

Le neutrino, particule fantomatique !

Alain Bellerive

Chaire de recherche du Canada en physique des particules

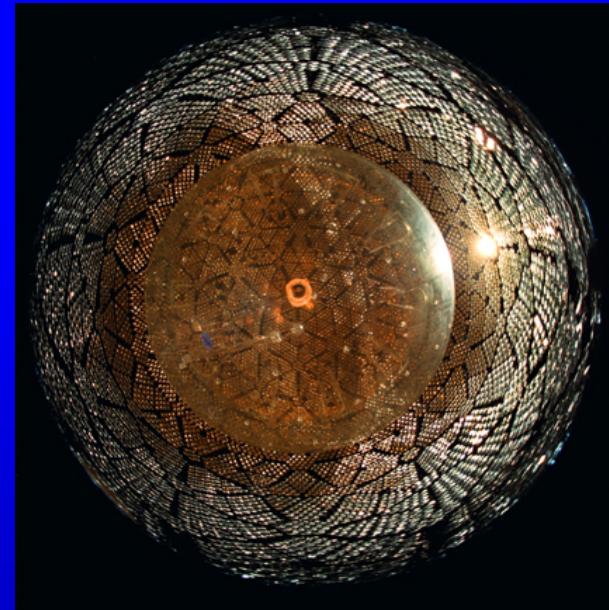
Université Carleton

Représentant de l'Observatoire
de Neutrinos de Sudbury



FAAQ2006

Alain Bellerive



Carleton
UNIVERSITY

Pourquoi l'étude des neutrinos !?!

31^{ème} Congrès de la FAAQ 2006:

- *Plaisir – Curiosité – Passion*
- *Science d'observation*
- *Physique et astronomie*

Le neutrino:

- *La particule la plus abondante dans l'univers après le photon*
- *Nos origines et la fabrique de l'espace/temps*
- *Mieux comprendre la matière et les lois fondamentales qui gouvernent le cosmos*

L'Observatoire de Neutrinos de Sudbury:

- *Étoiles... sources de neutrinos*
- *Étude de notre soleil*
- *Implication en physique subatomique*

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Les grandes questions du 21^{ème} siècle en astrophysique des particules

- *Comment les particules acquièrent-elles leur masse ?*
- *Qu'est-ce que la masse manquante de l'univers ?*
- *Pourquoi la matière domine-t-elle l'antimatière ?*
- *Comment la matière a-t-elle évolué juste après le big bang ?*

Sommaire

- Introduction
 - ❖ Forces fondamentales de la nature
 - ❖ Le Modèle Standard de la physique des particules
 - ❖ Histoire du neutrino
 - ❖ Outils: détecteurs de particules
- L'ABC de l'Interaction électrofaible
- La physique au cœur du soleil
- Le fameux problème des neutrinos solaires
- L'appareil expérimental: ONS / SNO
- Les résultats sur l'oscillation des neutrinos
- La connexion cosmique
- Le futur



The First Piece:

- Fundamental Forces
- Standard Model
- The Neutrino
- Particle Detectors



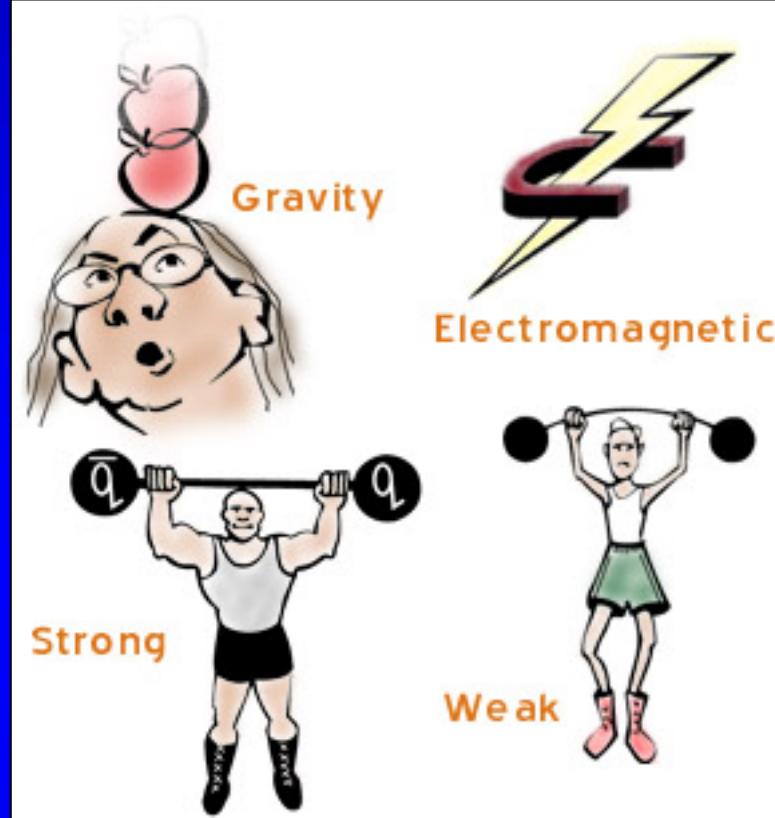
Fundamental Forces

Gravity: Gravity governs the attraction between two massive objects. It is negligible at the subatomic scale.

Electromagnetic: Most of us are familiar with electric and magnetic phenomena.

Strong: In the Standard Model, hadrons (neutrons & protons) are considered to be made of quarks bound together by the strong force.

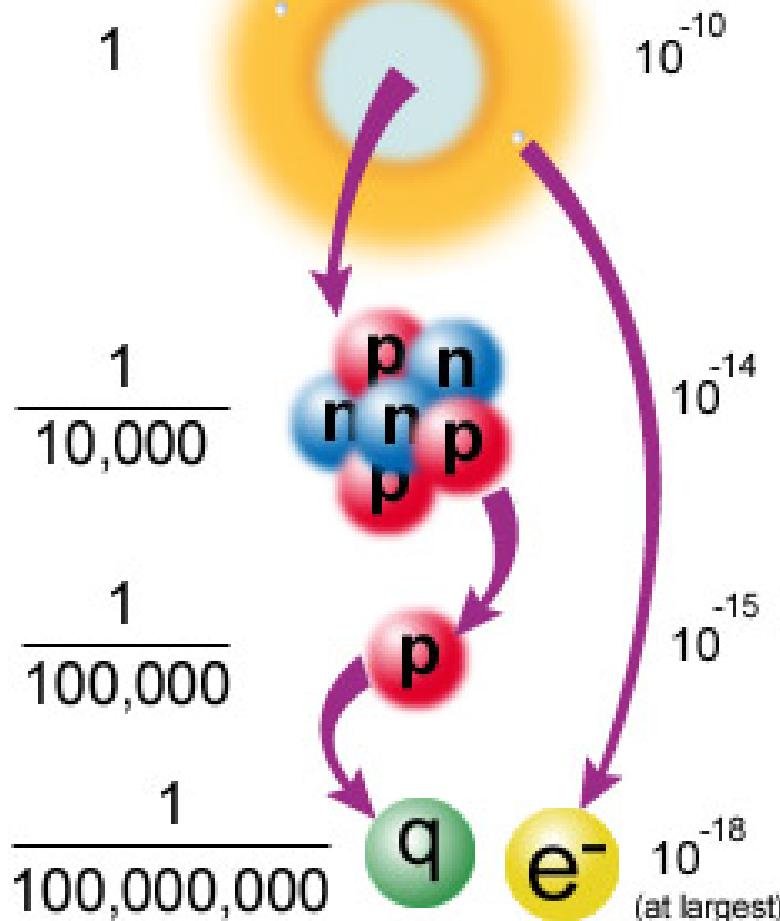
Weak: The weak interaction is more subtle! It is responsible for the instability of some nuclei via β -decay (e.g. $n \rightarrow p e \bar{\nu}$).



Interaction	Particle	Range (m)	Coupling
EM	photon	infinity	10^{-2}
Strong	gluon	10^{-15}	1
Weak	W & Z	10^{-18}	10^{-6}

Scope of Particle Physics

size in atoms
and in meters



Standard Model

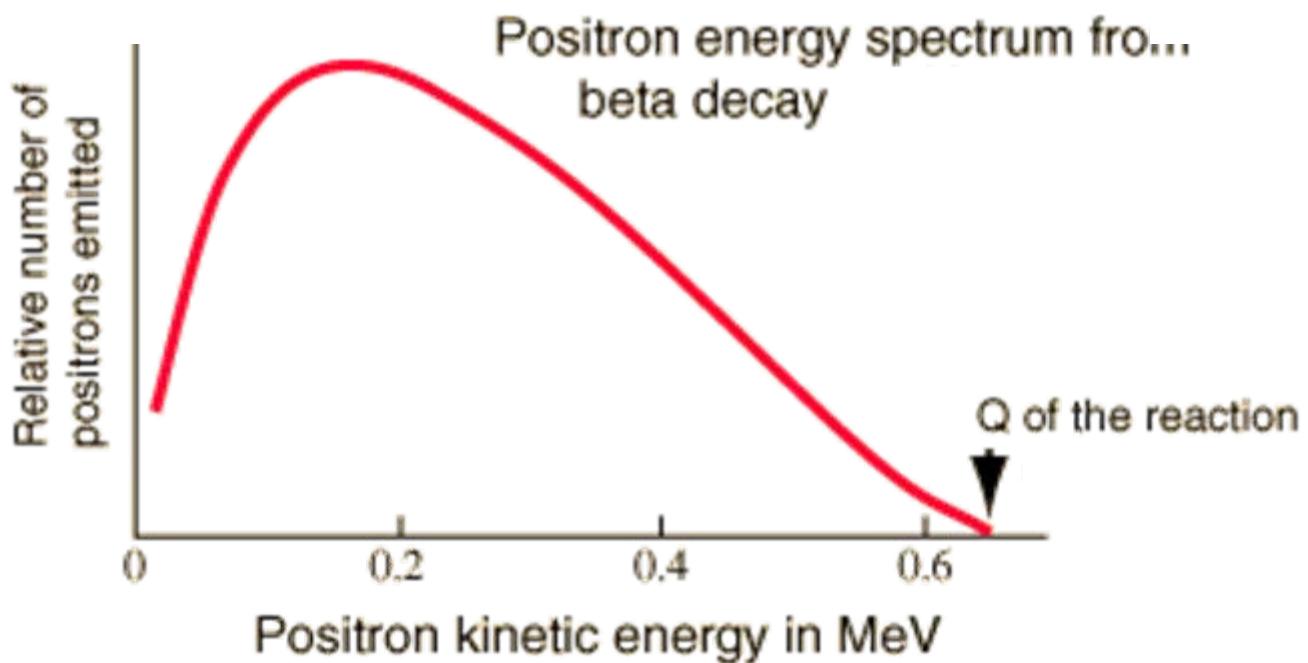
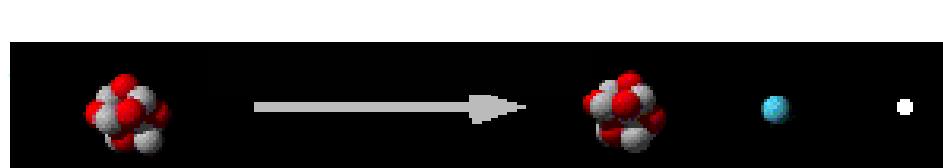
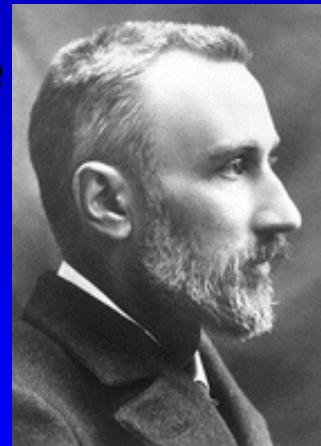
The Standard Model provides a general description of the physics currently accessible with modern particle accelerators. The minimal Standard Model postulates that matter is composed of fundamental spin-½ quarks and spin-½ leptons interacting via spin-1 bosons.

Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e e- Neutrino	ν_μ μ- Neutrino	ν_τ τ- Neutrino
	e electron	μ muon	τ tau

I II III
The Generations of Matter

History of the Neutrino

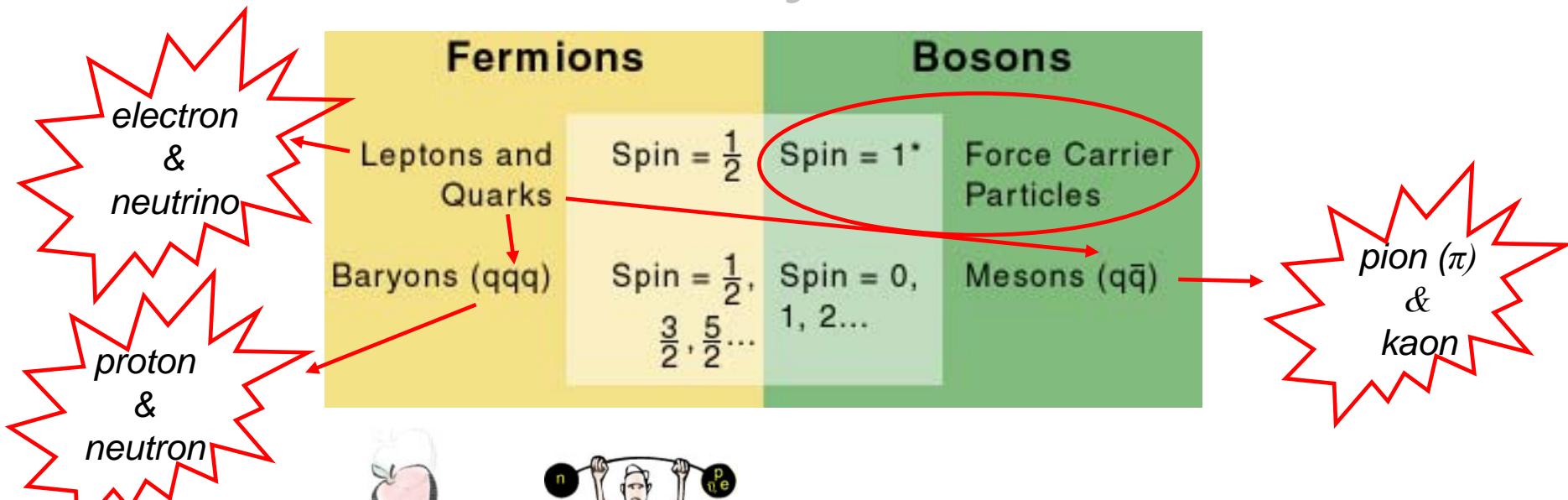
- Discovery of radioactivity by Marie and Pierre Curie (Nobel Price in Physics 1903)
- Beta Decay: nucleus emit an electron or a positron when $n \rightarrow p e^-$ or $p \rightarrow n e^+$



History of the Neutrino

- In 1931, the neutrino was postulated by the theorist Wolfgang Pauli. Pauli based his prediction on the fact that energy and momentum did not appear to be conserved in certain radioactive decays. Pauli suggested that this missing energy might be carried off by an invisible neutral particle.
- Later Enrico Fermi takes the neutrino hypothesis and builds his theory of beta decay (weak interaction).
- Clyde Cowan and Fred Reines announced in 1959 the discovery of a particle fitting the expected characteristics of the neutrino. This neutrino is later determined to be the partner of the electron.

Elementary Particles



Carried by →

Gravity	Weak Electroweak	Electromagnetic	Strong
Graviton (not yet observed)	$W^+ W^- Z^0$	Photon	Gluon
All Massive	Quarks and Leptons	Quarks and Charged Leptons and $W^+ W^-$	Quarks and Gluons

Quarks and leptons can be sub-divided into families which interact via the exchange of weak vector bosons

Quark Sector

$$Q = +2/3 \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

Lepton Sector

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} Q = -1$$

$$Q = 0$$

Neutrinos only interact via the weak force since they have no electric charge!

$$L(\text{em NC}) = e J_\mu^{\text{em}} A^\mu$$

$$L(\text{weak NC}) = \frac{g}{\cos\theta_W} \left(J_\mu^0 + \sin^2\theta_W J_\mu^{\text{em}} \right) Z^\mu$$

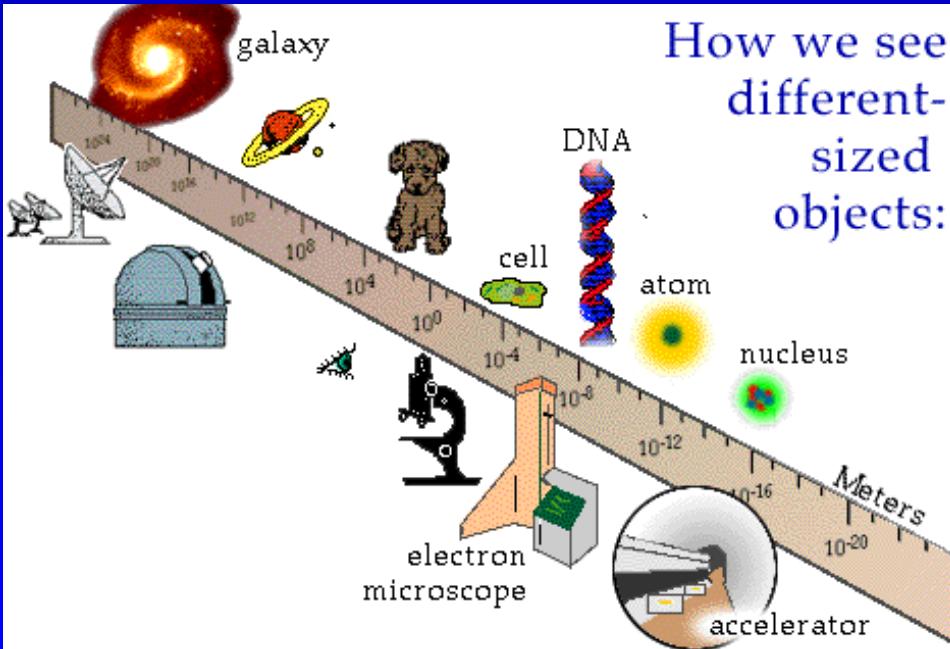
$$L(\text{weak CC}) = \frac{g}{\sqrt{2}} \left(J_\mu^+ W^{\mu-} + J_\mu^- W^{\mu+} \right)$$

Open Questions in Neutrino Physics

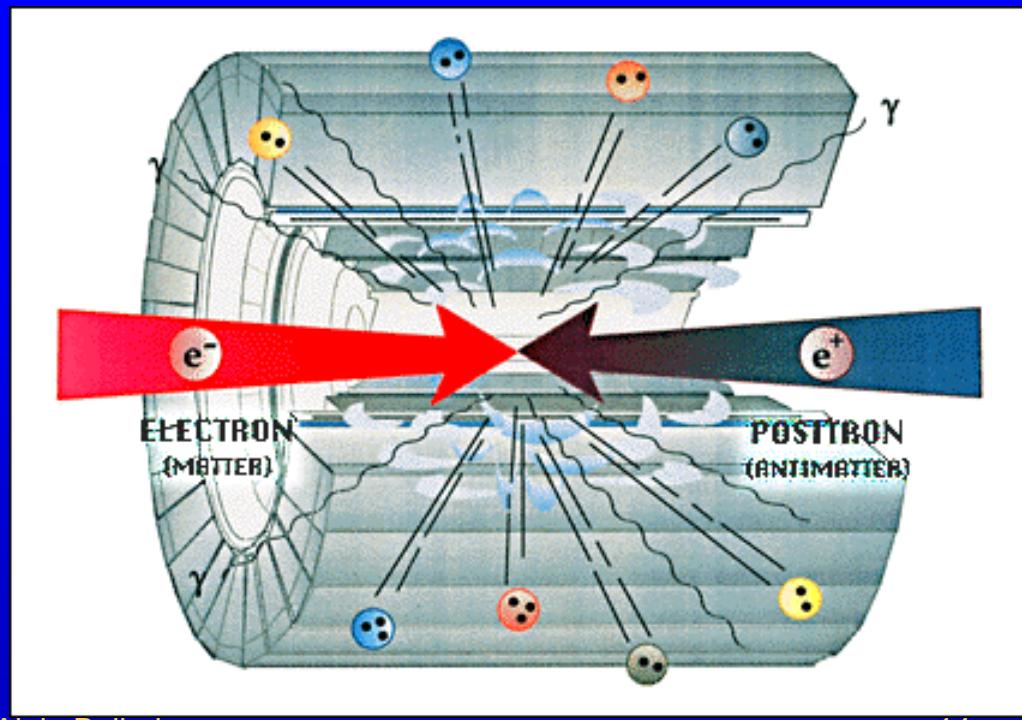
In the theoretical framework of the Standard Model, there are presently two fundamental open questions at the forefront of neutrino physics

- 1) The Solar Neutrino Problem !**
- 2) Are neutrinos massless ?**
- 3) Neutrino mixing and CP violation**

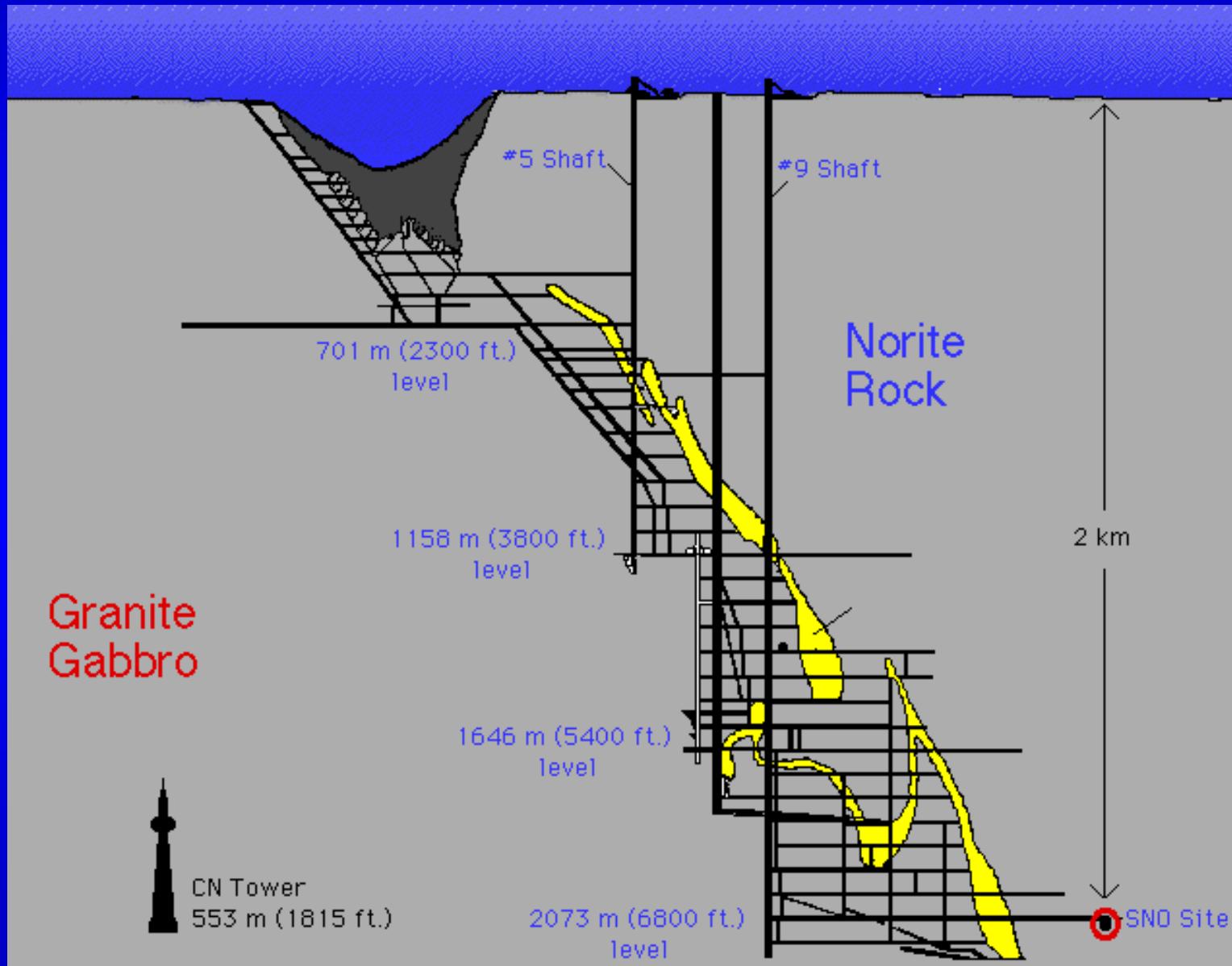
Tools to study subatomic particles



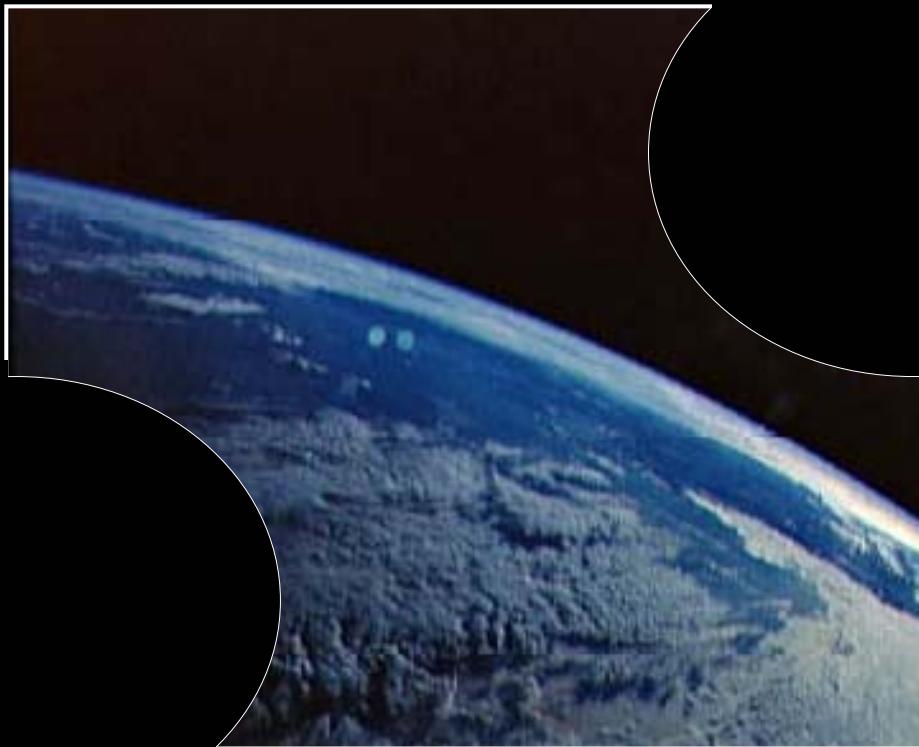
1) Multipurpose detectors operating at high energy accelerators
e.g. ATLAS - ILC



