Results from SNO and Neutrino'04

neutrino.lbl.gov/∼snoman/currat/talks/

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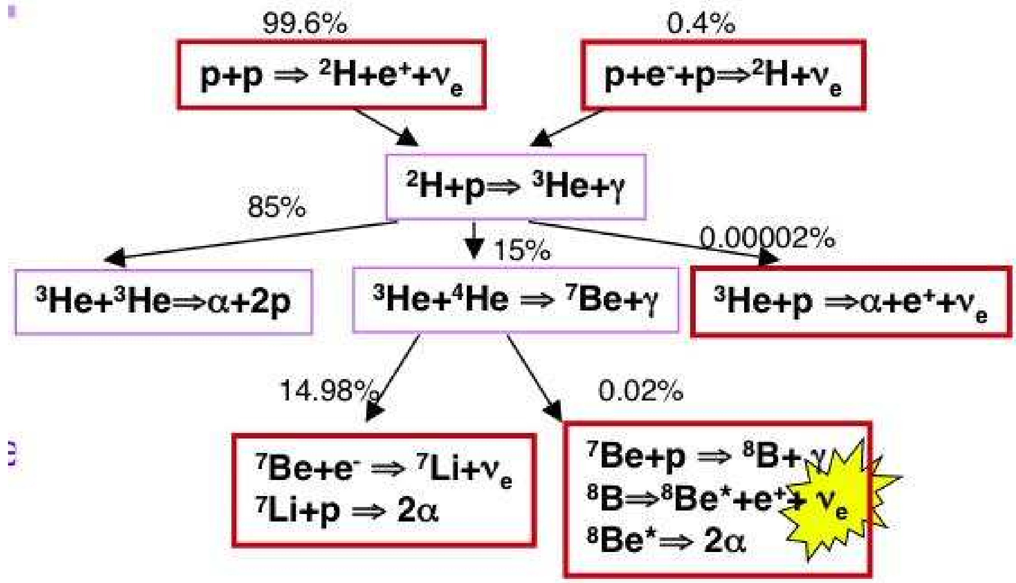
LBNL

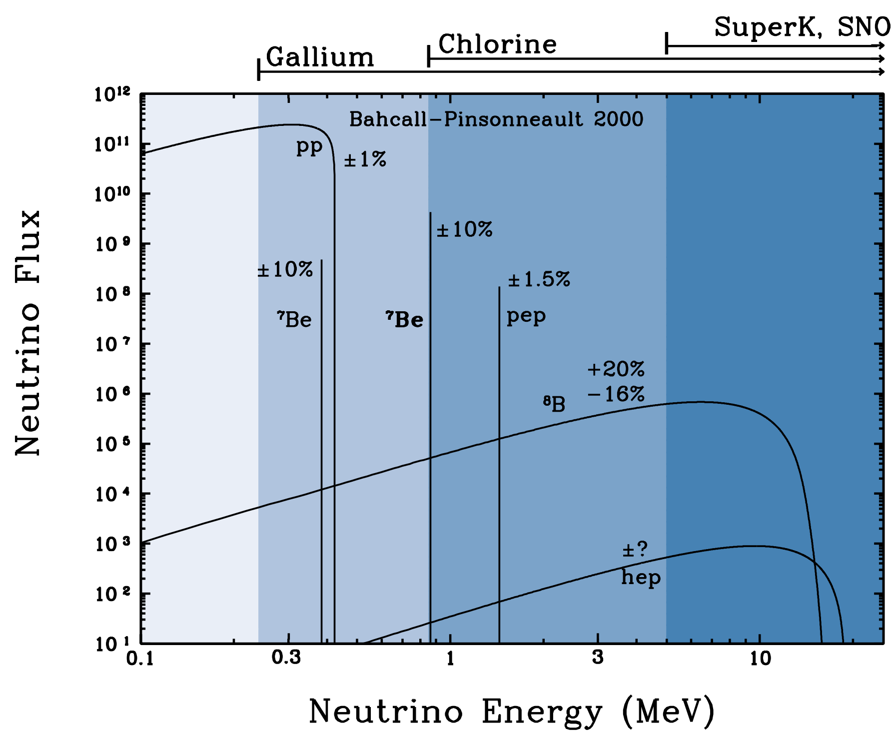
June 23, 2004
Seminar ETH Lausanne

- Recent results from SNO and phase III
- Highlights from Neutrino'04

Solar neutrinos

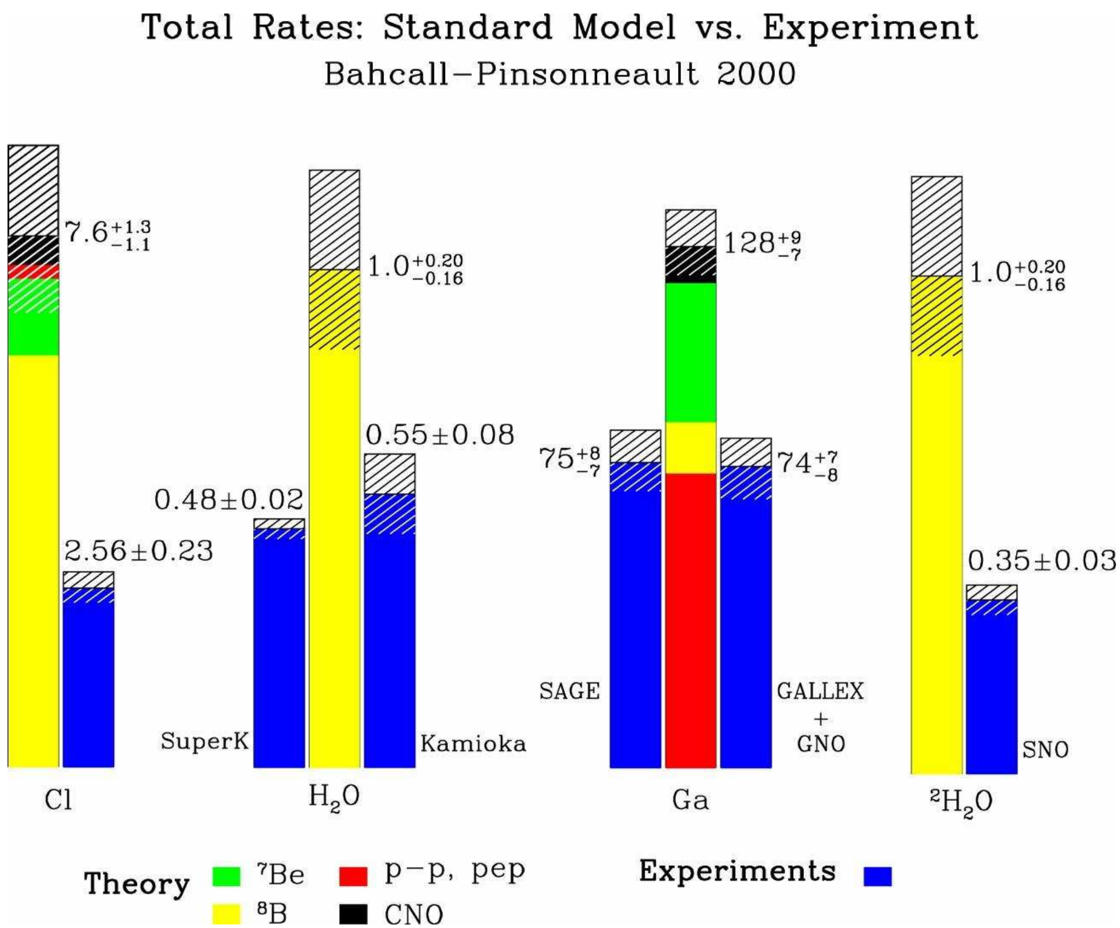
The Sun creates its energy via nuclear fusion:
$4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$





The solar ν problem in a nutshell

Prior to SNO, 5 experiments, with 3 different target materials over 35 years have measured a deficiency of solar neutrinos.

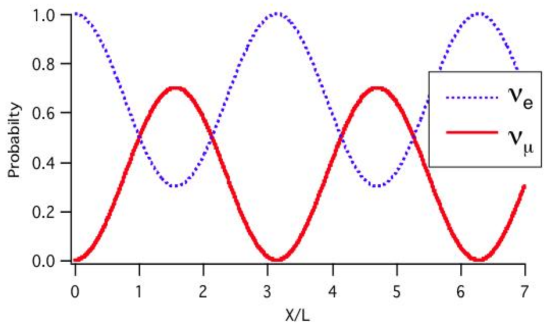


- Solar models are incomplete or incorrect
- Standard Model of particles is incomplete (not much constraining to startwith) ⇨ New Physics

Neutrino mixing

If: ν have mass, masses are not equal, mass states are different from the flavor states ➪ neutrinos can change flavor.

$$|\nu_\alpha\rangle = U_{\mathsf{PNMS}}\, |\nu_i\rangle$$



Similar to mixing seen in quarks. Probability of a ν with momentum p remaining in given flavor state ℓ as a function of distance traveled is governed by 2 parameters θ and Δm^2

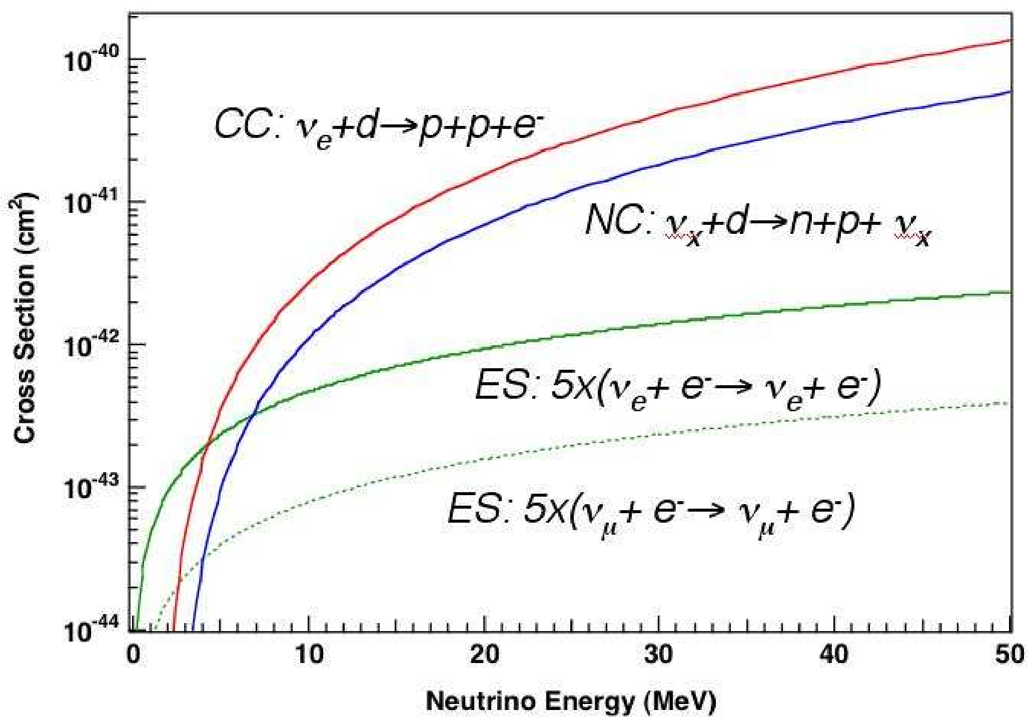
$$P(\ell \to \ell, x) = 1 - \sin^2 2\theta \sin^2(\pi \frac{x}{L}), \qquad L = \frac{4\pi p}{|M_2^2 - M_1^2|} = \frac{4\pi p}{\Delta M^2}$$

Parameterization of neutrino mixing, Pontecorvo-Maki-Nakagava-Sakata (PNMS) matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-\imath\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-\imath\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

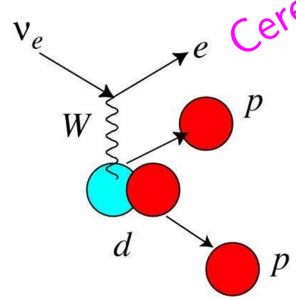
SNO: a neutral current detector

- SNO was first proposed in mid-1980s
- Realized that using heavy water instead of water can allow for the detection of all active neutrino flavors (late Herb Chen, UCI)
- SNO was designed to provide a "smoking gun" for oscillations by measuring whether or not total solar neutrino flux is greater than the electron neutrino flux



NC detector: key physics signatures

CC

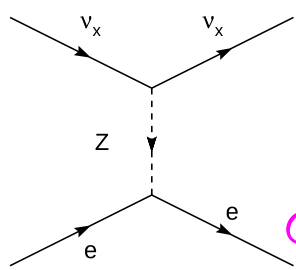


Cerenkov

$\nu_e + d \rightarrow p + p + e^-$

- gives ν_e energy spectrum well
- weak direction sensitivity $\propto 1 - \frac{1}{3}\cos\theta$

ES

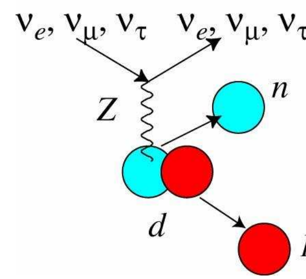


Cerenkov

$\nu_x + e^- \rightarrow \nu_x + e^-$

- low statistics
- mainly sensitive to ν_e, some sensitivity to ν_μ and ν_τ
- strong direction sensitivity

NC



capture!

