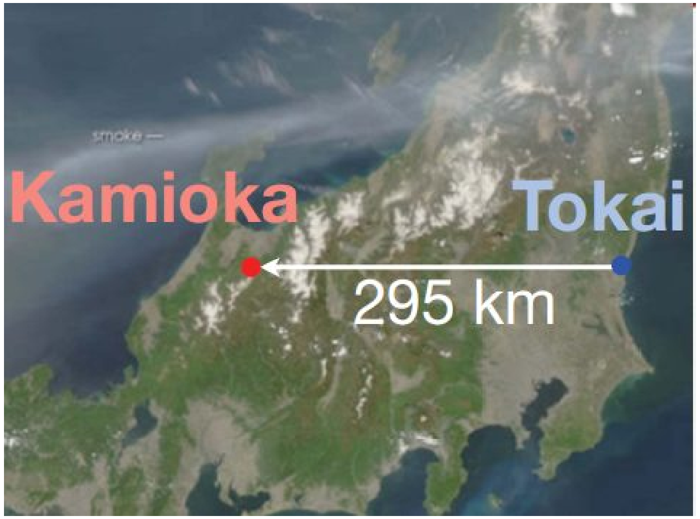
Note: $\Delta m = \Delta m_{32}$,and $\theta = \theta_{23}$



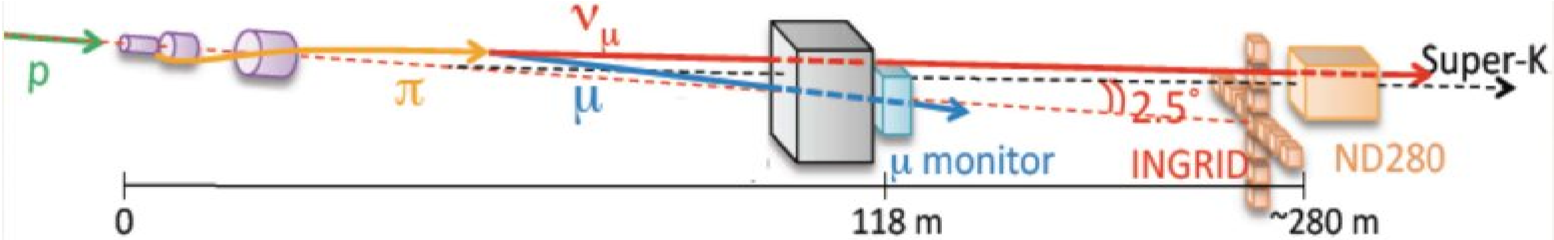
R. Nichol, Neutrino 2012

T2K (Tokai to Kamioka)

Super-K in Kamioka



J-PARC accelerator in Tokai



- High power accelerator
- Powerfull and high quality neutrino beam
- High resolution near detector
- Huge far detector (Super-Kamiokande)

Goal: Measure θ_{13} through the appearance of ν_e's in a ν_μ beam.

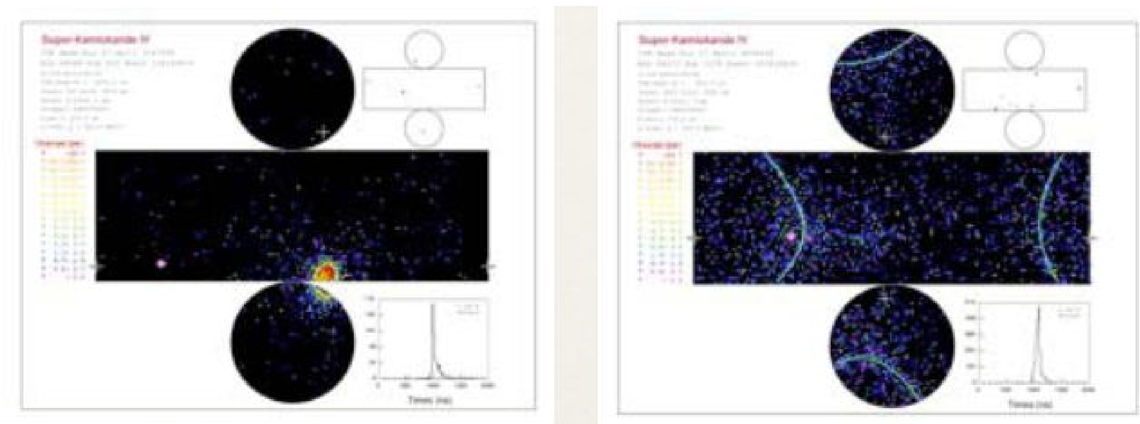
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2 (1.27\, \Delta m^2_{23}\, L/E)$$

11 March, 2011 earthquake affected the J-PARC accelerator complex severely.
Back in operation since December 2011.

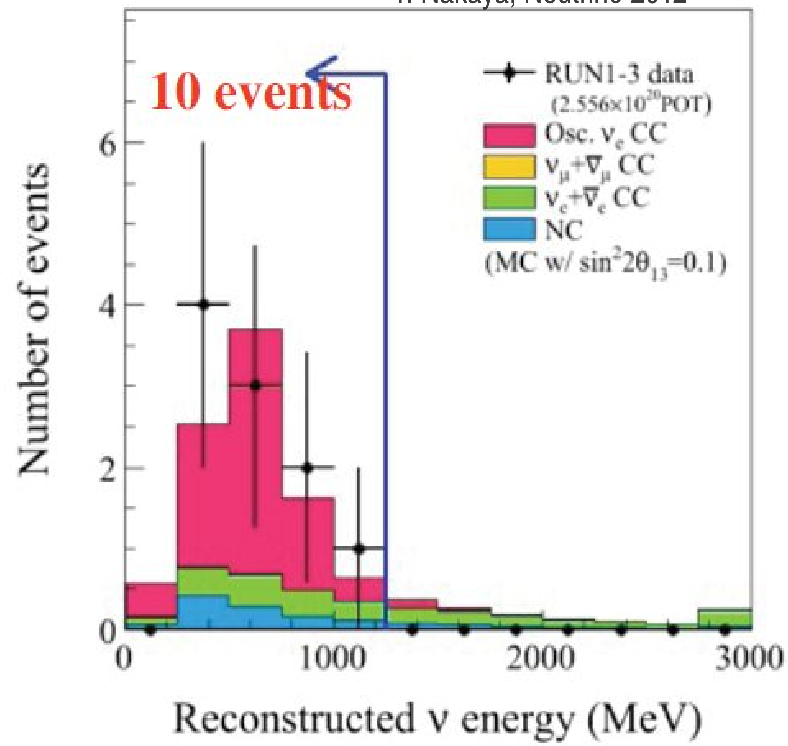
T2K, electron neutrino events

ν_e event selection:

- T2K beam timing
- Fully Contained events (FC)
- Vertex within fiducial volume (FV)
- 1 e-like Cherenkov ring.
- Visible energy E_{vis}>100 MeV
- No aditional signals from μ-decay electrons.
- π^0 Invariant mass < 105 MeV (assumes 2 rings)
- Reconstructed neutrino energy E_ν< 1250 MeV



T. Nakaya, Neutrino 2012



Observed: 10 events

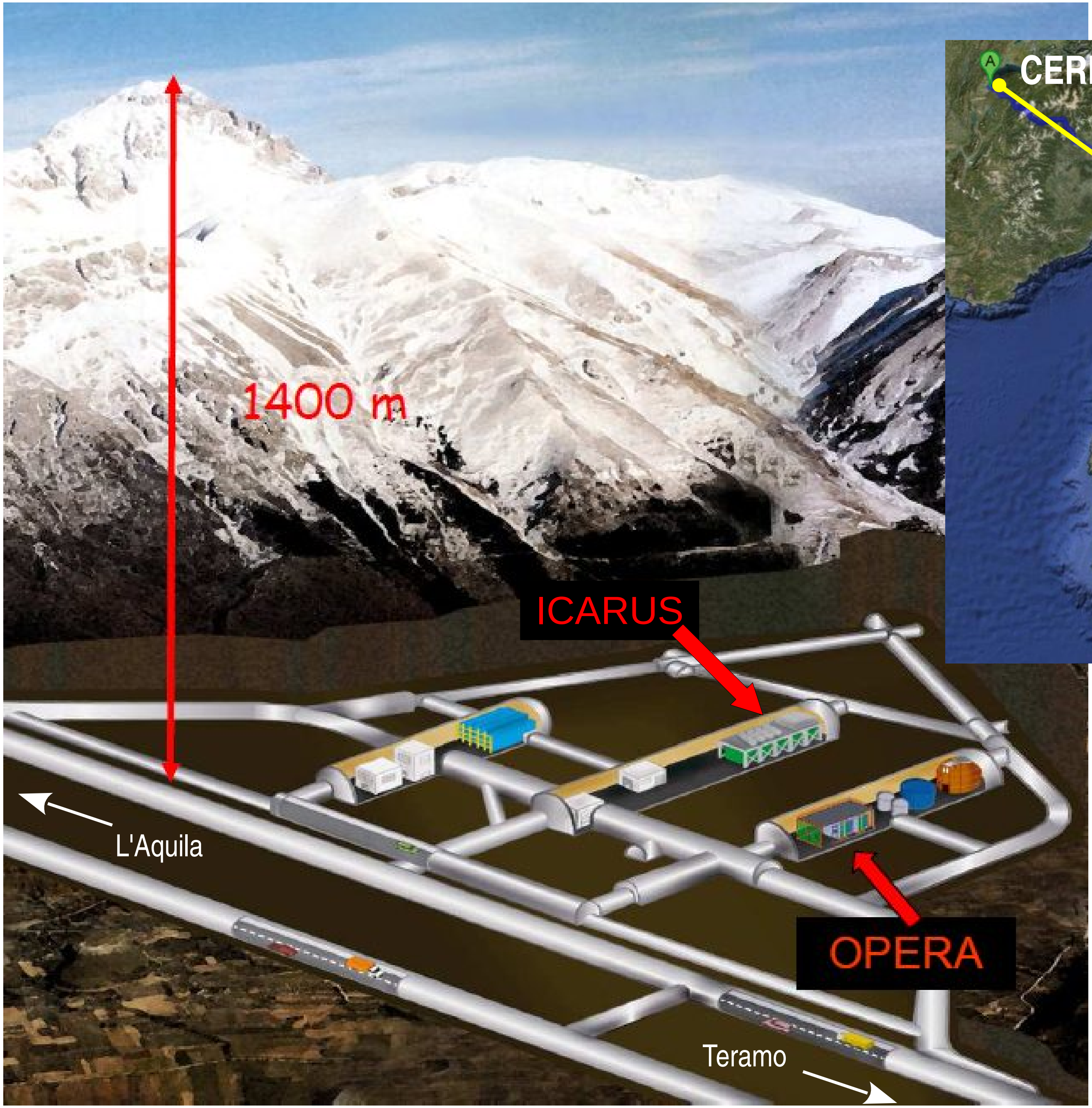
Expected (no osc): 2.73±0.37

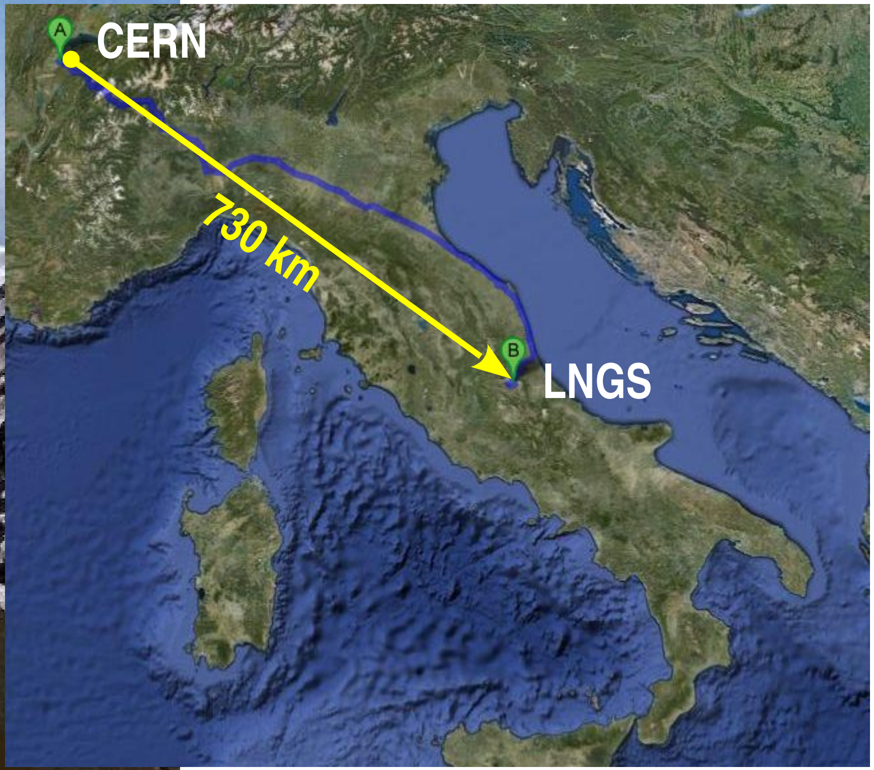
Evidence for $\nu_\mu \rightarrow \nu_e$ appearance!

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(1.27\, \Delta m^2_{23}\, L/E)$$

$$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045} \quad \text{for } \Delta m_{32}^2 = 2.4\times10^{-3} eV^2,\ \delta_{CP}=0,\ \theta_{23}=\pi/4$$

Laboratori Nazionali del Gran Sasso (LNGS)



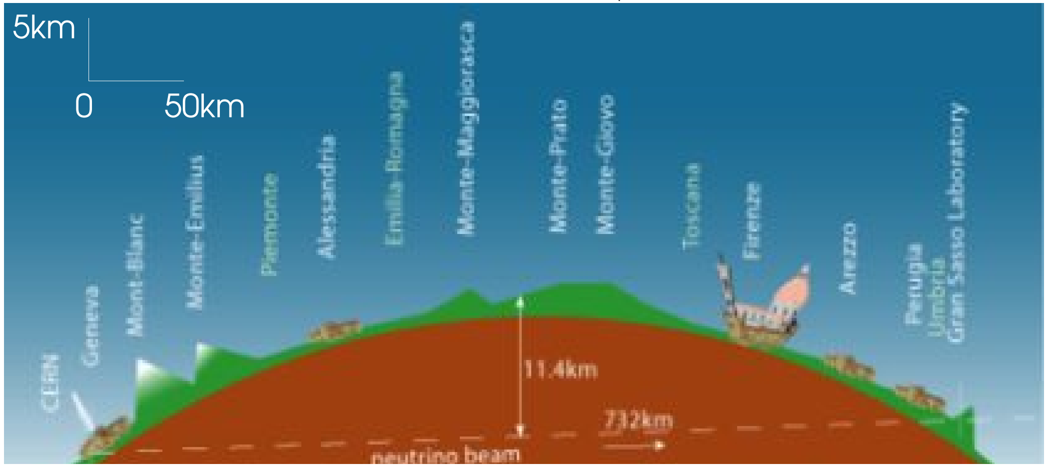


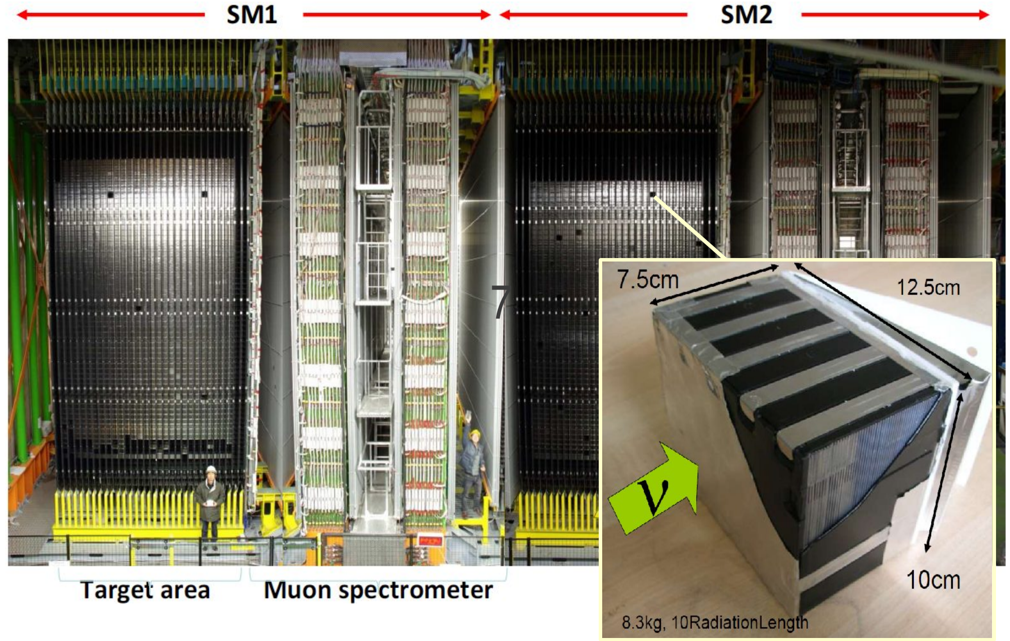
Beam breath at LNGS:
~2.8 km (FWHM)

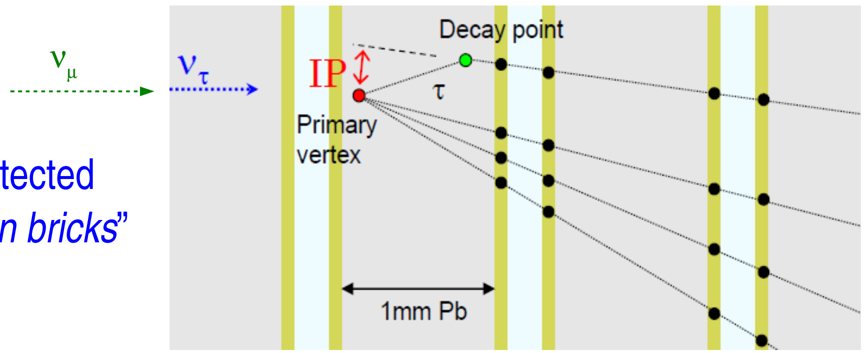
OPERA (Oscillation Project with Emulsion-tRacking Aparatus)

Searches for $\nu_\mu \rightarrow \nu_\tau$ oscillations through the appearance of ν_τ (also $\nu_\mu \rightarrow \nu_e$ appearance)

Uses the CNGS beam, with $<E_\nu> \sim 17$ GeV







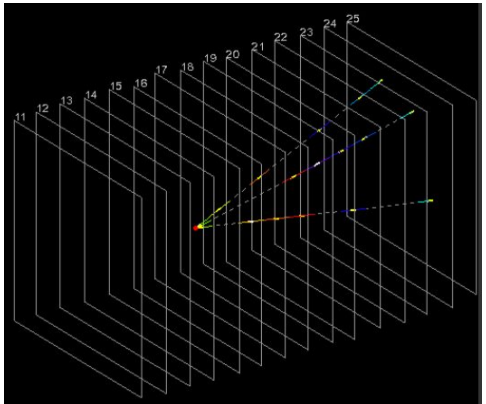
τ vertex detected in "*emulsion bricks*"

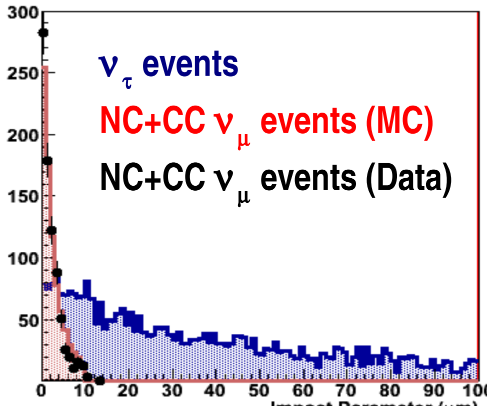
Two 900 ton detector modules (SM1, SM2):

- target: Pb plates interleaved with walls of "*emulsion bricks*", and scintillator strips.
- Magnetic spectrometer

Total 150,000 bricks, mass of 1,250 ton.

