

#### Outline



#### **LECTURE I**

- Neutrino Sources
- Discovery of neutrinos at reactor
- Solar Neutrino Puzzle
- Neutrino oscillations: solar neutrinos and experiments

#### **LECTURE II**

- Reactor neutrino oscillations in KamLAND experiment
- Measuring the last unknown neutrino mixing angle  $\theta_{13}$  with the Double Chooz, Daya Bay and RENO reactor neutrino experiment
- Open questions in neutrino oscillations:
  - CP-violation effect in leptons;
  - Neutrino mass ordering
- JUNO reactor experiment and neutrino mass ordering
- Conclusion

# Discovery of Neutrino at Reactors





Neutrinos from supernova SN198A: 1,000 million/cm<sup>2</sup> over several seconds

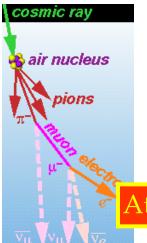
Big Bang neutrinos: 330 cm<sup>-3</sup>





Solar neutrinos: 10,000 million/cm<sup>2</sup>/s





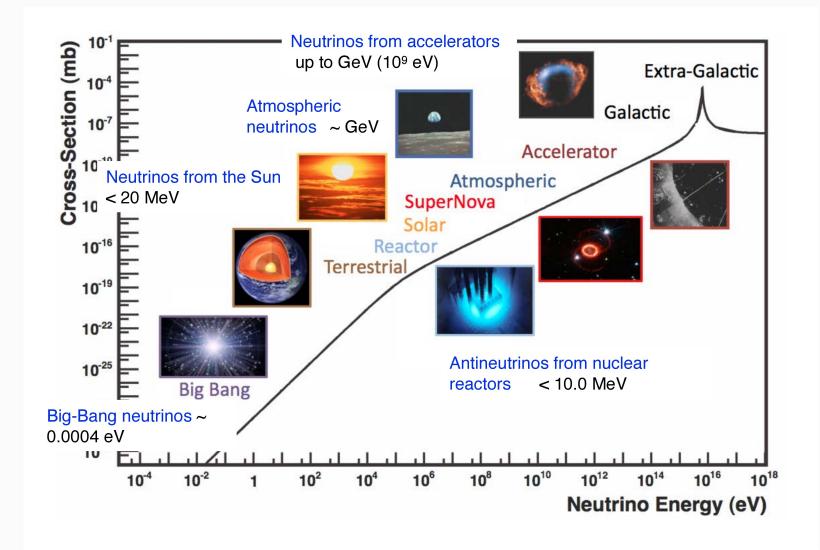
Geoneutrinos: 1 million/cm<sup>2</sup>/s



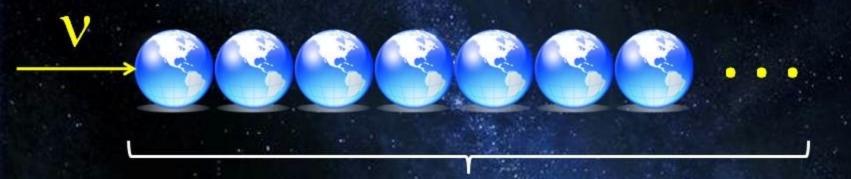
Accelerator neutrinos

## Neutrino Energy Scales





#### Neutrino Interaction Cross-Section



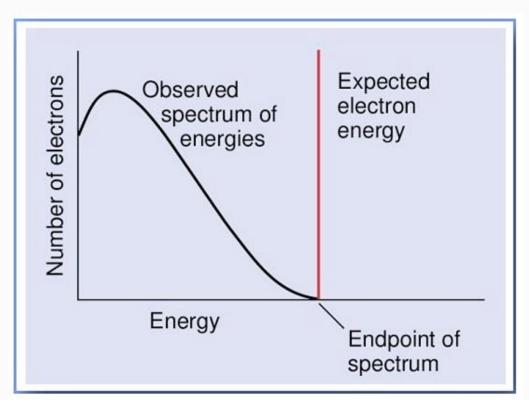
Neutrino can easily pass through 200 Earths before interacting at all!

- For typical neutrinos produced in the Sun (with energies of a few MeV), it would take approximately one light year ( $\sim 10^{16}$  m) of lead to block half of them.
- Probability of interaction is 20 orders of magnitude smaller than for proton.
- Detection of neutrinos is therefore challenging, requiring large detection volumes or high intensity artificial neutrino beams or sources.

# Neutrino Discovery with Reactor Neutrinos

## Deep and troubling mystery of beta decay energy spectrum





Single beta decay energy spectrum. The observed spectrum is continuous and not at a constant energy as was initially expected. [D. Stewart]

Continuous
 beta spectrum was
 the first hint that
 there is
 an extra particle in
 beta decay reaction:
 n -> p + e<sup>-</sup> + ?

Bohr: At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of  $\beta$ -ray disintegrations.

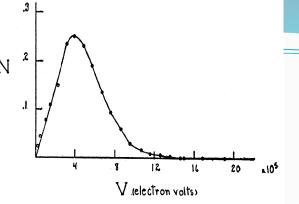
### Pauli's Desperate Remedy

4th December 1930 Tübingen

Dear Radioactive Ladies and Gentlemen,



As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...



#### And the Original...



Fig. 5. Energy distribution curve of the beta-rays.

Absortity 15.12.55 M

Offener Brief en die Gruppe der Radicaktiven bei der Genvereins-Tagung zu Tübingen.

#### Absobrift

Physikelisches Institut der Eidg. Technischen Hochschule Werich

Zirich, 4. Des. 1930 Clorisatranse

Liebe Radioaktive Damen und Herren.

Wie der Veberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des nEheren auseinendersetzen wird, bin ich angesichts der "felschen" Statistik der M- und bi-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einem versweifelten Ausweg verfallen um den "Wecheelsate" (1) der Statistik und den Energiesate su retten. Mimlich die Möglichkeit, es könnten elektrisch neutrale Tellohen, die ich Meutronen nennen will, in den Ternen existieren, welche dem Spin 1/2 beben und das Ausechliessungsprinzip befolgen und wich won Lichtquanten wasserden noch dackrich unterscheiden, dass sie micht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen **inns**te von derselben Grossenordsung wie die klektronensesse sein und jedenfalle nicht grösser als 0,00, Protonemagese- Des kontinuierliche **bein-** Spektrum wäre dann varständlich unter der Ammalme, dass beim bete-Zerfall mit dem blektron jeweils noch ein Meutron emittiert **wird. derar**t, dass die Summe der Energien von Meutron und klektron konstant ist.

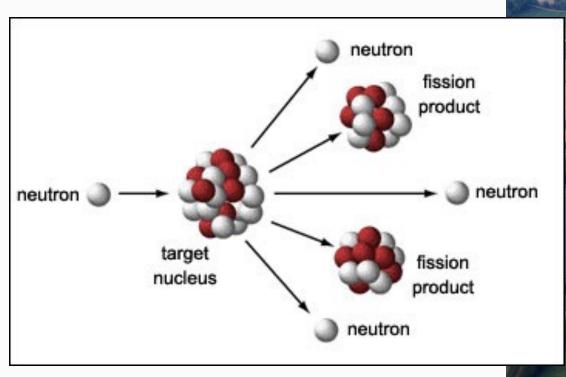
During the next few years, scientists elaborated farther Pauli's theory and conclude that the new particle must be very weakly interacting and extremely light.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December.

# Reactors as Powerful Free Neutrino sources

Large power reactor produces about 6·10<sup>20</sup> antineutrinos/s

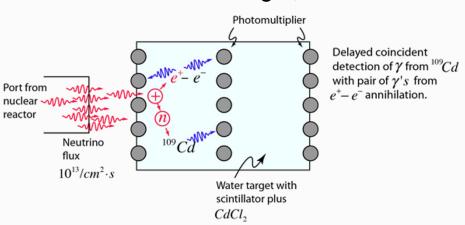
Reactor neutrinos are byproducts of fission in nuclear reactors.