$\nu_x + d \rightarrow p + n + \nu_x$

- measures total ^{8}B ν_x flux from the sun
- equal cross section for all ν types

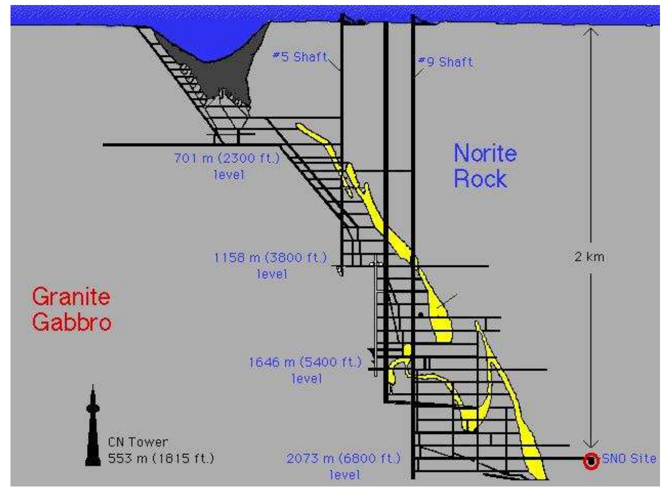
$$\frac{\Phi_{\text{CC}}}{\Phi_{\text{NC}}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$

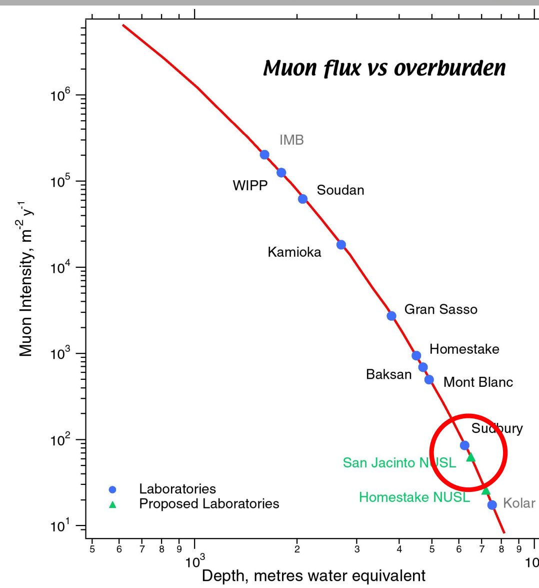
$$\frac{\Phi_{\text{CC}}}{\Phi_{\text{ES}}} = \frac{\nu_e}{\nu_e + 0.154 \cdot (\nu_\mu + \nu_\tau)}$$

Geography

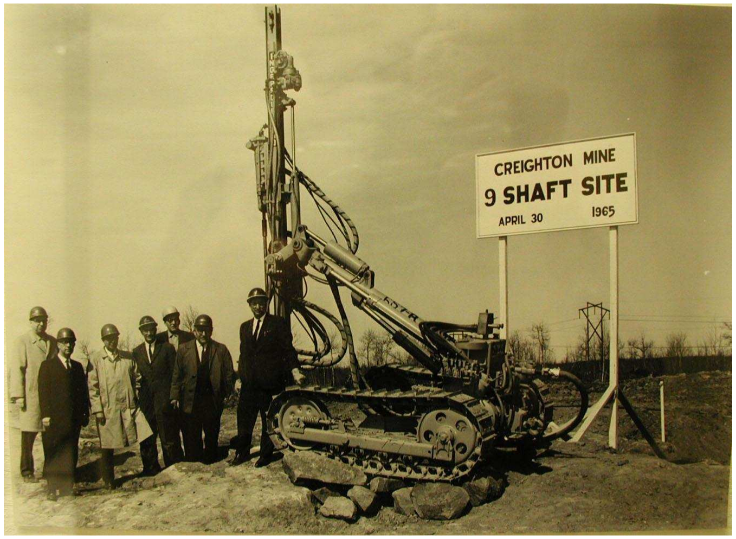
SNO detector located at the INCO Ltd Creighton Mine, Sudbury ON, Canada

➪ deepest mine in activity ⊕ heavy water on loan from CAN government





Back to the 60s.



The SNO collaboration

- U of British Columbia
- Carleton U
- U of Guelph
- Queen's U
- Laurentian U
- TRIUMF

- Brookhaven NL
- Lawrence Berkeley NL
- Los Alamos NL
- U of Pennsylvania
- U of Texas at Austin
- U of Washington

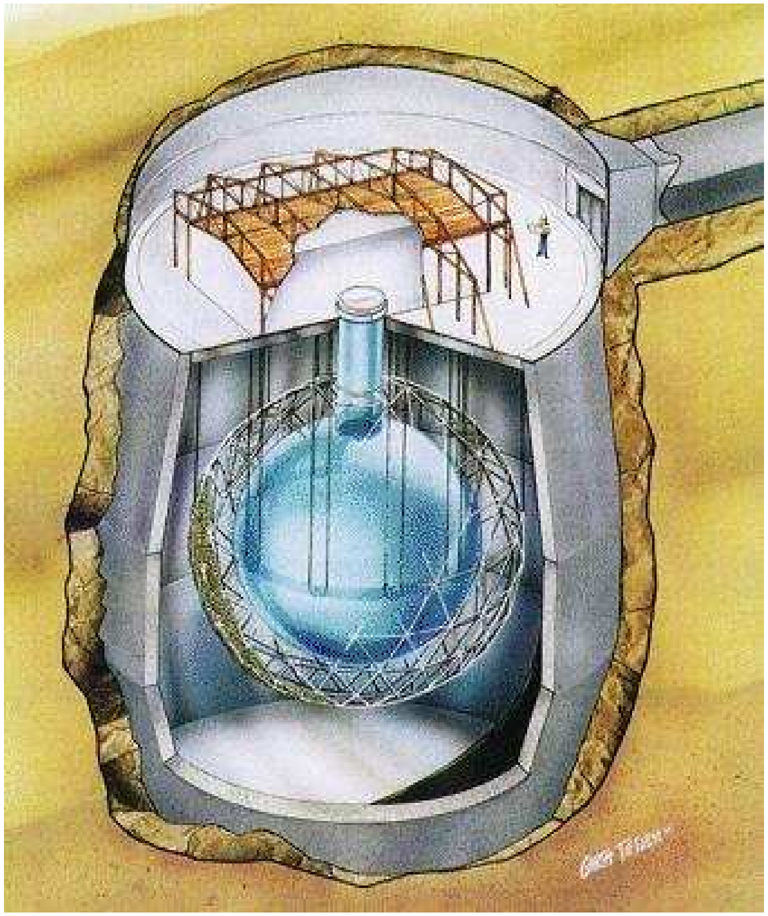
- U of Oxford
- RAL
- U of Sussex

Mr Proper

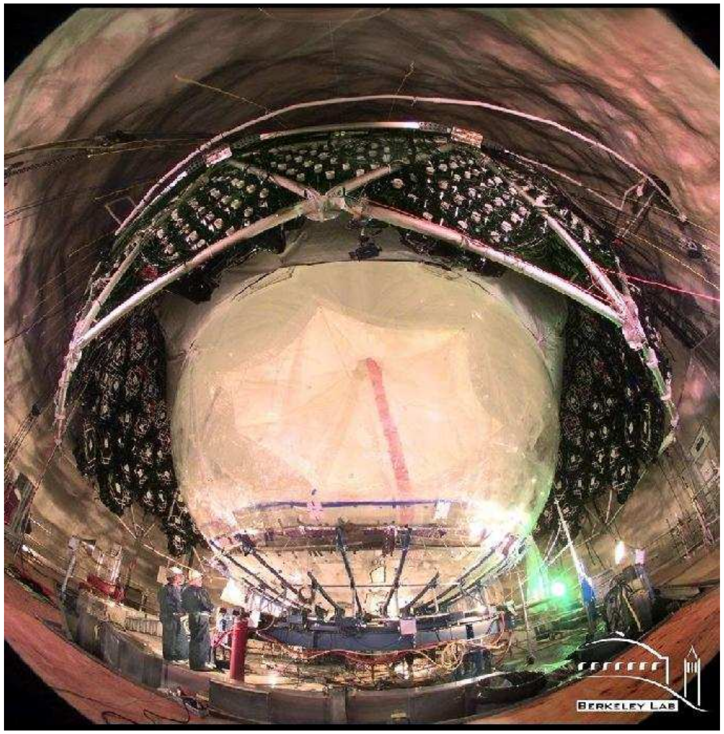
Class 2000 clean laboratory 6800 ft (2000 m) underground...

The detector

- 1k tonnes D_2O,
- 1.7k tonnes H_2O inner shielding
- 5.3k tonnes outer shielding H_2O
- neck (chimney), 1m diameter = interface w/detector



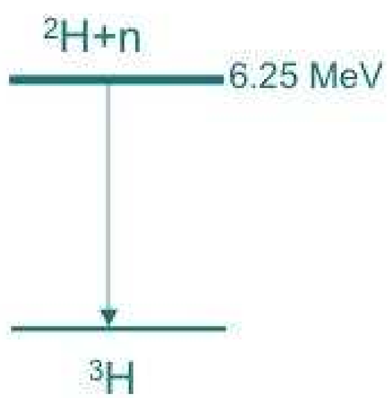
- 9500 PMTs (60% coverage)
- icosahedron (3 periods) support structure (LBNL)
- 12m diameter acrylic vessel (2in thick panels)
- urylon liner and radon seal
- 10 suspension ropes (loops)
- yes, the whole detector is buoyant!