2) Underground laboratories: e.g. Sudbury



The Second Piece: Electroweak Reactions



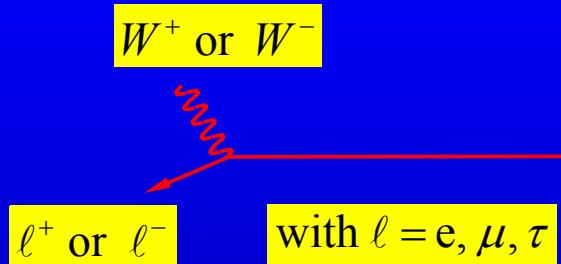
Electroweak Interactions

$$L(\text{em NC}) = e J_\mu^{\text{em}} A^\mu$$

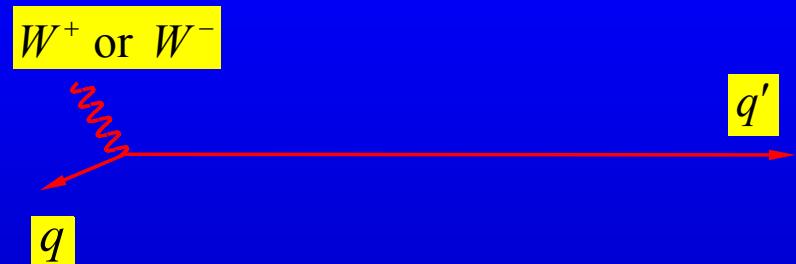
with $f = e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, u, c, t, d, s, b$



$$L(\text{weak NC}) = \frac{g}{\cos\theta_W} (J_\mu^0 + \sin^2\theta_W J_\mu^{\text{em}}) Z^\mu$$

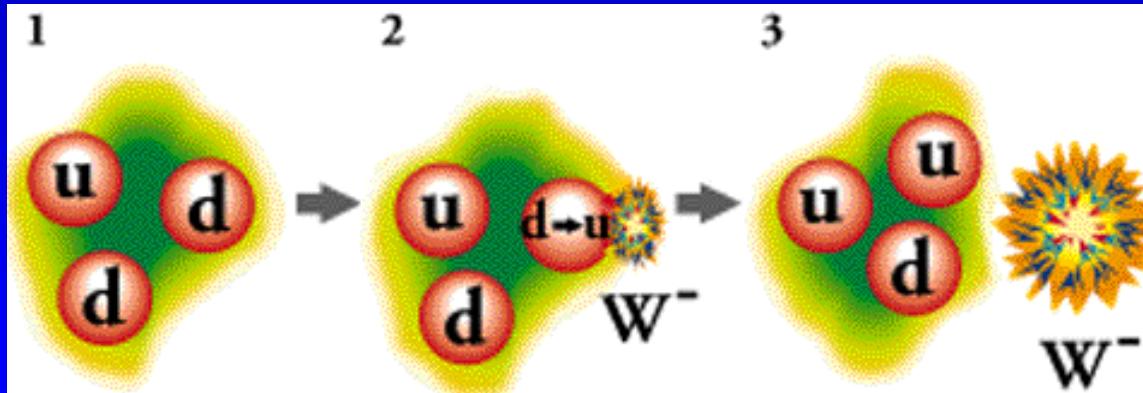


$$L(\text{weak CC}) = \frac{g}{\sqrt{2}} (J_\mu^+ W^{\mu-} + J_\mu^- W^{\mu+})$$



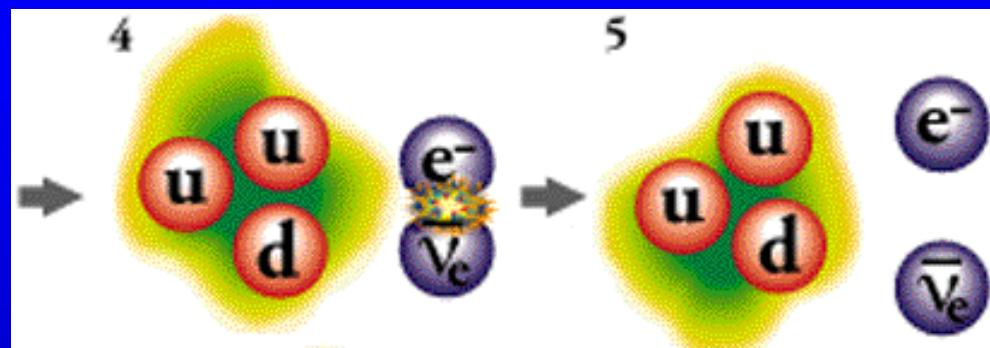
Electroweak Reactions

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



Since the down quark has a charge of $-1/3$ and the up quark has a charge of $2/3$, it follows that this process is mediated by a **virtual W^-** particle.

3) The new up quark rebounds away from the emitted W^- . The neutron now has become a proton.



4) An electron and antineutrino emerge from the virtual W^- boson.

5) The proton, electron, and the antineutrino move away from one another.

In this decay the W^- particle, which carries away a (-1) charge; thus charge is conserved!

Quark Mixing (CKM)

- Define a quark mixing matrix which relates the mass and weak eigenstates
- In the minimal Standard Model CP violation in the quark sector is built in the CKM matrix since the elements of V are complex

Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Neutrino Mixing

- Just as in the quark sector, it is possible to define a neutrino mixing matrix which relates the mass and weak eigenstates
- In the minimal Standard Model there is NO neutrino mixing...

Neutrino Mixing Matrix

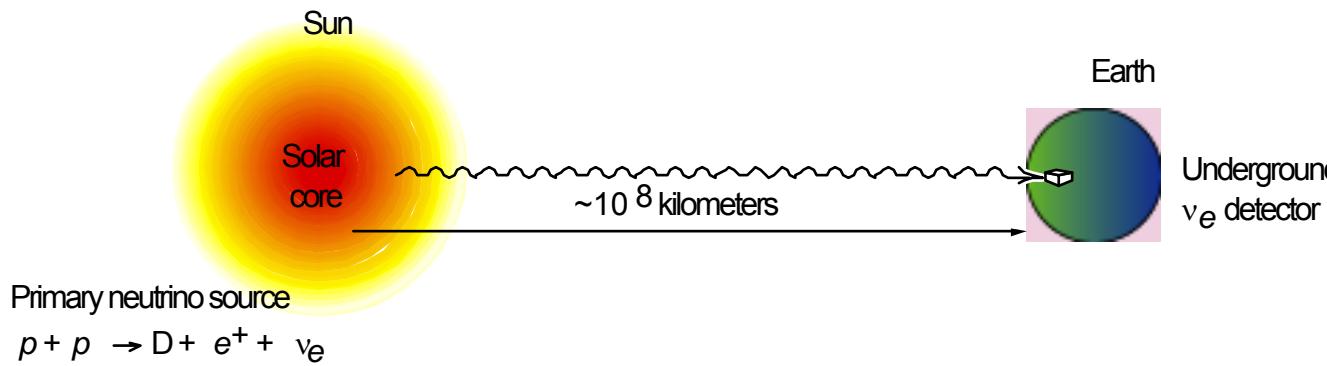
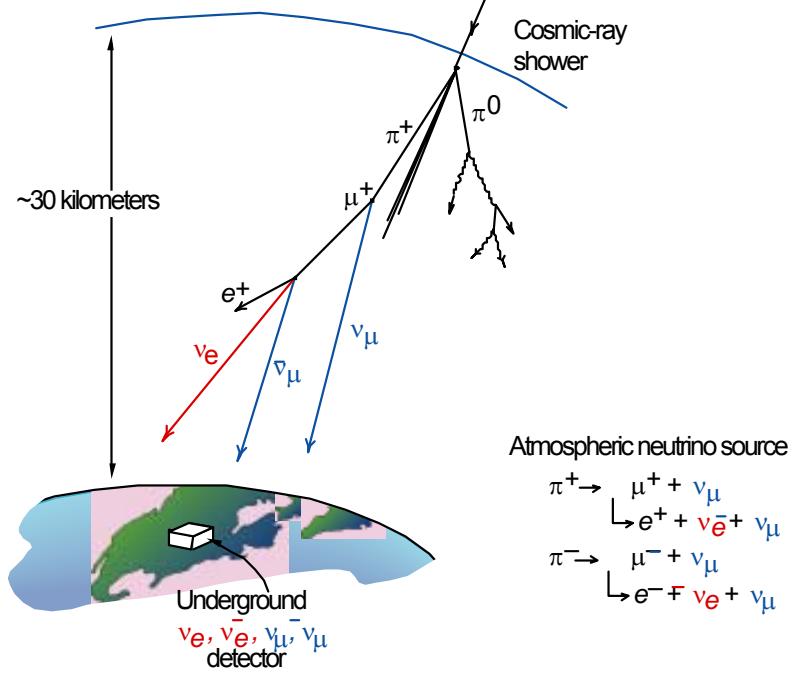
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Evidence for Neutrino Oscillations

First evidence of neutrino oscillation

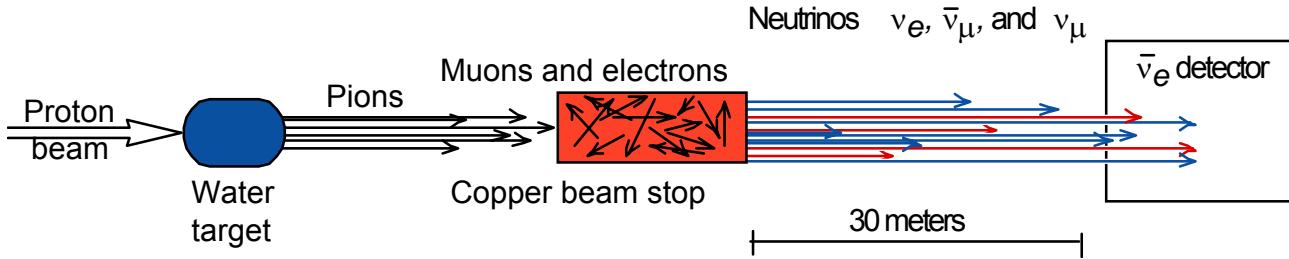
$$\frac{\nu_\mu}{\nu_e} \neq 2$$

**Atmospheric Neutrinos
high energies**



**Solar Neutrinos
low energies**

Today's talk !!!



**Neutrino Beams
and Reactors**

*Tunable energies
and distances!*

Arranging the Pieces: Solar Neutrino Physics



Macroscopic Properties of the Sun

Mean Distance from the Earth: 1.5×10^{11} m

Mass: 2×10^{30} kg

Radius: 6.96×10^8 m

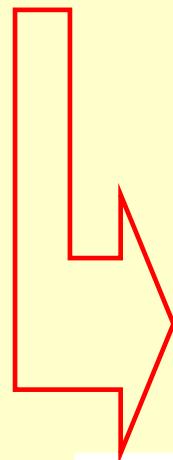
Luminosity: 3.8×10^{26} W

Neutrino flux: 6.5×10^{11} cm $^{-2}$ s $^{-1}$

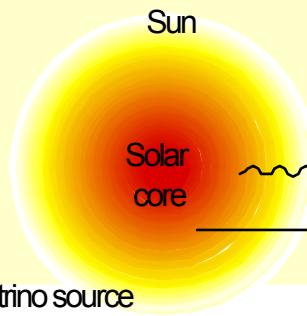
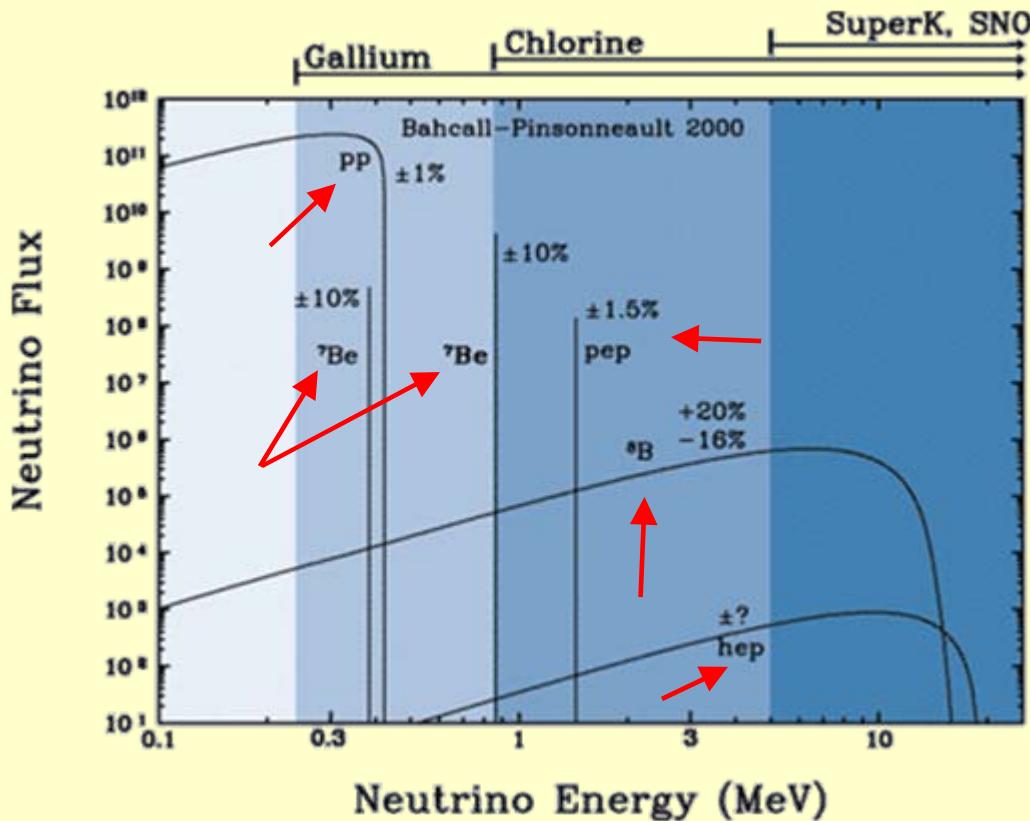
Neutrino Production in the Sun

Light Element Fusion Reactions

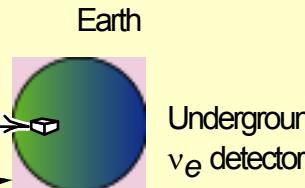
- ★ $p + p \rightarrow {}^2H + e^+ + \nu_e$ 99.75 %
- ★ $p + e^- + p \rightarrow {}^2H + \nu_e$ 0.25 %
- ★ ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$ $\sim 10^{-5}$ %
- ★ ${}^7Be + e^- \rightarrow {}^7Li + \nu_e$ 15 %
- ★ ${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$ 0.02 %



Primary neutrino source
 $p + p \rightarrow D + e^+ + \nu_e$

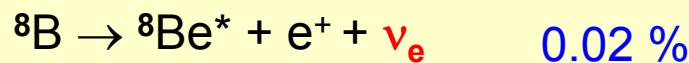
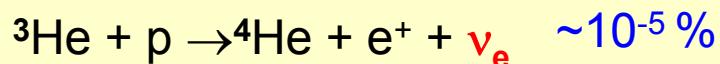
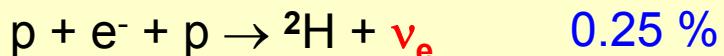
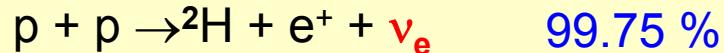


$\sim 10^{8}$ kilometers



Neutrino Production in the Sun

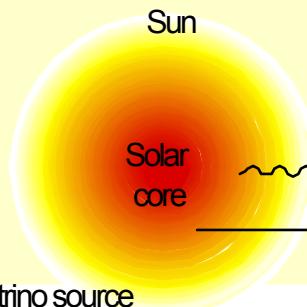
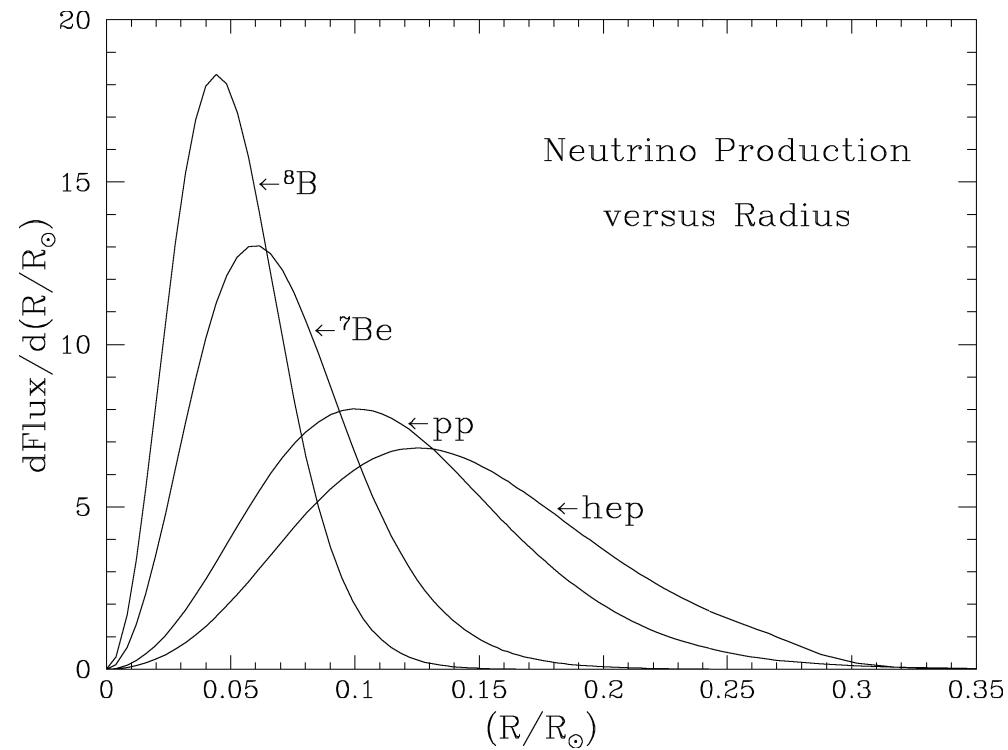
Light Element Fusion Reactions



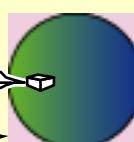
Primary neutrino source



Neutrino Production Radius



wavy line
~10⁸ kilometers



Earth

Underground
 ν_e detector

Neutrino from the Sun

- Our sun emits around 2×10^{38} neutrinos per second.
- The earth receives more than 100 billions neutrinos per second and cm^2 . This huge raining is undetected by the five senses of the homo sapiens.

Neutrino Detectors

- Underground, undersea or under ice, the experimental apparatus detect either the Cerenkov light emitted when a neutrino interact with the water or the transformation of atoms under neutrino interaction.

Strategy

- Deep and clean = low background.
- **HUGE** = Neutrino have small probability of interacting!

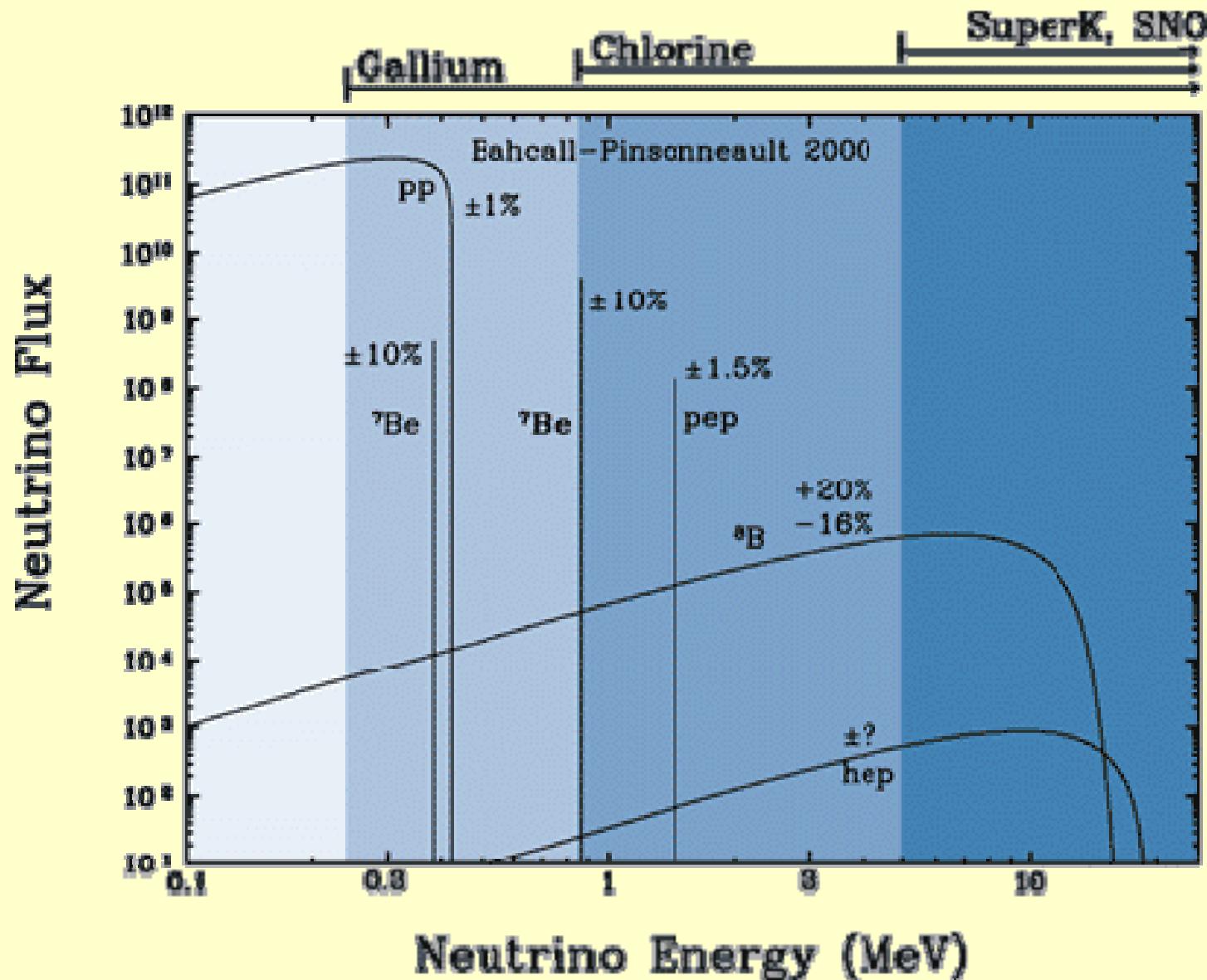
Solar Neutrino Experiments

- Review of the Solar Standard Model (SSM)

How ν_e are produced and detected ?

- Radiochemical experiments: Chlorine – Gallium
- SuperKamiokande (some preliminary results)
- Sudbury Neutrino Observatory (Latest Results)

Solar ν Flux and Experimental Sensitivity



Chlorine Measurements: Homestake (USA)

- 1960's: $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$
Construction of the Chlorine detector by Ray Davis
- Depth: 4850 ft
- Detector fluid: 3.8×10^5 l of C_2Cl_4
- Energy Threshold: 0.814 MeV
- 1970 – 1995
Measurements of solar ν flux
Sensitive to ^8B & ^7Be ν 's
- **Observed rate (SNU)**
 $2.56 \pm 0.16(\text{stat}) \pm 0.16(\text{syst})$
- **Expected rate (SNU)**
 $8.5^{+1.8}_{-1.8}$ [1 σ from BP2004]



Cleveland et al., Ap. J. 496, 505(1998)

Gallium Experiments



Radiochemical Target

Small proportional counters are used to count the Germanium

Energy Threshold: 0.233 MeV

Sensitive to pp, ^7Be , ^8B , CNO, and pep ν 's

SAGE: Russian-American
Gallium solar neutrino
Experiment (INR RAS)

GALLEX/GNO: Gallium Neutrino Observatory in Gran Sasso

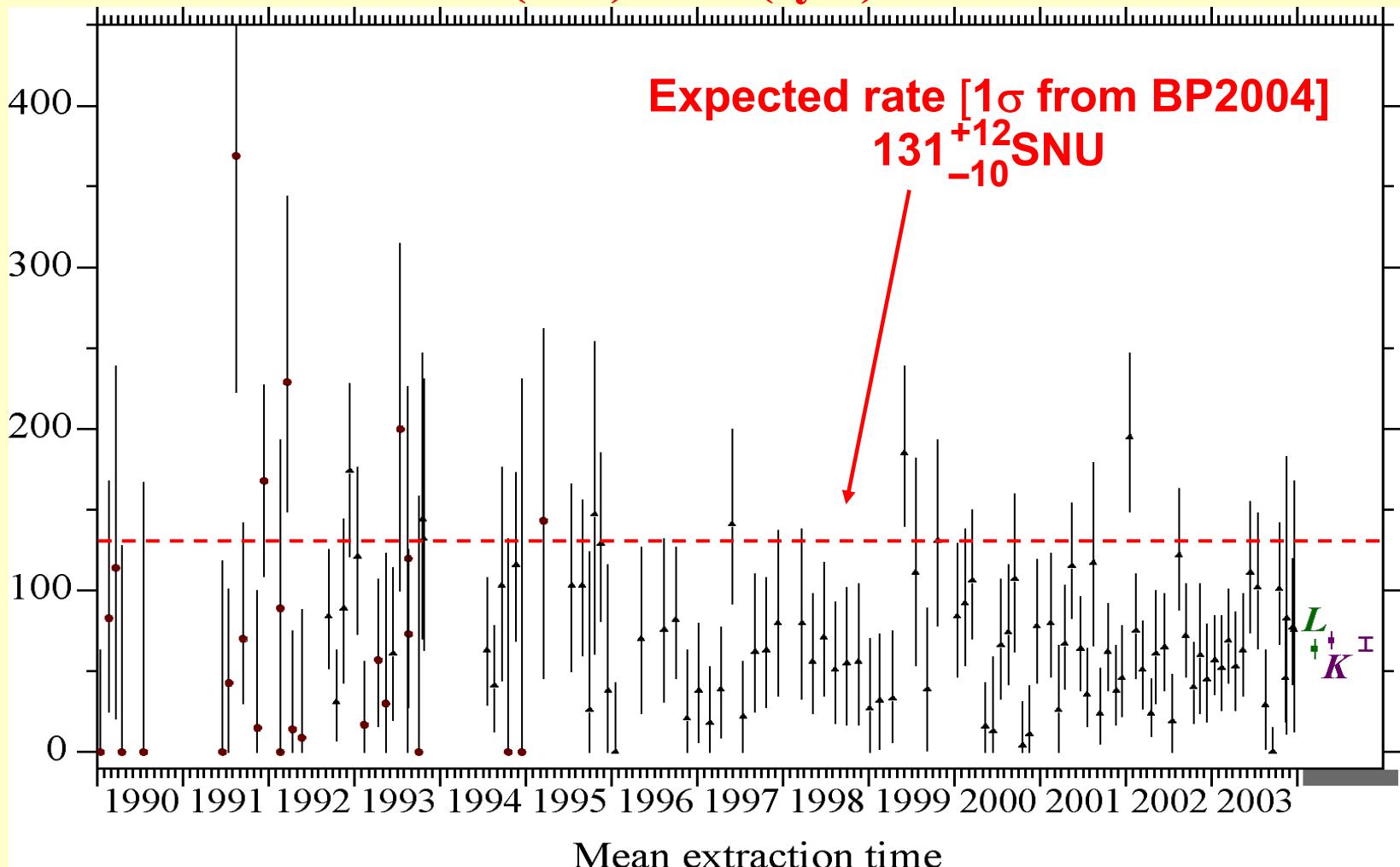
➤ A liquid metal target which contains 50 tons of gallium.

