Detection of Neutrinos and Neutrino Oscillations
(mainly solar neutrinos, reactor neutrinos)

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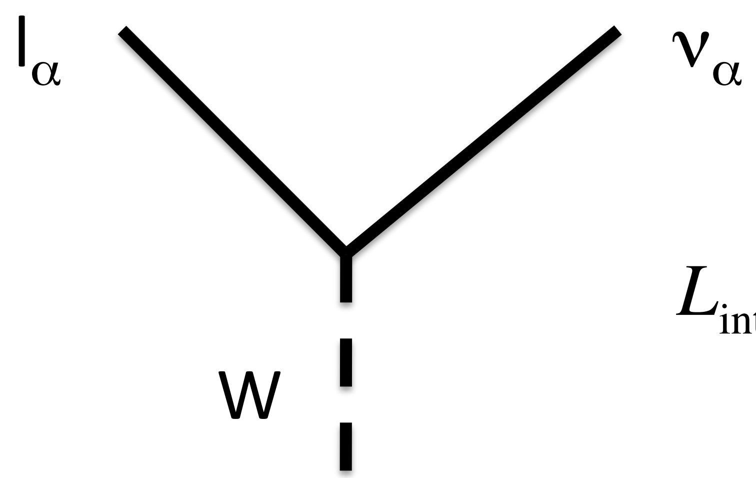
Neutrino Interactions

In the Standard Model neutrinos show up in 3 flavours and they are "partners" of charged leptons

$(\nu_e, \nu_\mu, \nu_\tau) \longleftrightarrow (e\,,\ \mu,\ \tau)$



$$L_{\text{int}} = -\frac{g}{\sqrt{2}} W^{\mu} \sum_{\alpha=\{e,\mu,\tau\}} \bar{\nu}_{L,\alpha} \gamma_{\mu} l_{L,\alpha} + \text{h.c.}$$

How to detect neutrinos

- **Elastic scattering**: $\nu_\alpha + l_\alpha \rightarrow \nu_\alpha + l_\alpha$
  - ✓ Mixture of Charge Current and Neutral Current
  - ✓ Measured quantity: kinetic energy of recoiled lepton in CC interactions; energy released by ionizing particles in NC
  - ✓ By conservation of energy and momentum determine $T^{max} = f(E_\nu)$ and $E_\nu^{min} = g(T)$
  - ✓ $\sigma \sim 10^{-44}$ cm^2 @ 1 MeV; $\sigma \sim 10^{-43}$ cm^2 @ 10 MeV
- **Inverse-beta decay**: **anti-ν_e + p -> n + e^+**
  - ✓ $\sigma \sim 10^{-42}$ cm^2
  - ✓ Strong tagging due to delayed neutron capture
- **ν_e–capture:** **ν_e + (A,Z) -> e^- + (A,Z+1)**
  - ✓ $\sigma \sim 9.3\times10^{-42} (E_\nu/10\text{MeV})^2$ cm^2

    $\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ (Q = 0.236 MeV)

    $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ (Q = 0.814 MeV)
- **NC**: **ν_α + A -> ν_α + A* and ν_α + p -> ν_α + p**
- Interactions on deuteron
  - ✓ **ν_e + d -> e^- + p + p**
  - ✓ **ν_x + d -> ν_x + p + n**

Interactions on nucleons **ν_α + N -> l_α + N**

Cross sections (order of magnitude)

$$\sigma\left(\nu_e + e^- \rightarrow \nu_e + e^-\right) \approx 0.95 \cdot 10^{-43} \left(\frac{E_\nu}{10\,MeV}\right) \text{cm}^2$$

$$\sigma\left(\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-\right) \approx 0.40 \cdot 10^{-43} \left(\frac{E_\nu}{10\,MeV}\right) \text{cm}^2$$

$$\sigma\left(\nu_\mu + e^- \rightarrow \nu_\mu + e^-\right) \approx 0.16 \cdot 10^{-43} \left(\frac{E_\nu}{10\,MeV}\right) \text{cm}^2$$

$$\sigma\left(\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-\right) \approx 0.40 \cdot 10^{-43} \left(\frac{E_\nu}{10\,MeV}\right) \text{cm}^2$$

$$\sigma\left(\bar{\nu}_e + p \rightarrow n + e^+\right) \approx 9.3 \cdot 10^{-42} \left(\frac{E_\nu}{10\,MeV}\right)^2 \text{cm}^2$$

$$\sigma(\nu N) \approx 10^{-38} \text{ cm}^2 / \text{nucleon @ 1GeV}$$

ultra high energy

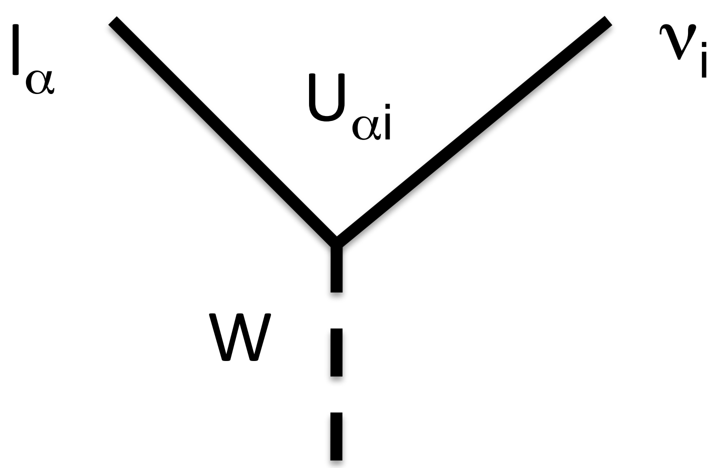
$$\sigma_{CC}(\nu N) \approx 3 \cdot 10^{-36} \left(\frac{\text{E}_\nu}{\text{1GeV}}\right)^{0.4} \text{cm}^2 / \text{nucleon}$$

$$\sigma_{NC}(\nu N) \approx 10^{-36} \left(\frac{\text{E}_\nu}{\text{1GeV}}\right)^{0.4} \text{cm}^2 / \text{nucleon}$$

Neutrino Mixing

If neutrino are massive one can distinguish between mass and flavour eigenstates

$(\nu_e, \nu_\mu, \nu_\tau) \longleftrightarrow (\nu_1, \nu_2, \nu_3)$



$$\nu_{L,\alpha} = \sum_{i=1}^{3} U_{\alpha i} \nu_i$$

$$\sum_{i=1}^{3} U_{\alpha i} U^*_{\beta i} = \delta_{\alpha\beta}$$

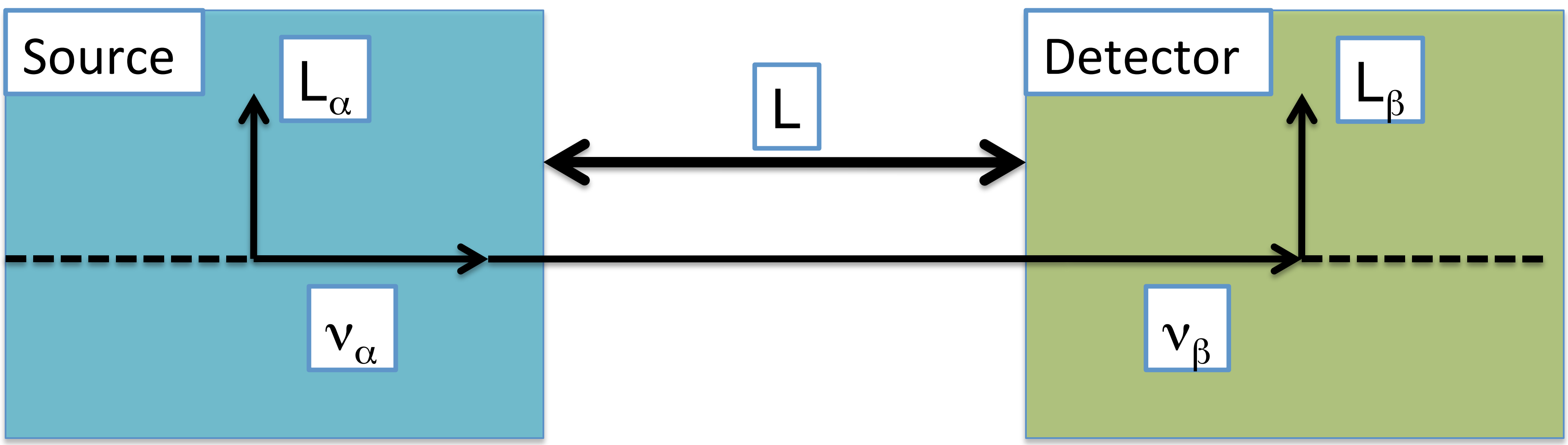
The Mixing Matrix

For the case of n=3 there are
3 angles
1 Dirac phase
2 Majorana phases

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

Neutrino Oscillations

Consider a neutrino source and a detector located a distance L away



$$A(\alpha \rightarrow \beta) = \langle \nu_\beta | propagator | \nu_\alpha \rangle = \sum U^*_{\beta i} U_{\alpha i} \mathrm{Pr}\,op(i)$$

Evolution equation

For a mass eigenstate the evolution equation in the rest frame is written:

$$i\frac{d}{d\tau}\left|\nu_i\right\rangle = m_i\left|\nu_i\right\rangle$$

$$\left|\nu_i\right\rangle = e^{-im_i\tau}\left|\nu_i(0)\right\rangle$$

Moving to the lab. frame:

$$(m_i,0)\cdot(\tau_i,0) = (E_i,p)\cdot(t,L)$$

$$m_i\tau_i = E_i t - pL = E_i(t-L) + \frac{m_i^2}{2E}$$

Dropping a constant phase:

$$\text{using E} = \sqrt{p^2 + m_i^2} \approx p + \frac{m_i^2}{2p}$$

$$\Pr op(i) = e^{-i\frac{m_i^2}{2E}L}$$

Oscillation Probability in vacuum

$$P_{\alpha\to\beta} = \left|\sum_i U^*_{\beta i} U_{\alpha i} e^{-i\frac{m_i^2}{2E}L}\right|^2 = \sum_{i,j} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\frac{m_i^2 - m_j^2}{2E}L}$$

$$P_{\alpha\to\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 + 2\sum_{j>i} U^*_{\beta i} U_{\alpha i} U^*_{\alpha j} U_{\beta i} e^{-i\frac{m_i^2 - m_j^2}{2E}L}$$

$$V_{\alpha\beta ij} = U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}$$

$$k_{ij} = \frac{m_i^2 - m_j^2}{2E}$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{j>i} \mathrm{Re}(V_{\alpha\beta ij}) \sin^2\left(\frac{k_{ij}}{2}L\right) + 2\sum_{j>i} \mathrm{Im}(V_{\alpha\beta ij}) \sin\left(k_{ij}L\right)$$

The Oscillation phase

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{j>i}\mathrm{Re}(V_{\alpha\beta ij})\sin^2\left(\frac{k_{ij}}{2}L\right) + 2\sum_{j>i}\mathrm{Im}(V_{\alpha\beta ij})\sin\left(k_{ij}L\right)$$

$$\text{Oscillation phase:}\quad \phi \equiv \frac{k_{ij}}{2}L = \frac{m_i^2 - m_j^2}{4E}L$$

$$\begin{cases} P_{\alpha\to\beta} = 0 \text{ if } \phi << 1 \\ P_{\alpha\to\beta} \text{ observable if } \phi \sim \pi/2 \;\Rightarrow\; \Delta \mathrm{m}^2 \sim E/L \\ P_{\alpha\to\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2 \text{ if } \phi >> \pi/2 \text{ very long distance} \end{cases}$$

$$\text{Problem: prove that } \phi = 1.27\left(\frac{\Delta m^2}{eV^2}\right)\left(\frac{MeV}{E}\right)\left(\frac{L}{m}\right)$$

The case of two-neutrino oscillations

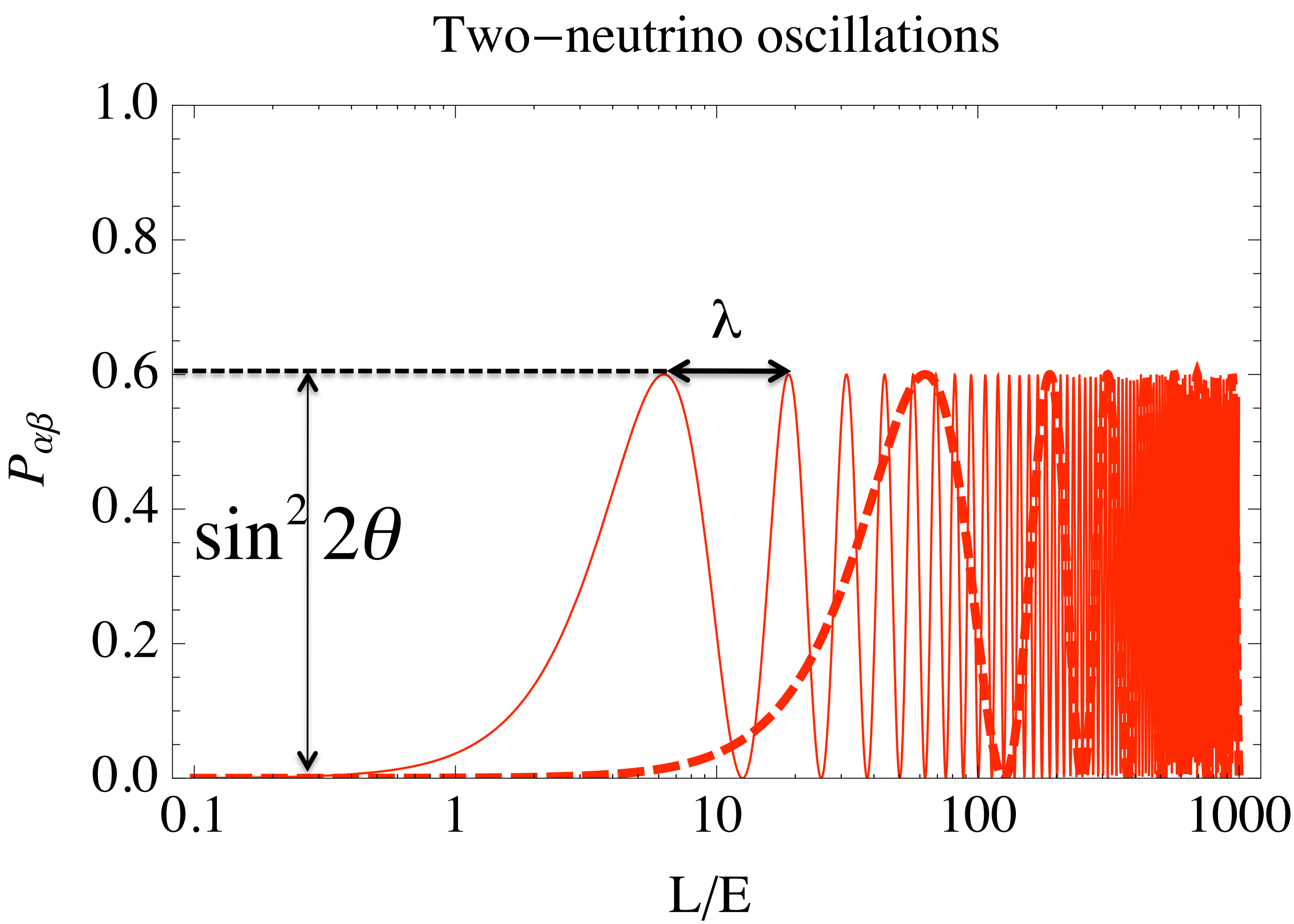
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m_{12}^2}{4E} L\right) = \sin^2 2\theta \sin^2\left(\frac{k_{12}}{2} L\right) =$$

We can define an oscillation length: $\lambda = \frac{2\pi}{\mathrm{k}_{12}} = \frac{4\pi E}{\Delta m_{12}^2}$

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\pi \frac{L}{\lambda}\right)$$

Maximum sensitivity to oscillations phase when L ~ $\lambda/2$

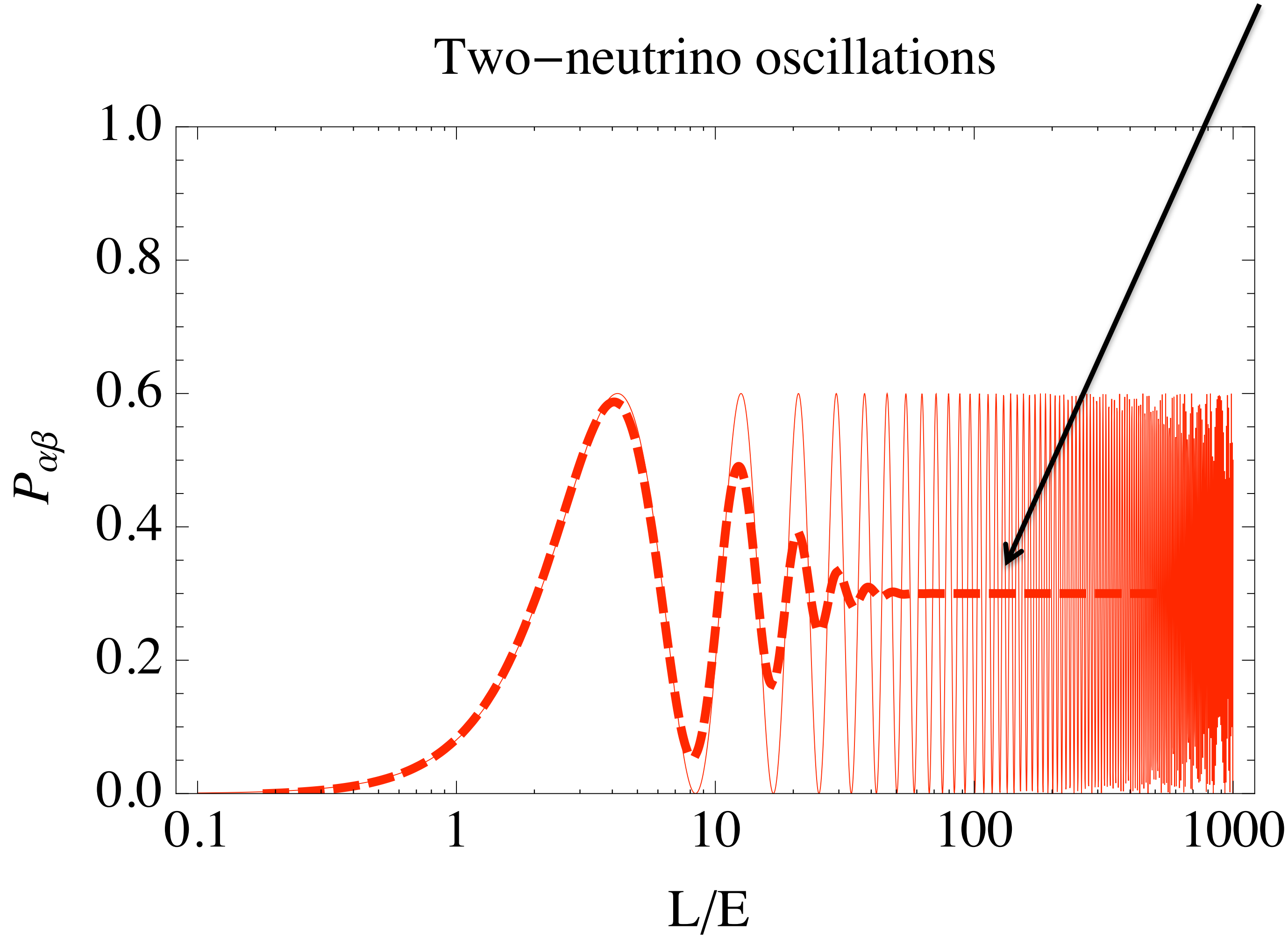


Δm^2 = 1[0.1] eV^2 and $\sin^2 2\theta$=0.6

Including detector properties:
- detector finite energy resolution
- source energy spectrum

Smearing of oscillation term

$$\langle P_{\alpha\beta} \rangle = 1 - \frac{1}{2}\sin^2 2\theta$$



Neutrino oscillation experiments

APPEARANCE: search for a new flavour in a given flavour neutrino beam

$$P_{\alpha\beta}(\Delta m_{ij}{}^2, \theta_{ij}, E, L) \quad \text{with} \quad \alpha \neq \beta$$

DISAPPEARANCE: measure the survival probability

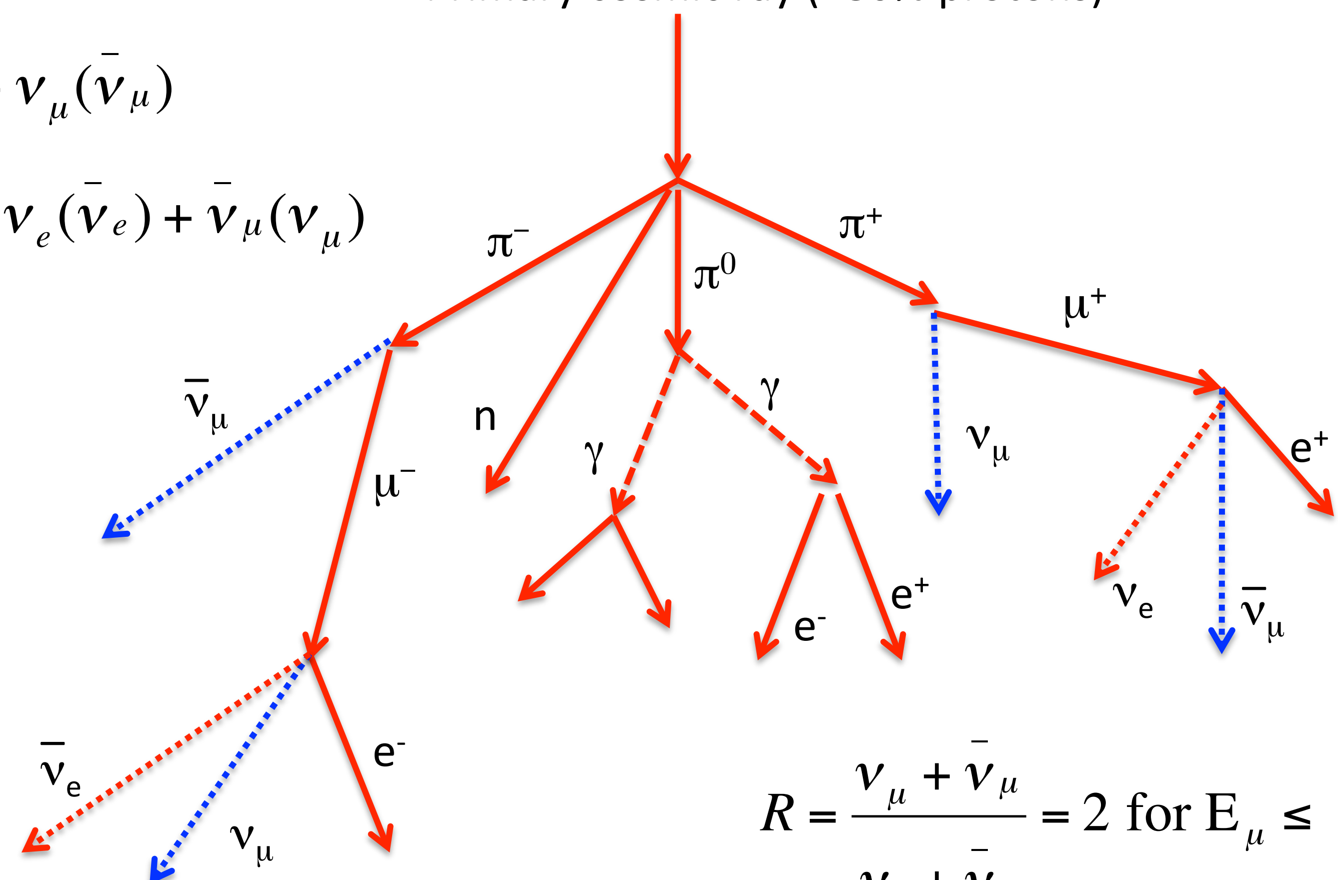
$$P_{\alpha\alpha}(\Delta m_{ij}{}^2, \theta_{ij}, E, L)$$

Δm_{ij}^2 and θ_{ij} are physical constant
E and L source-detector properties to be tuned

