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NEUTRINO OSCILLATION EXPERIMENTS

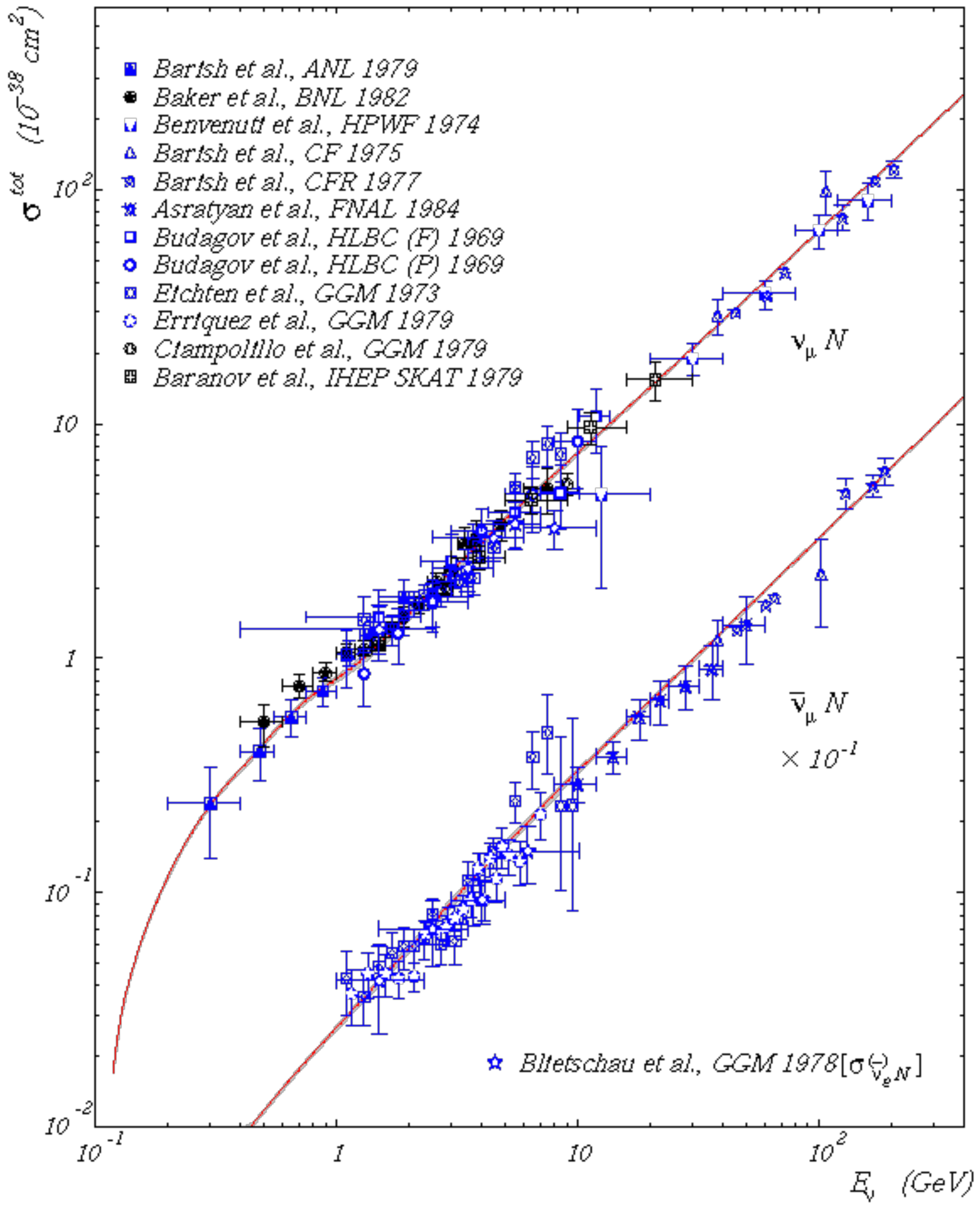
TRISEP 2016

OVERVIEW

- Today:
  - Challenges of studying neutrinos experimentally
  - Neutrino sources
  - Basic categorization of neutrino detectors
  - Quick review of neutrino oscillations
  - "Classical era" of neutrino oscillations
    - reactor and solar neutrino oscillations
    - atmospheric neutrino oscillations
- Tomorrow:
  - Verifying atmospheric neutrino oscillations
    - accelerator-based experiments
  - Three-flavour mixing
    - ν_e appearance, CP violation, θ_{23} octant, mass hierarchy . . .
  - Other relevant measurements and anomalies.

NEUTRINO INTERACTION CROSS SECTION

- Fundamental challenge of neutrino experiments
- How to put $\sigma = 10^{-38}$ cm^2 in perspective?
  - this is the typical cross section for 1 GeV neutrino
- Recall how to obtain "interaction length"
- $1/L = \sigma \times n$
  - σ = cross section (cm^2)
  - n = number density of target particles
  - for normal matter with ρ ~ O(1 gm/cm^3) n ~ N_A/cm^3 = 10^{24}/cm^3
  - L ~10^{11} cm = 10^{14} km ~ 10 light years
  - If we consider lead (r = 11.35 g/cm^3)
    - The interaction length of a 1 GeV neutrino is ~1 light year in lead.
    - in comparison, L_{rad} for a photon is 0.56 cm
  - Illustrates the weakness of the weak interaction at low energy
    - alternatively the massiveness of the W and Z



NEUTRINO ECONOMICS

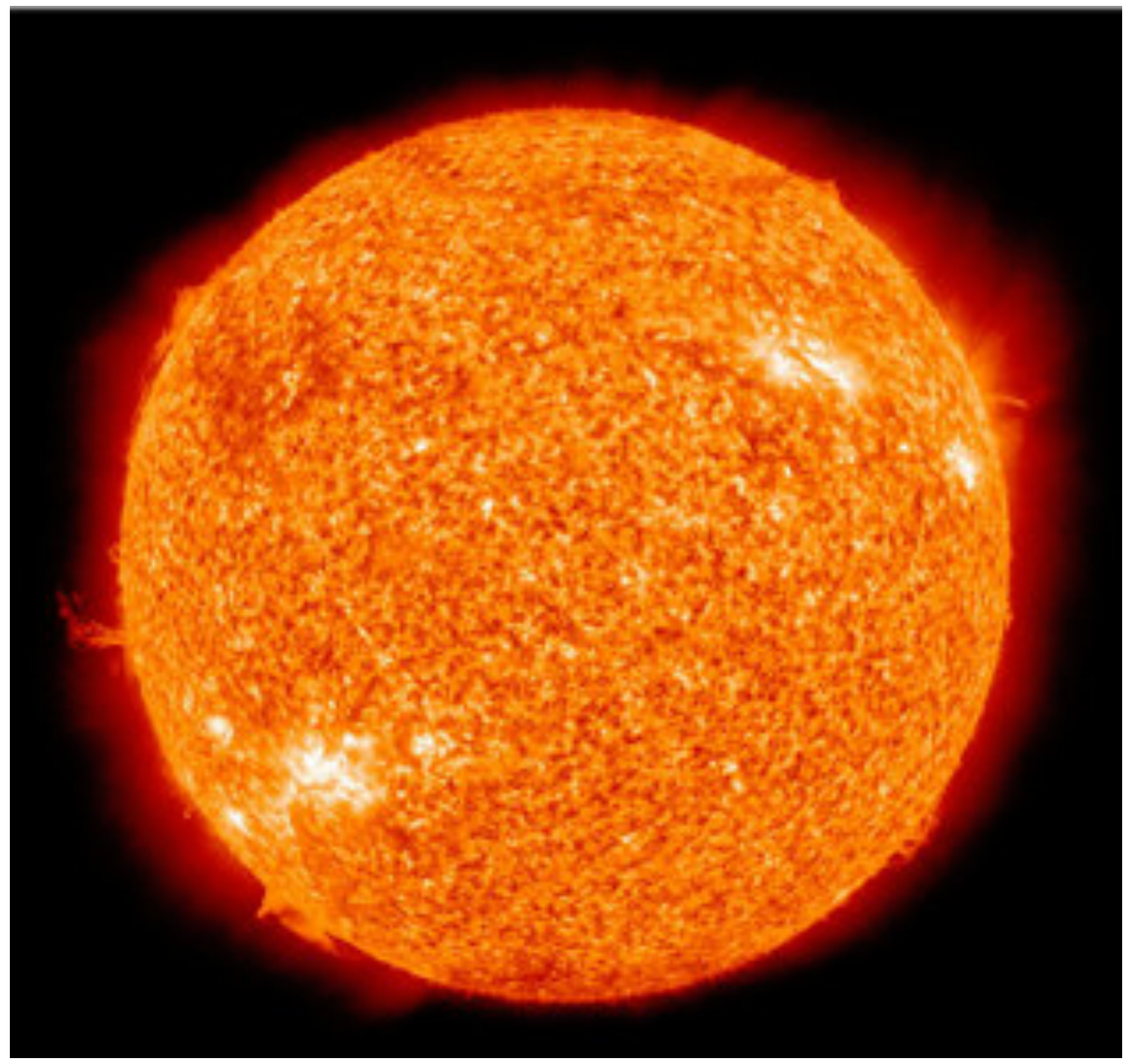
$$R = \varphi \times \sigma \times V \times n$$

- R: rate of neutrino interactions (/sec)
    - φ: flux of neutrinos (neutrinos/cm^2/sec)
    - σ: neutrino cross section on target(cm^2)
    - V: size of detector (cm^3)
    - n: number density of target particles in detector
- Neutrino experiments need:
    - intense neutrino sources (maximize φ)
    - large detectors (maximize $V \times n$)

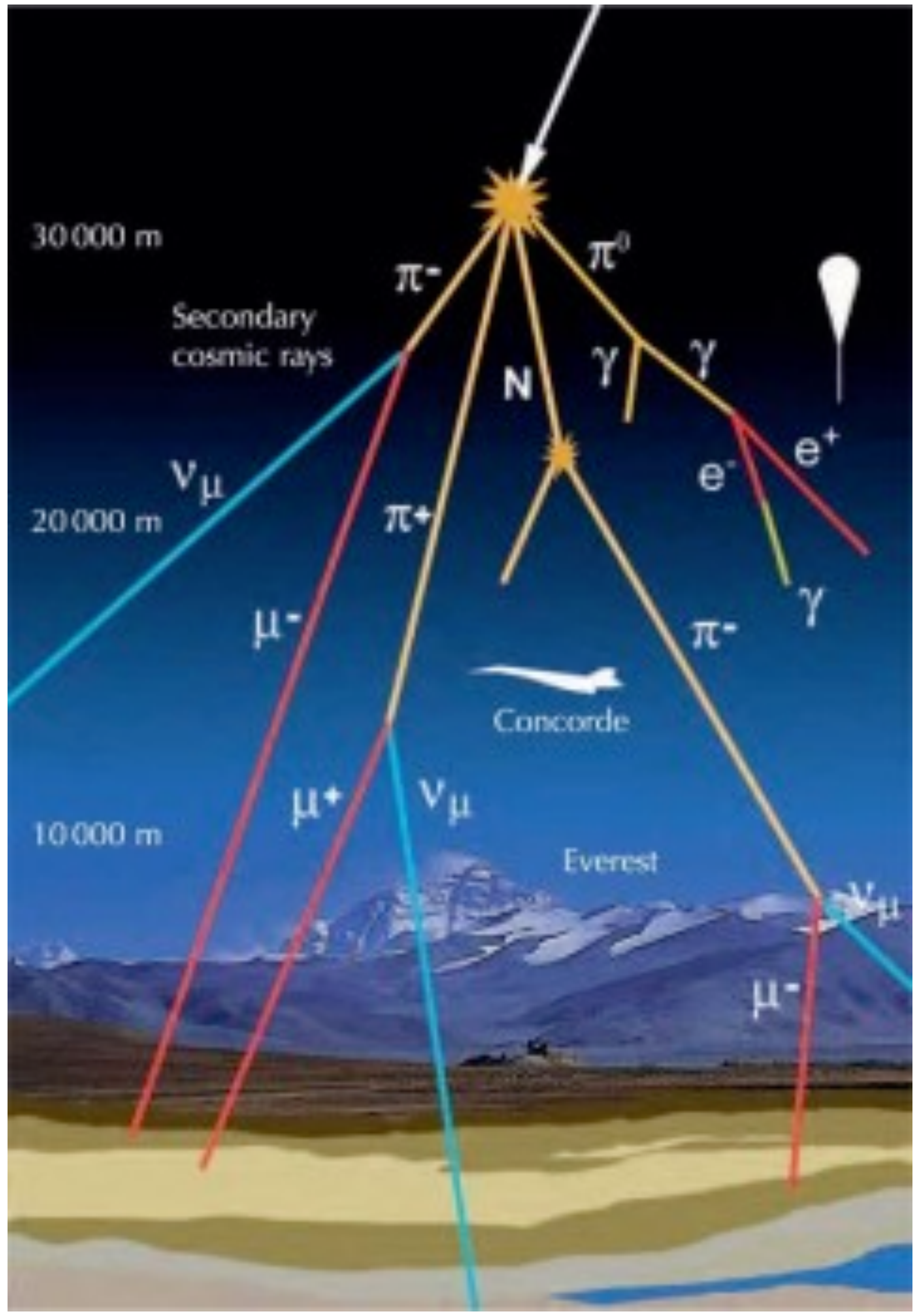
H. Bethe and R. Peirels:

- “**there is no practically possible way of observing the neutrino**"

NEUTRINO SOURCES



- Nuclear decays:
  - solar
    - 3% of sun's energy radiated as neutrinos
    - 10^{11} ν/cm^2/sec on surface of earth
  - reactor:
    - ~5% of reactor power emitted as antineutrinos
    - 10^{20} $\bar{\nu}$/sec emitted by typical GW reactor
  - Typical energy ~O(MeV)
    - only ν_e charged-current and neutral current interactions visible



- Meson/muon decays
  - e.g. pion decay ($\pi \rightarrow \nu_\mu + \mu$)
  - atmospheric neutrinos
    - $\pi/K/\mu$ produced in atmosphere by cosmic ray protons
  - accelerator-based neutrinos
    - $\pi/K/\mu$ produced by high energy protons produced by accelerators
  - Typical energy ~O(GeV)
    - can observe charged current interactions of ne, nm, sometimes nt

FIRST IDEA:

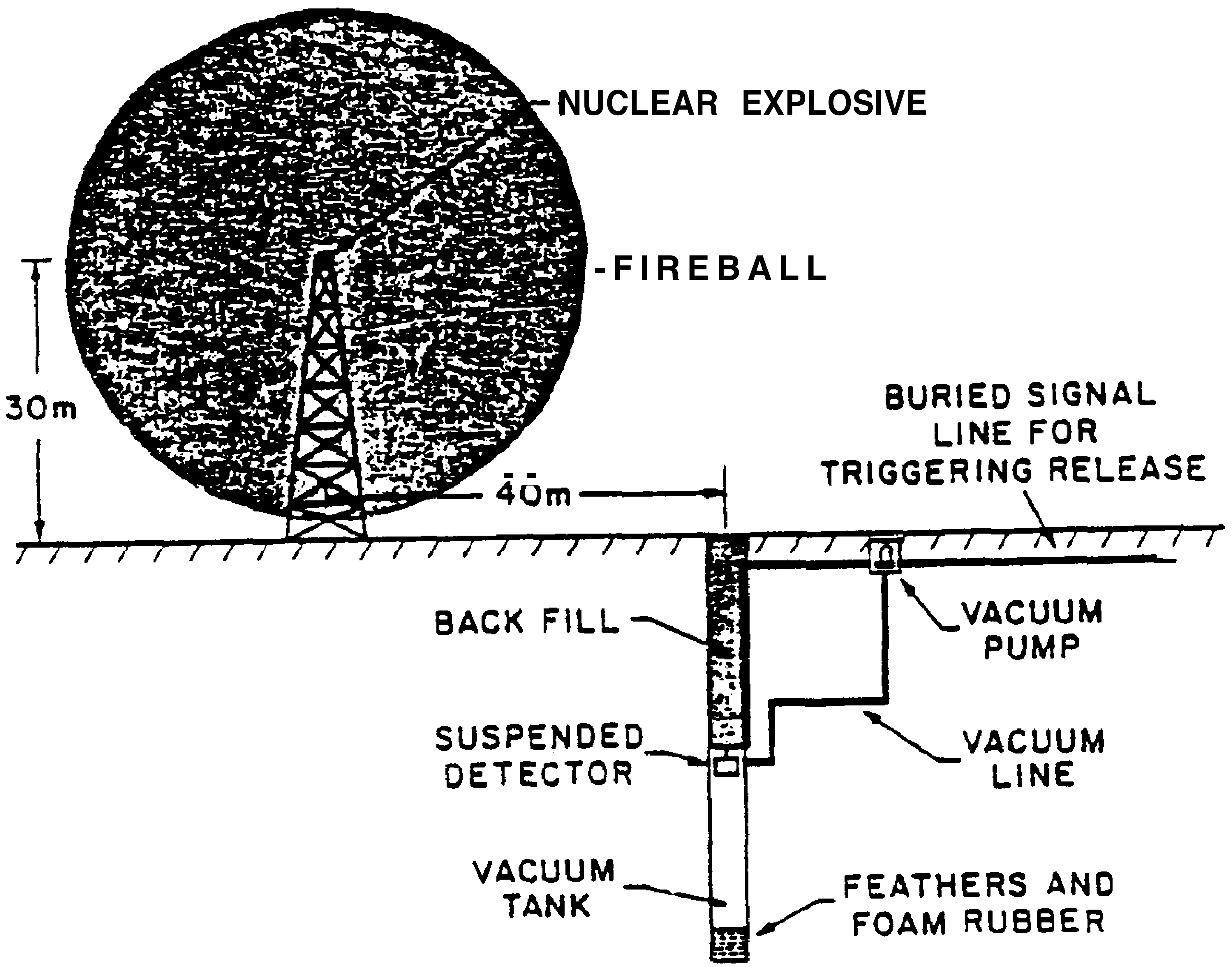


Figure 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor.

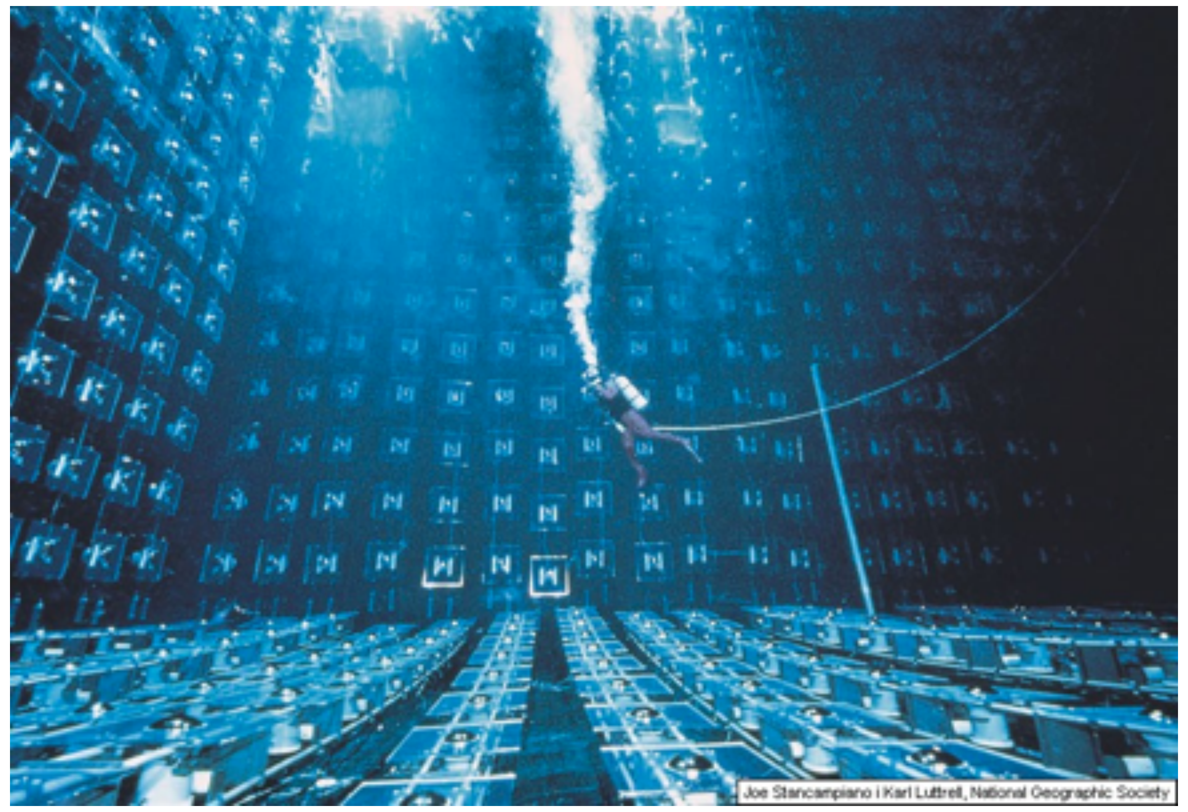
So why did we want to detect the free neutrino? Because everybody said, you couldn't do it. Not very sensible, but we were attracted by the challenge. After all, we had a bomb which constituted an excellent intense neutrino source. So, maybe we had an edge on others. Well, once again being brash,

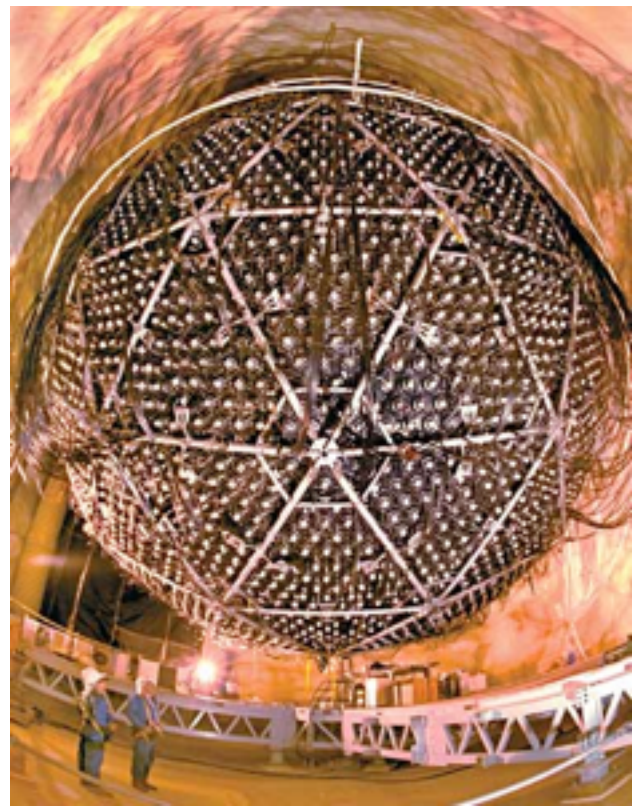
It happened during the summer of 1951 that Enrico Fermi was at Los Alamos, and so I went down the hall, knocked timidly on the door and said, "I'd like to talk to you a few minutes about the possibility of neutrino detection." He was very pleasant, and said, "Well, tell me what's on your mind?" I said, "First off as to the source, I think that the bomb is best." After a moment's thought he said, "Yes, the bomb is the best source." So far, so good! Then I said, "But one needs a detector which is so big. I don't know how to make such a detector." He thought about it some and said he didn't either. Coming from the Master that was very crushing. I put it on the back