➤ 30 tons of natural gallium in an aqueous acid solution.

Gallium Measurements: SAGE (on-going)

SAGE overall 1990-2003 (121 runs)

66.9 ± 3.9 (stat) ± 3.6 (syst) SNU



Source: Neutrino 2004

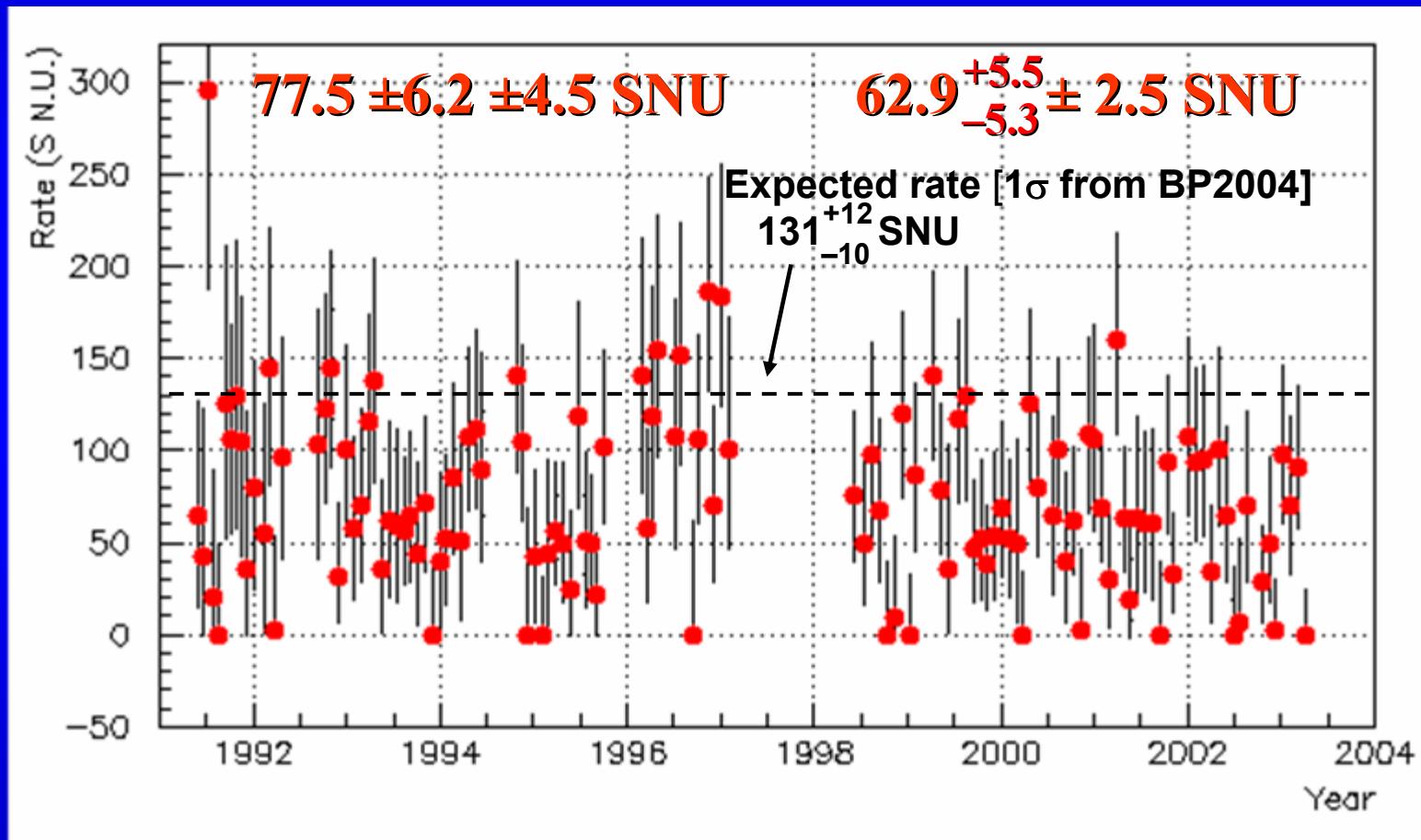
Gallium Measurements

GALLEX

65 Solar runs = 1594 d
23 Blank runs

GNO (terminated)

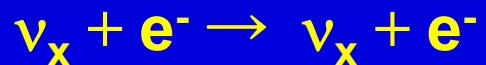
58 Solar runs = 1713 d
12 Blank runs



Source: Neutrino 2004

Water Detector: Super-Kamiokande (Japan)

- ${}^8\text{B}$ neutrino measurement by



- Sensitive to ν_e , ν_μ , ν_τ

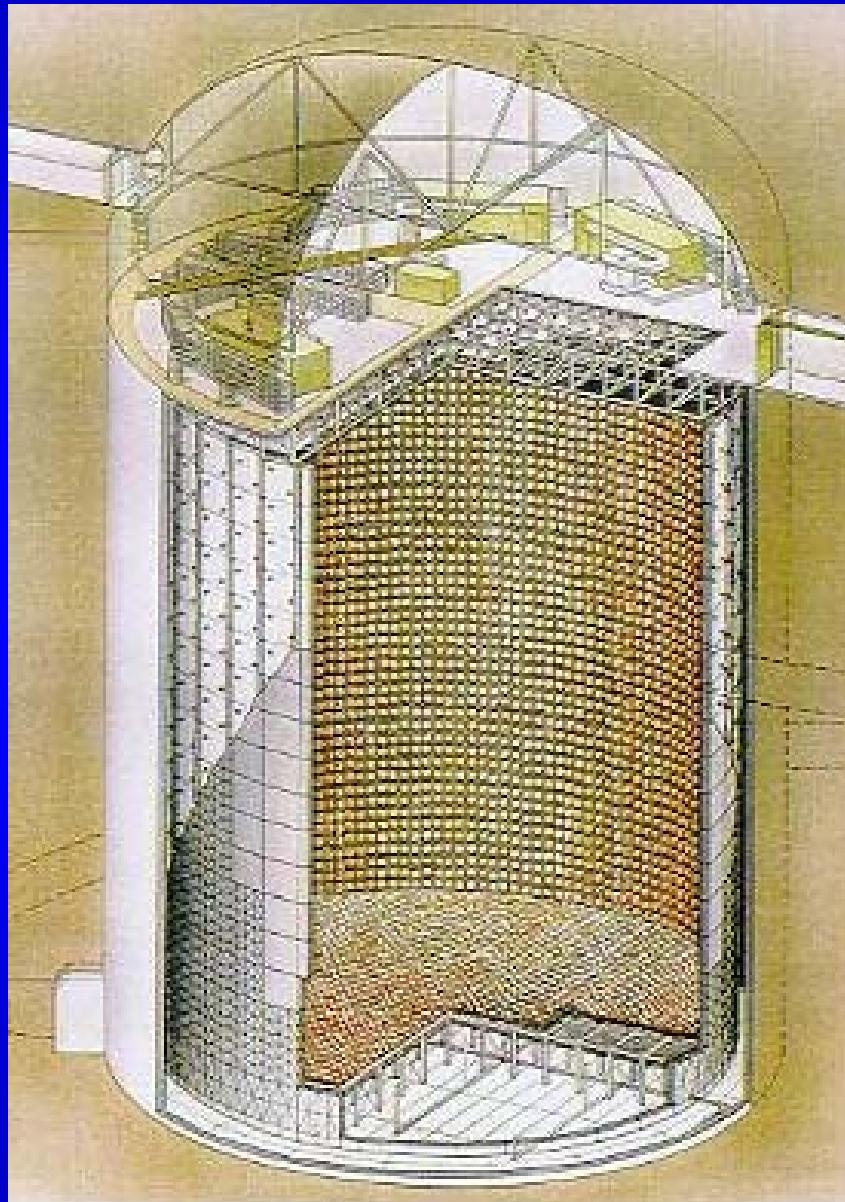
$$\sigma(\nu_{\mu,\tau} + e^-) \approx 0.15 \times \sigma(\nu_e + e^-)$$

- High statistics $\sim 15\text{ev./day}$

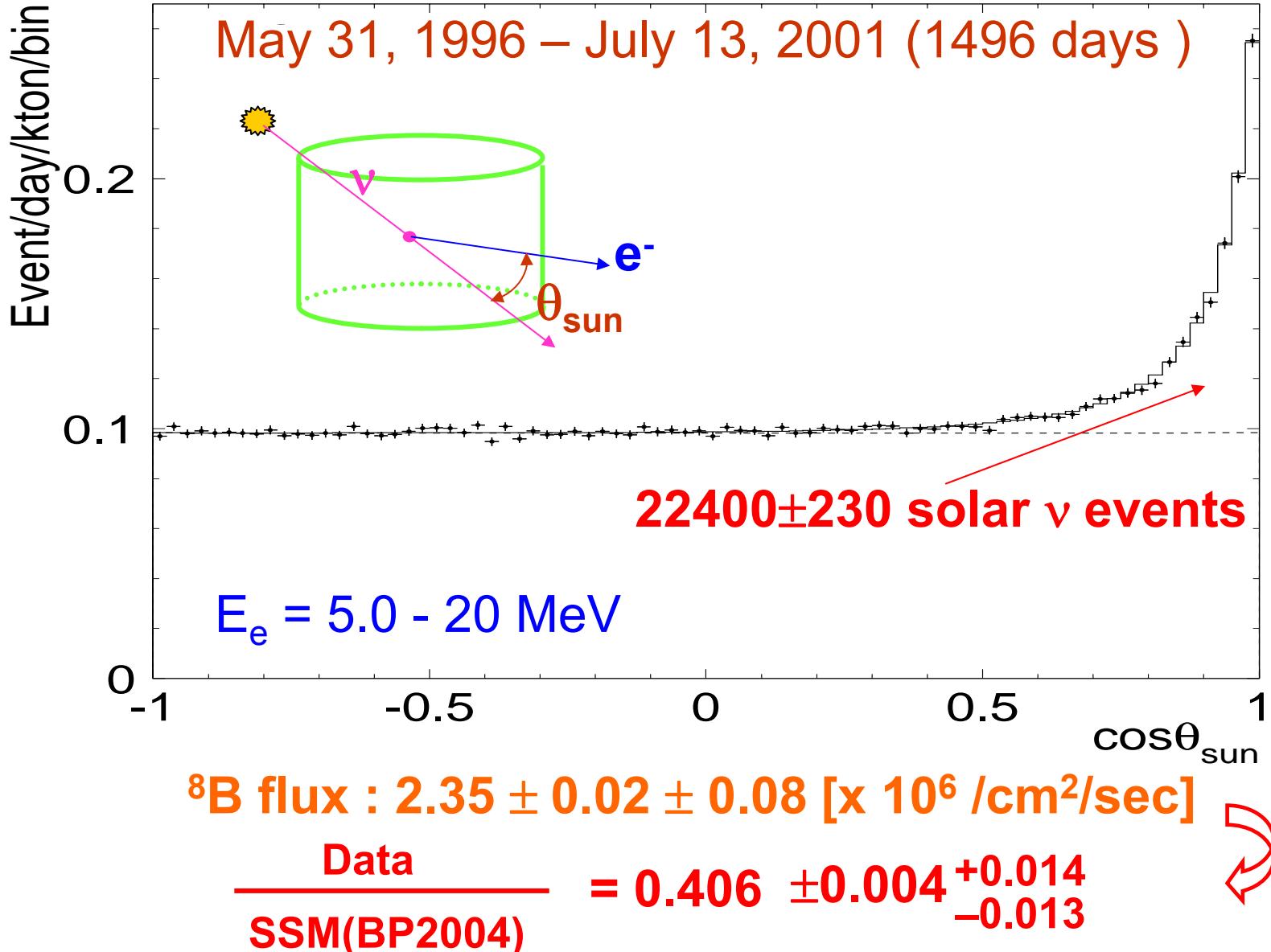
- Real time measurement allow studies on time variations

- Studies energy spectrum

- 50 ktons of pure water with 11,146 PMTs (fiducial volume of 22.5 ktons for analysis)



Solar neutrino data in SK (period I)



Solar ν Flux Measurement Results

Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

Chlorine – Gallium – Water experiments
have
different energy threshold

!!! The data suggest an energy dependence !!!

??? What could explain such a variation ???

Solar ν Flux Measurement Results

Experiment	Year	Detection Reaction	Ratio Exp/P2000
Chlorine (127 t)	1970-1995	$^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^-$	0.44 ± 0.02
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	
SAGE (23 t)	1990-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	
Gallex + GNO (12 t)	1991-	$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$	
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.51 ± 0.015

PROBLEM !

Chlorine – Gallium – Water experiments
have
different energy threshold

!!! The data suggest an energy dependence !!!

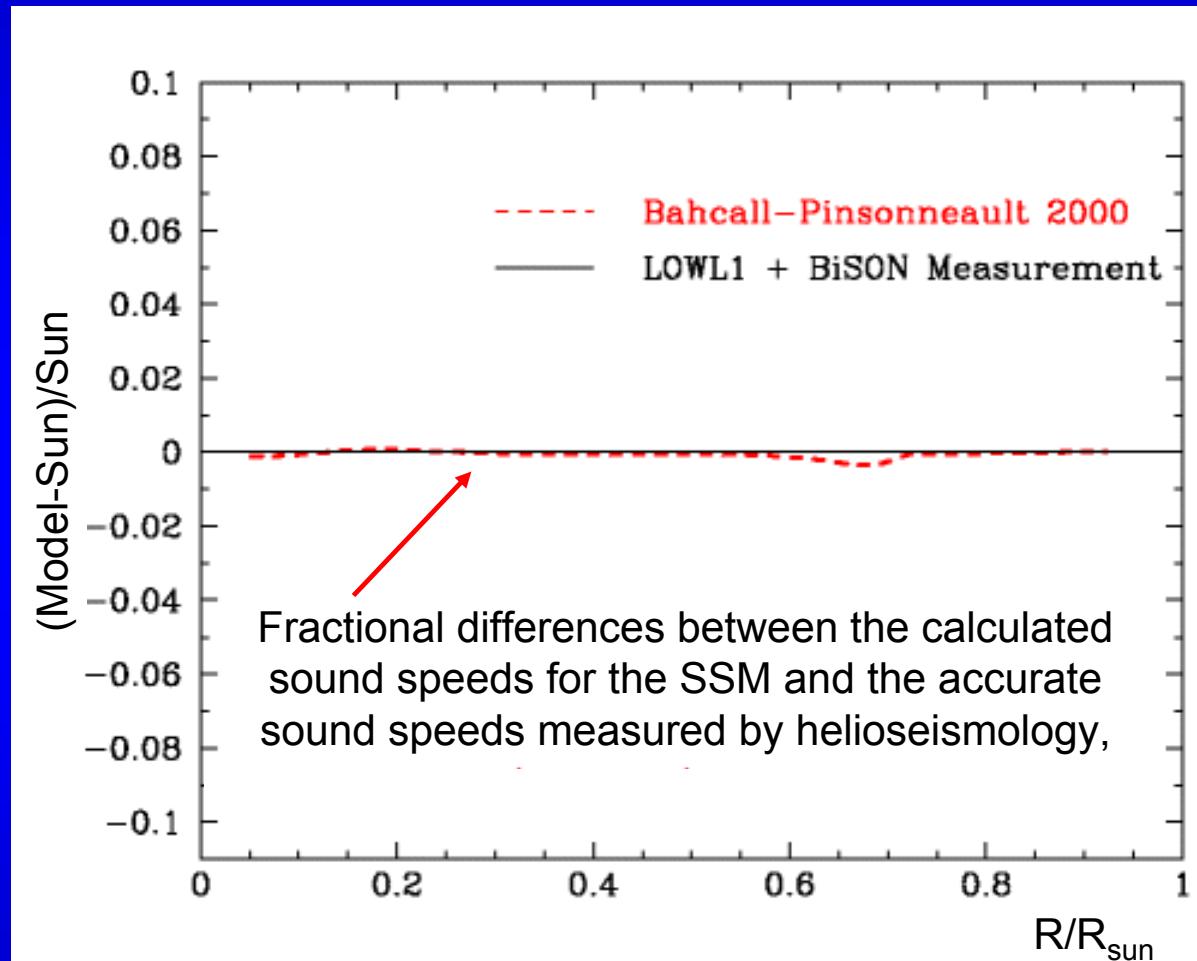
??? What could explain such a variation ???

Solar Neutrino Problem

- Historically the first culprit was assumed to be the method of determining the solar ν flux.
- In fact, the last 30 years showed that the SSM provides an accurate description of the macroscopic properties of our Sun.
- The mass, radius, shape, luminosity, age, chemical composition, and photon spectrum of the Sun are precisely determined and used as input parameters.
- Equation of state relates pressure and density; while the radiative opacity dictates photon transport.
- Experimental fusion cross sections used to determine the nuclear reaction rates.

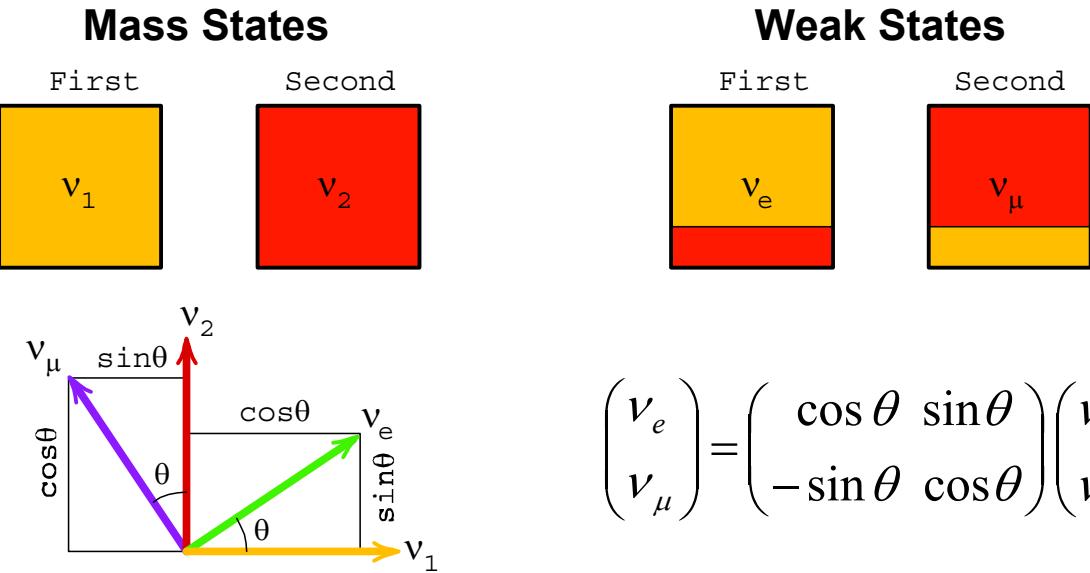
Test of Standard Solar Model

SSM determines the present distribution of physical variables inside the Sun (like the core temperature and density), photon spectrum, the speed of sound, , and the neutrino fluxes.

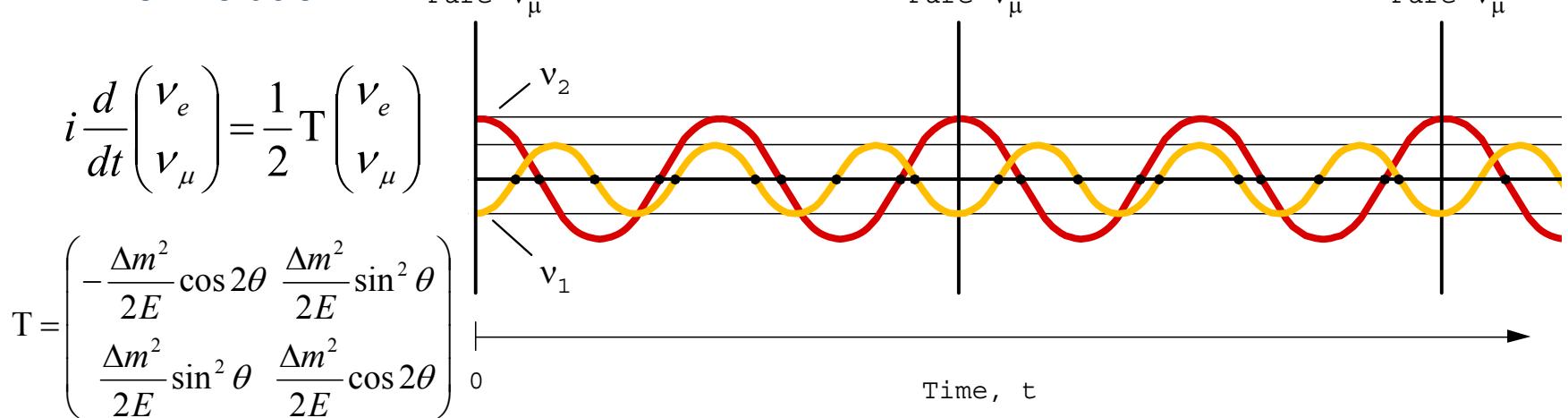


Neutrino Oscillations

Neutrino States



Time Evolution

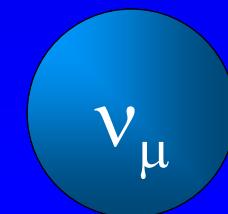


Neutrino Oscillations:

$$\Delta m^2 = \left| m_2^2 - m_1^2 \right|$$

$$P_{ee} \sim \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L / E)$$

- Physics:
 Δm^2 & $\sin(2\theta)$
- Experiment:
Distance (L) & Energy (E)



The state evolve with time or distance

Solar Neutrino Oscillations

$$P_{ee} = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L / E)$$

- Physics:

$$\Delta m^2 \text{ & } \sin(2\theta)$$

- Experiment:

Distance (L) & Energy (E)

$$\Delta m^2 \equiv \Delta m_{12}^2 \text{ and } \theta \equiv \theta_{12}$$

3 Parameters !

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

θ = Mixing angle

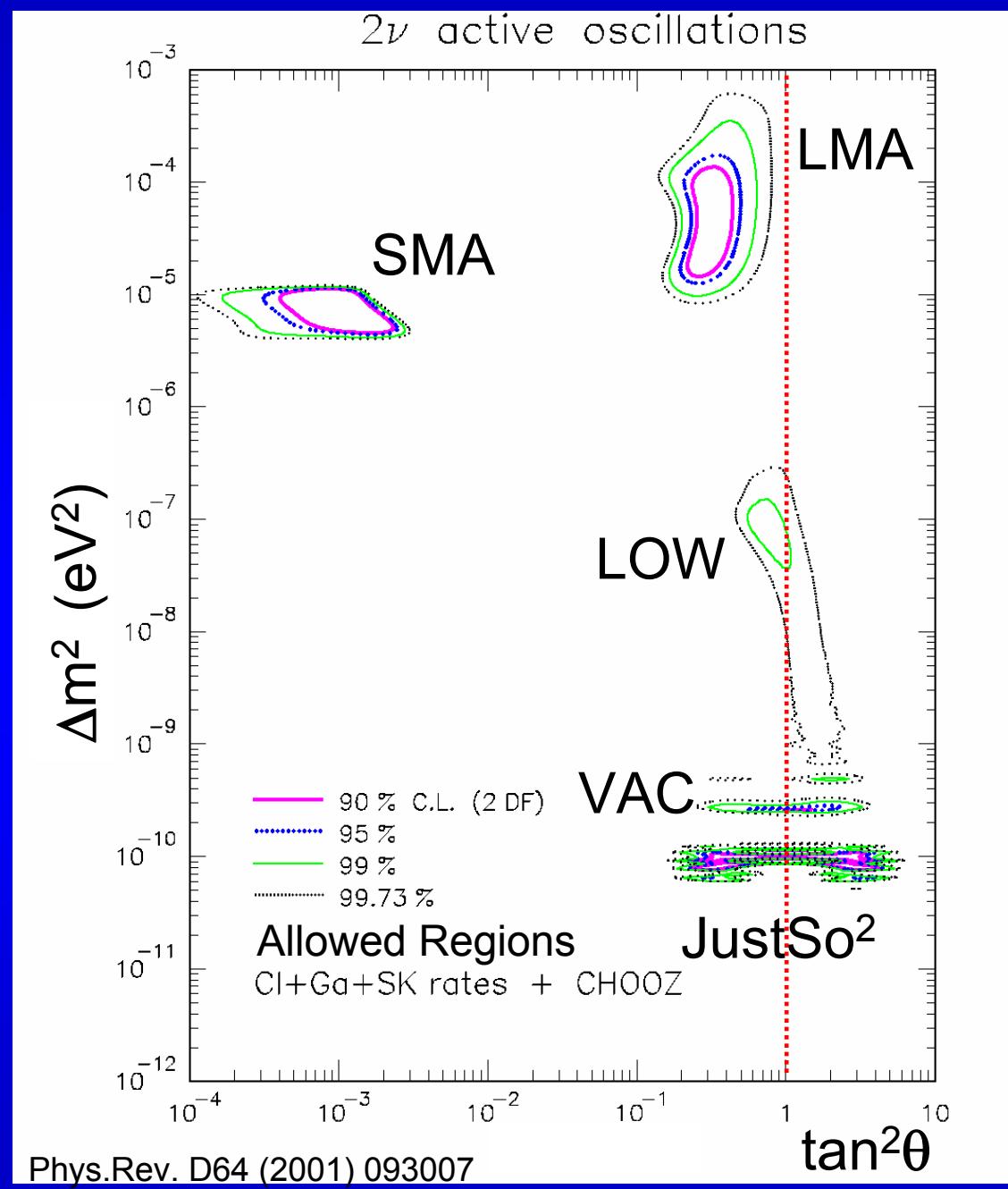
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The state evolves with time or distance

Mixing Parameters

Combination of the Chlorine, Gallium, SK, and CHOOZ restricted the mixing parameters

Pre SNO



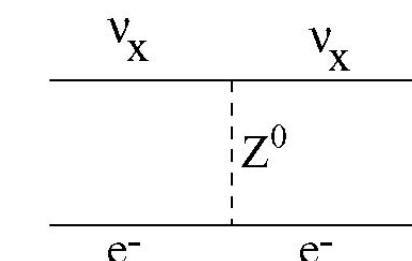
Matter-Enhanced Neutrino Oscillations

Neutrinos produced in weak state ν_e

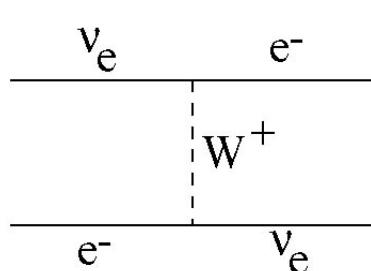
⇒ High density of electrons in the Sun

⇒ Superposition of mass states $\nu_{1, 2, 3}$ changes through the MSW resonance effect