Atmospheric Neutrinos

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$



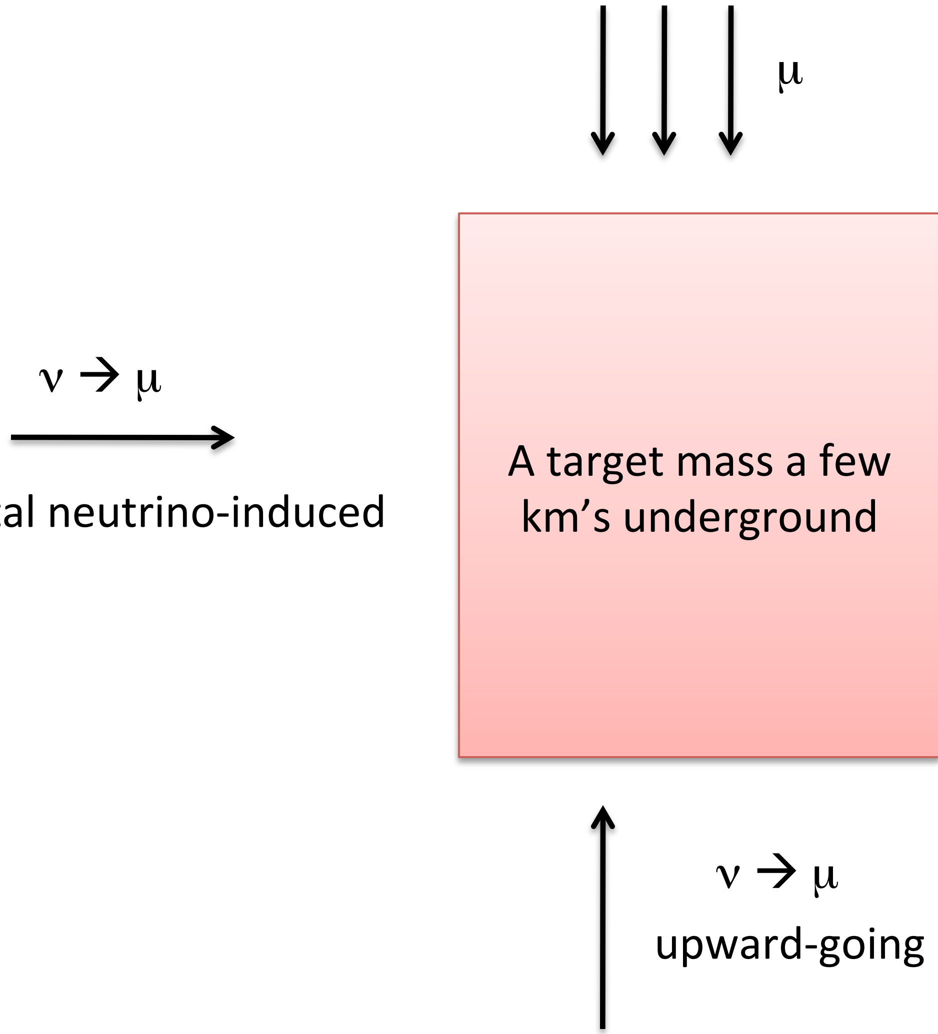
$$R = \frac{\nu_{\mu} + \bar{\nu}_{\mu}}{\nu_{e} + \bar{\nu}_{e}} = 2 \text{ for } \mathrm{E}_{\mu} \leq 1\mathrm{GeV}$$

$$\frac{\phi_{\nu_{\mu}}}{\phi_{\bar{\nu}_{\mu}}} \sim 1 \quad \frac{\phi_{\nu_{\mu}}}{\phi_{\bar{\nu}_{\mu}}} \sim \frac{\phi_{\nu_{e}}}{\phi_{\bar{\nu}_{e}}}$$

Neutrino energy range of experimental
Interest: 100 MeV – 100 GeV

Searching for atmospheric neutrinos underground

secondary downward-going cosmic-ray muons in underground site



horizontal neutrino-induced muon

upward-going neutrino-induced muon

- atmospheric neutrino flux almost isotropic
- neutrinos can generate upward-going and horizontal muons
- detectors can record muon tracks and/or identify muon-induced events

Classes of Events from Atmospheric Neutrinos

- Sub-GeV and multi-GeV contained events
  - Fully contained events in the range 0.1 – 100 GeV
- Stopping and through-going muons
  - Events induced by muons which have been produced outside the detector
  - Energy range: 1 GeV – 10 TeV
- Pathlengths
  - ~20 km downward-going muons
  - ~13000 km upward-going muons

- Depth of atmosphere: $\rho=\rho_0 \exp(-h/H)$
  - H = 6.5 km
  - ρ_0 = 1030 g/cm^2

- Mean life of $\pi^{\pm}$ ~ 26ns, $m_\pi c^2$=139 MeV
  - mean distance ~ 55 m for 1 GeV π

- Mean life of $\mu^{\pm}$ ~ 2200ns, $m_\pi c^2$=105 MeV
  - mean distance ~ H for 1 GeV μ
  - μ with energy < 1GeV will decay in flight before arriving to the Earth's surface
  - A multi-GeV muon will arrive to the surface w/o decaying or being absorbed due to ionization

    [$dE/dx(\text{multi-GeV})_{ion}$ ~ 2 MeV/(g/cm^2)]

Neutrino flux calculation

- Measure primary cosmic ray: $\phi(E) \sim E^{-(1+\delta)}$ with $\delta \sim 1.7\text{-}2$
  - Flux of primary cosmic rays ($1 - 10^4$ GeV) ~ 10^4 nucleons/m^2 s sr GeV
- Model interactions of primary particles
- Model production and propagation of secondary particles
- Determine neutrino fluxes from decays of mesons and muons

$$\frac{d\phi_\pi}{dh} = -\frac{\phi_\pi}{\lambda_{\text{int}}} - \frac{\phi_\pi}{\lambda_{decay}} + \Gamma_{N\pi} + \Gamma_{\pi\pi}$$

$$\lambda_{\text{int}} = \frac{\rho}{n\sigma} \quad \lambda_{decay} = \rho c \gamma \tau$$

$$\frac{d\phi_{\nu_\mu}}{dh} = \int_E^0 dE_\pi \frac{\phi_\pi}{\lambda_{decay}} \frac{dN_{\nu_\mu}}{dE}$$

Observations of Atmospheric Neutrinos [1]

- **M. Markov** advocate the experimental feasibility of atmospheric neutrino detection in **1960**
- **Late 1960s** two tracking scintillator detectors deep underground in South **India** and **South Africa** – gold mines
- Deep underground muons almost vertical downward-going
- Upward-going neutrinos can produce upward-going or <u>horizontal</u> muons

Observation of Atmospheric Neutrinos [2]

- In **1980s** two water Cherenkov detectors: **IMB**(USA) and **Kamiokande**(Japan)
  - Neutrino interactions in the detector and upward-going muons
  - Kamiokande: 2142 ton of purified water; outer detector with 1500tons
  - IMB: 8000 ton of water; FM=3300 ton
- **1996**: Super-Kamiokande could observe an up-down asymmetry
  - 50kton of purified water with 22.5 FM; 11146 50cm diamter PMTs, 40% coverage
- Same result from **MACRO**(1988-2000, Gran Sasso) with a liquid scintillator and tracking detectors for muons; and, **Soudan-2**, iron tracking calorimeter

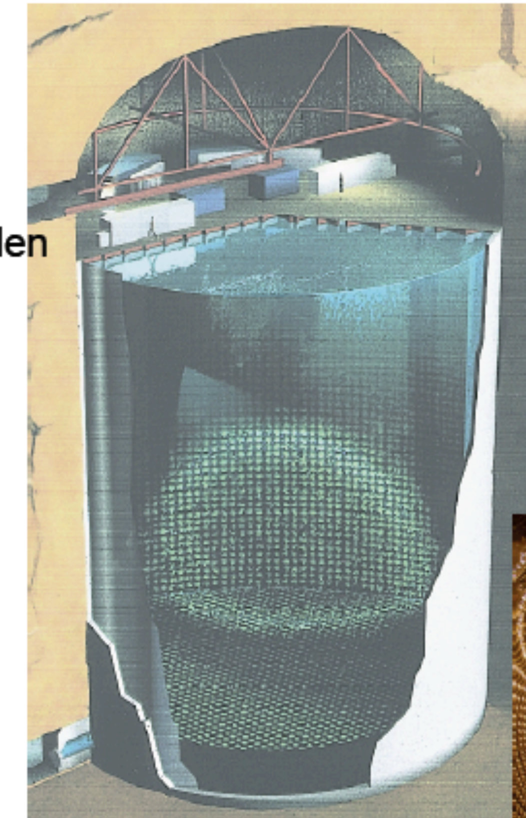
Super-Kamiokande

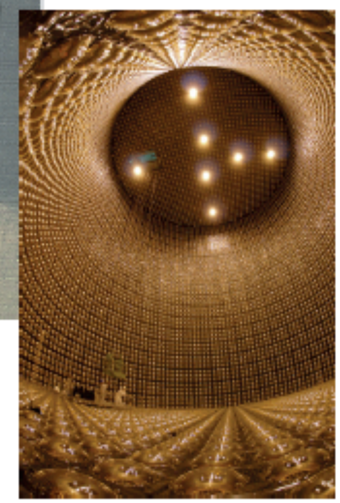
Kamioka-Mozumi zinc mine
1 km (2700 meters-water-equiv.) rock overburden

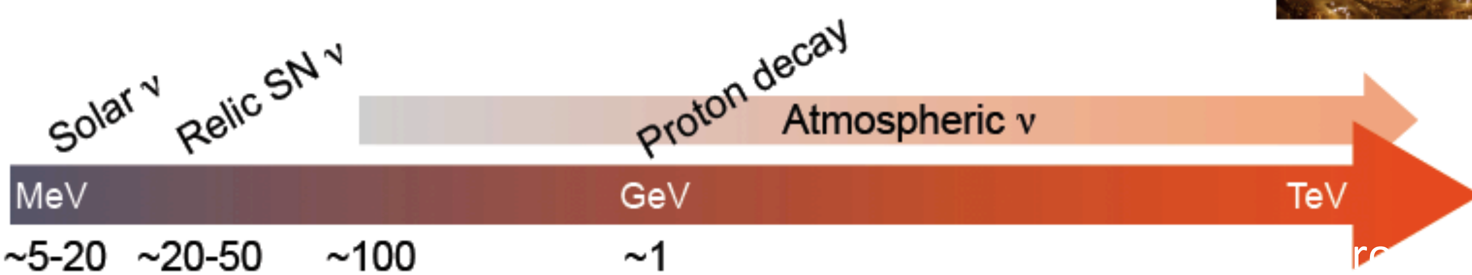
Water Čerenkov detector
50 ktons (22.5 ktons fiducial)

Instrumented with
50-cm PMTs in Inner Detector (ID)
20-cm PMTs in Outer Detector (OD)

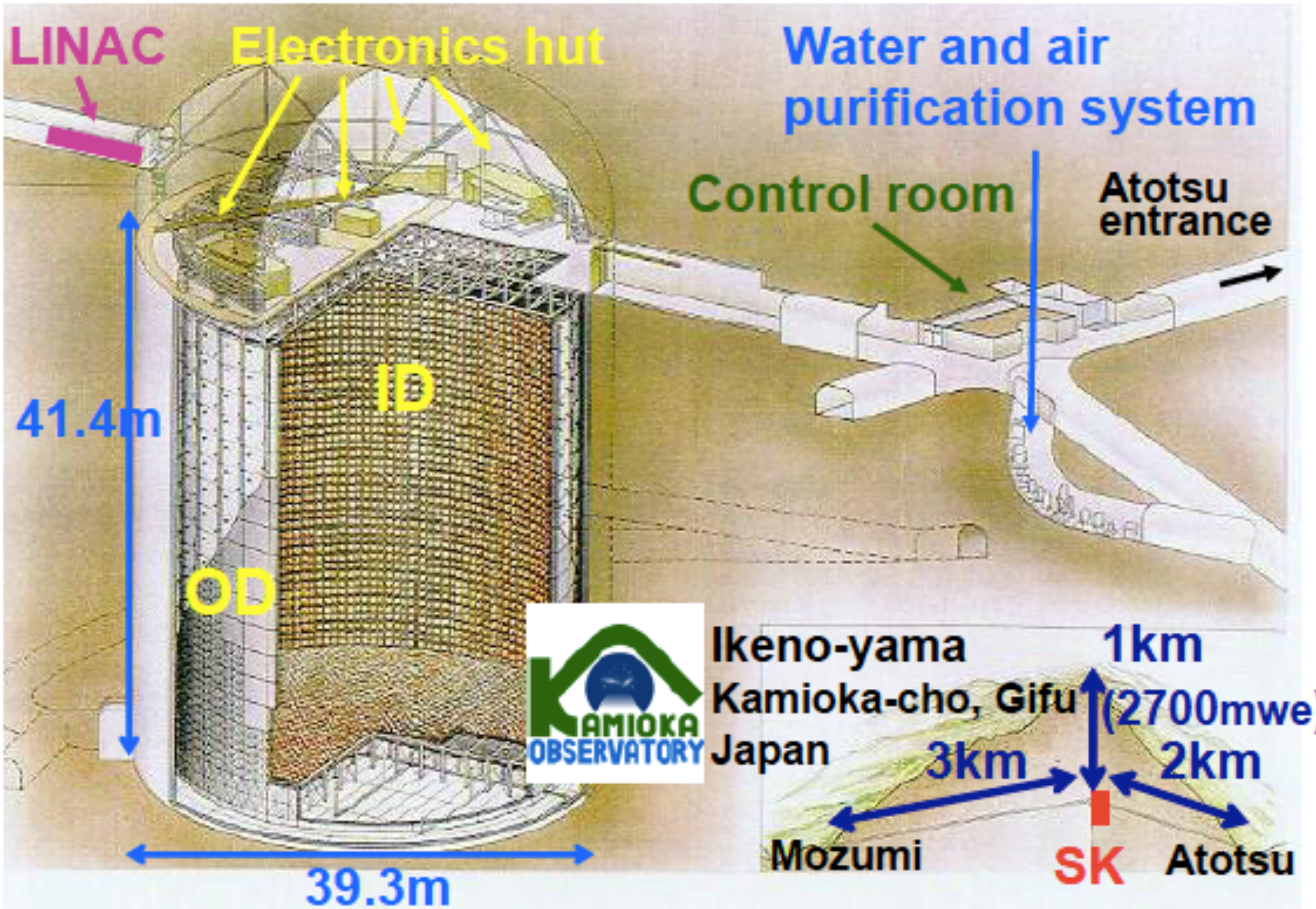
Goals of Super-K
Solar neutrinos
Supernova neutrinos (+ relic SN)
Atmospheric neutrinos
Proton decay







Super-Kamiokande detector

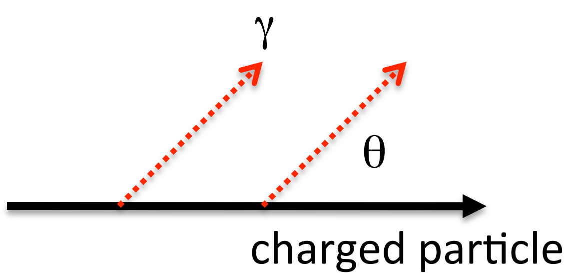


- 50kton water
- ~2m OD viewed b
  8-inch PMTs
- 32kt ID viewed by
  20-inch PMTs
- 22.5kt fid. vol.
  (2m from wall)
- SK-I: April 1996~
- SK-IV is running
- Trigger efficiency
  >99%@4.0MeV$_{ki}$
  ~86%@3.5MeV$_{ki}$

Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

Y. Takeuchi at PHYSUN 3rd

Consideration on Water Cherenkov Detector



$$\cos\theta = \frac{1}{n\cdot\beta} \quad \text{with } \beta \geq \frac{1}{\mathrm{n}}$$

$$T_{threshold} = mc^2\left(\frac{n}{\sqrt{n^2-1}} - 1\right)$$

$$n_{H_2O} = 1.33 \text{ for e}^- \ \mathrm{T}_{\mathrm{threshold}} = 0.264\,MeV \text{ for } \mu^- \ \mathrm{T}_{\mathrm{threshold}} = 54.3\,MeV$$

$$\frac{dN_\gamma}{dx} \approx 490\cdot\sin^2\theta_c \text{ photons/cm with } \cos\theta_{\mathrm{c}} = 1/n$$

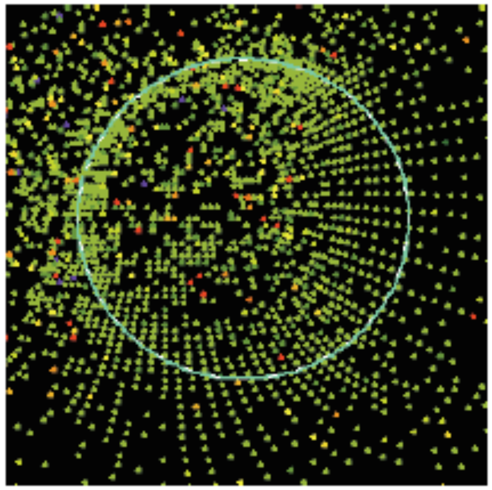
$$\text{in water: } \mathrm{N}_\gamma \approx 490\cdot 0.435\cdot L(cm)$$

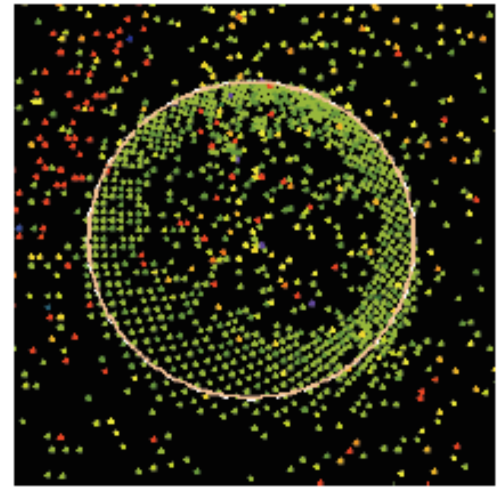
In Super-Kamiokande: take L~10m, light attenuation length ~ 80m, PMTs coverage ~ 40%, PMTs QE ~ 20%, 65% collection efficiency on 1st dynode

$$N_{p.e.} = C\cdot\eta\int d\nu N_\gamma(\nu) QE(\nu) e^{-L/\lambda(\nu)} \approx (490\cdot 0.435\ \gamma/\mathrm{cm})\cdot\left(0.45\frac{T_e}{MeV}\ \mathrm{cm}\right)\cdot e^{-10/80}\cdot 0.4\cdot 0.2\cdot 0.65 \approx 4\frac{T_e}{MeV}$$

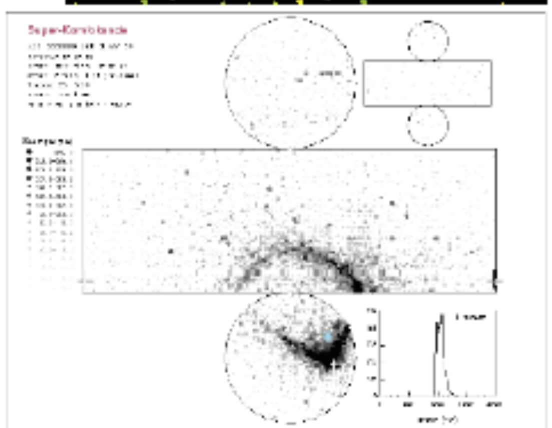
A threshold at 5MeV implies ~ 20 p.e. with an energy resolution of ~$0.20/\sqrt{T_e}$

Telling Electrons from Muons

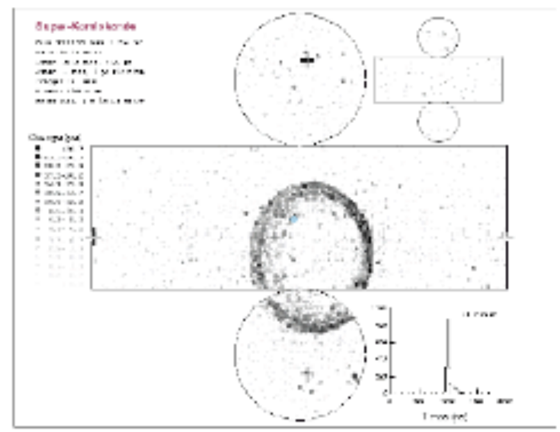




Compare profile of ring against a shape likelihood.



Electrons bremstrahlung and pair produce making many particles each making light.



Thickness gives momentum

Muons move forward producing a single cone of light.

C. Walter, INSS 2012

Liquid Scintillator

- Material reach in hydrogen and electrons
  - Good for neutrino-electron ES and inverse-beta decay
- Scintillator = solvent(bulk) + solute
  - Solvent needs to be transparent (low light quenching)
- Light yield ~ 10^4 photons/MeV
  - $N_{p.e.} \sim 10^4\ e^{-6/10}\ 0.25\ 0.9\ 0.3 = 370$ p.e./MeV
  - Energy resolution ~ $0.05/\sqrt{T_e}$

Scintillation

$$N_{\mathrm{ph}} = Y_{\mathrm{scint}} \times E \times Q(E)$$

$$Q(E) = \frac{1}{E} \int_0^E \frac{\mathrm{d}E'}{1 + kB \frac{\mathrm{d}E}{\mathrm{d}x}(E')}$$

$$N_{\mathrm{pe}} = Y_{\mathrm{det}} \times E \times Q(E)$$

Y_{det} and kB are detector parameters

Photoelectrons picked up by photomultipliers (PMTs)

Sources of background

- Long-lived radio-isotopes (**^{238}U,^{232}Th,^{40}K**)
- **^{222}Rn** (noble gas) -> **^{214}Bi** (3.2MeV β with many γ-rays)
- ^{232}Th -> **^{208}Tl** (2.6 MeV γ-ray largest in natural radioactivity + 5 MeV β)
- In water Rn as large as 10^4 Bq/m^3
- Reduce Rn background by means of N_2 Rn-free stripping

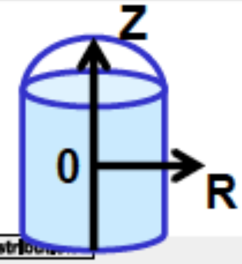
Tight fiducial volume cut in SK-IV

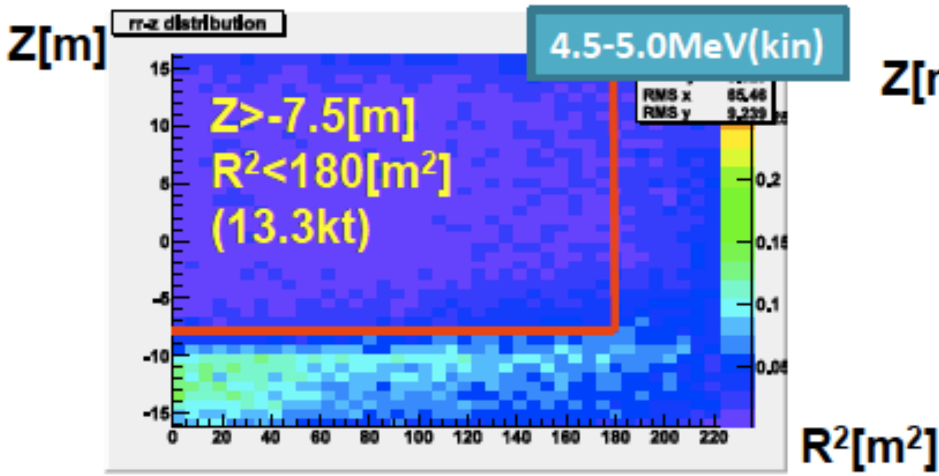
May 2012

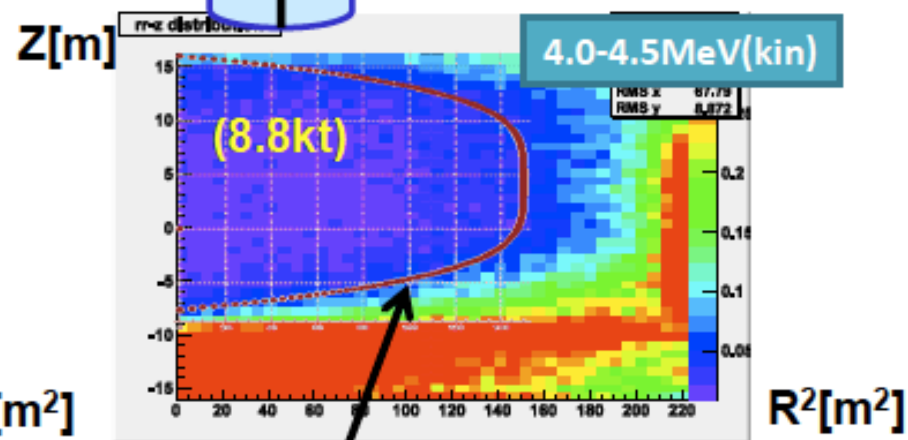
Preliminary

SK-IV 1069 days

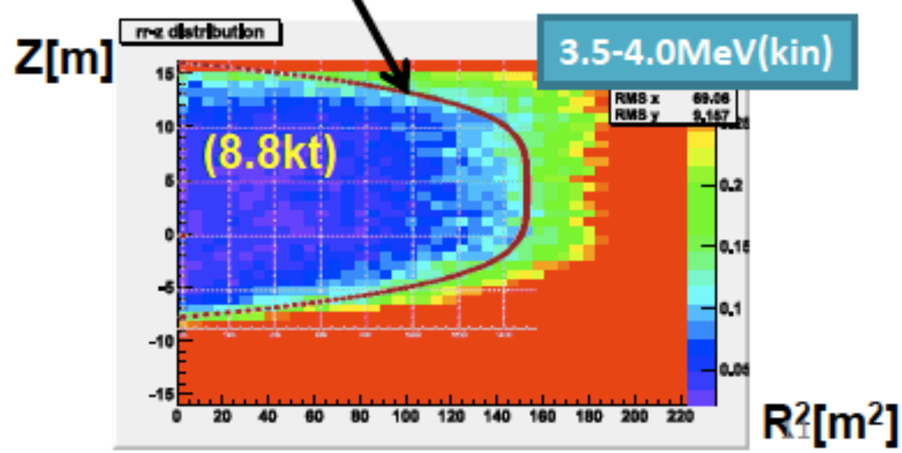
Color : Events/day/bin low→high







R+(150/11.75⁴)*|Z-4.25|⁴<150



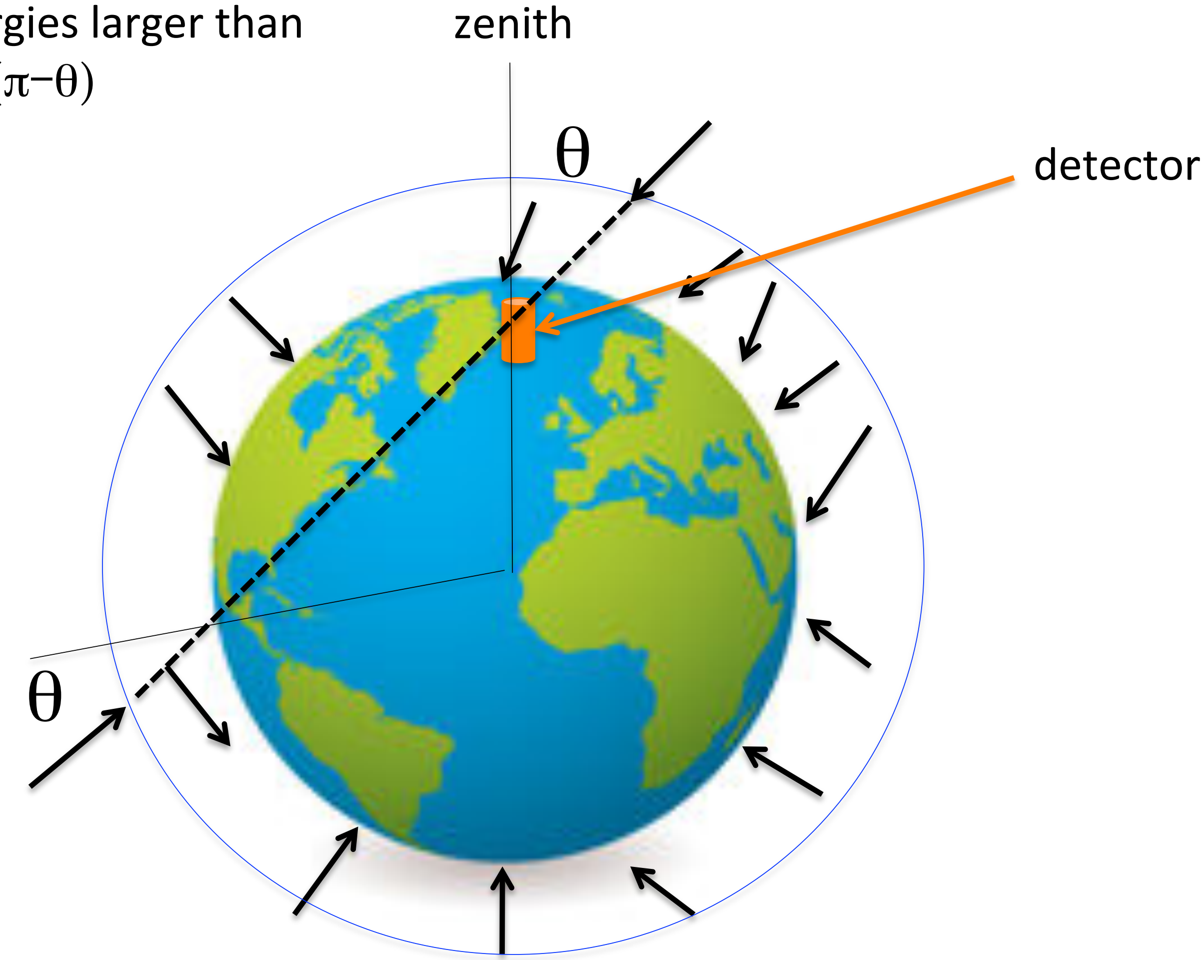
- Whole area in these plots corresponds to 22.5kton
- Above 5.0MeV(kin), fiducial volume is 22.5kton
- Below 5.0 MeV(kin), tight fid. vol. cut is applied to reduce events from detector wall.