SNO timeline

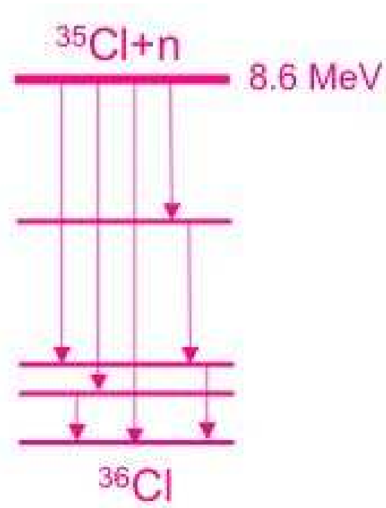
Phase I (D_2O):
Nov'99 – May 01

n captures on
$^2H(n,\gamma)^3H$
$\sigma = 0.0005$ b
Observe 6.25 MeV γ
PMT array readout



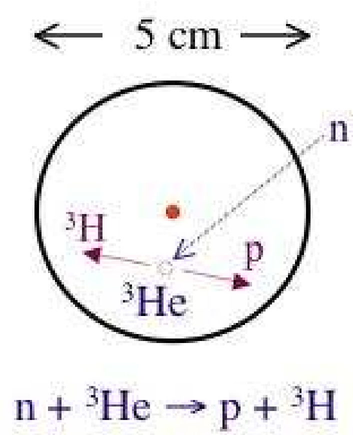
Phase II (salt):
Jul'01 – Sep'03

2t NaCl, n captures
on $^{35}Cl(n,\gamma)^{36}Cl$
$\sigma = 44$ b
Observe multiple γs
PMT array readout



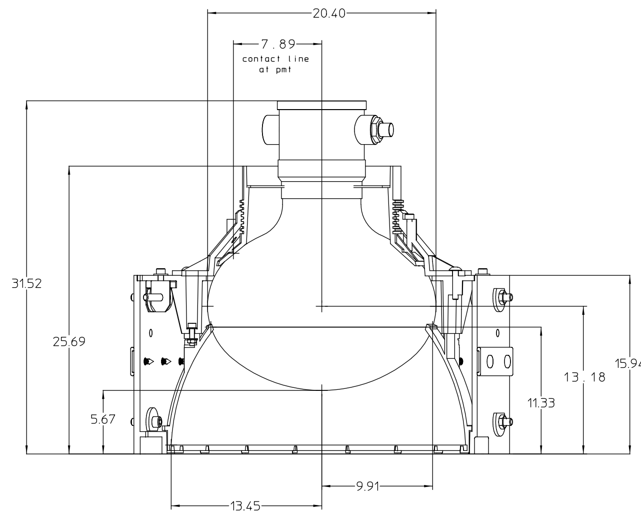
Phase III (^3He):
current – Dec'06

40 proportionnal
counters
$^3He(n,p)^3H$
$\sigma = 5330$ b
Observe p and ^3H
PC independent
readout



SNO operation

- (9456 pieces) 8-in Hamamatsu PMTs, housed in black plastic hexagons. Hexagons support light concentrators made from petals of dielectric coated Al
- time resolution 1.6 ns (50 cm)
- Photocathode coverage 31%, increased to 56% with concentrators (to be compared with KamLAND/MiniBooNE, WC+ scintillator).



- 67% neutrino runs
- 20% calibration
- 6% maintenance and calibration setup
- 7% no run

SNO electronics & trigger

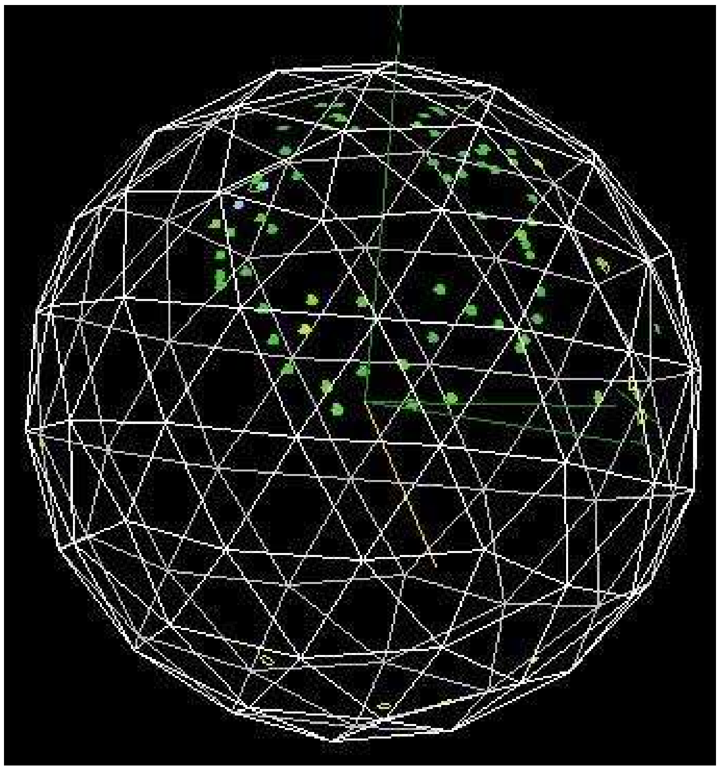
☞ NIM A 449 (2000), 172–207

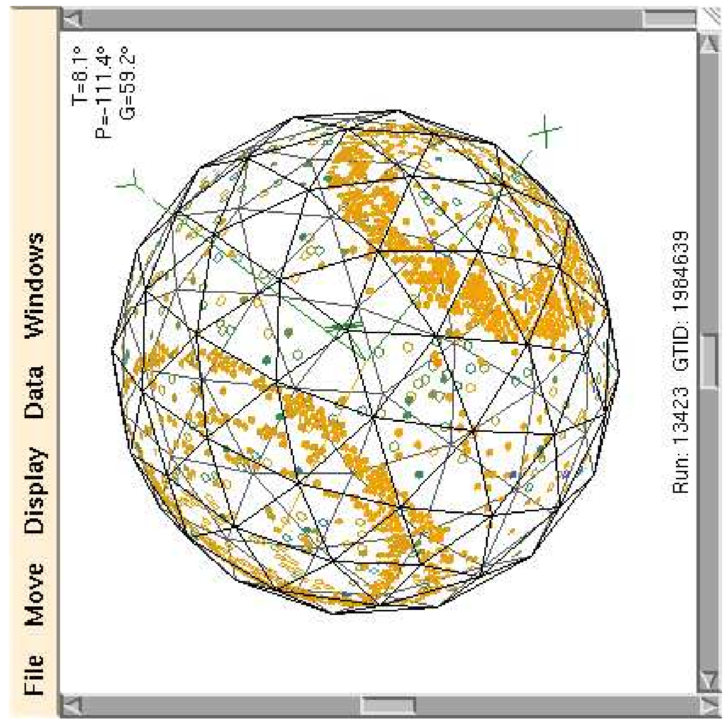
- Designed to provide sub-nanosecond timing and to cover a wide range of charge measurements
- Can handle bursts up to 1 MHz and sustained rates up to 1 kHz (typical rate is 20 Hz)
- Signal and high voltage is carried on a single cable
- Overall trigger dead time is less than 10 ns, per PMT dead time is 400 ns
- A commercial GPS system and a 50 MHz quartz oscillator record the absolute and relative event times

- Low channel threshold < 0.3 photoelectron
- Average noise rate is ~ 500 Hz, that is ~ 2 noisy PMT/event
- Detector total trigger rate stable at 15–20 Hz.
- Data flow is ~ 1.9 GB per day
- Dead channels ~ 600 total ➪ -1.3%/year from all causes

The lord of the (electron) rings

We measure Cerenkov rings produced by electrons (solar analysis). PMTs timing information allows to reconstruct interaction vertex.

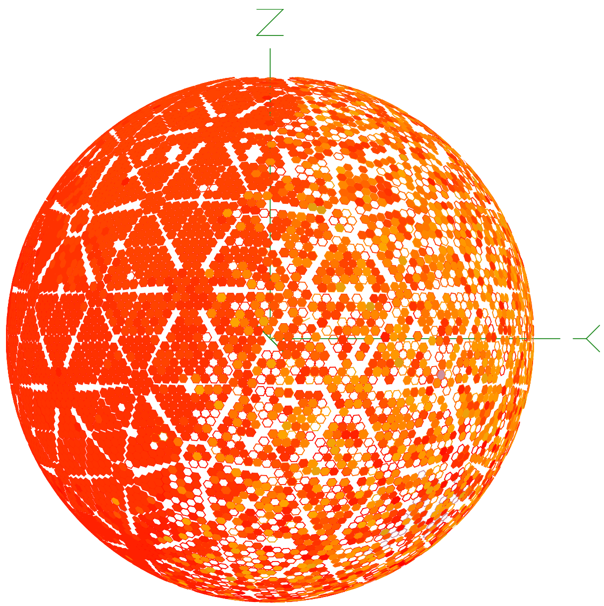




The lord of the (muon) rings

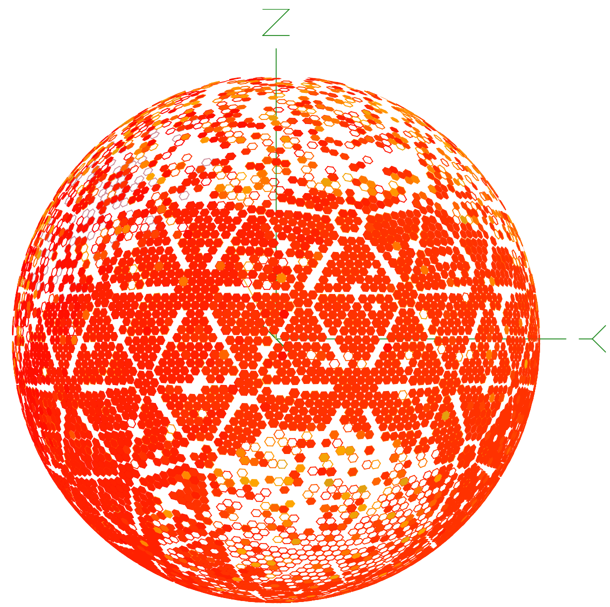
We measure Cerenkov light produced by muons too (atmospheric analysis). PMTs timing information allows to reconstruct the direction of the traversing muon. Very few muon stop in the detector (range is 18 m for $E_\mu = 4$ GeV).

$E_\mu \simeq 150$ GeV



Run: 1 GTID: 33

$E_\mu \simeq 2$ GeV



Run: 1 GTID: 26

Backgrounds

Source	Events
D_2O photodisintegration	$73.1^{+24.0}_{-23.5}$
$^2H(\alpha,\alpha)pn$	2.8 ± 0.7
$^{17,18}O(\alpha,n)$	1.4 ± 0.9
Fission, atmospheric ν (NC + sub-Cherenkov threshold CC)	23.0 ± 7.2
Terrestrial and reactor $\bar{\nu}$'s	2.3 ± 0.8
Neutrons from rock	≤ 1
^{24}Na activation	8.4 ± 2.3
n from CNO ν's	0.3 ± 0.3
Total internal neutron background	$111.3^{+25.3}_{-24.9}$
Internal γ (fission, atmospheric ν)	5.2 ± 1.3
^{16}N decays	< 2.5 (68% CL)
External-source neutrons (from fit)	$84.5^{+34.5}_{-33.6}$
Cherenkov events from $\beta - \gamma$ decays	< 14.7 (68% CL)
"AV events"	< 5.4 (68% CL)

Uncertainties

Source	NC uncert. (%)	CC uncert. (%)	ES uncert. (%)
Energy scale	-3.7,+3.6	-1.0,+1.1	±1.8
Energy resolution	±1.2	±0.1	±0.3
Energy non-linearity	±0.0	-0.0,+0.1	±0.0
Radial accuracy	-3.0,+3.5	-2.6,+2.5	-2.6,+2.9
Vertex resolution	±0.2	±0.0	±0.2
Angular resolution	±0.2	±0.2	±2.4
Isotropy mean †	-3.4,+3.1	-3.4,+2.6	-0.9,+1.1
Isotropy resolution	±0.6	±0.4	±0.2
Radial energy bias	-2.4,+1.9	±0.7	-1.3,+1.2
Vertex Z accuracy †	-0.2,+0.3	±0.1	±0.1
Internal background neutrons	-1.9,+1.8	±0.0	±0.0
Internal background γ's	±0.1	±0.1	±0.0
Neutron capture	-2.5,+2.7	±0.0	±0.0
Cherenkov backgrounds	-1.1,+0.0	-1.1,+0.0	±0.0
"AV events"	-0.4,+0.0	-0.4,+0.0	±0.0
Total experimental uncertainty	-7.3,+7.2	-4.6,+3.8	-4.3,+4.5
Cross section [13]	±1.1	±1.2	±0.5

Extracting signals

- Data points for NC, CC and ES are extracted in each energy bin using isotropy, angular information and radius within the detector

Change of variables:

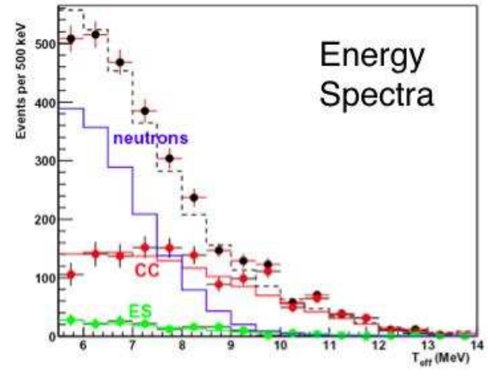
$$\phi_e = 1.76^{0.05}_{0.05}\text{stat}^{+0.09}_{-0.09}(syst)$$