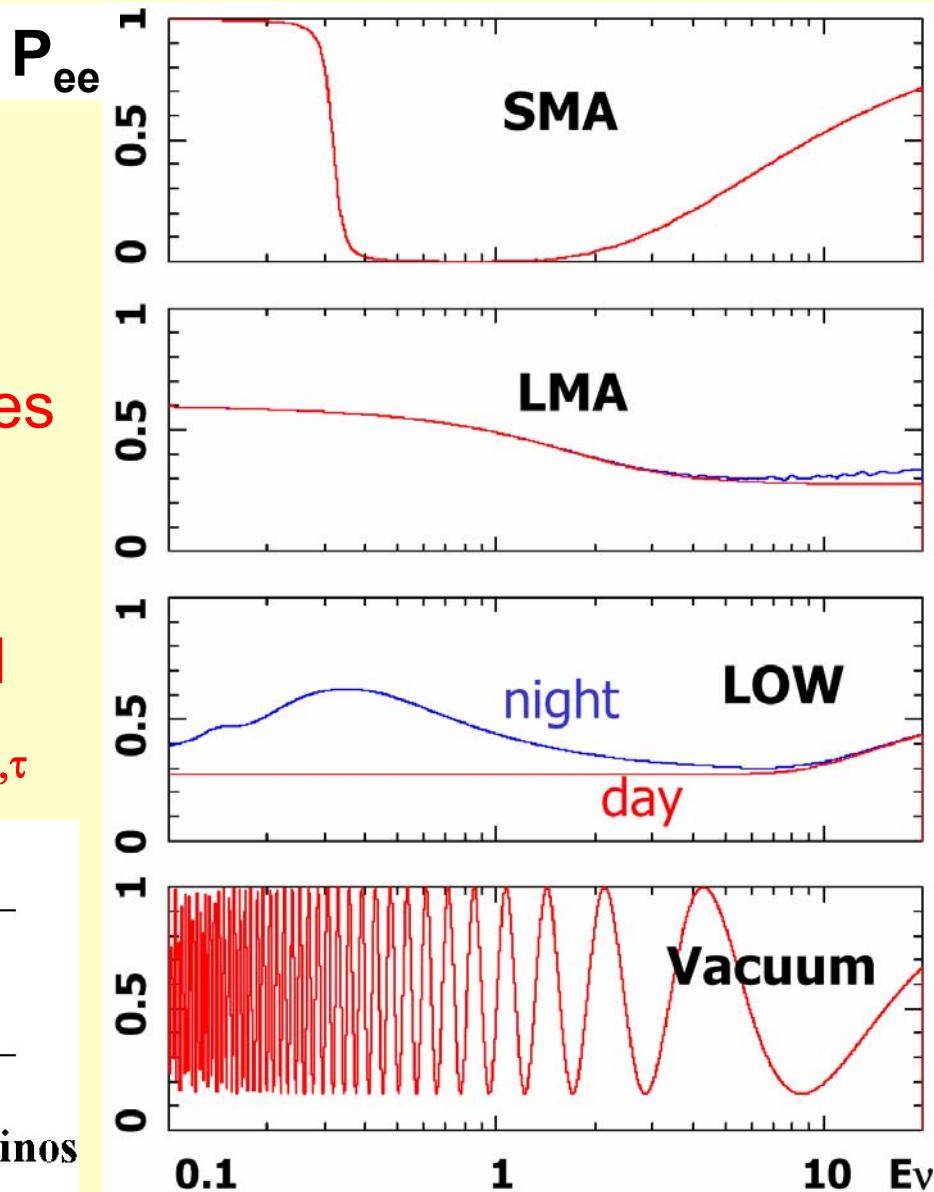
⇒ Solar neutrino flux detected on Earth consists of $\nu_e + \nu_{\mu, \tau}$



All neutrino flavors



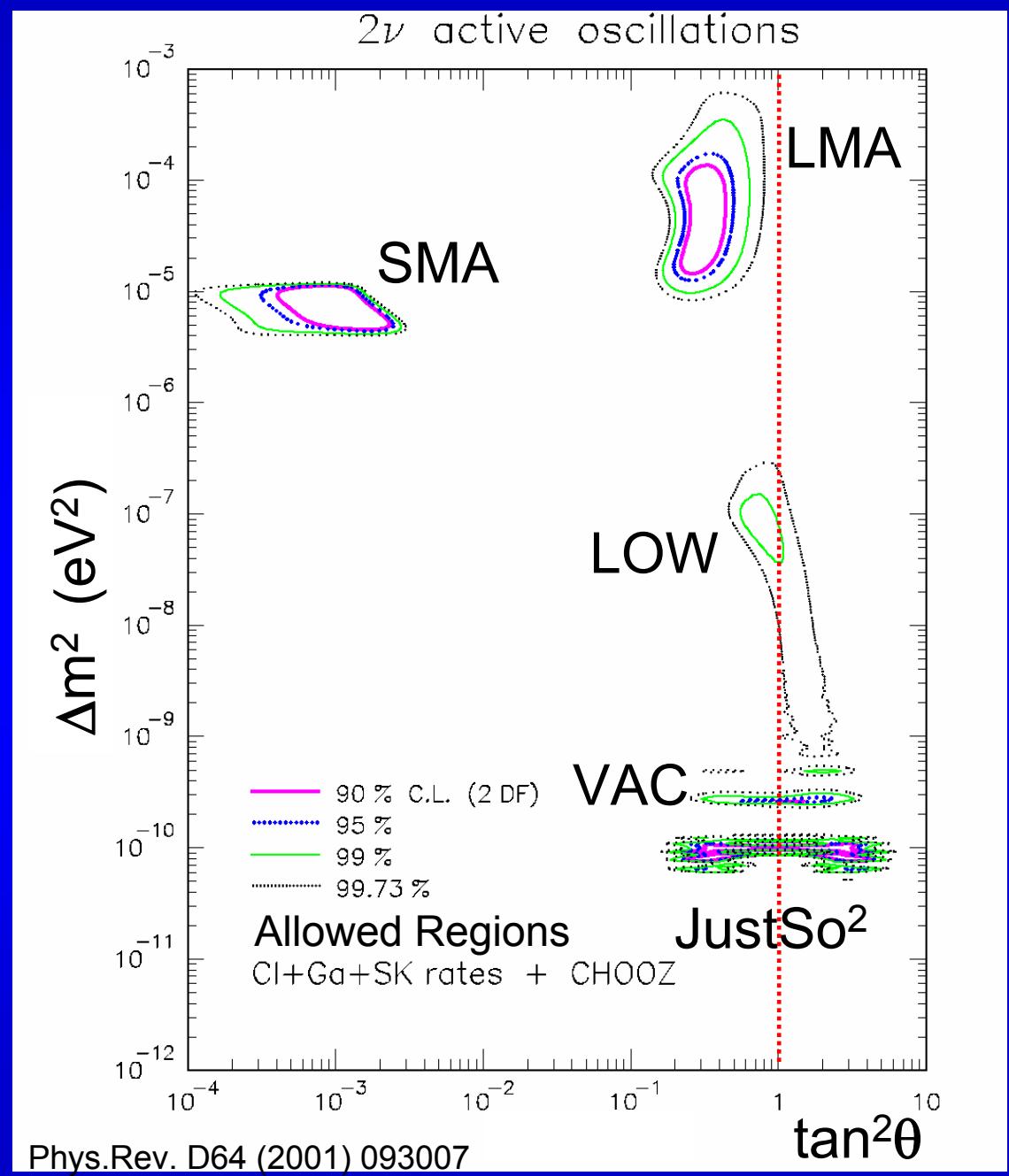
Only electron neutrinos



Mixing Parameters

Combination of the Chlorine, Gallium, SK, and CHOOZ restricted the mixing parameters

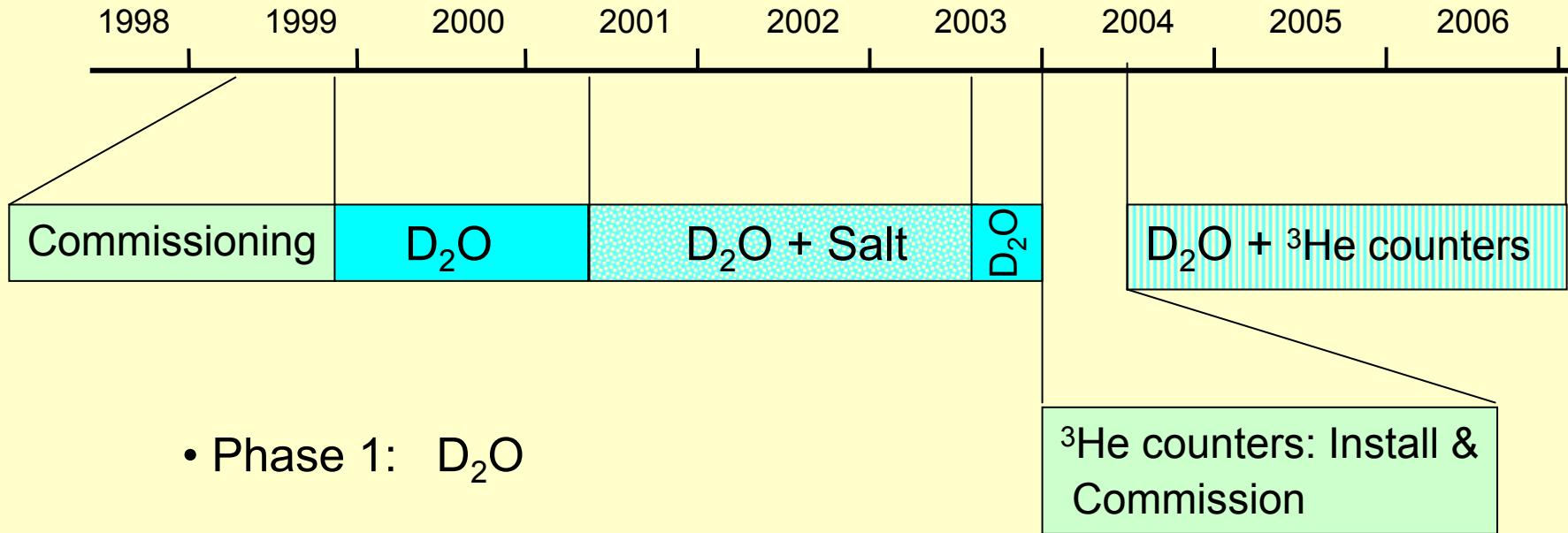
Pre SNO



Somewhere in the Depths of
Canada...



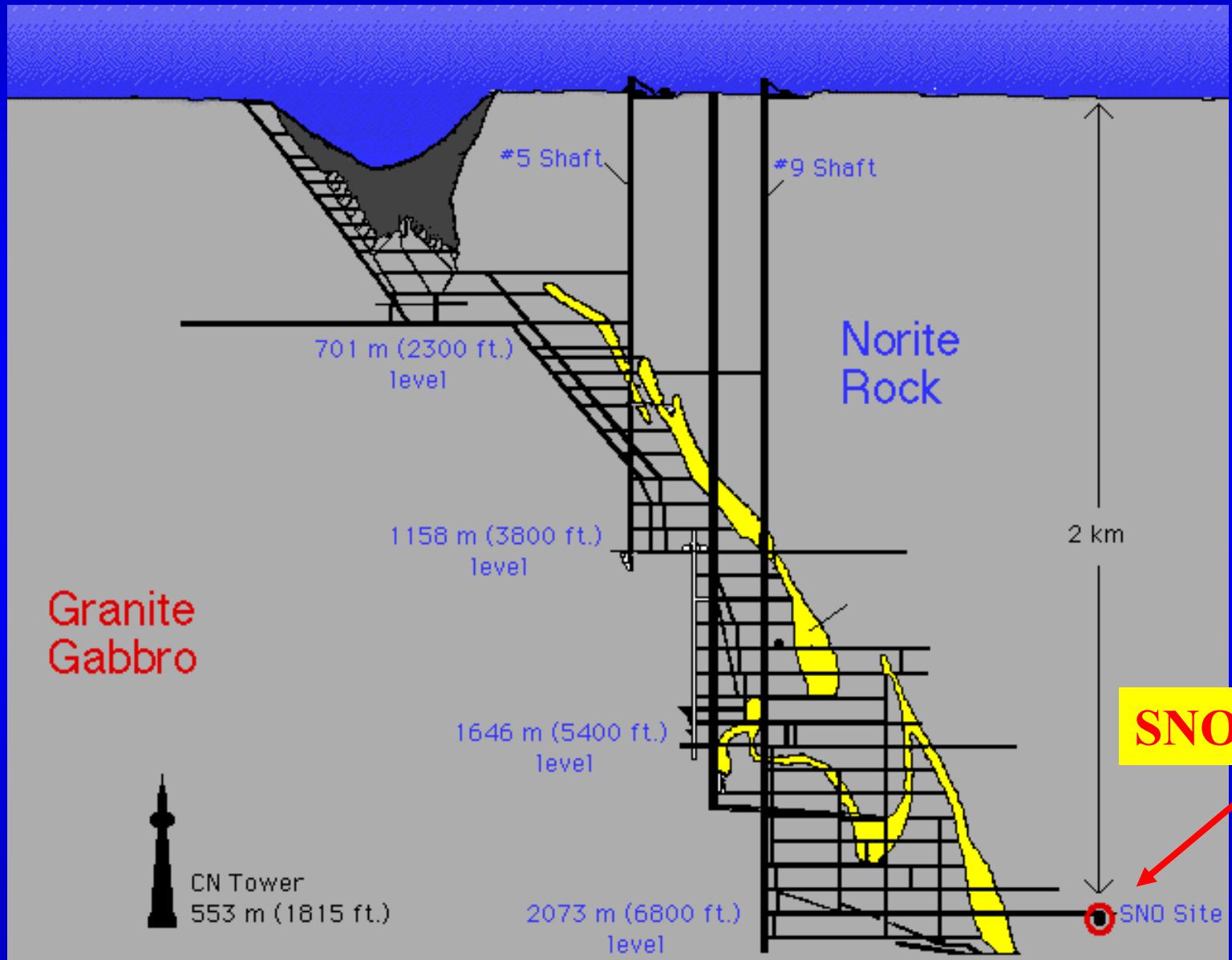
SNO Timeline



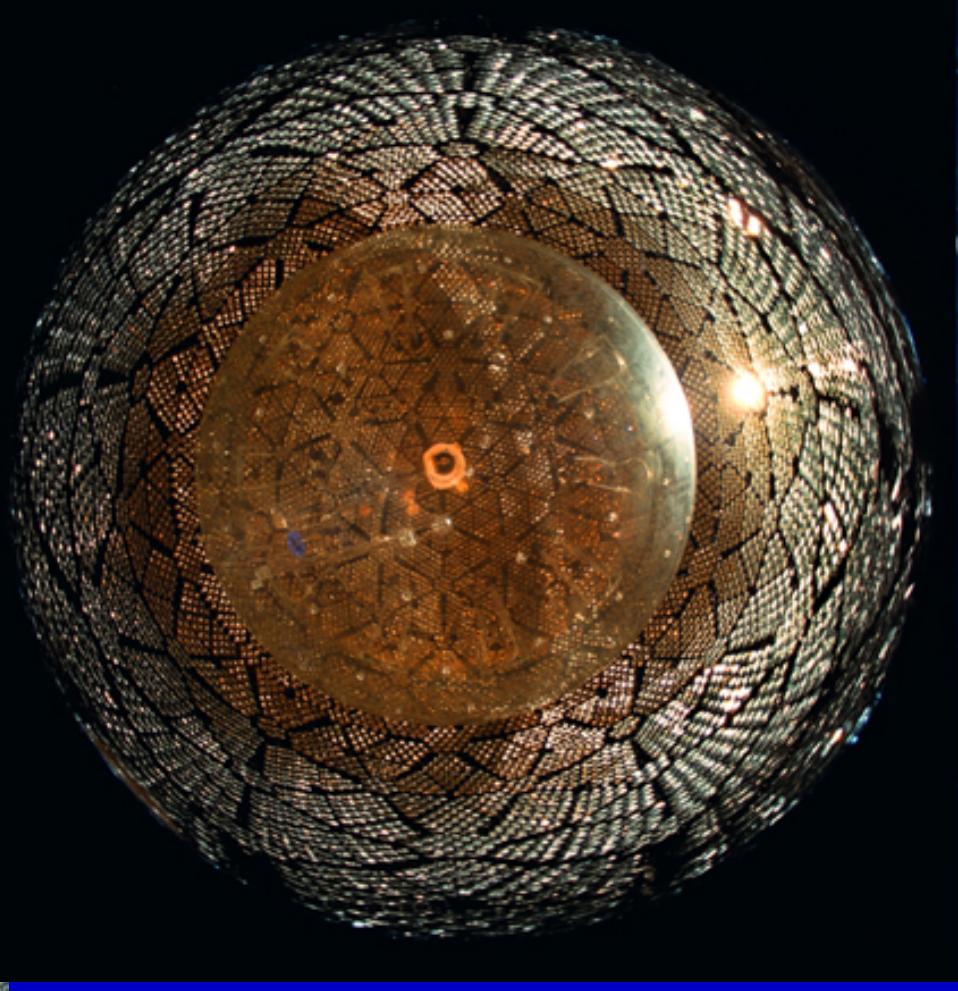
- Phase 1: D₂O
- Phase 2: D₂O + Salt (NaCl)
- Phase 1a: D₂O
- Phase 3: D₂O + ³He counters

³He counters: Install & Commission

Underground laboratory in Sudbury



The SNO Detector during Construction



Subury Neutrino Observatory

- Timeline
- Experimental Apparatus
- First Results from the D₂O Phase
- Most Recent Results from the Salt Phase
- Outlook to the new NCD Phase



OVERAL PICTURE

Sudbury Neutrino Observatory (Canada)

2092 m to Surface (6010 m w.e.)

PMT Support Structure, 17.8 m

9456 20 cm PMTs

~55% coverage within 7 m

Acrylic Vessel, 12 m diameter

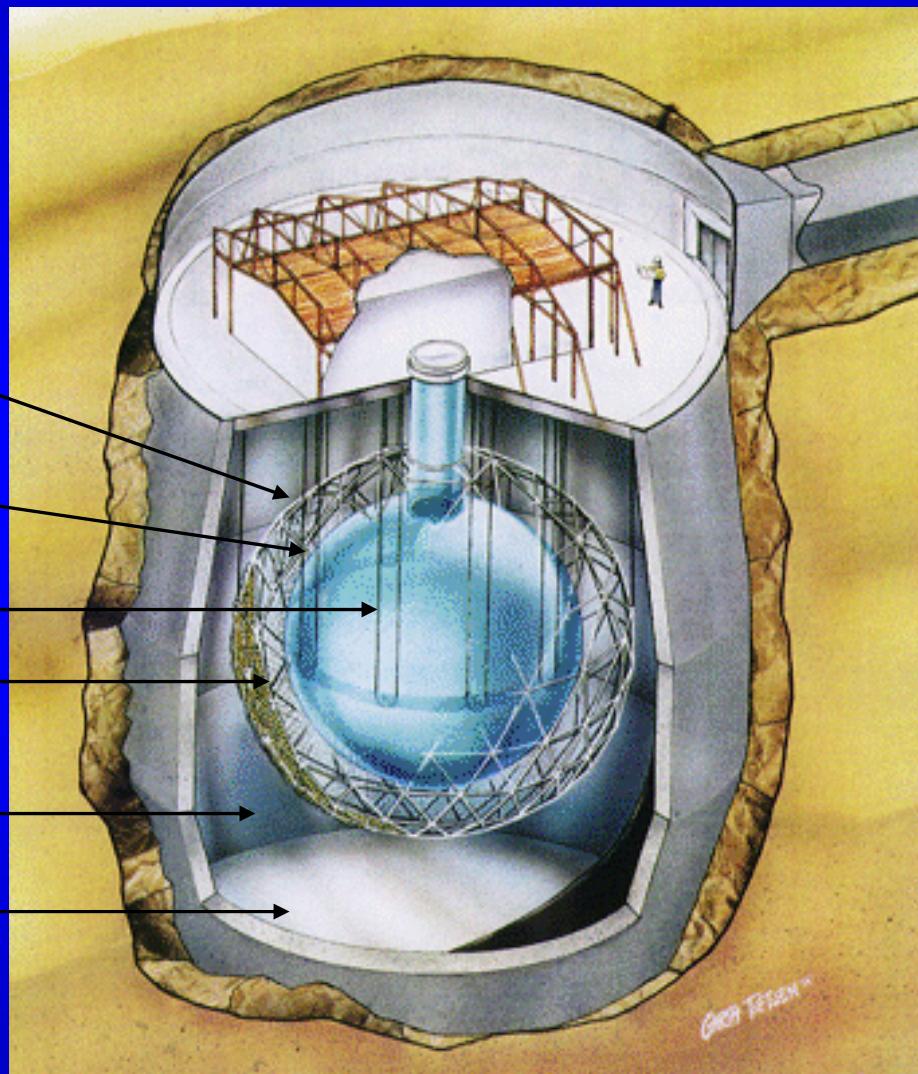
1000 tonnes D₂O

1700 tonnes H₂O, Inner Shield

5300 tonnes H₂O, Outer Shield

Urylon Liner and Radon Seal

Energy Threshold = 5.511 MeV



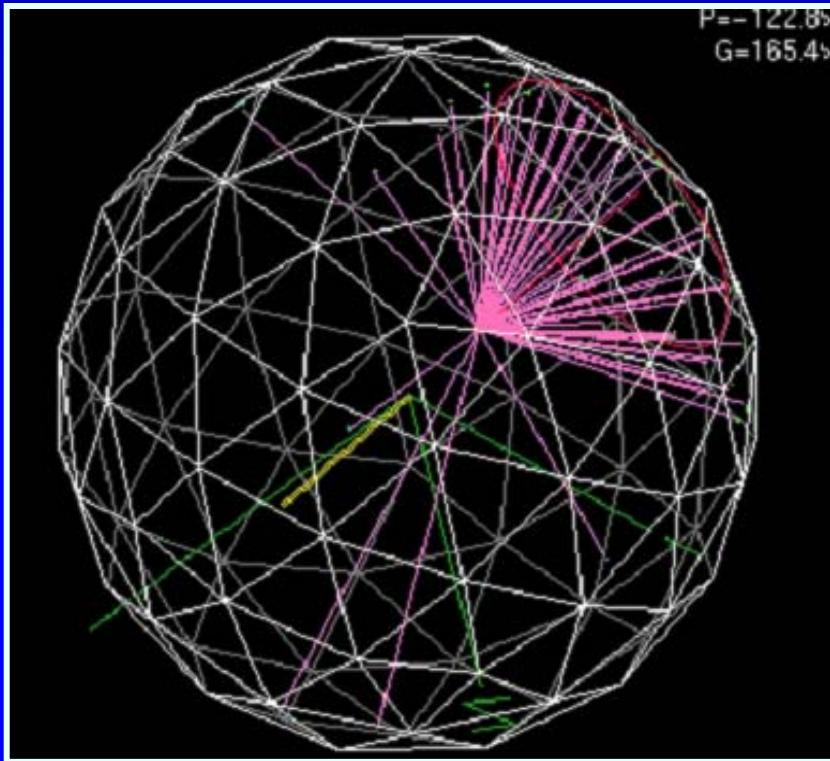
Purpose of SNO

- If Solar Neutrino Problem due to ν_e flavour mixing to ν_μ and/or ν_τ , SNO should provide direct evidence .
- SNO measures flux of ν_e and flux of $(\nu_e + \nu_\mu + \nu_\tau)$.
- Previous expt's sensitive to only ν_e or mainly ν_e .

Water Čerenkov expt's:
Kamiokande, Super-K

Radiochemical expt's:
 ^{37}Cl at Homestake and
 ^{71}Ga at Gran Sasso/Baksan

Solar Neutrino Events in SNO



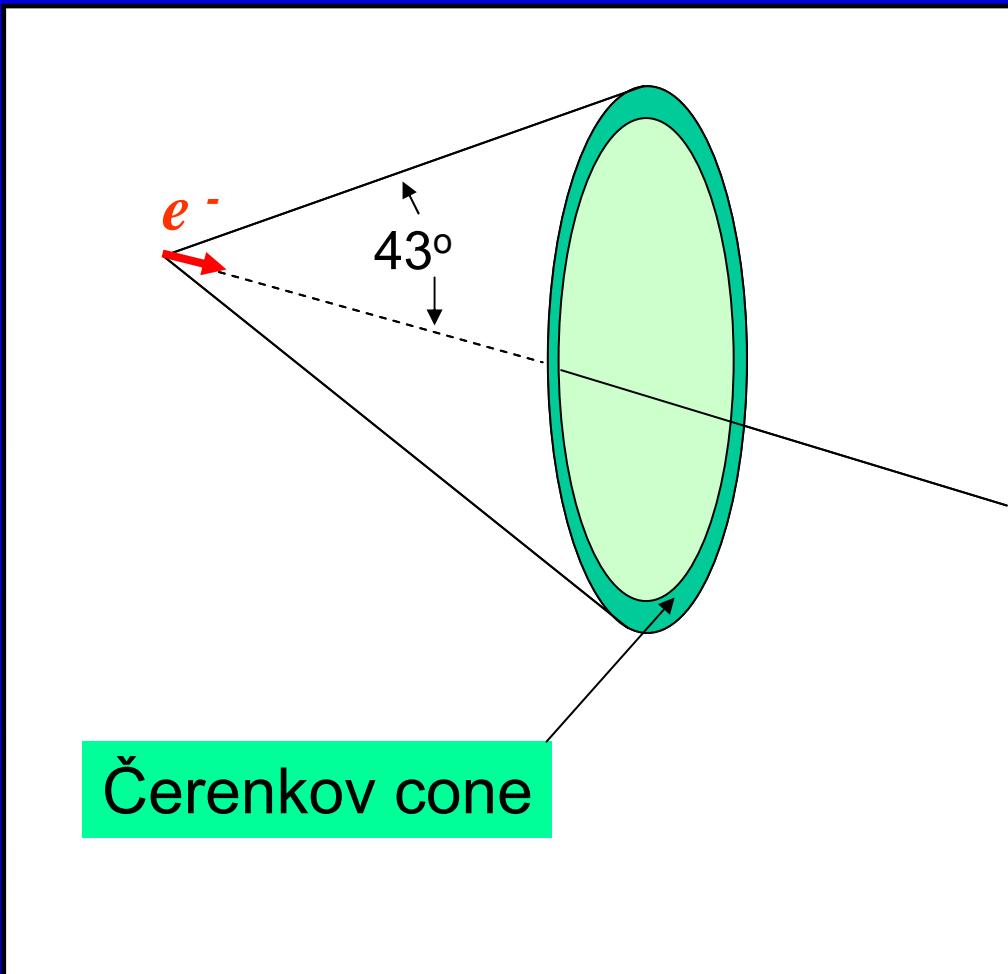
SNO
Heavy Water
Cherenkov Detector

Cherenkov Light

When a particle travels through a medium such that its velocity v is greater than the velocity of light in the medium c/n , radiation is emitted. The radiation is confined to a **CONE** around the direction of the incident particle.

