PHYS 5326 – Lecture #6

Wednesday, Feb. 14, 2007
Dr. Jae Yu

1. Neutrino Oscillation Formalism
2. Neutrino Oscillation Measurements
   1. Solar Neutrinos
   2. Atmospheric neutrinos
   3. Accelerator Based Oscillation Experiments

Neutrino Oscillation

- First suggestion of neutrino mixing by B. Pontecorvo to explain K^0, K^0-bar mixing in 1957
- Solar neutrino deficit in 1969 by Ray Davis in Homestake Mine in SD. ➔ Called MSW (Mikheyev-Smirnov-Wolfenstein) effect
  - Describes neutrino flavor conversion in medium
- Caused by the two different eigenstates for mass and weak
- Neutrinos change their flavor as they travel ➔ Neutrino flavor mixing
- Oscillation probability depends on
  - The distance between the source and the observation point
  - The energy of the neutrinos
  - The difference in square of the masses

Neutrino Oscillation Formalism

- Two neutrino mixing case:

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

OR

$$|\nu_\mathrm{e}\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

where $|\nu_\mathrm{e}\rangle$ and $|\nu_\mu\rangle$ are weak eigenstates, while $|\nu_1\rangle$ and $|\nu_2\rangle$ are mass eigenstates, and θ is the mixing angle that gives the extent of mass eigenstate mixture, analogous to Cabbio angle

Oscillation Probability

- Let ν_μ at time t=0 be the linear combination of ν_1 and ν_2 with masses m_1 and m_2, the wave function becomes:

$$\left|\nu_\mu(t=0)\right\rangle = -\sin\theta\left|\nu_1\right\rangle + \cos\theta\left|\nu_2\right\rangle$$

- Then later time t the ν_μ wave function becomes:

$$\left|\nu_\mu(t)\right\rangle = -\sin\theta\exp\left[-i\left(E_1/\hbar\right)t\right]\left|\nu_1\right\rangle + \cos\theta\exp\left[-i\left(E_2/\hbar\right)t\right]\left|\nu_2\right\rangle$$

- For relativistic neutrinos ($E_\nu >> m_i$), the energies of the mass eigenstates are:

$$E_k = \sqrt{p^2 + m_k^2} \cong p + \frac{m_k^2}{2p}$$

Oscillation Probability

- Substituting the energies into the wave function:

$$|\nu_\mu(t)\rangle = \exp\left[-it\left(p+\frac{m_1^2}{2E_\nu}\right)\right]\left[-\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle\exp\left[\frac{i\Delta m^2 t}{2E_\nu}\right]\right]$$

where $\Delta m^2 \equiv m_1^2 - m_2^2$ and $E_\nu \cong p$.

- Since the ν's move at the speed of light, t=x/c, where x is the distance to the source of ν_μ.
- The probability for ν_μ with energy E_ν oscillates to ν_e at the distance $\mathcal{L}$ from the source becomes

$$\boxed{P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)}$$

Why is Neutrino Oscillation Important?

- Neutrinos are one of the fundamental constituents in nature
  - Three weak eigenstates based on SM
- Left handed particles and right handed anti-particles only
  - Violates parity → Why only neutrinos?
  - Is it because of its masslessness?
- SM based on massless neutrinos
- Mass eigenstates of neutrinos makes flavors to mix
- SM in trouble…
- Many experimental results showing definitive evidences of neutrino oscillation
  - SNO giving 5 sigma results

ν Sources for Oscillation Experiments

- Must have know the flux by the species
  - Why?
- Natural Sources
  - Solar neutrinos
  - Atmospheric neutrinos
- Manmade Sources
  - Nuclear Reactor
  - Accelerator