Brick data

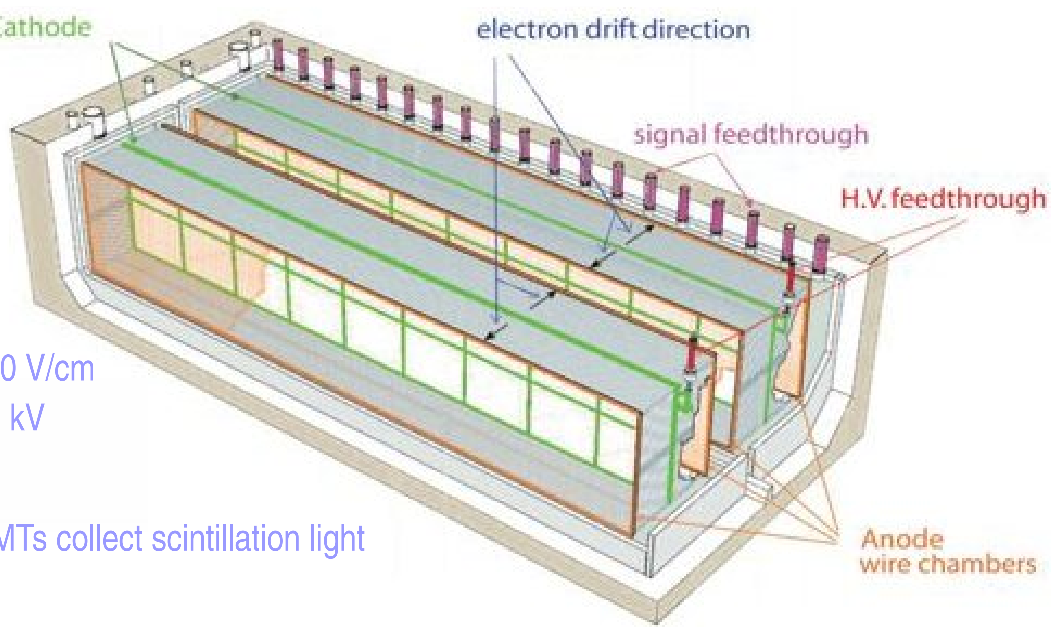




- Collecting CNGS events since 2008.
- Partial data analysis (up to 2011): ***observed 2 ν_τ candidate events*** (expected 2.1 with 0.2 bkgd.)
- For 22.5×10^{19} POT expects 7.6 evt. (w/~0.8 bkgd) according to $\nu_\mu \rightarrow \nu_\tau$ with $\mathbf{\Delta m^2 \sim 2.5 \times 10^{-3}}$

New Journal of Physics, 14, 033017 (2012)

ICARUS T600 [Imaging Cosmic And Rare Underground Singals]



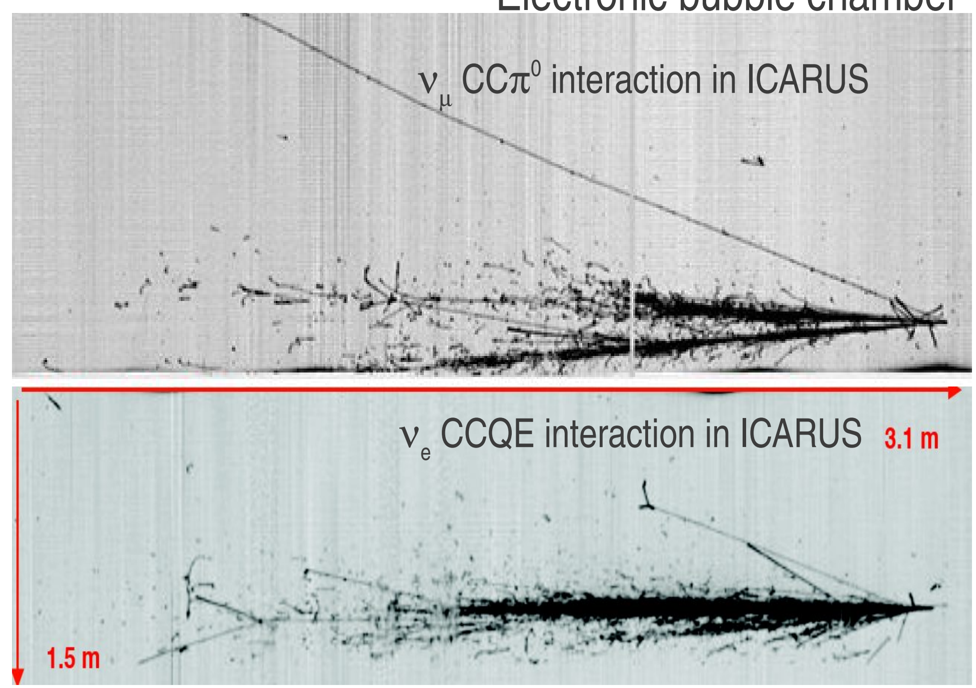
E_{drift}=500 V/cm
HV=-75 kV

75 8" PMTs collect scintillation light

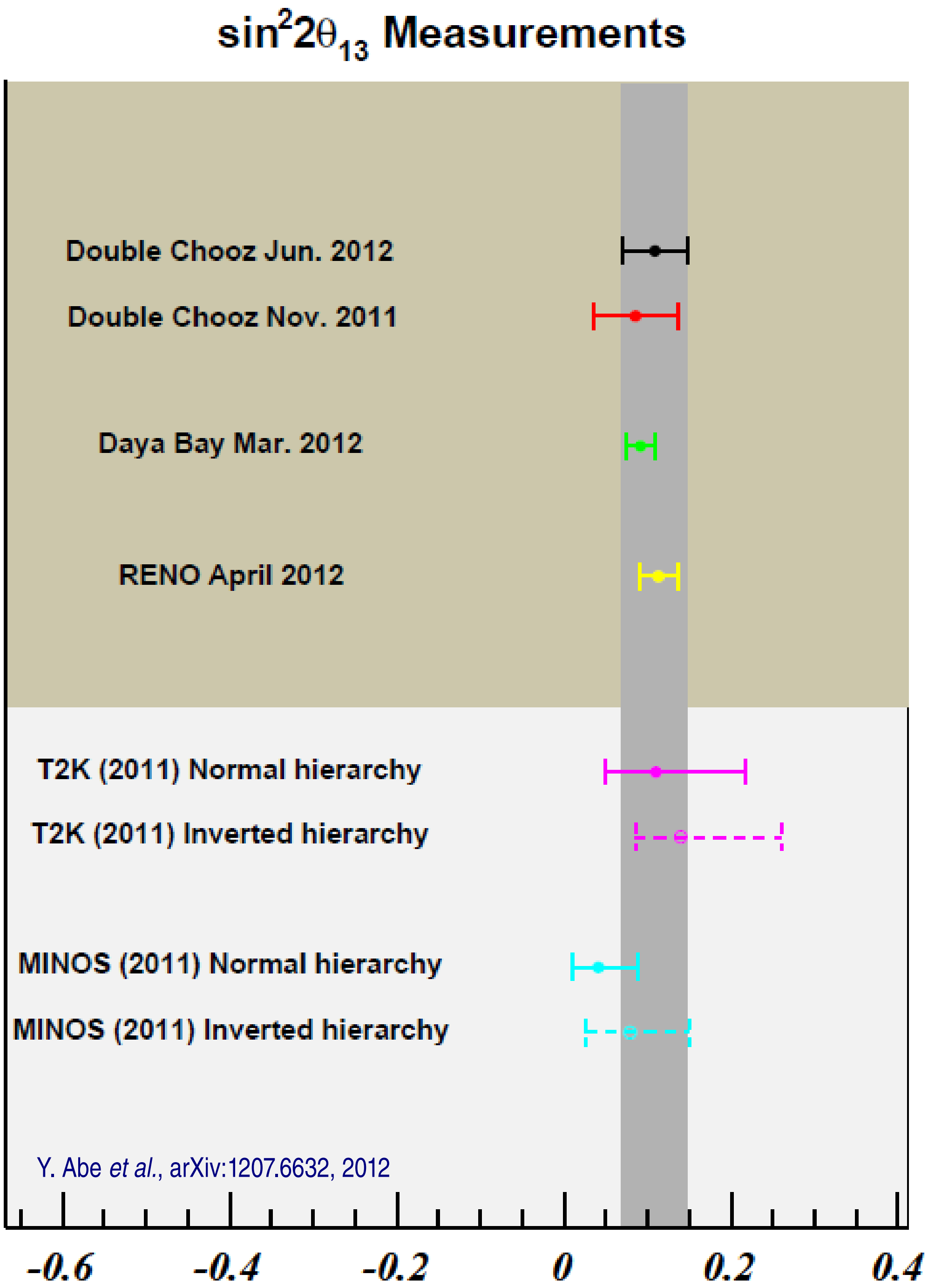
- Liquid Argon TPC (LAr-TPC), two modules of 3.6 x 3.9 x 19.6 m^3, total mass ~760 ton.
- Can reconstruct tracks of "all" charged particles in an event. Good energy resolution.
- Acquiring data w/o interruption since Oct. 2010.
- First large LAr-TPC operated underground. Major milestone towards more massive LAr detector.

Physics: $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations

"Electronic bubble chamber"

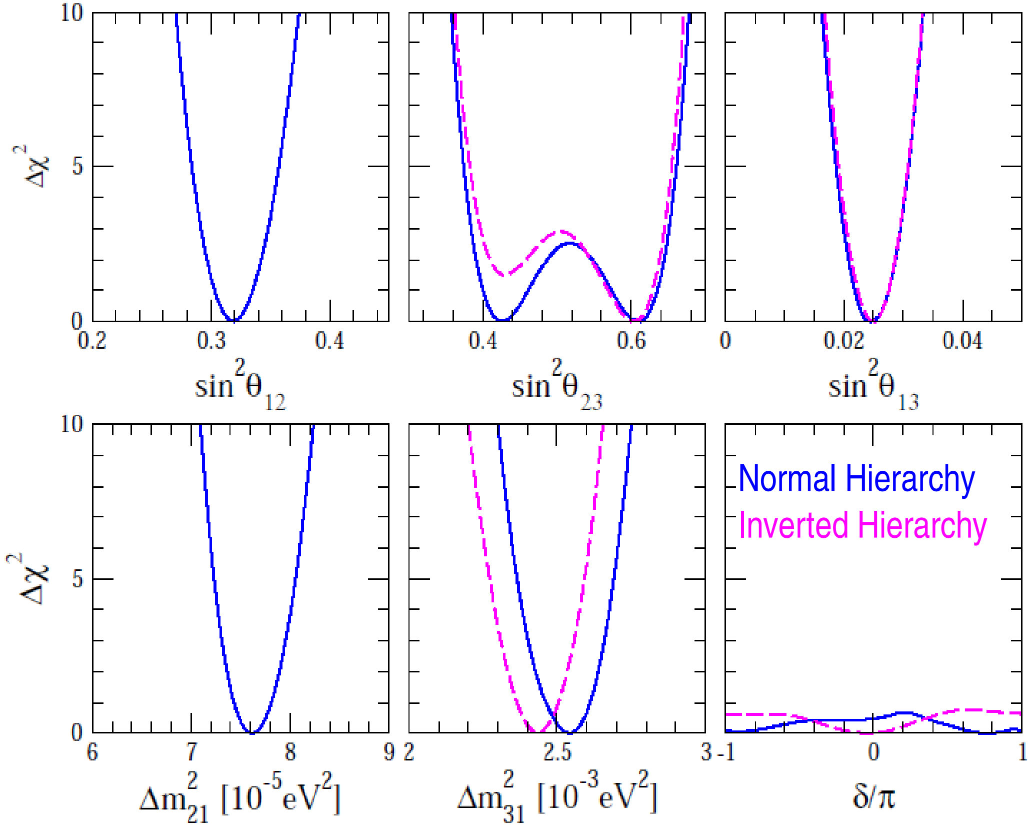


$\sin^2 2\theta_{13}$ measurements



A global analysis: arXiv:1205.4018(2012)

Solar: Cl, Gallex/GNO, SAGE, Super-K I-III, SNO I-III,
Reactor: KamLAND, Double-CHooz, Daya Bay, RENO,
Atmospheric and accelerator: Super-Kamiokande I-III, MINOS ν, $\overline{\nu}$, T2K,



parameter	best fit	1σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.62	7.43–7.81
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$	2.55 2.43	2.46 – 2.61 2.37 – 2.50
$\sin^2\theta_{12}$	0.320	0.303–0.336
$\sin^2\theta_{23}$	0.613 (0.427)[a] 0.600	0.400-0.461 & 0.573–0.635 0.569–0.626
$\sin^2\theta_{13}$	0.0246 0.0250	0.0218–0.0275 0.0223–0.0276
δ	0.80π -0.03π	$0 - 2\pi$

D.V.Forero, M. Tortola, J.W.F. Valle, arXiv:1205.4018 (2012)

Neither the Mass Hierarchy, nor the phase δ can be determined with current experiments.

Oscillation probability $\nu_\mu \rightarrow \nu_e$ through the Earth (3ν)

Δ_{12} : solar ν oscillations ~ small
$\Delta_{13} \sim \Delta_{23}$: atmospheric ν oscillations
$S^2_{23} \sim 0.5$, $S^2_{12} \sim 0.3$ $S^2_{13} \sim 0.03$

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

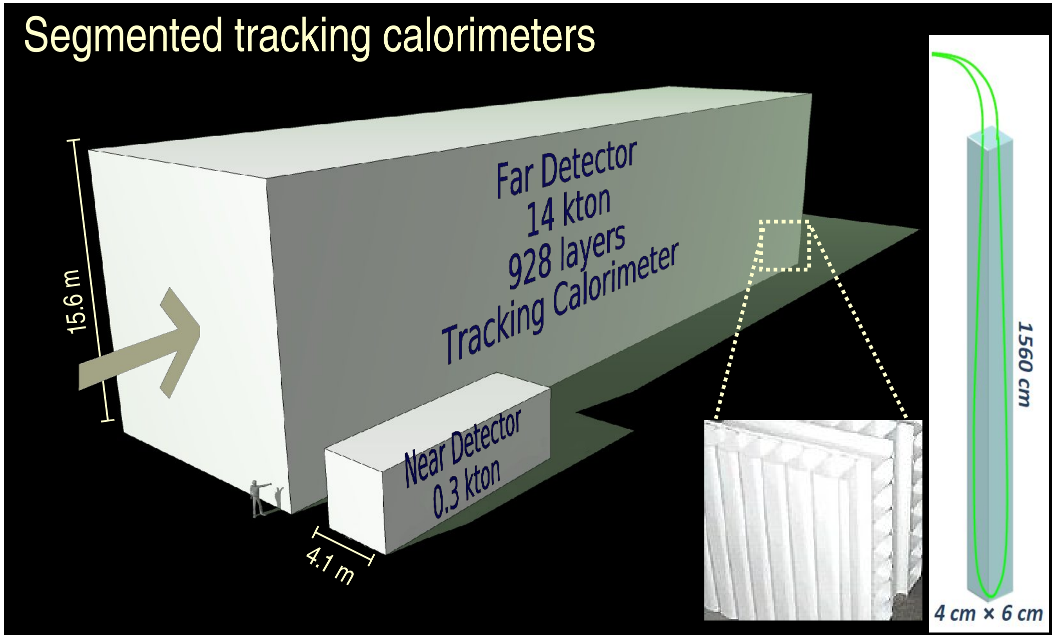
$$4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$
$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$
$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$
$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$
$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2 \Delta_{31},$$

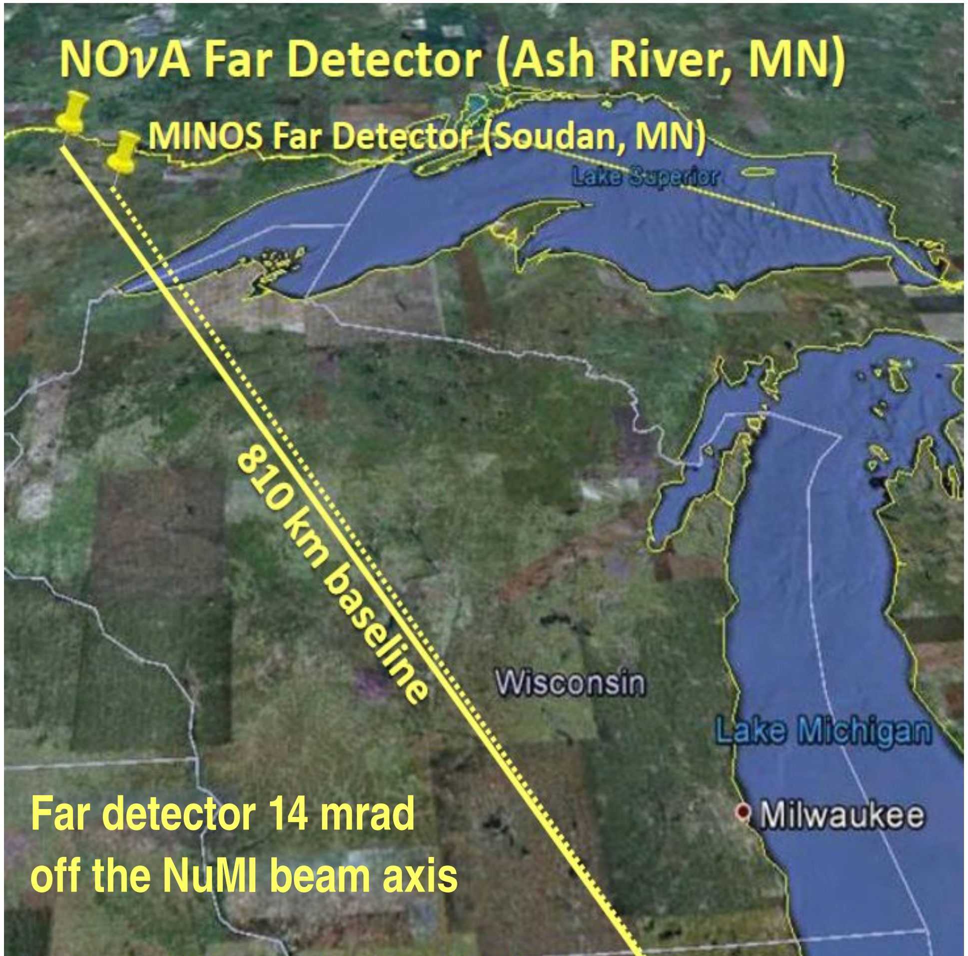
For $\nu \rightarrow \overline{\nu}$,
$a \rightarrow -a$, $\delta \rightarrow -\delta$

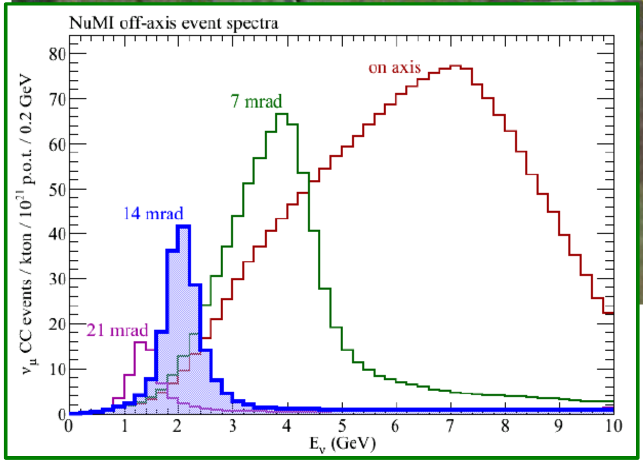
Oscillation term $\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$

Matter effect $a[\mathrm{eV}^2] = 7.56 \times 10^{-5} \times \rho[\mathrm{g/cm}^3] \times E_\nu[\mathrm{GeV}]$

NOvA (NuMI Off-Axis)







R.Patterson, Neutrino 2012

Physics capabilities

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

- *Measure* θ_{13} using ν_e appearance
- Determine the ν *mass hierarchy*
- Search for ν *CP violation*
- Determine if θ_{23} is >, <, or = to $\pi/4$

With $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

- Precision measurement of the atmospheric parameters θ_{23} ,$|\Delta m^2_{atm}|$

Will start taking data in May 2013, NuMI beam ramp up to 700 kW in 6 months.