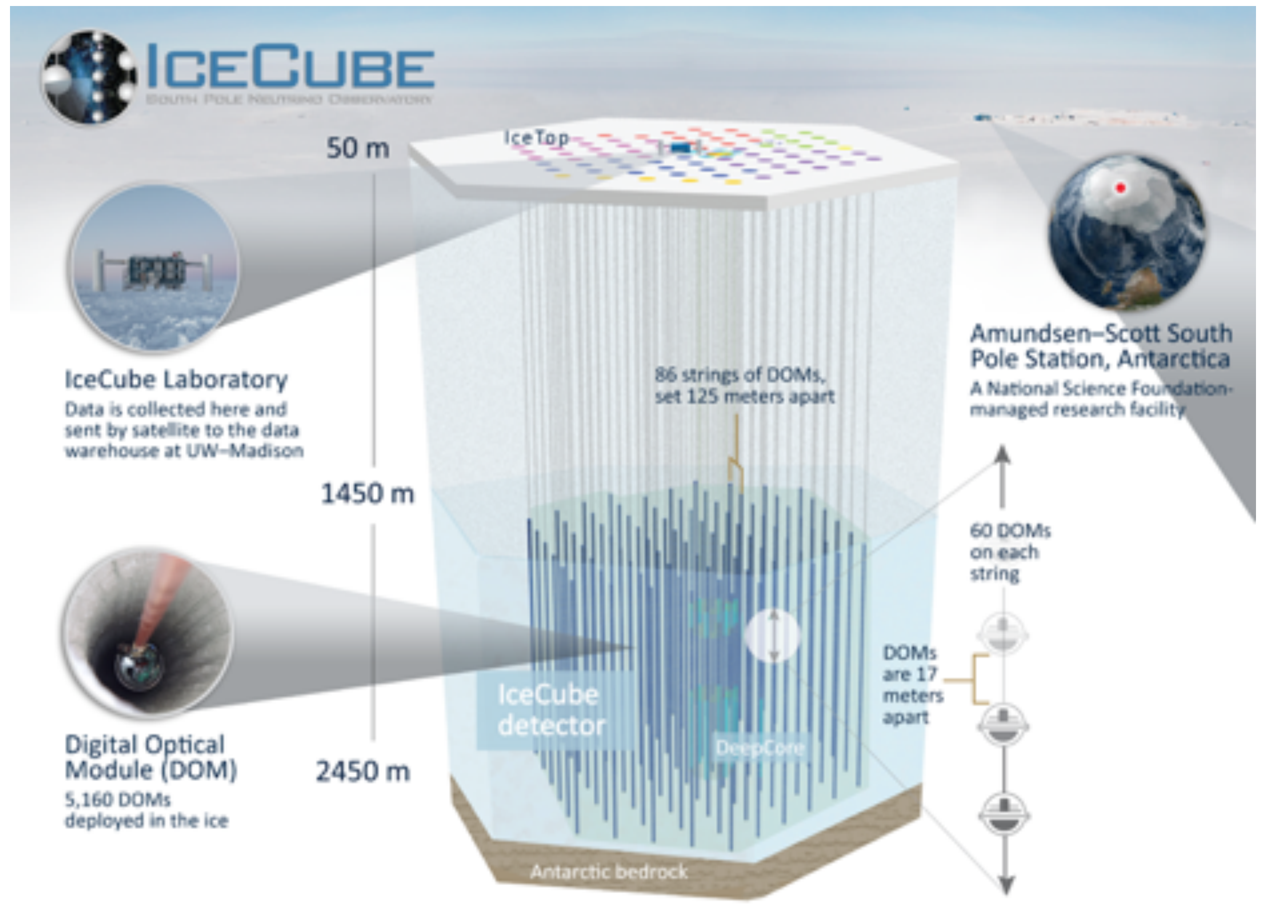
The idea that such a sensitive detector could be operated in the close prox imity (within a hundred meters) of the most violent explosion produced by man was somewhat bizarre, but we had worked with bombs and felt we could design an appropriate system. In our bomb proposal a detector would be sus

F. Reines (1995 Nobel Lecture)

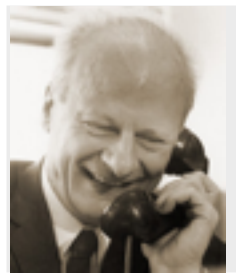
NEUTRINO DETECTORS





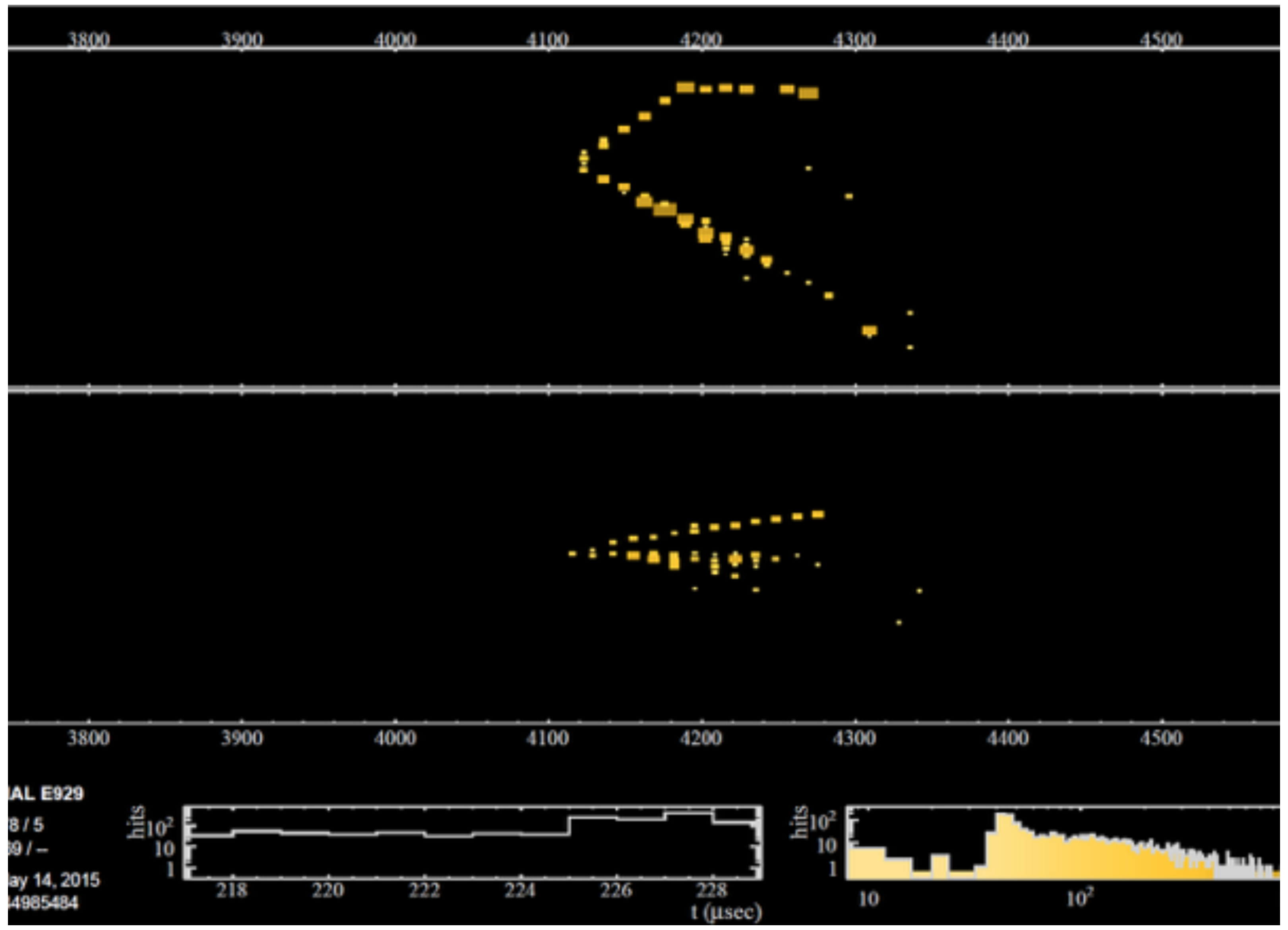


- Large detector/volume needed to gather neutrino interactions
  - neutrino detectors have long been about scalability
    - massive detectors that provide the information we need about the neutrino interactions
    - steel from decommissioned battleships
    - mineral oil/scintillator
    - large extruded PVC cells