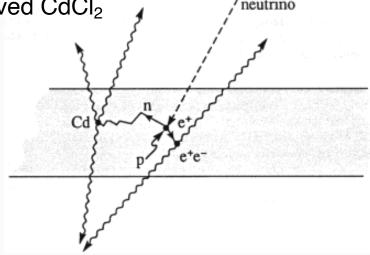


### Project Poltergeist

- Clyde Cowan and Frederick Reines set up an experiment to directly detect anti-neutrinos at (Hanford in 1953) and conclusively Savannah river nuclear reactor (Georgia) in 1955
- At Savannah river detector placed underground (12 m overburden),
- 11 m from reactor Use water as a target, scintillator and dissolved CdCl<sub>2</sub>



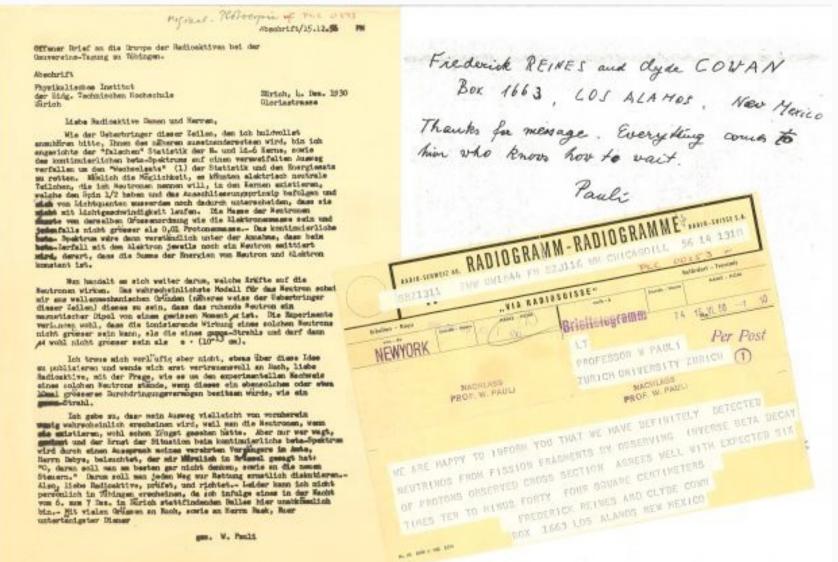




Inverse beta decay (IBD) reaction with double coincidence signature

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

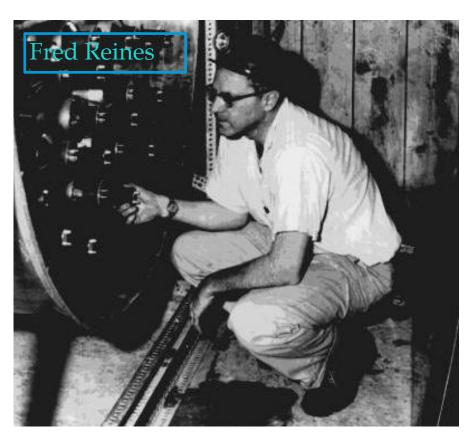
## Discovery of (electron anti) neutrino announced by Reines and Cowan in 1956



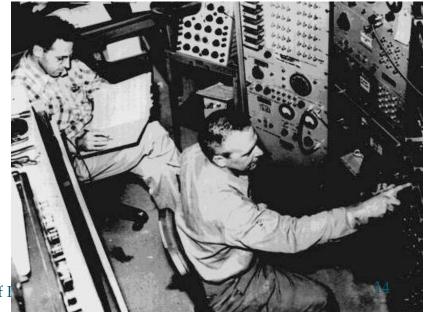
Following the direct detection of the anti-neutrino at Los Alamos by Reines and Cowan, Pauli sent this message

# First Detection of Neutrinos Led to First Nobel Prize for Neutrino





• In 1995, Fred Reines received Nobel Prize in Physics for discovery of neutrino.

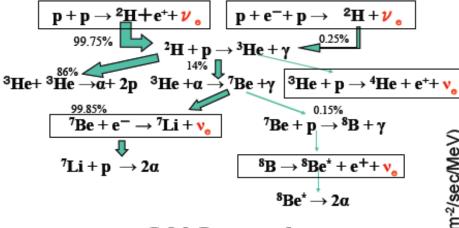


J. Maricic, University of I

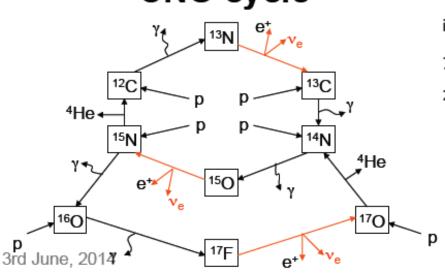
# First Hint of Neutrino Oscillations: Solar Neutrino Puzzle

#### Sun is a Copious Neutrino Source

#### pp-chain

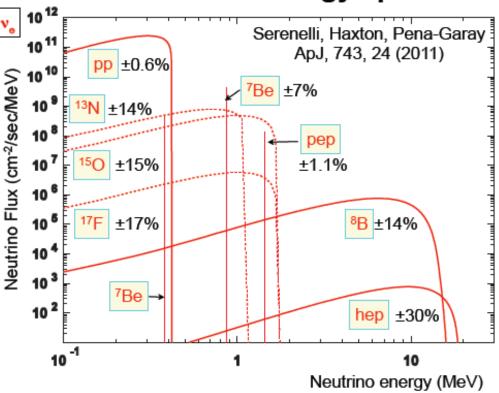


#### **CNO** cycle



CNO and pp-chain fusion cycles that power stars, discovered by Hans Bethe in 1938 (Nobel prize in 1967)

#### Solar neutrino energy spectrum



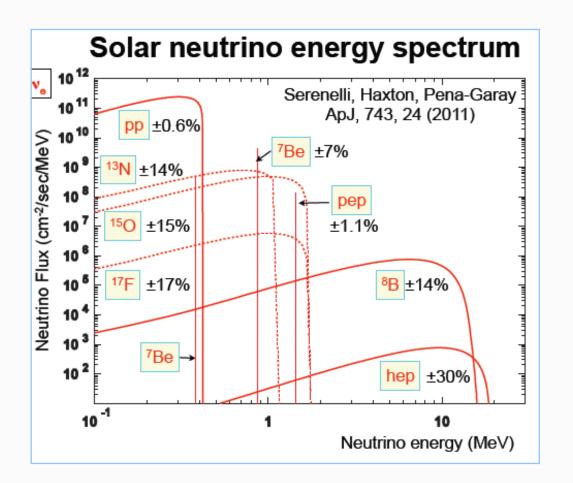
Solar neutrino flux on Earth: 10,000 million/cm<sup>2</sup>/s

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## Standard Solar Model (SSM) and Solar Neutrinos



John Bachall calculated neutrino fluxes and spectra expected from the Sun known as Standard Solar Model (SSM)



John Bachall

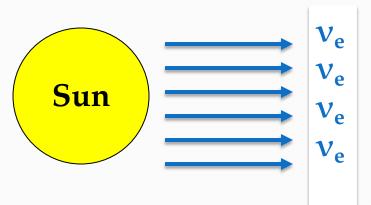


<sup>7</sup>Be lines and pep line are products of 2 body decays:

- 0.863 MeV (90%)
- 0.385 MeV (10%)

## Studying the Sun with Neutrinos

- In mid 1960's, Ray Davis and John Bahcall set up a radiochemical experiment in the Homestake mine in South Dakota to study neutrinos from the Sun and check SSM.
- HomestakeExperiment
- Study of neutrinos goes underground





$$v_e + {}^{37}CI \rightarrow {}^{37}Ar + e^{-}$$
 $v_e \rightarrow {}^{37}Ar + e^{-}$ 

Earth

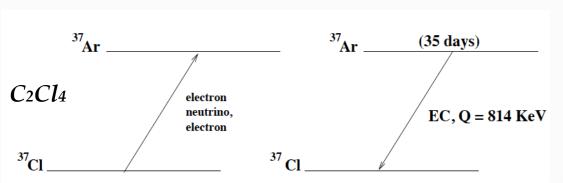
#### Homestake experiment

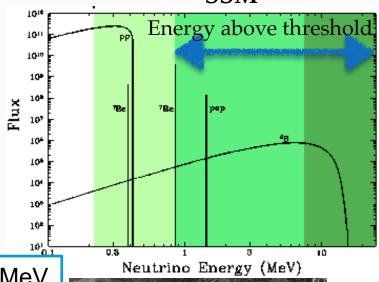


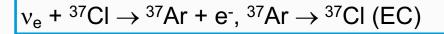
400,000 liters of cleaning fluid C2Cl4 placed in a giant underground tank.