NOvA measurement principle

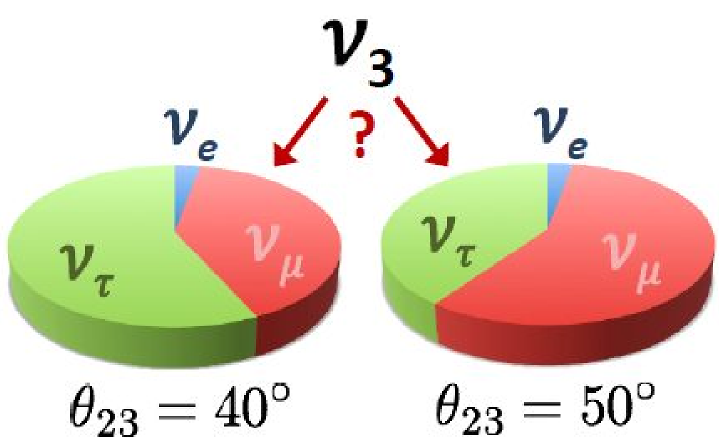
NOνA will measure:

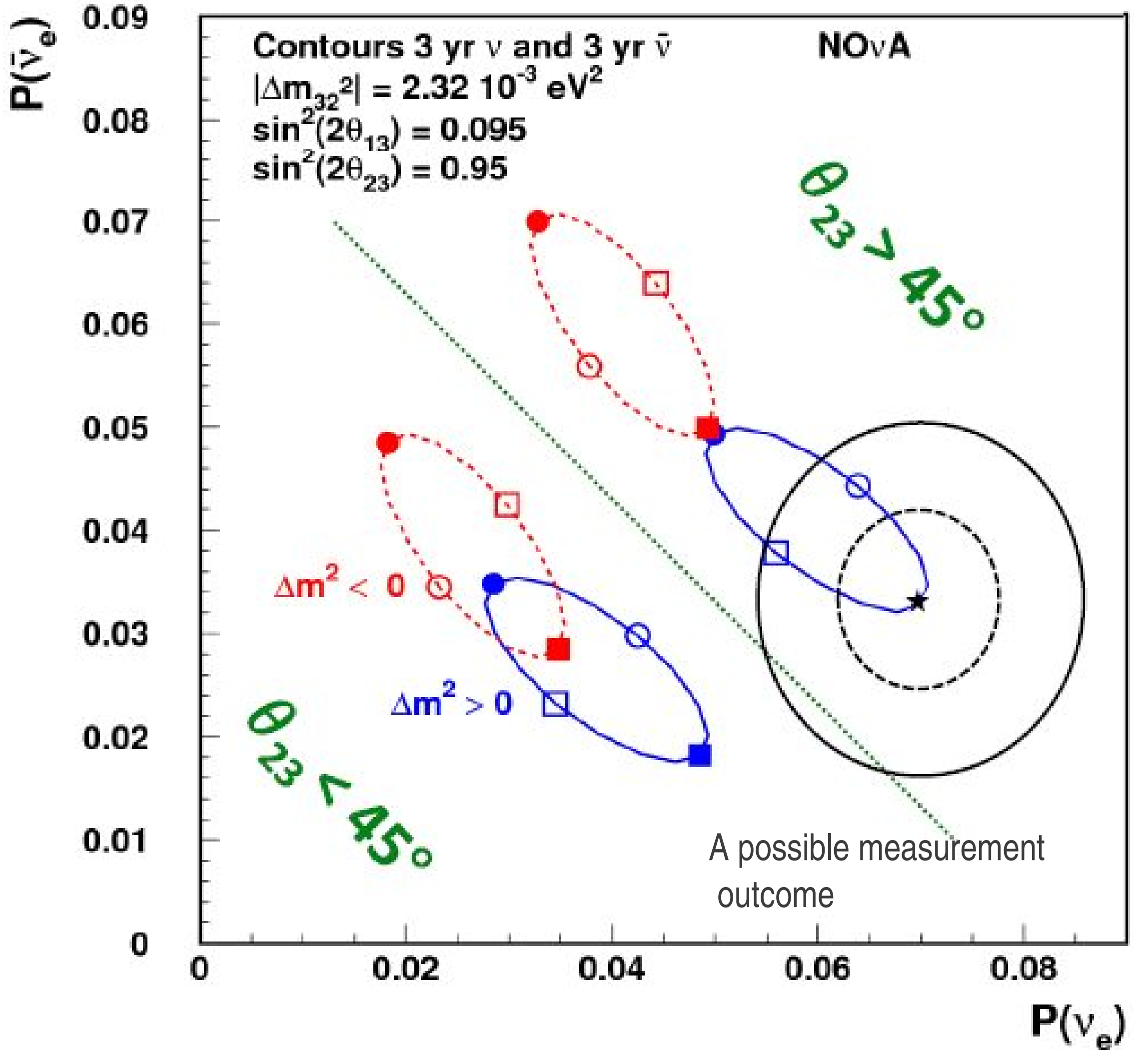
$P(\nu_\mu \rightarrow \nu_e)$ at 2 GeV

and

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ at 2 GeV

These depend *in different ways* on the CP phase δ and on sign(Δm^2) .





If $\delta \sim 3\pi/2$, and $\theta_{23} > 45°$ the measurement could Exclude all inverted hierarchy scenarios at $>2\sigma$

R.Patterson, Neutrino 2012

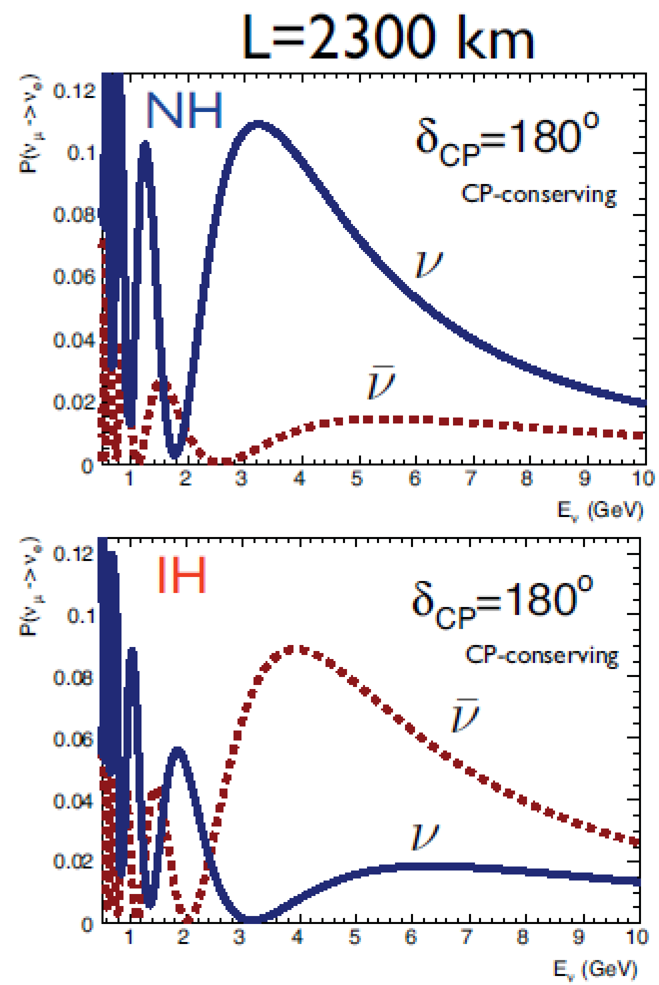
Determining the Mass Hierarchy and the phase δ

Could be achieved by comparing the oscillation probabilities of neutrinos and antineutrinos with the effect of the Earth matter over very long baselines:. $P(\nu_\mu \to \nu_e)$ **vs** $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

Need:

- A very intense beam (~ Mega-Watt power)
- Massive detectors (depending on technology chosen)
  - 20 kton Lar-TPC, or
  - few 100 kt Water Cherenkov
- A long baseline (>1500 km)
- Several years of data (5-10 yr)

Could achieve a better sensitivity than a T2K+NOvA.

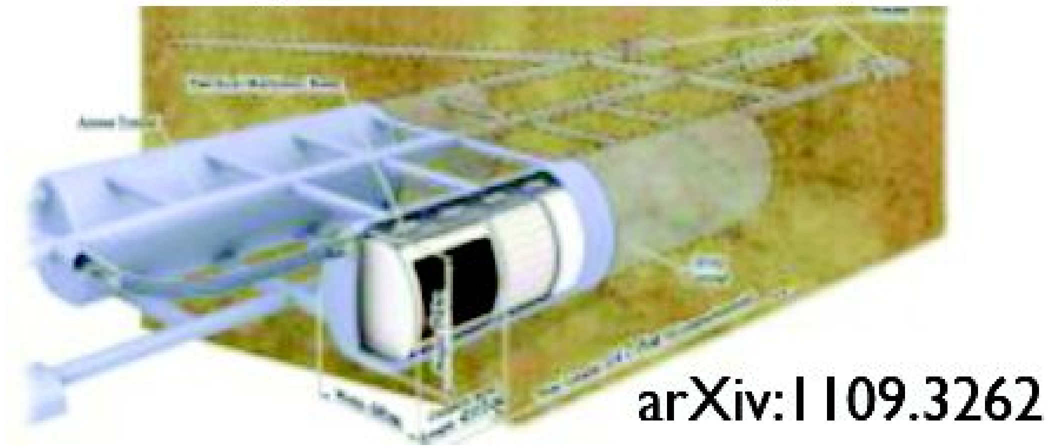


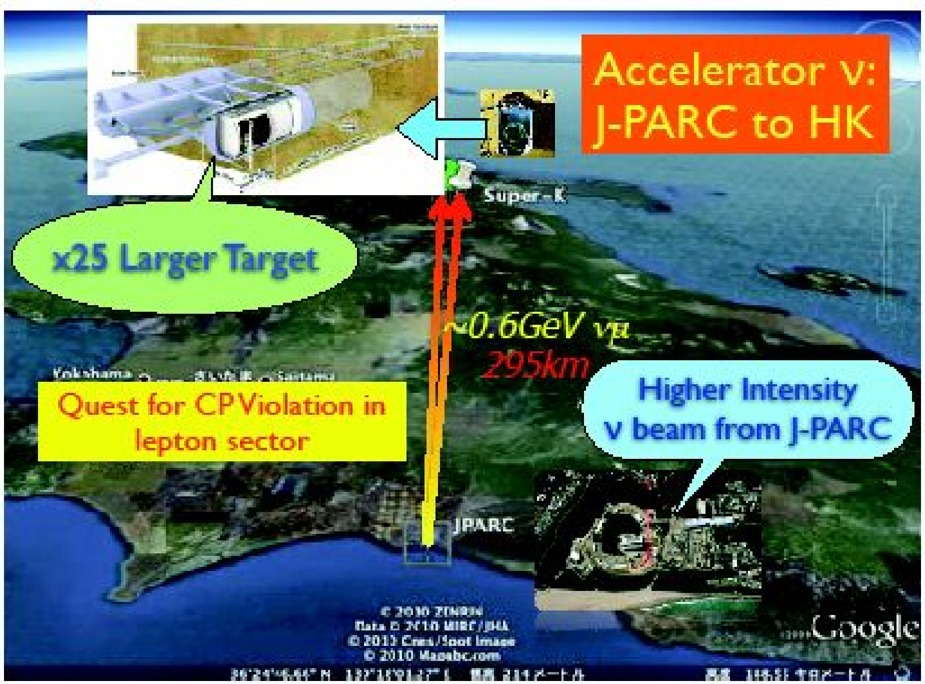
A finely grained Magnetized Iron calorimeter for atmospheric neutrinos with good energy and direction resolution could provide complementary information.

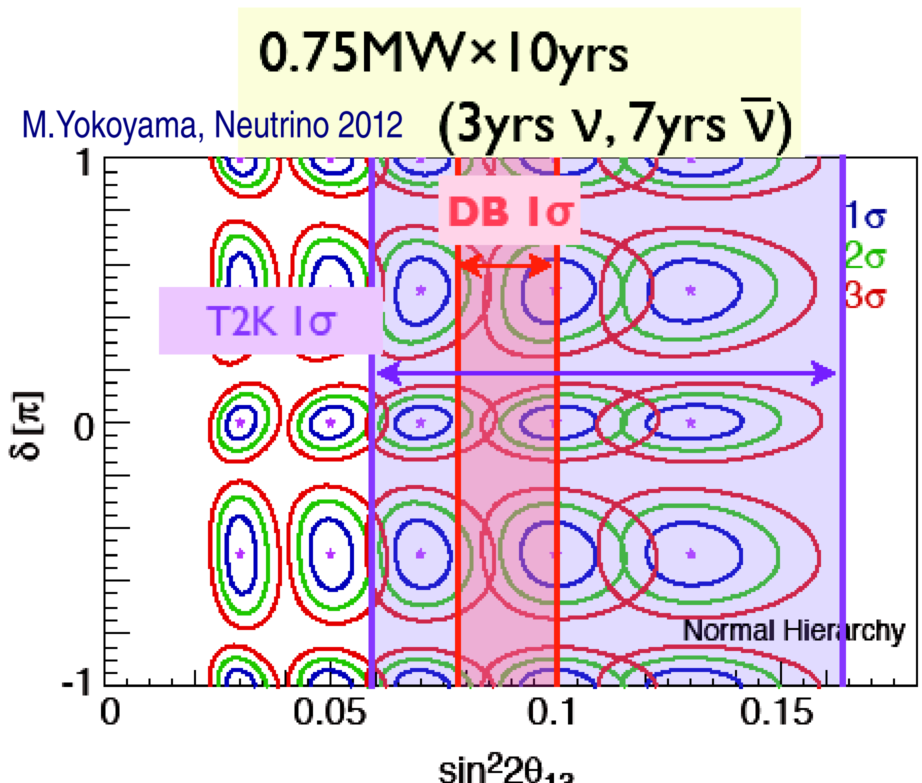
Hyper-Kamiokande + JParc

- Mton-scale Water Cherenkov detector
- Proven technology, can be reliably used.
- With JParc upgraded beam can resolve the Mass Hierarchy and look for CPV.

Hyper-Kamiokande (JP)



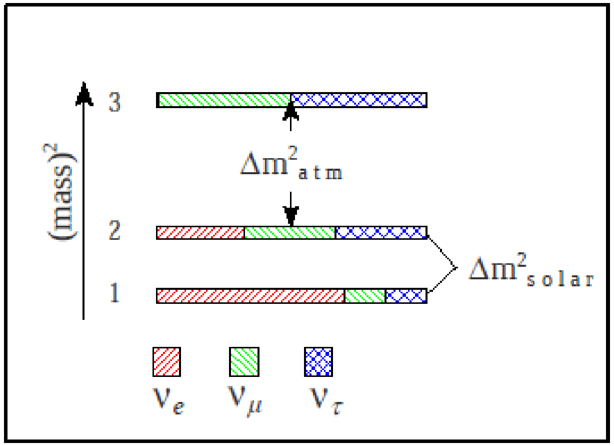




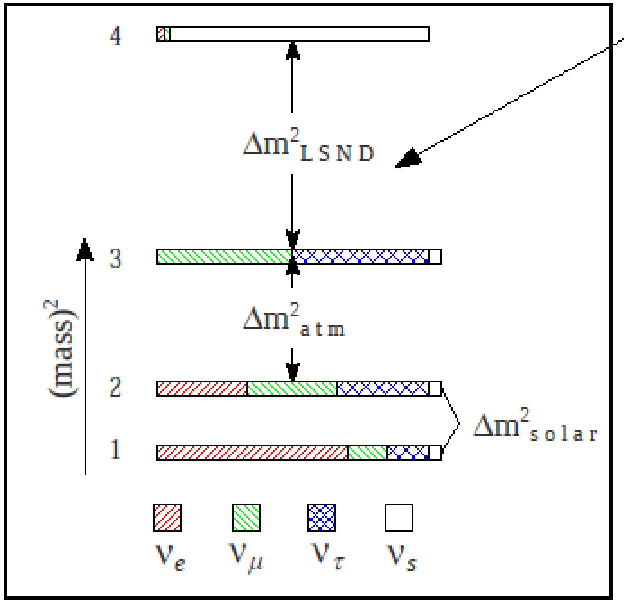
Anomalies and sterile neutrinos

- Most experiments are consistent with 2 Δm^2 values: **$\Delta m^2_{12} \sim 10^{-5}$ eV^2**, and **$\Delta m^2_{13} \sim 10^{-3}$ eV^2**
- Oscillations at a different Δm^2 value would signal the existence of more than 3 neutrinos.
- LEP constrains the number of light active neutrinos to **3**, therefore, the new states would have to be *sterile*.

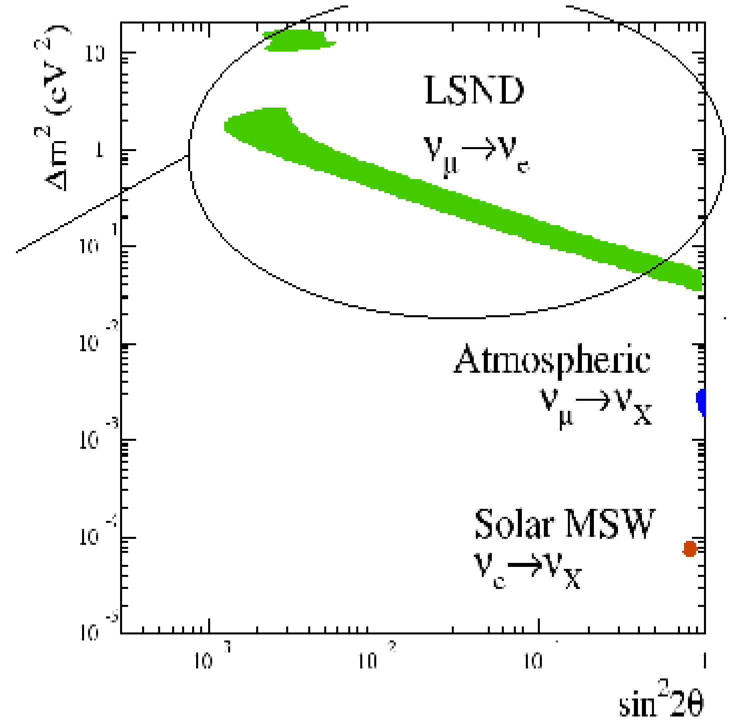
3+1 model



3 neutrinos ⇒ 2 distinct Δm^2 's



4 neutrinos ⇒ 3 distinct Δm^2 's



Anomaly	Type	Channel	Significance
LSND	DAR	$\bar{\nu}$ CC	3.8 σ
MiniBooNE	SBL accelerator	ν CC	3.0 σ
MiniBooNE	SBL accelerator	$\bar{\nu}$ CC	1.7σ
Gallium/Sage	Source - e capture	ν CC	2.7σ
Reactor	Beta-decay	$\bar{\nu}$	3.0σ

A few positive indicators exist of a $\Delta m^2 \sim 1$ eV^2, all at short baselines, but there is tension with other data.

Maybe more than 1 sterile? 3+N?

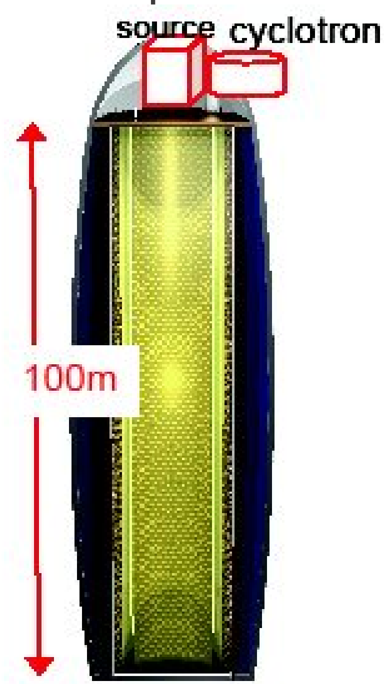
Short baseline oscillations with Decay at rest sources (DAR)

- Intense DAR source placed near a large detector ⇒ good oscillation sensitivity
- For a small source (<25 cm) with energies 20-50 MeV it is possible to observe *L/E* oscillations ***within the detector***.
- Detectors: Water Cherenkov, Liquid Argon, or Liquid Scintillator

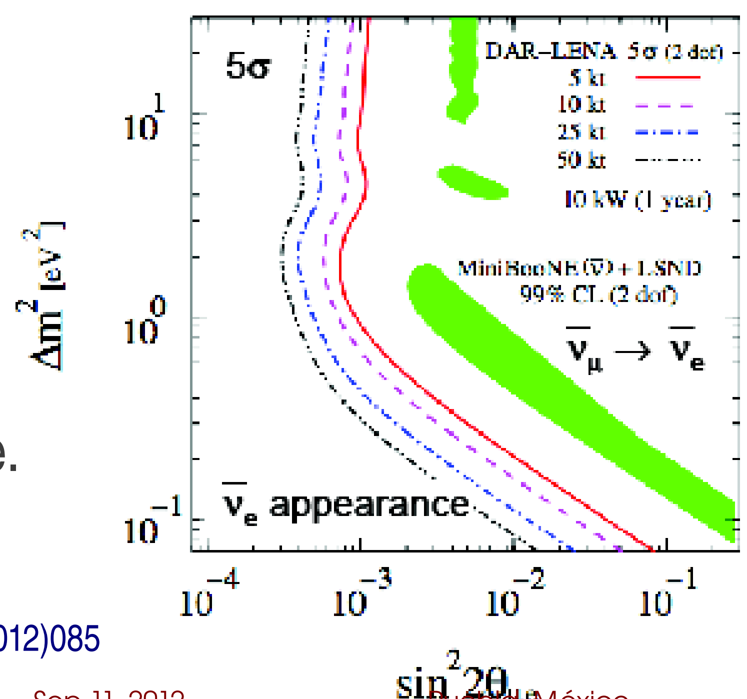
Intense (Mega-Curie) ν_e source: ν_e disappearance

Stopped π^- source of ν_μ's: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

Example: LENA (**L**ow **E**nergy **N**eutrino **A**strophysics) scintillator detector:



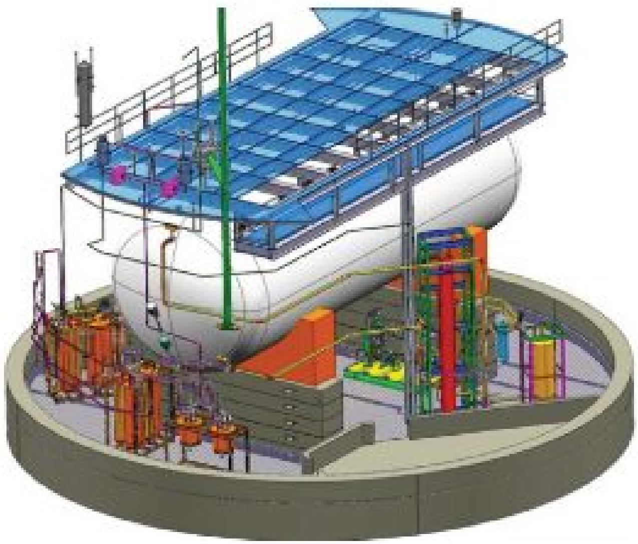
- Deep location (4000 m.w.e.) for minimal muon backgrounds
- Need 10 kW source with 5 kt detector for 1 year for 5σ coverage
- Appearance and disappearance possible.