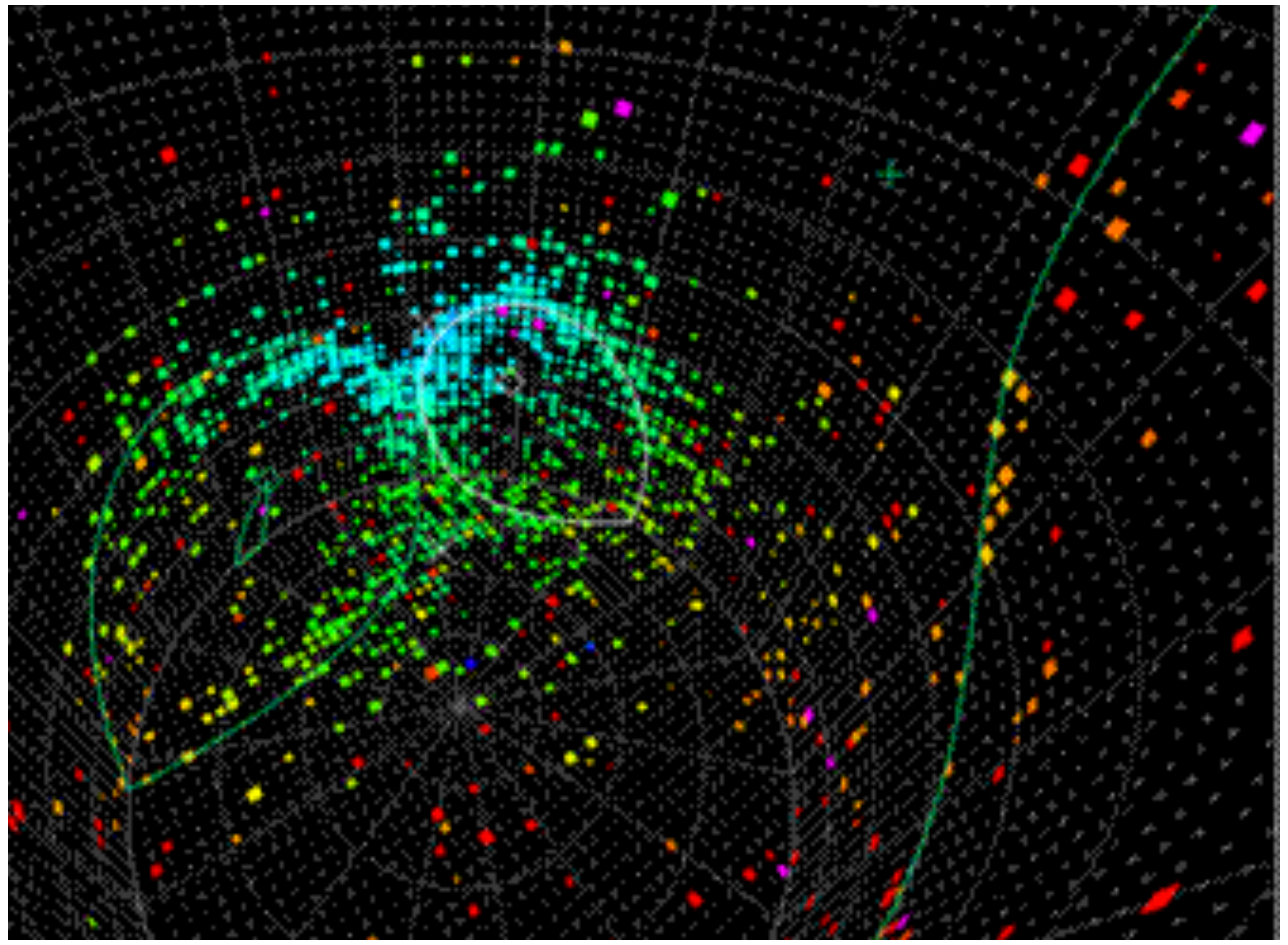


Hans Bethe: you shouldn’t believe everything you read in papers

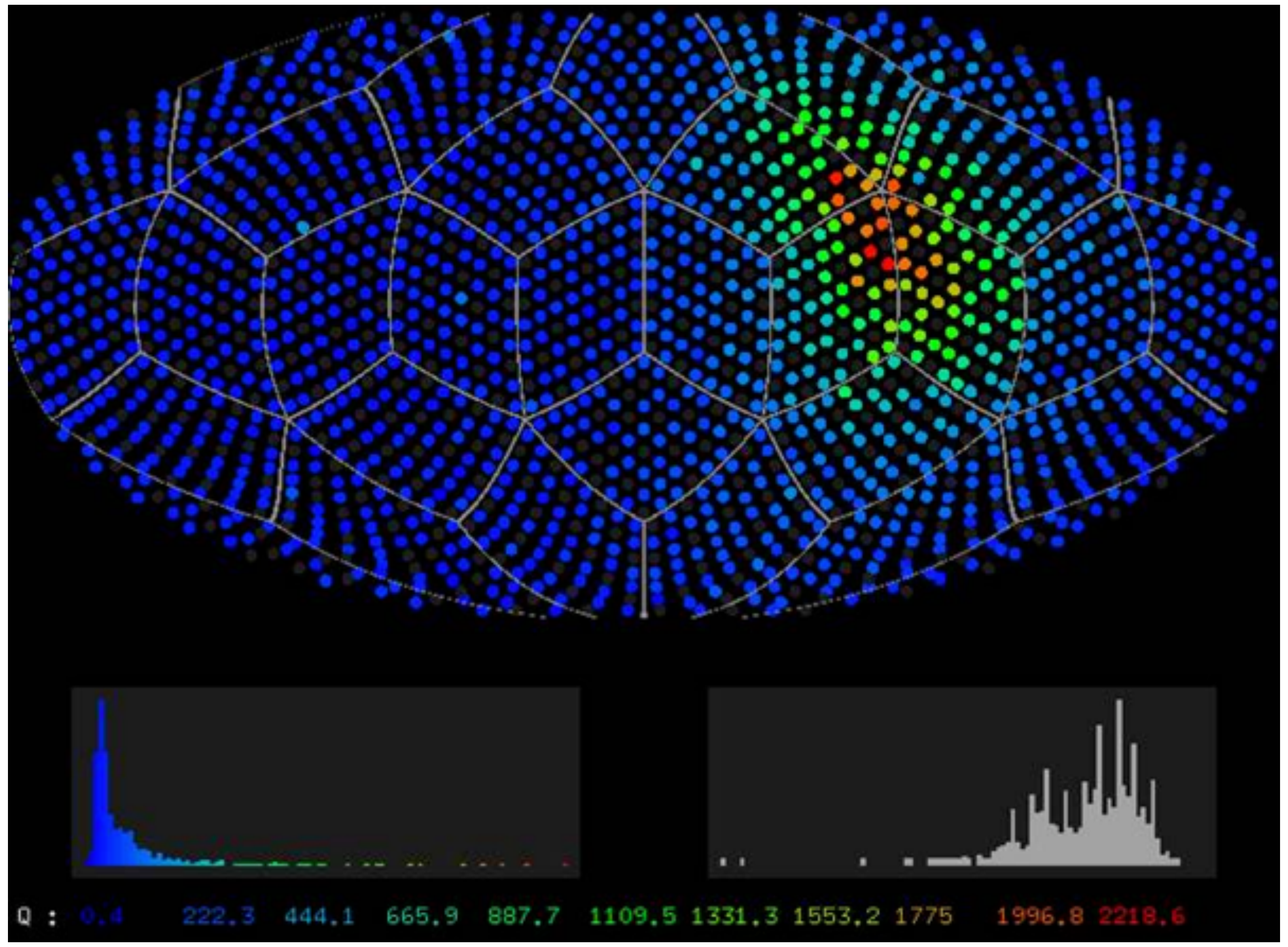
BASIC DETECTOR TYPES



- Tracking detectors
  - detector elements “track” charged particles based on ionization
  - can allow detailed characterization of outgoing particles
    - segmented scintillator bars
    - photographic emission
    - drift ionization in gas or liquid
  - particularly powerful in high energy interactions



- Cherenkov Detectors
  - detect “fast” particles exceeding the velocity of light in a medium (e.g. water)
  - cone of radiation detected with photosensors
  - multiple particle final states identified by multiple rings

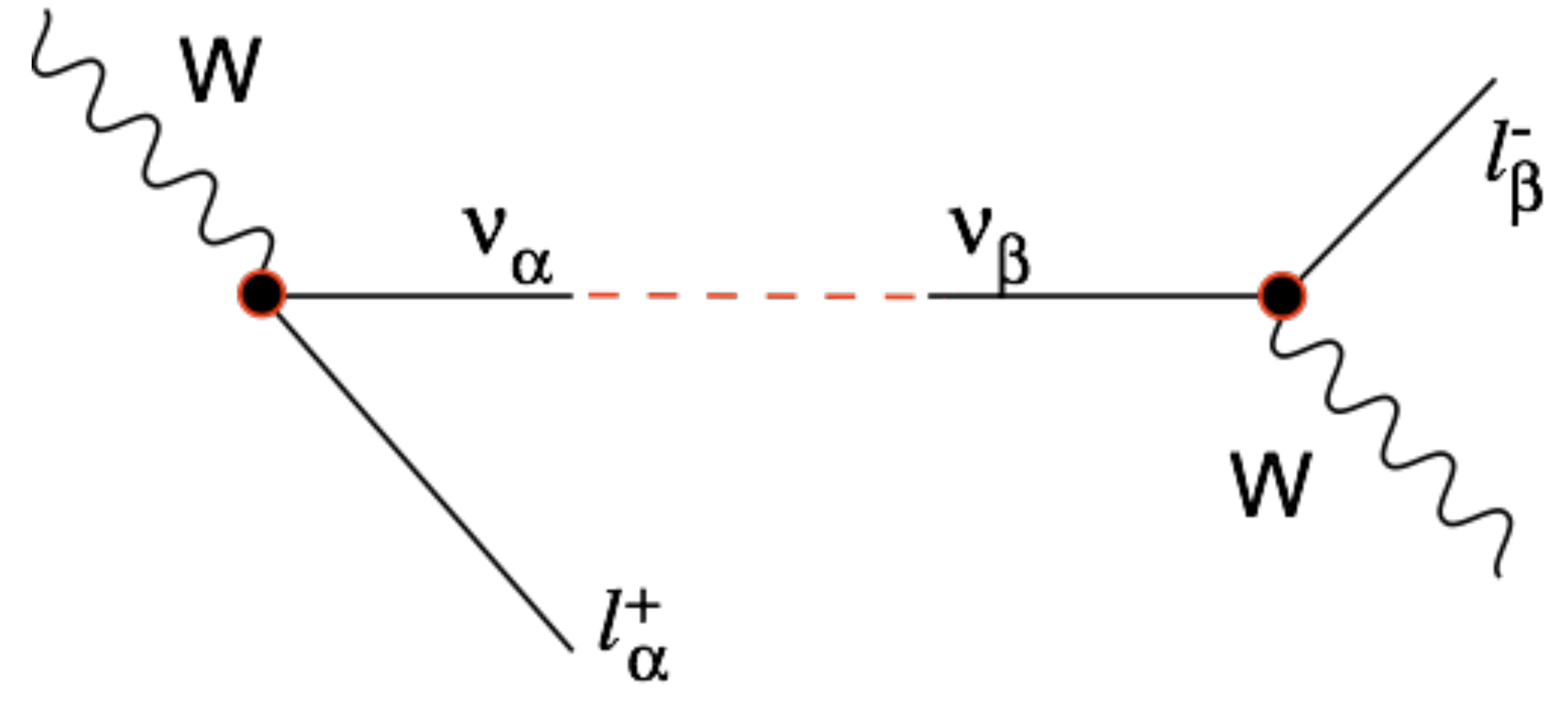


- Scintillation detectors
  - typically large volume of liquid scintillator
  - ionization converted into large yield of optical photons detected with photosensors
  - often used for low energy neutrinos where energy resolution and backgrounds reduction are critical

QUICK REVIEW OF NEUTRINO OSCILLATIONS

- Neutrino flavour states (created or interacting via the weak decays are linear combinations of mass/energy eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$



- Time evolution: flavour content "oscillates" in L(distance)/E(neutrino)

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\Sigma_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27 \Delta m^2_{ij} (L/E)] + 2\Sigma_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin[2.54 \Delta m^2_{ij} (L/E)]$$

in vacuo

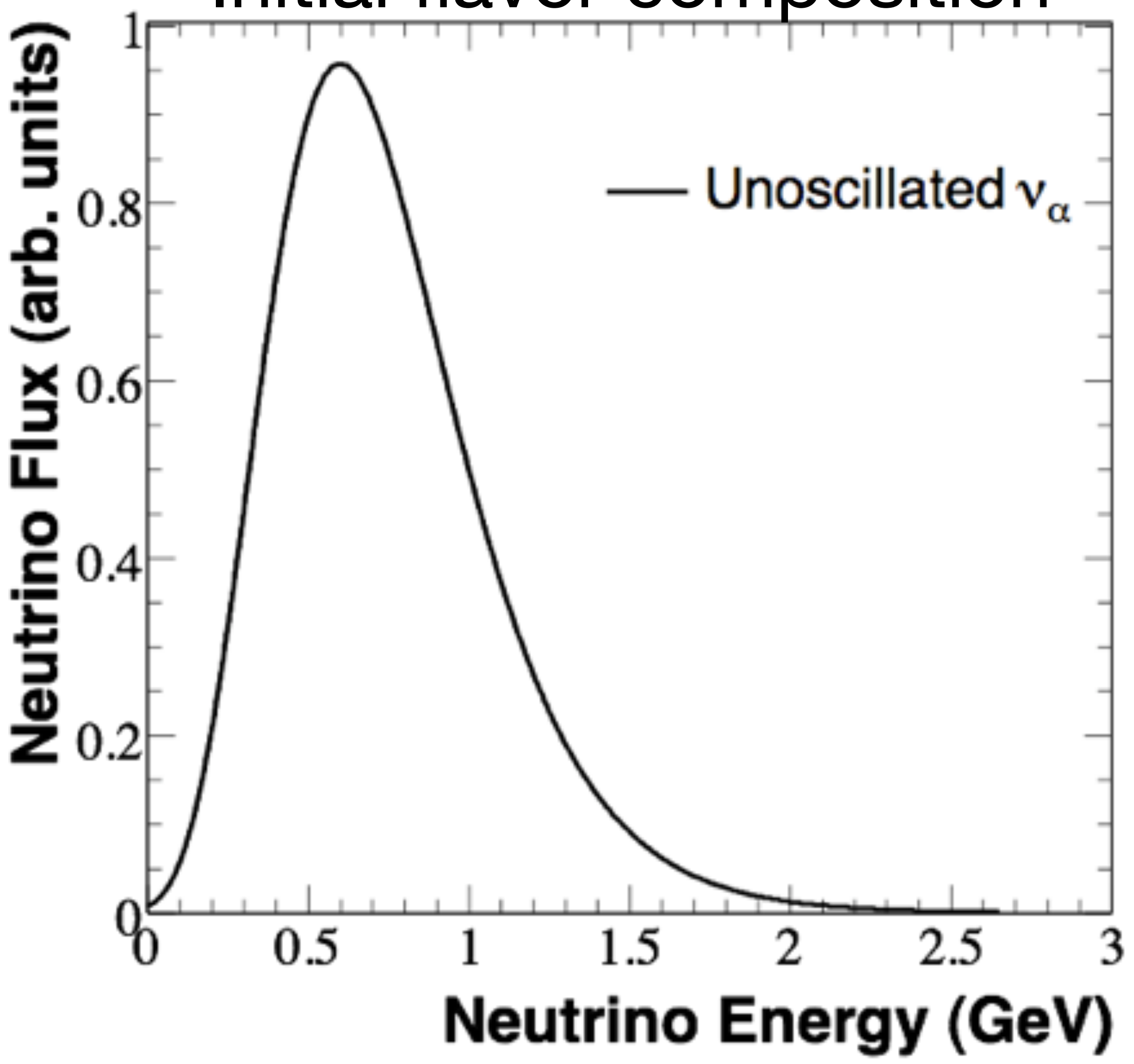
additional effects in the presence of matter