Oscillation Detectors

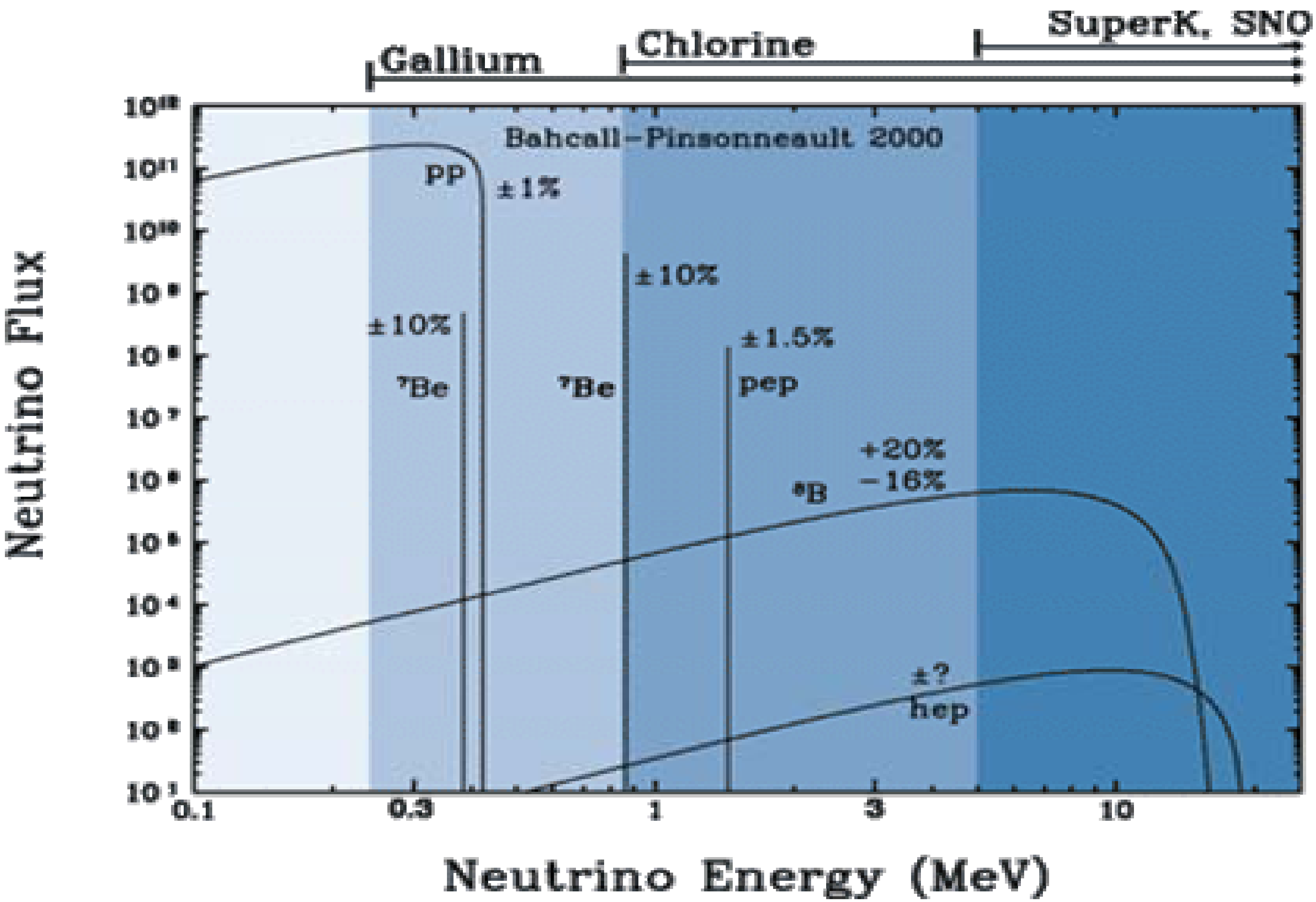
- The most important factor is the energy of neutrinos and its products from interactions
- Good particle ID is crucial
- Detectors using natural sources
  - Deep underground to minimize cosmic ray background
  - Use Čerenkov light from secondary interactions of neutrinos
    - $\nu_e + N \rightarrow e + X$: electron gives out Čerenkov light
    - ν_μ CC interactions, resulting in muons with Čerenkov light
- Detectors using accelerator made neutrinos
  - Look very much like normal neutrino detectors
    - Need to increase statistics