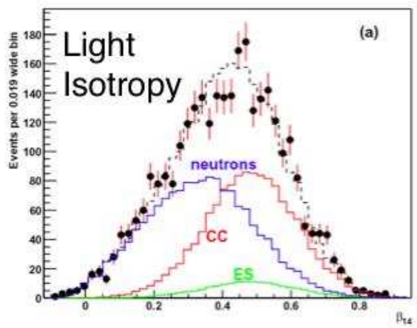
$$\phi_{\mu\tau} = 3.41^{0.45}_{0.45}\text{stat}^{+0.48}_{-0.45}(syst)$$

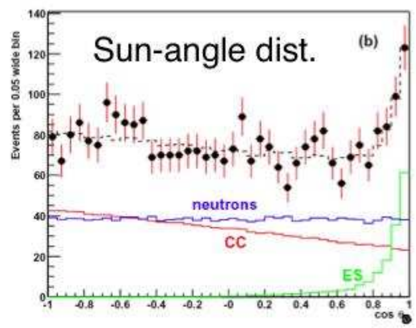
$$\frac{\phi^{\rm SNO}_{\rm CC}}{\phi^{\rm SNO}_{\rm NC}} = 0.306 \pm 0.026\ (\text{stat}) \pm 0.024\ (\text{syst})$$

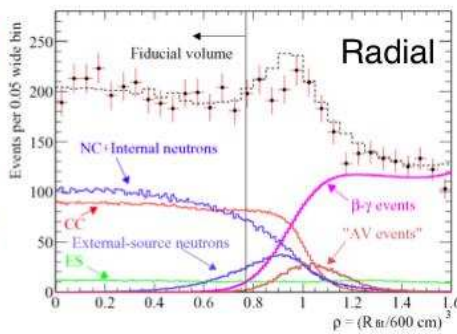
#EVENTS

- CC $1339.6^{+63.8}_{-61.5}$
- ES $170.3^{+23.9}_{-20.1}$
- NC $1344.2^{+69.8}_{-69.0}$



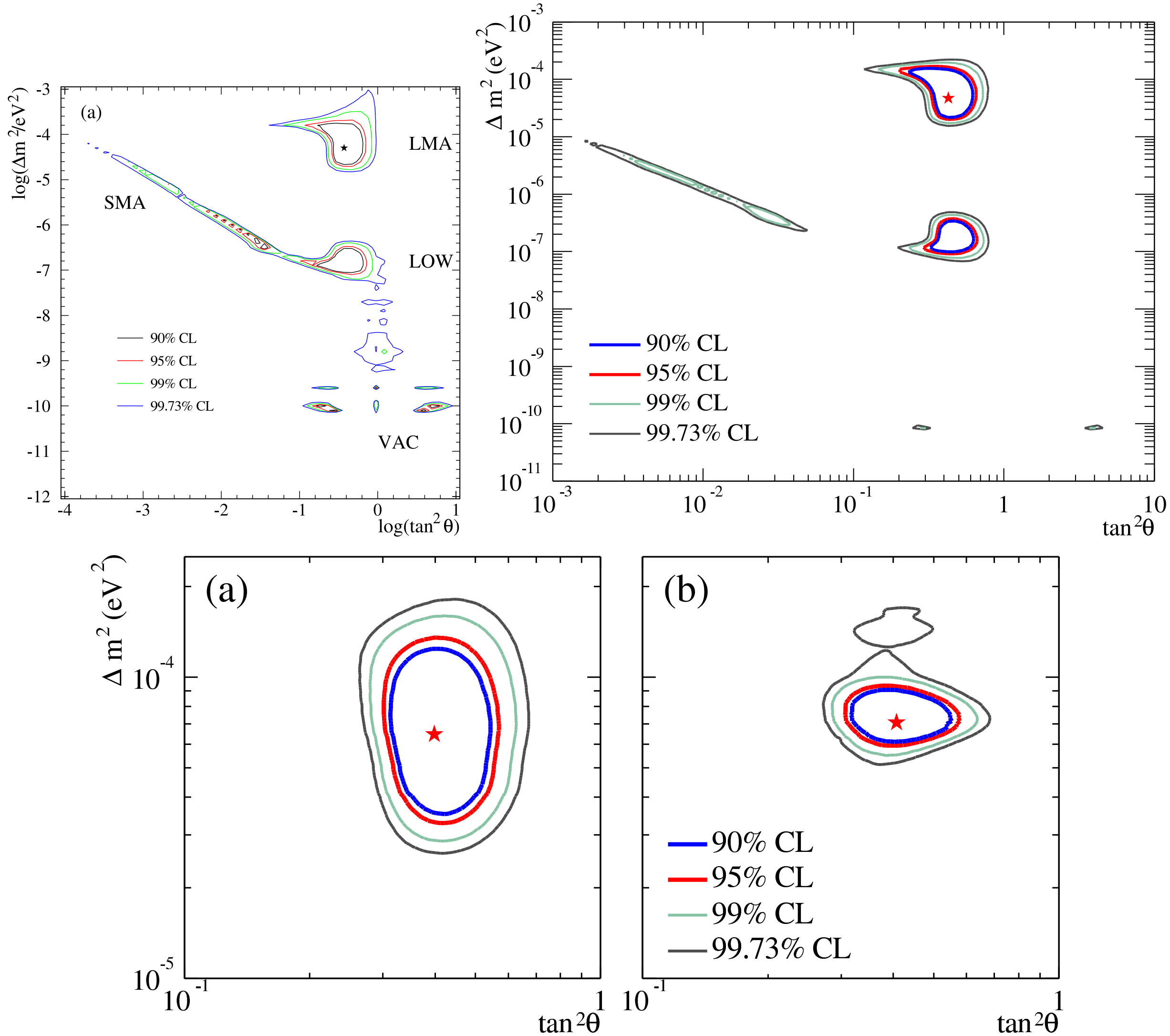






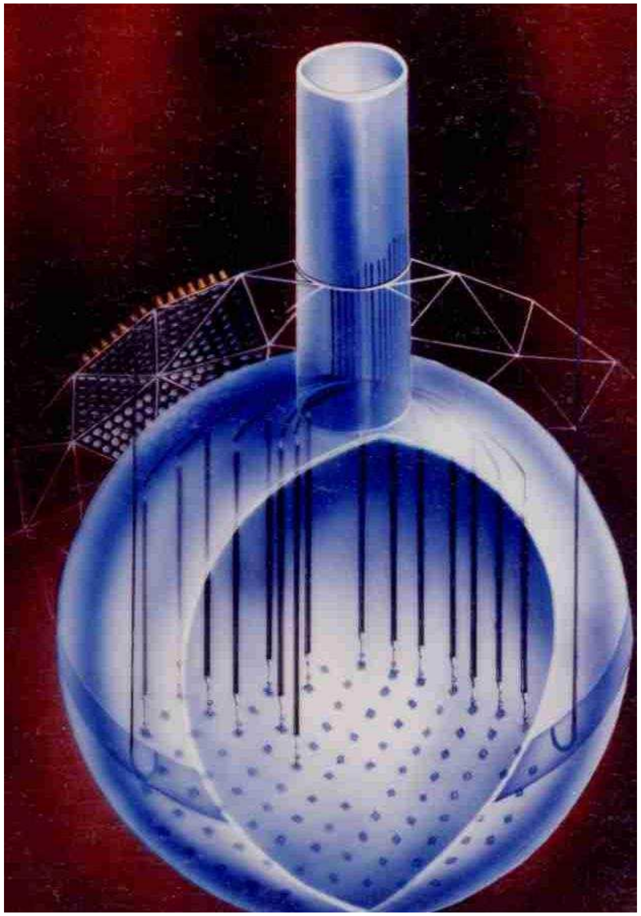
Global oscillation parameters

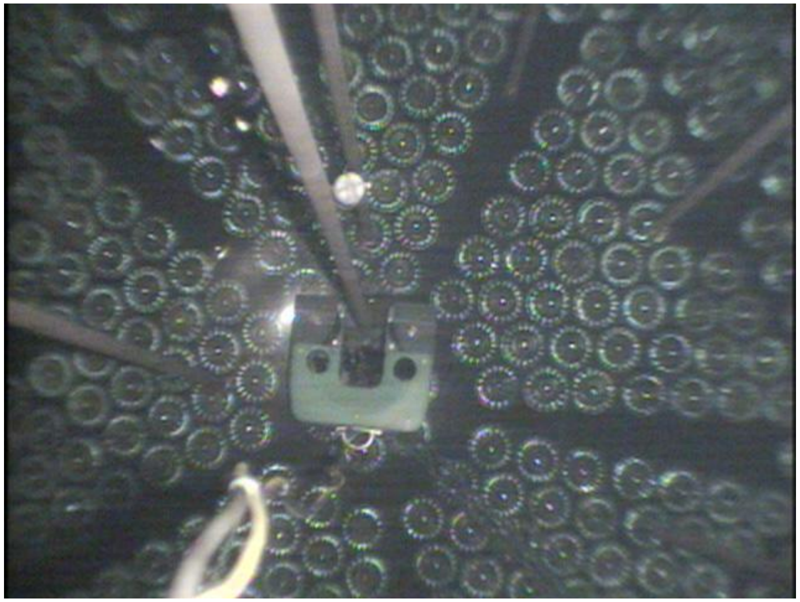
Respectively: SNO only, D20 / SNO only, salt I / all solar / all solar + KamLAND (first result). LMA strongly favored. Maximal mixing rejected at 5.4σ CL.



Phase III

Independent measurement of the neutrons with 3He proportional counters, NCDs, array of 40 strings about 9m long. Reaching end of commissioning period.





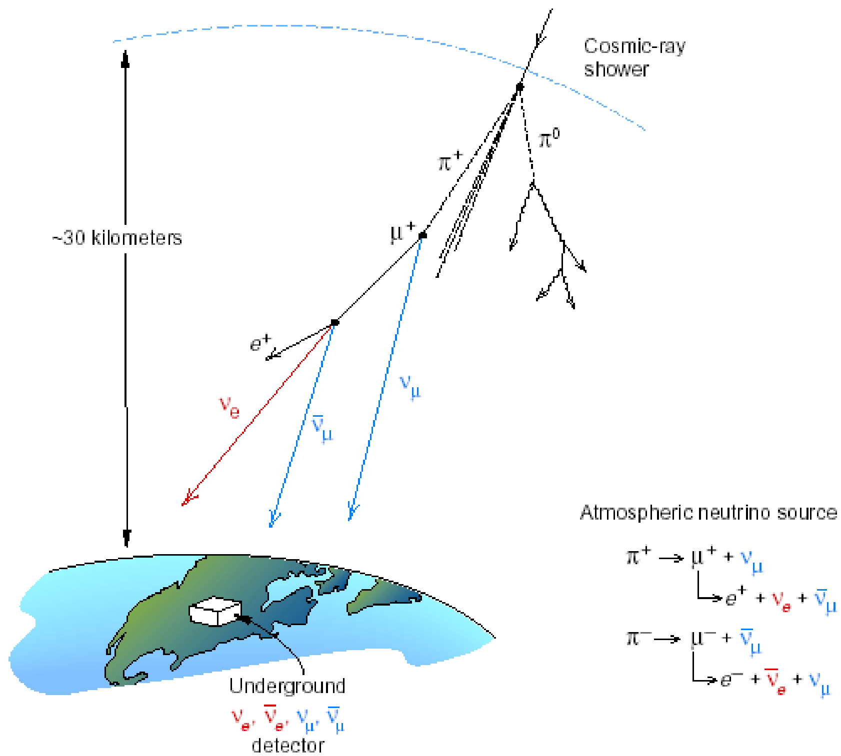
Other physics

Number of other ongoing analyses in SNO:

- day-night asymmetry ➪ MSW effect
- anti-neutrino (D2O + salt)
- atmospheric neutrinos ➪ neutrino induced muons
- supernova neutrino detection (SNEWS network)