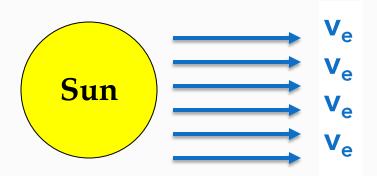
Neutrino flux measured by detection of 814 keV gamma line emitted **SSM** 

in <sup>37</sup>Ar radioactive decay.











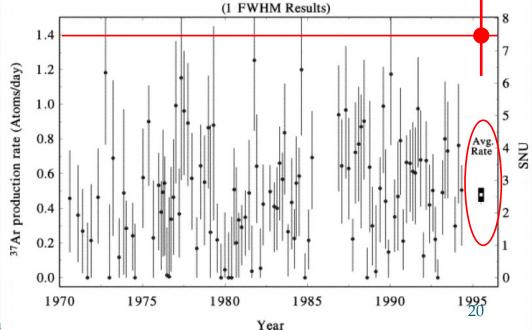
#### Homestake results

- Homestake mine, 1400 m underground (4850 ft underground, i.e. Davis cavern)
- 615 t of C<sub>2</sub>Cl<sub>4</sub> (perchloroethilene) = 2.2x10<sup>30</sup> atoms of <sup>37</sup>Cl
- Bubble He, and use <sup>36</sup>Ar and <sup>38</sup>Ar to carry-out the few atoms of <sup>37</sup>Ar (~ 1 atom/day)
- Count radioactive <sup>37</sup>Ar decays
- Every month, Davis carefully collected argon gas. The experiment carried on for 30 years (1994) and collected 2,000 <sup>37</sup>Ar atoms total!

$$v_e$$
 +  $^{37}CI$   $\rightarrow$   $^{37}Ar$  + e,  $^{37}Ar$   $\rightarrow$   $^{37}CI$  (EC)  $E_v$ >0.8 MeV





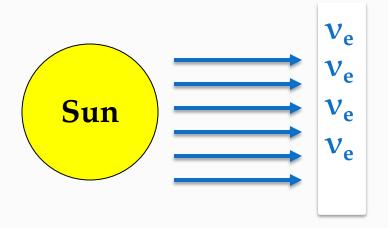


J. Ma

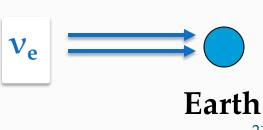
## Solar Neutrino Puzzle

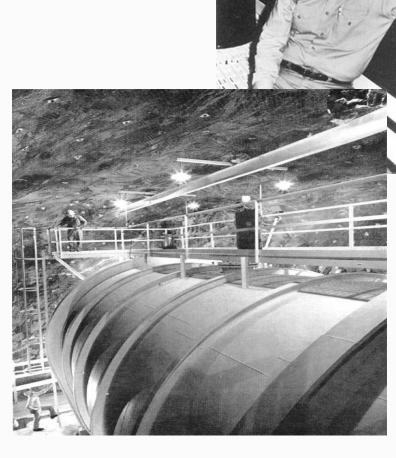
 Only 1/3 of the expected number of solar neutrinos detected!

→ Solar Neutrino Puzzle









## Possible Explanations

- Is the Standard Solar Model wrong (Bachall's calculation)?
- Does the Homestake experiment suffer from some large systematic error (measurement of Davis)?
- Does something happen to neutrinos while traveling from the Sun to the Earth?
- Do neutrinos oscillate among different neutrino flavors along their flight?
  - Part of v<sub>e</sub>'s turn into v<sub>μ</sub>'s
  - Important consequence this is only possible if neutrinos are massive!





## Neutrino Oscillations



- δ phase (CP symmetry violation phase)
- $\theta_{13}$
- $\theta_{12}$
- $\theta_{23}$

## Probability of Flavor Conversion



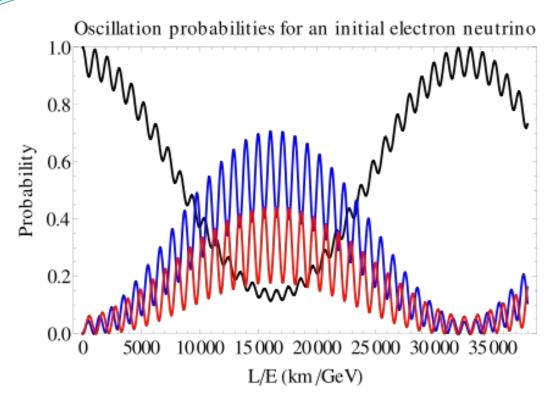
$$P_{\nu_l \to \nu_{l'}}(E, L) = |\langle \nu_{l'}(0) | \nu_l(L, t) \rangle|^2 = |\sum_{j=1}^3 U_{lj} U_{l'j}^+ e^{-i\frac{m_j^2}{2E}L}|^2.$$

$$P_{\nu_l \to \nu_{l'}}(E, L) = \sum_{j=1}^{3} U_{lj} U_{l'j}^{+} e^{-i\frac{m_j^2}{2E}L} \sum_{k=1}^{3} U_{lk} U_{l'k}^{+} e^{-i\frac{m_k^2}{2E}L}$$

•Which leads to the following result when expanded:

$$\begin{split} P_{\nu_l \to \nu_{l'}}(E,L) &= \sum_{j=1}^{3} \sum_{k=1}^{3} U_{lj} U_{l'j}^{+} U_{lk}^{+} U_{l'k} e^{-i\frac{\Delta m^2}{2E}L} \\ &= \sum_{k=1}^{3} |U_{lk} U_{l'k}^{+}|^2 + \sum_{j=1}^{3} \sum_{k \neq j}^{3} U_{lj} U_{l'j}^{+} U_{lk}^{+} U_{l'k} e^{-i\frac{\Delta m^2}{2E}L}, \\ &= \sum_{k=1}^{3} |U_{lk}|^2 |U_{l'k}^{+}|^2 + \sum_{j=1}^{3} \sum_{k \neq j}^{3} Re(U_{lj} U_{l'j}^{+} U_{lk}^{+} U_{l'k}) cos \frac{\Delta m^2}{2E} L \\ &+ \sum_{j=1}^{3} \sum_{k \neq j}^{3} Im(U_{lj} U_{l'j}^{+} U_{lk}^{+} U_{l'k}) sin \frac{\Delta m^2}{2E} L, \end{split}$$

#### **Example Oscillation Probability**



$$\Delta m^2_{21}$$
=(7.49±0.19)×10<sup>-5</sup> eV<sup>2</sup>  
 $\Delta m^2_{31}$ =(2.41±0.13)×10<sup>-3</sup> eV<sup>2</sup>

- Oscillations between electron and muon oscillations, strongly decouple from muon to tau neutrino oscillations.
  - → justifies simplification for two neutrino flavor oscillation.

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 1.27 \frac{\Delta m_{21}^2 [eV^2]}{E[MeV]} L[m]$$

## Summary of two neutrino oscillation



With units included, the probability of flavor change becomes:

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 1.27 \frac{\Delta m_{21}^2 [eV^2]}{E[MeV]} L[m]$$

While the survival probability of the same flavor is:

$$P_{\nu_e \to \nu_e} = 1 - P_{\nu_e \to \nu_\mu}$$

- Assumption made: neutrinos have non zero mass, but still very close to zero, since speed is ~c.
- Angle θ is called neutrino mixing angle, while Δm² is called neutrino mixing mass.
- Mixing angle controls the level of mixing, while mixing mass governs oscillation length.