Solar Neutrinos

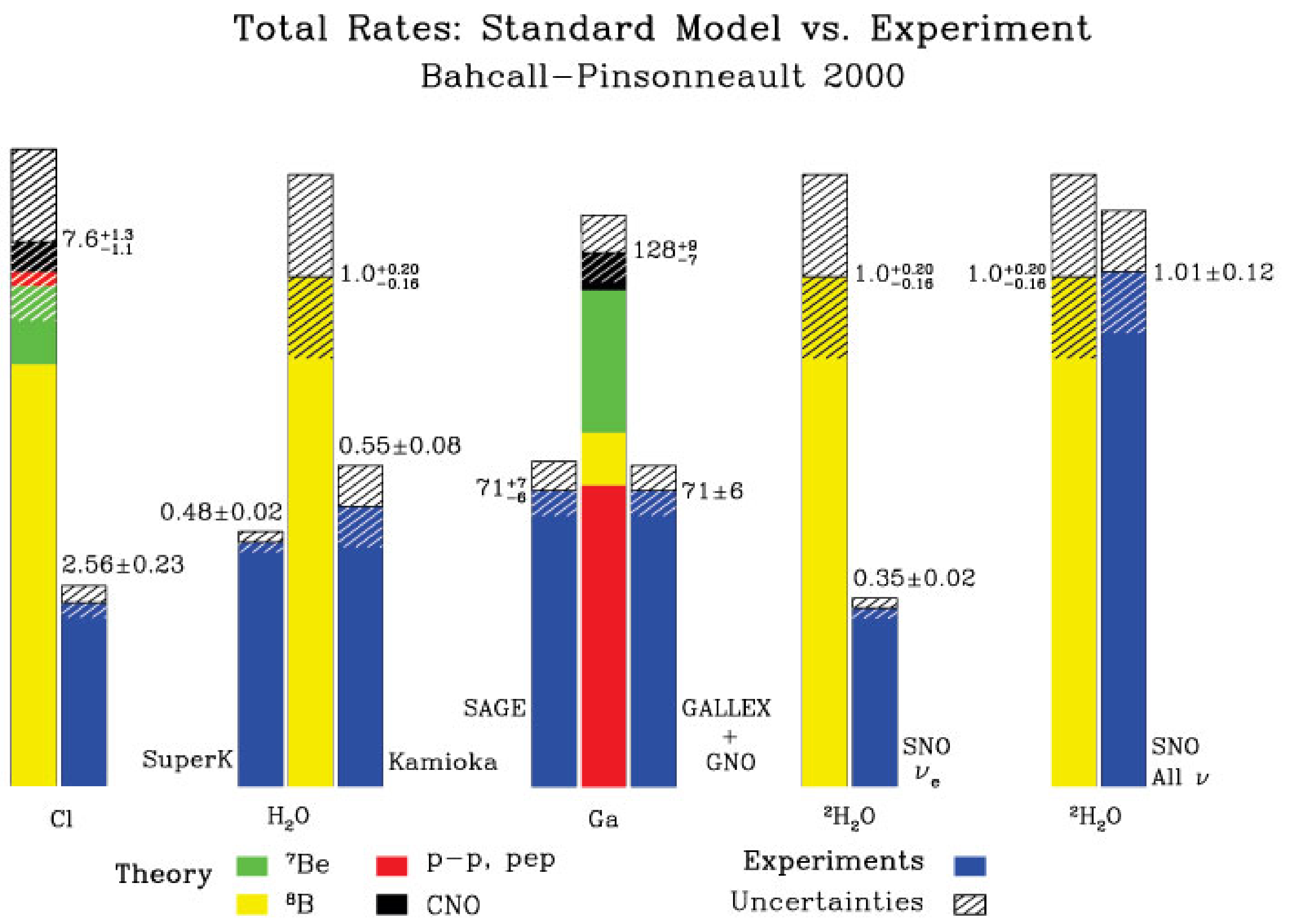
- Result from nuclear fusion process in the Sun
- Primary reactions and the neutrino energy from them are:

Name	Reaction	E_ν End point (MeV)
pp	$p+p \rightarrow D+e^{+}+\nu_e$	0.42
pep	$p+e^{-}+p \rightarrow D+\nu_e$	1.44
^{7}Be	$^7Be+e^{-} \rightarrow {}^7Li+\nu_e$	0.86
^{8}B	$^8B \rightarrow 2\left({}^4He\right)+e^{+}+\nu_e$	15

Solar Neutrino Energy Spectrum



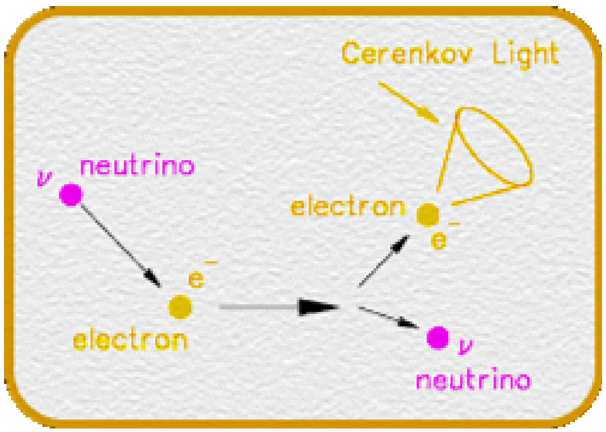
Comparison of Theory and Experiments



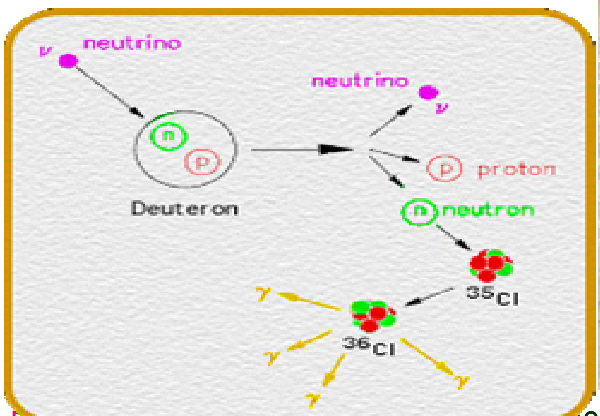
Sudbery Neutrino Observatory (SNO)