Atmospheric neutrinos are produced in the interactions of primary cosmic rays in the atmosphere. They penetrate the Earth arriving almost isotropically at the detector. The most accurately predicted feature of the atmospheric neutrinos is the ratio of the muon neutrino to the electron neutrino flux ($\pm 5\%$)

$$R = \frac{\nu_e + \bar{\nu_e}}{\nu_\mu + \bar{\nu_\mu}}$$

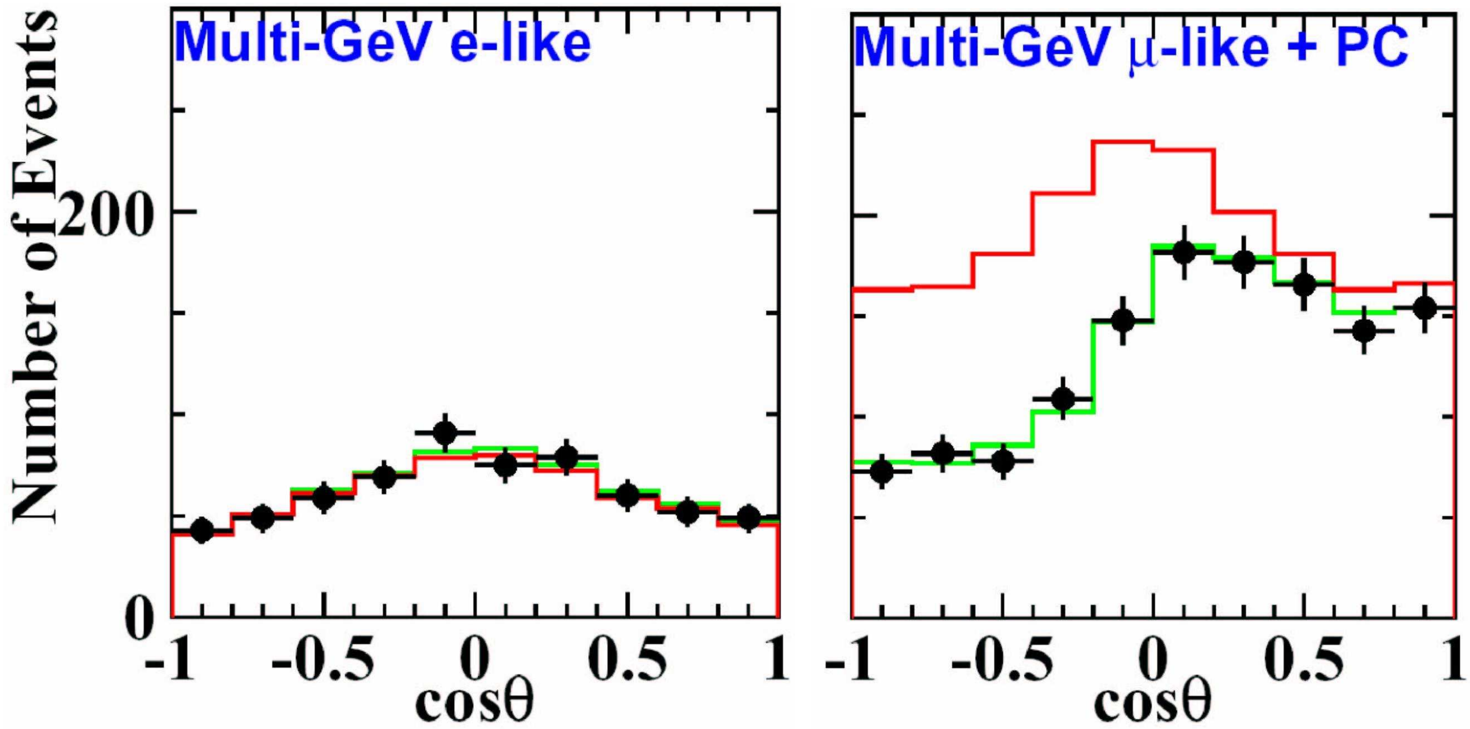


Better to measure deviation from

$$R = \frac{[N(\mu\text{-like})/N(e\text{-like})]_{\text{obs}}}{[N(\mu\text{-like})/N(e\text{-like})]_{\text{exp}}}$$

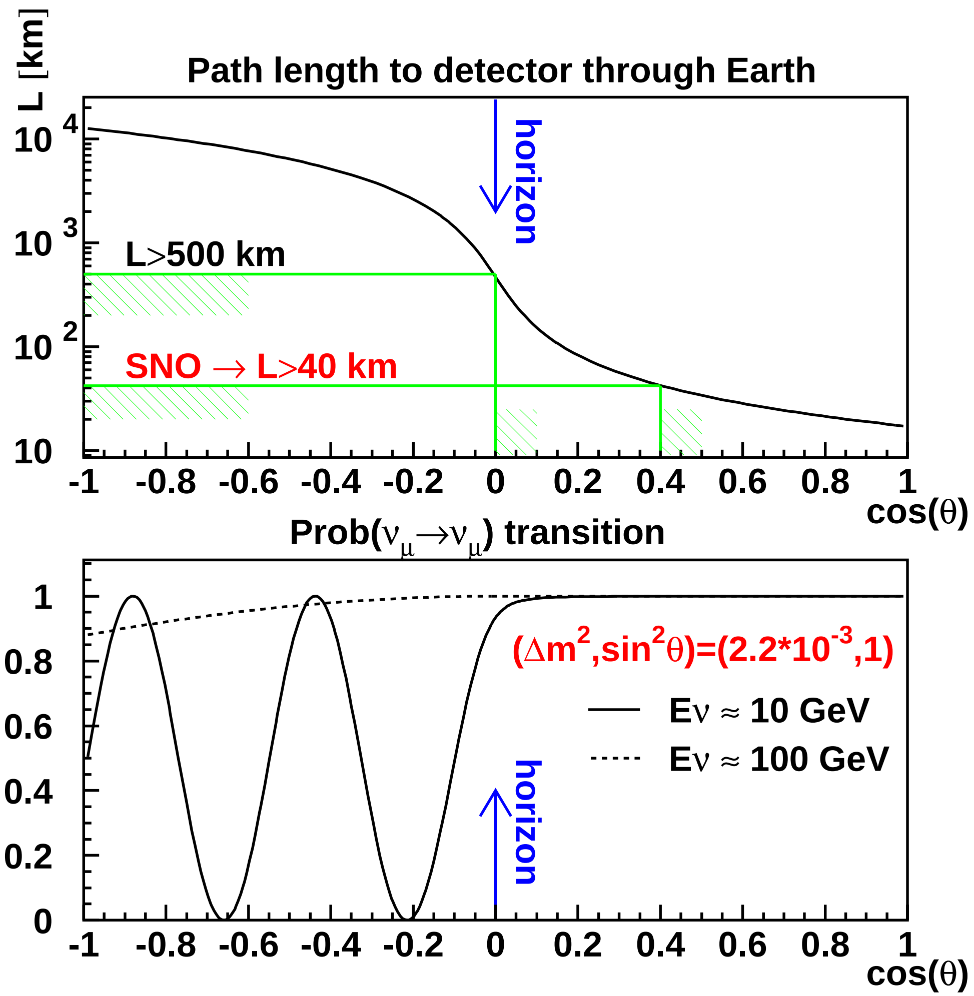
Experiment	R	Significance (kT·y)
Super-K (sub-GeV)	$0.638 \pm 0.017 \pm 0.050$	79
Super-K (multi-GeV)	$0.675^{+0.034}_{-0.032} \pm 0.080$	79
Soudan2	$0.69 \pm 0.10 \pm 0.06$	5.9
IMB	$0.54 \pm 0.05 \pm 0.11$	7.7
Kamiokande (sub-GeV)	$0.60^{+0.06}_{-0.05} \pm 0.05$	7.7
Kamiokande (multi-GeV)	$0.57^{+0.08}_{-0.07} \pm 0.07$	7.7
Frejus	$1.00 \pm 0.15 \pm 0.08$	2.0
Nusex	$0.96^{+0.32}_{-0.28} \pm 0.07$	0.74

SuperK (WC, 50k tonnes H_2O) found evidence of atmospheric neutrino mixing, June'98, ν_μ disappearance. Kamioka mine, Japan (1000 m rock overburden). Half of the ν_μ is lost!

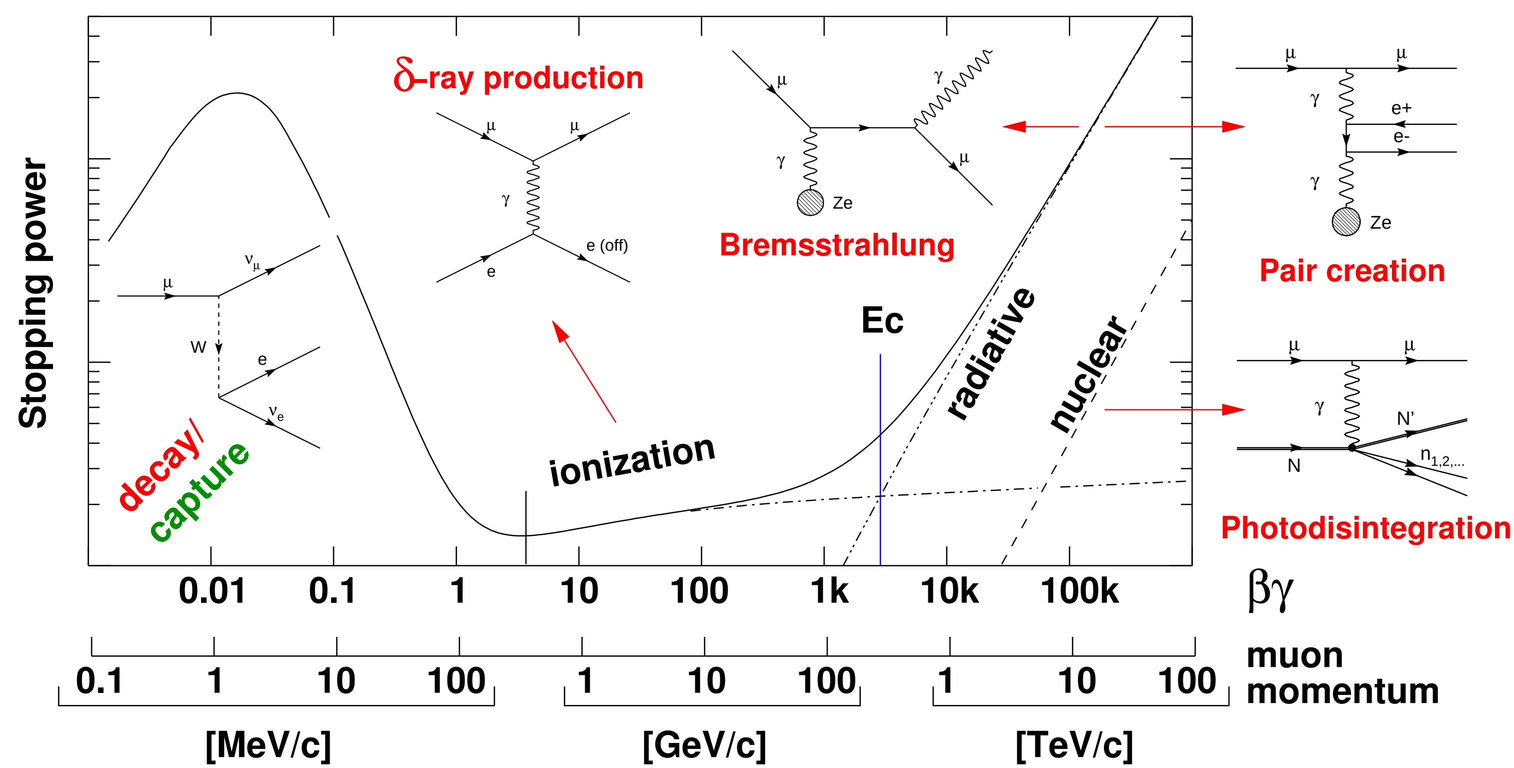


Atmospheric neutrinos in SNO

Challenging for SNO since volume is much smaller than SuperK: 2.7 kton vs 22 kton fiducial (50 kton total). But at its depth SNO is in a unique position amongst underground detectors. Normalization comes for free!