Expected events in Super-Kamiokande

- Rate = Flux(E) × Cross-Section × Target
- For Super-K: 22.5 kton of water
- Atmospheric neutrinos on average ~ 1GeV
- Flux ~ 1 cm^2/s
- Cross-section ~ 10^{-38} cm^2/nucleon @ 1GeV
- Target nucleons: $(N_A/18) \times 18 \times 22.5 \times 10^6 = 1.35 \times 10^{34}$ nucleons/kton

$$Rate[cpd/FM] \approx \left(1\ \mathrm{cm}^2/s\right) \cdot \left(10^{-38}\ \mathrm{cm}^2/nucleons\right) \cdot \left(1.35 \cdot 10^{34}\ \mathrm{nucleons/FM}\right) \cdot \left(8.64 \cdot 10^4\ \mathrm{s/day}\right) = 11.7$$

Isotropic flux of primary cosmic rays
implies up-down neutrino flux symmetry at energies larger than ~ 2GeV: $\phi_\nu(\theta)=\phi_\nu(\pi-\theta)$



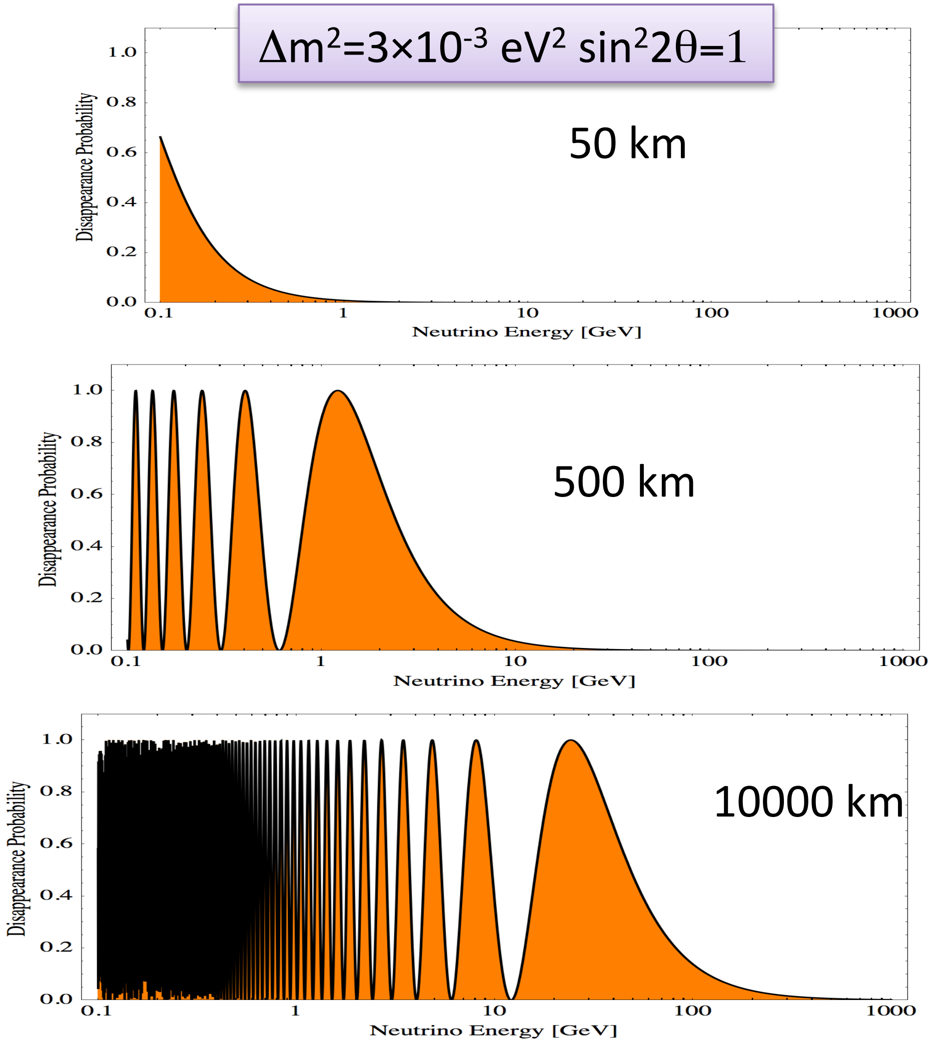
Detection of Atmospheric Neutrinos

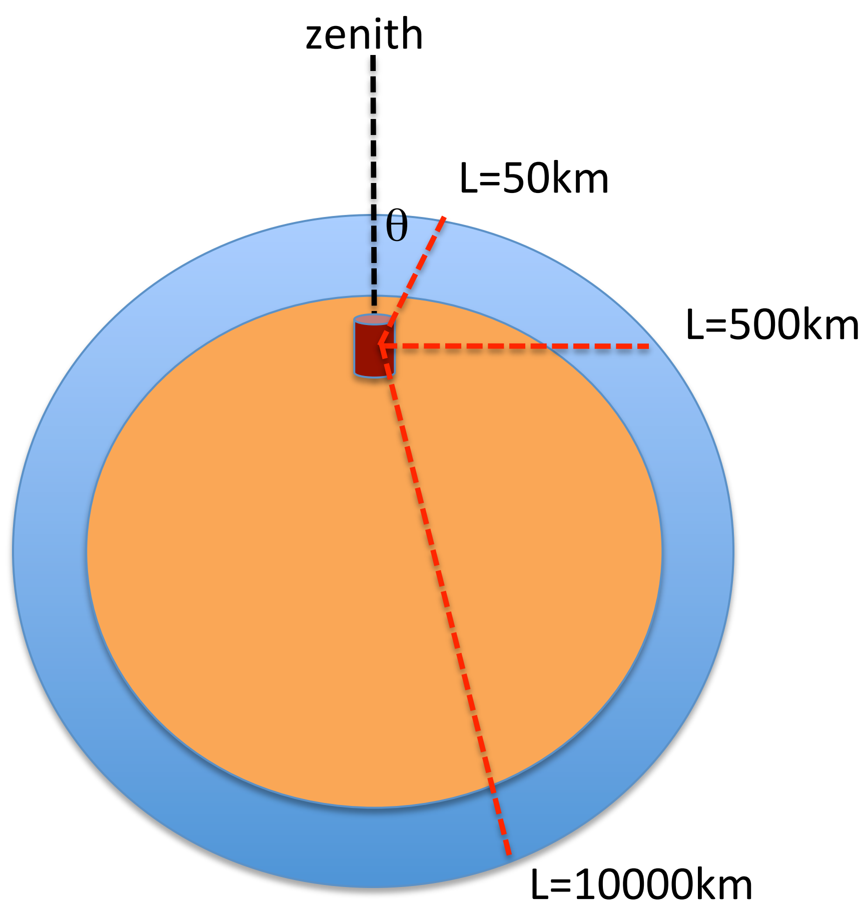
- Neutrino-nucleon interaction $\sigma \sim 10^{-38}$ cm^2 at 1GeV
- Neutrino flux peaked at ~ 10 GeV
- Neutrino flux significant in ~ 0.1-100GeV
- Production of muon's: ν_μ + n -> μ^- + p asks for a threshold energy of ~ 110 MeV
- Production of tau's: ν_τ + n -> τ^- + p asks for a threshold energy of ~ 3.45 GeV

Neutrino Oscillations for atmospheric neutrinos

$$P_{\alpha\beta}(E,L) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

$\Delta m^2 = 3\times10^{-3}$ eV^2 $\sin^2 2\theta = 1$

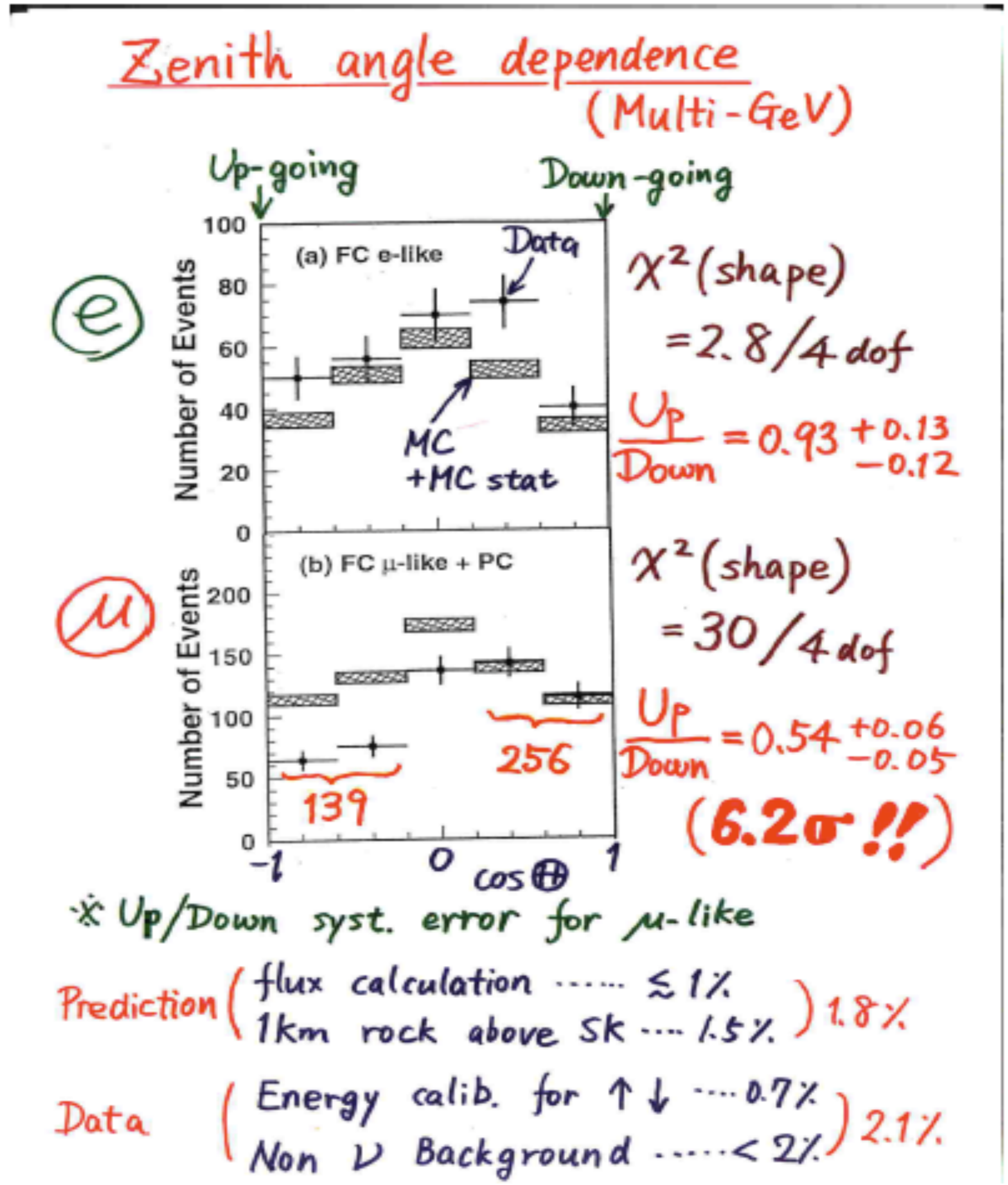




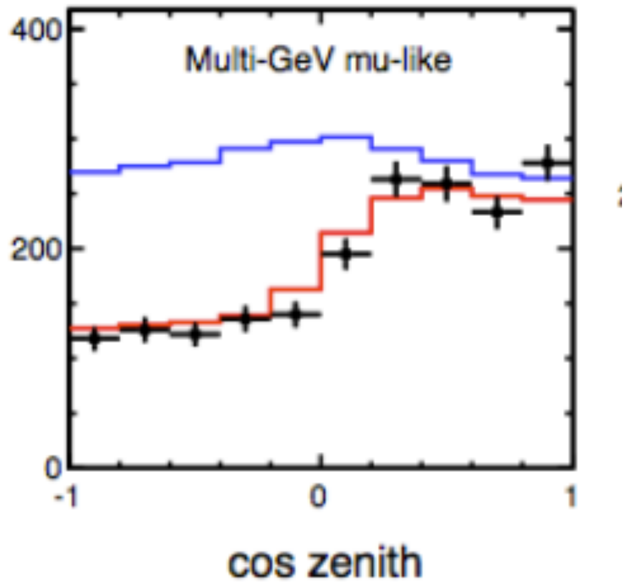
Discovery of Atmospheric Neutrino Oscillations

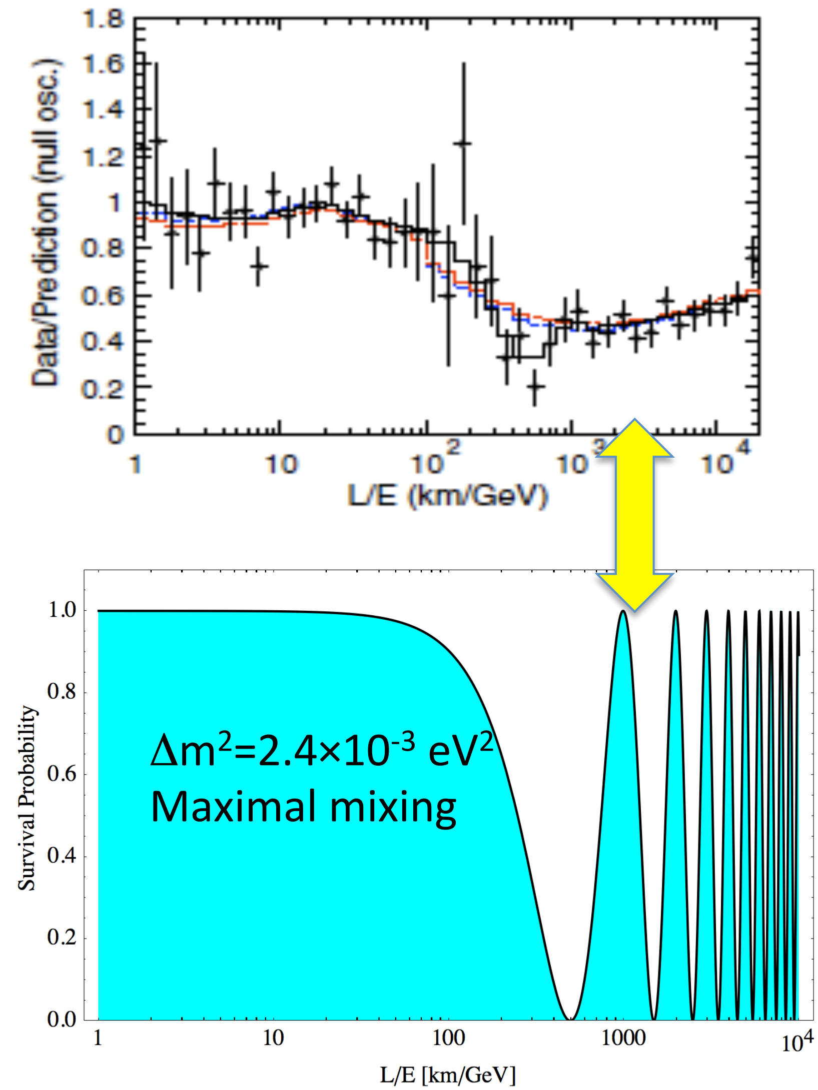
- Neutrino 1998,

Takayama, Japan



Super-Kamiokande results





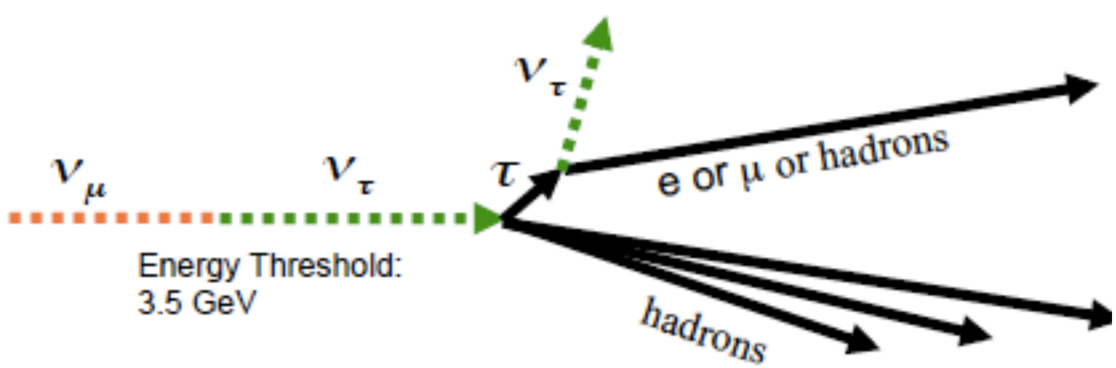
For multi-GeV events:

$\Phi(\nu_\mu,\text{UP})/\Phi(\nu_\mu,\text{DOWN}) = 0.54\pm0.04$ for $E_\nu > 1.3$GeV

$\Delta m^2 \sim E/L \sim 10\text{GeV}/10^4\text{km} \sim 10^{-3}$ eV^2

Search for ν_τ appearance in Super-K

- No-tau appearance hypothesis excluded at ~4σ
- Selection of contained events with > 1.3 GeV energy
- Search for electrons from pions/muons decays



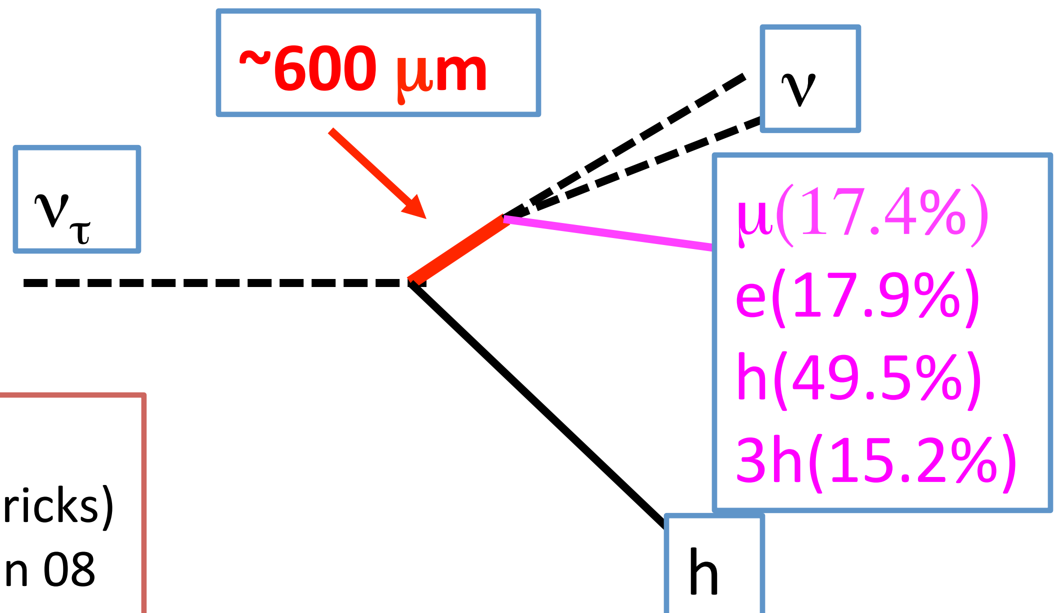
Compare this method with that in OPERA …

Oscillations Project with Emulsions tRacking Apparatus

Goal: first experimental evidence of ν_τ appearance in
$\nu_\mu - \nu_\tau$ leading oscillations $P_{\mu\tau} \approx \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2(1.27\Delta m^2 L/E_\nu)$

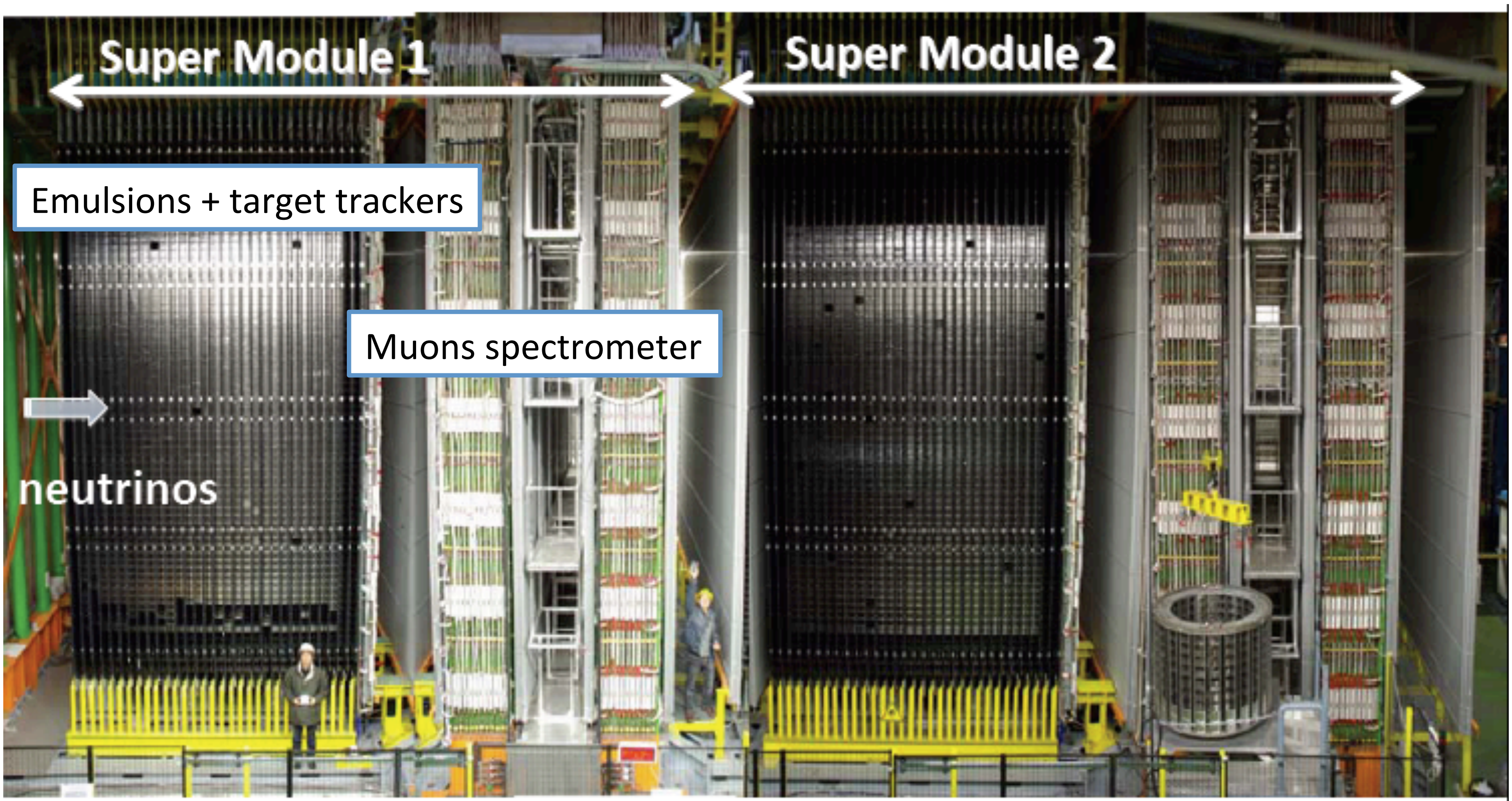
Nominal Beam of ν_μ:
$<E_\nu> \sim 17$ GeV
$<L/E_\nu> \sim 43$
Nominal 4.5 10^{19} pot/year
7.45 10^{-13} $\nu_\mu/(cm^2$ pot)
$<\sigma_{\nu N}> \sim 10^{-37}$ cm^2