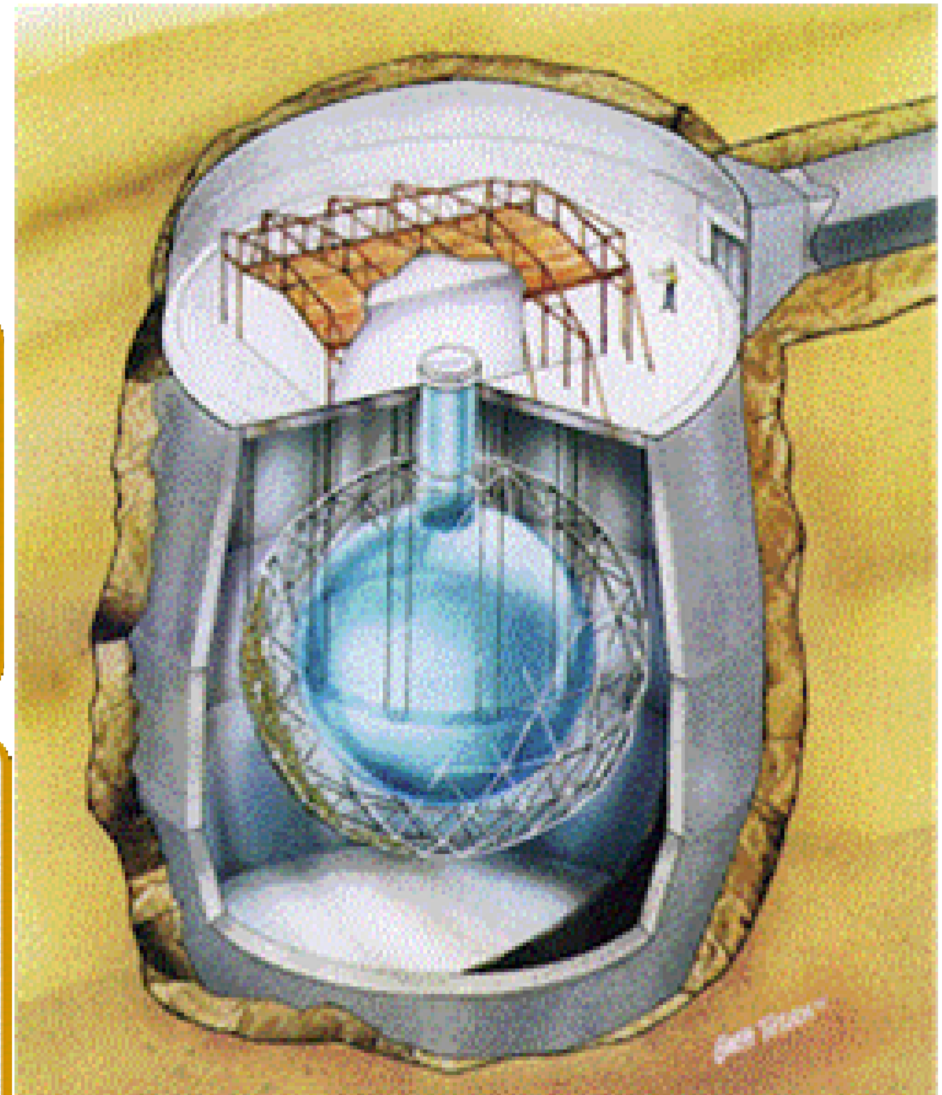
- Sudbery mine, Canada
- 6800 ft underground
- 12 m diameter acrylic vessel
- 1000 tons of D_2O
- 9600 PMT's