- **Amplitudes determined by mixing matrix U_{ij}**
- **Wavelengths determined by mass² differences Δm^2_{ij}**

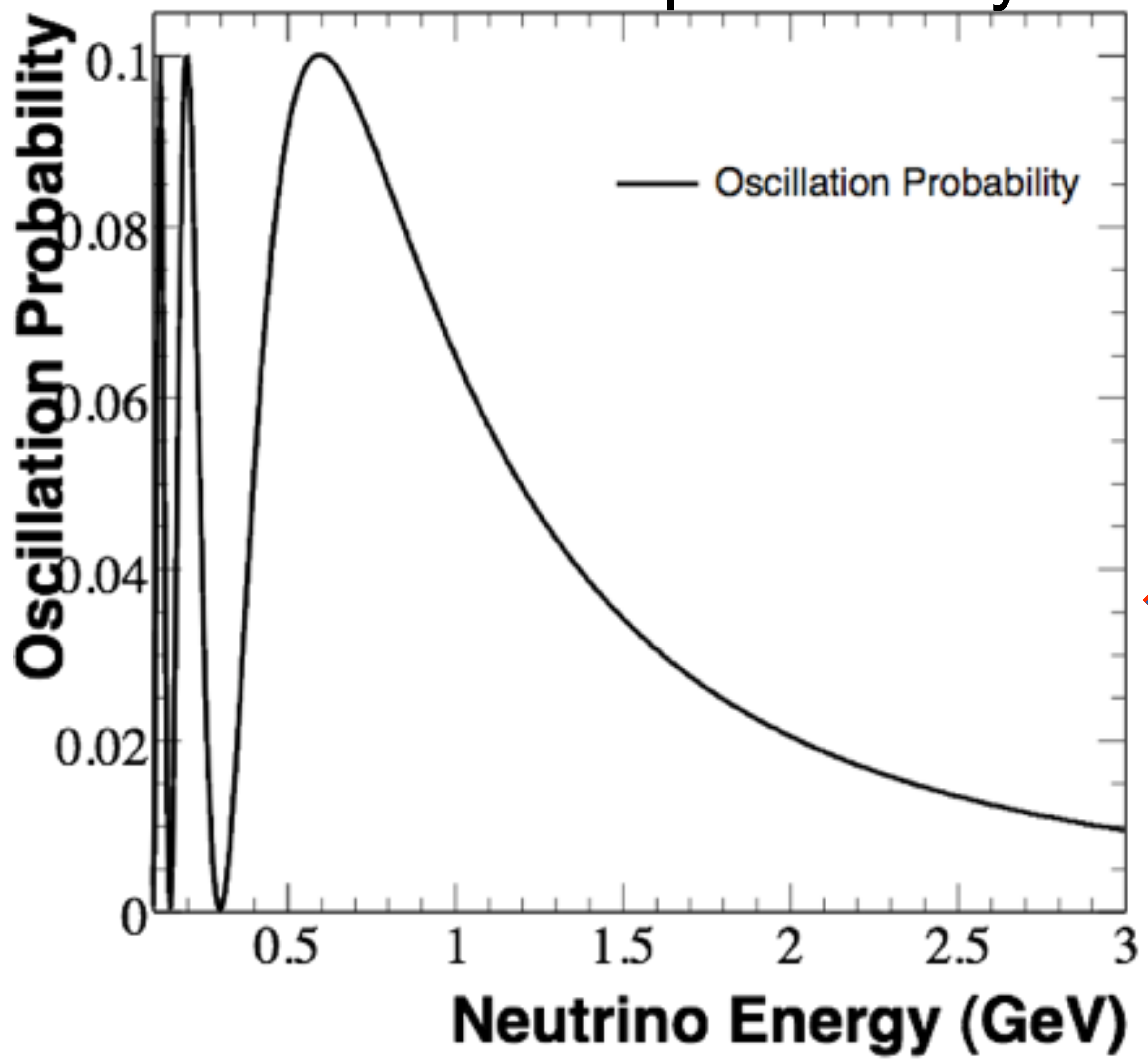
- Each mass/energy eigenstate evolves with a different frequency
- After some time, the flavour content changes

NEUTRINO OSCILLATIONS

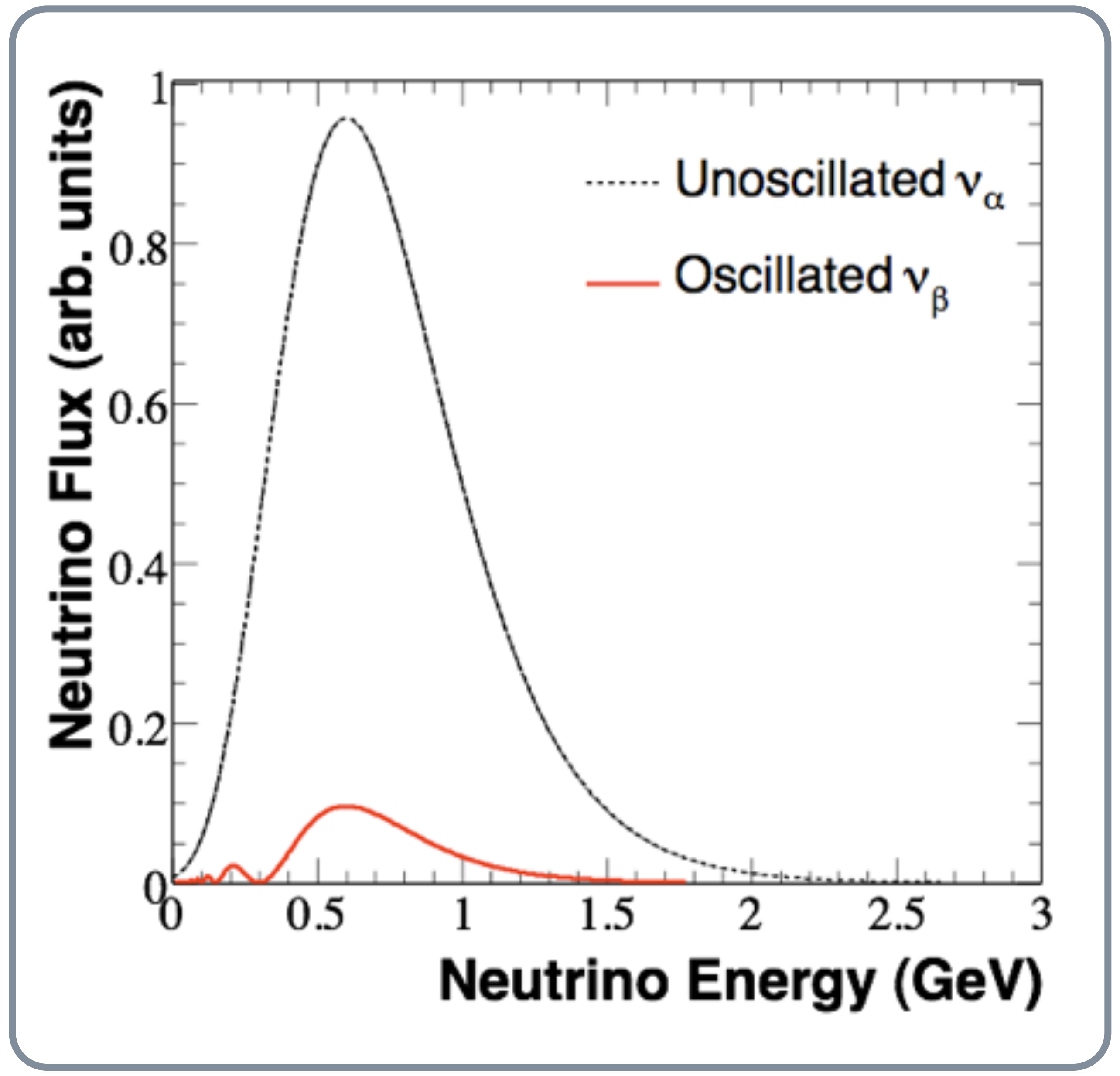
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \times \sin^2 \left[1.27\Delta m^2 \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$