Principle of detection



High spatial resolution needed ➔
use nuclear emulsions (Pb-emulsion bricks)
150000 bricks built from May 07 to Jun 08
1.25 kton Pb target

OPERA detector in Hall C



Lesson from atmospheric neutrinos

From observation of atmospheric neutrinos we learn:

R ~ 0.6 there is a deficit of muon neutrinos

There is a dominant oscillation $\nu_\mu \rightarrow \nu_\tau$

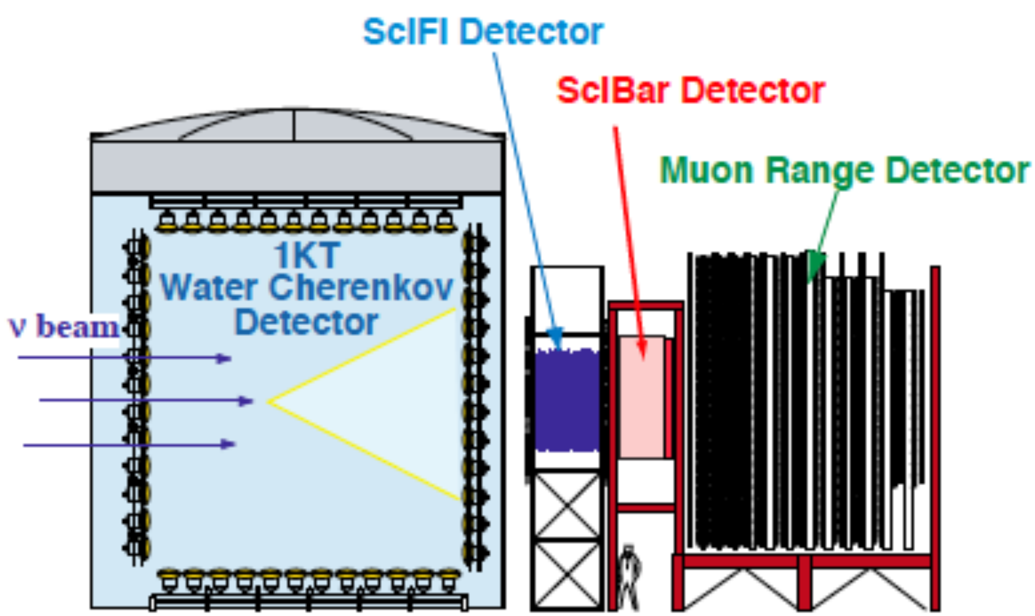
$\Delta m^2 \sim 2 \cdot 10^{-3}$ eV^2

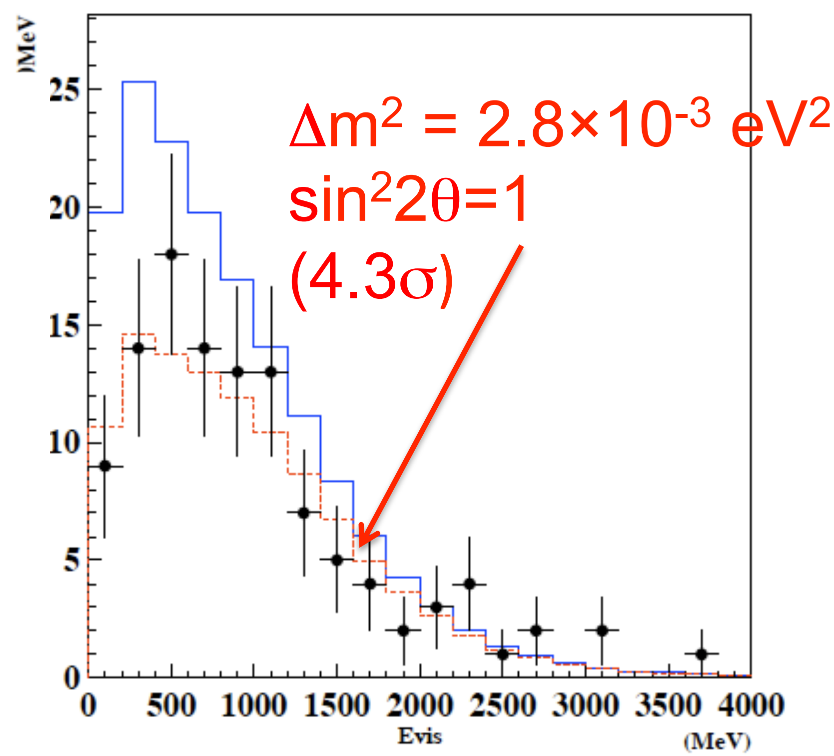
$\sin^2 2\theta > 0.96$ (90% C.L.) compatible to maximal mixing

K2K long-baseline neutrino oscillation experiment

Conventional muon neutrino beam from KEK (12 GeV protons on target) to Super-Kamiokande detector to confirm atmospheric neutrino observations.

Near Water Cherenkov detector to characterize the beam.





MINOS far detector

- Magnetised steel-scintillator tracking calorimeter at a depth of 2070 m.w.e. in Soudan Mine (USA)
  - 486 octagonal steel planes 2.54cm thick
  - 1cm thick polystyrene scintillator, divided in 192 strips
  - Scintillation light collected by wavelength-shifting fibers and detected by multi-anode PMTs
- 5.4 kton target detector mass
- 1.3T magnetic field, charge discrimination of muons
- Scintillator veto for cosmic muons above the detector
- Sensitive to $N\mu^+/N\mu^-$ (=1.374±0.004 ±0.012)

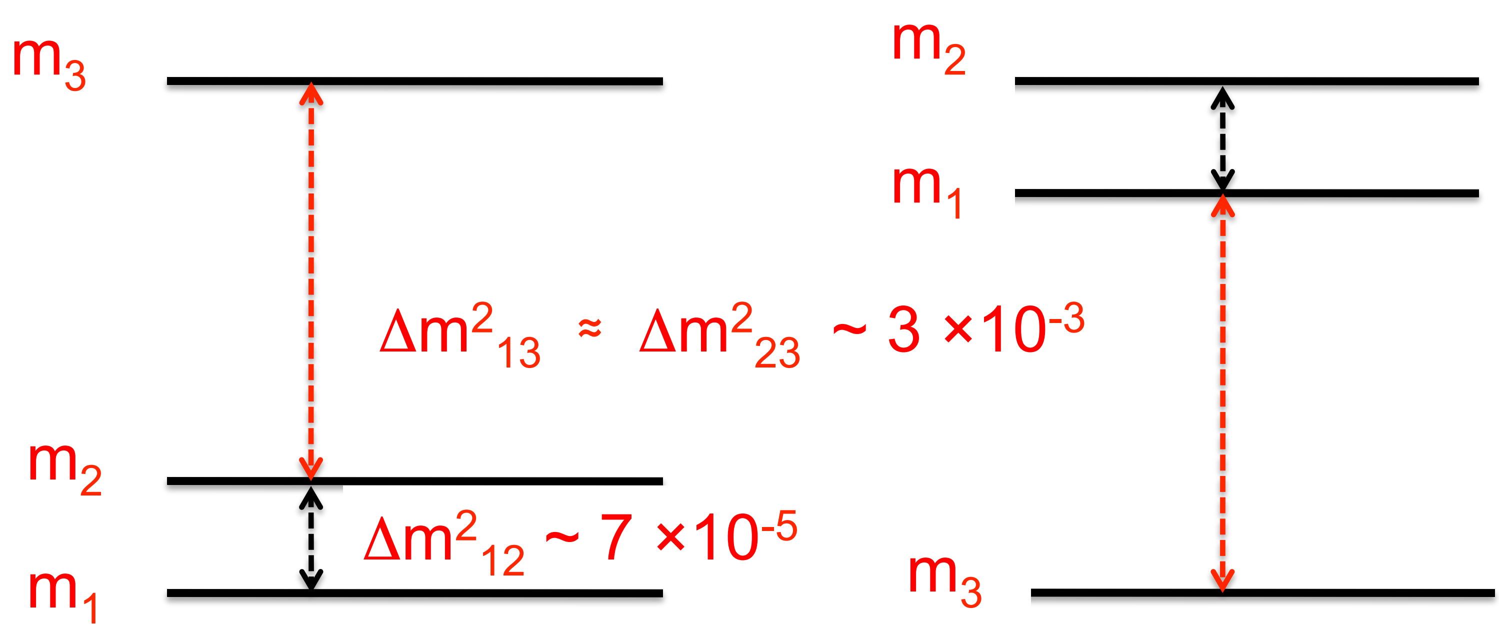
Long-baseline accelerator experiments

Super-Kamiokande results confirmed by long-baseline accelerator experiments

	K2K	MINOS
Source	KEK	Fermilab
Detector	Super-Kamiokande	Magnetised steel-scintillator tracking calorimeter
Distance	250 km	735 km
Energy	1.3 GeV	3 GeV
1.24 E/L [eV^2]	6.4×10^{-3}	5.0×10^{-3}
Experiment	ν_μ disappearance	ν_μ disappearance
No oscillations [events]	**417**	**2451**
Observed	**291**	**1986**

Normal and Inverted Mass Ordering

From observation we can hint the following mass ordering (or hierarchy)



Looking at the Sun through neutrinos

- The Sun shines by burning H fuel

  $4p \rightarrow {}^{4}He+2e^{+}+2\nu_{e}+(24.69+2\cdot 1.022)MeV$

  <E>=0.53 MeV, 2% of energy produced

- Electroweak processes in the core of the Sun produce **electron neutrinos**
- Neutrinos interact only weakly in matter

($\sigma_{\nu N}$~10^{-42} cm^2)* and stream out at velocity c

*For comparison: $\sigma_{Thomson}$ ~ 10^{-24} cm^2

Solar Neutrinos Sources: pp chain

$$p + p \rightarrow d + e^{+} + \nu_e + 0.42\ \mathrm{MeV}$$

$$p + e^{-} + p \rightarrow d + \nu_e + 1.442\ \mathrm{MeV}$$

~0.4%

$$p + d \rightarrow {}^{3}He + \gamma + 5.494\ \mathrm{MeV}$$

~85%

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p + 12.860\ \mathrm{MeV}$$

~15%

$$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma + 1.586\ \mathrm{MeV}$$

$$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e + 0.862\ \mathrm{MeV}$$

$$^{7}Li + p \rightarrow 2\,{}^{4}He + 17.347\ \mathrm{MeV}$$

~0.02%

$$^{7}Be + p \rightarrow {}^{8}B + \gamma + 0.137\ \mathrm{MeV}$$

$$^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e + 15.04\ \mathrm{MeV}$$

$$^{8}Be^{*} \rightarrow 2\,{}^{4}He + 3.03\ \mathrm{MeV}$$

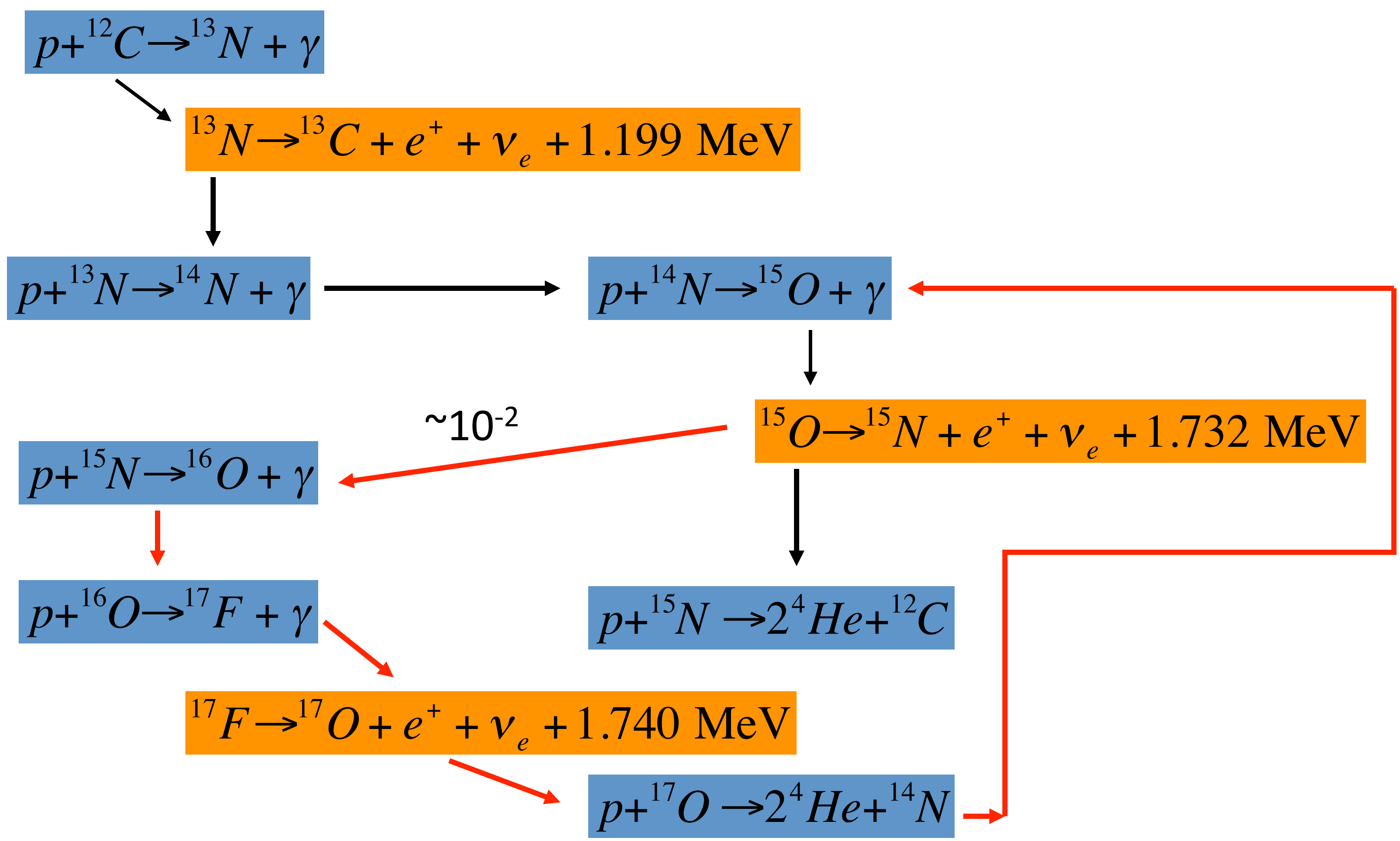
How many Solar Neutrinos

- pp-I chain (2% of liberated energy lost by neutrinos) [max flux when only ν_{pp} produced]

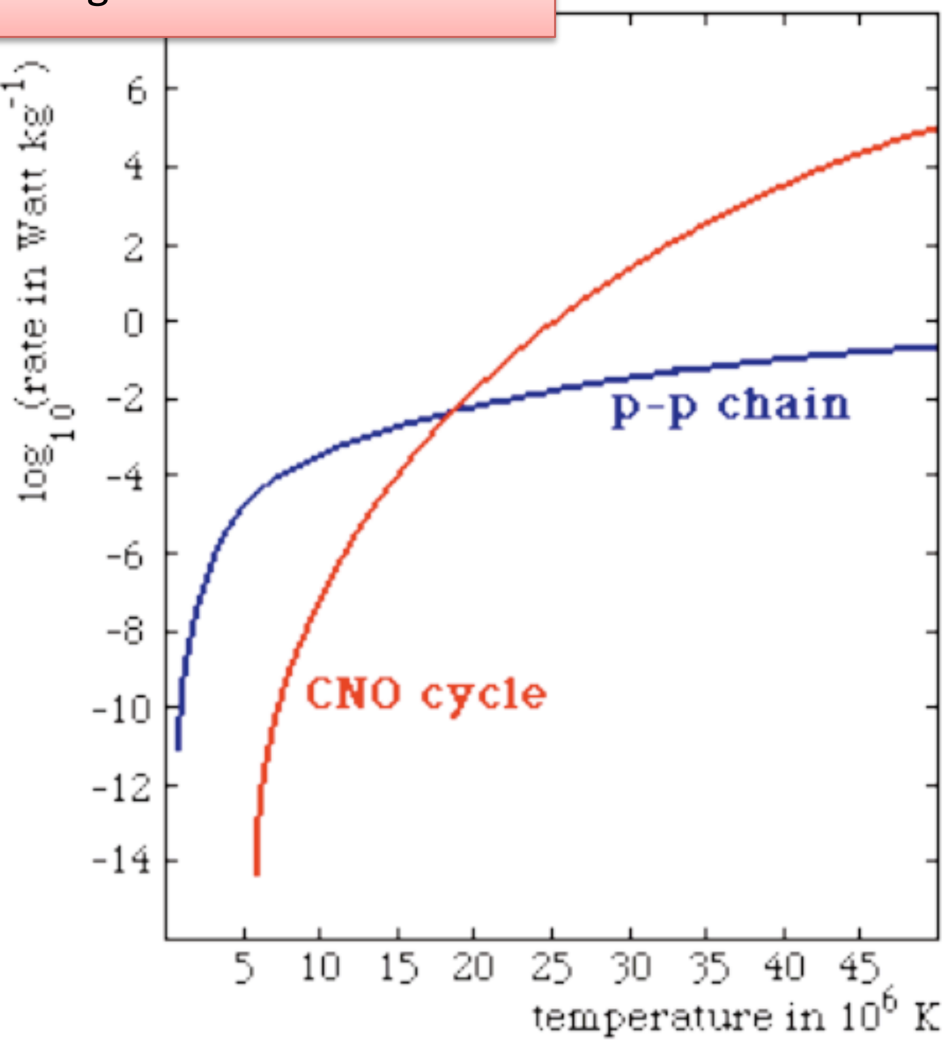
$$\phi_{pp} = 2 \cdot \frac{2.4 \cdot 10^{39}\ \text{MeV/s}}{26.73MeV - 0.53MeV} \cdot \frac{1}{4\pi(A.U.)^2} \approx 6.5 \cdot 10^{10}\ \text{cm}^{-2} s^{-1}$$

- pp-II side chain ($1\nu_{pp} + 1\nu_{Be}$) reduces pp flux by 0.15·0.5=7.5%
  - ϕ_{pp}~ $6.0 \cdot 10^{10}$ cm^{-2} s^{-1}
  - ϕ_{Be}~ $5.0 \cdot 10^{9}$ cm^{-2} s^{-1}
  - ϕ_{B} ~ 10^{6} cm^{-2} s^{-1}

Solar Neutrinos: CNO chain



Burning rate in stars



Solar Standard Model

- Assumptions of the SSM
  - Hydrostatic equilibrium
  - Energy generation by H burning
  - Homogeneous zero-age Sun: primordial core metal abundance equal to today's surface metal abundance
  - Boundary conditions: present mass, luminosity, radius

Solar Standard Model

The SSM is the framework from which we make predictions on the production of solar neutrinos

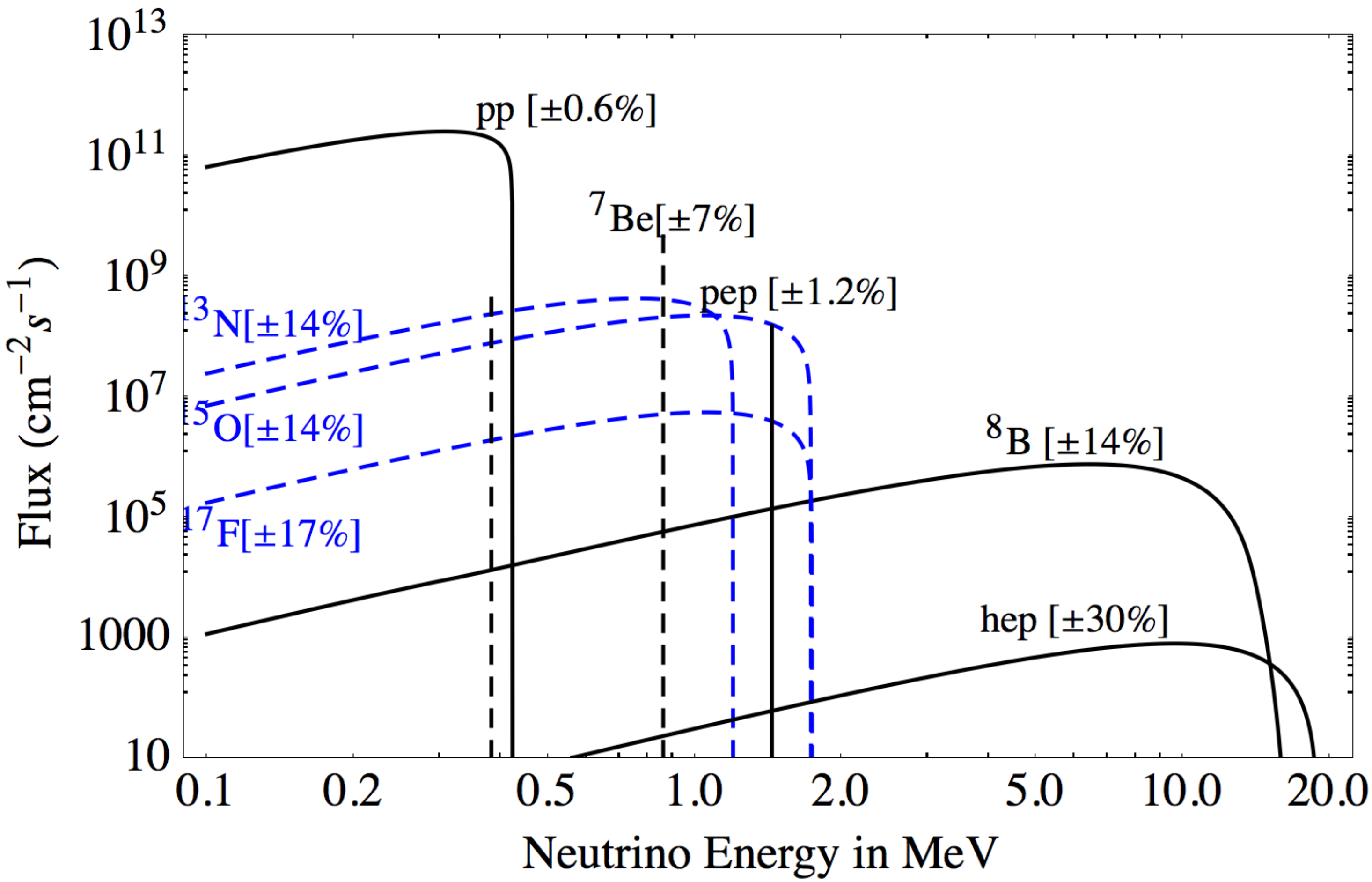
Within the SSM solar neutrino fluxes are written as:

$$\phi_{\rm pp} \propto {S_{11}}^{+0.14} \cdot {S_{33}}^{+0.03} \cdot {S_{34}}^{-0.06} \cdot {S_{1,14}}^{-0.02} \cdot {L_\odot}^{+0.73} \cdot {\tau_\odot}^{-0.07} \cdot {Op_\odot}^{+0.14} \cdot (Z/X)^{-0.08},$$

$$\phi_{\rm Be} \propto {S_{11}}^{-0.97} \cdot {S_{33}}^{-0.44} \cdot {S_{34}}^{+0.88} \cdot {L_\odot}^{+3.56} \cdot {\tau_\odot}^{+0.69} \cdot {Op_\odot}^{-1.49} \cdot (Z/X)^{+0.59},$$

$$\phi_{\rm B} \propto {S_{11}}^{-2.59} \cdot {S_{33}}^{-0.40} \cdot {S_{34}}^{+0.81} \cdot {L_\odot}^{+6.76} \cdot {\tau_\odot}^{+1.28} \cdot {Op_\odot}^{-2.93} \cdot (Z/X)^{+1.36}.$$