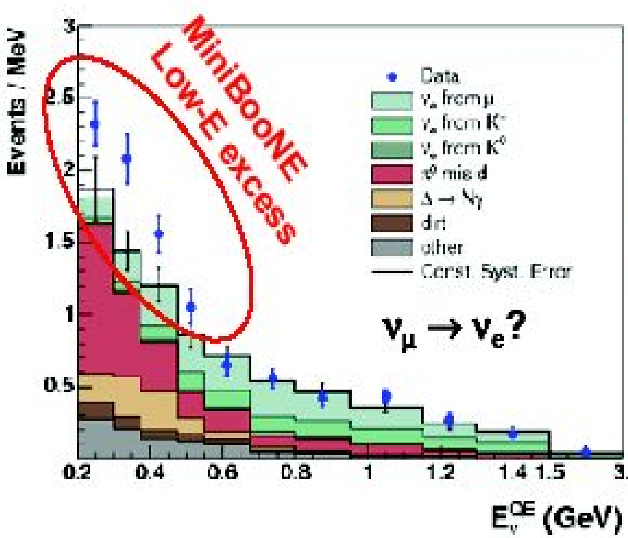


Argawalla, et al. JHEP 1112(2012)085

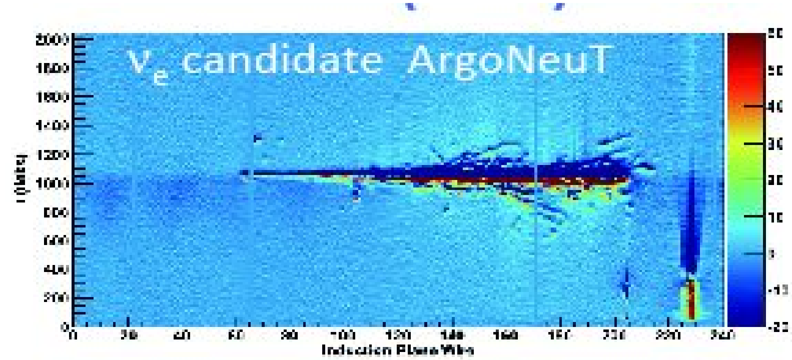
MicroBooNE (under construction)

170 ton LAr-TPC to explore the MiniBooNE excess



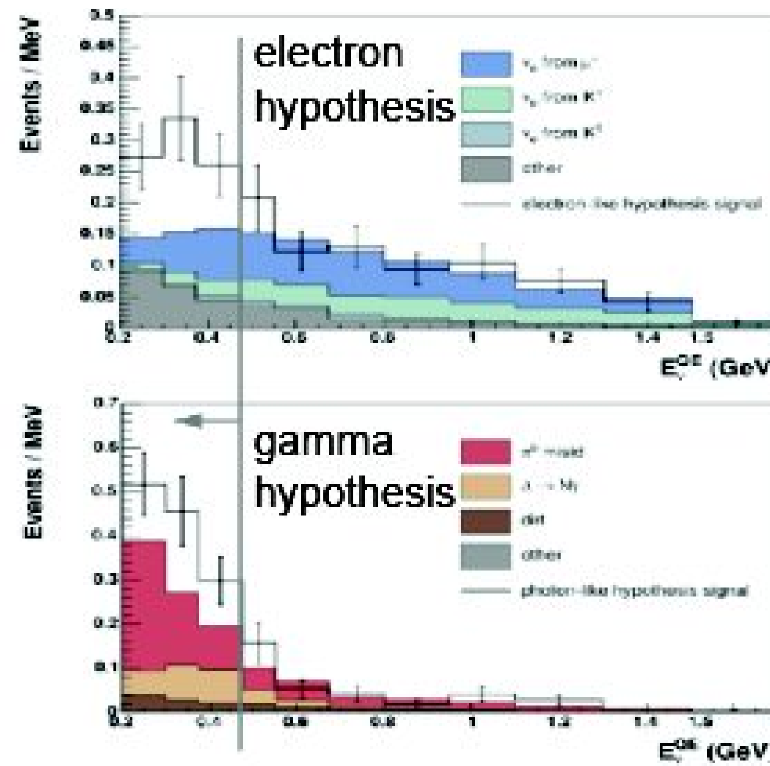


Is it electrons or gammas?



Use topology and dE/dx to differentiate electrons (signal) from gammas (background)

(Indistinguishable in Cerenkov imaging detectors)

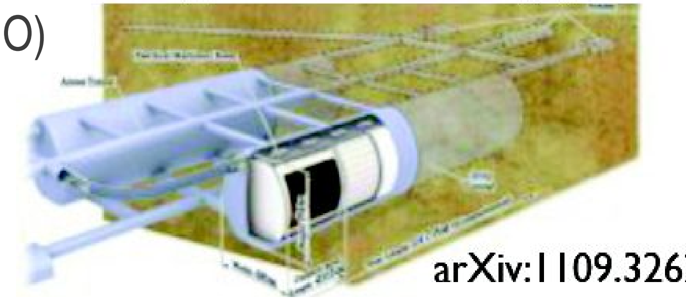


Some other future detectors

Atmospheric ν experiments:

- Magnetized Iron calorimeters: ICA@India-based Neutrino Observatory (INO)
- Water Cherenkov Detectors: Hyper-Kamiokande Mton size Super-K type.
- (Magnetized) Liquid Argon: Glacier
- Multi-Mton Ice detectors: PINGU denser string infill of IceCube

Hyper-Kamiokande (JP)

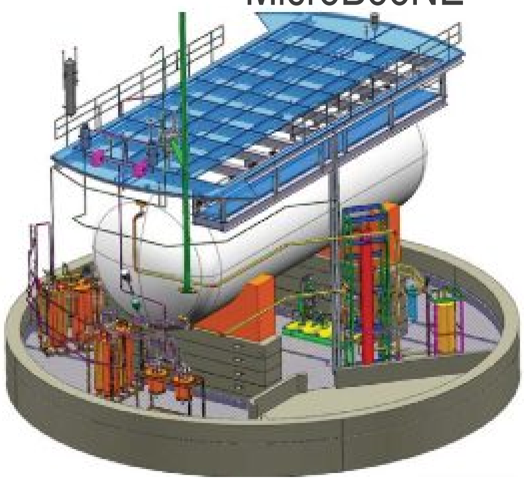


arXiv:1109.3262

Long/Short Baseline oscillations with Lar TPC's:

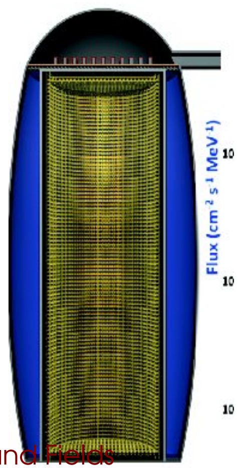
• MicroBooNE:	170 t,	0.47 km,	FNAL BNB	**in construction**
• LAr1 :	1000t	0.7 km	FNAL-BNB	proposal
• ICARUS-NESSIE:	150 t+ 478 t,	0.3+1.6	CERN	proposal
• GLADE:	5000 t,	810 km,	NuMI Off-axis	Letter of Intent
• LBNE+LAr:	2 x 17,000 t	1300 km	Homestake	Reconfiguration
• GLACIER-LAGUNA	20,000 t +	2,300 k	Finland	
• GLACIER-Okinoshima:	100,000 t,	665 km	Jparc beam	R&D proposal

MicroBooNE

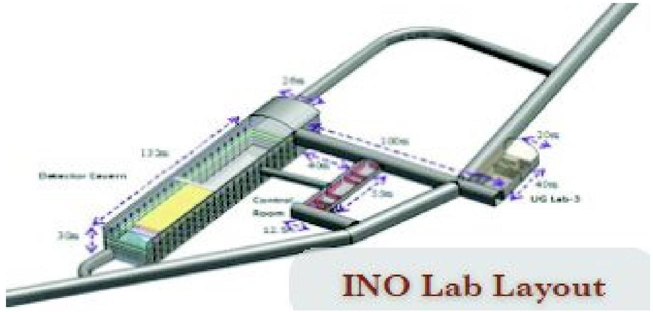


Large scintillator detectors:

- LENA 50 kt, Phyasalmi, Finland, 4000 m.w.e. depth
  Radioactive source short distance oscillometry,
  LBL Far detector, Solar, Super-Nova, Geo-ν,



LENA



Summary

- Neutrino oscillations well established. Experiments are now measuring with high precision the parameters of the oscillations (dominant behavior from Solar+Atmos+reactor+LBL accel.)
- Reactor experiments have measured a $\theta_{13} \neq 0$ larger than expected. Determination of the Mass Hierarchy will be easier. Opens possibility to measure CPV.
- Earth matter effects in neutrino vs antineutrino oscillations will be exploited by future experiments to try to measure the Mass Hierarchy and explore CPV in the leptonic sector.
- Will take several years (5-10 yr) of data taking after construction of the new large experiments to finally measure precisely all the properties of neutrinos.
- Experiments will test the anomalies of LSND/MiniBooNE. Establishing the existence of sterile neutrinos would be a major result for particle physics.
- Note that all these experiments will not be able to find the neutrino absolute masses! $\Rightarrow$ other experiments are being performed to address this (subject of another full talk!)
- Exciting times to be do neutrino physics!

Thank you!

Backup

Neutrino interactions

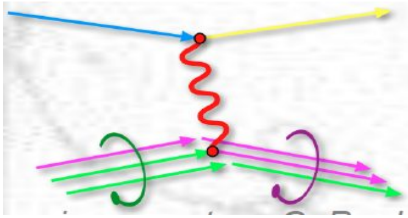
ν-electron elastic scattering: (CC &/or NC)

$$\nu_l + e \rightarrow \nu_l + e \qquad l = e, \mu, \tau$$

$\sigma(\nu_e) = 0.93 \times 10^{-41}\,cm^2\,(E_\nu/GeV)$
$\sigma(\nu_{\mu,\tau}) = 0.16 \times 10^{-41}\,cm^2\,(E_\nu/GeV)$
strongly directonal: $\theta_e \leq 2m_e/E_\nu$

ν-nucleon (N=n,p) scattering:

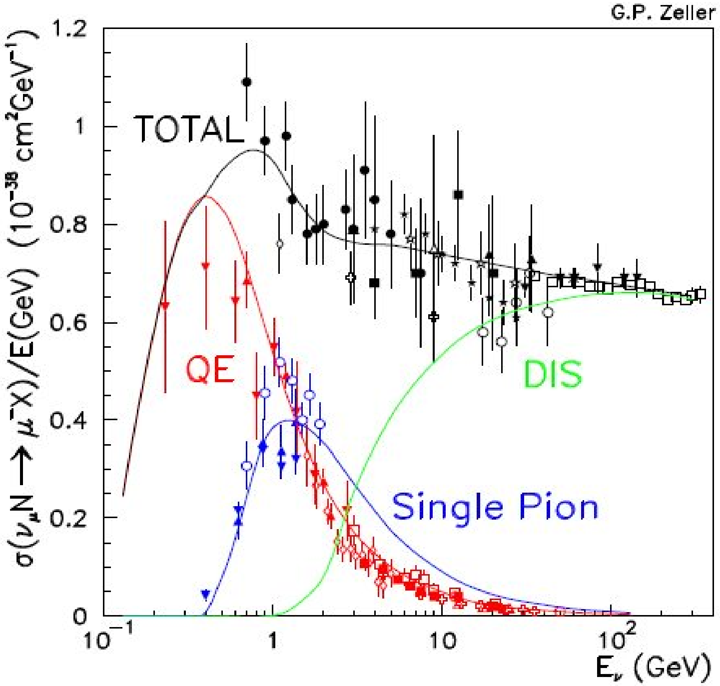
- Elastic scattering (NC) $\qquad \nu_l + N \rightarrow \nu_l + N$
- Quasi-elastic (CC)



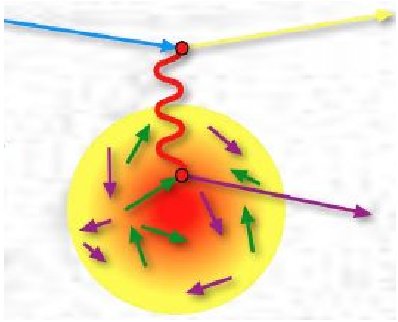
$$\bar{\nu}_l + p \rightarrow l^+ + n$$
$$\nu_l + n \rightarrow l^- + p$$

- π production

$$\nu_l + p \rightarrow l^- + \Delta^{++}\,(\rightarrow p + \pi^+)\ (CC)$$
$$\nu_l + p \rightarrow \nu_l + \Delta^{+}\,(\rightarrow p + \pi^0)\ (NC)$$



Deep inelastic scattering (DIS)
- CC interactions → charged lepton + debris
- CN interactions → outgoing neutrino + debris



Atmospheric neutrino oscillations

Oscillation probabilities for neutrinos with E_ν~1-50 GeV

L (km), *E* (GeV)

$$P(\nu_\mu \to \nu_\tau) \approx \cos^4\theta_{13}\ \sin^2\theta_{23}\ \sin^2(1.27\ \Delta m^2_{23}\ L/E)$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13}\ \sin^2\theta_{23}\ \sin^2(1.27\ \Delta m^2_{23}\ L/E) \quad = P(\nu_e \to \nu_\mu)$$

$$P(\nu_e \to \nu_\tau) \approx \sin^2 2\theta_{13}\ \cos^2\theta_{23}\ \underbrace{\sin^2(1.27\ \Delta m^2_{23}\ L/E)}$$

~π/2 when *L*~5,000 km and E~10 GeV

$\Delta m^2_{23} = 2.5\times10^{-3}\ \text{eV}^2$
$\theta_{13} = 8.8°$

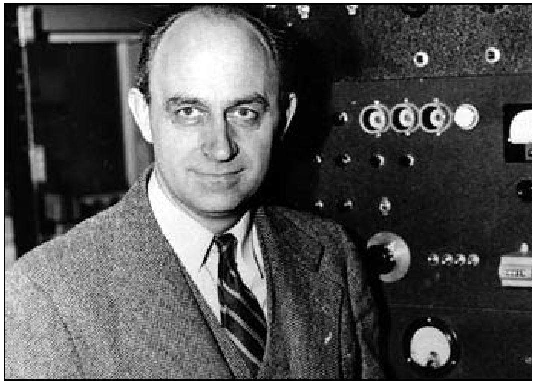
θ_{13} small(ish) $\Rightarrow$ $P(\nu_\mu \to \nu_\tau)$ dominates

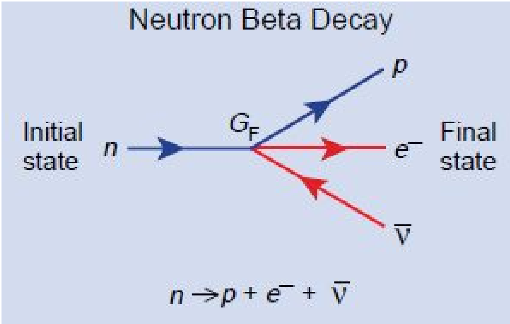
Note: Artificial beam with E_ν~1.5 GeV along ~750 km would have the same *L/E*.

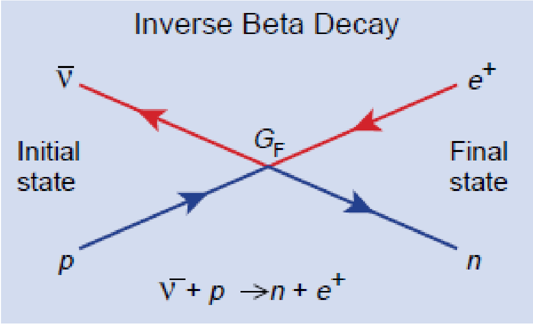
Neutrinos

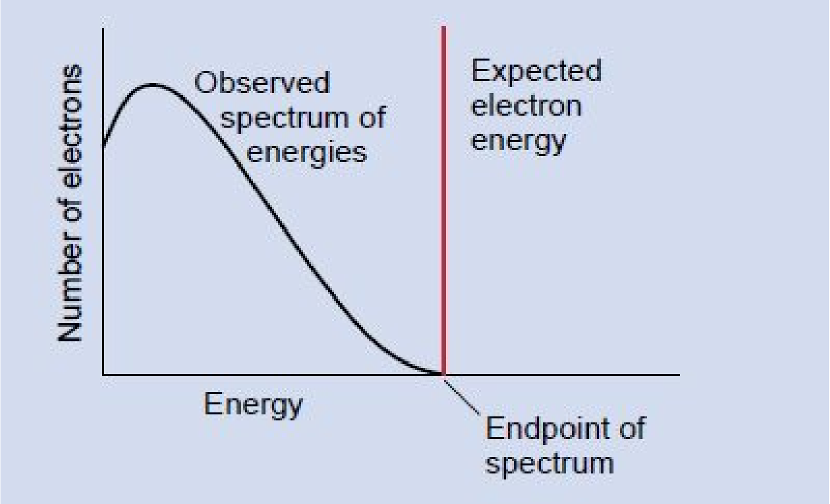
In 1930, Pauli postulated the existence of a new particle to explain the observed energy spectrum of the electrons emitted in nuclear beta decay.

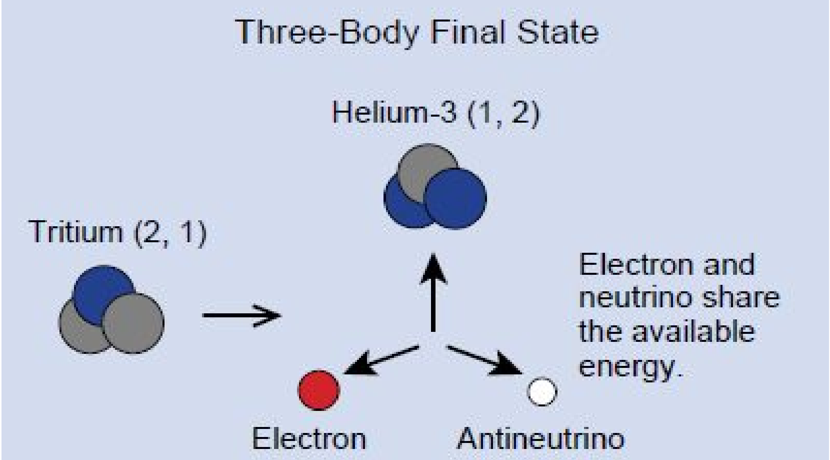
In 1934, Enrico Fermi introduces the “neutrino” in his theory of beta decay.