Elastic Scattering

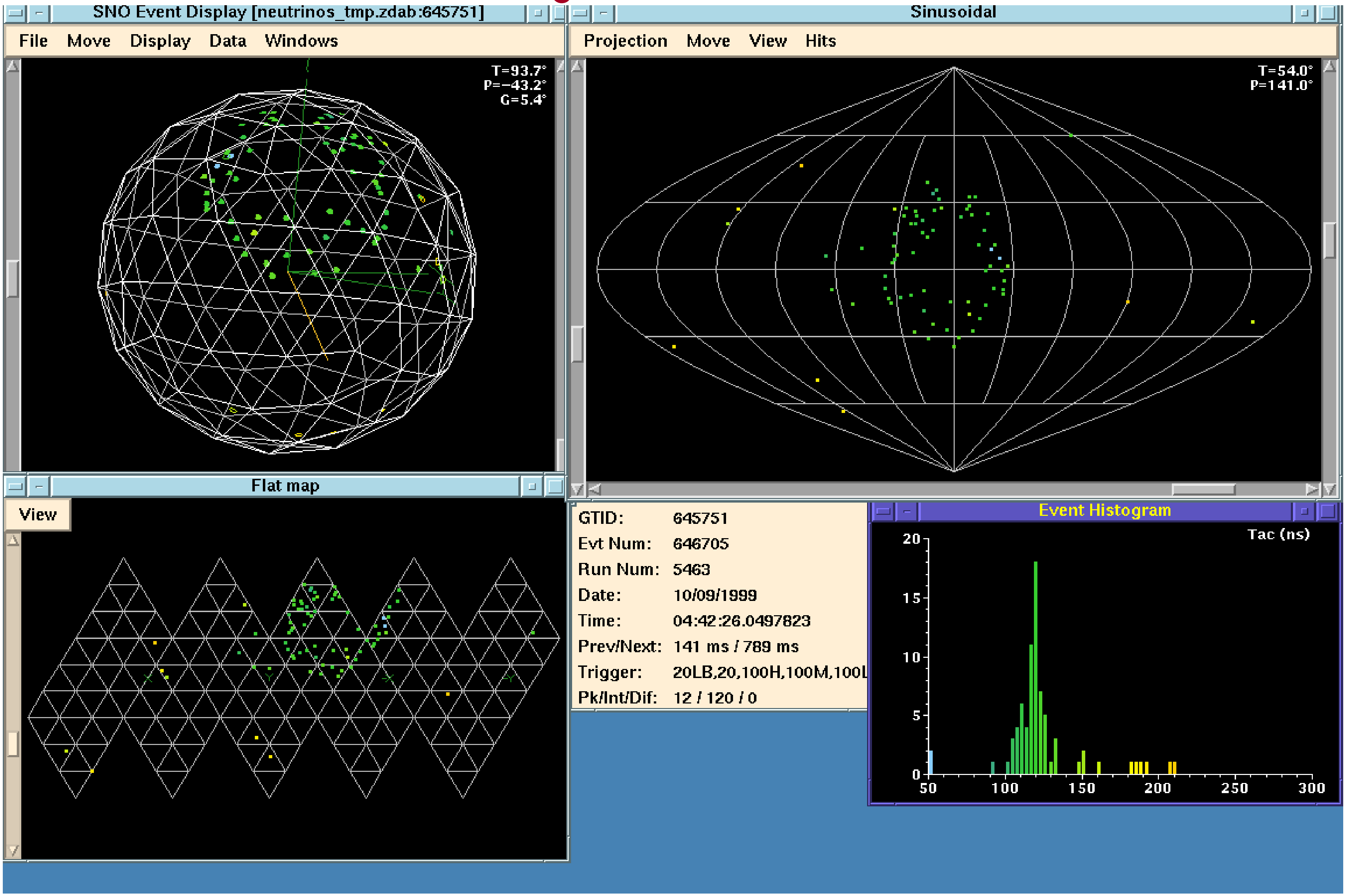


Inelastic Scattering

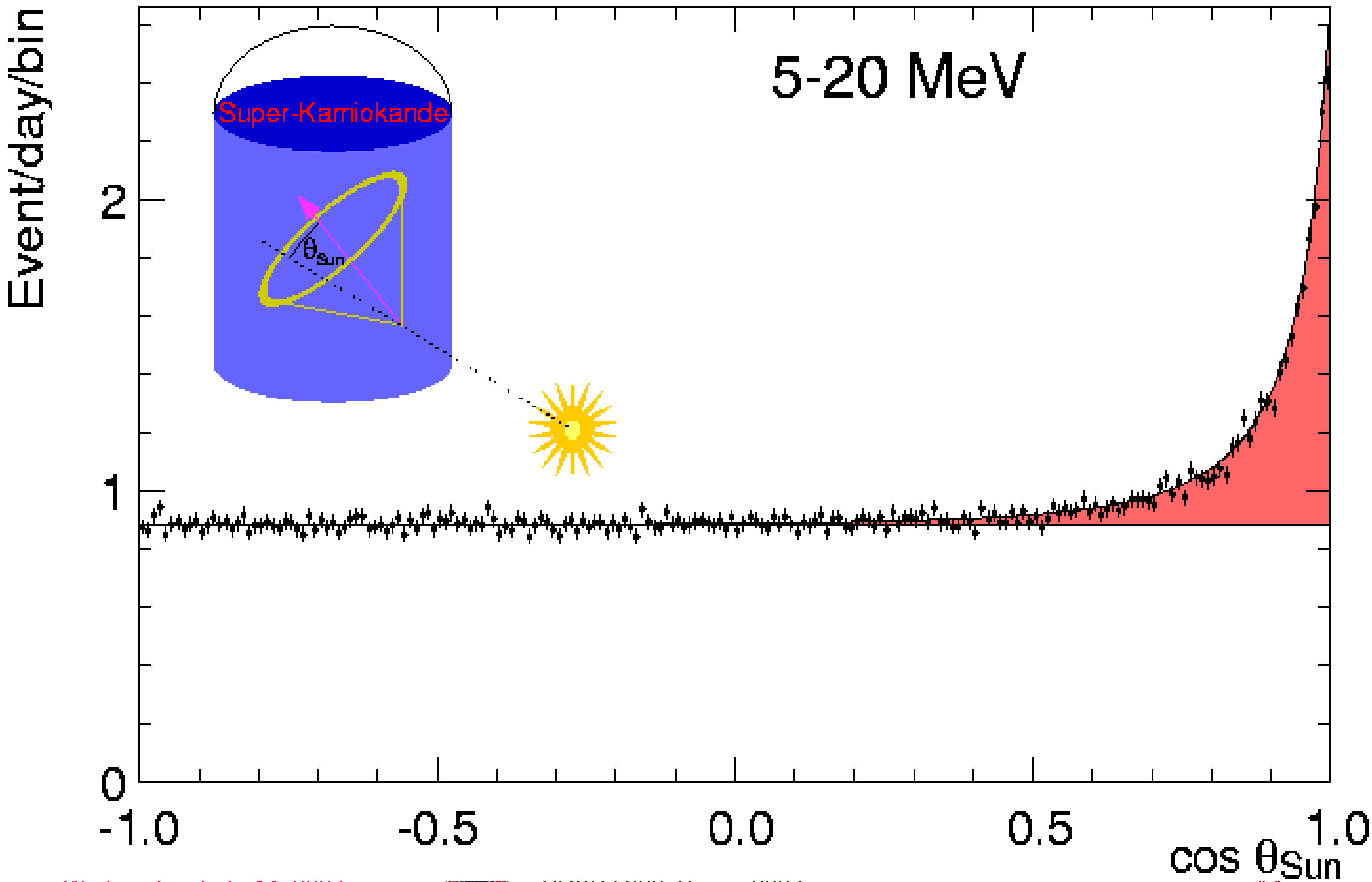




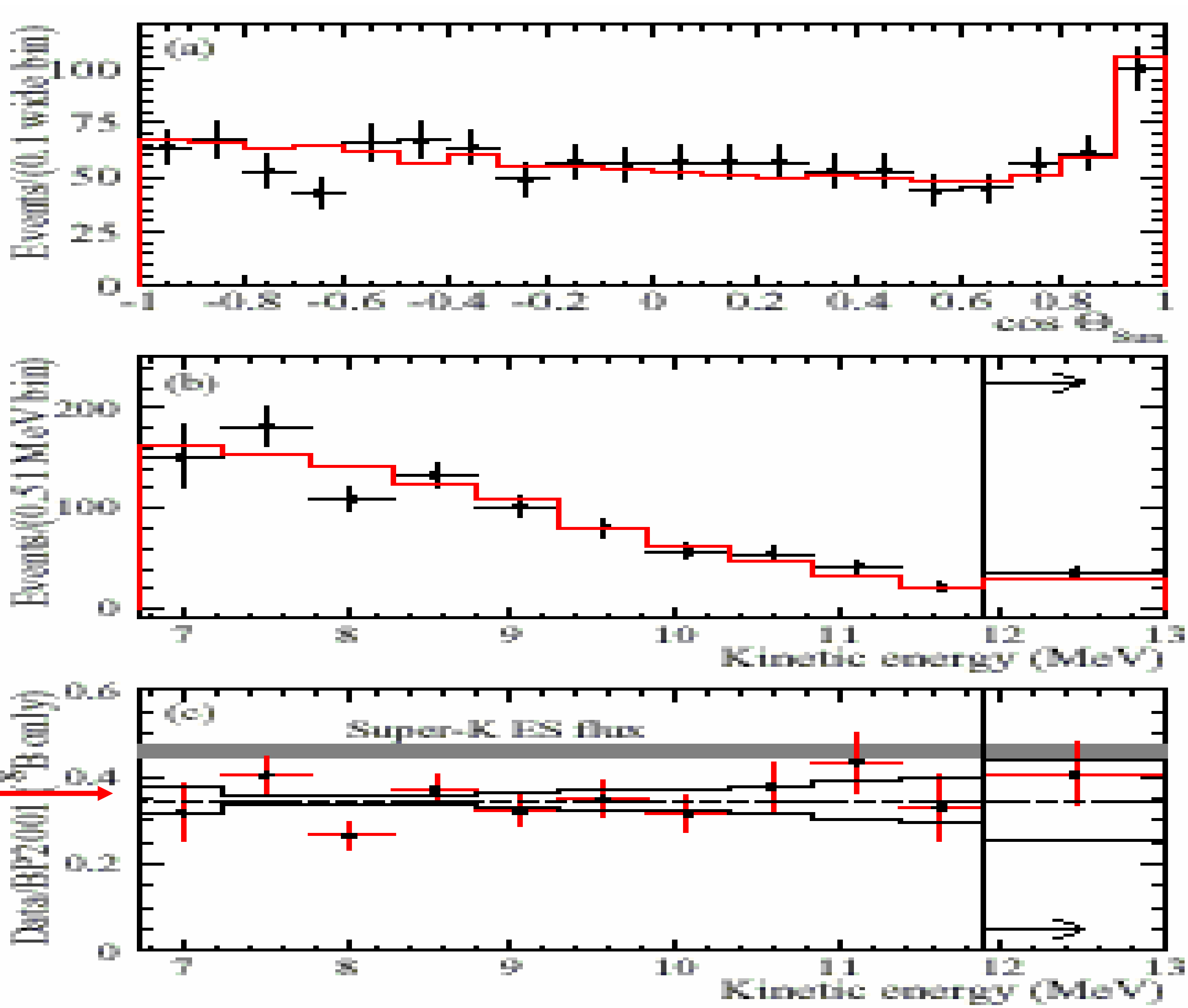
SNO ν_e Event Display



Solar Neutrino Flux



SNO First Results



0.35

Atmospheric Neutrinos

- Neutrinos resulting from the atmospheric interactions of cosmic ray particles
  - ν_μ to ν_e is about 2 to 1
  - He, p, etc + N $\rightarrow$ π,K, etc
    - $\pi \rightarrow \mu+\nu_\mu$
    - $\mu \rightarrow e+\nu_e+\nu_\mu$
  - This reaction gives 2 ν_μ and 1 ν_e
- Expected flux ratio between ν_μ and ν_e is 2 to 1
- Form a double ratio for the measurement