## Oscillation length of two neutrino oscillation



Oscillation length is defined as:

$$L_{osc} = 2\pi \frac{2E}{|m_j^2 - m_k^2|}$$

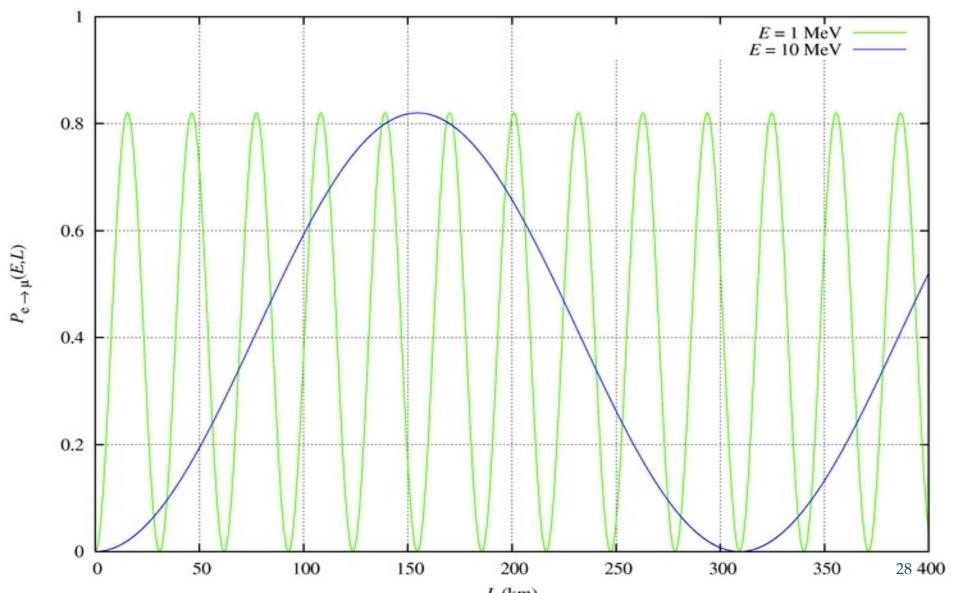
With units included:

$$L_{osc} = 2\pi \hbar c \frac{E[MeV]}{\Delta m^{2}[eV^{2}]} = 2.48 \frac{E[MeV]}{\Delta m^{2}[eV^{2}]}$$

 Oscillation length therefore depends on the energy of neutrino in addition to mixing mass: higher energy neutrinos change flavor less frequently (i.e. require longer distances).

# Example survival probability for different neutrino energies





#### Neutrino Mass in a Larger Prospective



- Proving neutrino oscillations effectively proves that neutrinos are massive.
- Standard Model assumed zero neutrino mass.
- Therefore neutrino oscillations provide window in the physics Beyond Standard Model.
- Leads to a very different picture of neutrinos where each flavor is a specific mix (linear combination) of three neutrino masses!

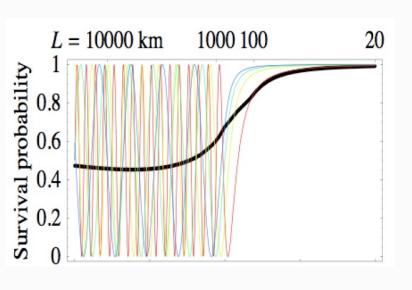
## Average Survival Probabil

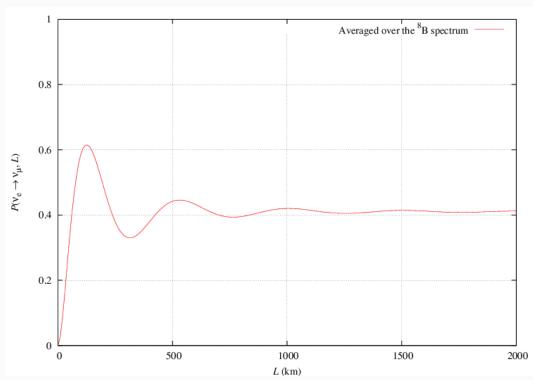
$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 1.27 \frac{\Delta m_{21}^2 [eV^2]}{E[MeV]} L[m]$$

 If we average probability over energy spectrum and large distance:

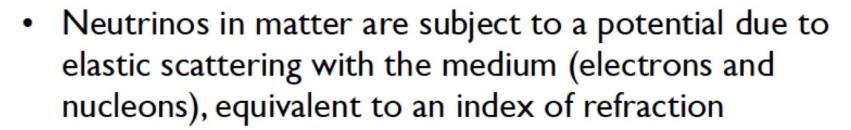
$$P(\nu_e \to \nu_\mu) = \frac{1}{E_{max}} \int_0^{E_{max}} P(E)\rho(E)dE$$

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)/2$$





#### Resonant flavor transition in matter



Feynmann diagrams for the elastic scattering processes that generate the CC potential ( $V_{CC}$ , left) and the NC potential ( $V_{NC}$ , right).  $G_F$  Fermi coupling constant and  $N_e$  ( $N_n$ ) number density of electrons (neutrons)



#### Propagation in matter

- In the presence of matter the Hamiltonian changes
   H<sub>o</sub> → H = H<sub>o</sub> + V (H<sub>o</sub> Hamiltonian in vacuum)
- The Schroedinger equation can be written in terms of matter mixing angle and effective squared-mass difference

$$i\frac{d}{dx} \begin{pmatrix} \Psi_{ee} \\ \Psi_{e\mu} \end{pmatrix} = \frac{1}{4E} \ \begin{pmatrix} -\Delta m_M^2 \cos 2\theta_M & \Delta m_M^2 \sin 2\theta_M \\ \Delta m_M^2 \sin 2\theta_M & \Delta m_M^2 \cos 2\theta_M \end{pmatrix} \begin{pmatrix} \Psi_{ee} \\ \Psi_{e\mu} \end{pmatrix}$$

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \sin 2 heta)^2 + (\Delta m^2 \cos 2 heta \mp 2\sqrt{2}G_F N_e E)^2} \ an 2 heta_M = rac{\Delta m^2 \sin 2 heta}{\Delta m^2 \cos 2 heta \mp 2\sqrt{2}G_F N_e E}$$

 The eigenstates and the eigenvalues (and therefore the mixing angle) depend on the matter density and on the neutrino energy



#### 1960's - 1990's

- After the original indication of the solar neutrino puzzle from Homestake a whole range of experiments probed neutrino properties and searched for neutrino oscillations.
- Different neutrino sources used in different experiments:
  - Solar neutrinos
  - Reactor neutrinos
  - Atmospheric neutrinos

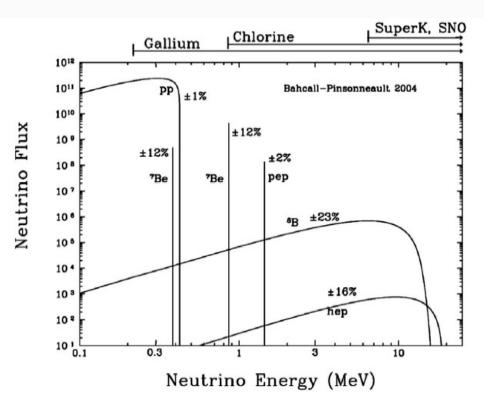
## 1960's - 1990's: Solar Neutrino Radiochemical Experiments



 Homestake experiment was followed by two more radiochemical experiments GALLEX (Italy) and SAGE (Soviet Union/Russia):