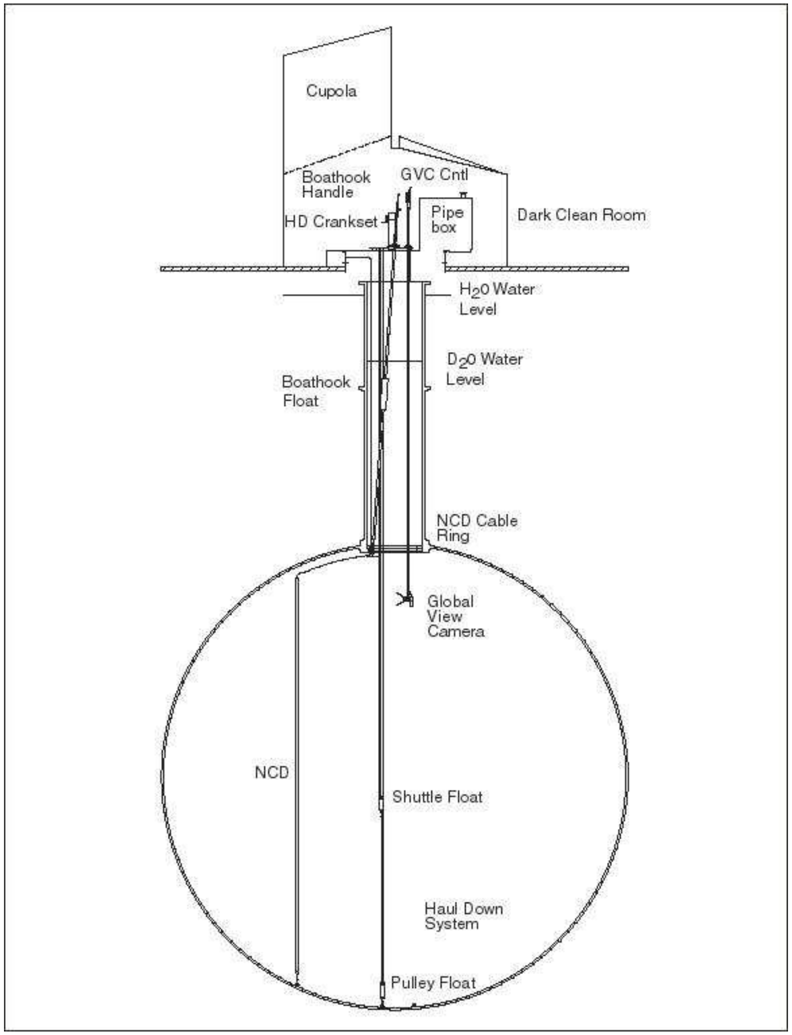


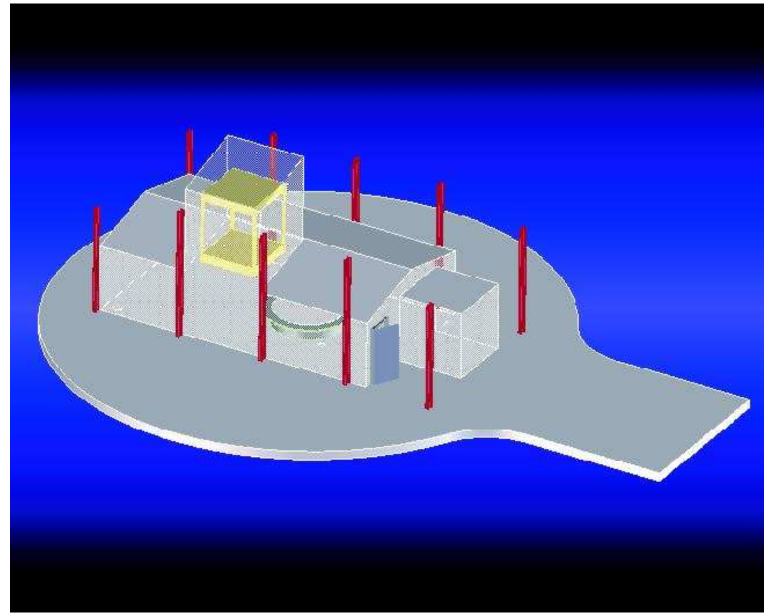
Muons simulation in SNO Monte Carlo

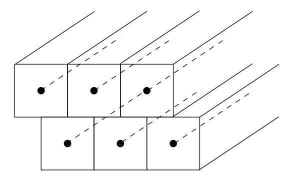


☞ From O(10 TeV) down to explicit thermalization of spallation products (neutron 1/40 eV) the same data structure accomodates 15 orders of magnitude in energy!!

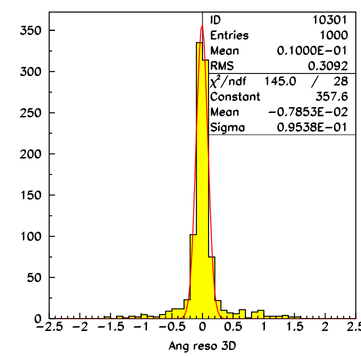
Project: independent calibration of muons with tracking chambers.





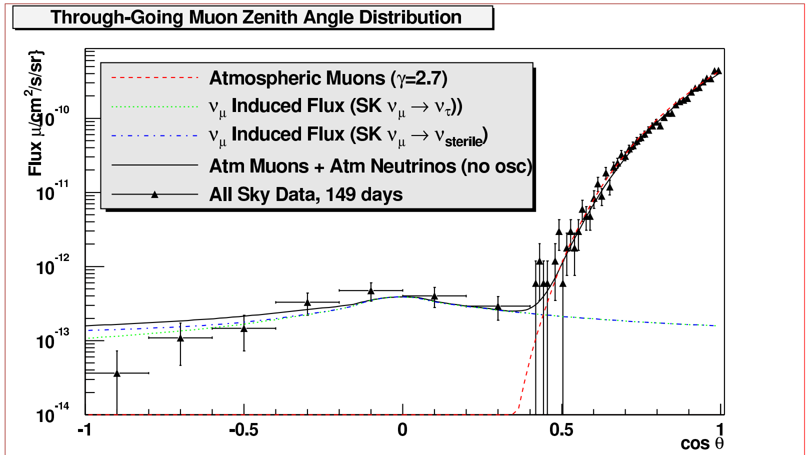


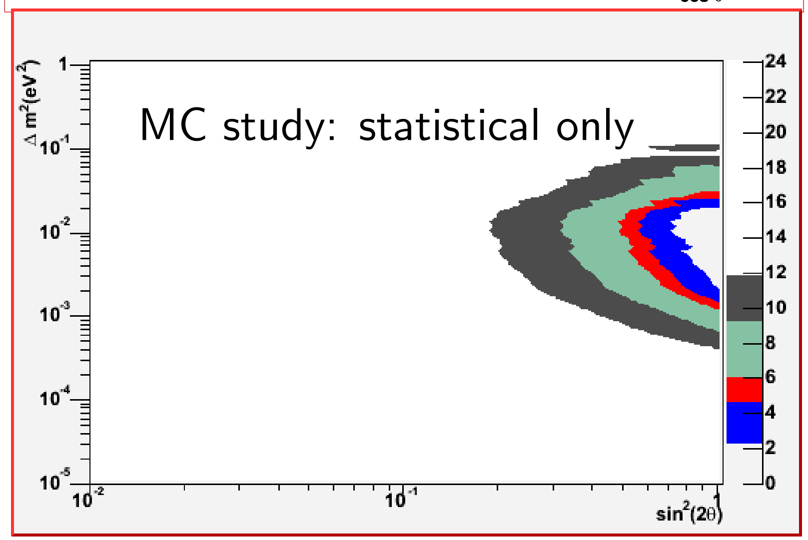
Cell size: 7.5 cm x 7.5 cm
Longitudinal resolution: 5 mm
Transverse resolution: 500 microns
Stations: 2, 2 layers each, 2 m apart



Atmospheric neutrinos in SNO

Preliminary analysis with 150 days of data (courtesy of N. Tagg) Perspective at SNO with 730 days of data (probably over 800 days available, ultimately $\sim \times 2$)



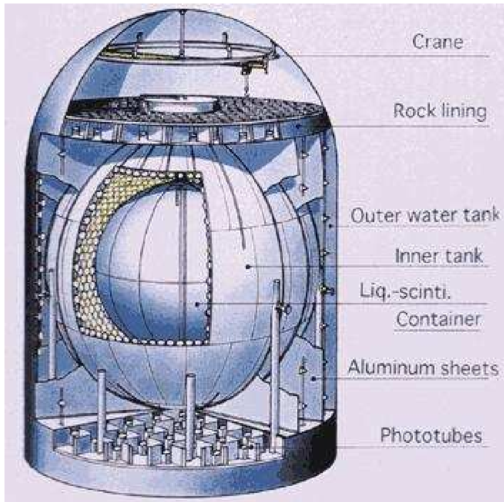


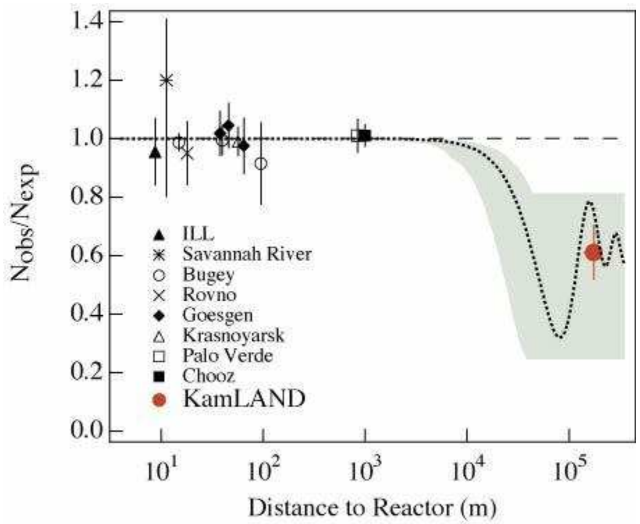
☞ stop/thru analysis à la SuperK under investigation (bin over horizon)

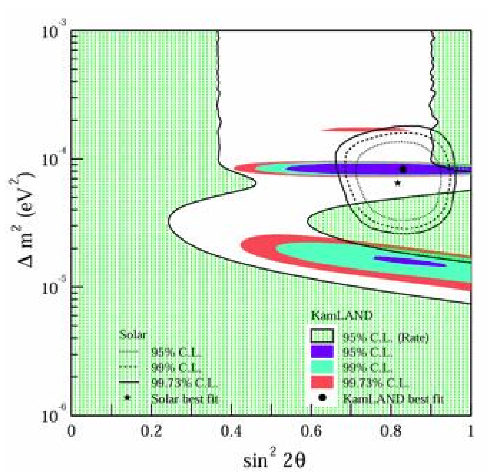
Highlights...

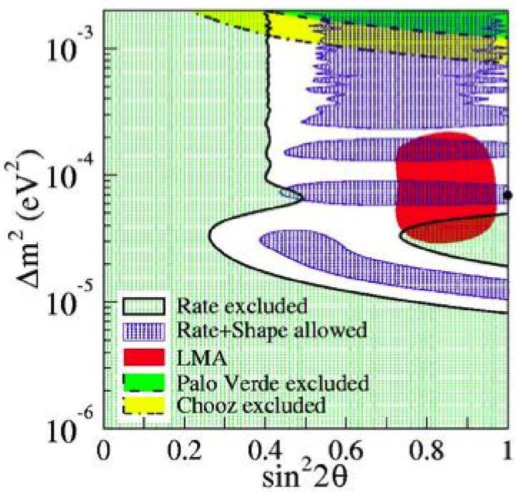
- KamLAND shrinks its contours
- $0\nu\beta\beta$ claimed to be found (?!)
- K2K, MiniBooNE are taking data
- Minos, Borexino on their way
- Lots of ongoing projects (too much to be ever funded?)

How to get terrestrial solar neutrinos... Can we convincingly verify oscillation with man-made neutrinos? Probing $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ (assuming CPT is a good symmetry).