$$R \equiv \frac{\left(N_{\nu_e} / N_{\nu_\mu} \right)_{Exp}}{\left(N_{\nu_e} / N_{\nu_\mu} \right)_{The}}$$

Super Kamiokande

- Kamioka zinc mine, Japan
- 1000m underground
- 40 m (d) x 40m(h) SS
- 50,000 tons of ultra pure H_2O
- 11200(inner)+1800(outer) 50cm PMT's
- Originally for proton decay experiment
- Accident in Nov. 2001, destroyed 7000 PMT's
  - Virtually all PMT's below the surface of the water
- Dec. 2002 resumed data taking

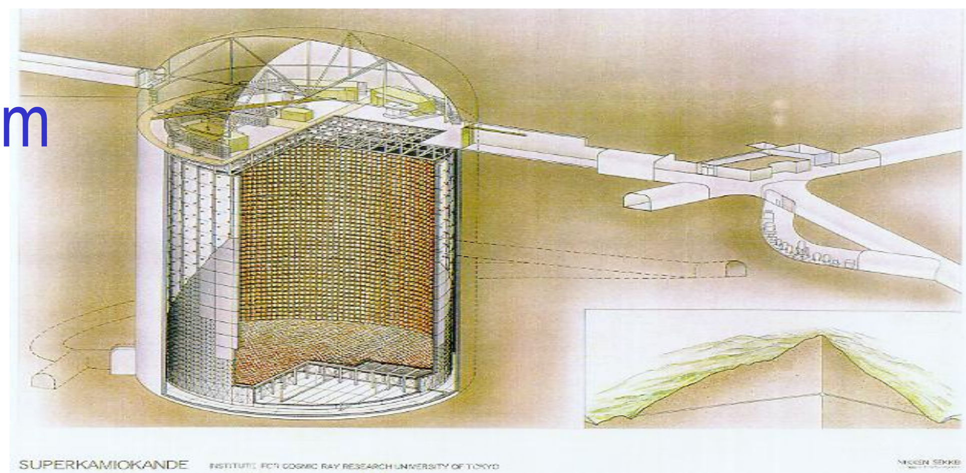
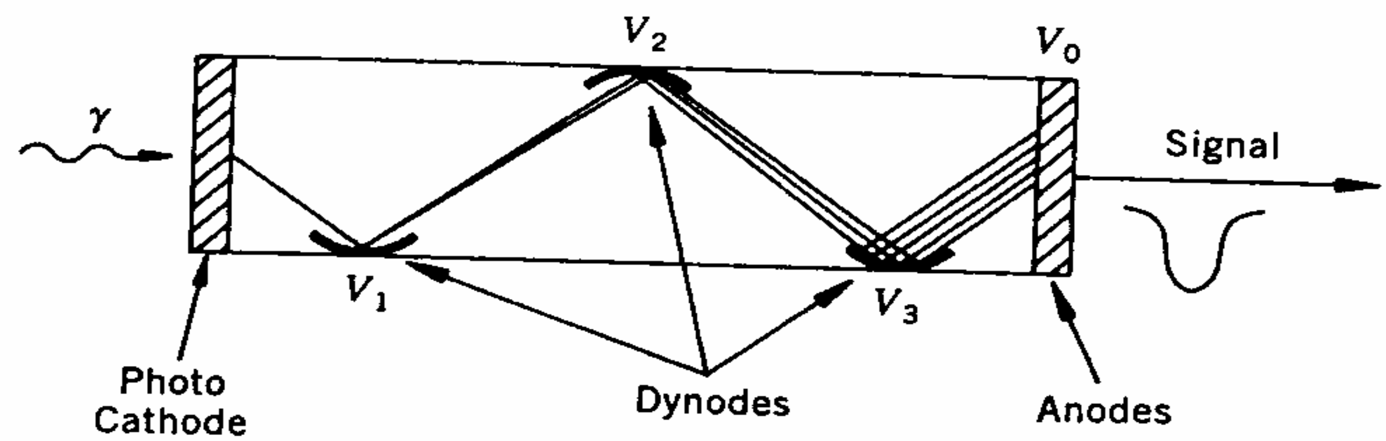
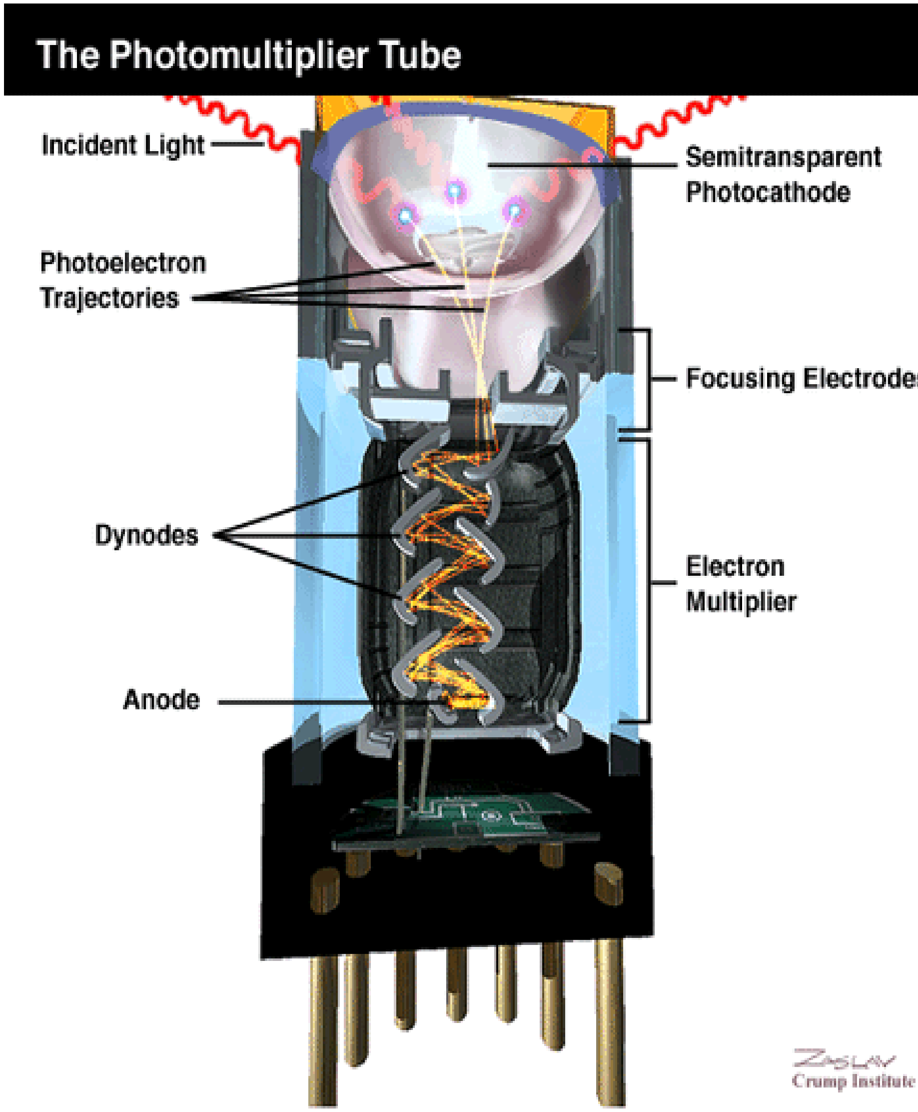