Solar Neutrino Spectrum

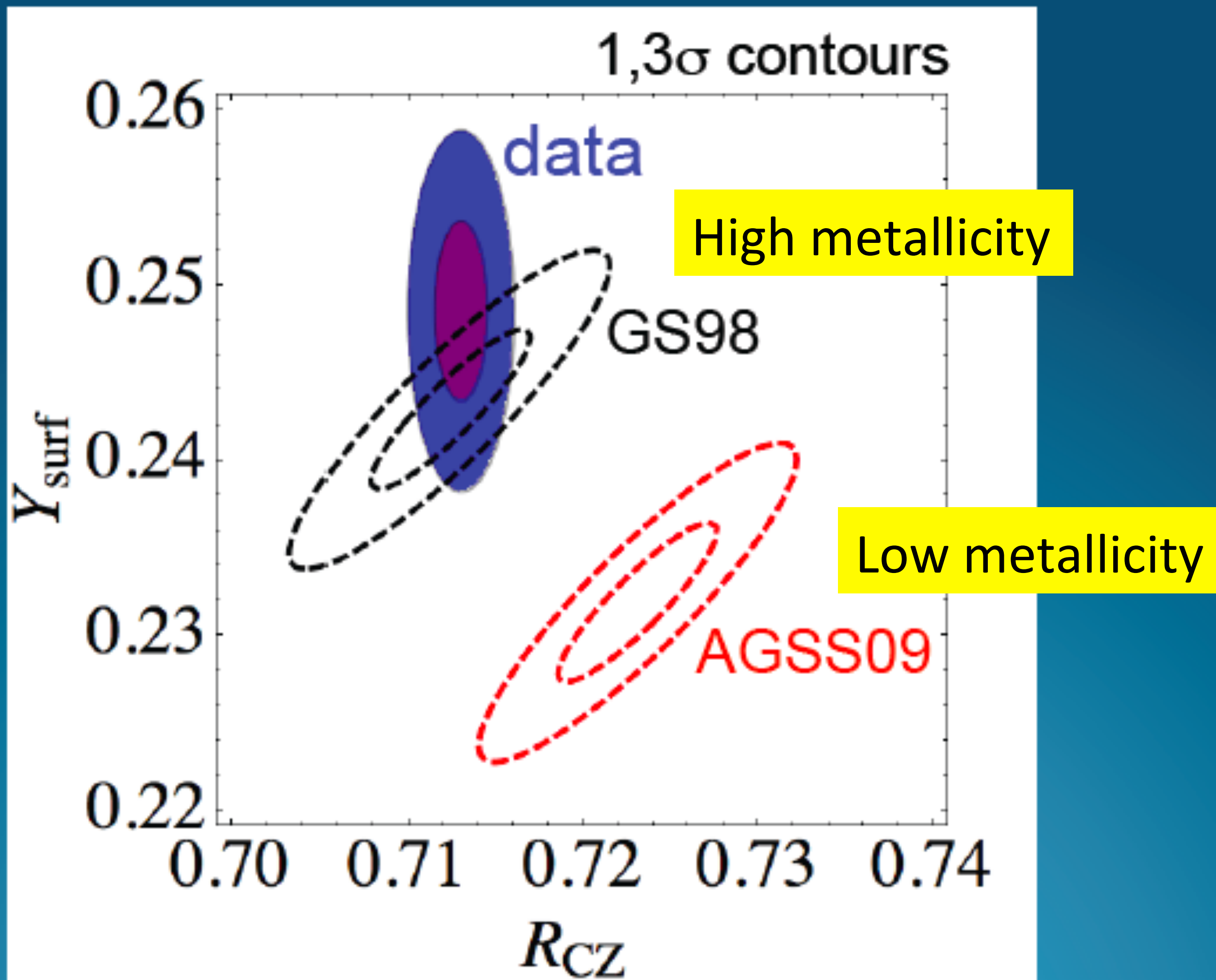


Solar Standard Model neutrino flux predictions

Source	Flux $[cm^{-2}s^{-1}]$ SSM-GS98	Flux $[cm^{-2}s^{-1}]$ SSM-AGSS09	Flux $[cm^{-2}s^{-1}]$ SSM-GS98-2004
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	$5.94(1\pm0.01)\times10^{10}$
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	$1.40(1\pm0.02)\times10^{8}$
^{7}Be	$5.00(1\pm0.07)\times10^{9}$	$4.56(1\pm0.07)\times10^{9}$	$4.86(1\pm0.12)\times10^{9}$
^{8}B	$5.58(1\pm0.13)\times10^{6}$	$4.59(1\pm0.13)\times10^{6}$	$5.79(1\pm0.23)\times10^{6}$
^{13}N	$2.96(1\pm0.15)\times10^{8}$	$2.17(1\pm0.15)\times10^{8}$	$5.71(1\pm0.36)\times10^{8}$
^{15}O	$2.23(1\pm0.16)\times10^{8}$	$1.56(1\pm0.16)\times10^{8}$	$5.03(1\pm0.41)\times10^{8}$
^{17}F	$5.52(1\pm0.18)\times10^{6}$	$3.40(1\pm0.16)\times10^{6}$	$5.91(1\pm0.44)\times10^{6}$

Total CNO: 5.24×10^{8} 3.76×10^{8} 10.8×10^{8}

The Solar Abundance Problem



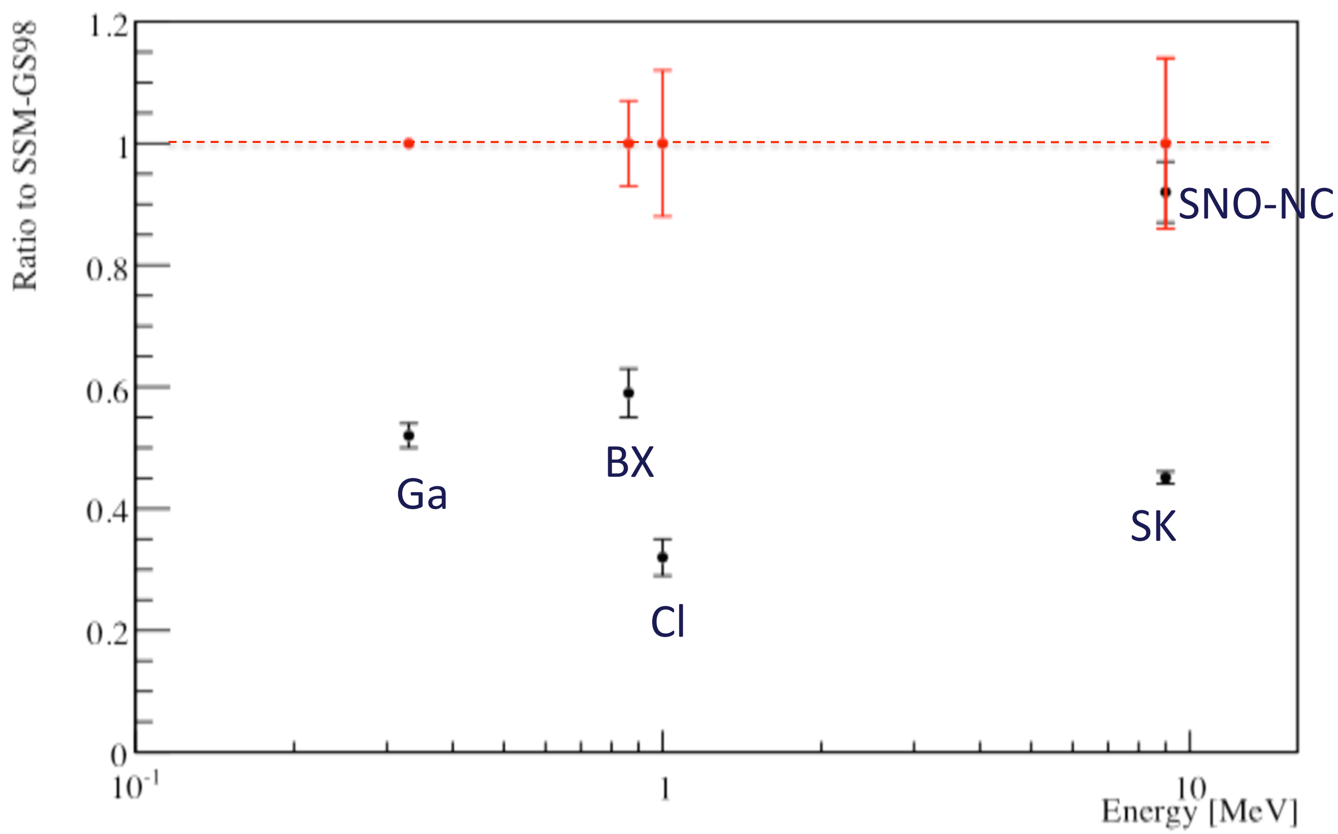
Detecting Solar Neutrinos

- Electron capture: $\nu_e + (A,Z-1) \rightarrow (A,Z) + e^-$ ($\sigma \sim 10^{-42} cm^2$)
  - charged-current interaction
  - can be associated with a correlated delayed event from the produced (A,Z) nucleus
- Elastic Scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$ ($\sigma \sim 10^{-44} cm^2$)
  - neutral-current interaction
  - Specific signature for monenergetic neutrinos
- $\nu_e + d \rightarrow e^- + p + p$ ($E_\nu \geq 1.44$ MeV) ($\sigma \sim 10^{-42} cm^2$)
- $\nu_x + d \rightarrow \nu_x + p + n$ ($E_\nu \geq 2.74$ MeV)
  - Associated with $n + d \rightarrow {}^3H + \gamma$(6.25 MeV) or $n + {}^{35}Cl \rightarrow {}^{36}Cl + \sum\gamma$(8.6 MeV)

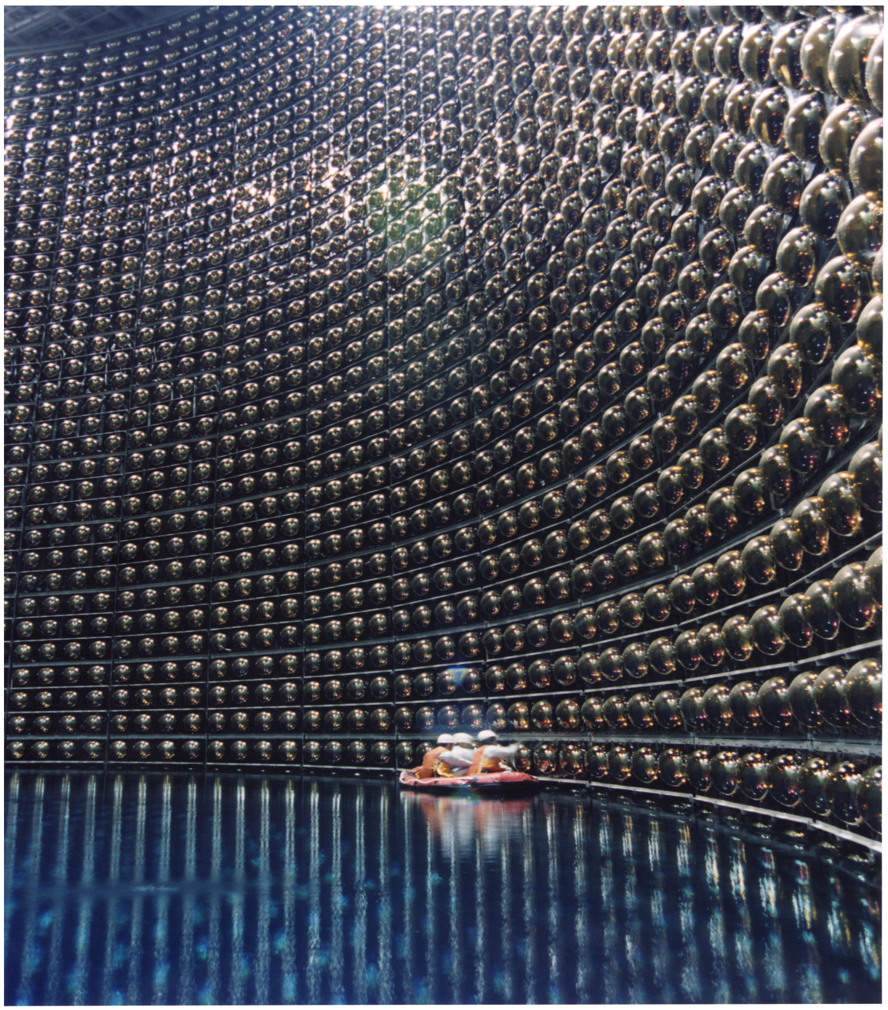
Solar Neutrino Experiments

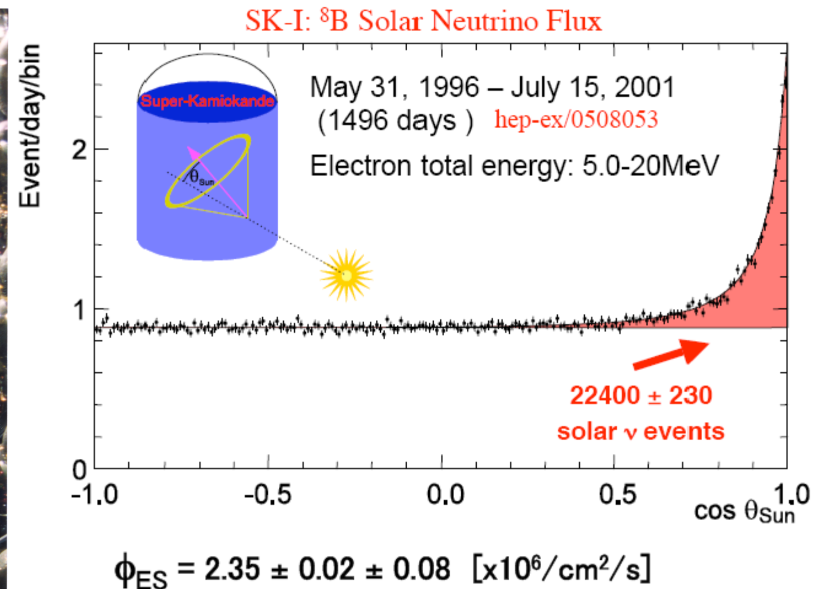
Detector	Target mass	Threshold [MeV]	Data taking
Homestake	615 tons C_2Cl_4	0.814	1970-1994
Kamiokande	3ktons H_2O	7.5 /7.0	1983-1995
SAGE	50tons molted metal Ga	0.233	**1989-present**
GALLEX	30.3tons $GaCl_3$-HCl	0.233	1991-1997
GNO	30.3tons $GaCl_3$-HCl	0.233	1998-2003
Super-Kamiokande	22.5ktons	4.5 6.5 4.5 4	1996-2001 2003-2005 2006-2008 **2008-present**
SNO	1kton D_2O	5[3.5]	1999-2006
Borexino	300ton C_9H_{12}	0.2 MeV	**2007-present**

Observations vs Predictions



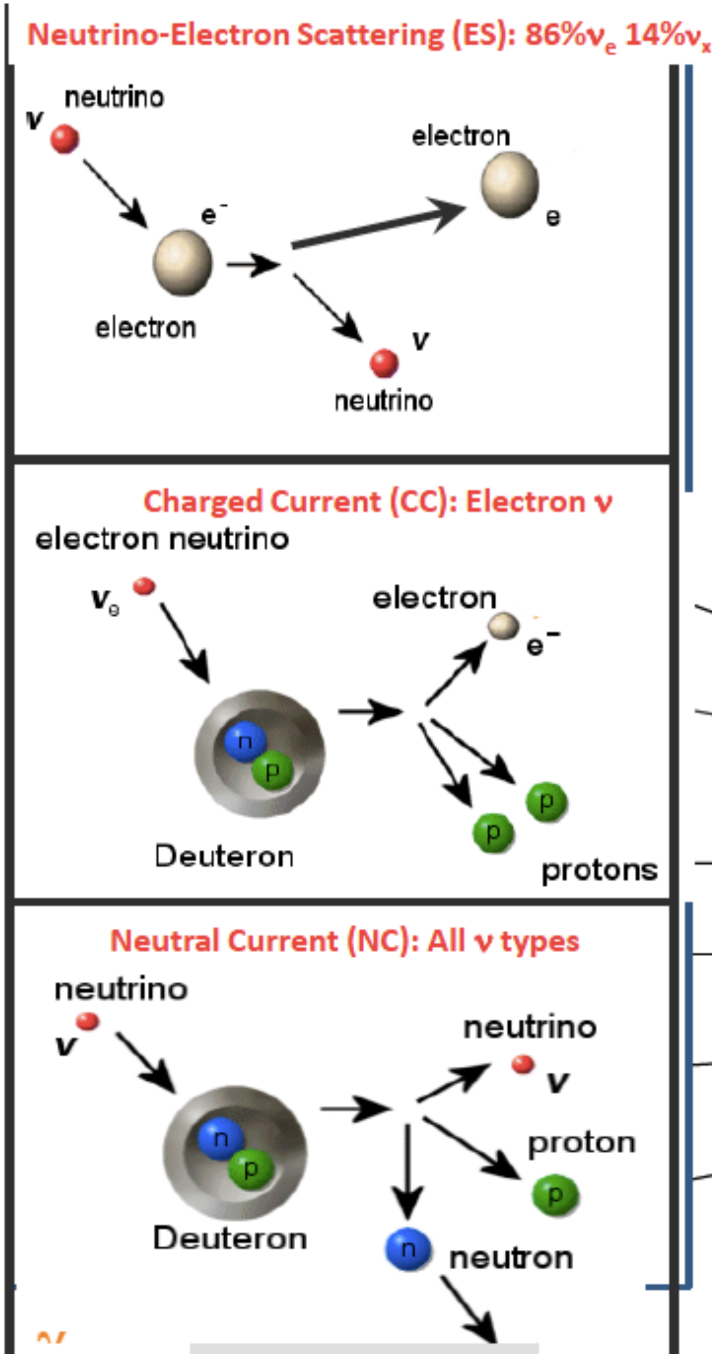
Neutrino Detectors are HUGE

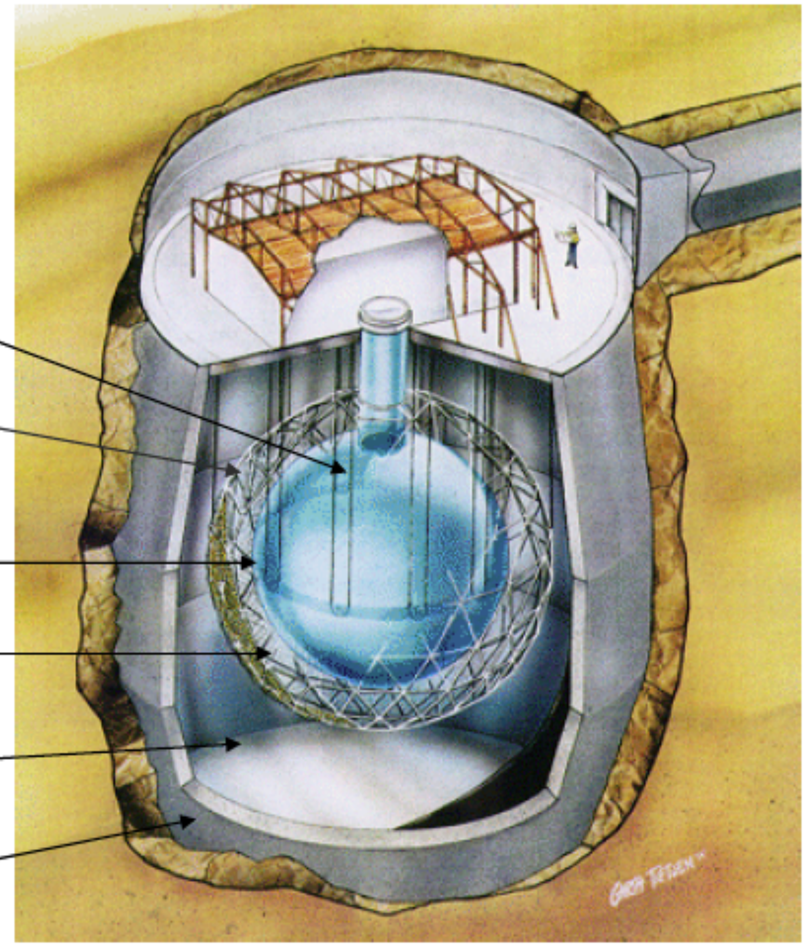




SuperKamiokande

Sudbury Neutrino Observatory





SNO Neutral Current Trilogy

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

"long" archival papers with complete details

PRC **81**, 055504 (2010)

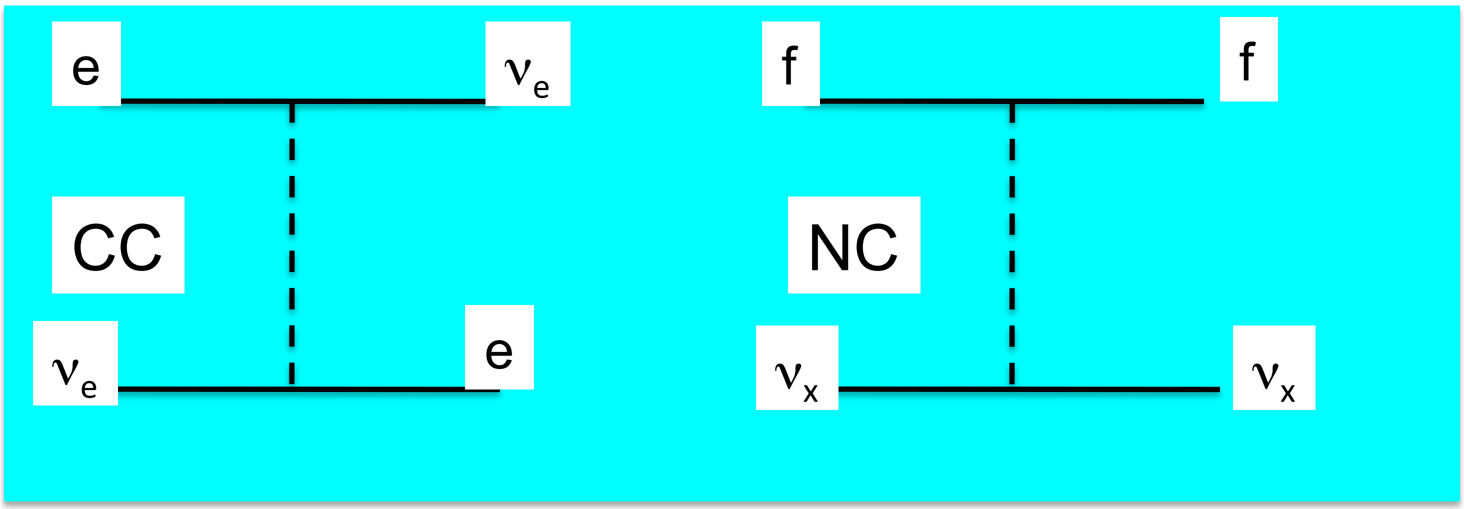
combined analysis with lower energy threshold

ARXIV: 1109.0763 (2011)

combined analysis of all three phases with pulse shape discrimination for ^{3}He counters

Effective interaction potential in matter

Taking into account both CC and NC processes and averaging over many interactions



$$V = \begin{pmatrix} \sqrt{2}G_F n_e + V_Z & 0 & 0 \\ 0 & +V_Z & 0 \\ 0 & 0 & +V_Z \end{pmatrix}$$

Neutrino Oscillations in Matter

- For neutrinos traveling in matter we account for charged (only for ν_e) and neutral current interactions

In a two neutrino scheme:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix} = \begin{pmatrix} -\frac{\delta m_2}{4E}\cos 2\theta + \sqrt{2}G_F n_e & \frac{\delta m_2}{4E}\sin 2\theta \\ \frac{\delta m_2}{4E}\sin 2\theta & \frac{\delta m_2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}$$

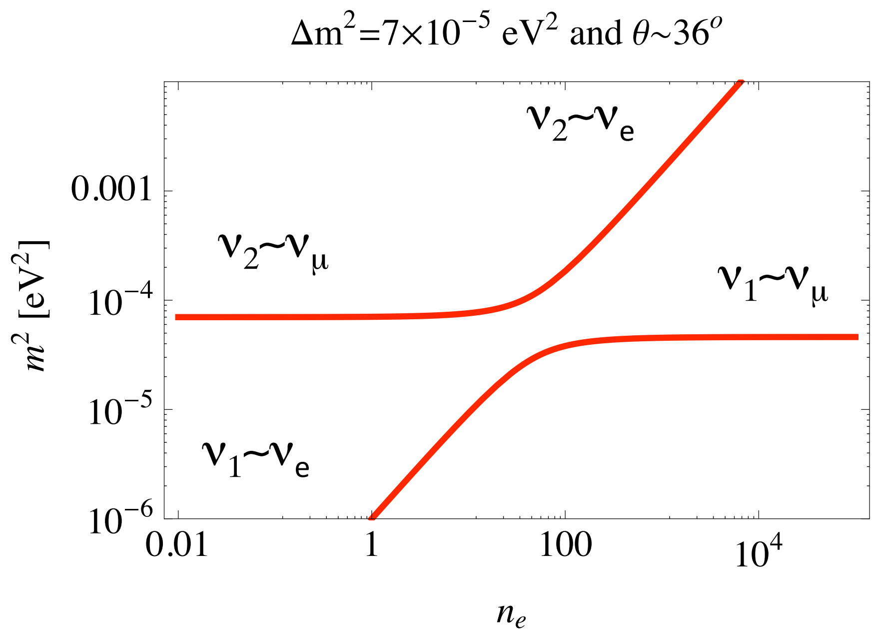
Survival probability can be written in terms of an effective mixing angle:

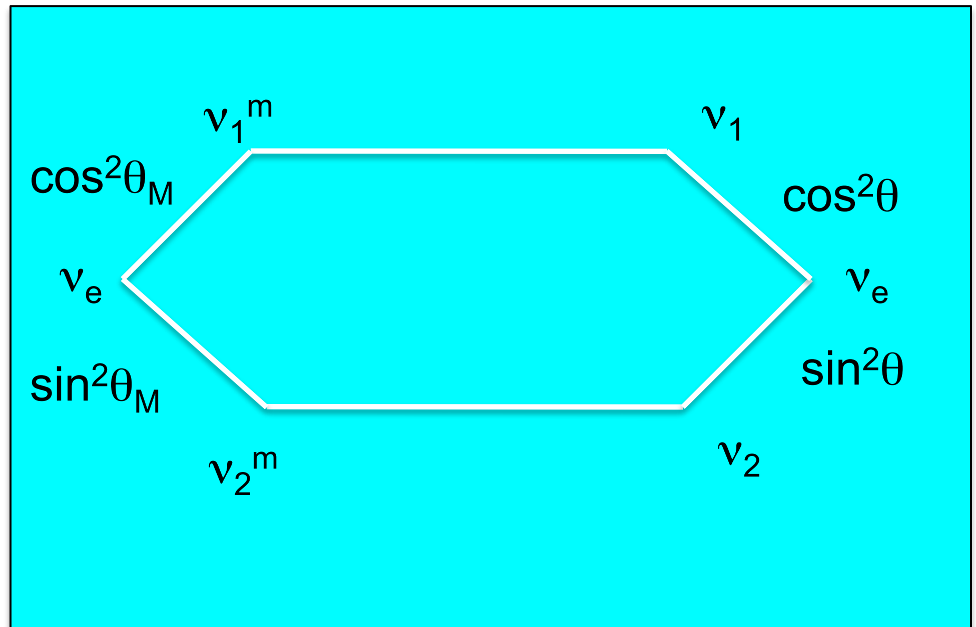
$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \quad \text{with } x = \frac{2\sqrt{2}G_F n_e E}{\delta m^2}$$