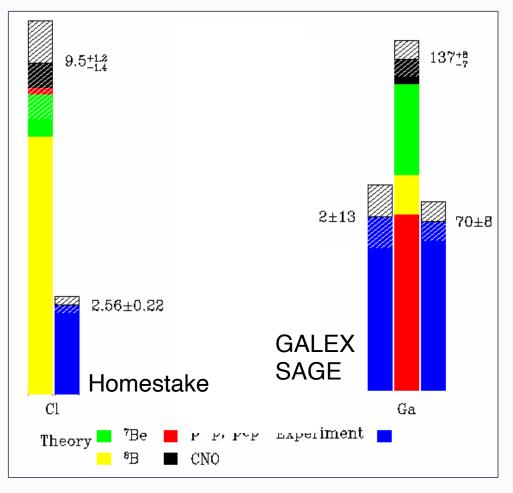
Cl<sub>2</sub> detectors 
$$v_e$$
 +  $^{37}$ Cl  $\rightarrow$   $^{37}$ Ar +  $e^-$ ,  $^{37}$ Ar  $\rightarrow$   $^{37}$ Cl (EC)  $E_v$ >0.8 MeV Ga detectors  $v_e$  +  $^{71}$ Ga  $\rightarrow$   $^{71}$ Ge +  $e^ E_v$ >0.2 MeV

- Lower energy threshold means sensitivity to additional fusion processes in the Sun:
  - pp neutrinos
  - <sup>7</sup>Be lower energy.



# Solar Neutrino Radiochemical Experimental Results

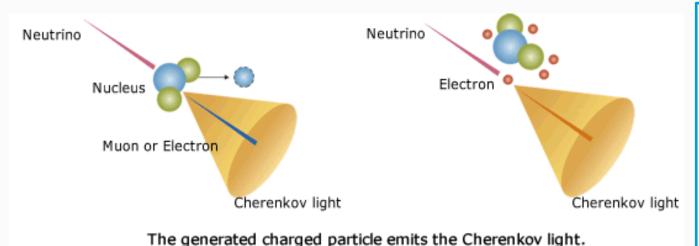
- Deficit observed in Homestake experiment confirmed by gallium experiments:
  - GALLEX (1991 1997)
  - SAGE (1989 2013)
- Measure the total rate of neutrinos above threshold, but **not** the spectrum, nor in real time



#### 1980's:

#### Kamiokande and IMB experiments

 For the first time neutrino detections detected and measured in real time on event by event bases using Cherenkov light: Kamiokande (Japan) and IMB (USA). Excellent sensitivity to atmospheric neutrinos (GeV) and some sensitivity to solar neutrinos (< 15 MeV).</li>



Giant water detectors: water is target for neutrino to interact.

Originally designed to search for proton decay.

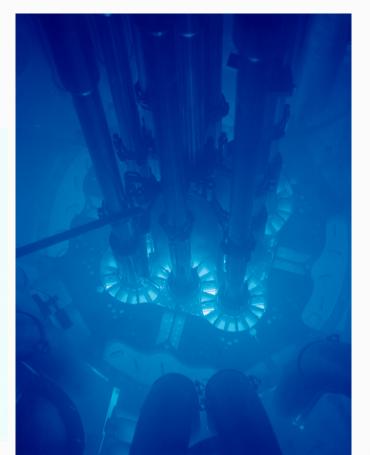
Light is detected with sensitive photo devices called photomultiplier tube or PMT.

Kamiokande, IMB and BNO are the only experiments that detected neutrinos from Supernova burst 1987A.

# Cherenkov Radiation

- Cherenkov radiation is coherent electromagnetic radiation emitted when charged particle passes through dielectric medium at a speed greater than phase velocity of light in that medium.
- Cherenkov radiation can be seen as blue glow in cooling water tanks around nuclear reactors.



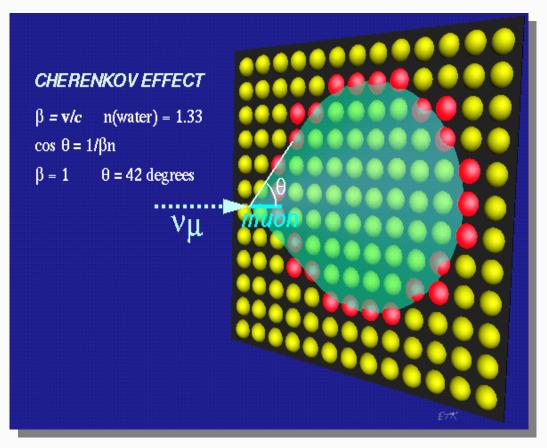


## How Water Cherenkov Detector

### Works?



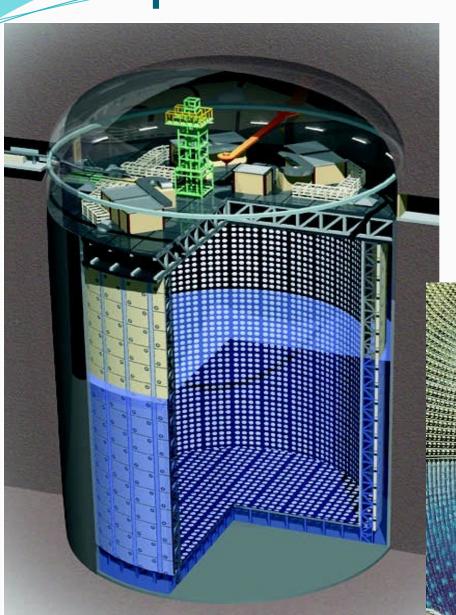
- Cheap target material
- Surface instrumentation
- Vertex from PMT timing
- Direction from ring edge
- Energy from pulse height, range and opening angle
- Particle ID from hit pattern and delayed muon decay signature
- Cherenkov threshold in water:
  - $\beta > 1/n \sim 0.75$



$$\cos heta = rac{1}{n eta}$$

# Extraordinary Neutrino Years 1998 - 2012

# SuperKamiokande



Largest artificial water detector (50 kt)

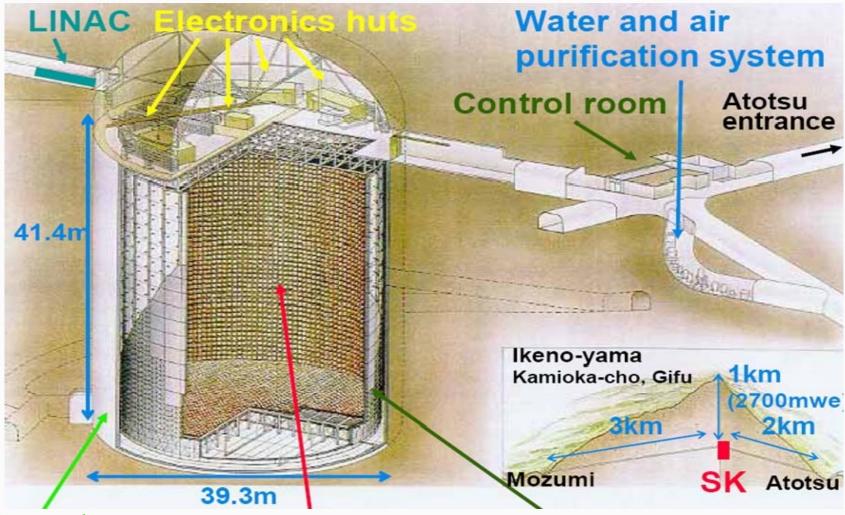
Started operation in 1996

 Sensitive to neutrinos from a few MeV to hundreds of GeV energy

 Built to solve three puzzles:
 nucleon decay, solar neutrinos and atmospheric neutrinos

# Super-Kamiokande Detector





50 kton total 22.5 kt fiducial

Inner detector: (40% coverage) 11,186 20" PMTs Outer detector: (veto) 1885 8" PMTs