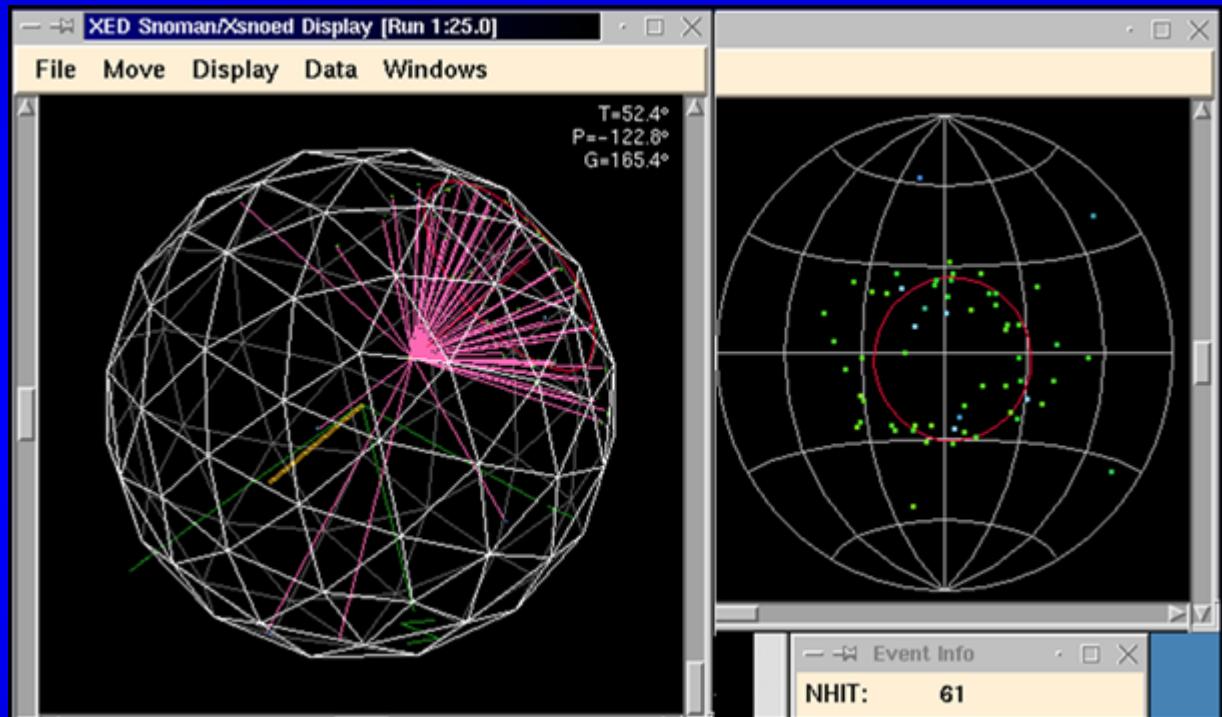
Neutrino detection in SNO

- PMTs detect Čerenkov photons from relativistic e^- :
 - e^- from CC or ES reaction
 - γ from n -capture (NC reaction) usually Compton-scatters e^- (pair production less likely).



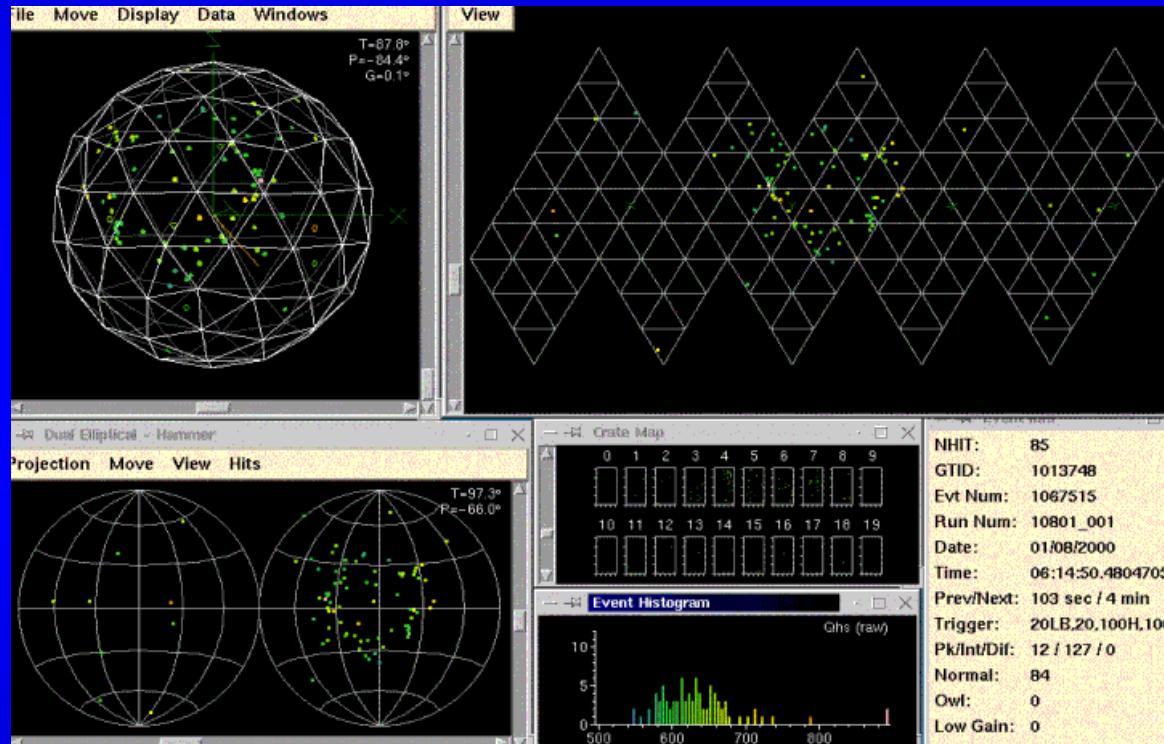
Neutrino detection in SNO

- Hit pattern from Čerenkov cone indicates physics event.
- PMT hit times and locations used to reconstruct e^- direction and location
- Number of PMT hits used to estimate electron energy.



SNO observables - event by event

PMT Information: Positions, Charges, Times

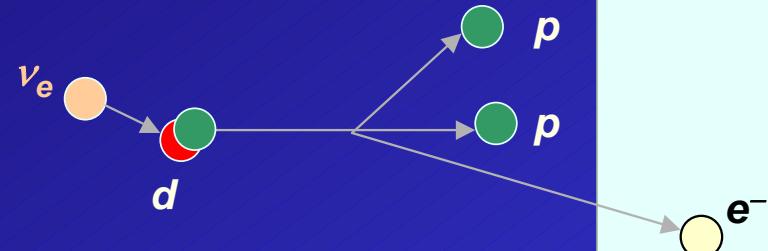


Event Reconstruction
Vertex, Direction, Energy, Isotropy

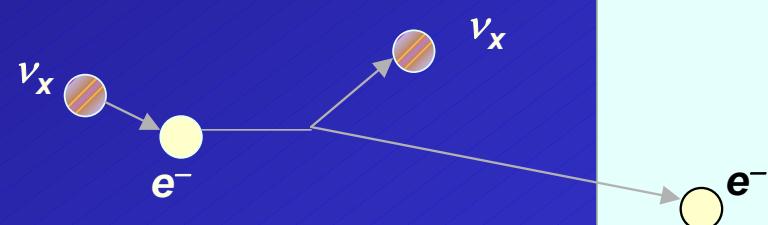
The SNO detector observes the following interactions:



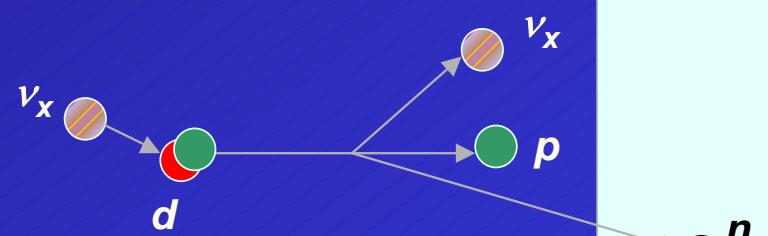
Charged Current



Elastic Scattering



Neutral Current

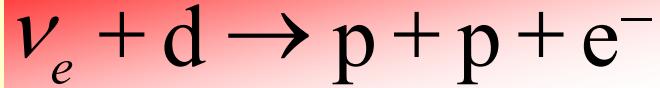


$$x = e, \mu, \tau$$

Detected Particle

Neutrino Reactions in SNO

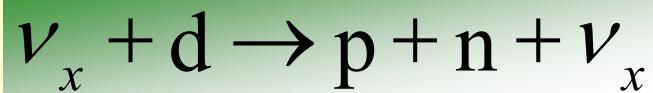
cc



Produces Cherenkov Light Cone in D₂O

- Q = 1.445 MeV
- good measurement of ν_e energy spectrum
- some directional info ∝ (1 – 1/3 cosθ)
- ν_e only

NC



n captures on deuteron
²H or ³⁵Cl or ³He

- Q = 2.22 MeV
- measures total ⁸B ν flux from the Sun
- equal cross section for all ν types

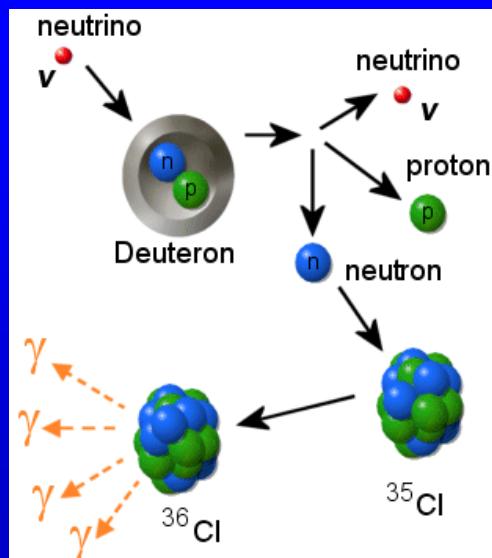
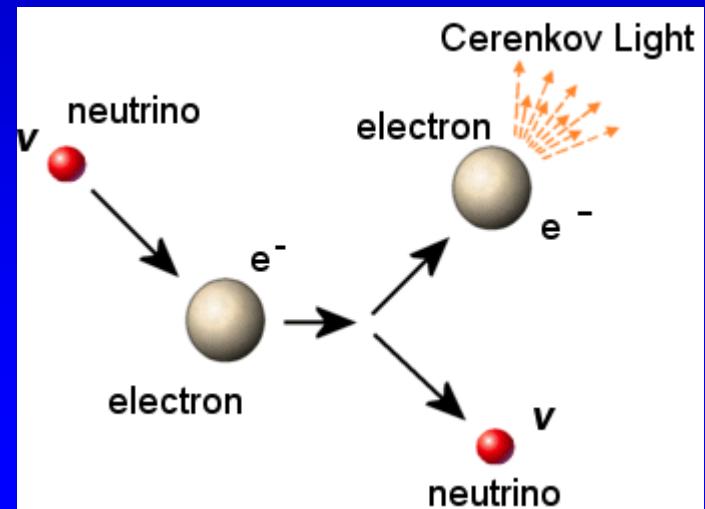
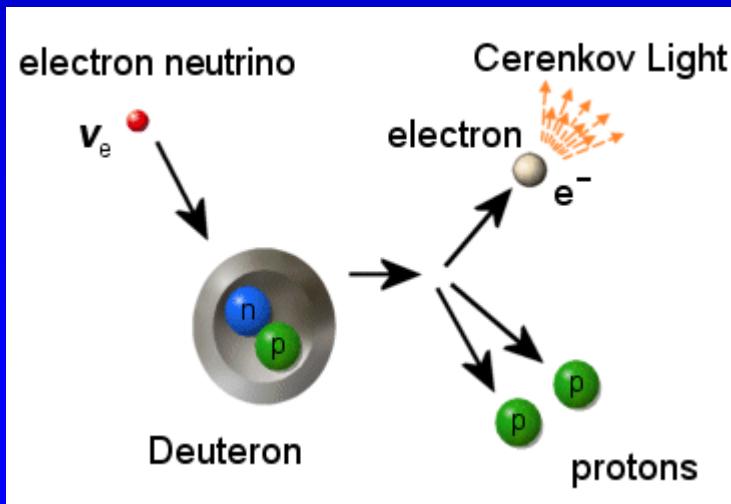
ES



Produces Cherenkov Light Cone in D₂O

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

Heavy water and neutrino interaction in SNO



SNO measures flux of $\phi_{CC} = \nu_e$
and

the total flux $\phi_{NC} = (\nu_e + \nu_\mu + \nu_\tau)$

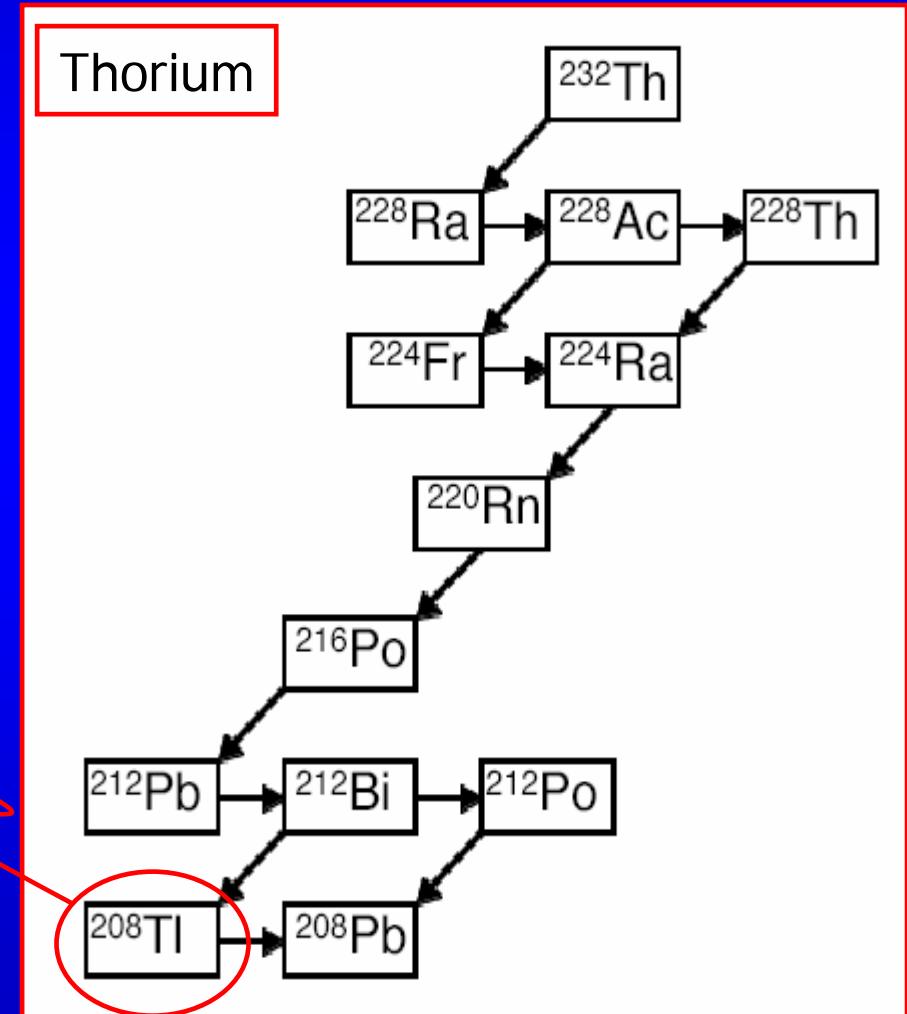
$\phi_{CC} \neq \phi_{NC} \rightarrow \text{oscillation}$

An Ultraclean Environment

- Highly sensitive to any γ above neutral current (2.2 MeV) threshold.

2.615 MeV γ

- Sensitive to ^{238}U & ^{232}Th decay chains

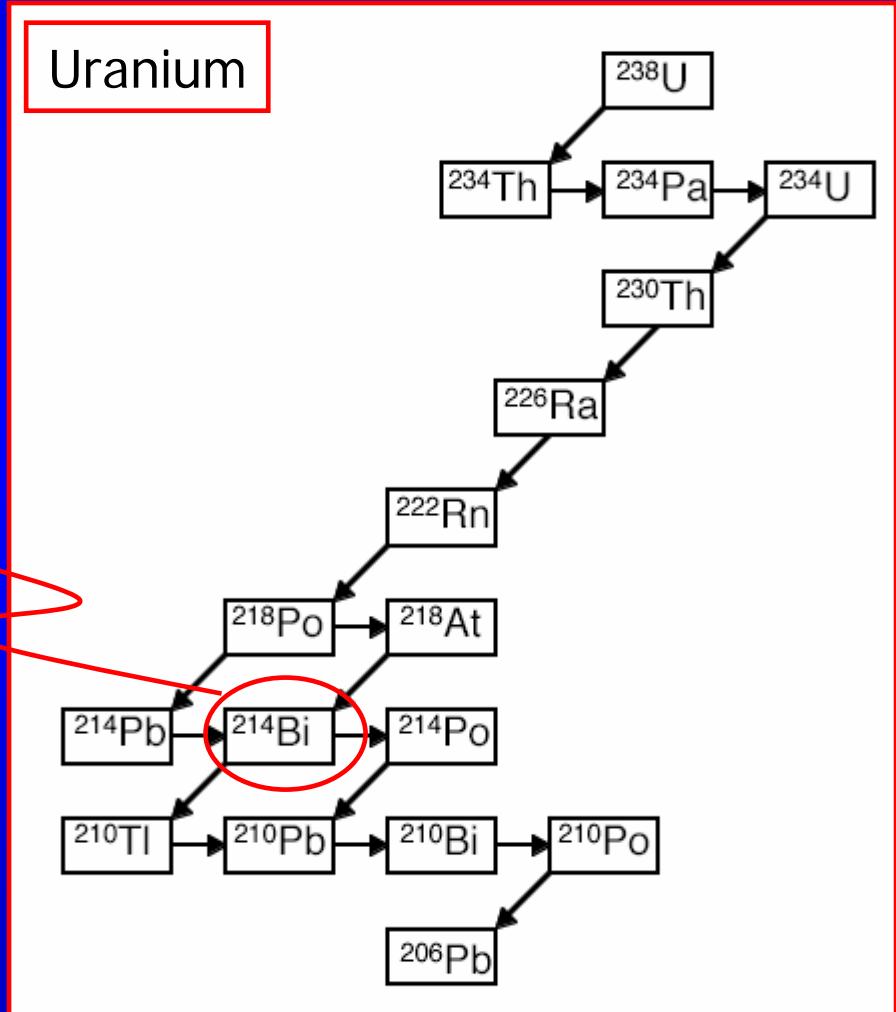


An Ultraclean Environment

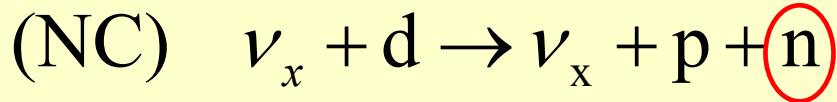
- Highly sensitive to any γ above neutral current (2.2 MeV) threshold.

3.27 MeV β

- Sensitive to ^{238}U & ^{232}Th decay chains



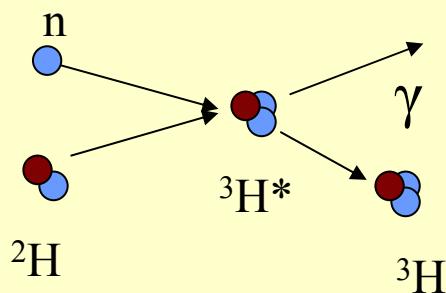
Three Ways to Catch Neutrons!



Pure D₂O

Nov. 99 - May 01

n captures on deuterium
 $\sigma = 0.0005\text{b}$
 6.2 MeV γ



PRL 87, 071301, 2001

PRL 89, 011301, 2002

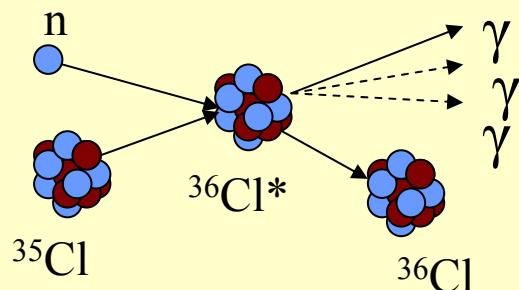
PRL 89, 011302, 2002

Salt

July 01 - Aug. 03

n captures on chlorine
 $\sigma = 44\text{b}$

8.6 MeV multiple γ 's



PRL 92, 181301, 2004

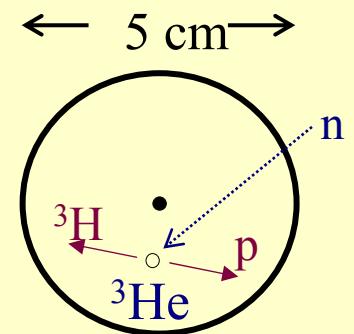
PRC 72, 055502, 2005

³He

Summer 04 - Dec. 06

n captures on ³He in discrete prop. counter array

$\sigma = 5330\text{b}$
 0.764 MeV γ



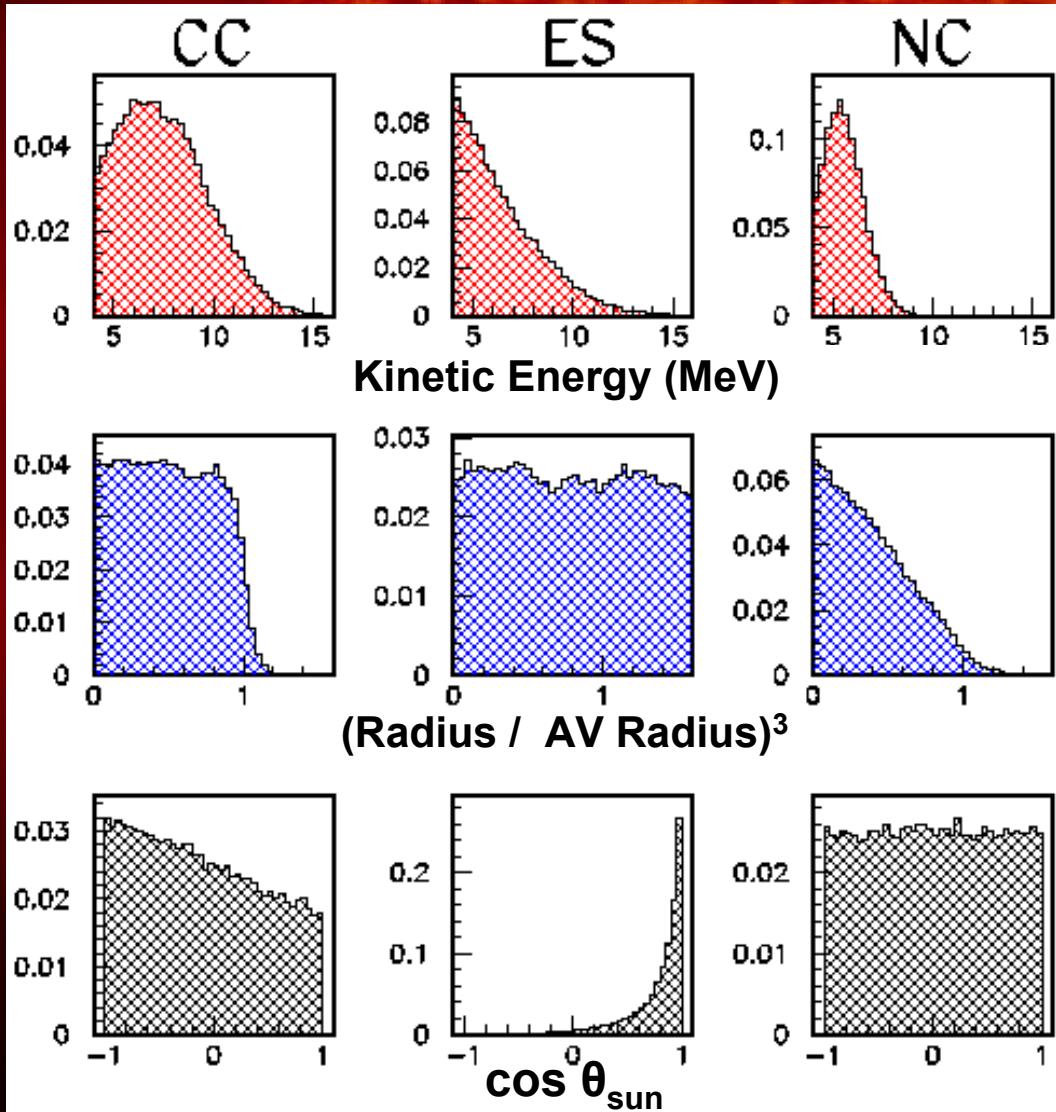
$$n + {}^3\text{He} \rightarrow p + {}^3\text{H}$$



Global View:
SNO Results

Subury Neutrino Observatory D_2O Results (2002)

The limitation and weakness ?!?!?



Used the energy PDF to statistically discriminate CC, ES, and NC

Assume and undistorted energy spectrum

In other words, a FLAT survival probability!!!