Matter effects dominate when:

$$\cos 2\theta < \frac{2\sqrt{2}G_F n_e E}{\delta m^2}$$

Adiabatic propagation in the Sun





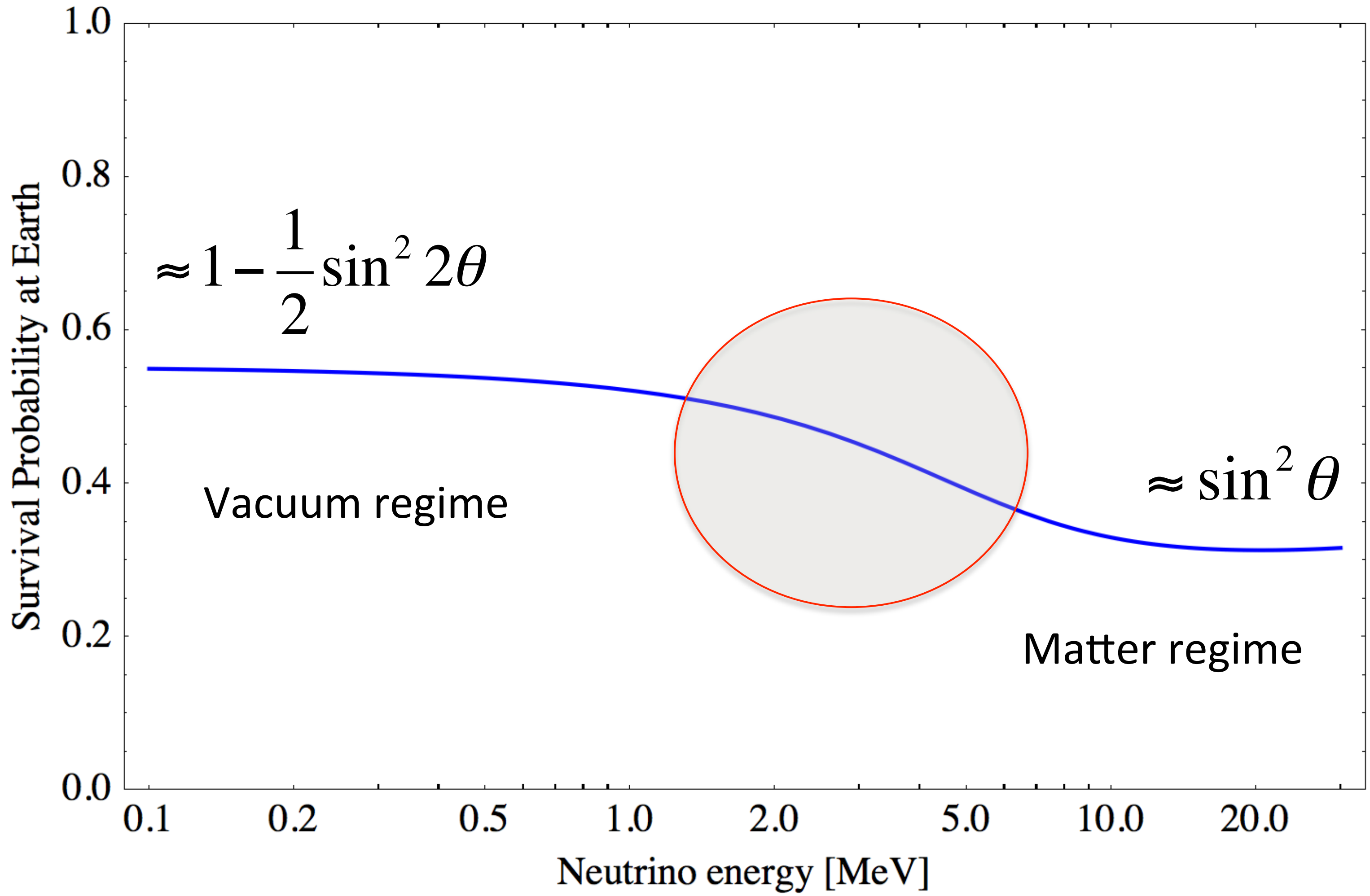
$$\mathrm{P_{ee}} = \cos^2\theta_M \cos^2\theta + \sin^2\theta_M \sin^2\theta = \frac{1}{2} + \frac{1}{2}\cos 2\theta_M^{(i)} \cos 2\theta$$

$$\text{At production: } \cos 2\theta_{\mathrm{M}}^{\mathrm{i}}(0) \approx -1$$

$$P_{ee} \approx \sin^2\theta$$

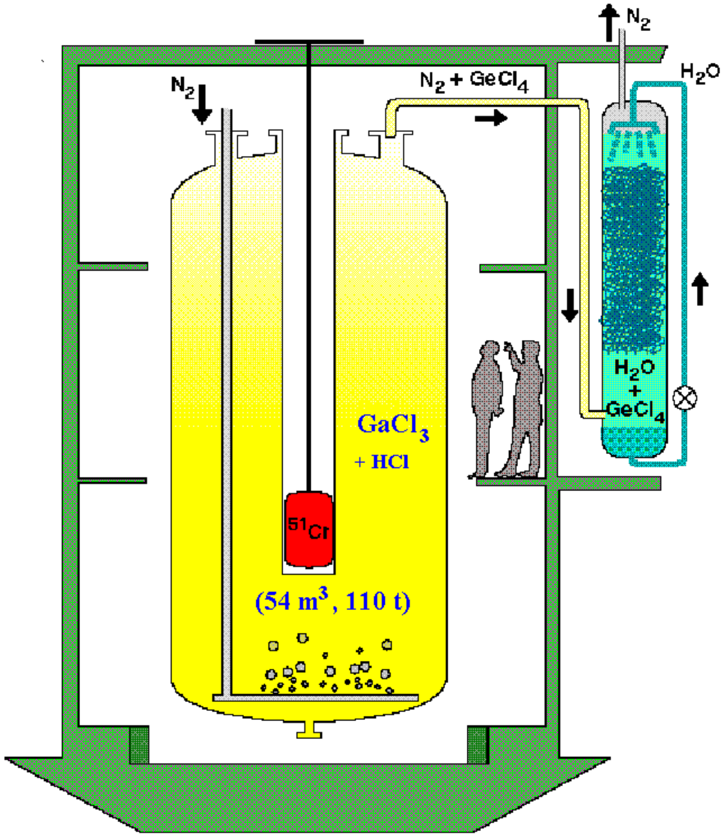
$$P_{ee} \approx 1 - \frac{1}{2}\sin^2 2\theta \text{ when matter effects negligible}$$

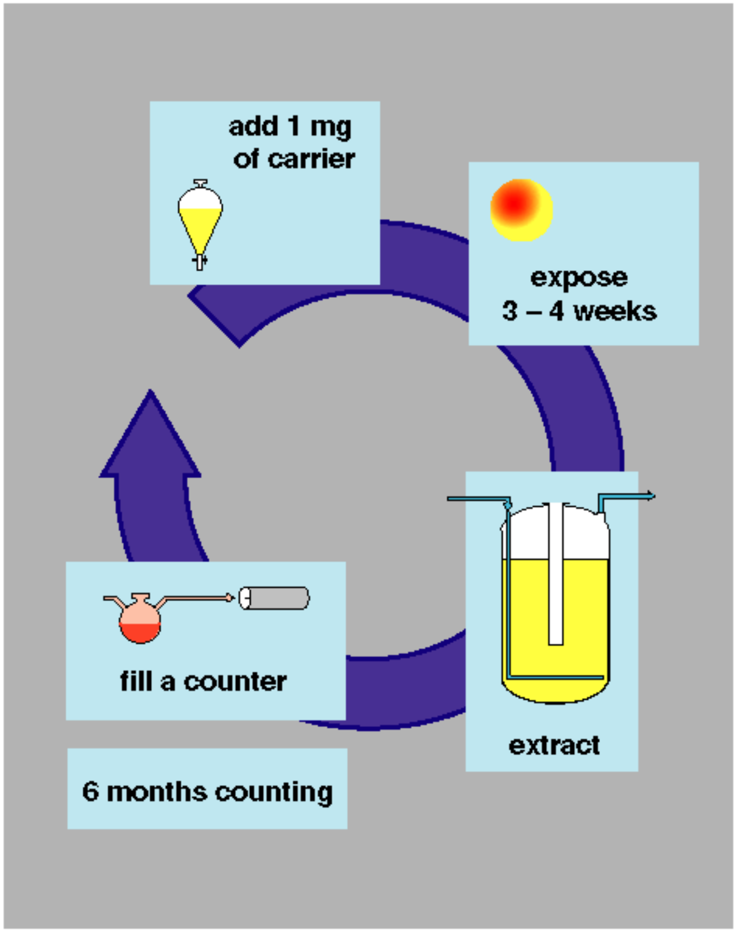
Predicted Survival Probability at Earth for electron neutrinos from the Sun



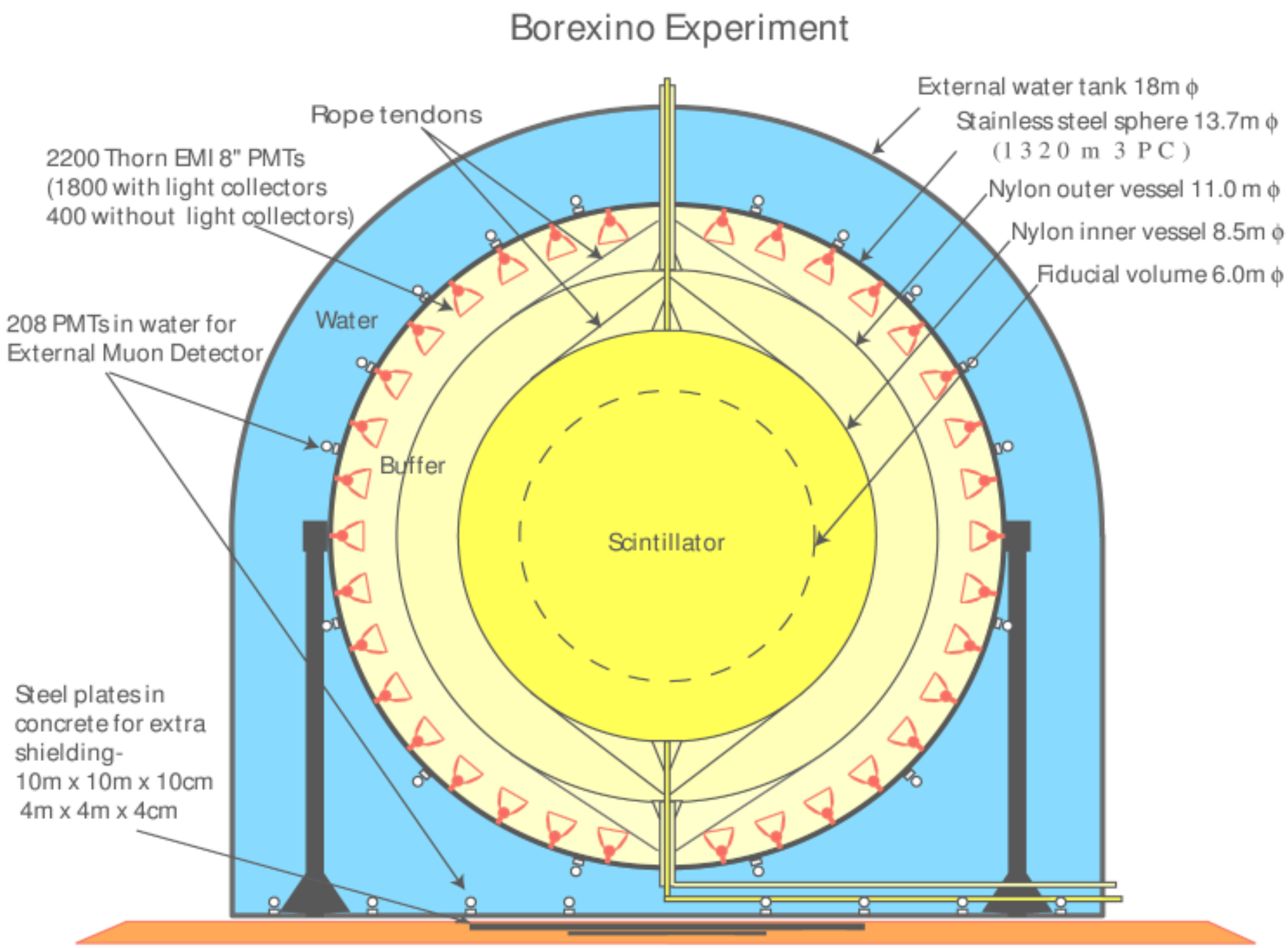
GALLEX/GNO

$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge \rightarrow EC$
$\rightarrow {}^{71}Ga\ (T_{1/2}=11.4d)$