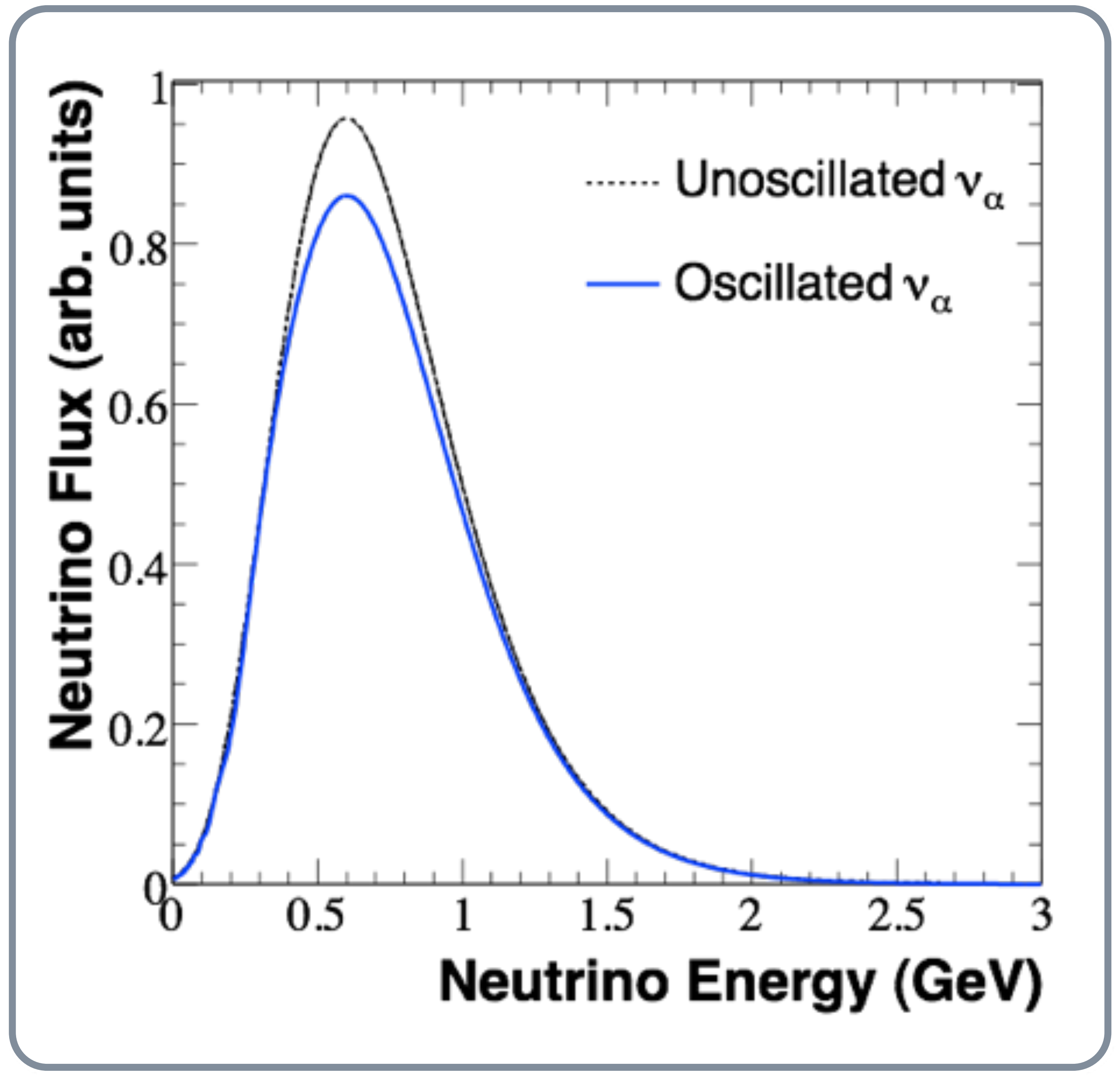
L



appearance of new flavor



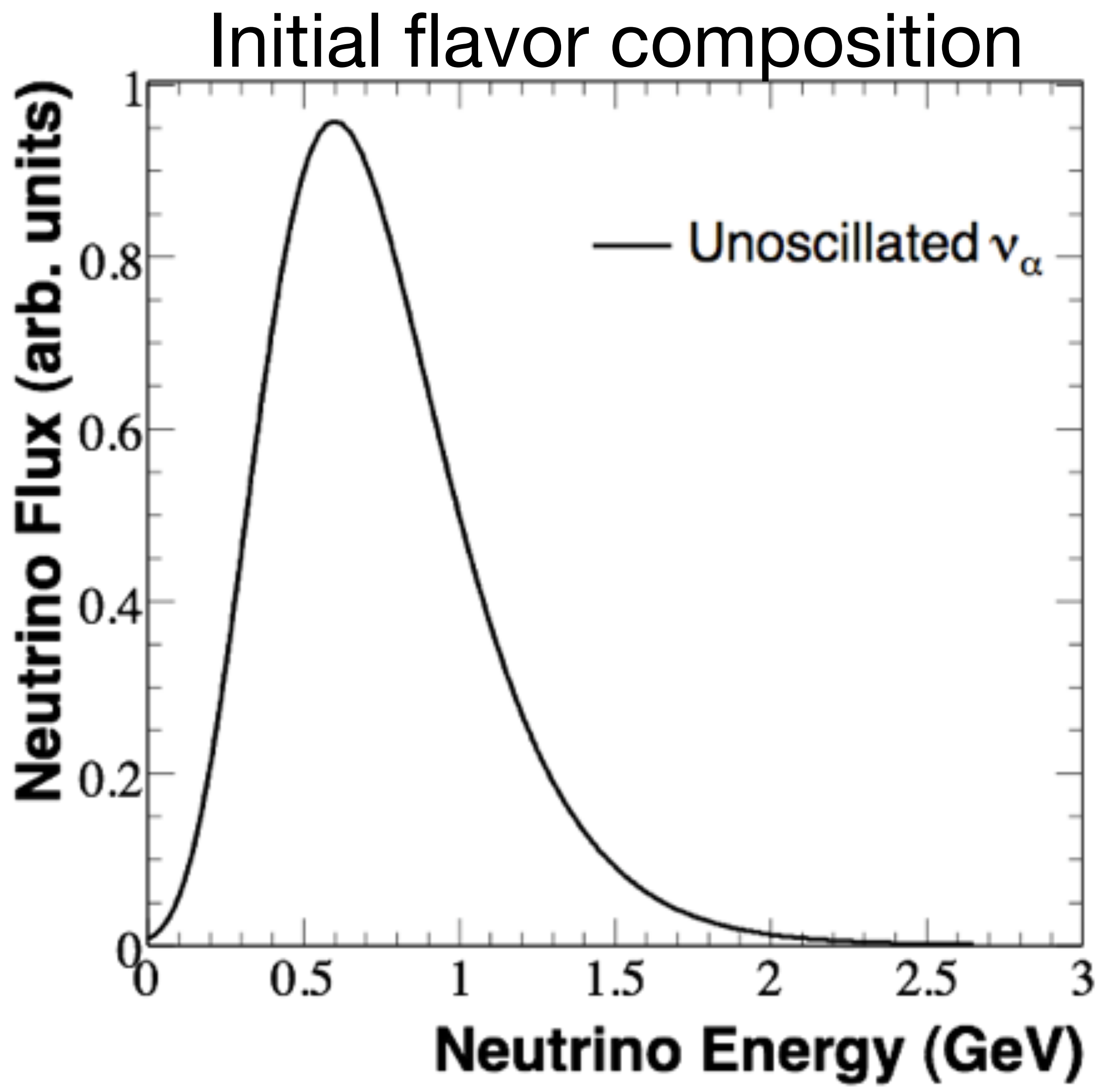
disappearance of initial flavor

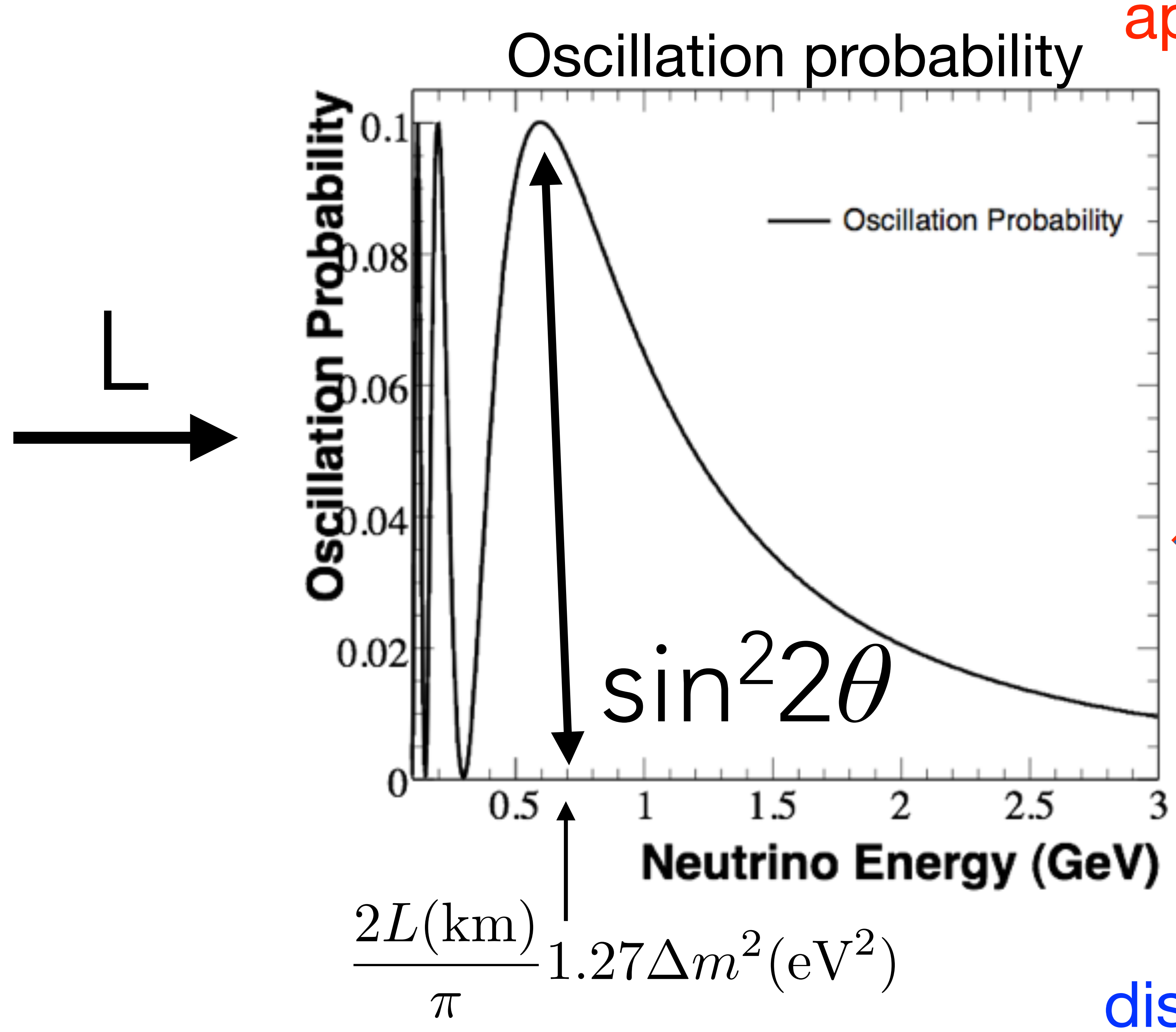


- Typical experiment:
  - prepare a pure beam of ν_α
  - neutrino oscillations then result in $\nu_\alpha \rightarrow \nu_\beta$ transitions ($\alpha \neq \beta$)
- Two basic types of measurements
  - Deficit of ν_α relative to initial state
  - Appearance of ν_β not present in initial state
- Both have definitive energy dependences

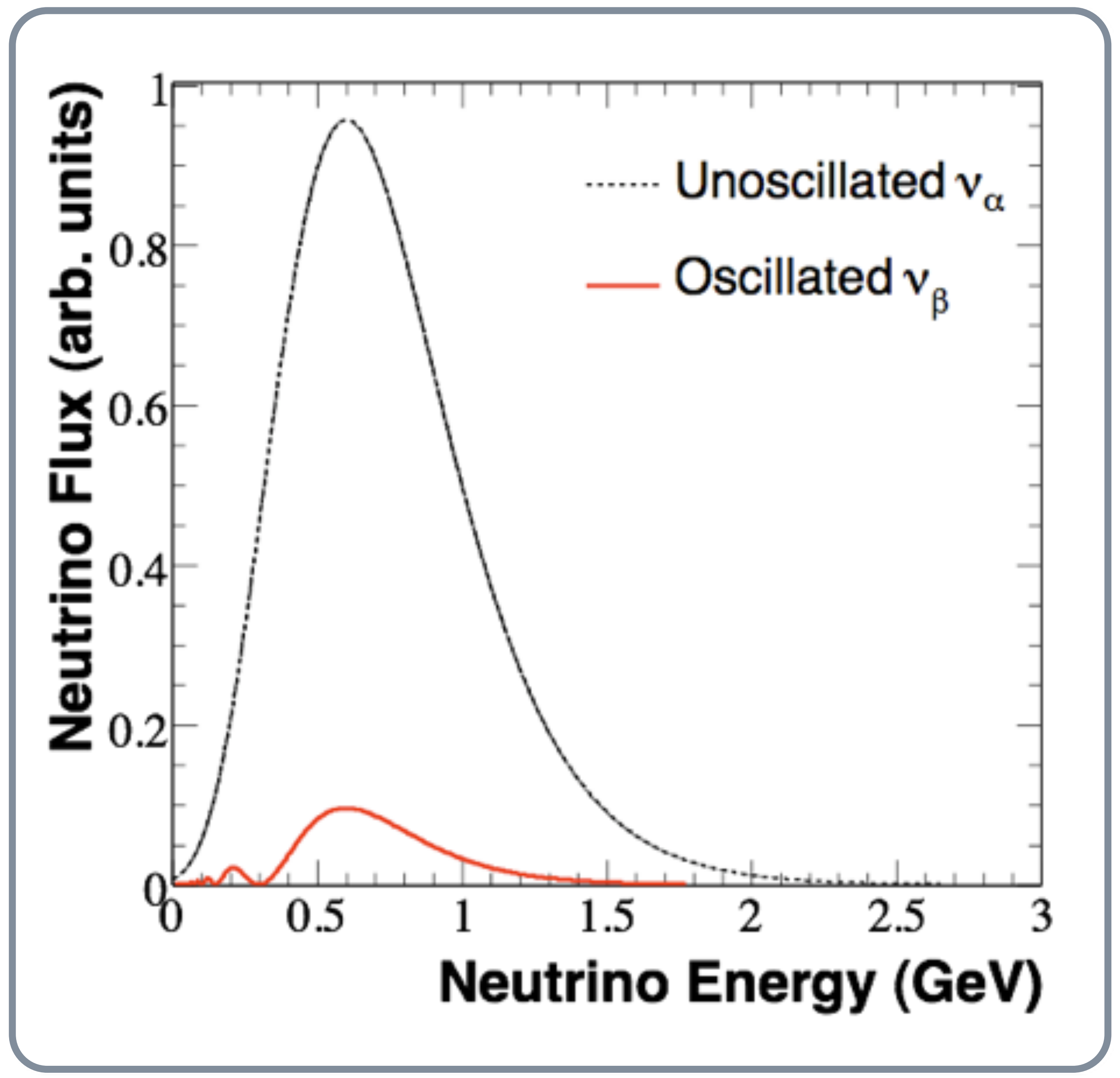
NEUTRINO OSCILLATIONS

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \times \sin^2\left[1.27\Delta m^2 \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