Shape Constrained Signal Extraction Results

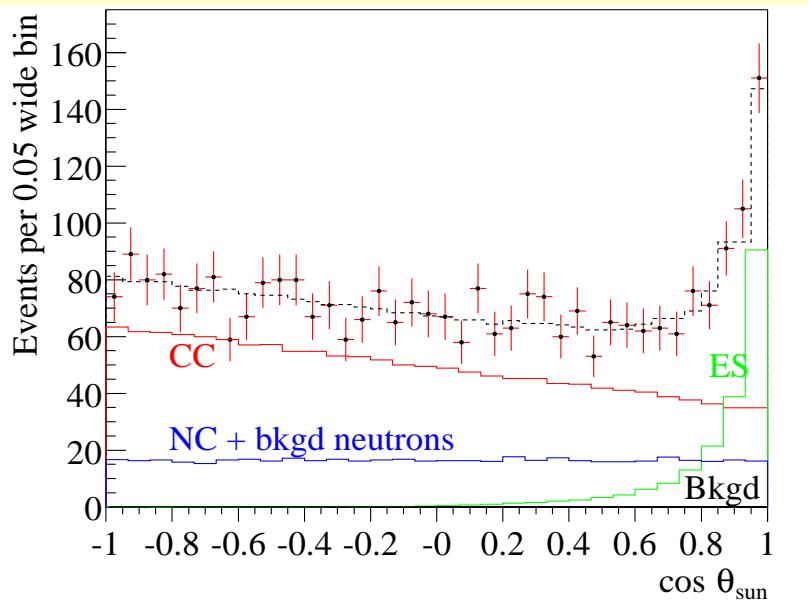
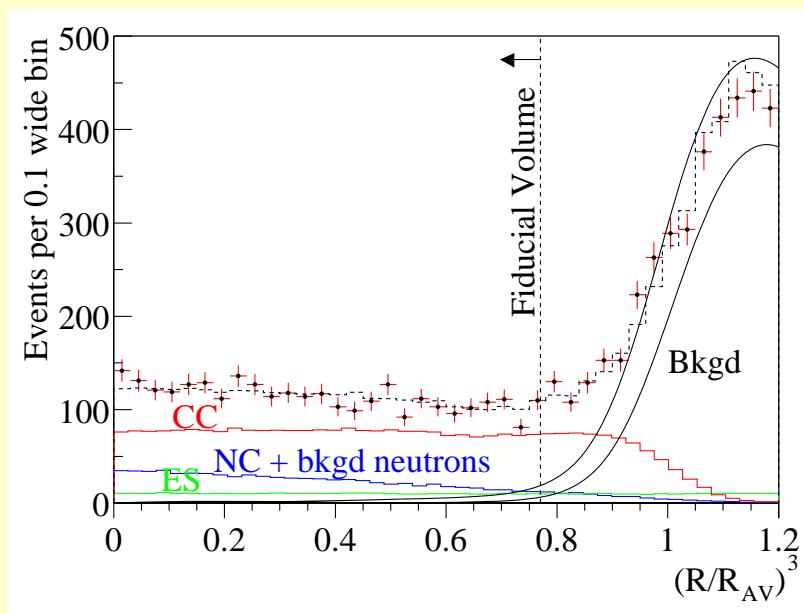
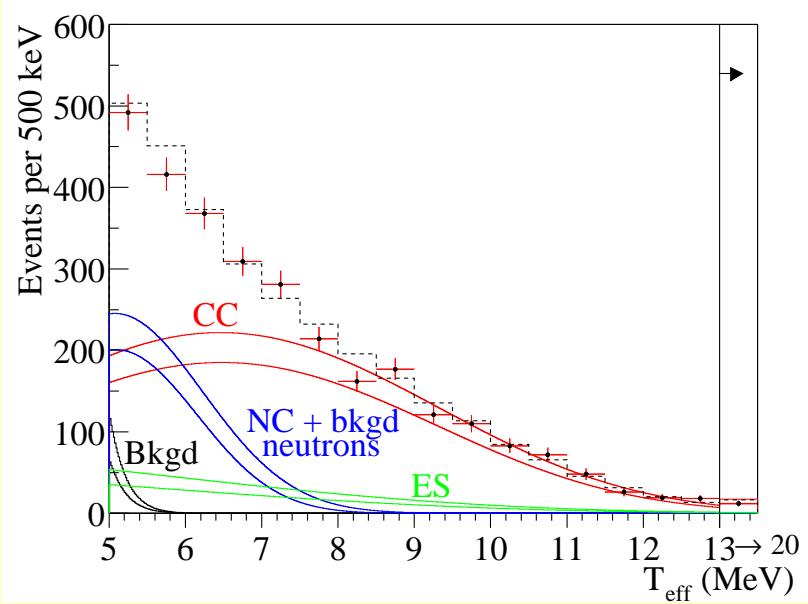
SN
0

#EVENTS

CC **1967.7** $^{+61.9}_{-60.9}$

ES **263.6** $^{+26.4}_{-25.6}$

NC **576.5** $^{+49.5}_{-48.9}$



Shape Constrained Neutrino Fluxes (D_2O)

Signal Extraction in Φ_{CC} , Φ_{NC} , Φ_{ES} with $E_{\text{Threshold}} > 5 \text{ MeV}$

$$\Phi_{cc}(\nu_e) = 1.76^{+0.06}_{-0.05} \text{ (stat.)}^{+0.09}_{-0.09} \text{ (syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39^{+0.24}_{-0.23} \text{ (stat.)}^{+0.12}_{-0.12} \text{ (syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09^{+0.44}_{-0.43} \text{ (stat.)}^{+0.46}_{-0.43} \text{ (syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

Signal Extraction in Φ_e , $\Phi_{\mu\tau}$

$$\Phi_{cc}(\nu_e) = \Phi_e \quad \text{and} \quad \Phi_{nc}(\nu_x) = \Phi_e + \Phi_{\mu\tau}$$

$$\Phi_{es}(\nu_x) = (1 - \varepsilon) \Phi_e + \varepsilon \Phi_{\mu\tau} \quad \text{with } \varepsilon \approx 0.15$$

Shape Constrained Neutrino Fluxes (D_2O)

Signal Extraction in Φ_{CC} , Φ_{NC} , Φ_{ES} with $E_{\text{Threshold}} > 5 \text{ MeV}$

$$\Phi_{cc}(\nu_e) = 1.76^{+0.06}_{-0.05} \text{ (stat.)}^{+0.09}_{-0.09} \text{ (syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39^{+0.24}_{-0.23} \text{ (stat.)}^{+0.12}_{-0.12} \text{ (syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09^{+0.44}_{-0.43} \text{ (stat.)}^{+0.46}_{-0.43} \text{ (syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

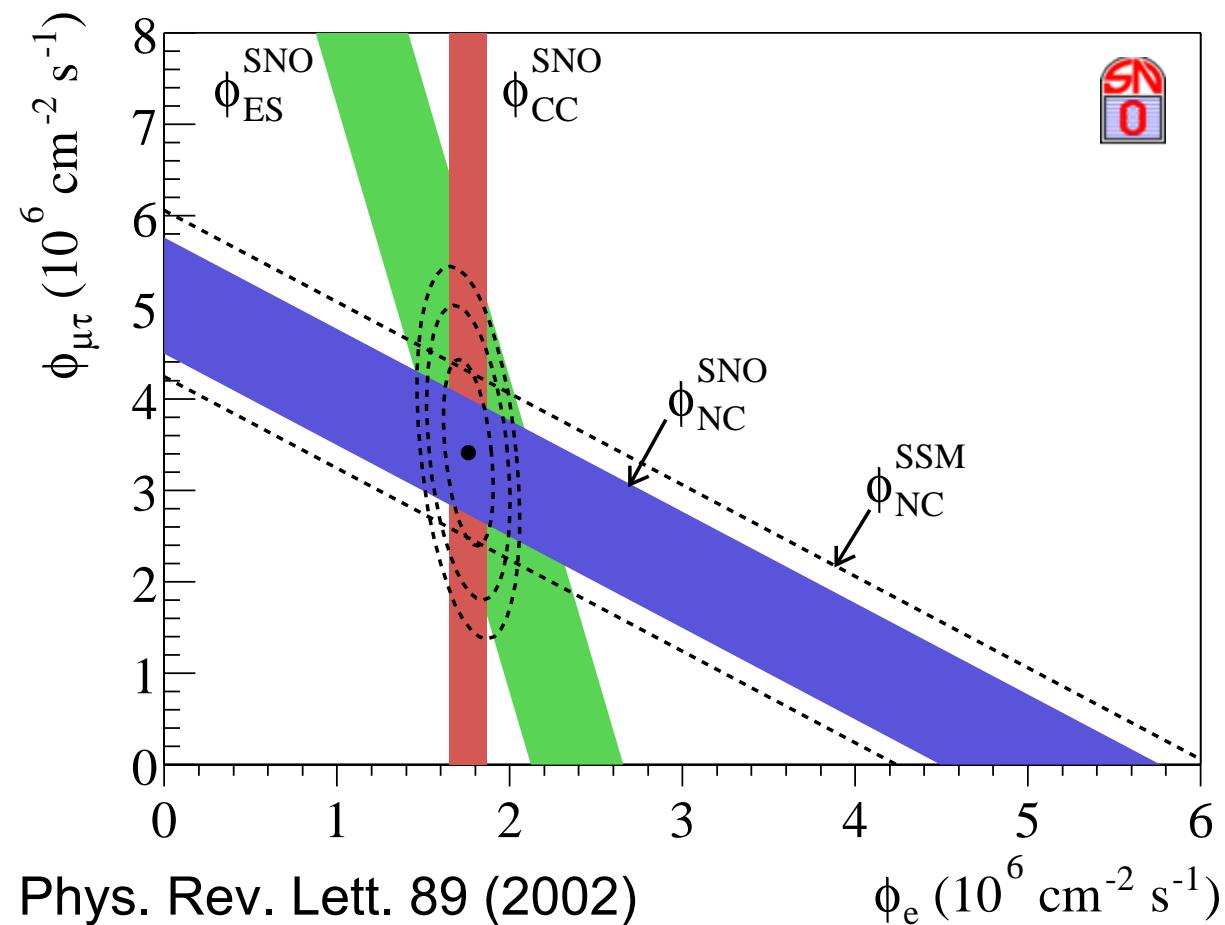
Signal Extraction in Φ_e , $\Phi_{\mu\tau}$

$$\Phi_e = 1.76^{+0.05}_{-0.05} \text{ (stat.)}^{+0.09}_{-0.09} \text{ (syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45} \text{ (stat.)}^{+0.48}_{-0.45} \text{ (syst.)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

SNO NC in D₂O (April 2002)

~ 2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$



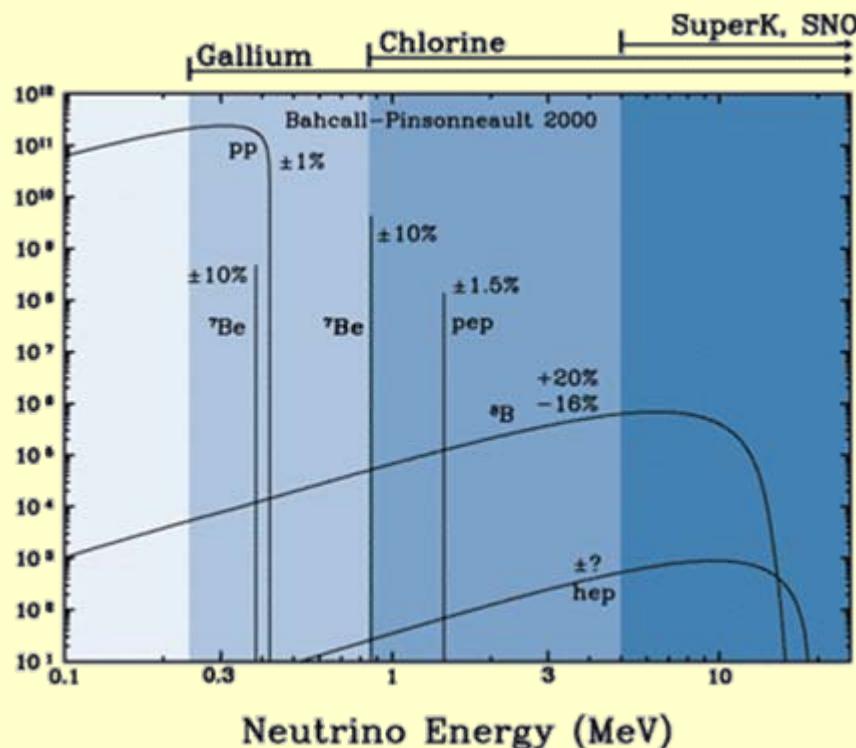
Flavor change
at 5.3 σ level.

Sum of all the
fluxes agrees
with SSM.

$$\Phi_{SSM} = 5.05^{+1.01}_{-0.81} \quad 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

$$\Phi_{SNO} = 5.09^{+0.44}_{-0.43} \quad 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

The Solar Neutrino Problem

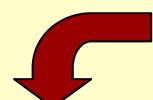


Experiment

Exp/SSM

- SAGE+GALLEX/GNO 0.55
- Homestake 0.34
- Kamiokande+SuperK 0.47
- SNO CC (June 2001) 0.35

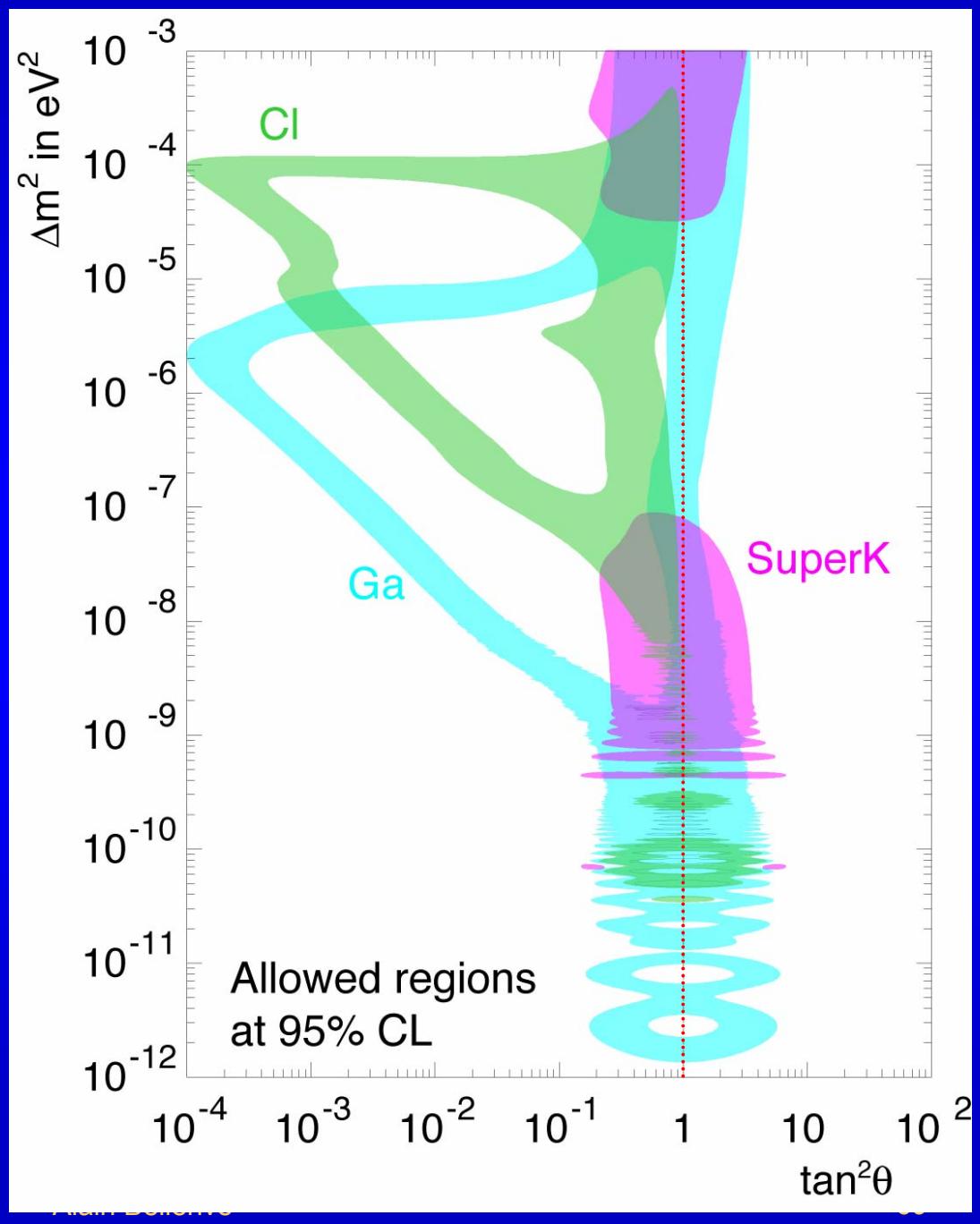
SNO NC (April 2002) 1.01



SNO CC vs NC implies flavor change, which can then explain other experimental results.

Progress in 2002 on the Solar Neutrino Problem

March 2002

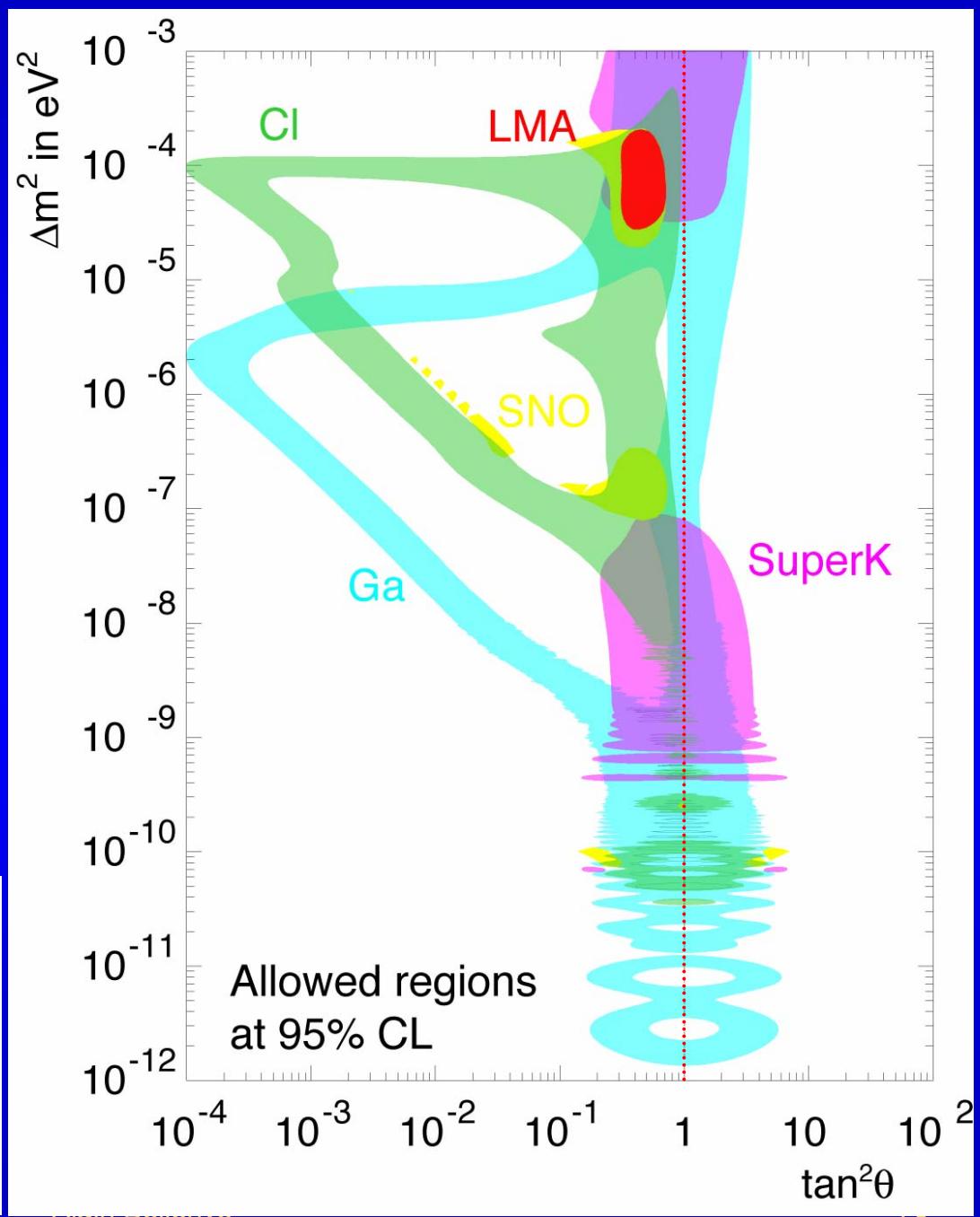
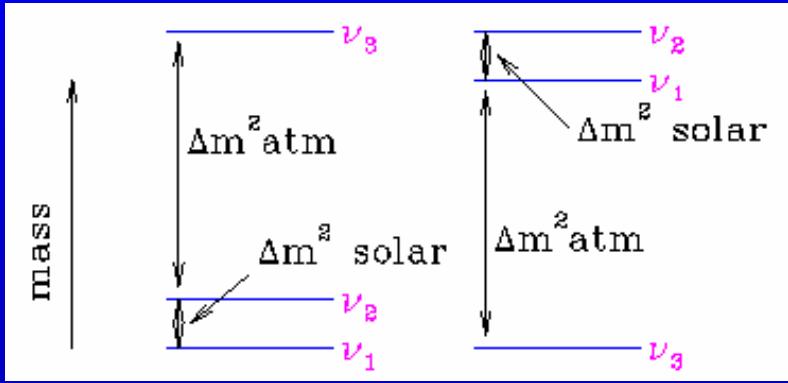


Progress in 2002 on the Solar Neutrino Problem

March 2002

April 2002
with SNO

LMA=Large Mixing Angle



Neutrino Mixing (detail)

As in the quark sector one defines a neutrino mixing matrix which relates the mass and weak eigenstates

Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Quark:	$\theta_{12} \approx \pi/14$	$\theta_{23} \approx \pi/76$	yes	$\theta_{13} \approx \pi/870$
Neutrino:	$\theta_{12} \approx \pi/6$	$\theta_{23} \approx \pi/4$???	$\theta_{13} < \pi/20$

solar atmospheric CP violation short-baseline

$$U_{\alpha i} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

where $c_{ij} = \cos \theta_{ij}$, and $s_{ij} = \sin \theta_{ij}$



The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"



Raymond Davis Jr.



Masatoshi Koshiba

The work of Davis and Koshiba has led to unexpected discoveries and a new, intensive field of research, *neutrino-astronomy*.

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"



Riccardo Giacconi

Giacconi constructed the first X-ray telescopes, which have provided us with completely new – and sharp – images of the universe.

Subury Neutrino Observatory

Salt Results (391 days)



PRC 72,055502, 2005

Flux results from fits

Units for ϕ are $10^6 \text{ cm}^{-2} \text{ s}^{-1}$

$$\phi_{\text{CC}} = 1.68^{+0.06}_{-0.06}(\text{stat})^{+0.08}_{-0.09}(\text{syst})$$

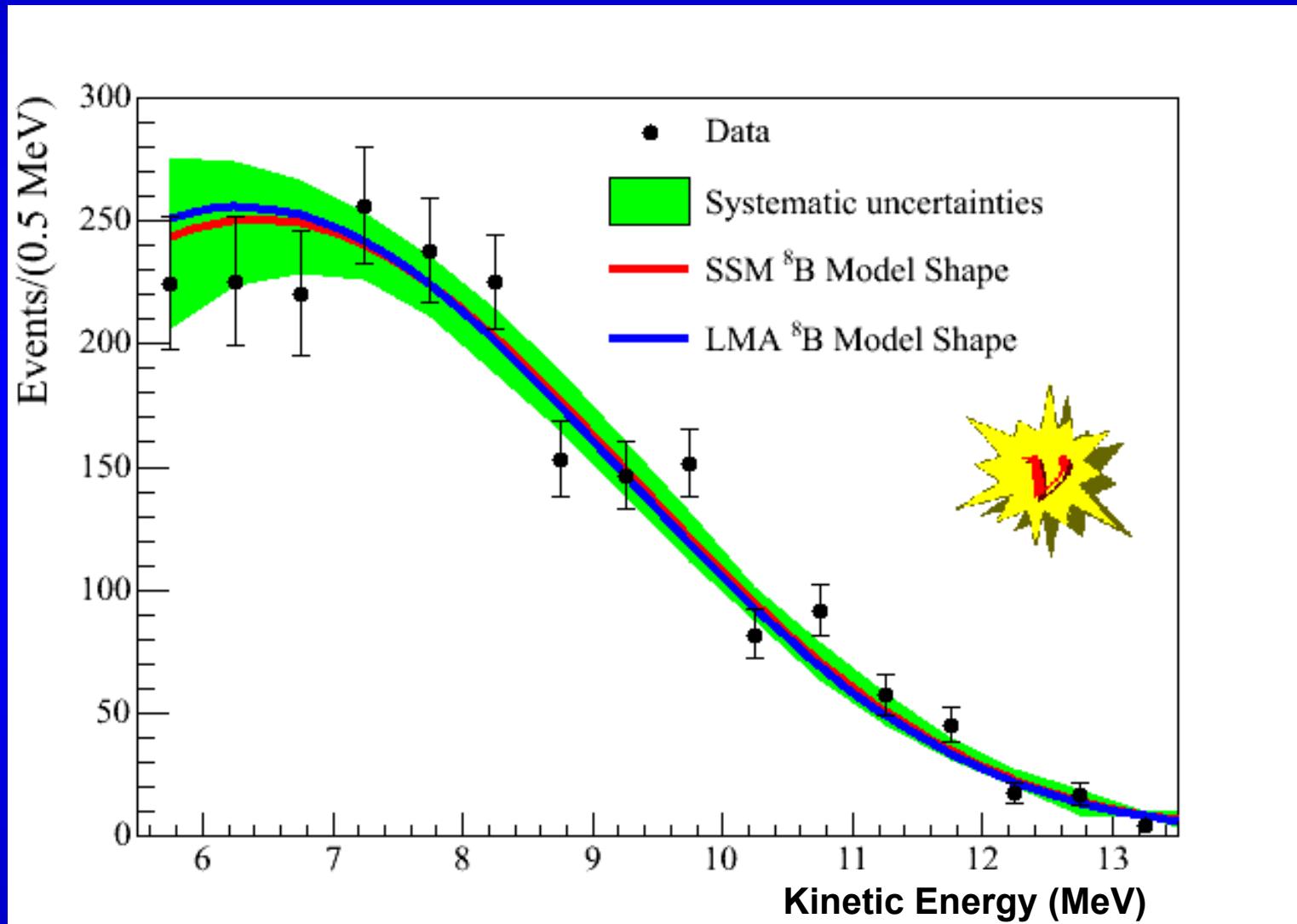
$$\phi_{\text{ES}} = 2.35^{+0.22}_{-0.22}(\text{stat})^{+0.15}_{-0.15}(\text{syst})$$

$$\phi_{\text{NC}} = 4.94^{+0.21}_{-0.21}(\text{stat})^{+0.38}_{-0.34}(\text{syst})$$

Standard Solar Model
(Bahcall, Pinsonneault 2004)