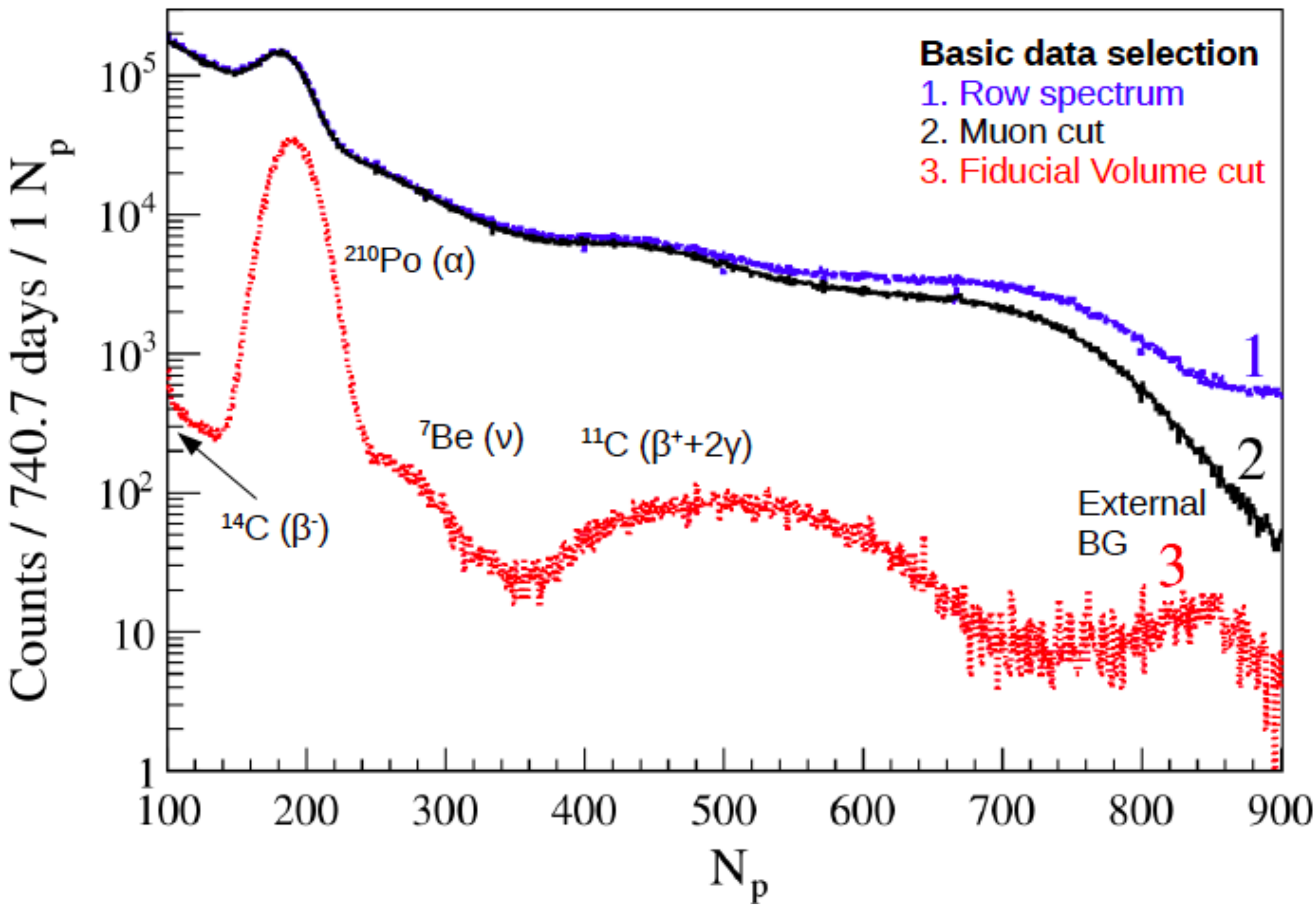




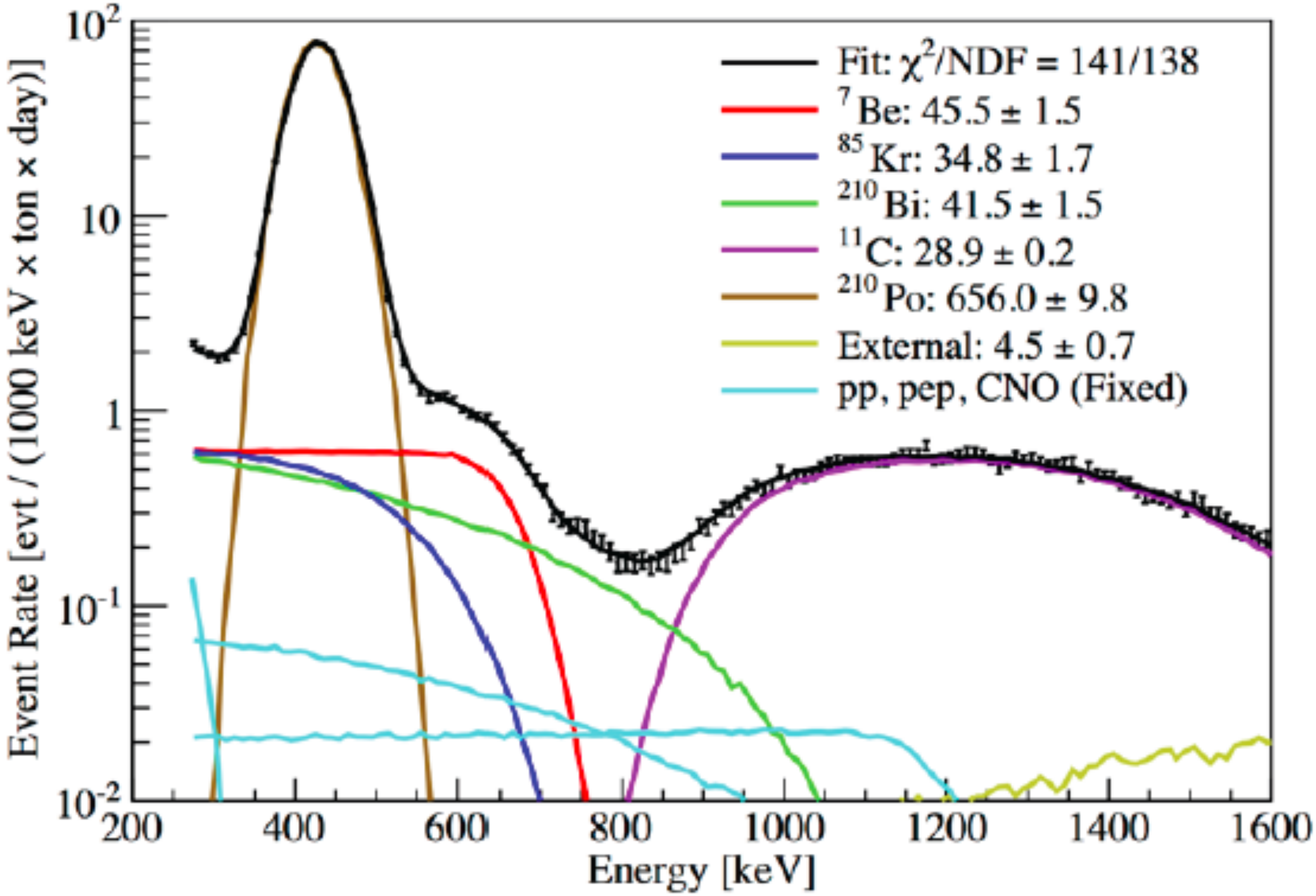
The BOREXINO detector



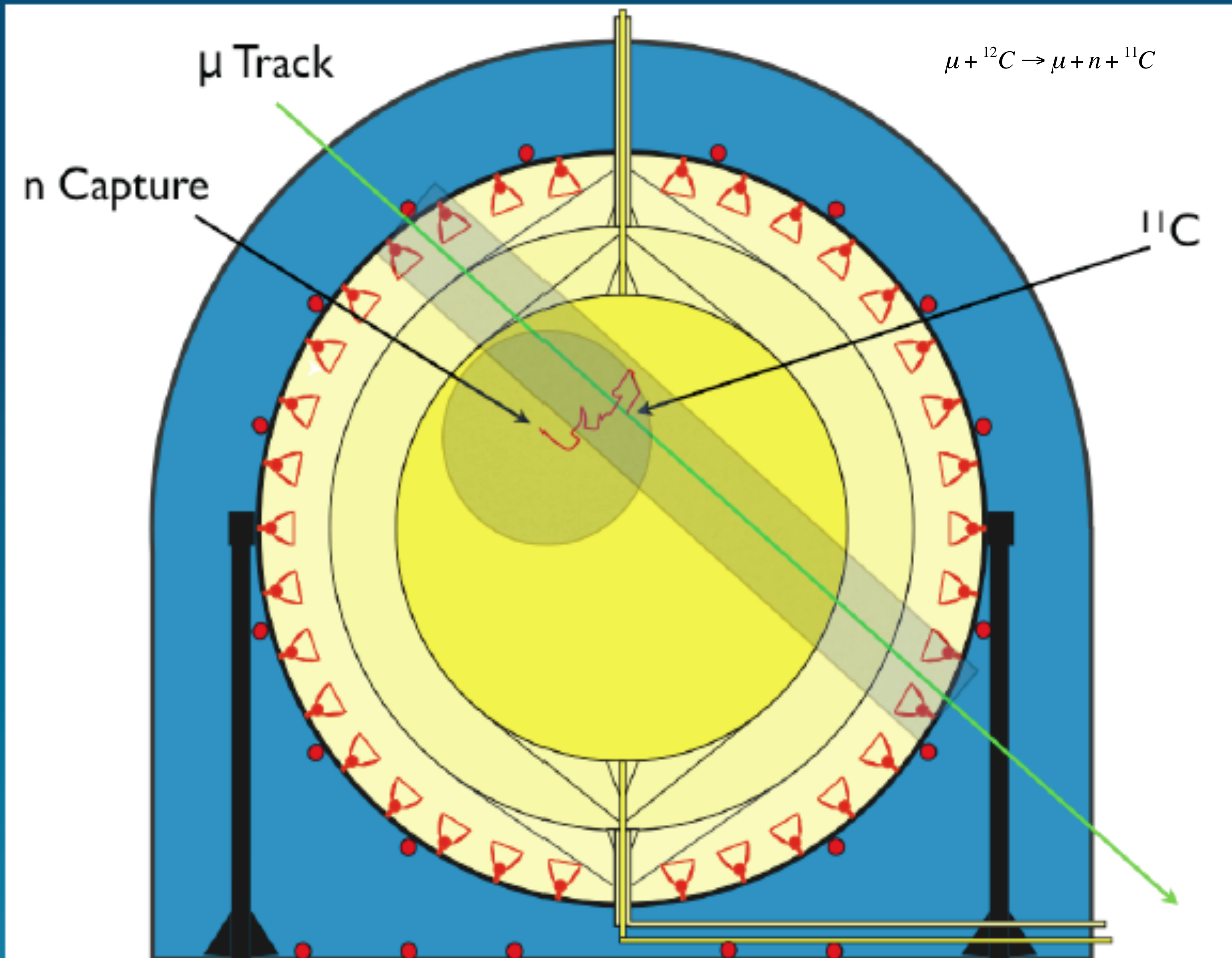
The β-like energy spectrum



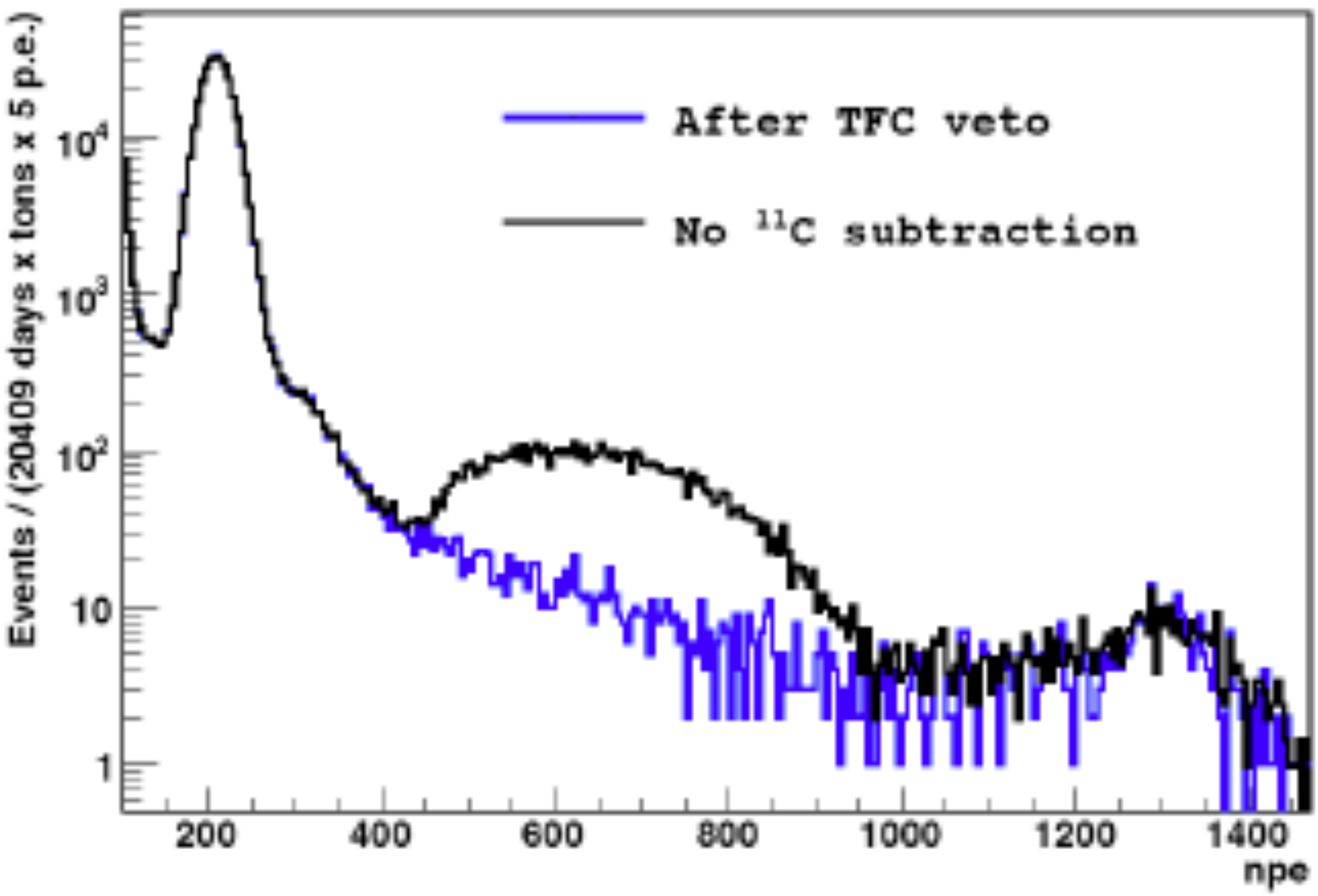
^{7}Be neutrinos in Borexino



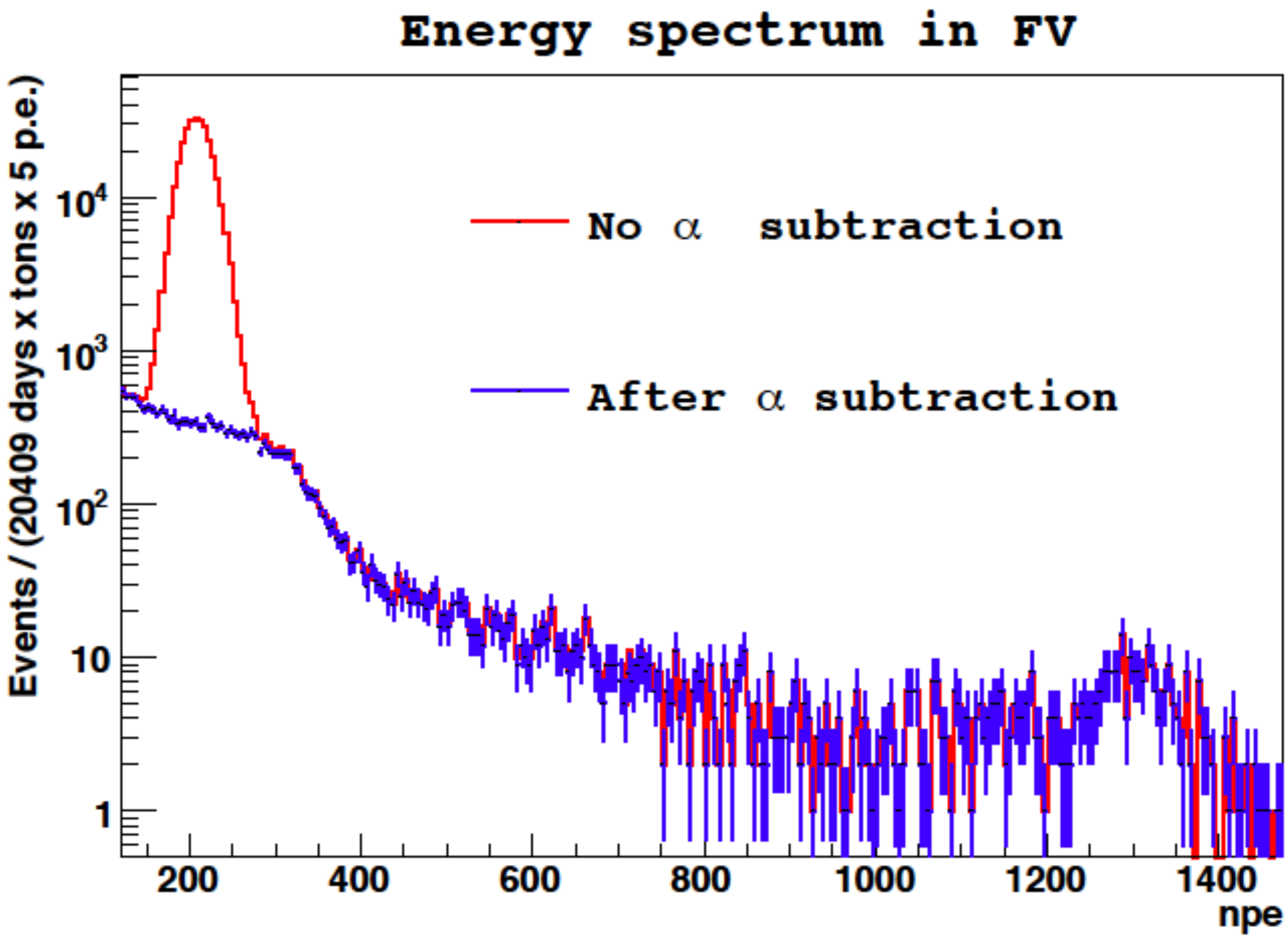
Tagging and removing ^{11}C cosmogenic background



Remove ^{11}C

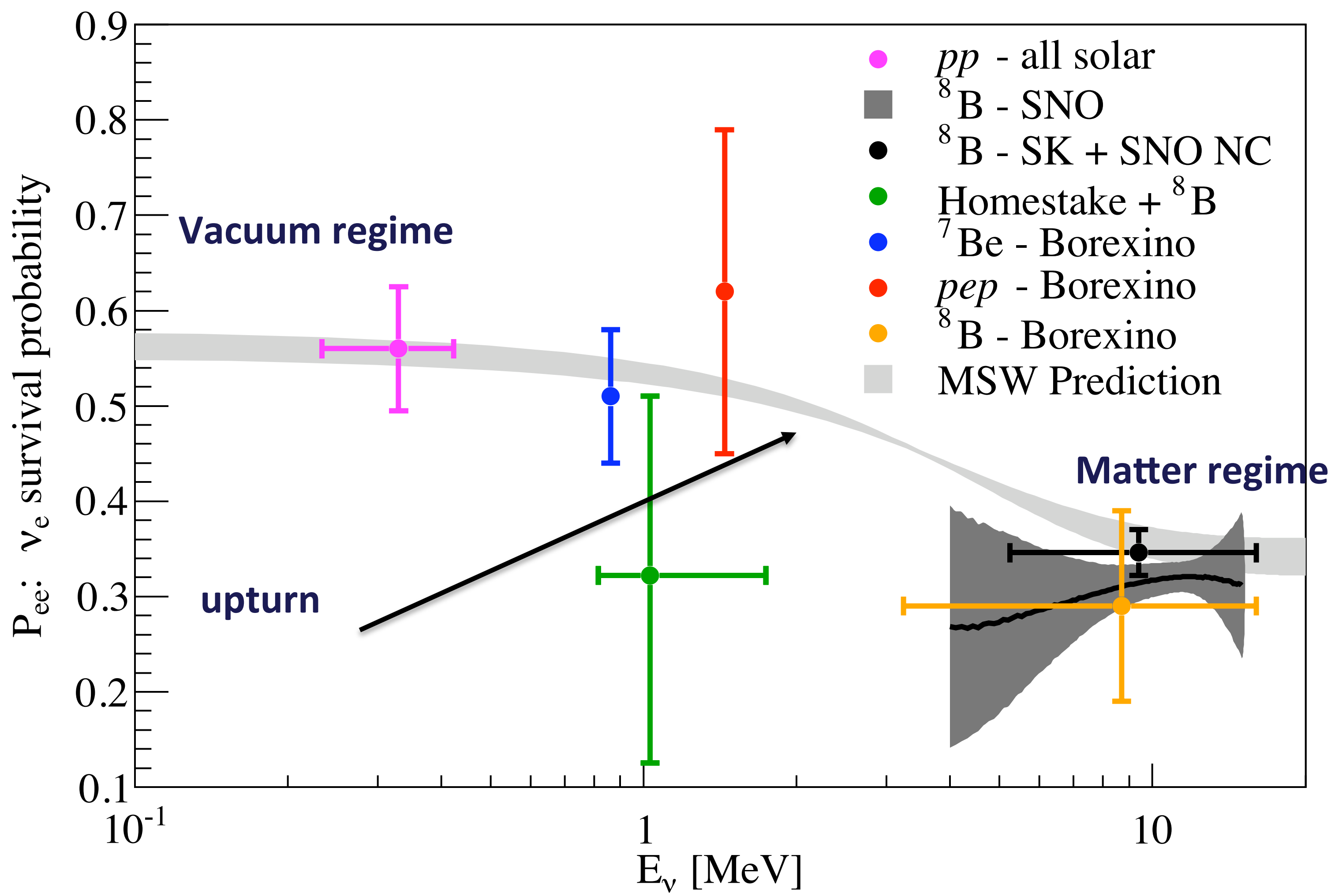

Events / (20409 days x tons x 5 p.e.)
1
10
10²
10³
10⁴
200
400
600
800
1000
1200
1400
npe
After TFC veto
No ¹¹C subtraction

PSD cut



Energy spectrum in FV
Events / (20409 days x tons x 5 p.e.)
No α subtraction
After α subtraction
10^4
10^3
10^2
10
1
200
400
600
800
1000
1200
1400
npe

Solar Neutrinos Survival Probability



Neutrino Oscillations from solar neutrinos

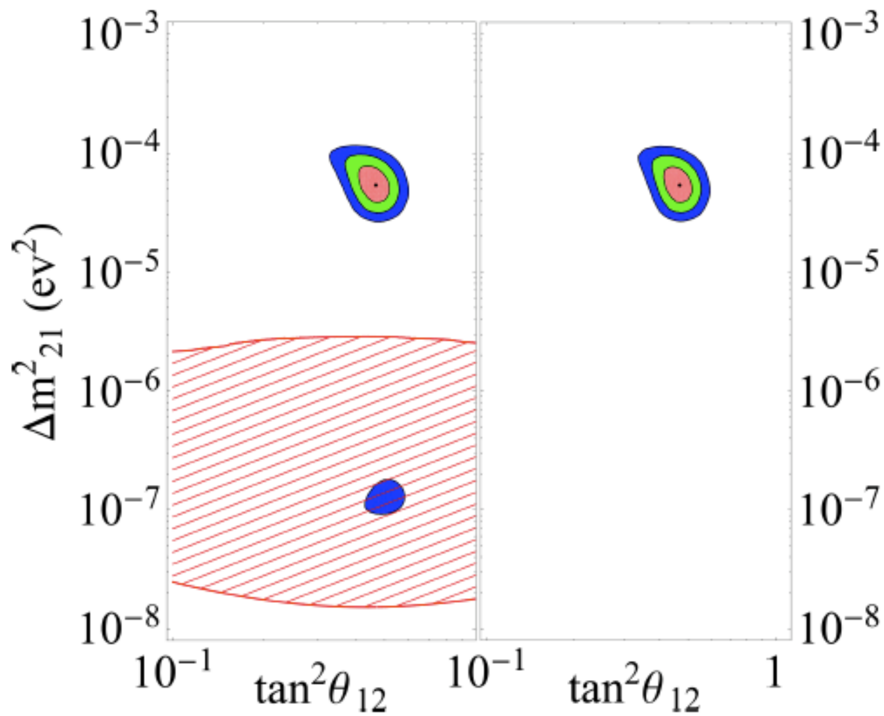
$$\chi^2_{\rm solar+KL} = \chi^2_{\rm solar}(\Delta m^2_{21},\, \tan^2\theta_{12},\, \sin^2\theta_{13}) + \chi^2_{\rm KL}(\Delta m^2_{21},\, \tan^2\theta_{12},\, \sin^2\theta_{13})$$

$$\Delta m^2_{21} = 7.50^{+0.18}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.457^{+0.038}_{-0.025}\ \left[0.462^{+0.032}_{-0.033}\right]$$

$$\sin^2\theta_{13} = 0.023^{-0.014}_{-0.018}\ \left[0.025^{-0.003}_{-0.004}\right]$$

Daya Bay and RENO included



Search for electron anti-neutrinos

Sources

1. Reactors (from β-emitter fission products)
   - energy < 10 MeV
2. Earth (Crust and Mantle) from β decays in ^{238}U and ^{232}Th chains
   - energy < 3 MeV
3. Supernova
   - during collapse: $e^{-} + p \rightarrow n + \nu_e$
   - during cooling: $p + e^{+} \rightarrow n + \text{anti-}\nu_e$
4. Atmosphere induced by primary cosmic rays

Electron anti-neutrinos from reactors

- Reactor fuel made of: $^{235}U(69\%) + ^{238}U(7\%) + ^{239}Pu(21\%) + ^{241}Pu(3\%)$
- β decay of fission products make electron anti-neutrinos
- on average 6 electron anti-neutrinos are emitted per fission
- on average 200 MeV are released per fission
- anti-neutrino spectrum determined by summing all β decay spectra

$$I_{\bar{\nu}_e} \approx 1GW \cdot \frac{1}{200}\frac{\text{fission}}{MeV} \cdot \frac{6\bar{\nu}_e}{\text{fission}} \approx 2 \cdot 10^{20} \ \ \bar{\nu}_e / s$$

$$\phi_{\bar{\nu}_e}\text{(at 1km)} \approx \frac{1}{4\pi 10^5 cm^2} I_{\bar{\nu}_e} \approx 2 \cdot 10^9 \ \ \bar{\nu}_e / cm^2 / s$$

Detection channel for electron anti-ν

Electron anti-ν's are detected by the inverse-beta decay reaction:

anti-ν + p -> e^+ + n (E$_{th}$= 1.806 MeV)

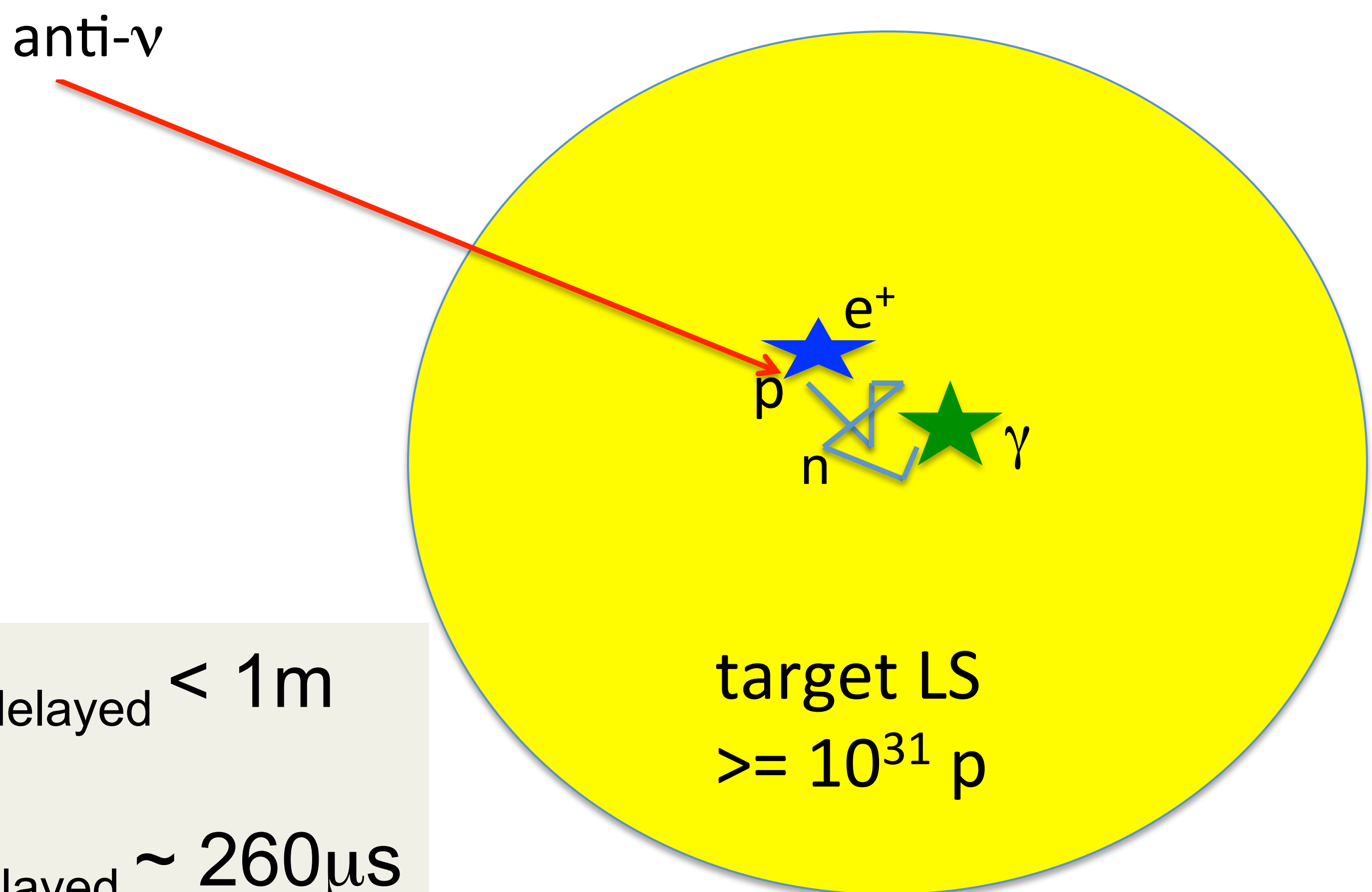
Two classes of signals:

1) Prompt (from the positron) with visible energy, $E_{prompt}=E_\nu-0.782$ MeV

2) Delayed (from neutron capture):

n+p->d+γ(2.22MeV)

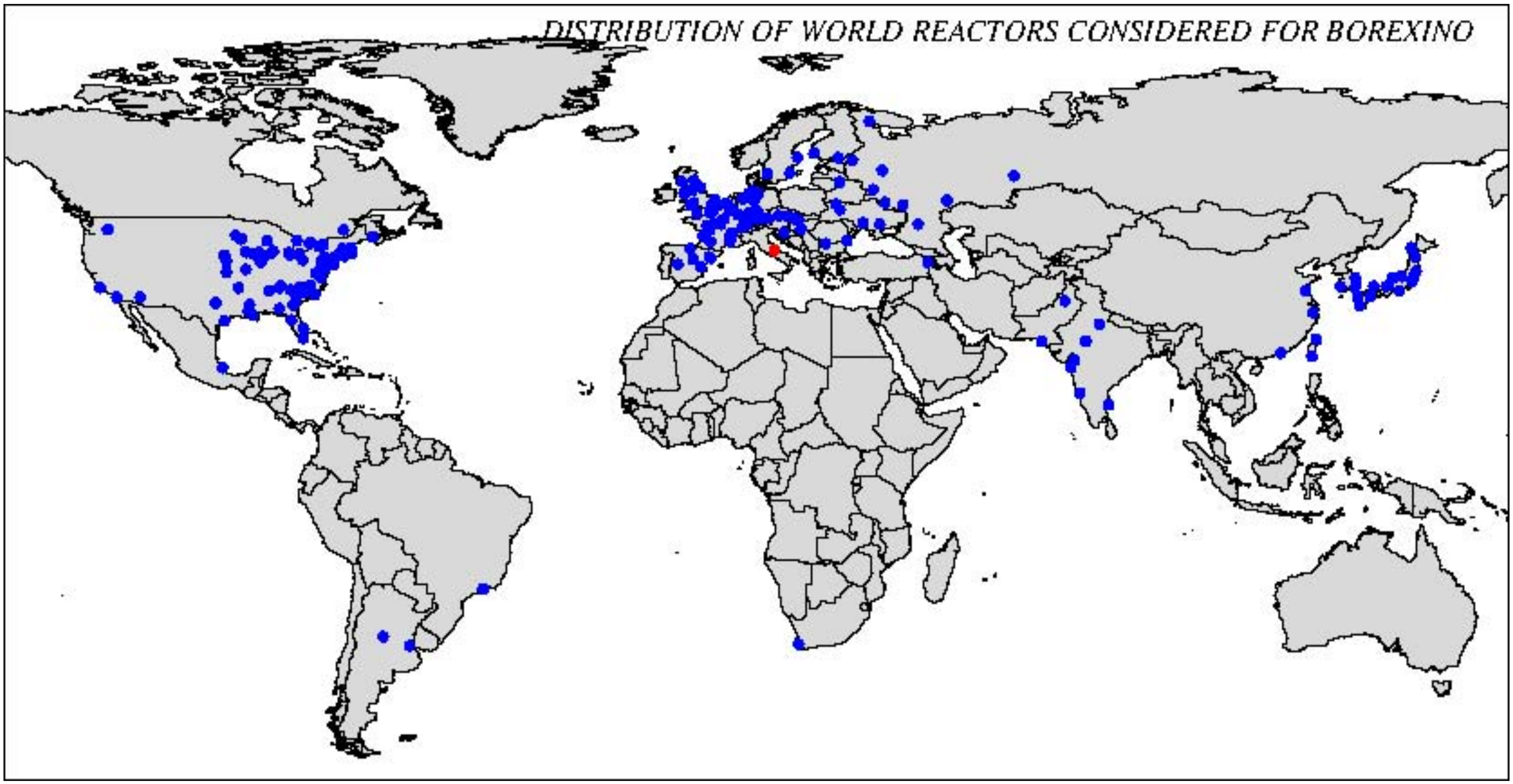
Topology of the electron anti-ν event



$\Delta R_{prompt\text{-}delayed} < 1\text{m}$

$\Delta t_{prompt\text{-}delayed} \sim 260\mu s$

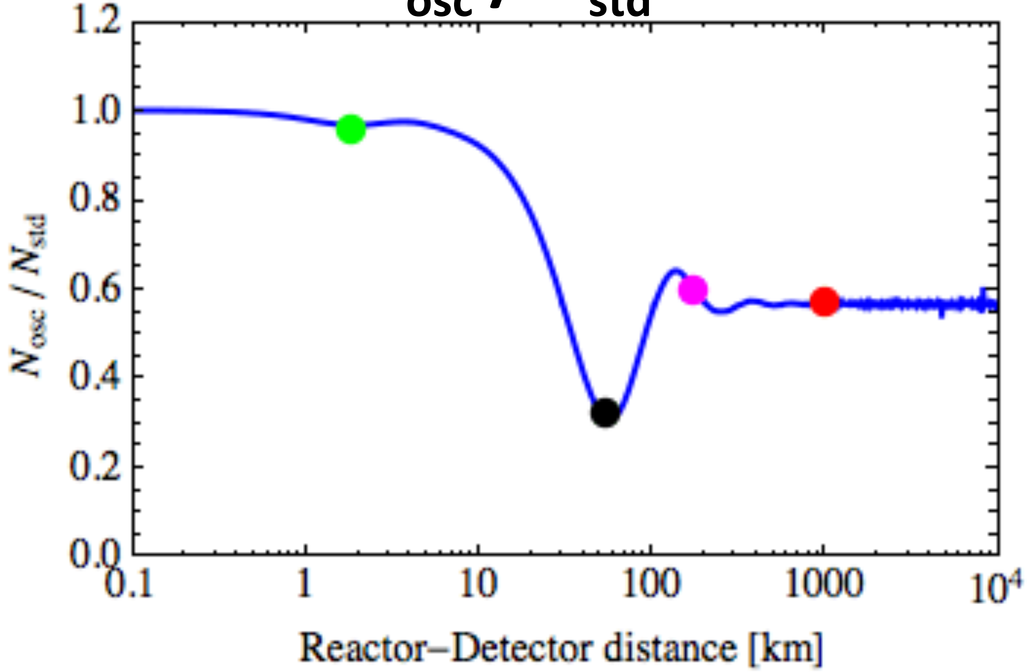
Reactors in the World



Reactor electron anti-ν search

CHOOZ/Day Bay
KamLAND
BOREXINO
JUNO

N_{osc} / N_{std}



Backgrounds

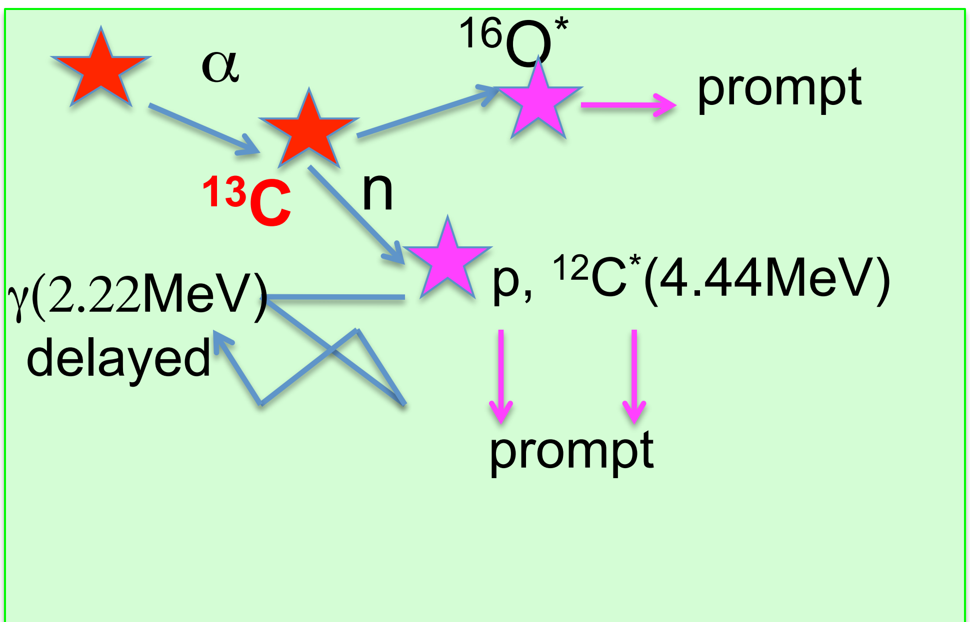
Look for possible sources of *fake* electron anti-ν events
(prompt + delayed):