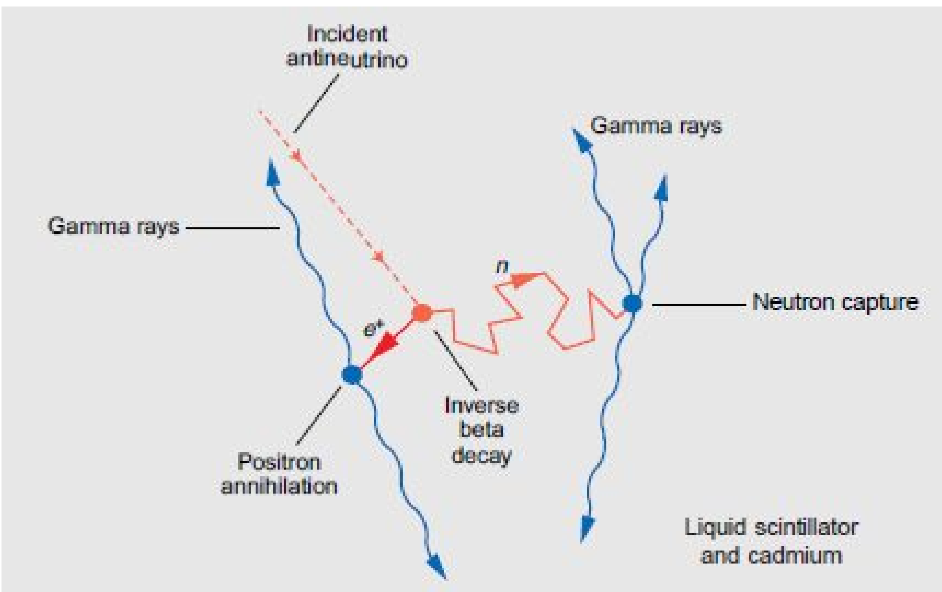
$$(N, Z) \rightarrow (N-1, Z+1) + e^- + \bar{\nu} \ .$$

where N = number of neutrons, and
Z = number of protons.

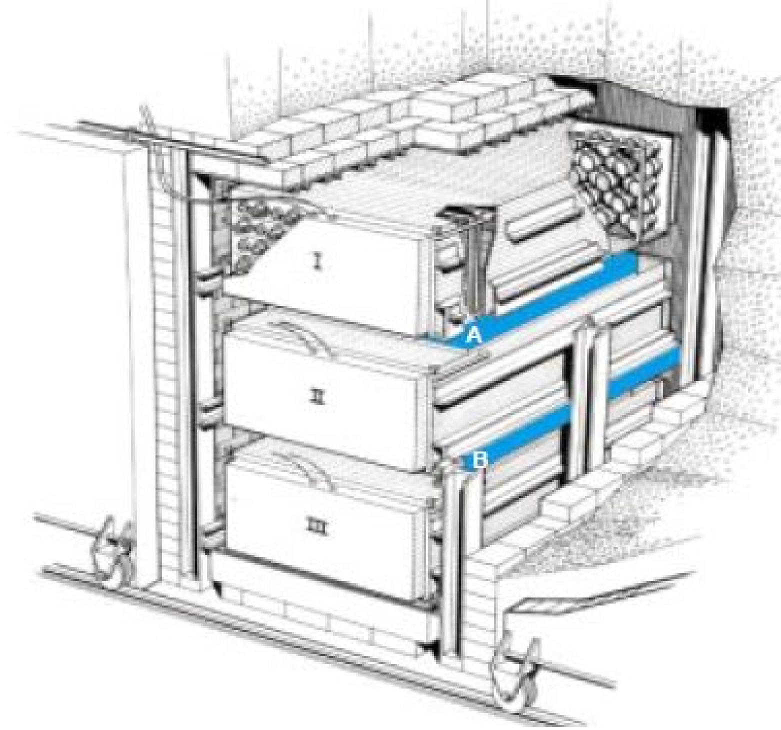
Experimental discovery, 1956

F. Reines and C. Cowan, Los Alamos, U.S.A.

Source: Nuclear reactor, Savannah River, SC
Detector: - 3 tanks with liquid scintillator
- 2 targets with H_2O w/ $CdCl_2$ dissolved



Frederick Reines   Clyde Cowan



June 14, 1956, telegram for W. Pauli:

```
"We are happy to inform you that we have
definitively detected neutrinos from fission
fragments by observing inverse beta decay. "
                        F. Reines & C. Cowan
```

Neutrino oscillations

- Studied experimentally by:

  appearance and ***disappearance***

- Relevant parameters:
  - Δm^2→frequency, θ→Amplitude **: Fixed by Nature**
  - Energy E of ν, distance L from source to detector

    : Fixed by Experimenter

- Disappearance

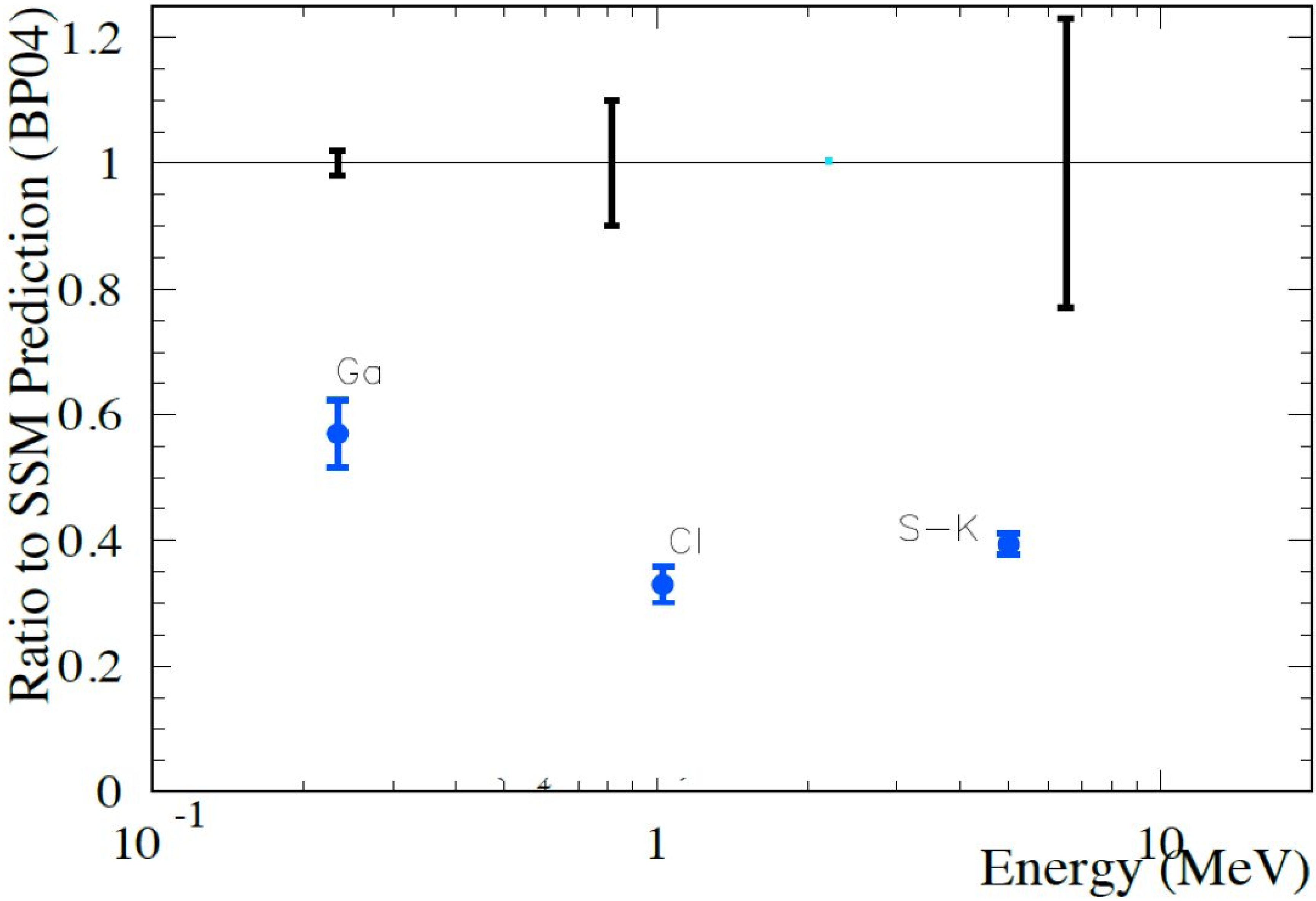
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Appearance

$$P(\nu_\alpha \underset{\alpha \neq \beta}{\to} \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Notation: $\frac{\Delta m^2 L}{4E} = \frac{1.27 \Delta m^2 L}{E}$, Δm^2 (ev^2), L (km), E (GeV)

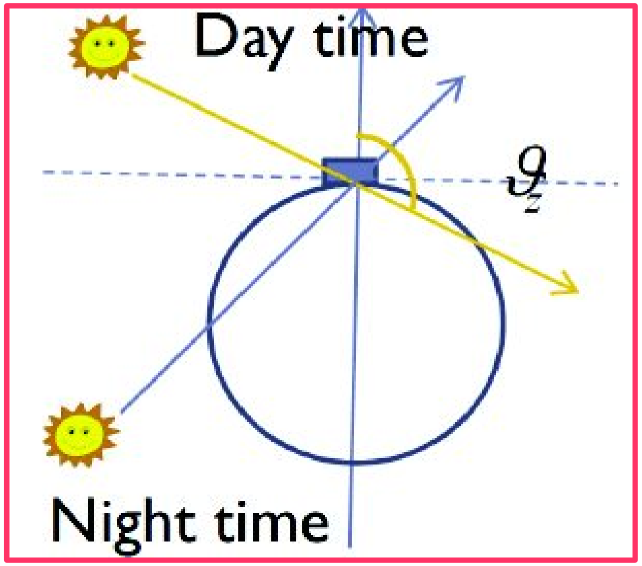
Solar neutrino problem



Three phases of SNO (neutron detection)

Pure D_2O	Salt (2 ton)	^{3}He Counters
Nov 99 – May 01	Jul 01 – Sep 03	Nov 04 – Nov 06
$n + d \rightarrow t + \gamma$	$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$	$n + {}^3He \rightarrow t + p$
$(E_\gamma = 6.25$ MeV$)$	$(E_{\Sigma\gamma} = 8.6$ MeV$)$	proportional counters $\sigma = 5330$ b
	enhanced NC rate and separation	event-by-event separation
PRL **87**, 071301 (2001) PRL **89**, 011301 (2002) PRL **89**, 011302 (2002)	PRL **92**, 181301 (2004)	
PRC **75**, 045502 (2007)	PRC **72**, 055502 (2005)	PRL **101**, 111301 (2008)

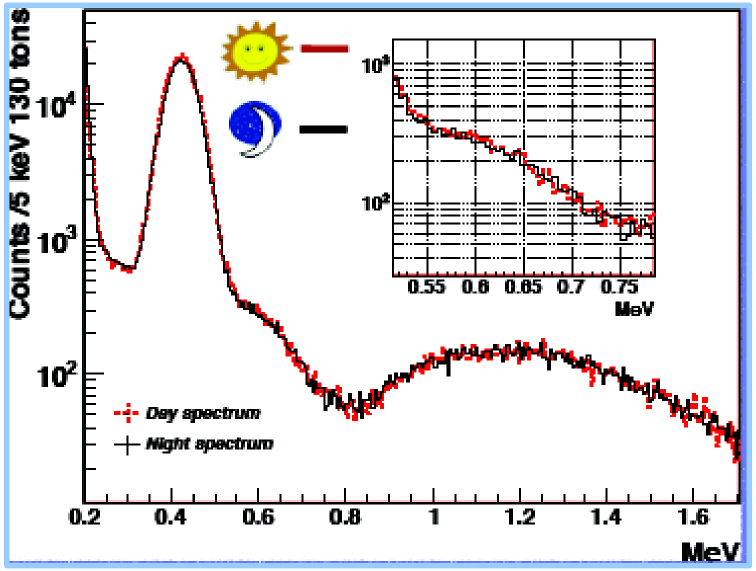
Borexino, day/night asymmetry



Phys.Lett. **B707**,22-26, 2012

$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} = $$
$$= 0.001 \pm 0.012 \pm 0.007$$

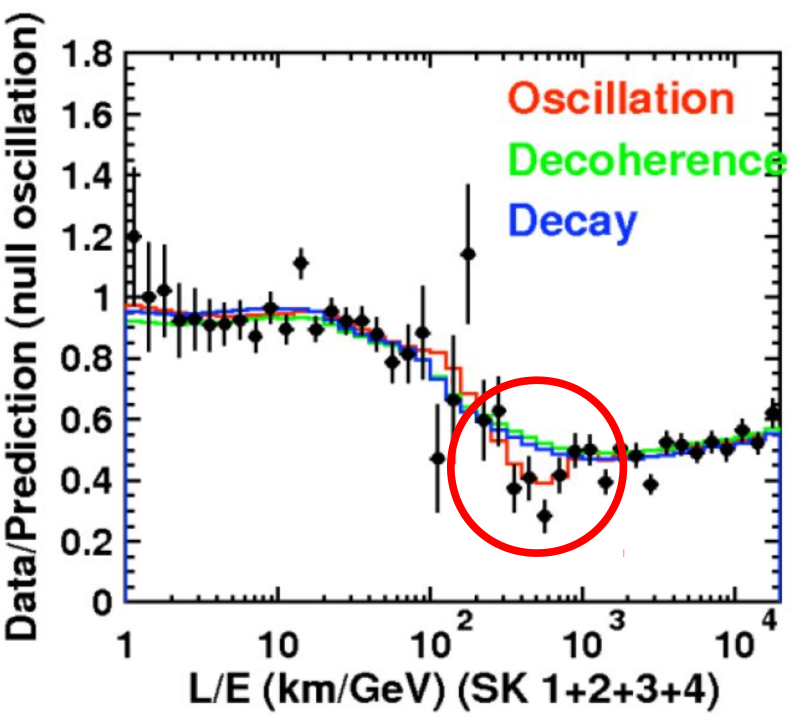
No asymmetry observed

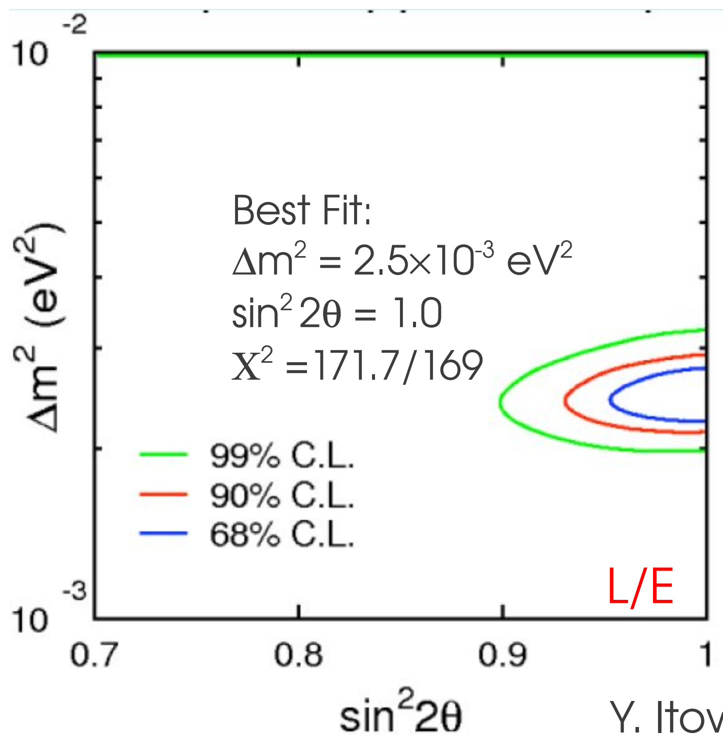


⇒ Earth matter effects are small for solar neutrinos. Allows to select LMA solution from solar data only (previously, one needed KamLAND data for this).

Super-K (I+II+III+IV): atmospheric neutrinos, L/E analysis

- Arival direction determines the traveled distance *L* across the Earth (or the atmosphere).
- Oscillation interpretation is strongly favored by the details in the L/E spectrum.
- Alternative explanations are disfavoured: decoherence (4.4 σ) y neutrino decay (5.4 σ)





$\Delta m_{23}^2 = 2.5\times10^{-3}$ eV^2
$\sin^2 2\theta_{23} = 1.0$

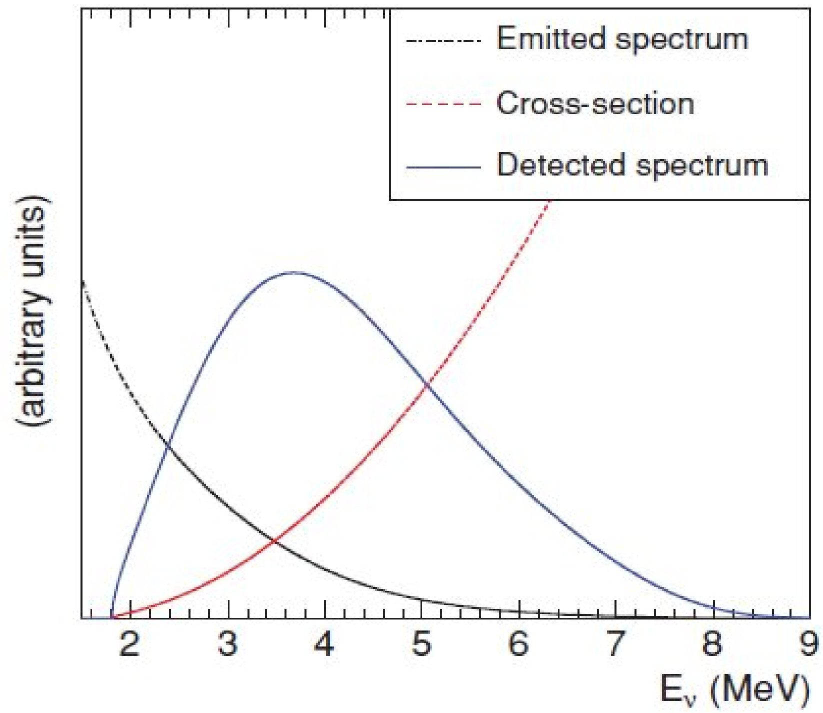
Y. Itow, **Neutrino 2012**

Neutrinos from nuclear reactors

Decaimiento β^-: $^A_Z X \rightarrow \, ^A_{Z+1}Y + e^- + \overline{\nu}_e$

	^{235}U	^{239}Pu	^{238}U	^{241}Pu
$E_{Fisión}$(MeV)	202	210	205	212
$\langle E_\nu \rangle$ (MeV)	1.46	1.32	1.56	1.44
$\langle N_\nu \rangle$ (E_ν>1.8 MeV)	5.58 (1.92)	5.09 (1.45)	6.69 (2.38)	5.89 (1.83)

Typically: ~ **2×10^{20} $\overline{\nu}_e$*/sec/GWatt***

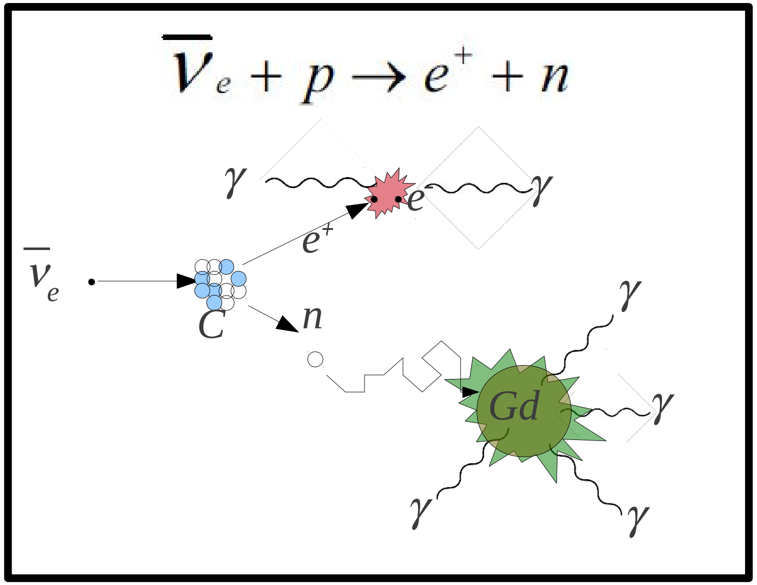


Detected through ***inverse β decay***:

- Reaction threshold: E_ν>1.8 MeV
- Cross section ($\propto E_\nu^2$): $\langle\sigma\rangle \sim 10^{-43}$ cm^2

Signal e^+: Cherenkov+γ's (annihilation)