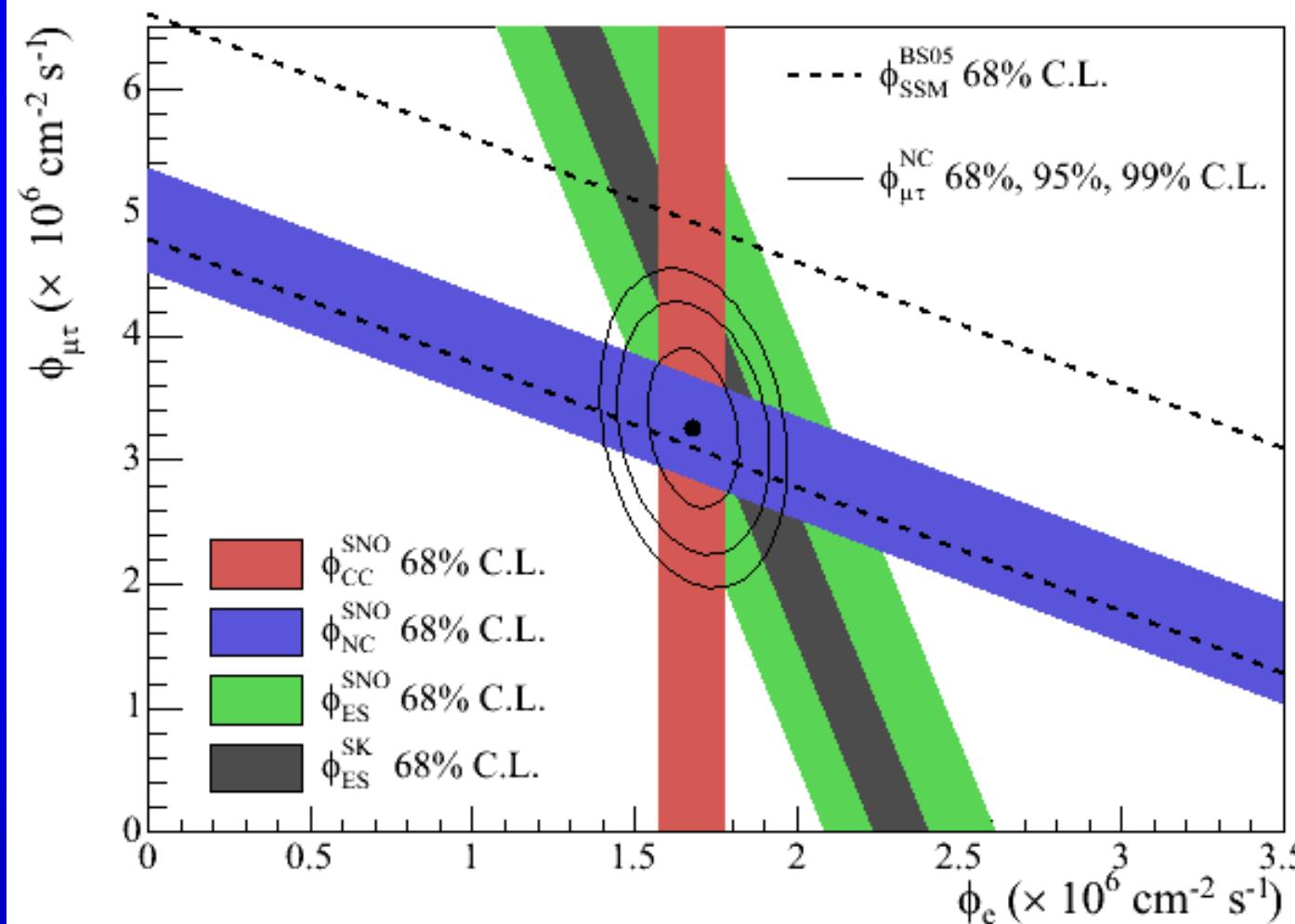
$$\phi_{\text{BP04}} = 5.79 \pm 1.33$$

Charged Current (CC= ν_e) Spectrum



SNO: Salt results and comparison to SSM

More precise salt results
confirm D₂O results



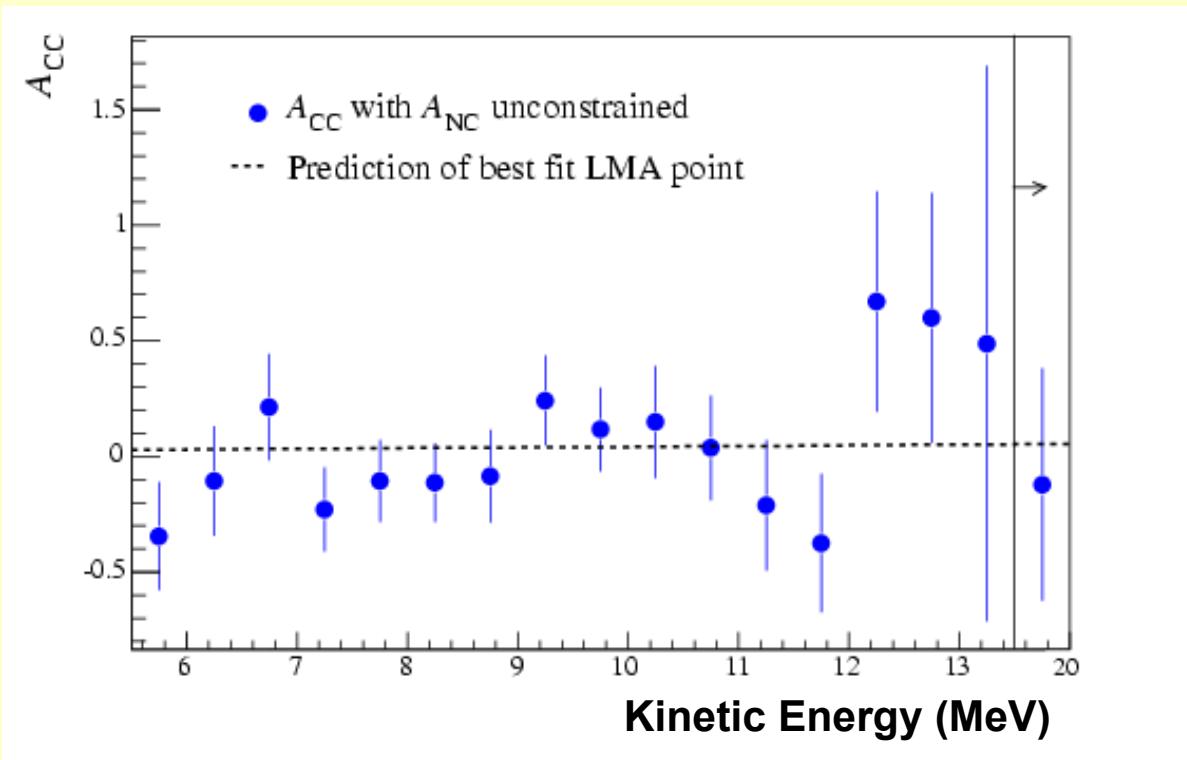
Day/Night Asymmetries

$$A_X = \frac{(\Phi_{\text{night}} - \Phi_{\text{day}})}{(\Phi_{\text{night}} + \Phi_{\text{day}})/2}$$

$$A_{CC} = -0.056 \pm 0.074 \text{ (stat.)} \pm 0.051 \text{ (syst.)}$$

$$A_{NC} = 0.042 \pm 0.086 \text{ (stat.)} \pm 0.067 \text{ (syst.)}$$

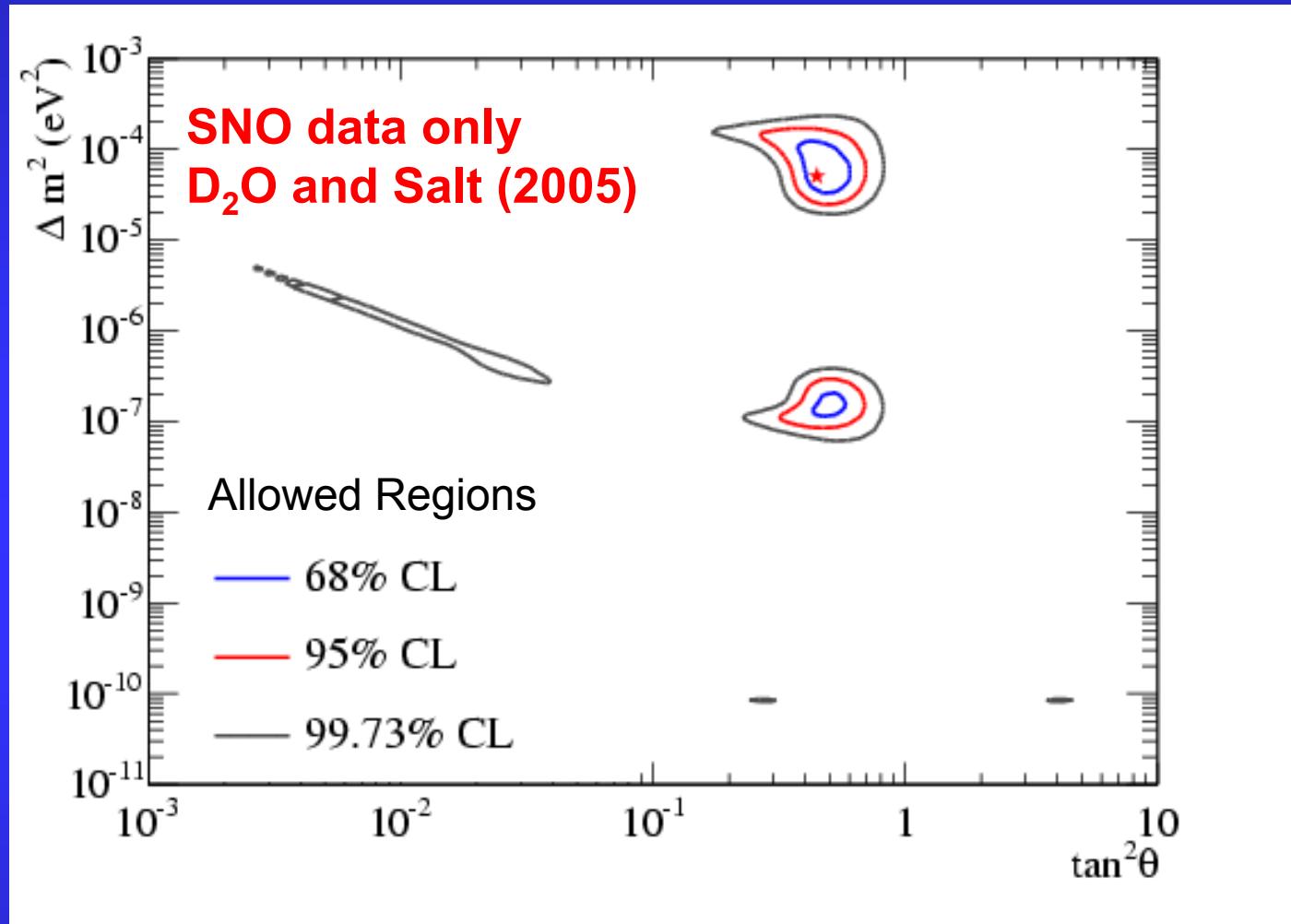
$$A_{ES} = 0.146 \pm 0.198 \text{ (stat.)} \pm 0.032 \text{ (syst.)}$$



A_{CC} and A_{NC} are correlated ($\rho = -0.532$)

In standard neutrino oscillations, A_{NC} should be zero...

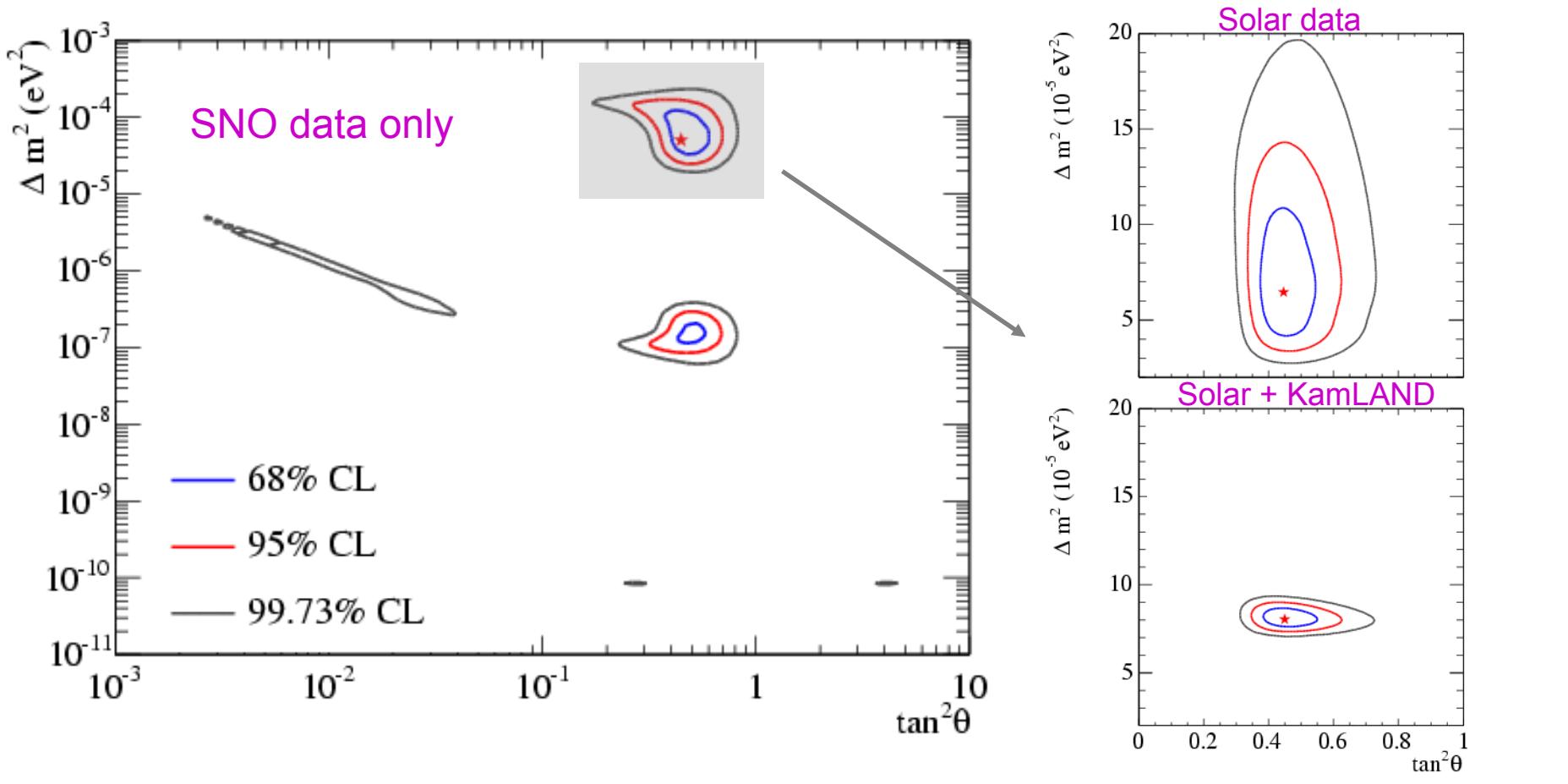
Solar neutrino oscillation parameters



Ratio of CC/NC fluxes gives $P(\nu_e \rightarrow \nu_e)$

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

SNO: Results Phase II: neutrino oscillation parameters



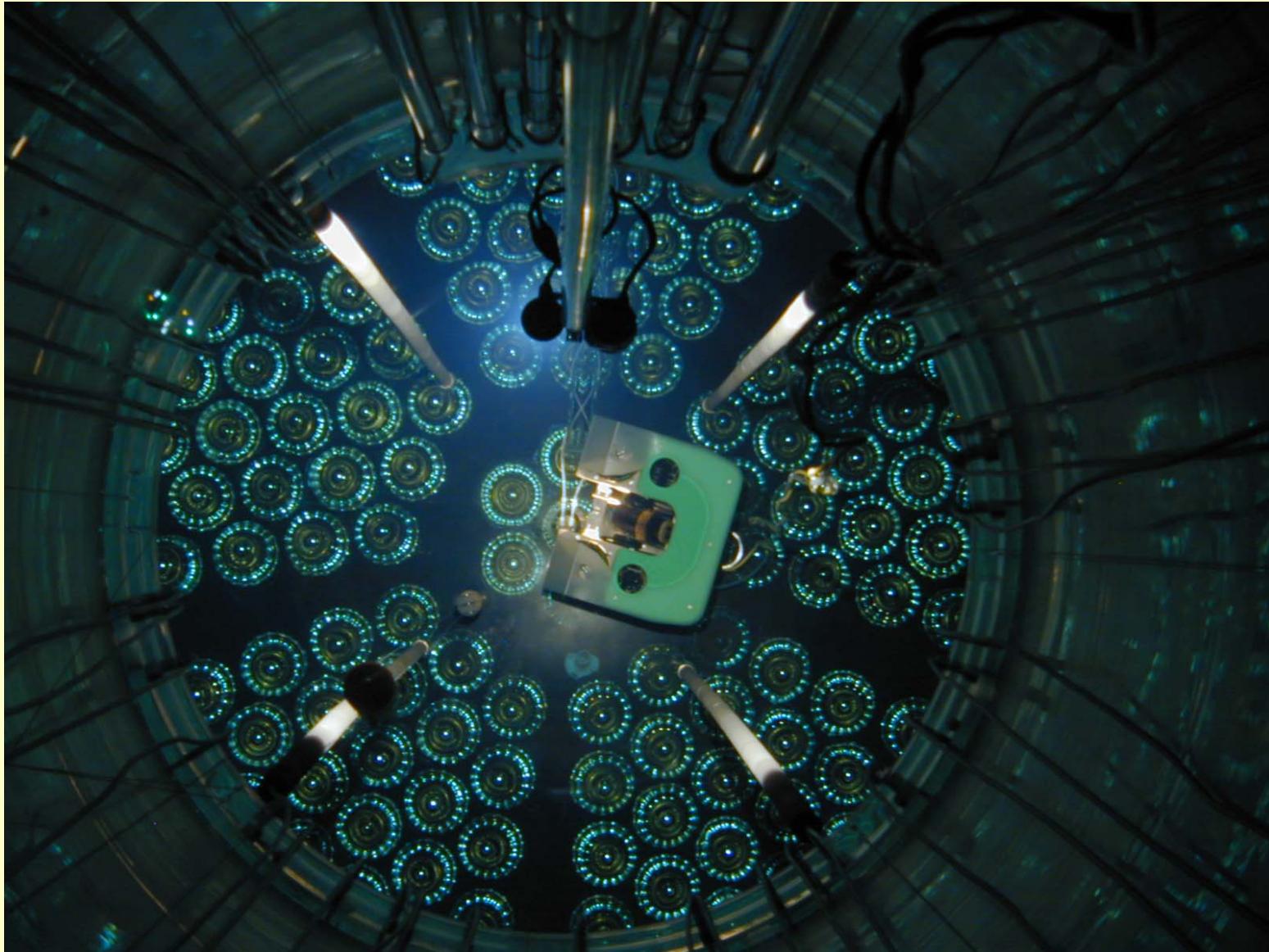
Ratio of CC/NC fluxes gives $P(\nu_e \rightarrow \nu_e)$

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Subury Neutrino Observatory

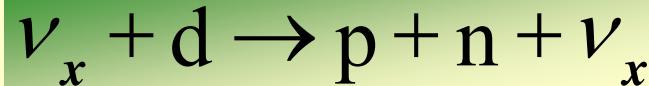
NCD Phase

NCD Deployment



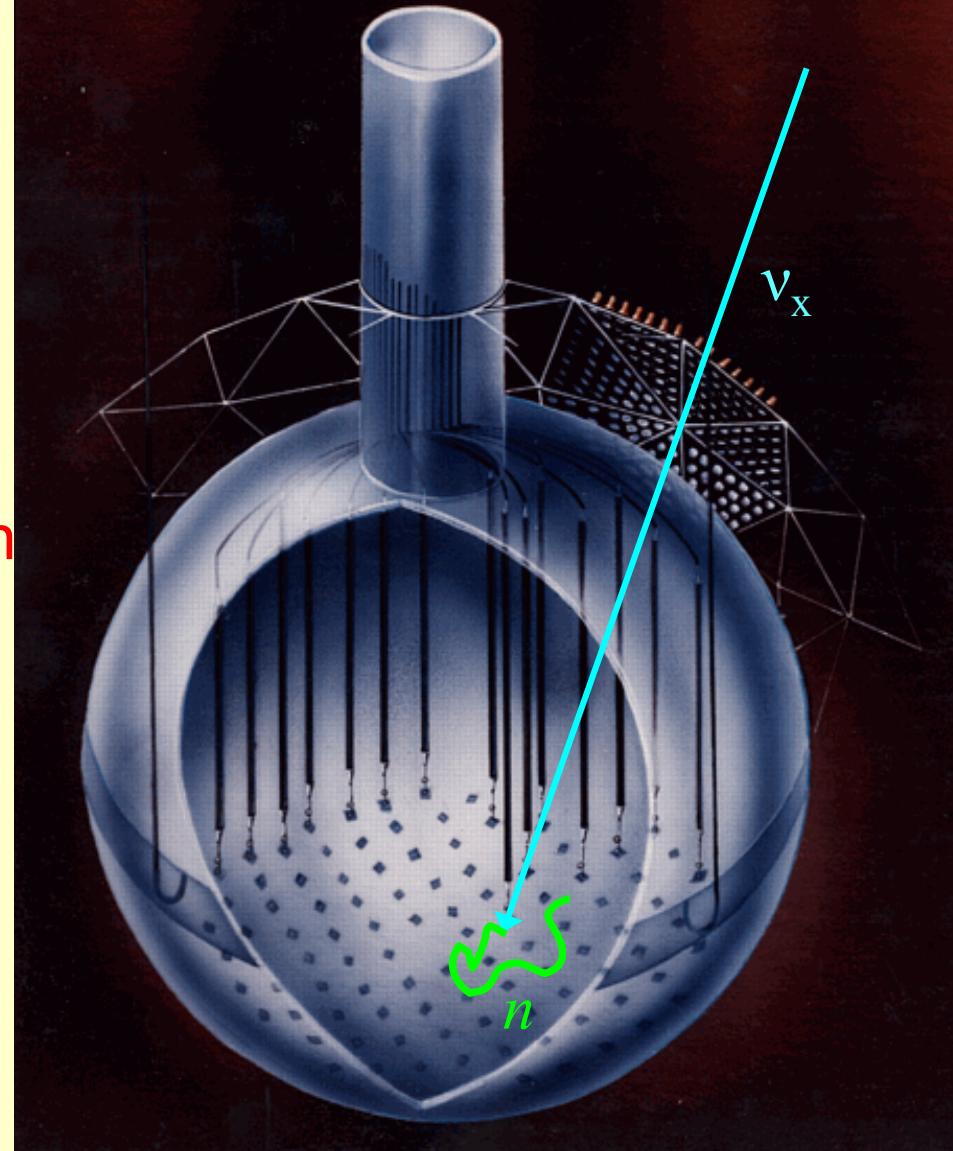
SNO at Present

NC

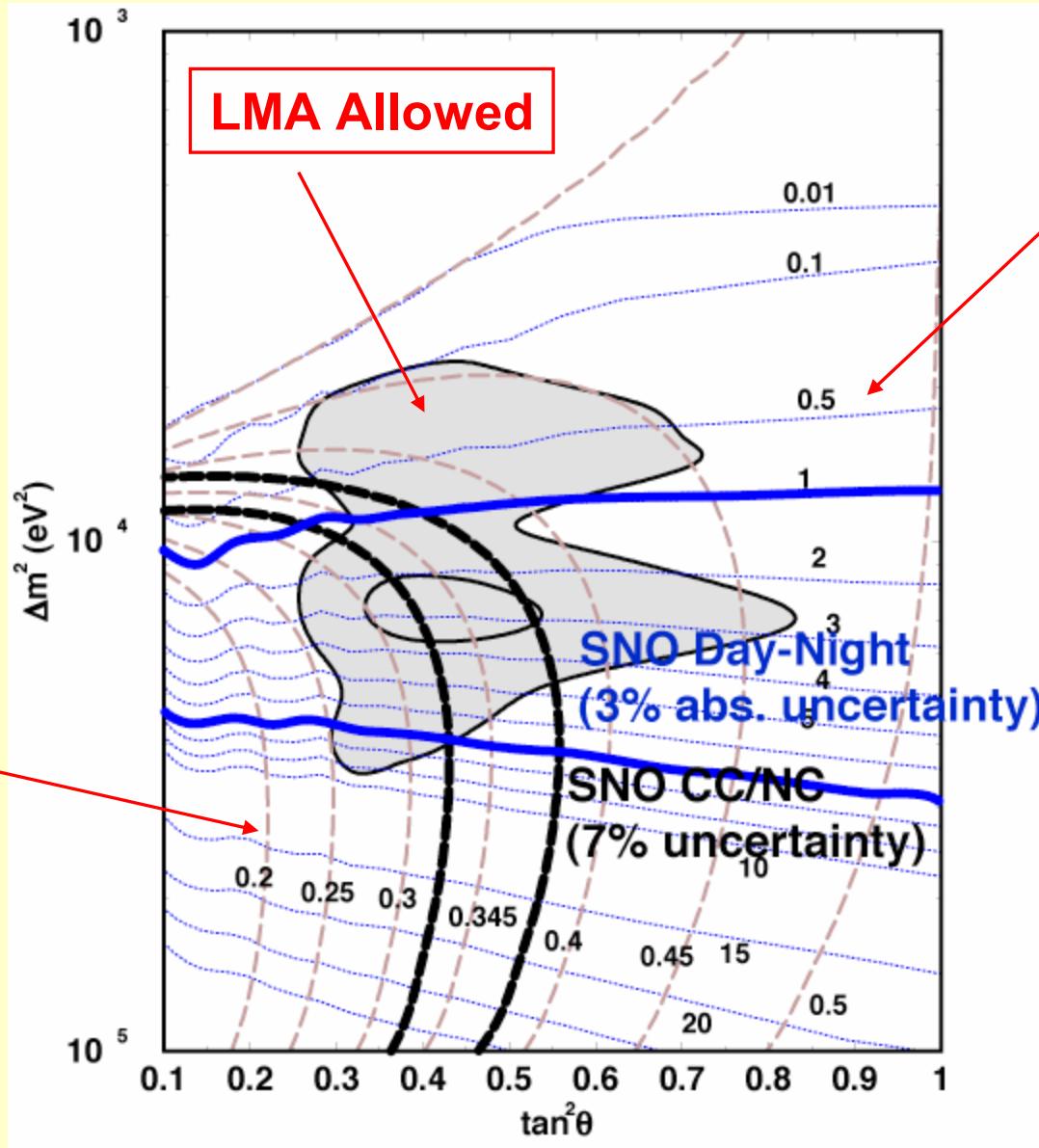


- Event by event separation
- Break the correlation between NC & CC events
- Measure in separate data streams NC & CC events
- Different systematic errors than neutron capture on NaCl
- Taking data until end of 2006

Neutral Current Detectors



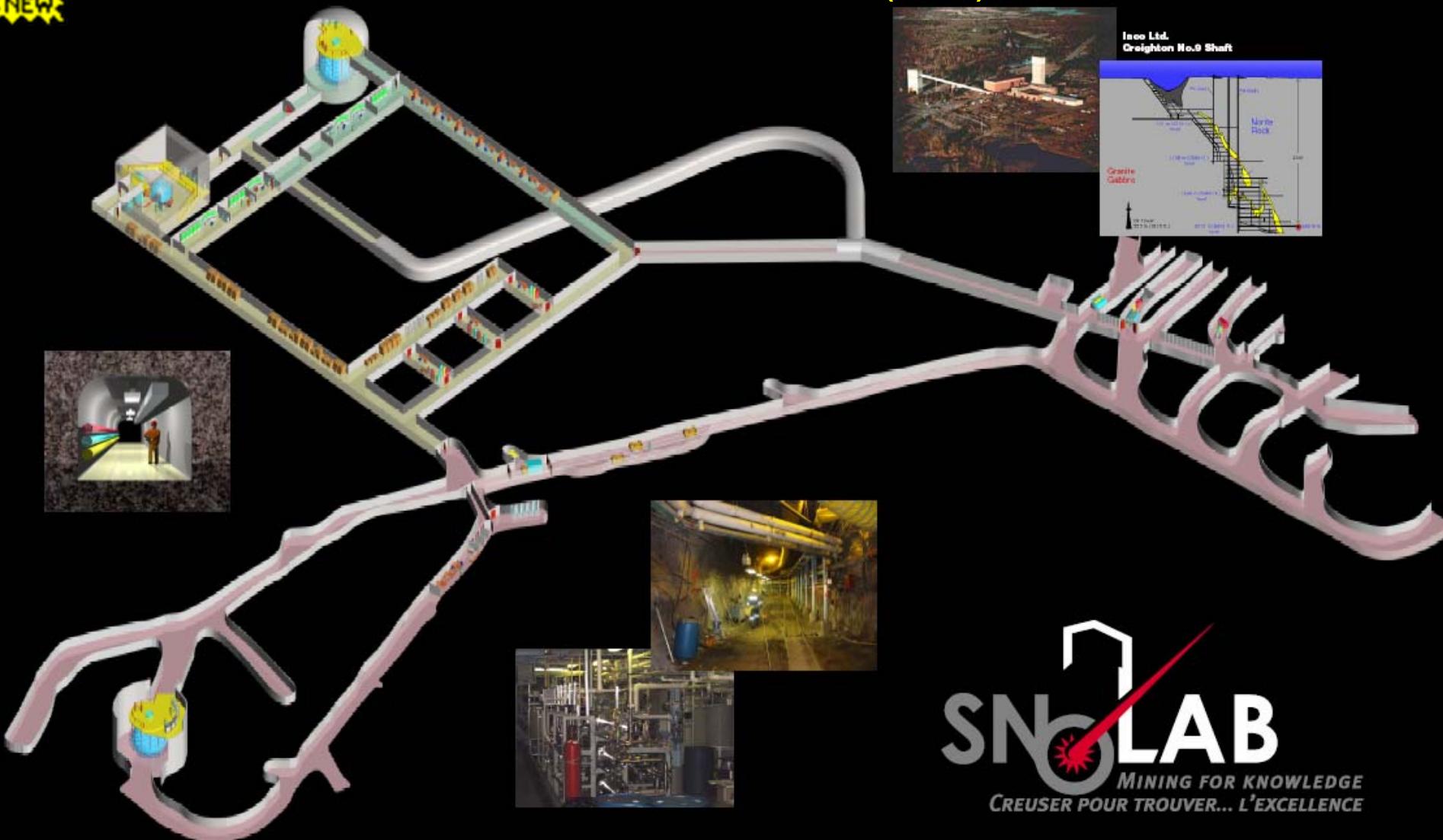
What SNO might tell us in the future...