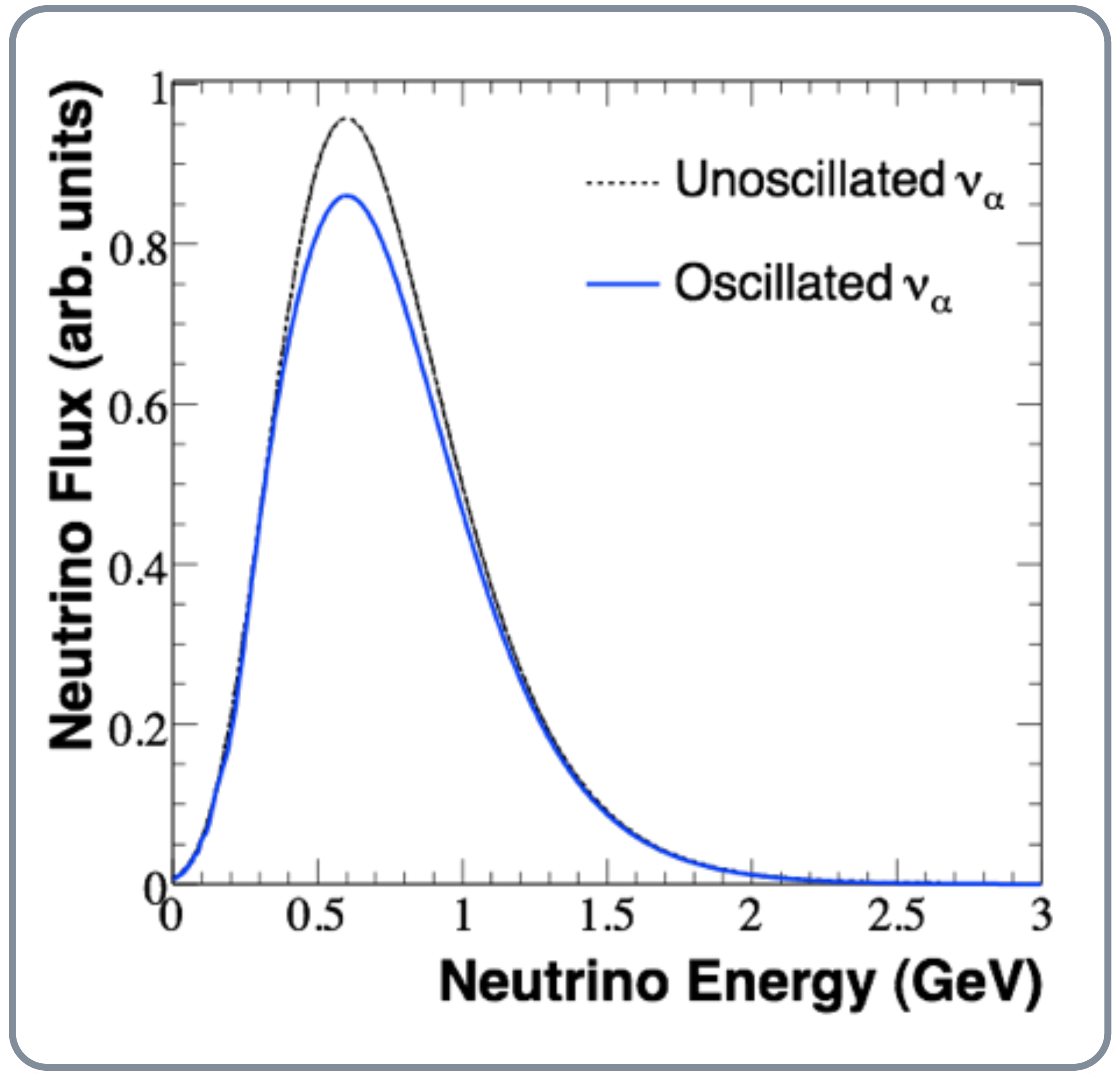




appearance of new flavor

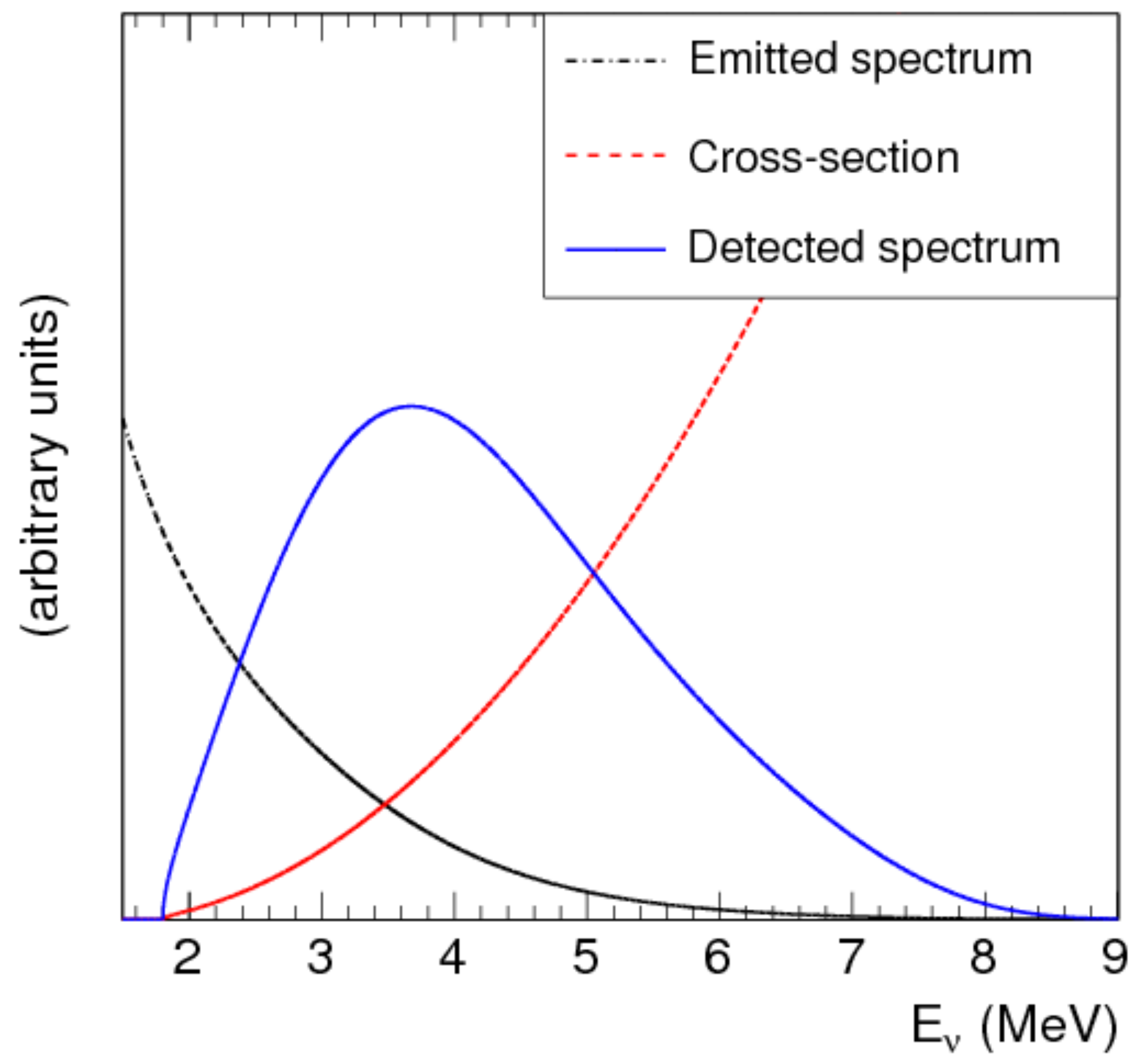


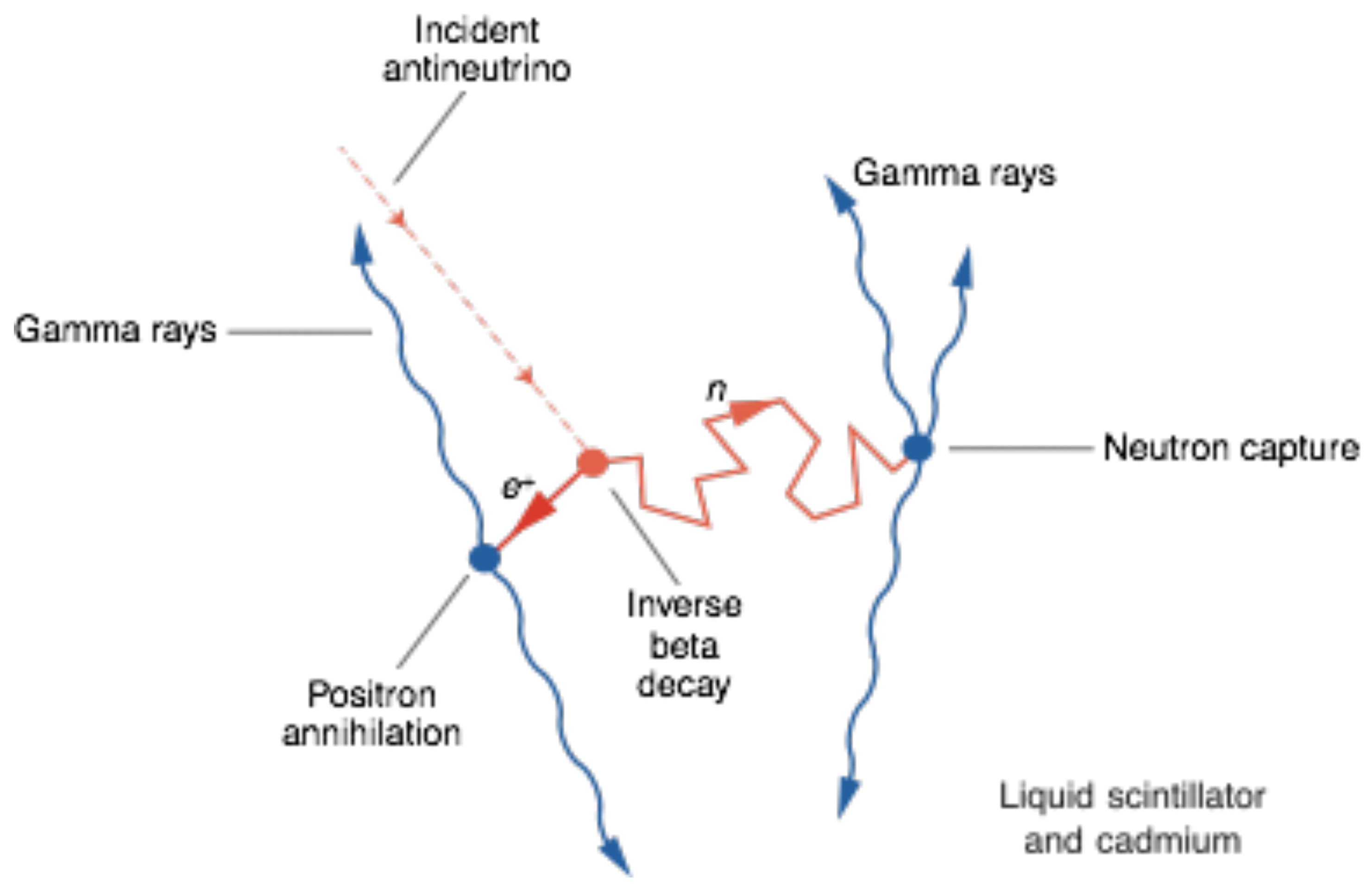
disappearance of initial flavor



- Amplitude of appearance or disappearance gives $\sin^2 2\theta$
  - or more generally the matrix elements (U_{ij})
- Location of maximum in energy gives Δm^2, assuming L is fixed
- Essential to determine flavour and energy of neutrino