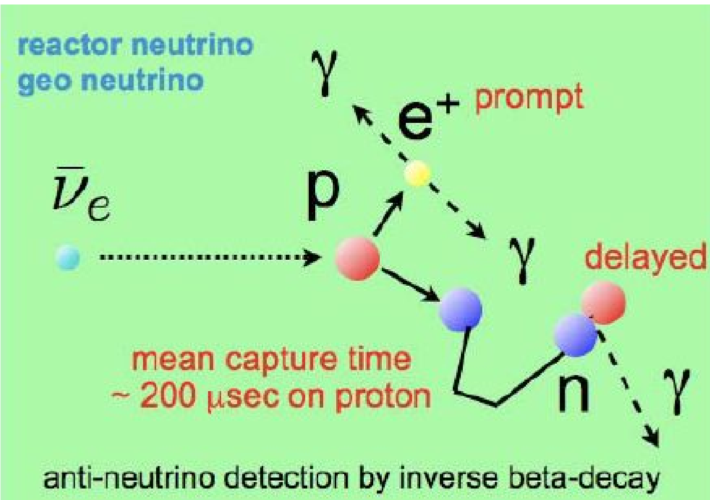
Signal n: γ's from capture in Gd (~8 MeV)

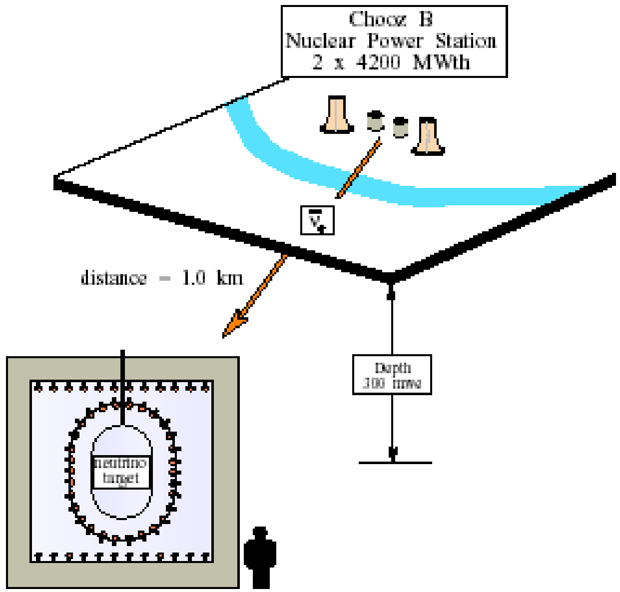


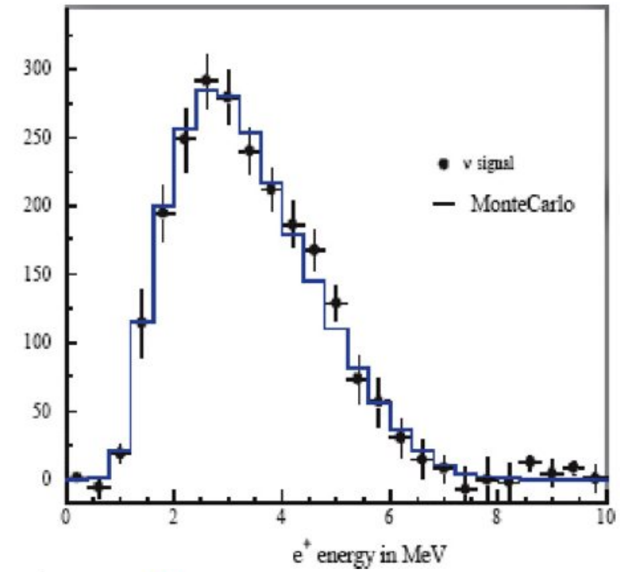
The delayed coincidence of the e$^+$ and n signals, I identify the interaction of a $\overline{\nu}_e$ with a proton.

Experimento CHOOZ

5 ton de centellador líquido dopado con Gd.





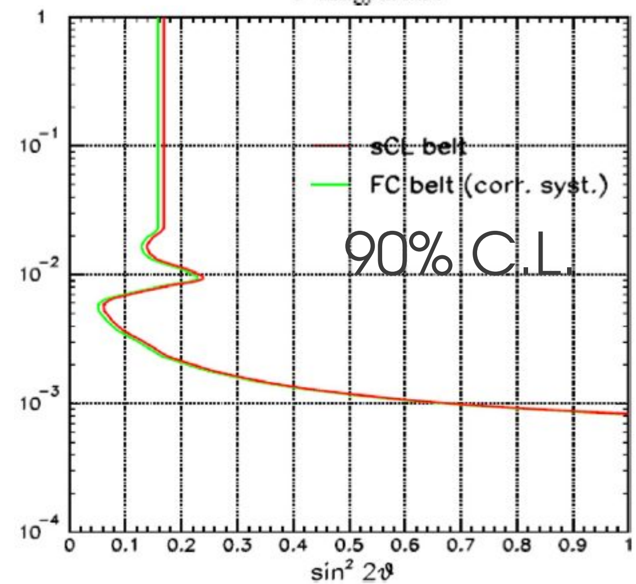


$$R = \frac{\text{dat}}{\text{no} - \text{osc}} = 1.01 \pm 0.0028 \pm 0.0027$$

Apollonio et al. (Eur.Phys.J **C 27** 331 (2003))

$$\bar{\nu}_e \rightarrow \bar{\nu}_x \text{ excluida para } \Delta m^2 \geq 8 \times 10^{-4} \text{eV}^2$$

$$\Rightarrow \text{SK} - \text{atm no es } \nu_\mu \rightarrow \nu_e \ (\Delta m^2_{\text{SK}-\text{atm}} \sim 10^{-3})$$



Reactor experiments measuring $\sin^2 2\theta_{13}$

Double-CHOOZ detectors

Outer Veto: *plastic scintillator strips*

=== Steel shield *(15 cm thick)* ===

78 8'"PMTs

Inner Veto: *LS (90 m^3)*

======= SS vessel =======

Holds 392 10" PMT's

Buffer: *mineral oil (110 m^3)*

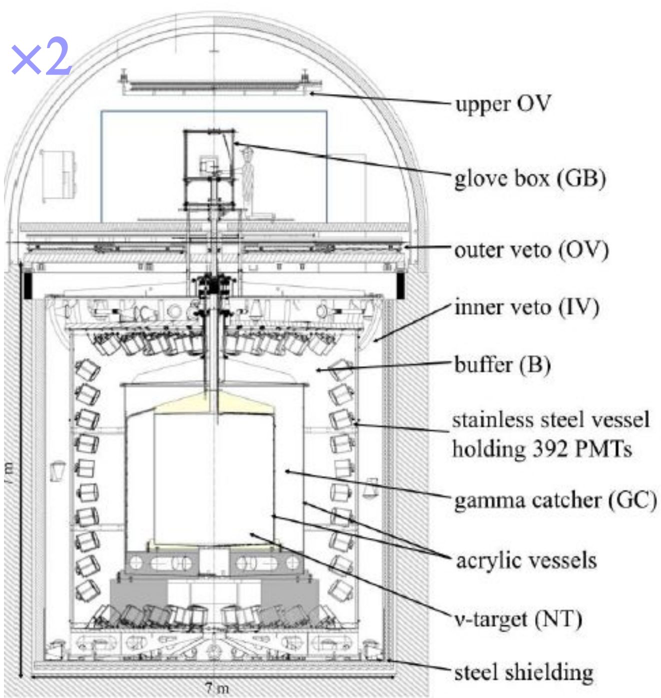
====== Acrylic vessel ======

γ–catcher: *LS (22 m^3)*

====== Acrylic vessel ======

ν target: *LS+Gd (10m^3)*

×2



Daya Bay detectors

Upper Veto: *RPC array*

=== Water veto shield ===

Segmented: outer/inner, *PMT's*

purified water (>2.5 m thick)

======== SS vessel ========

Holds 192 PMT's

Buffer: *mineral oil (37 ton)*

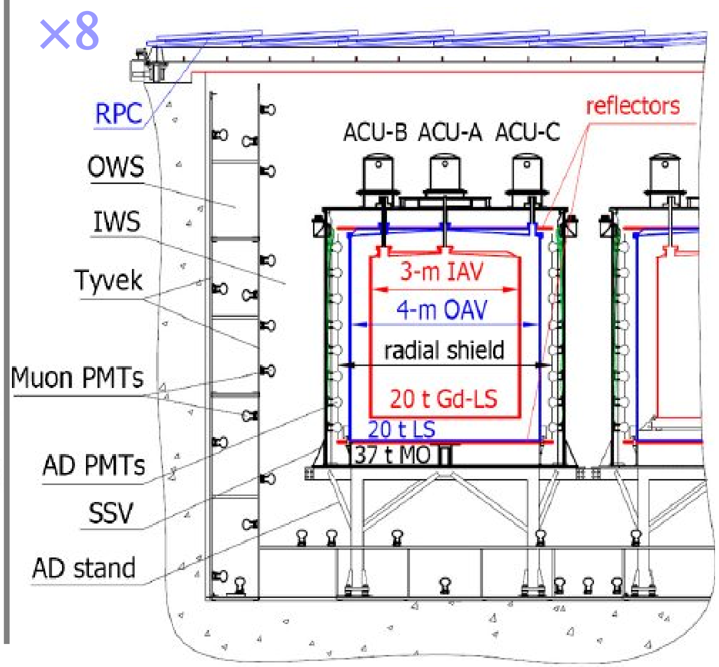
====== Acrylic vessel ======

γ-catcher: *LS (20 ton)*

====== Acrylic vessel ======

target: *LS+Gd (20 ton)*

×8



RENO detectors

Outer veto

===== Water veto shield =====

67 10" PMTs

purified water (1.5 m thick)

======== SS vessel ========

Holds 354 10" PMT's

Buffer: *mineral oil (65 ton)*

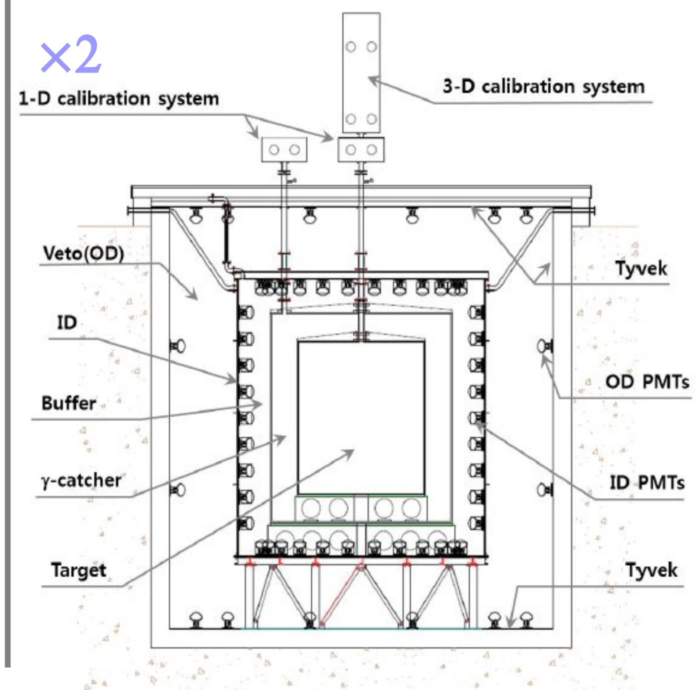
====== Acrylic vessel ======

γ–catcher: LS *(60 cm thick)*

====== Acrylic vessel ======

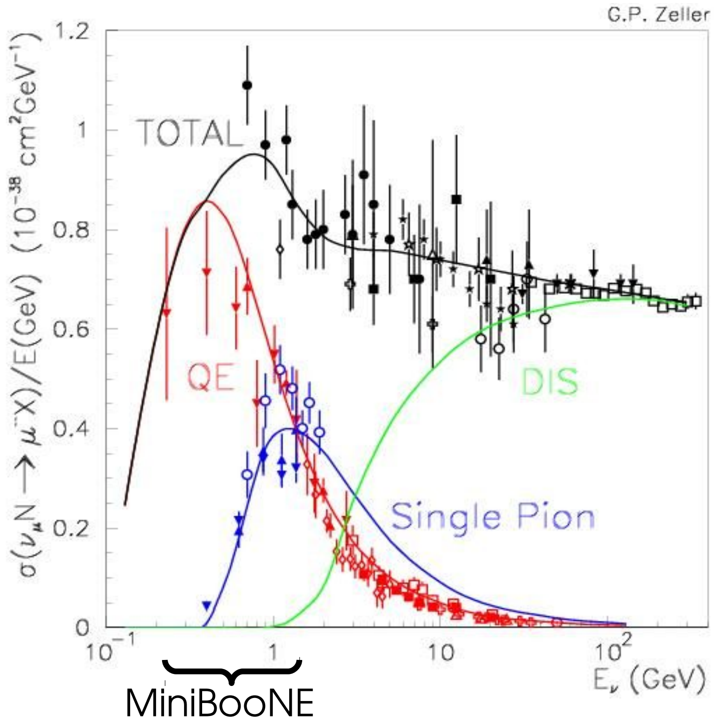
target: *LS+Gd (16 ton)*

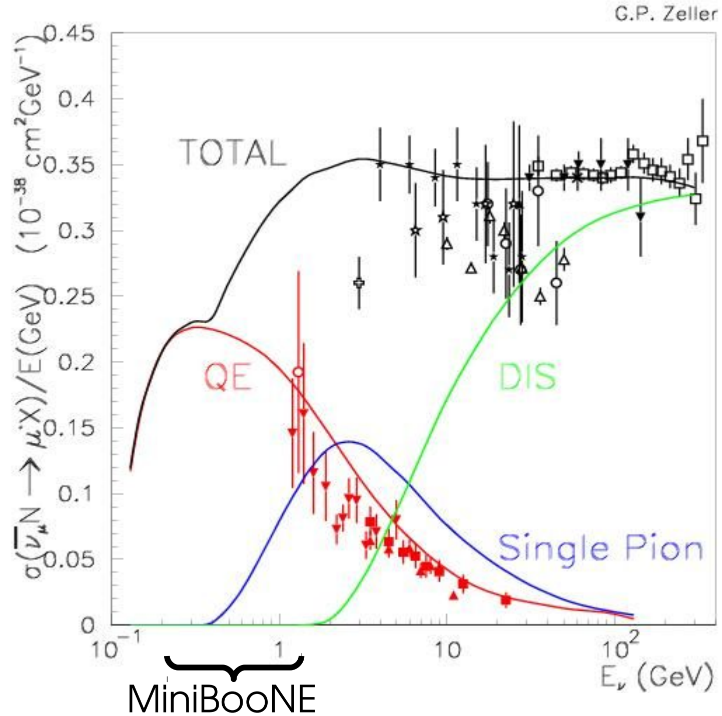
×2



Neutrino Interactions (ν & $\bar{\nu}$)

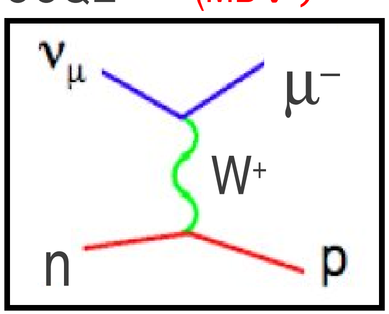
Cross sections modeled with NUANCE event generator (D. Casper, U.C. Irvine)





(T. Katori, J. Grange)

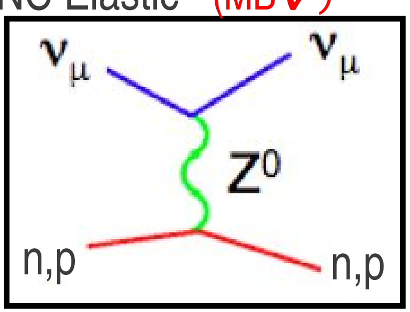
CCQE (MB ✓)



PRL **100**, 032301 (2008)
PRD **81**, 092005 (2010)

(D. Perevalov)

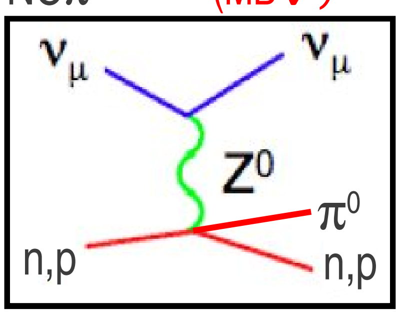
NC Elastic (MB ✓)



PRD **82**, 092005 (2010)

(C. Anderson, J. Link)

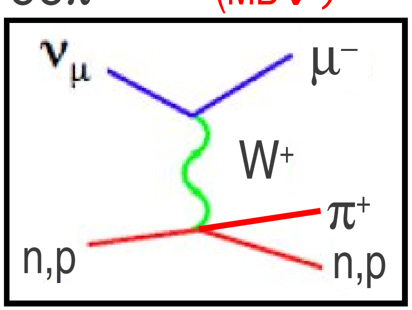
NCπ^0 (MB ✓)



PLB **664**, 41 (2008)
PRD **81**, 013005 (2010)

(S. Linden, M. Wilking)

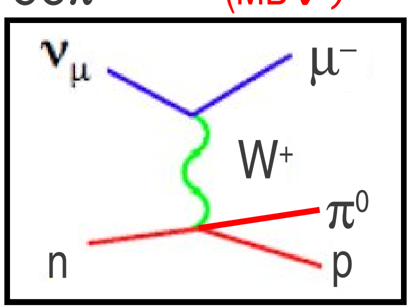
CCπ^+ (MB ✓)



PRL **103**, 081801 (2009)
PRD **83**, 052007 (2011)

(R. Nelson)

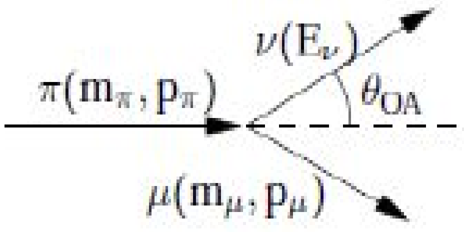
CCπ^0 (MB ✓)



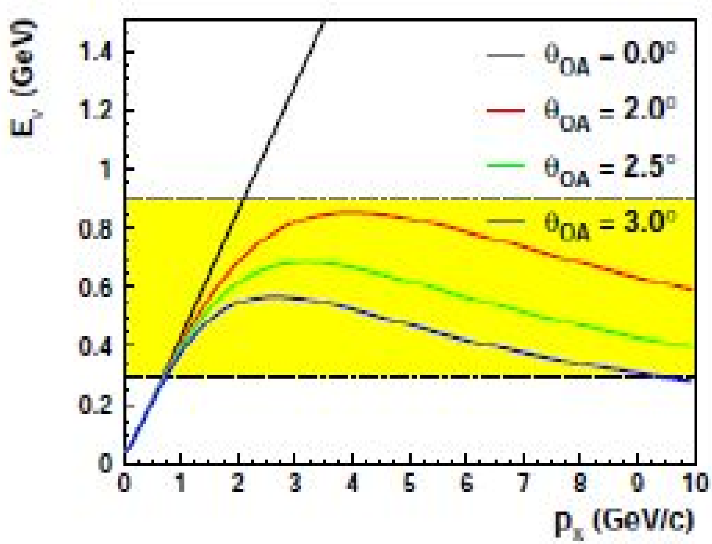
PRD **83**, 052009 (2011)

Experimentos “fuera del eje”, T2K y NOvA

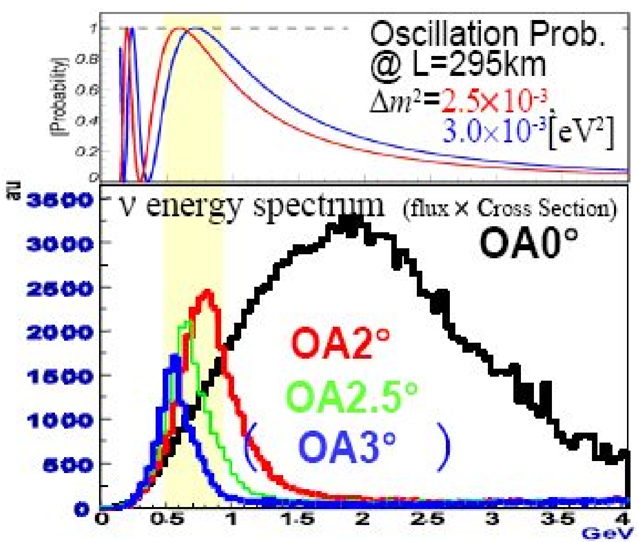
- haces enfocados con cuernos magnéticos
- ν's a un ángulo $\theta \neq 0$ respecto al eje.
- Espectro de E_ν pseudo-monocromático
- menor flujo, pero menor bkgd.
- NuMI-MiniBooNE: 1er ejemplo arXiv:0809.2447