# Photomultiplier tubes (PMTs)

dynodes

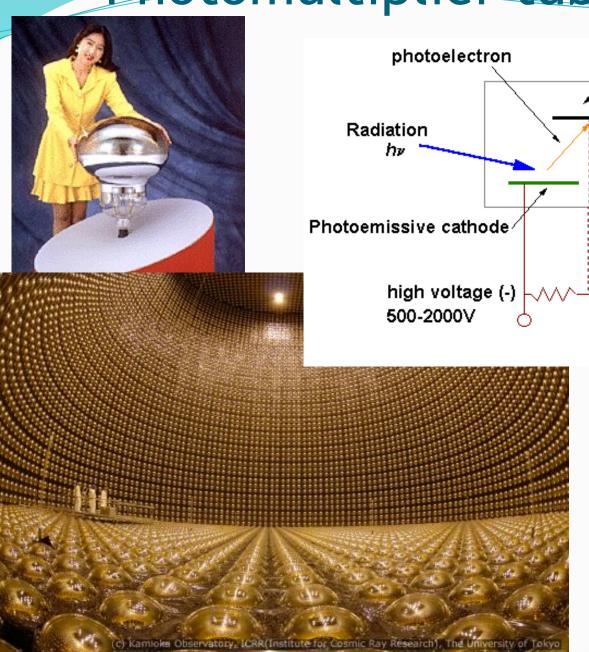


secondary electrons

anode

amplifier

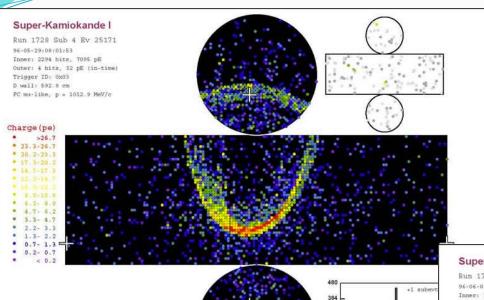
current-to-voltage

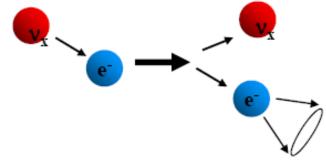


50 cm diameter
photosensor
Gain ~ 10<sup>7</sup>
Low dark noise
Require HV (~1,700 V)
Ability to detect
single visible photon!

# Superkamiokande (High





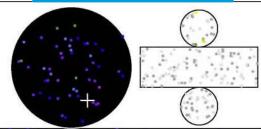


#### Electron neutrino

#### 480 384 288 192 96 0 500 1000 1500 Times (ns)

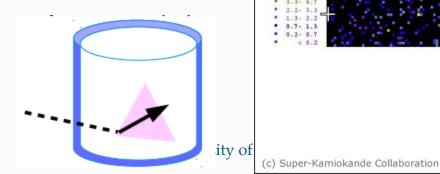
#### Super-Kamiokande I

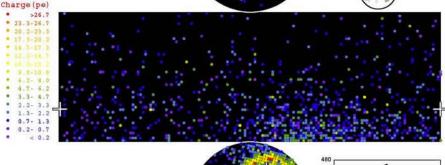
Run 1757 Sub 4 Ev 25716 96-06-03:07:51:37 Inner: 1946 hits, 5243 pB Outer: 4 hits, 30 pE (in-time) Trigger ID: 0x03 0 wall: 671.6 cm PC e-like, p = 618.1 MeV/c

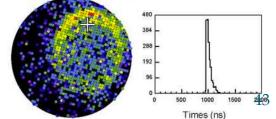


#### Muon neutrino

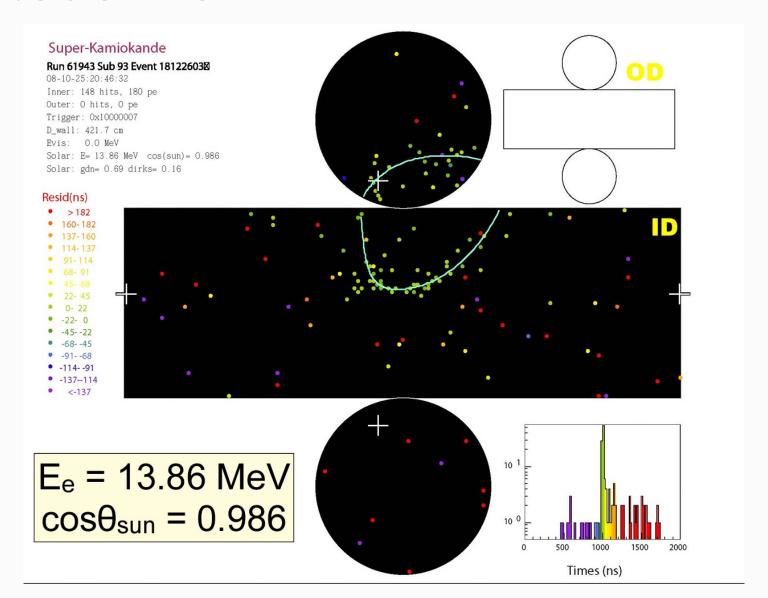
(c) Super-Kamiokande Collaboration







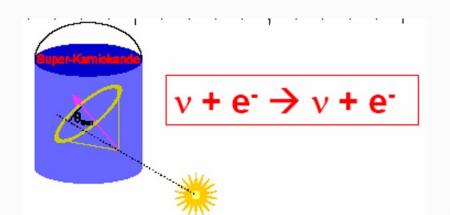
# SuperKamiokande Low Energy Neutrino

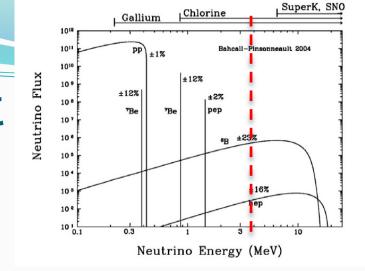


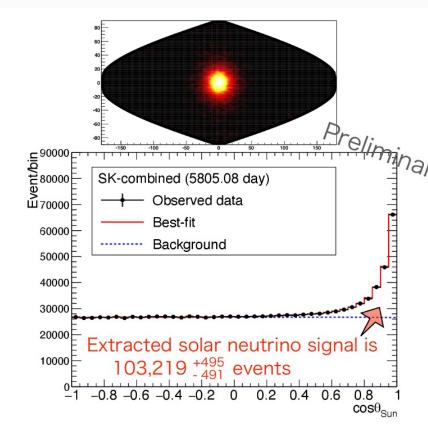
# SuperKamiokande Solar v<sub>e</sub> Measurement

- SuperKamiokande is sensitive to <sup>8</sup>B neutrinos > 3.5 MeV
- Neutrinos are observed through neutrino electron elastic scattering
- Reconstruction of Cherenkov rings gives neutrino direction, energy and particle ID
- Detects 45 % of expected v<sub>e</sub>'s