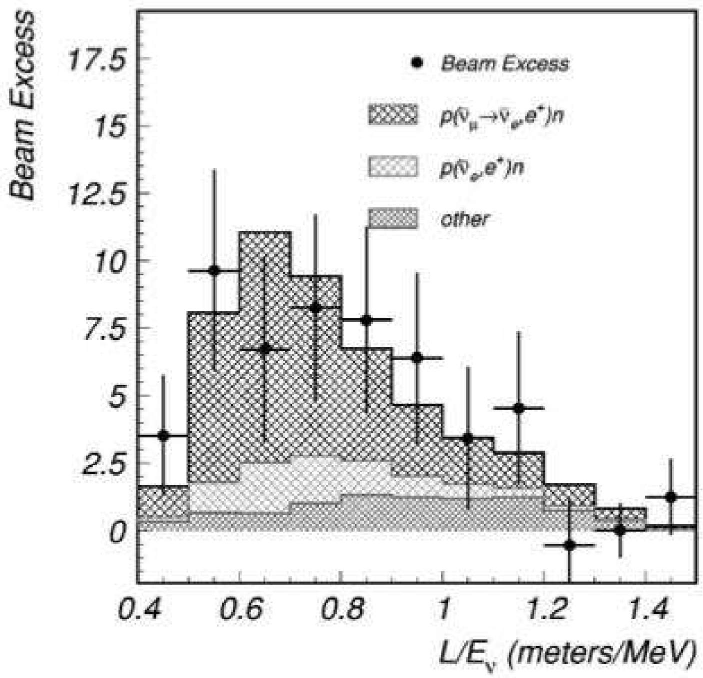


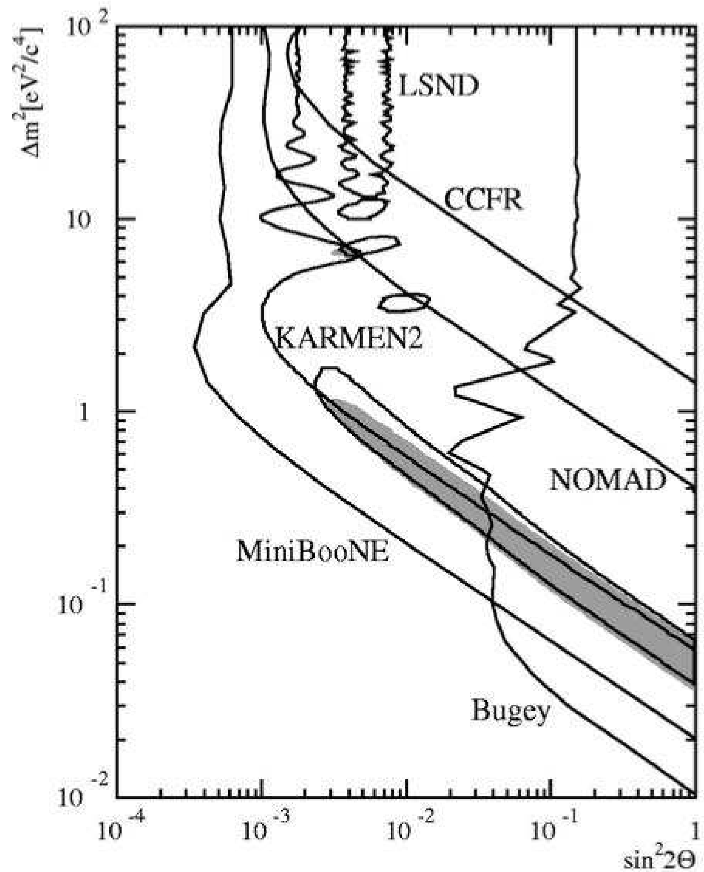




☞ New/old best fit: $(\Delta m^2, sin^2 2\theta) = (8.3 \cdot 10^{-5}, 0.83)/(6.9 \cdot 10^{-5}, 1.0)$

MiniBooNE (Fermilab booster) started taking data in Aug'02. Results by mid-05... (*rumors, rumors...*)



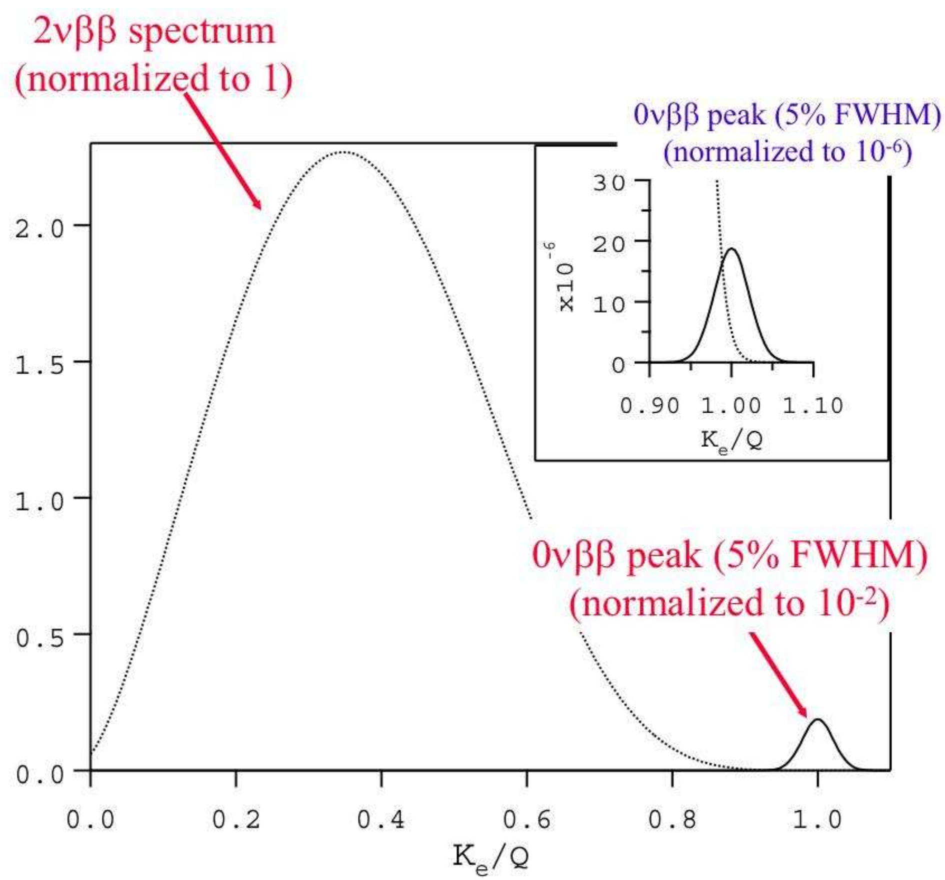


☞ Hit or miss...

Double beta decay experiments

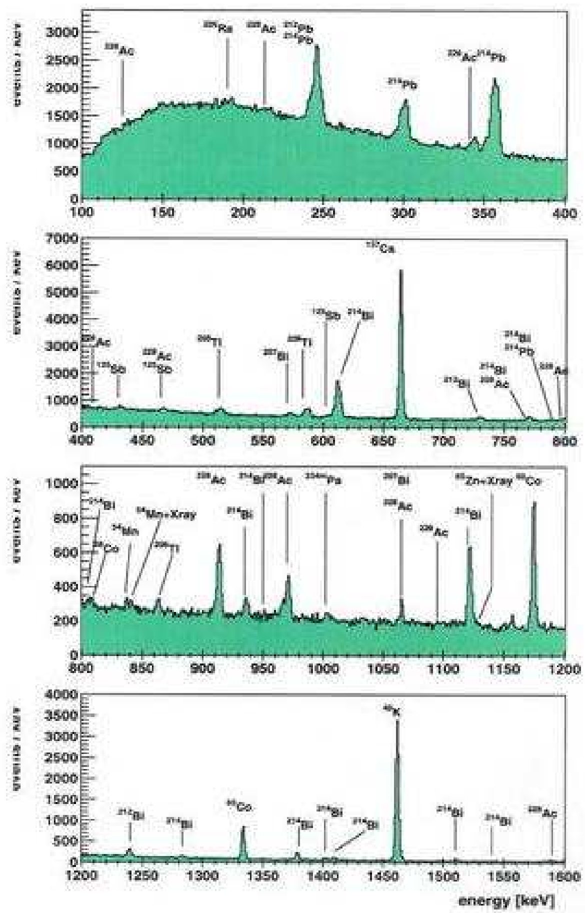
$$(Z, A) \longrightarrow (Z \pm 2, A) + 2e^{\mp} + X$$

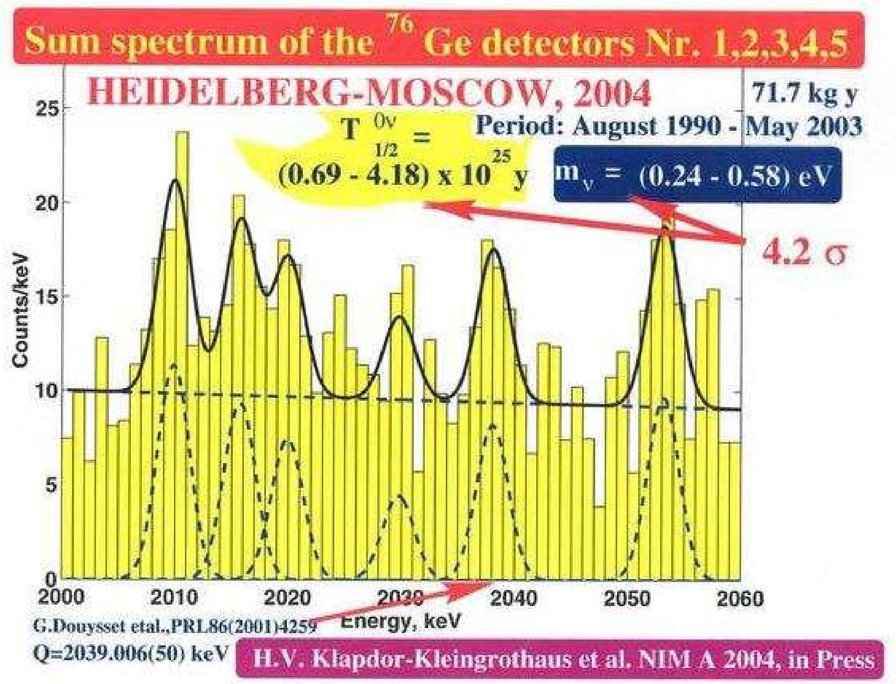
- $2\nu\beta\beta$ decay: $X = 2\nu$, allowed within SM, observed for 9 isotopes, half-lives $10^{(19-25)}$ years
- $0\nu\beta\beta$ decay: $X = 0\nu$, violates lepton number by 2 units experimentally *not observed* (Heidelberg-Moscow?), lower limits on half-lives of the order of 10^{25} years. Unambiguously implies that neutrinos are of Majorana type.