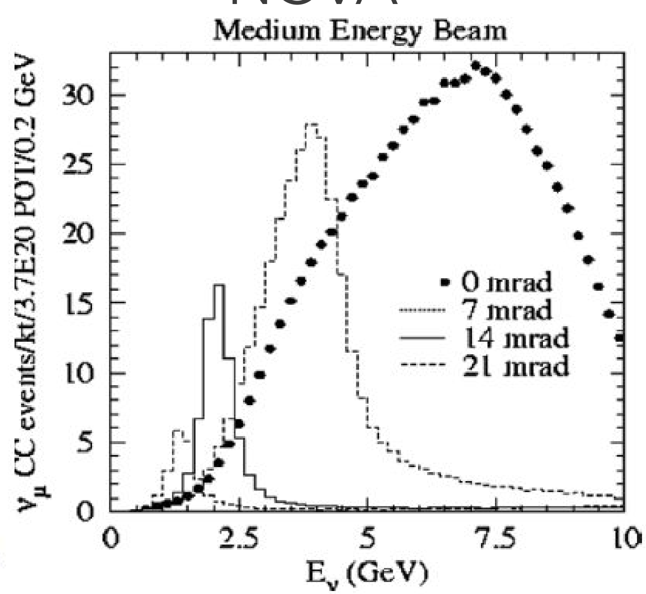
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta_{OA})}$$



T2K



NOvA



Eventos en MiniBooNE

Identificación basada en topología de eventos.
Usa principalmente luz Cherenkov, pero también de centelleo

$\nu_\mu\, n \to \mu^-\, p$

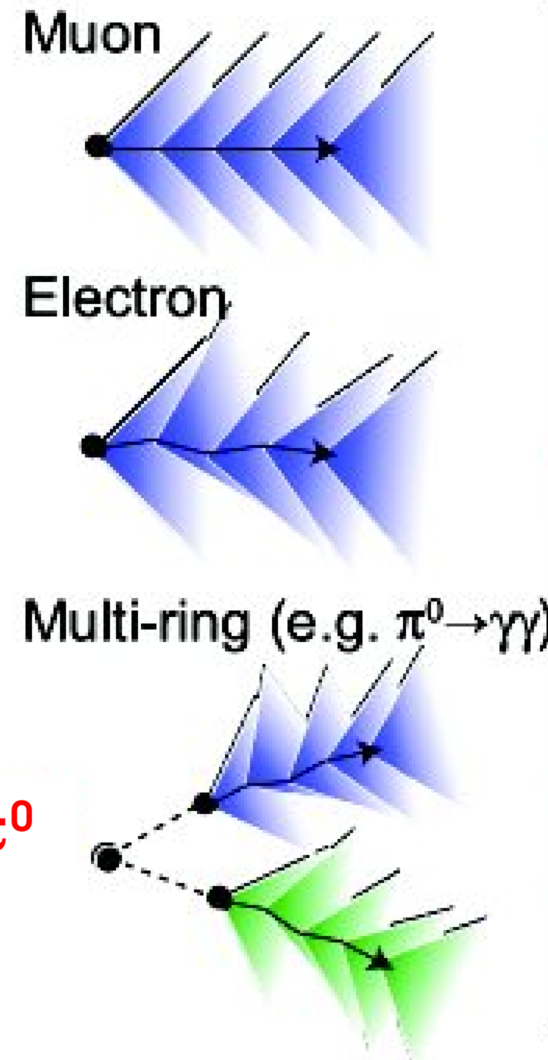
$\bar{\nu}_\mu\, p \to \mu^+\, n$

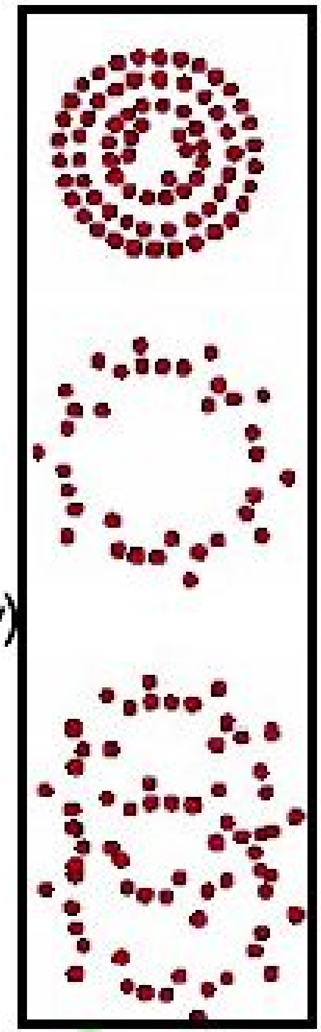
$\nu_e\, n \to e^-\, p$

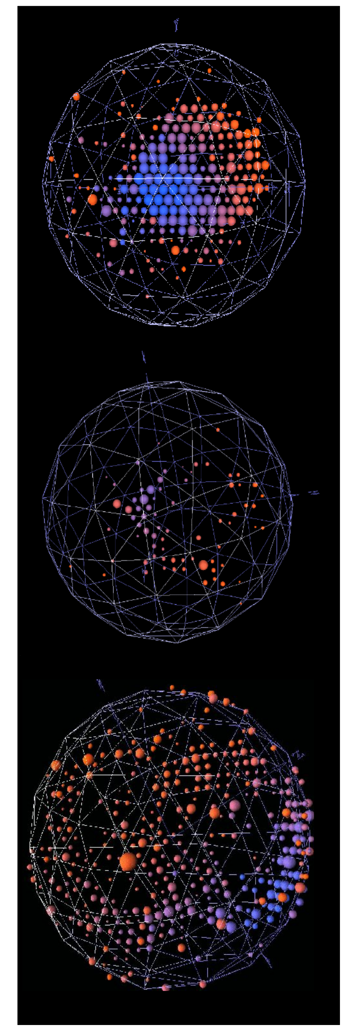
$\bar{\nu}_e\, p \to e^+\, n$

$\overset{(-)}{\nu}_\mu\, n \to \overset{(-)}{\nu}_\mu\, p\, \pi^0$

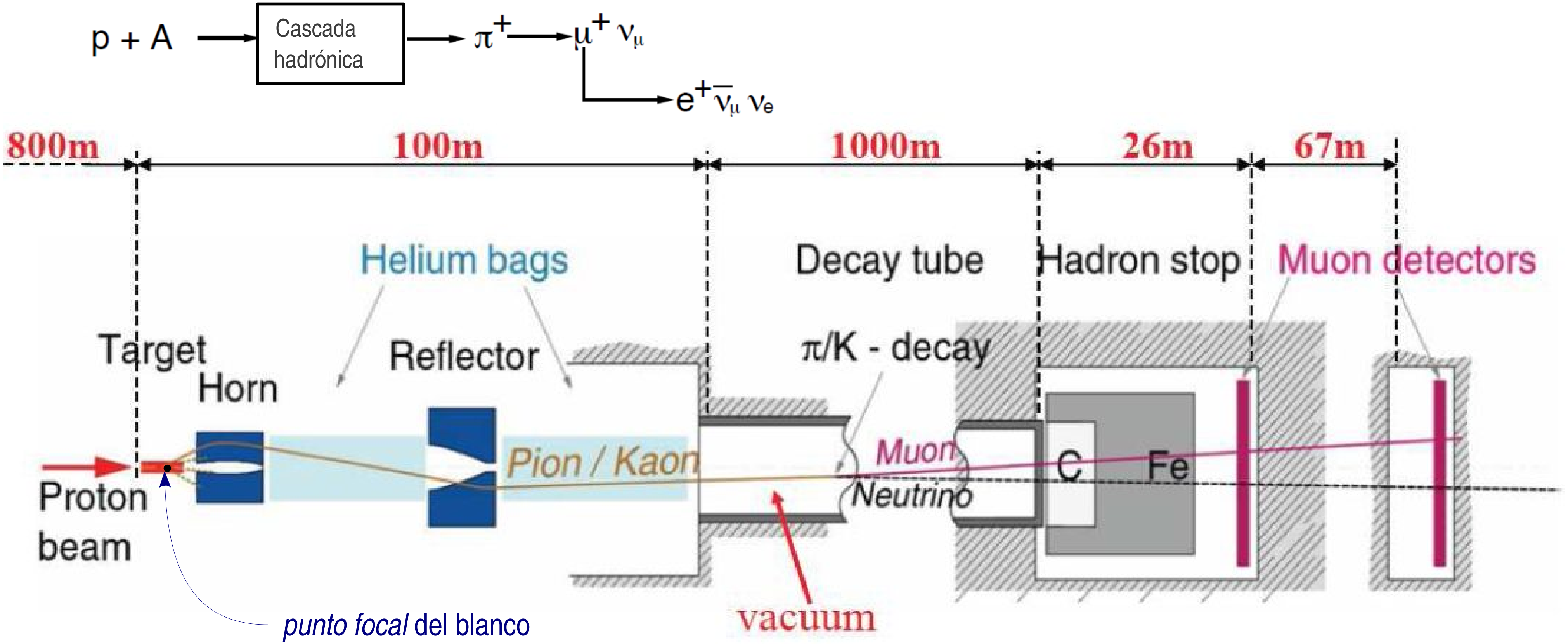
$\quad\;\; p \qquad\quad\; n$







Haz de neutrinos de CERN a Gran Sasso (CNGS)

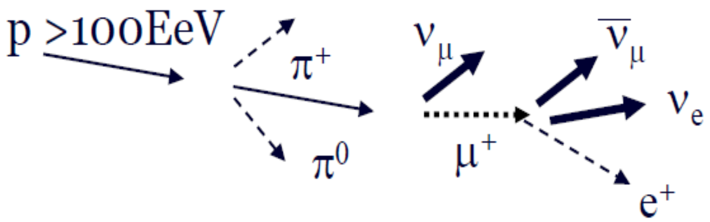


- Protones impactan blanco fijo de grafito (p+C $\rightarrow$ X+π/K).
- Mesones secundarios (π,K) enfocados por *cuernos magnéticos.*
- Mesones π,K decaen en túnel, produciendo neutrinos (ν_μ >99%)
- Componente hadrónica remanente detenida en blanco de Fe.
- Monitores de muones miden perfil cercano del haz.
- Haz inclinado ~5° hacia abajo toma en cuenta curvatura terrestre.

Ultra high energy neutrinos (UHE-ν's) (>PeV)

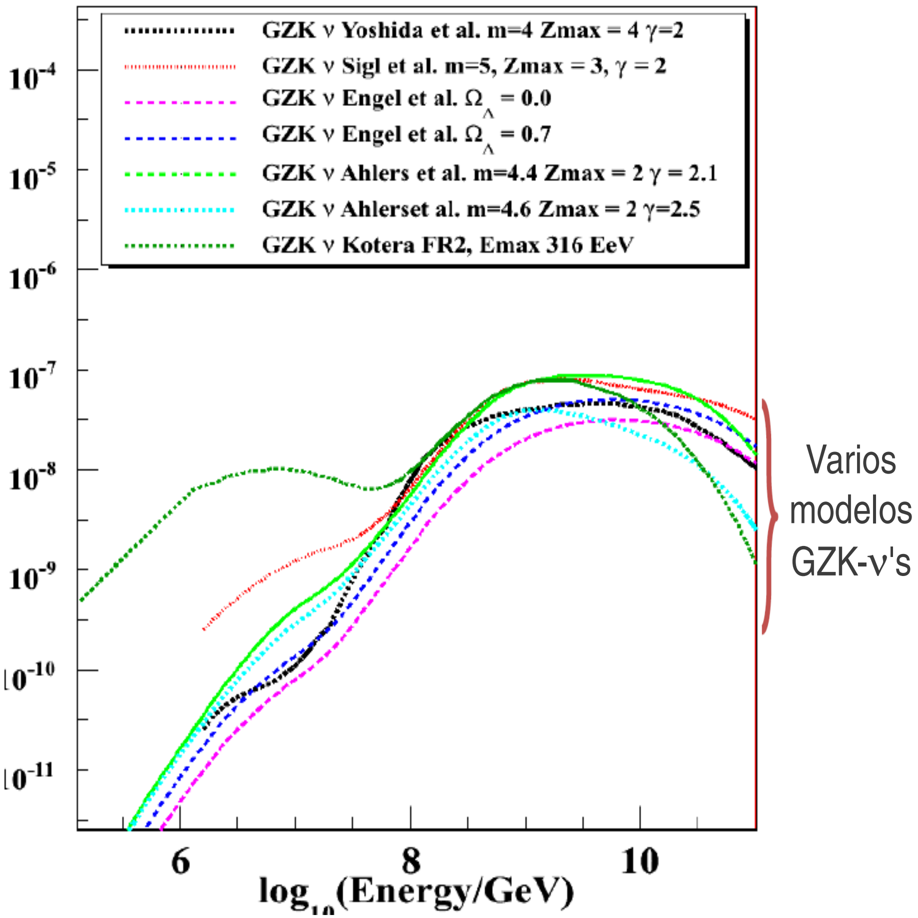
Cosmogenic neutrinos: induced by the interactions of cosmic rays with CMB photons

- Produced via the GZK (Greisen-Zatsepin-Kuzimnin) mechanism.



Energy range: **E_ν ~ $10^{8\text{-}10}$ GeV**

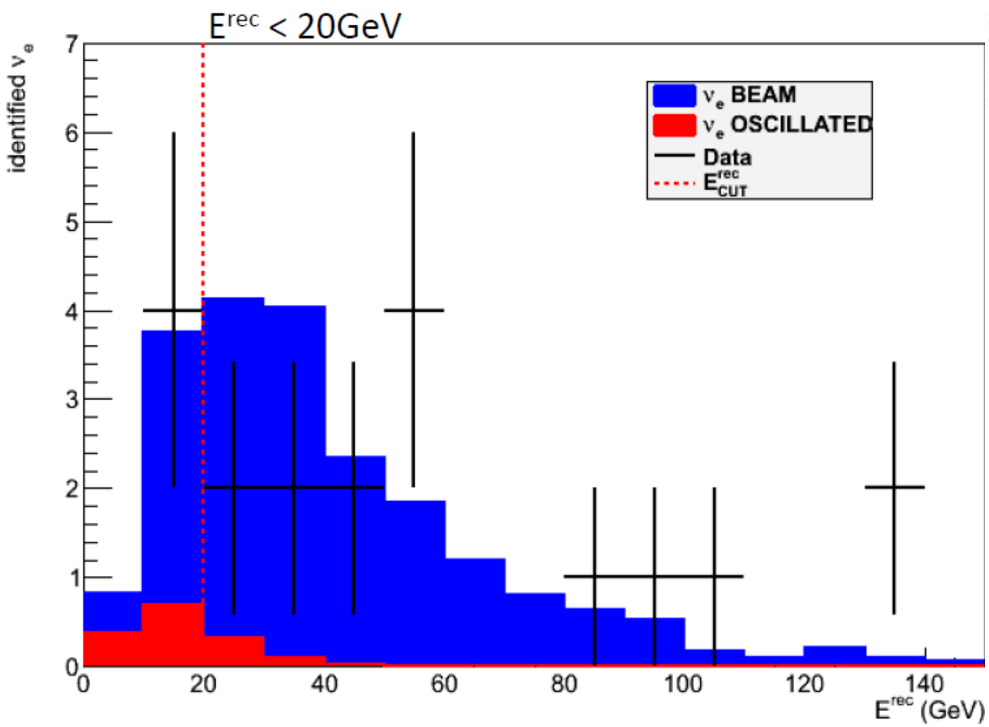
$$p\gamma_{2.7K} \rightarrow \pi^+ + X \rightarrow \mu^+ + \nu \rightarrow e^+ + \nu' s$$

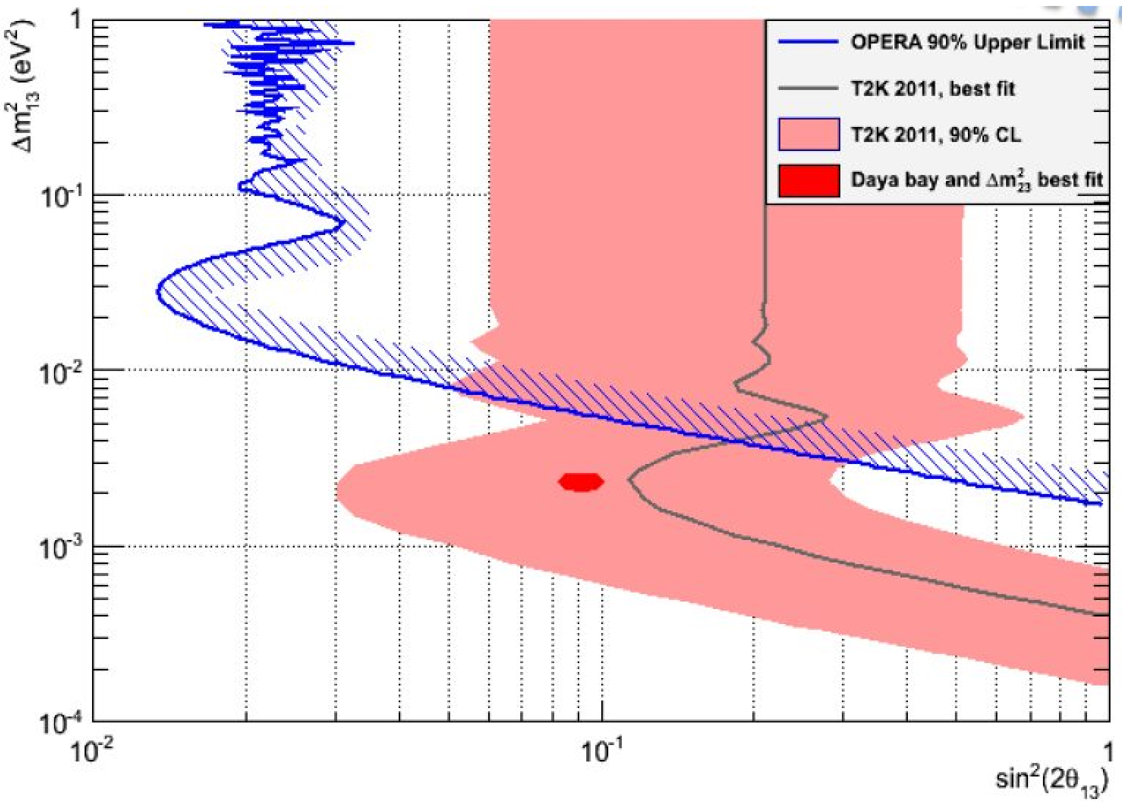


UHE-ν's carry information about:

- Location of cosmic ray sources.
- Cosmological evolution of these sources
- Cosmic ray spectrum *at the sources*
- Cosmic ray composition
- Particle physics beyond energy reach of accelerators.

OPERA, $\nu_\mu \rightarrow \nu_e$ appearance results





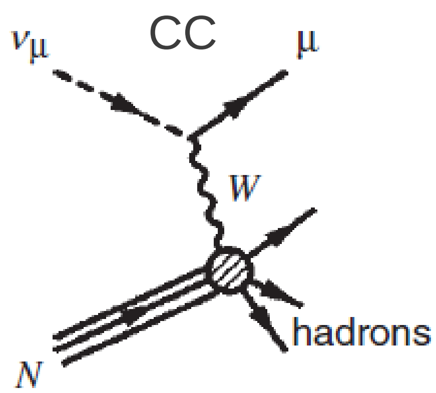
Expected events: oscillated νe 1.5, beam νe 19.2.