$$\Phi = 2.355 \pm 0.033 \times 10^6 \text{ [cm}^2\text{/sec]}$$



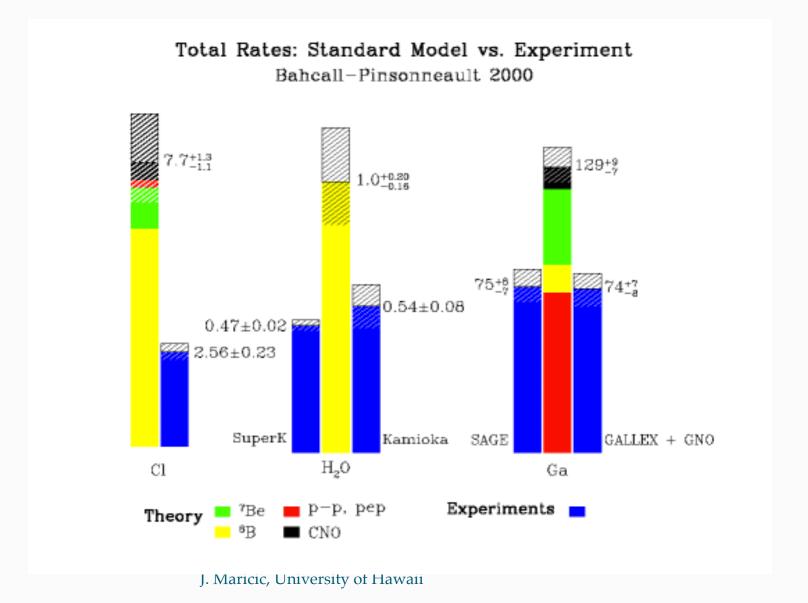






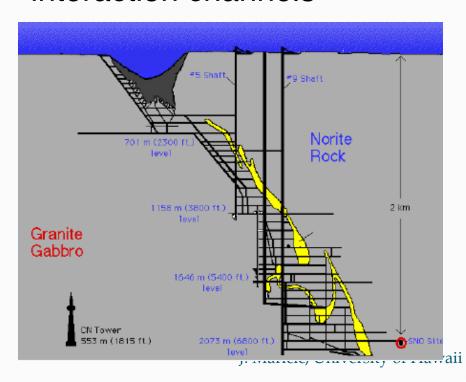
# Status of Solar Exp

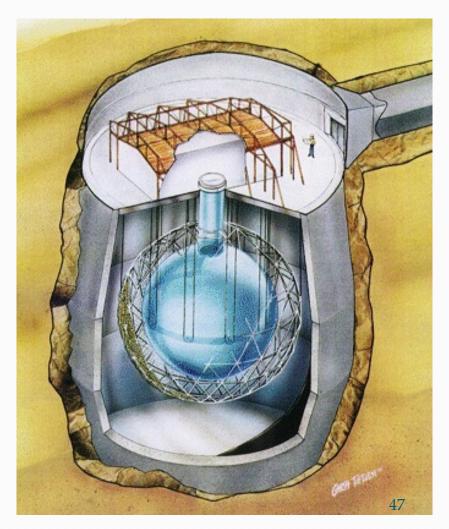




# Sudbary Neutrino Observatory SNO - Solar Neutrino Puzzle Resolution

- Located 2 km underground
- Sudbary mine in Canada
- Sensitivity to all neutrino flavors through different interaction channels

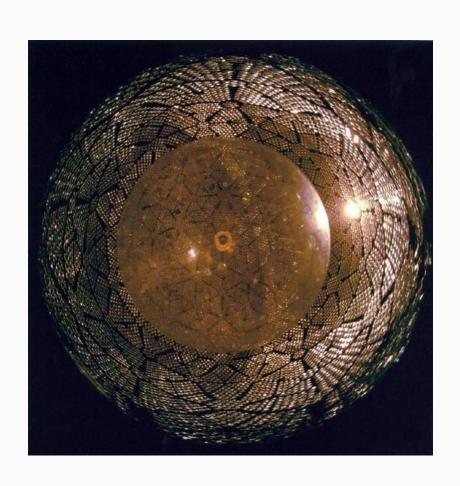


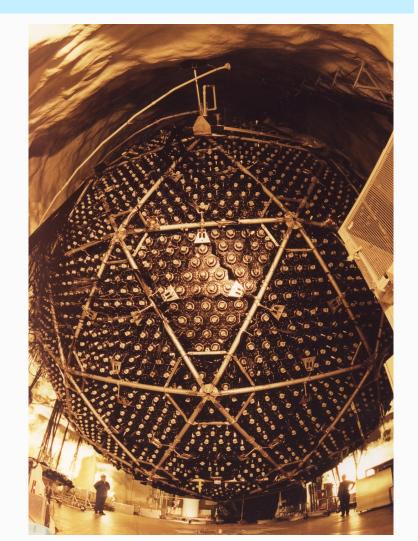




# SNO Detector

- 6 m radius transparent acrylic vessel
- 1000 t of heavy water (D<sub>2</sub>O)
- 9456 inward looking photo multipliers
- Add 2 tons of NaCl to detect neutrons



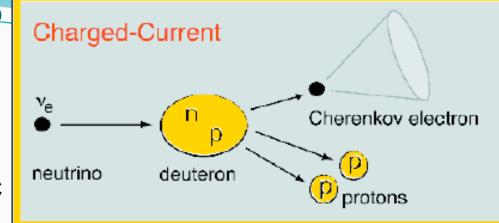


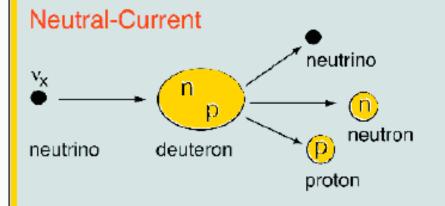
# Interactions in SNO

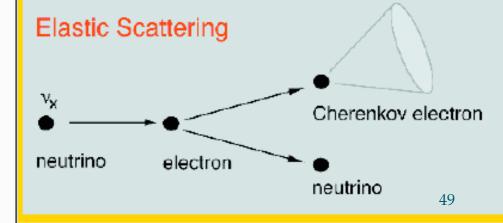
- Sensitive to ALL neutrino flavors via NC
- Sensitive to v<sub>e</sub> via CC and ES

CC:  $\nu_e+d \rightarrow e^-+p+p$ NC:  $\nu_\alpha+d \rightarrow \nu_\alpha+p+n$   $\nu_\alpha+e^- \rightarrow \nu_\alpha+e^-$ 

#### **Neutrino Reactions on Deuterium**







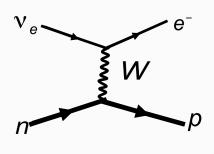
# SNO neutrino interactions

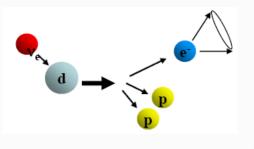


#### Charged current

$$\sigma(v_{\mu}) = \sigma(v_{\tau}) = 0$$

$$\phi_{v} = \phi_{v_{\theta}}$$



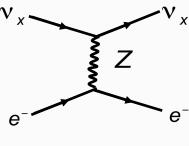


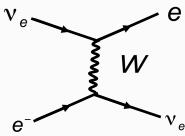
Cherenkov Light

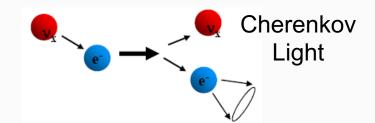
#### Elastic scattering

$$0.154 \cdot \sigma(v_e) = \\ \sigma(v_{\mu}) = \sigma(v_{\tau})$$

$$\phi_{v} = \phi_{v_e} + (\phi_{v_u} + \phi_{v_\tau})/6$$

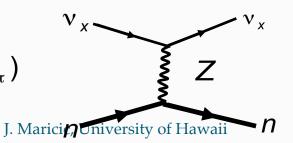


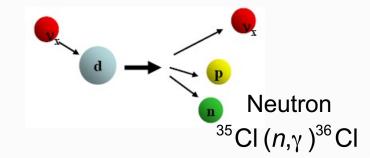




#### Neutral current

$$\sigma(v_e) = \sigma(v_\mu) = \sigma(v_\tau)$$

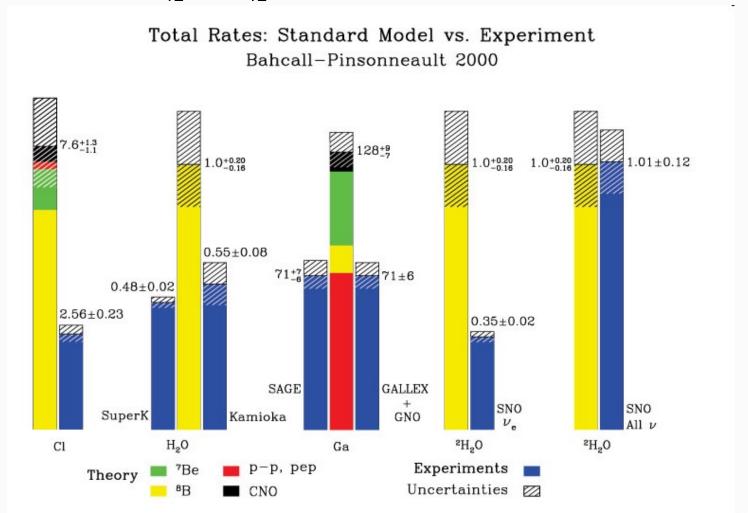




# SNO - 2001

In 2001, SNO solar neutrino experiment observed all three neutrino flavors coming from the Sun implying that

neutrino oscillations are the solution of solar neutrino puzzle characterized by  $(\theta_{12}, \Delta m_{12})$ .