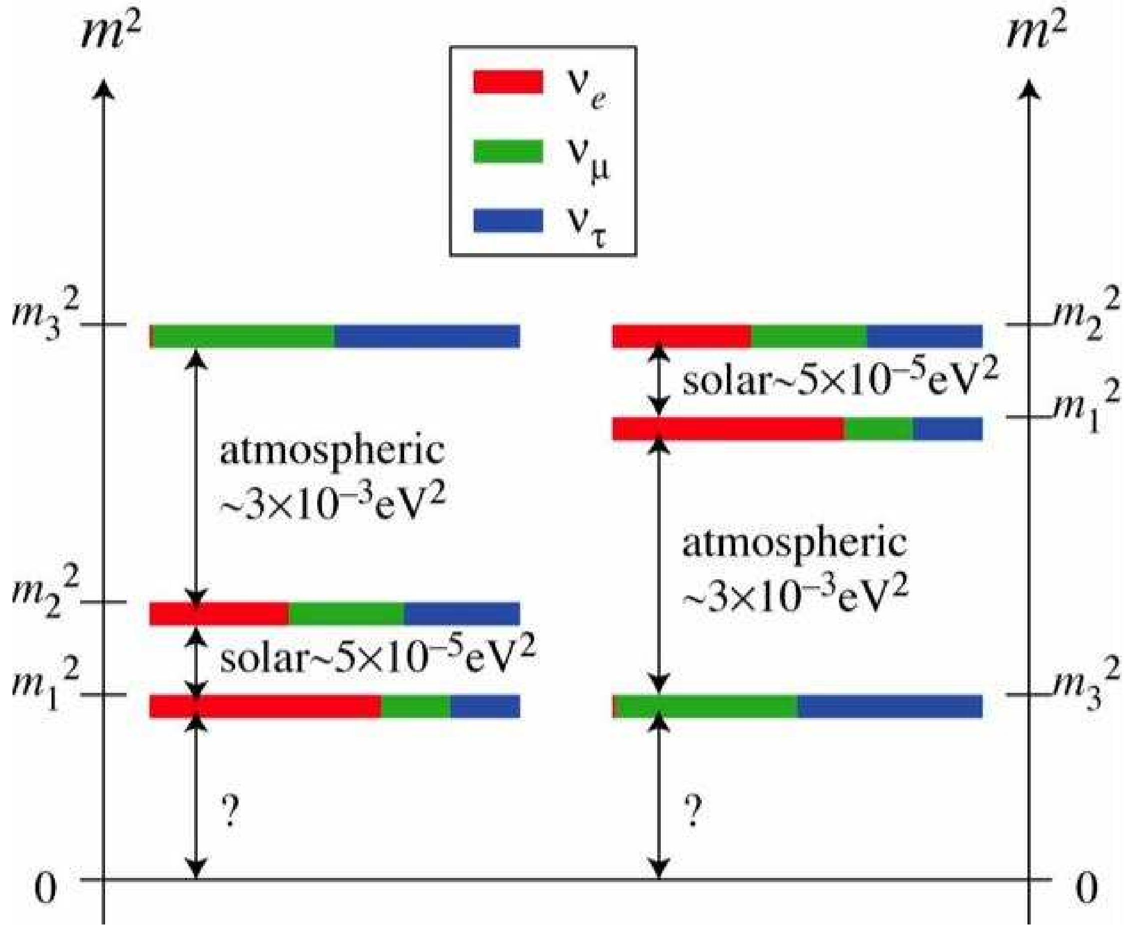
Double beta decay experiments

- Number of ongoing R&D: Majorana, EXO, Candles, XMASS, Genius ☞ one needs only one good one!
- Controversy: Heidelberg-Moscow experiment. Claim detection of $0\nu\beta\beta$ (1990–2003, 73 kg*y exposure)

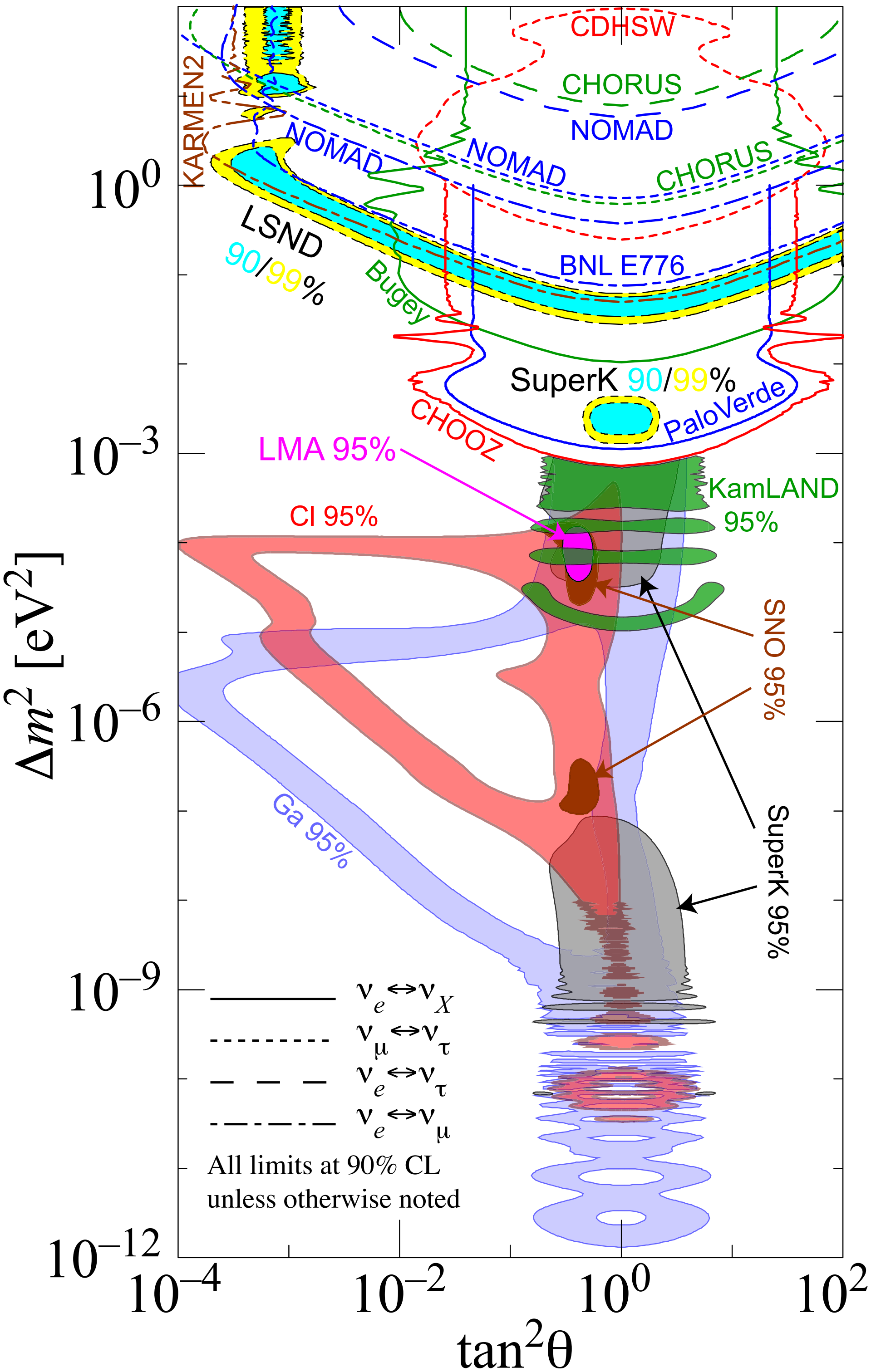




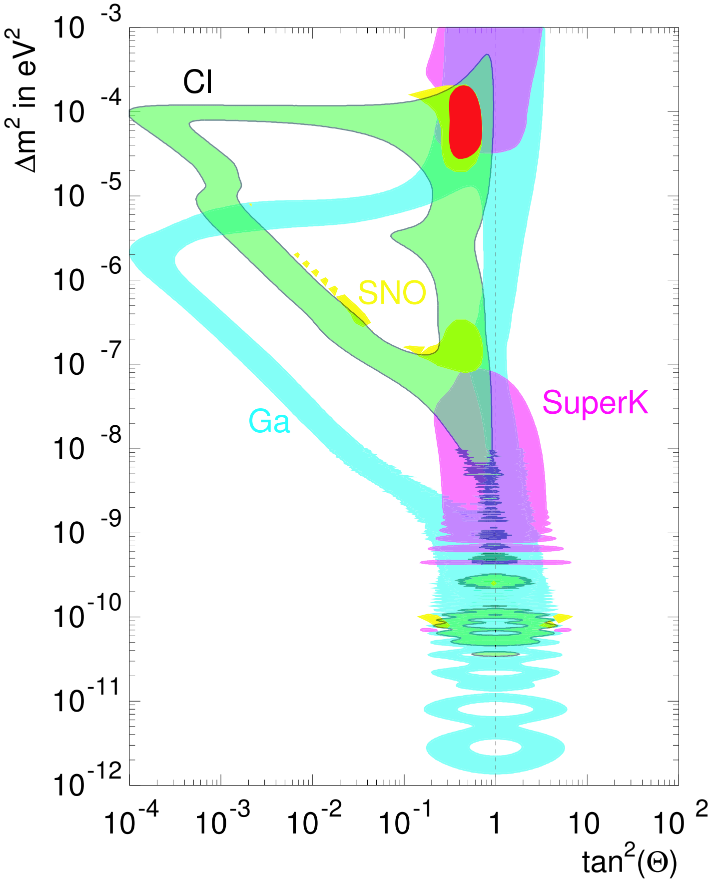
Mass hierarchy problem pending. What is the sign of Δm^2_{23}?

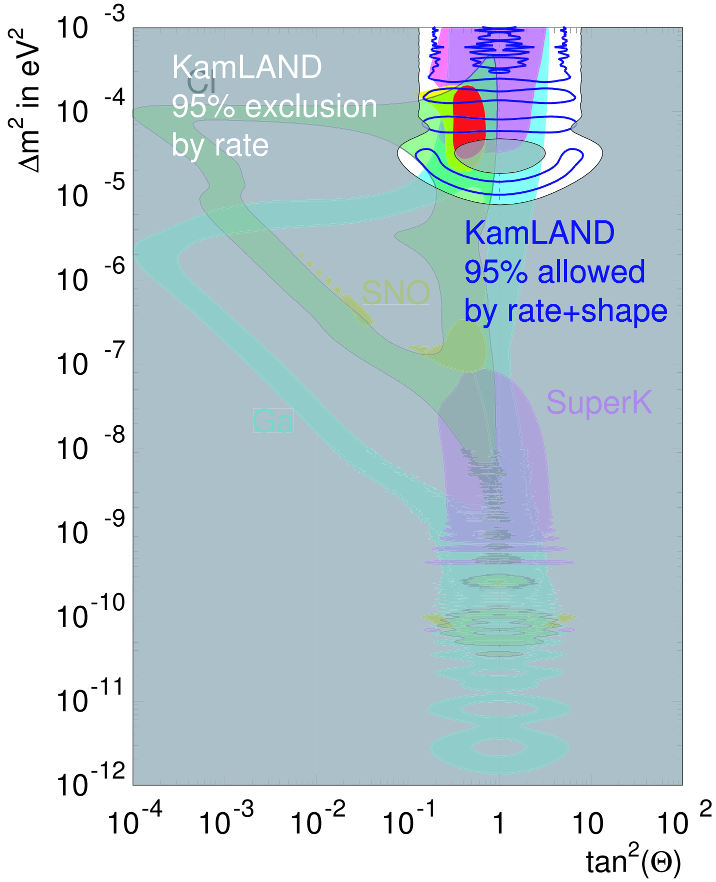


Latest summary: PDG 2004



LMA definitely favored





Future of neutrino physics in North America

- SNOLAB in Sudbury ➪ funded (Canada), infrastructure work started May'04. Call for LOI issued Feb'04.
- DUSEL (Deep Underground Scientific and Engineering Laboratory), US funds (federal DOE, some DOD, states). Setback for Homestake mine (SD) in Feb'04. New call to restart the selection process from scratch. Timescale before possible decision, 2 years.
- long baseline experiments, MiniBooNE, Fermilab to Soudan (MN)
- double beta decay experiments

Neutrino world in the 90s

What a typical theorist used to say back around 1990 (courtesy H. Murayama):

- The solution to the solar neutrino problem must be the small mixing angle (SMA) MSW solution since it is so beautiful
- The natural scale for $\nu_\mu \to \nu_\tau$ oscillation is $\Delta m^2 \sim 1\text{eV}^2$ because it is the cosmologically interesting range (hence CERN's SBL program in the 90s)
- The angle θ_{23} must be of the same order of magnitude as V_{cb} because of the grand unification
- The atmospheric neutrino anomaly must go away because it would require a large mixing angle to explain

Conclusion & perspectives

I unfortunately didn't cover many related topics. Let me mention in passing:

- θ_{13} experiments: Double CHOOZ (EU), Diablo Canyon (US, LBNL)
- HE, UHE neutrino searches: ANTARES, NESTOR, AMANDA and ICE CUBE, Pierre Auger project
- astronomical searches for CDM: SDSS, WMAP (NB: providing the most stringent constrain on M_ν to date: 0.7–1.9 eV!!)
- direct mass experiments (KATRIN, tritium beta decay experiment)

- are neutrino Majorana or Dirac particles: double beta decay exp flourishing
- measure θ_{13}
- three generation mixing matrix (PNMS matrix)
- CP violation, matter effects, sign of Δm^2_{23}
- is there a sterile neutrino, CP violation?