Observed νe : 19 events

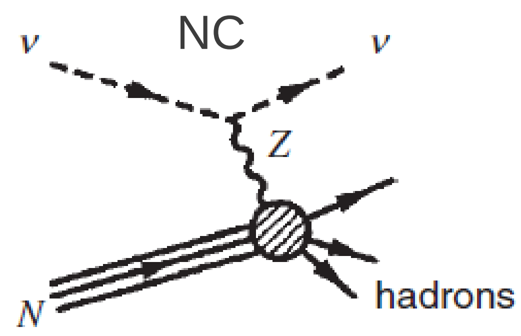
Interacciones de neutrinos

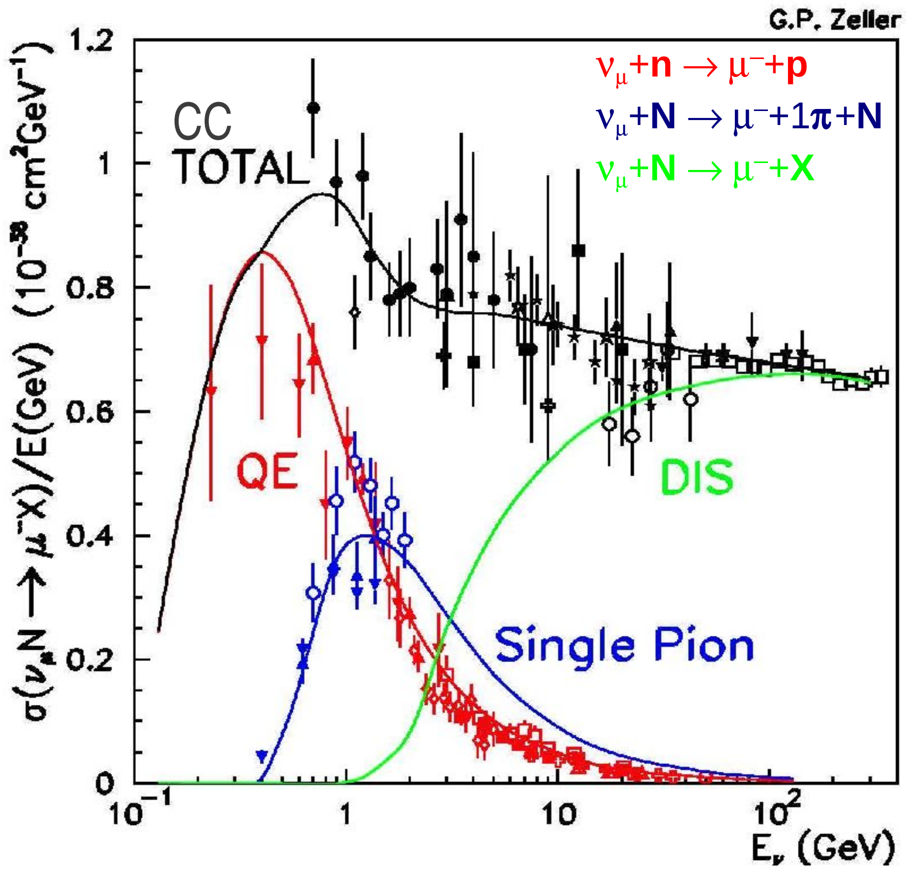
E_ν > 10 GeV: principalmente Dispersión Inelástica Profunda (DIS)

Corriente Cargada



Corriente Neutra

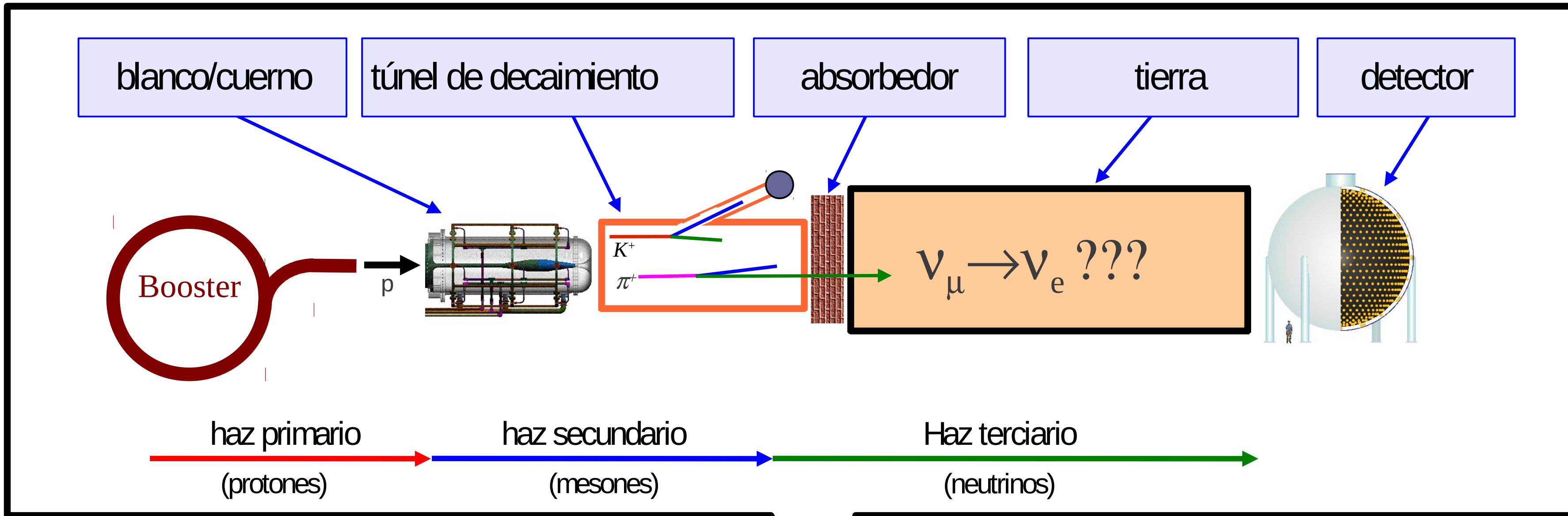


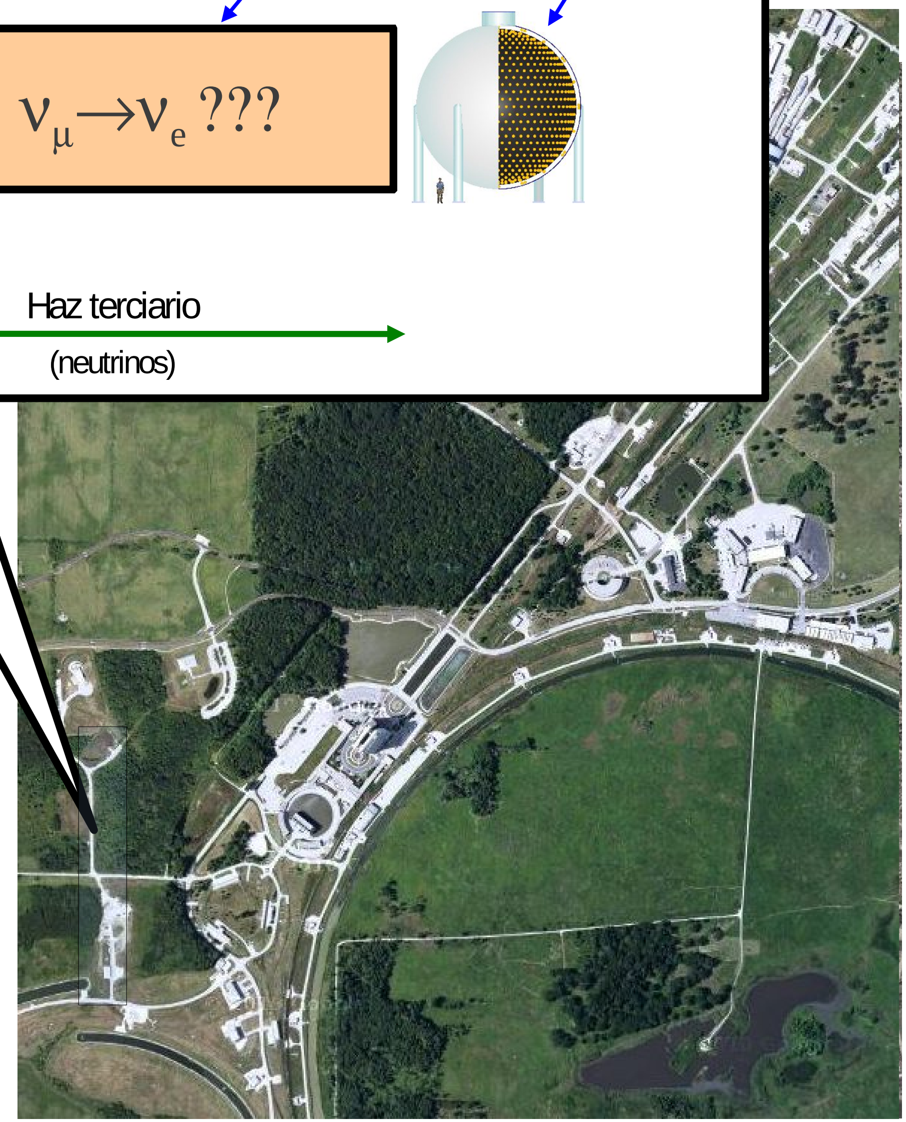


CC: El μ permite identificar al ν_μ,
Se puede medir la energía del neutrino incidente: $E_\nu \approx E_\mu + E_{had}$.

NC: Sólo la parte hadrónica es visible al detector $\Rightarrow$ mala estimación de E_ν.
(el ν_μ saliente no es observado)

Mini-Booster Neutrino Experiment





L/E similar to LSND

MiniBooNE ~500 m /~500 MeV

LSND ~30m / 30 MeV

Focused beam, "magnetic horn"

Polarity → neutrinos or anti-neutrinos

Cherenkov Detector

800 ton mineral oil

Supernova neutrinos

Supernova: • End phase of stellar evolution for massive stars (M>5-10 M_{Sol}).

(Tipo II) • Enormous explosion liberates E~10^{53} erg (~99% neutrinos and ~1% light)

• Stellar nucleus → *neutron star* or *black hole*

• Neutrinos escape the medium ~1 hr before photons (weakly interacting)

SN1987A: - Observed 23/Feb/1987, on the Great Magellanic Cloud (*D*~168,000 light-years)

- 3 neutrino detectors counted events from this supernova:

Kamiokande II (Japón):	11 events
IMB (EE.UU.):	8 events
Baksan (Rusia):	5 events

All within an interval of ~10 to 12 seconds approx. **4 hrs before the luminous signal**.

- Angular distribution and energy (E_ν~10 MeV) → *electron antineutrinos.*

Detectable with most large neutrino detectors: Solar, accelerator, ν-telescopes, etc.

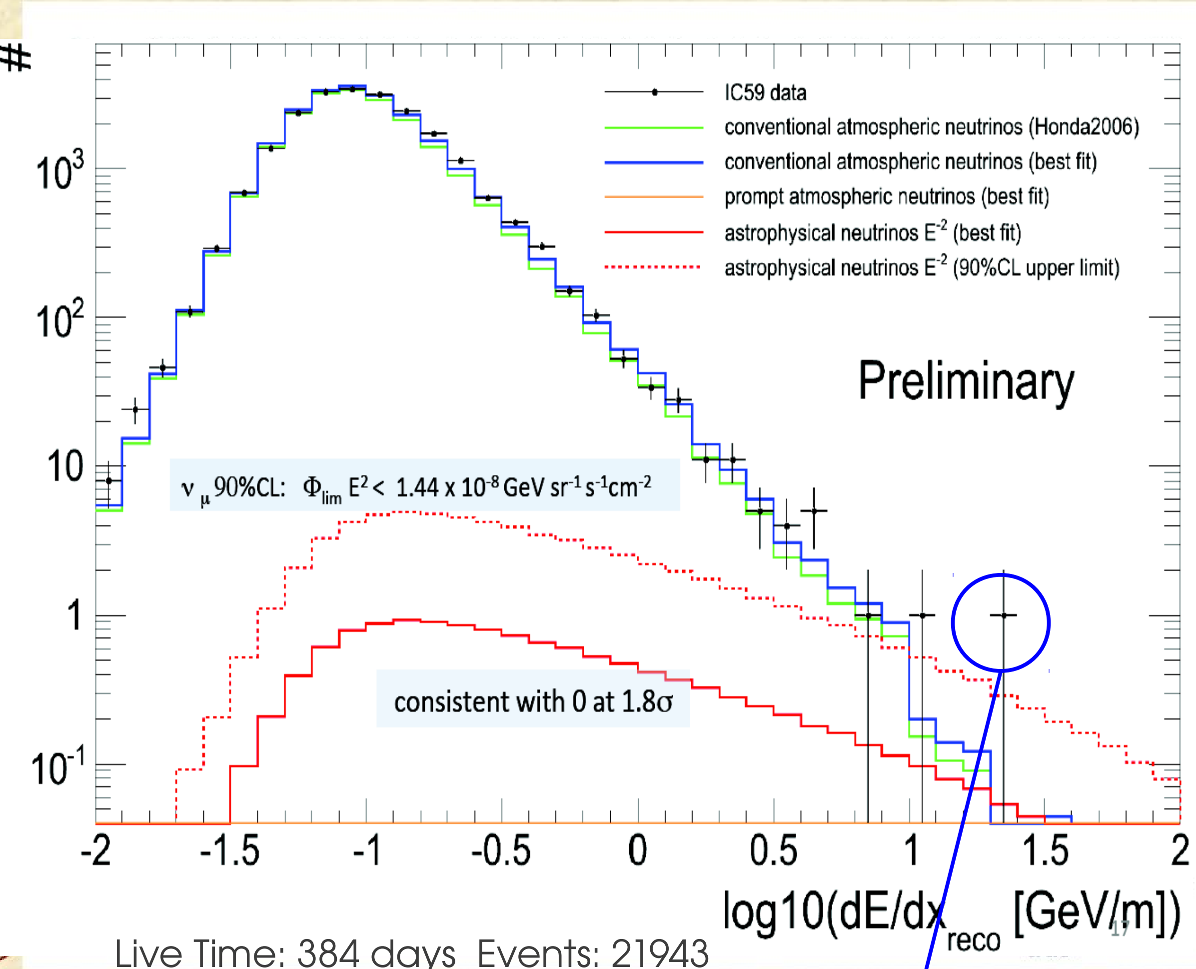
SNEWS network: **S**uper **N**ova **E**vent **W**arning **S**ystem

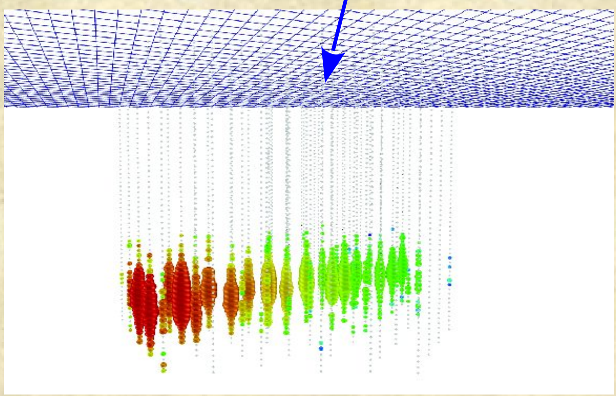
Search for diffuse ν_μ's, IceCube (59 cuerdas)

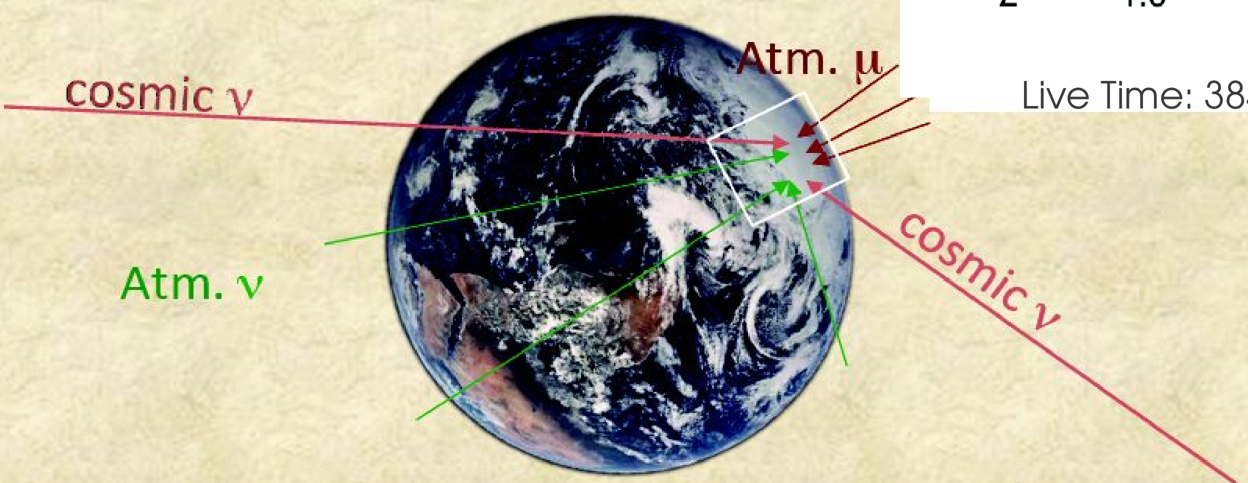
Look for upward-going tracks (↑) with energies higher than those of conventional atmospheric ν's.

Selection cuts eliminate:
- downward-going events
- mis-reconstructed cosmic ray μ's
- cosmic ray events with multiple μ's

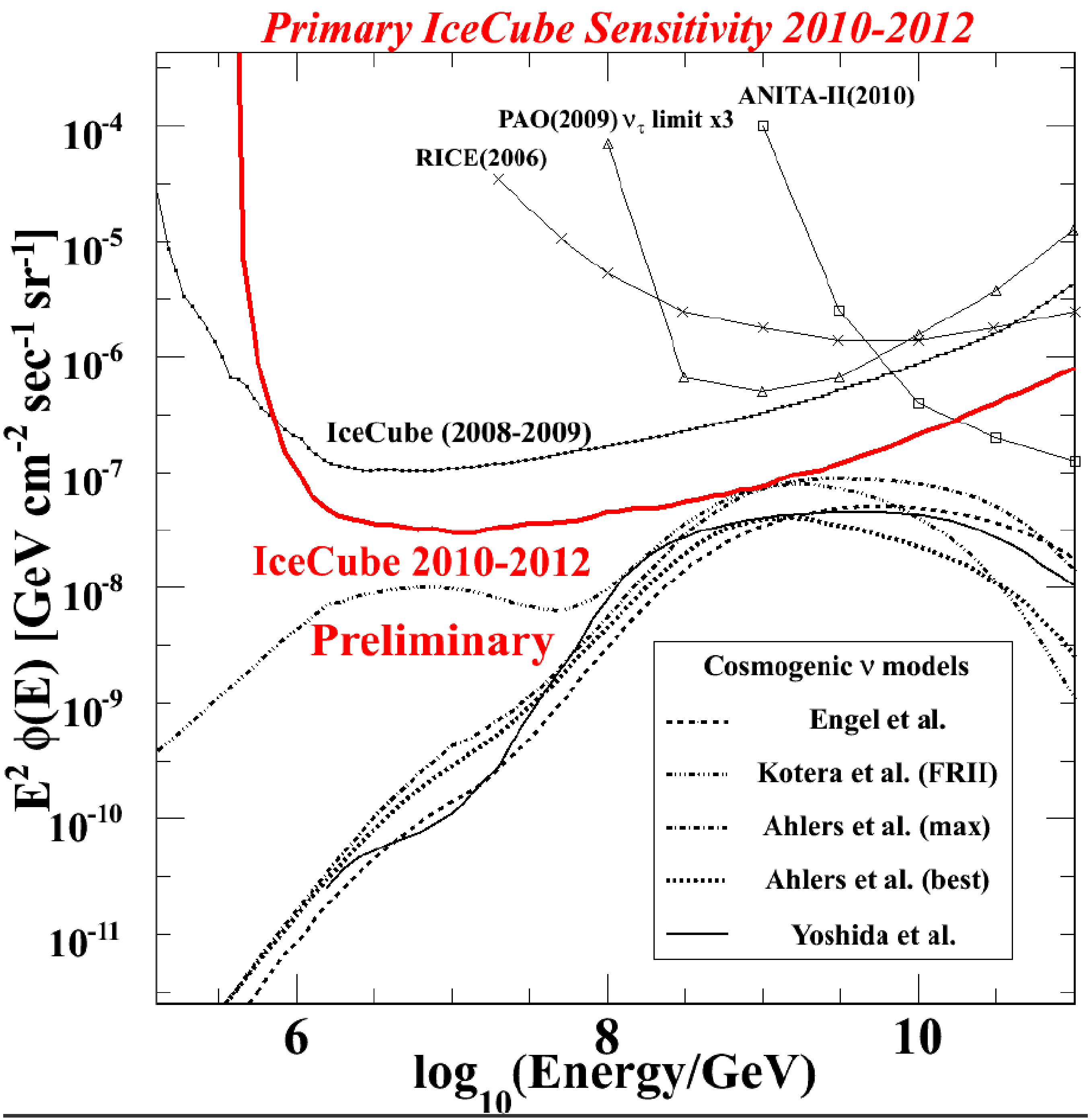
Achieves:
- 99.8% pure ν sample
- ~12% efficiency (atmospheric ν)
- ~30% efficiency (astrophysical ν)







IceCube, sensitivity to UHE neutrinos



Has the highest sensitivity to cosmogenic ν's.

Will exclude or detect the ν flux predicted by models with medium-strong intensity sources.

KATRIN (**KA**rlsrhue **TRI**tium **N**eutrino Experiment)