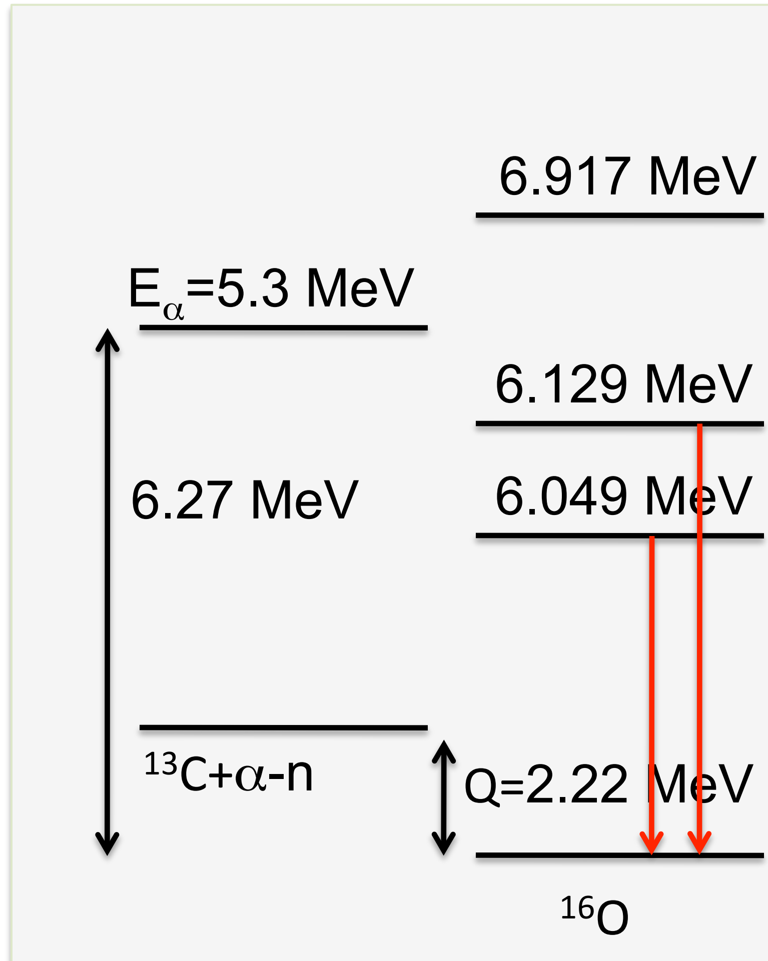
1. **Background induced from (α,n) and (γ,n) interactions**
    1. Mainly from $^{13}C(\alpha,n)^{16}O$
2. **Muons**
    1. β−n emitters such as ^{9}Li and ^{8}He
    2. High energy neutrons
3. **Accidental coincidences**

$^{13}C(\alpha,n)^{16}O$

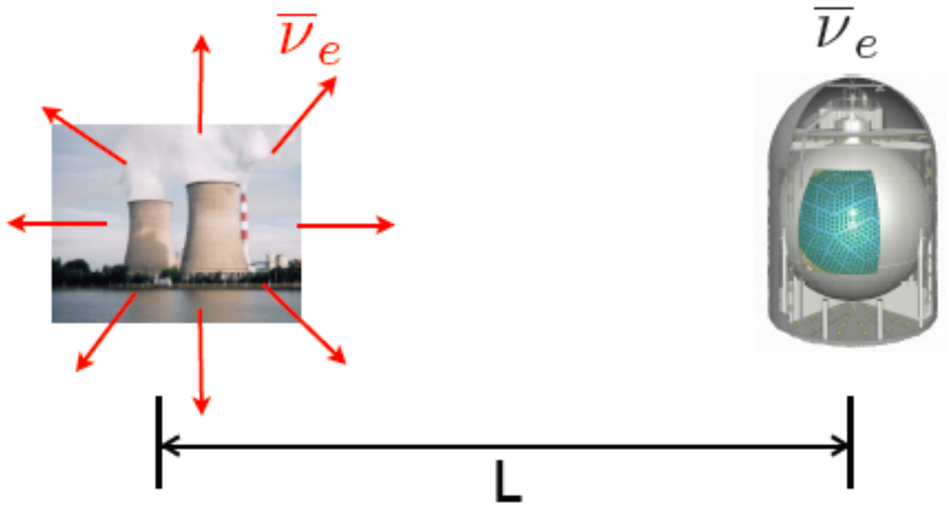
1) No threshold energy
2) Low abundance (1.1%) of ^{13}C
3) Background induced by contamination of ^{210}Po.
4) For E_α=5.3 MeV: 4.65 MeV ≤ $E_{neutron}$ ≤ 7.29 MeV for the ground state transition

through $^{13}C(\alpha,n)^{16}O$

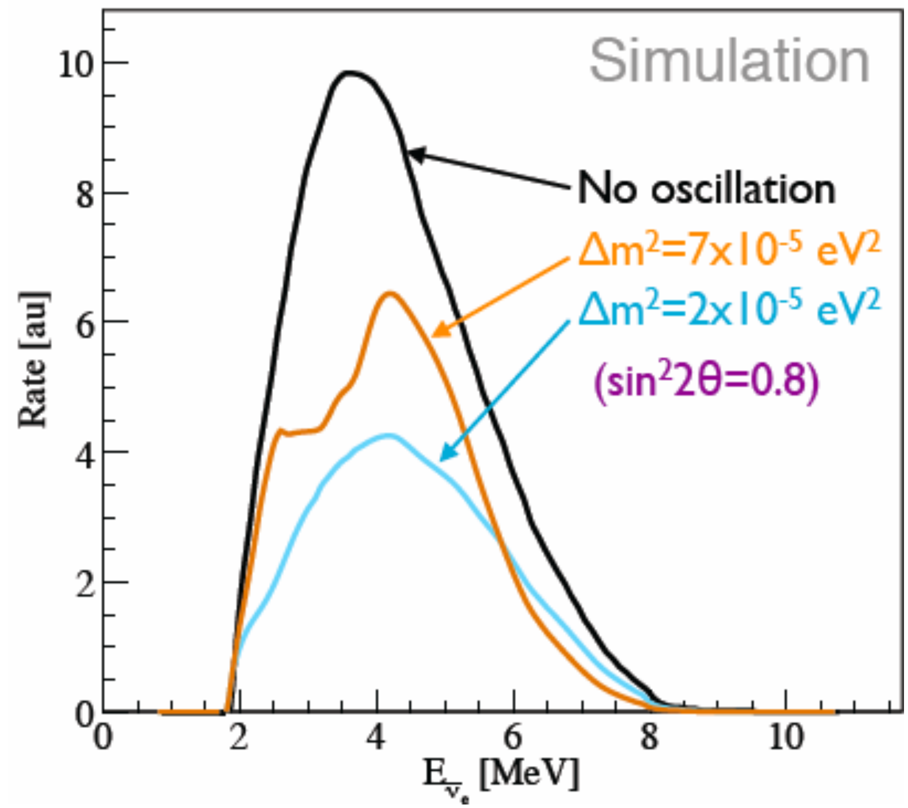




KamLAND



$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

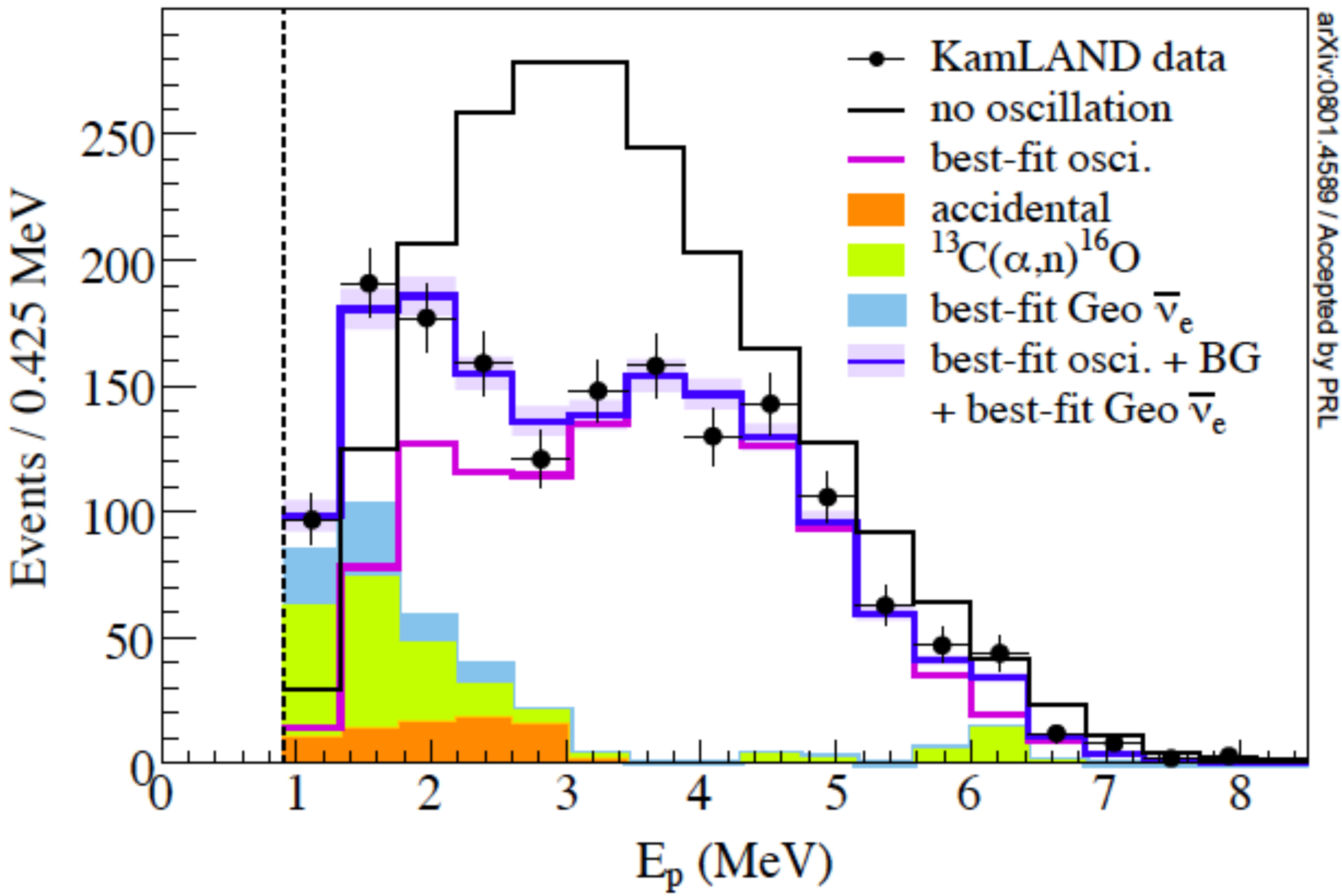


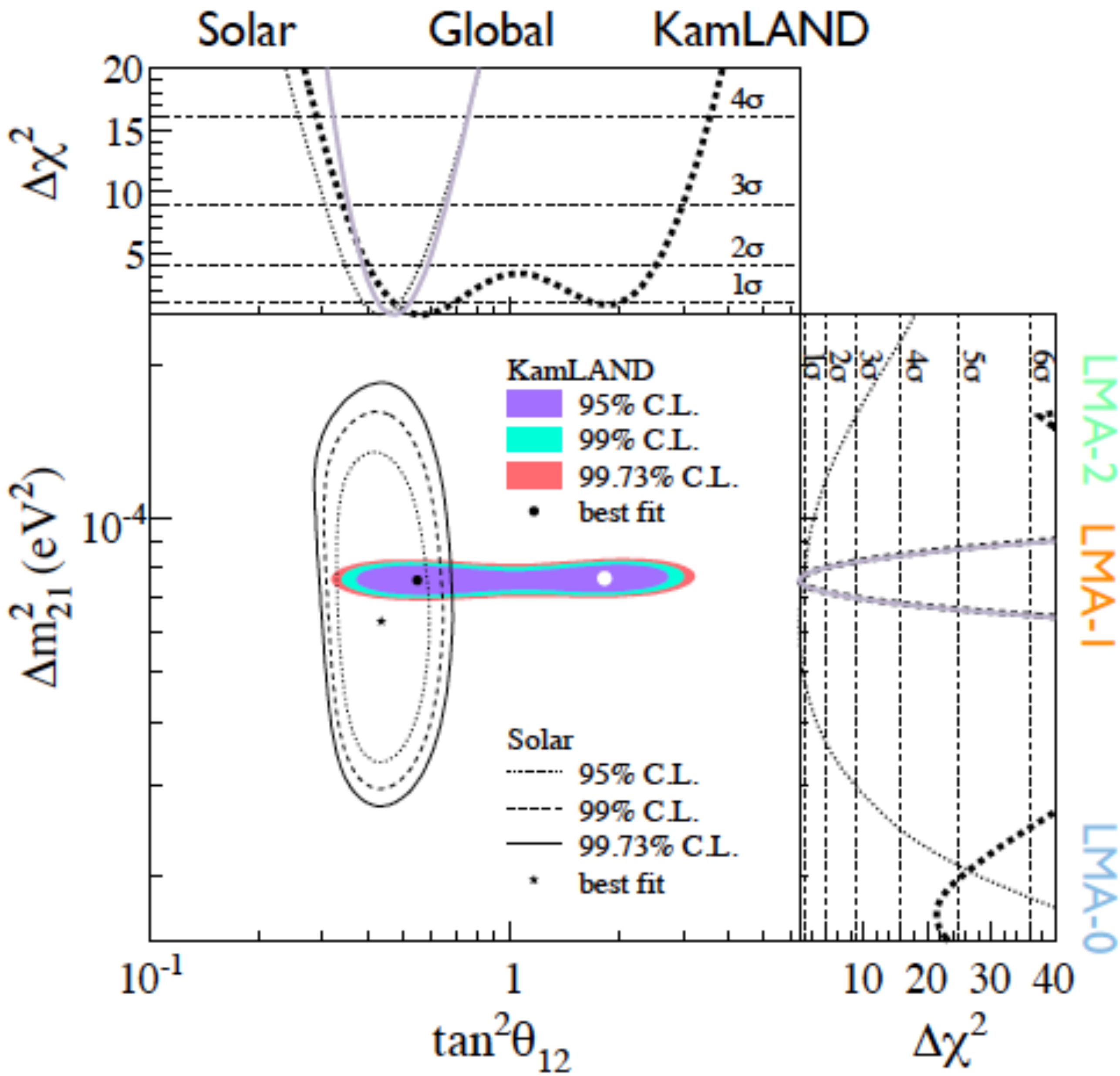
The neutrino oscillation changes the overall spectrum normalization and the energy shape

The KamLAND detector in Japan

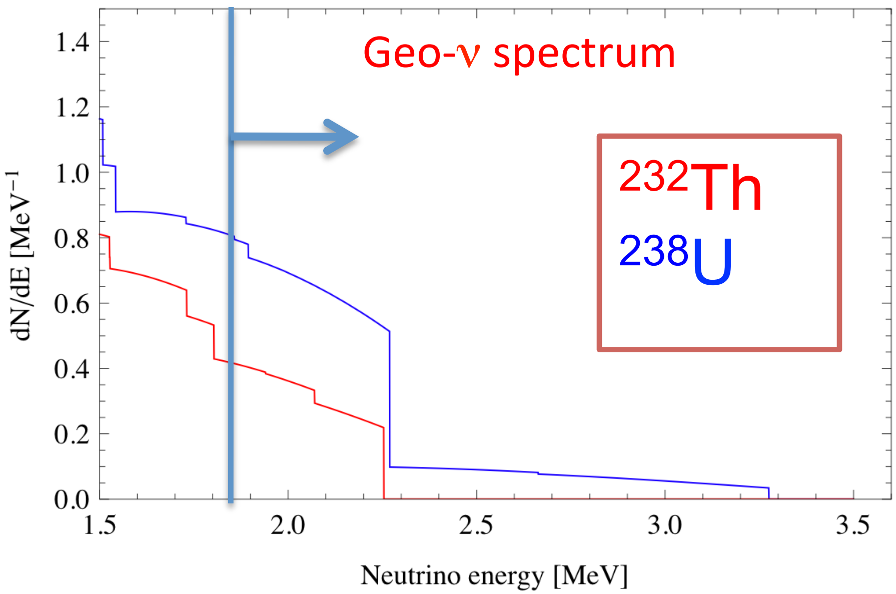
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

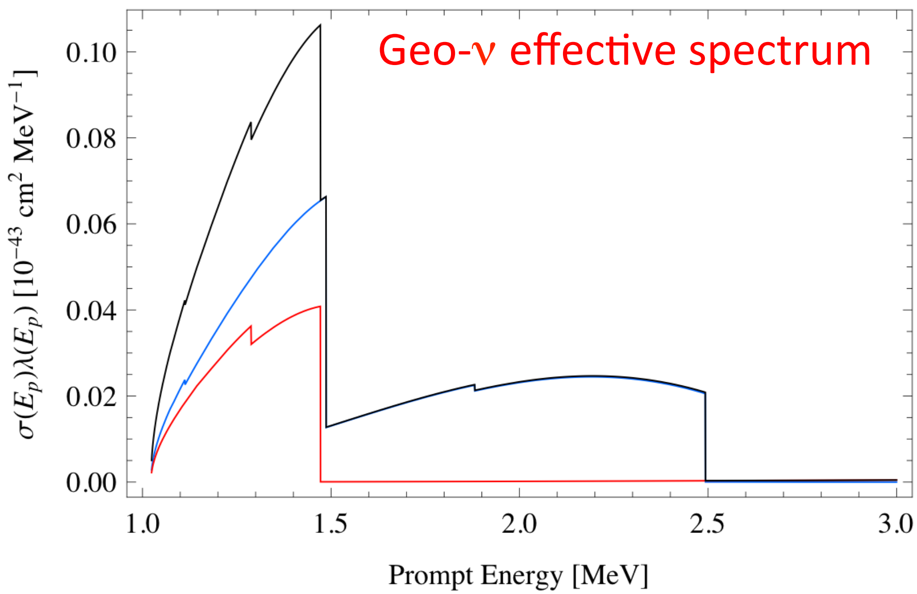
KamLAND: results




Solar
Global
KamLAND
$\Delta\chi^2$
4σ
3σ
2σ
1σ
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
best fit
Solar
95% C.L.
99% C.L.
99.73% C.L.
best fit
Δm^2_{21} (eV^2)
10^{-4}
10^{-1}
1
$\tan^2\theta_{12}$
1σ
2σ
3σ
4σ
5σ
6σ
10
20
30
40
$\Delta\chi^2$
LMA-2
LMA-1
LMA-0

Spectroscopy of geo-ν signal





$$S(U) = 4.0 \times 10^{-7} \left(\frac{N_p}{10^{32}} \right) \left(\frac{\phi_U}{10^6 \ \mathrm{cm}^{-2} s^{-1}} \right) \mathrm{s}^{-1}$$

$$S(Th) = 1.3 \times 10^{-7} \left(\frac{N_p}{10^{32}} \right) \left(\frac{\phi_{Th}}{10^6 \ \mathrm{cm}^{-2} s^{-1}} \right) \mathrm{s}^{-1}$$

$$\mathrm{S(Th)} = 0.07 \times \frac{[Th]}{[U]} S(U)$$

$$\frac{[Th]}{[U]} \approx 3.9$$

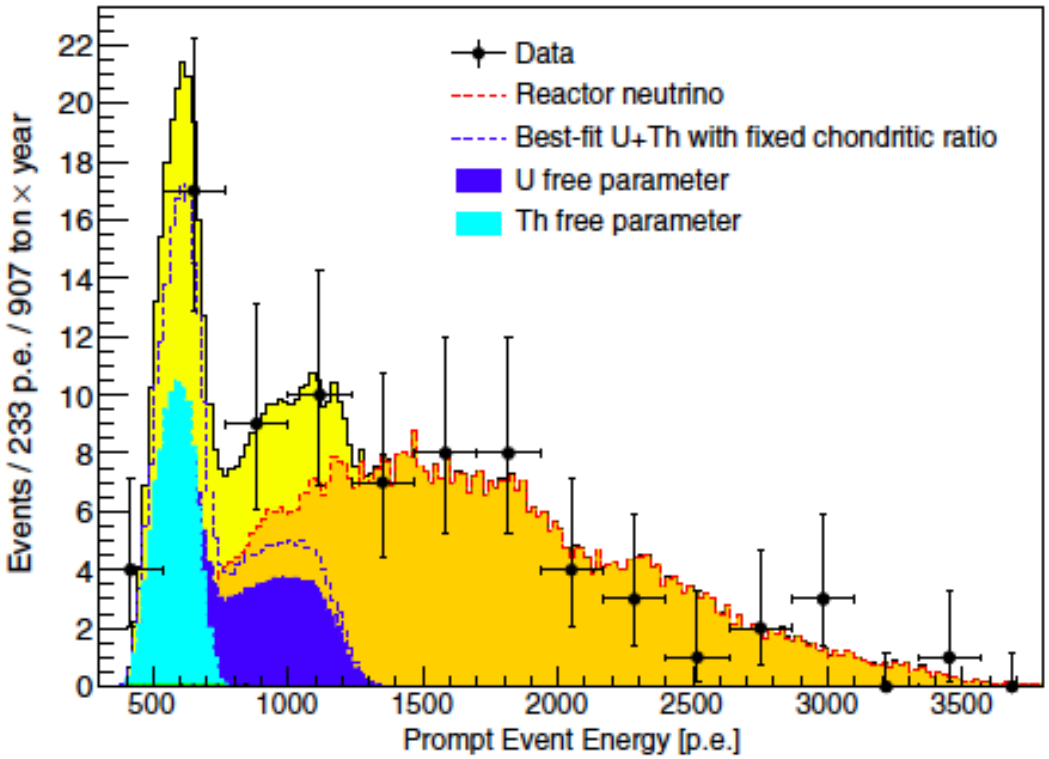
$$S(U) = 12.7 \left(\frac{N_p}{10^{32}} \right) \left(\frac{\phi_U}{10^6 \ \mathrm{cm}^{-2} s^{-1}} \right) \mathrm{yr}^{-1}$$

$$S(Th) = 4.1 \left(\frac{N_p}{10^{32}} \right) \left(\frac{\phi_{Th}}{10^6 \ \mathrm{cm}^{-2} s^{-1}} \right) \mathrm{yr}^{-1}$$

$$\mathrm{S(U)}_{\mathrm{LNGS}} \approx 30 \ \mathrm{TNU}$$

$$\mathrm{S(U)}_{\mathrm{Kamioka}} \approx 26 \ \mathrm{TNU}$$

Electron anti-neutrinos from Borexino



77 candidates passing selection cuts
Exposure (5.5±0.3)x10[31] protons-year

TABLE I. Estimated backgrounds for $\bar{\nu}_e$ given in number of events. Upper limits are given for 90% C.L.

^{9}Li-^{8}He	$0.194^{+0.125}_{-0.089}$
Accidental coincidences	0.221 ± 0.004
Time correlated	$0.035^{+0.029}_{-0.028}$
(α, n) in scintillator	0.165 ± 0.010
(α, n) in buffer	<0.51
Fast n's (μ in WT)	<0.01
Fast n's (μ in rock)	<0.43
Untagged muons	0.12 ± 0.01
Fission in PMTs	0.032 ± 0.003
^{214}Bi-^{214}Po	0.009 ± 0.013
Total	$0.78^{+0.13}_{-0.10}$
	<0.65(combined)

Conclusions

1. Solar neutrinos observed since 1968
   - established MSW oscillation pattern
   - measured solar neutrino flux at 3% (^{8}B) and 5%(^{7}Be)
   - established pp chain dominant energy source
   - goal for next future:
     - ✓ measure CNO contribution
     - ✓ solve solar abundance problem
2. Reactor neutrinos / long baseline beam
   - established oscillation pattern
   - goal for next future:
     - ✓ solve short range oscillation issue
     - ✓ improve accuracy of neutrino oscillation parameters
     - ✓ probe mass ordering
3. Supernova neutrinos
   - goal for next detection
     - ✓ confirm basic mechanism of collapse with high statistics
     - ✓ test matter oscillations