hep-ph/0212270
hep-ph/0204253

NEW

Canadian Foundation for Innovation (CFI) 50 M\$ Investment



Deep: 2092 m underground \Rightarrow 85 $\mu\text{m}^2/\text{y}$



Outreach

Scientific Program of SNOLAB

- **Low Energy Neutrinos**
 - Sudbury Neutrino Observatory (SNO)
 - SNO++ (upgrade with liquid scintillator)
- **Search for Cold Dark Matter**
 - Picasso
 - DEAP
 - SuperCDMS
- **Investigation of Double-Beta Decay**
 - Majorana
 - Enriched Xenon Observatory (EXO)

Summary

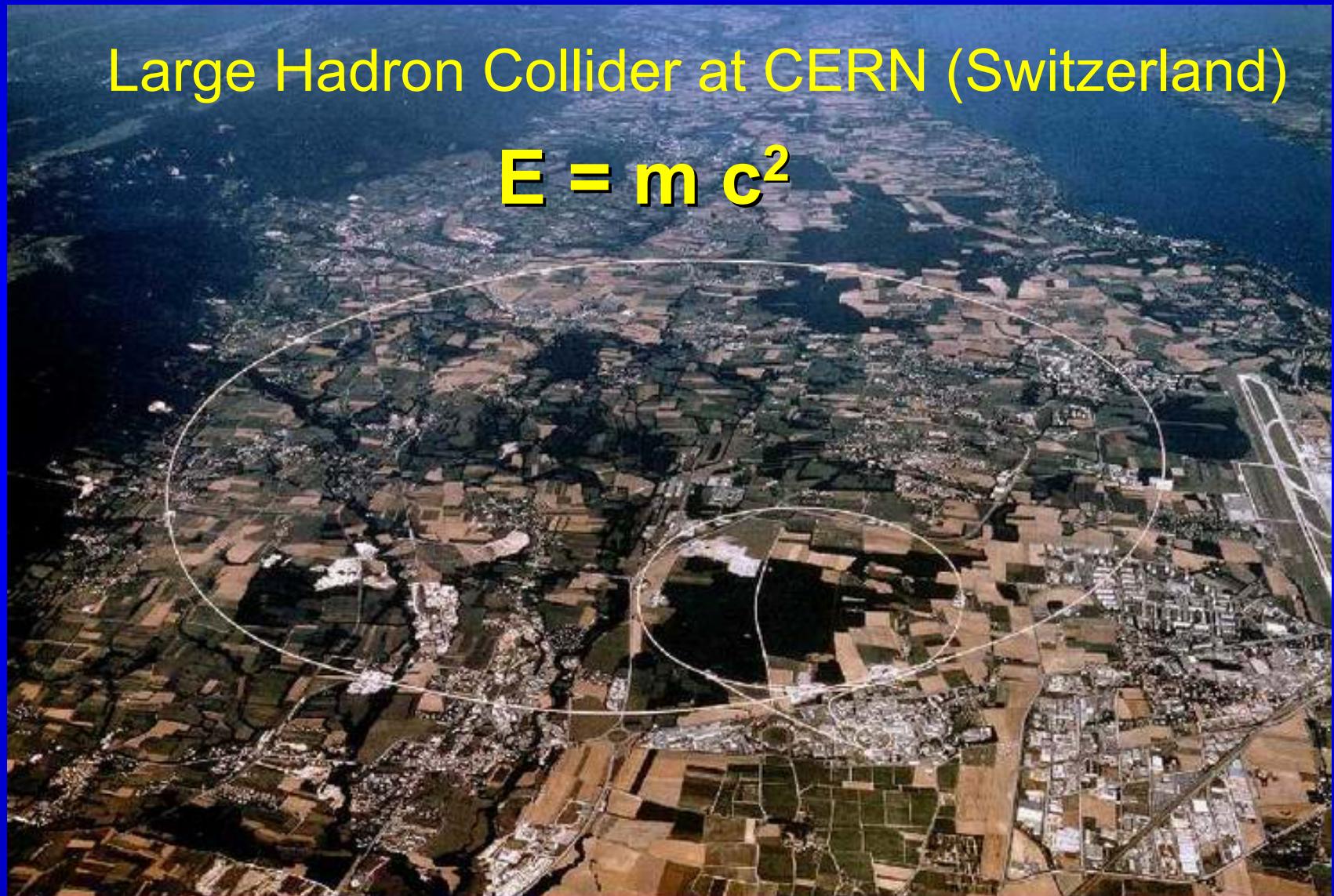
- SNO provided direct evidence of flavor conversion of solar ν_e 's – Neutrino is a massive particle !!!
- Matter Effect explains the energy dependence of solar oscillation
- Large mixing angle (LMA) solutions are favored
- Solar Neutrino Problem is now an industry for precise measurements of neutrino oscillation parameters – SNO (d₂O+salt+NCD) ultimate probe

Les grandes questions du 21^{ème} siècle en astrophysique des particules

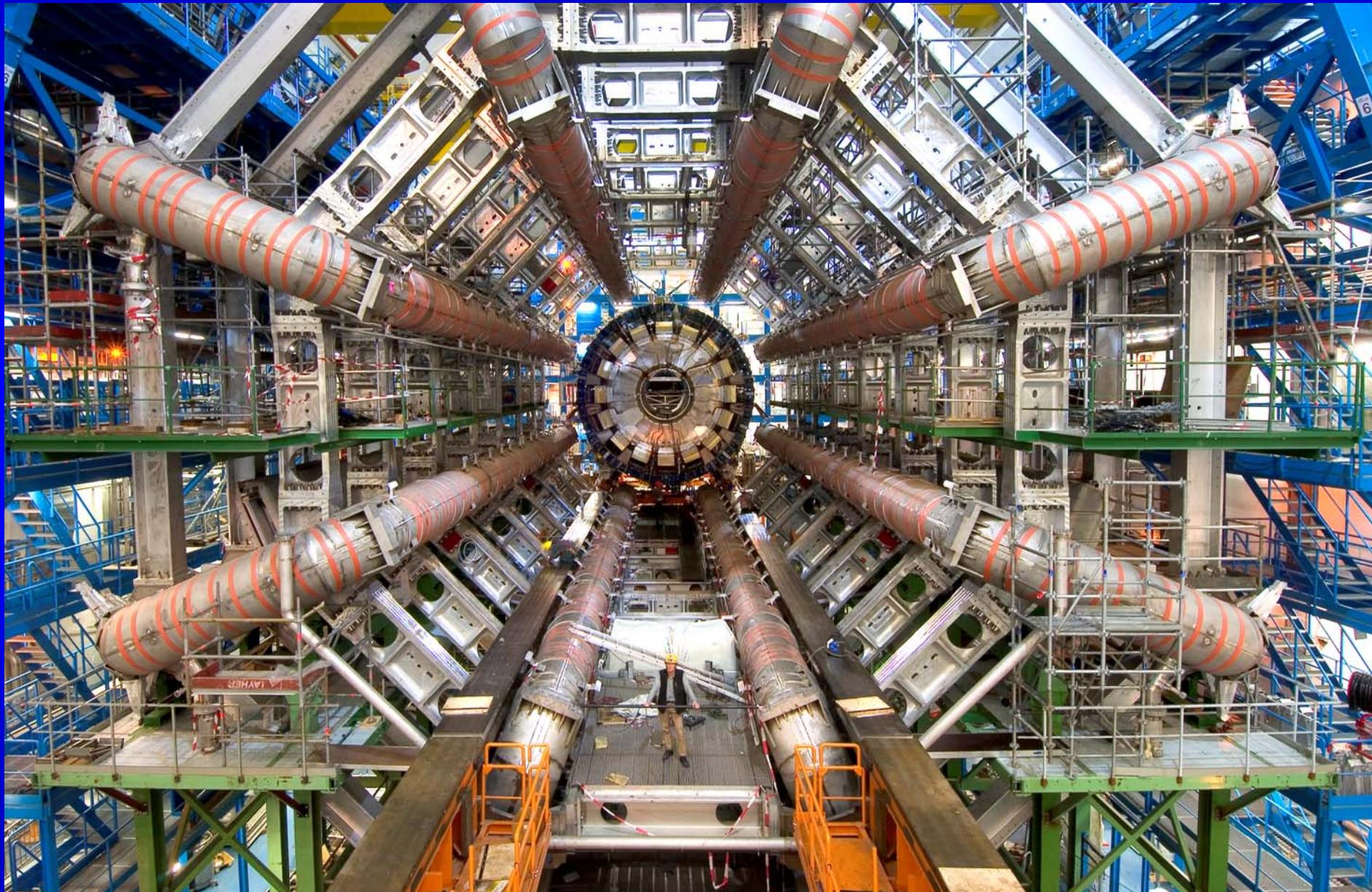
- *Comment les particules acquièrent-elles leur masse ?*
- *Qu'est-ce que la masse manquante de l'univers ?*
- *Pourquoi la matière domine-t-elle l'antimatière ?*
- *Comment la matière a-t-elle évolué juste après le big bang ?*

Quelle sont les implications des neutrinos massifs sur notre description de l'univers !?

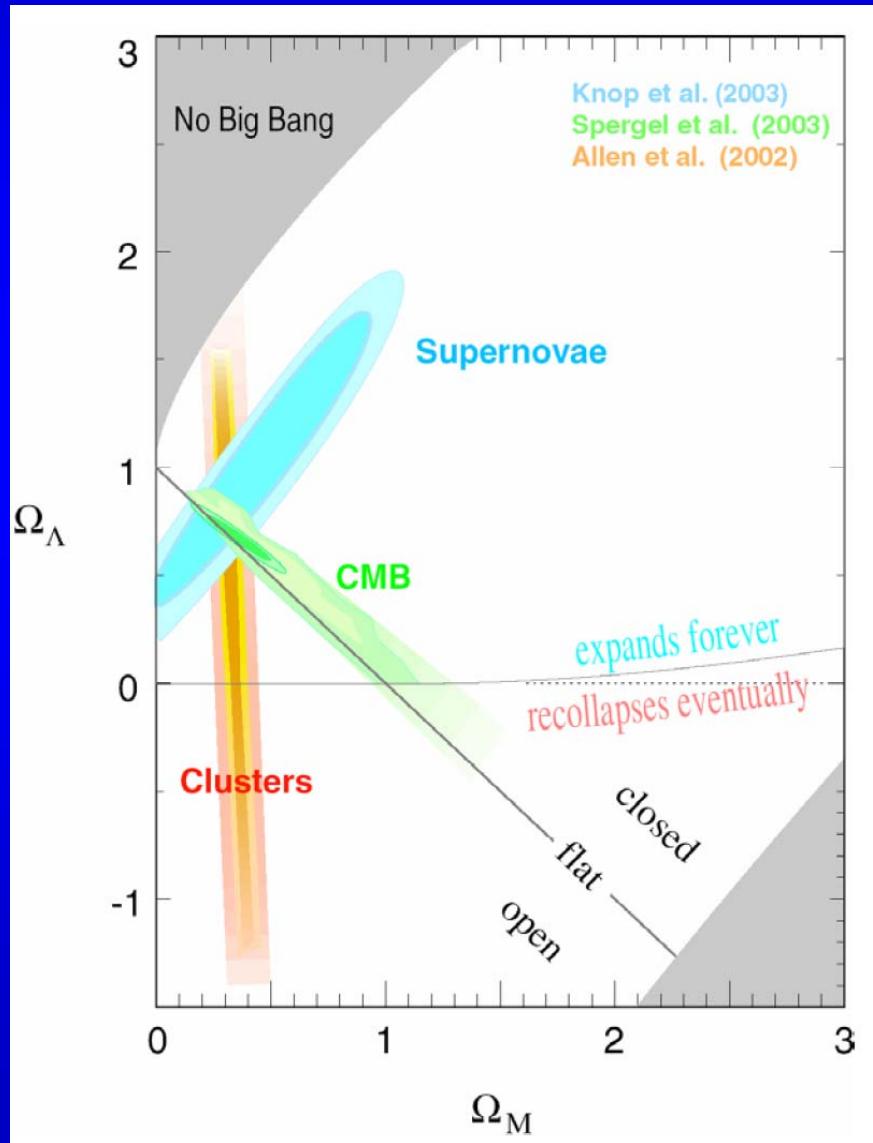
Comment les particules acquièrent-elles leur masse ? Le Boson de Higgs !



Comment les particules acquièrent-elles leur masse ? ATLAS !



Qu'est-ce que la masse manquante de l'univers ? Cosmic Microwave Background (CMB) et Supernova et Large Scale Structure (clusters)

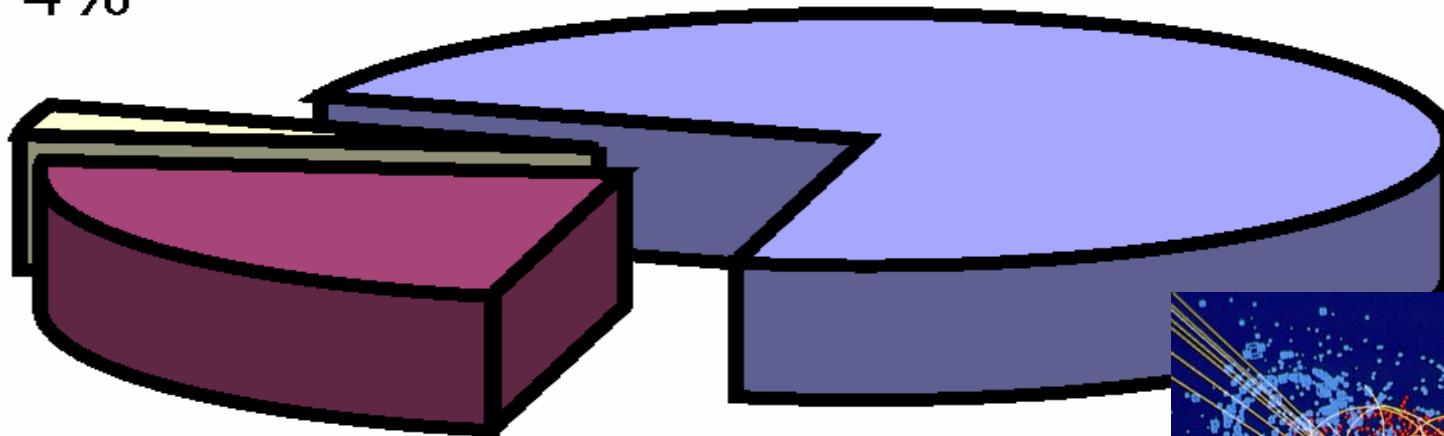


Qu'est-ce que la masse manquante de l'univers ? SUSY ! Neutralino ?

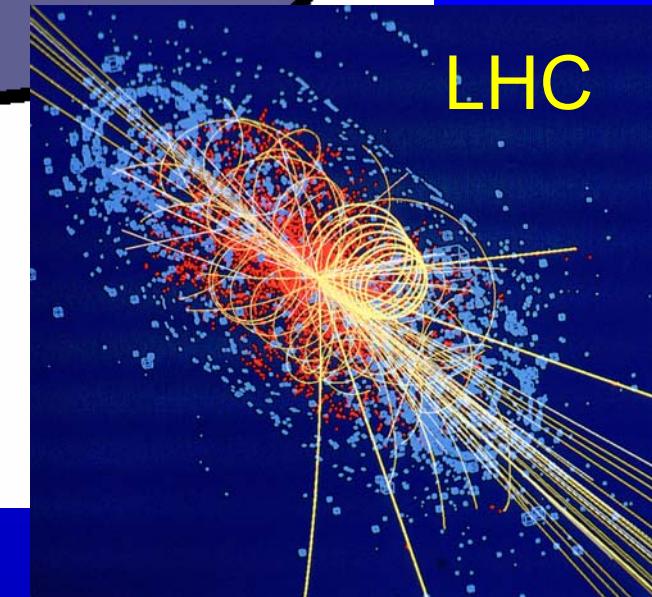
Search for WIMP
Weakly Interactive Massive
Particle

Atoms
4%

Dark energy
73%



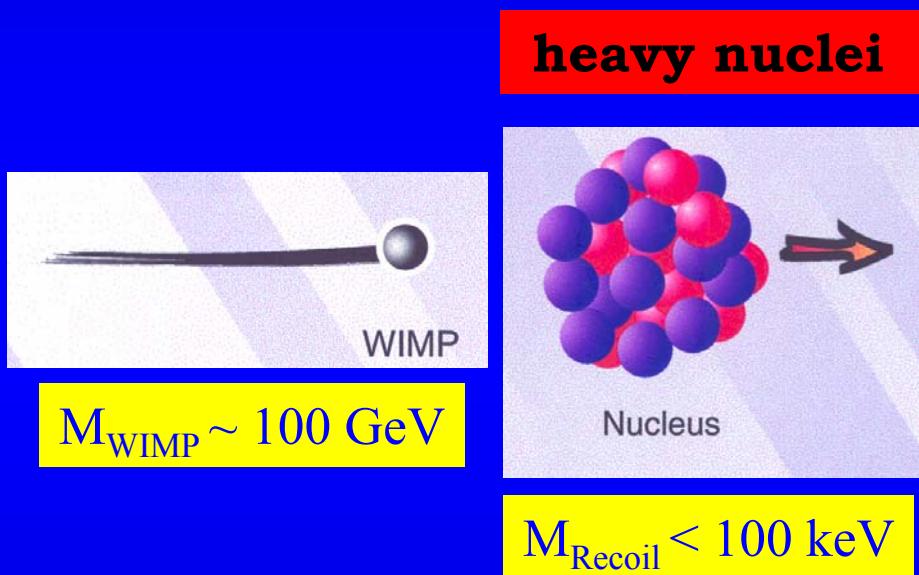
Dark matter
23%



LHC

WIMP Interaction with Matter

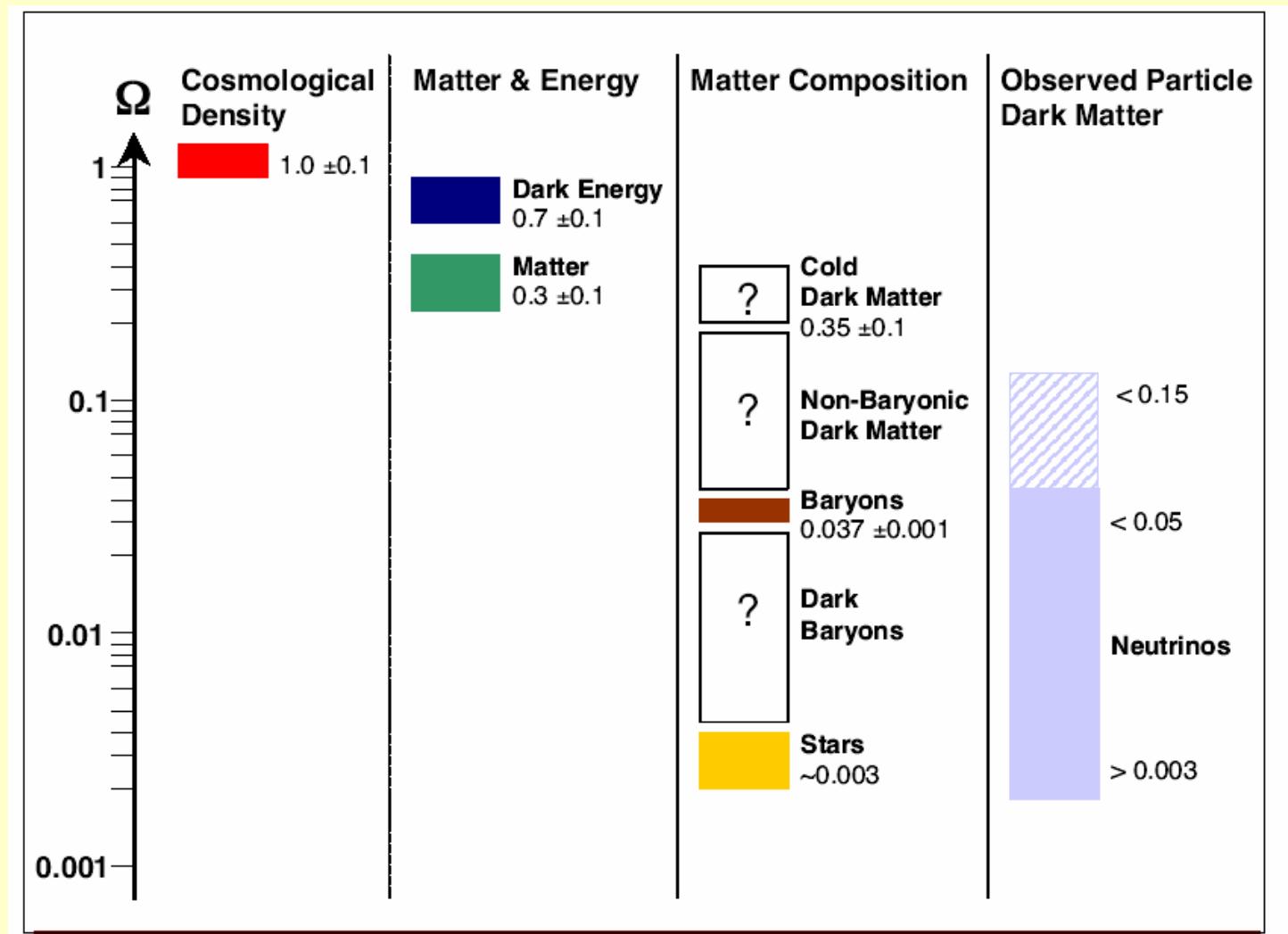
Spin independent interaction – scalar coupling



- ➔ Faint signals (heat, light, sound, electron)
- ➔ Clean and deep underground laboratory
- ➔ Low Energy Threshold
- ➔ Large Target Mass with Ultra-Low Background



What About Neutrino Mass?

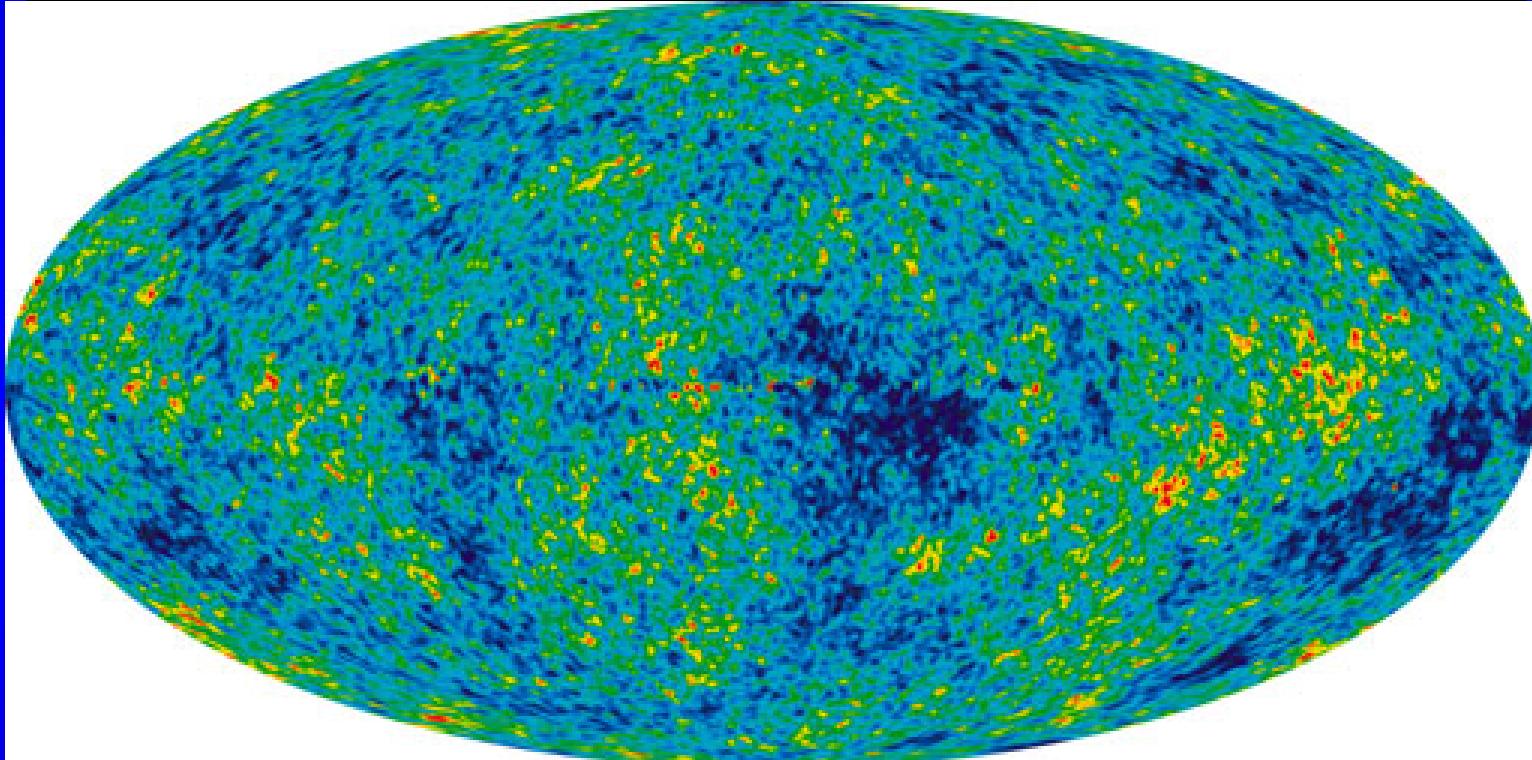


Pourquoi la matière domine-t-elle l'antimatière ? Violation CP !



Comment la matière a-t-elle évolué juste après le big bang ? WMAP

Wilkinson Microwave Anisotropy Probe



$$\sum m_\nu < (1.6 - 3.1)eV(95\% CL)$$

NASA/WMAP Science Team

Conclusion

- Plusieurs défis en astrophysique des particules
- Le neutrino en est un bon exemple
- Futur: ATLAS - SNOLAB - ILC
- Plusieurs applications en haute technologie
- Opportunités pour les jeunes (et les moins jeunes) scientifiques

FIN

<http://www.physics.carleton.ca/~alainb/>

<http://www.ocip.carleton.ca>