Photo-multiplier Tube

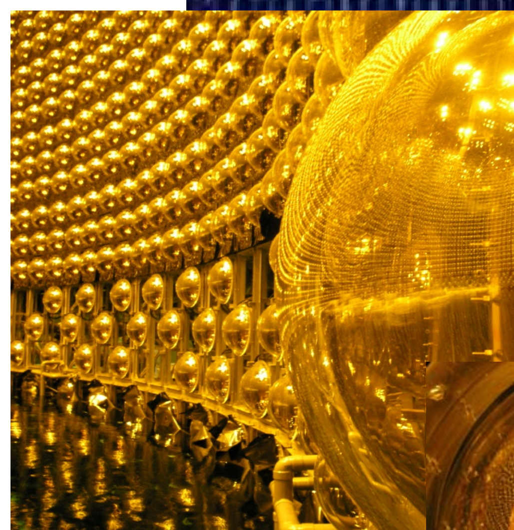


- The dynodes accelerate the electrons to the next stage, amplifying the signal to a factor of $10^4 - 10^7$
- Quantum conversion efficiency of photocathode is typically on the order of 0.25
- Output signal is proportional to the amount of the incident light except for the statistical fluctuation
- Takes only a few nano-seconds for signal processing
- Used in as trigger or in an environment that requires fast response
- Scintillator+PMT good detector for charged particles or photons or neutrons

Some PMT's



Super-Kamiokande detector



Homework Assignments

- Complete the derivation of the probability for ν_μ of energy E_ν to oscillate to ν_e at the distance $\mathcal{L}$ away from the source of ν_μ.
- Draw the oscillation probability distributions as a function of
  - Distance $\mathcal{L}$ for a fixed neutrino beam energy E_ν (=5, 50, 150 GeV)
  - E_ν for a detector at a distance $\mathcal{L}$ (=1.5, 735, 2200km) away from the source
- Due Wednesday, Feb. 21