# SNO results



$$\phi_{\text{CC}}^{\text{SNO}} = 1.76^{+0.06}_{-0.05}(\text{stat})^{+0.09}_{-0.09}(\text{syst}),$$

$$\phi_{\text{ES}}^{\text{SNO}} = 2.39^{+0.24}_{-0.23}(\text{stat})^{+0.12}_{-0.12}(\text{syst}),$$

$$\phi_{\text{NC}}^{\text{SNO}} = 5.09^{+0.44}_{-0.43}(\text{stat})^{+0.46}_{-0.43}(\text{syst}).$$

$$\phi_{\rm ES}^{\rm SNO} = 2.39^{+0.24}_{-0.23}({\rm stat})^{+0.12}_{-0.12}({\rm syst}),$$

$$\phi_{\text{NC}}^{\text{SNO}} = 5.09_{-0.43}^{+0.44} (\text{stat})_{-0.43}^{+0.46} (\text{syst}).$$

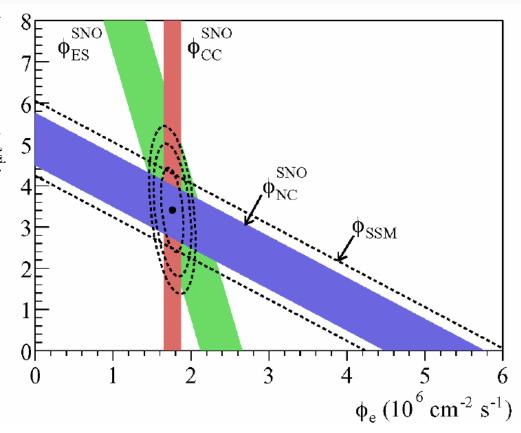
Phys. Rev.Lett. 89 (2002) 011301



Electron neutrino flux is too low:

$$P_{\text{veve}} = (35 \pm 2)\%$$

Total flux of neutrinos is correct.





Interpreted as  $\nu_e \leftrightarrow \nu_\mu \, \text{or} \, \, \nu_\tau \, \text{oscillation}$ 

# Impact of SNO and SuperKamiokande

10

10 -4

10

10 -6

10 -7

10 -8

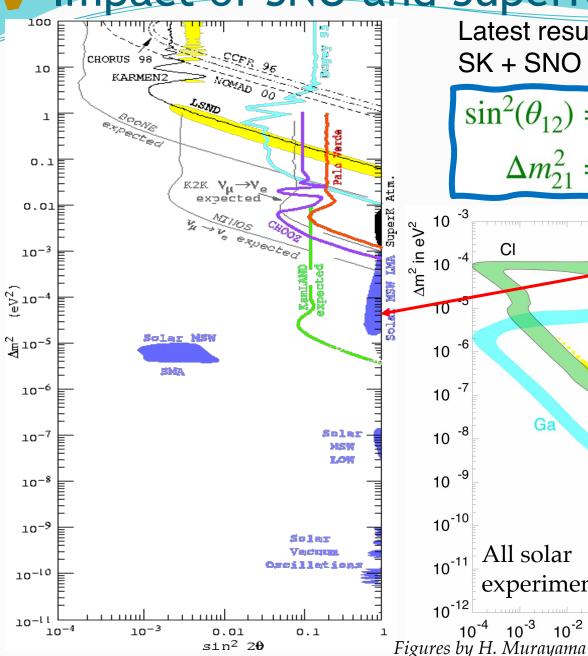
10 -9

10<sup>-10</sup>

All solar

experiments

10<sup>-3</sup> 10<sup>-2</sup>

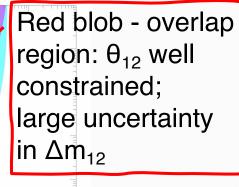


Latest results from SK + SNO solar experiments:

$$\sin^2(\theta_{12}) = 0.305 \pm 0.014$$
$$\Delta m_{21}^2 = 6.10^{+1.04}_{-0.75} \times 10^{-5} eV^2$$

SuperK

 $tan^2(\Theta)$ 



# Nobel Prizes for Neutrinos

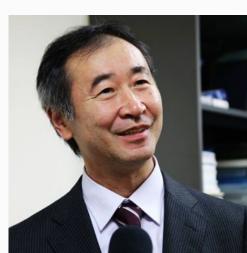


- 2002
  - Ray Davis (detection of solar neutrinos)
  - Masatoshi Koshiba (detection of supernova burst neutrinos
- 2015
  - Art McDonald (discovery of neutrino oscillations in solar neutrinos)
  - Takaaki Kajita (discovery of neutrino oscillations in atmospheric neutrinos









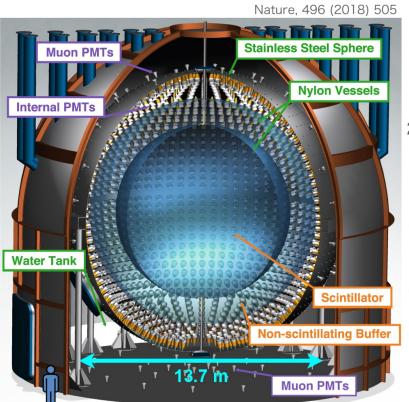
# Discovering the Details of Powering the Sun with Neutrinos

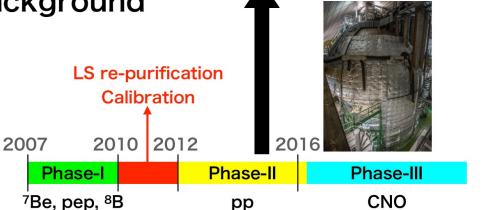
## Borexino Solar Neutrino Detector



#### Borexino

Ultimate low radioactive background





Multiple efforts for thermal stabilization

external tank insulation

- Active volume 280 tons of liquid scintillator (PC+PPO, 1.5g/l in a nylon vessel R=4.25m)
- $\cdot$  <sup>232</sup>Th < 5.7x10<sup>-19</sup> g/g, <sup>238</sup>U < 9.4x10<sup>-20</sup> g/g
- $\cdot$  R( $^{210}$ Bi) < 11.5±1.3 cpd/100ton(upper limit)! which is the background of CNO neutrino search (3~5 cpd/100ton is expected).

## Borexino - Comprehensive Solar Neutrino Measurement



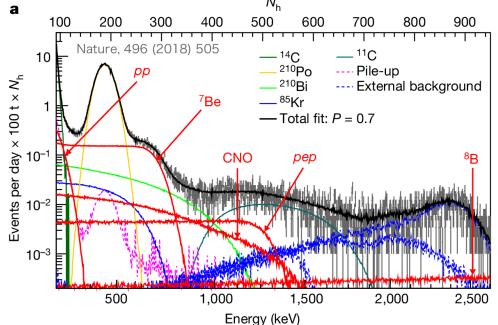




#### Borexino

#### As a solar neutrino detector

neutrino-electron elastic scattering  $\nu + e^- \rightarrow \nu + e^-$ 



Possible to access multiple solar neutrino sources by single detector thanks to its high light yield and low background.



- •First direct measurements of <sup>7</sup>Be, pep, pp, CNO, also first measurement of <sup>8</sup>B by LS.
- Verify neutrino oscillation scenario.
   Possible to simultaneously test neutrino flavor conversion both in the vacuum and the matter dominated region.
- · Astrophysical point of view:
  - ·Solar luminosity confirmation.
  - ·Solar metallicity problem investigation.

First observation of neutrinos from CNO fusion cycle.

# On to Reactor Neutrino Oscillations Tomorrow...