REACTOR EXPERIMENTS





- detect antineutrinos using "inverse beta decay" process

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

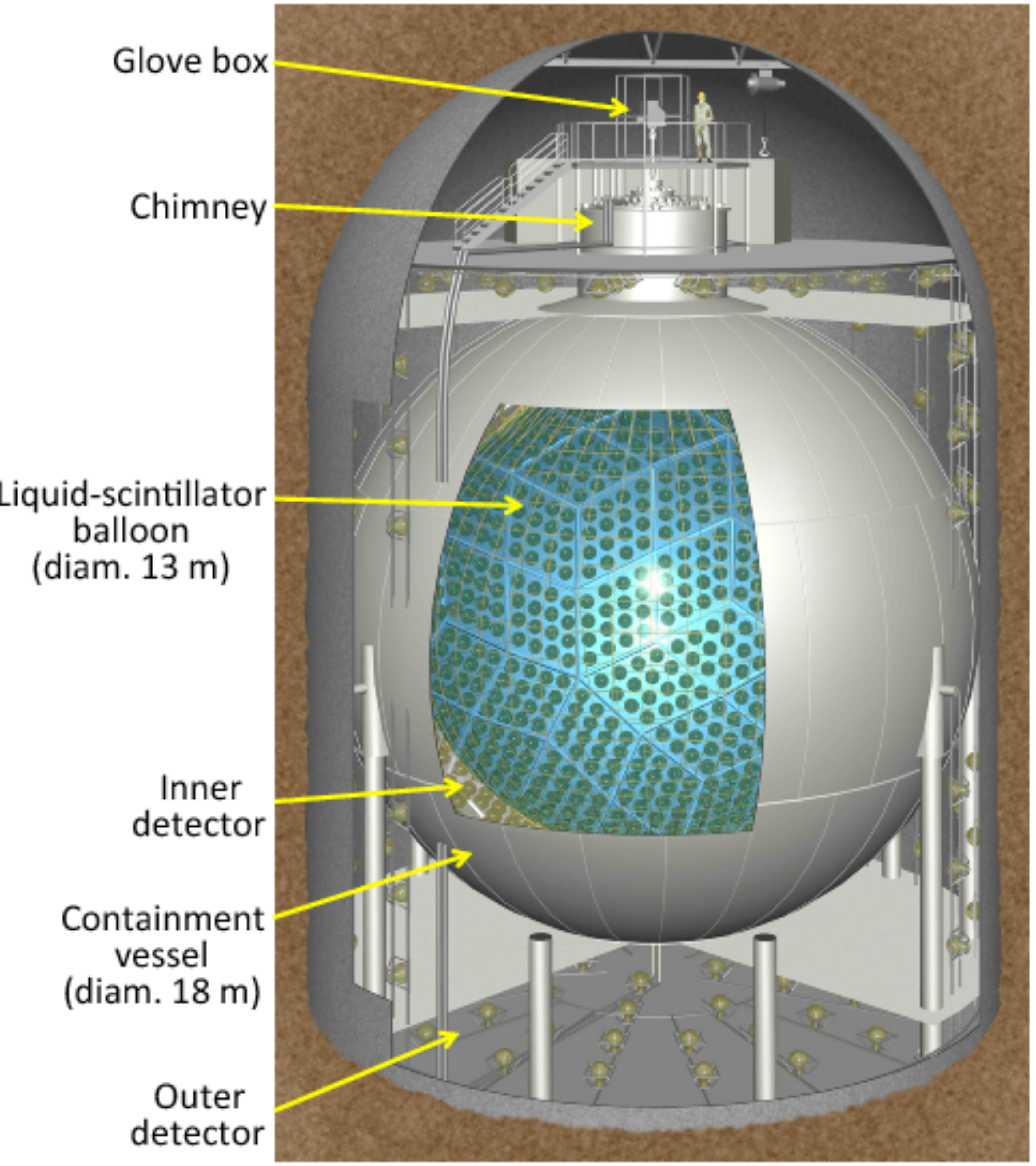
- two-step signature pioneered by Reines and Cowan
  - "prompt" signature from positron
  - "delayed" signature from neutron capture
- Due to low energies involved, large liquid scintillator detectors have been the preferred technology
  - large light yield from scintillation for good energy resolution
  - free protons allow neutron detection from capture process

$$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$$

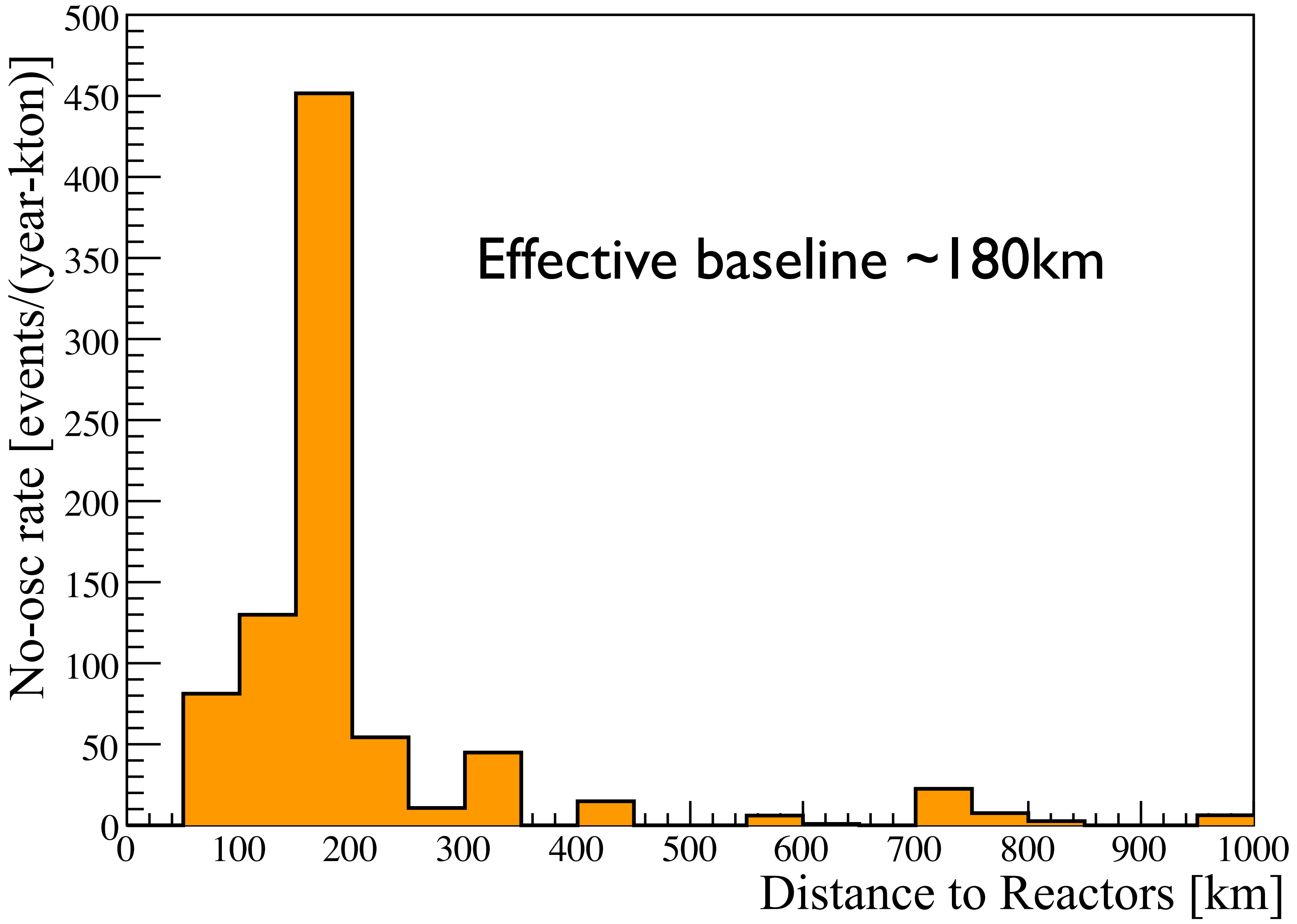
    - photon detection can be enhanced by doping with other nuclei with high neutron capture cross section and photon energy emission
- antineutrino energy can be reconstructed as:

$$E_{\bar{\nu}} \sim E_e + \langle E_n \rangle + 0.8\mathrm{MeV}$$

KAMLAND



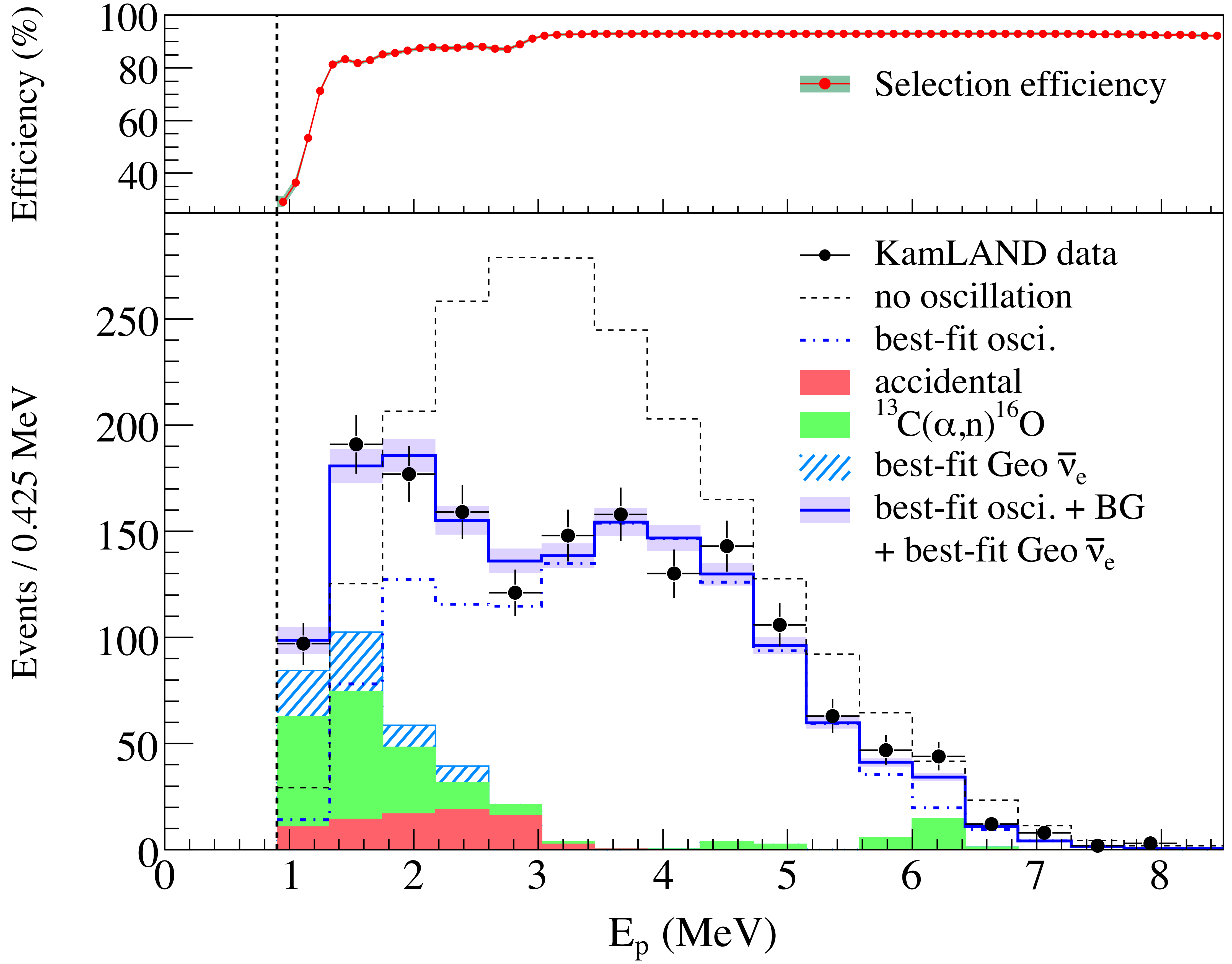
- Large liquid scintillator detector in the Kamioka mine (2002-2007)
  - 1 kT of liquid scintillator suspended in pure mineral oil
  - 1879 50 cm photomultiplier tubes to detect scintillation light
- detect antineutrinos from 55 nuclear reactors in Japan
  - 80% of antineutrinos produced by reactors between 130-220 km

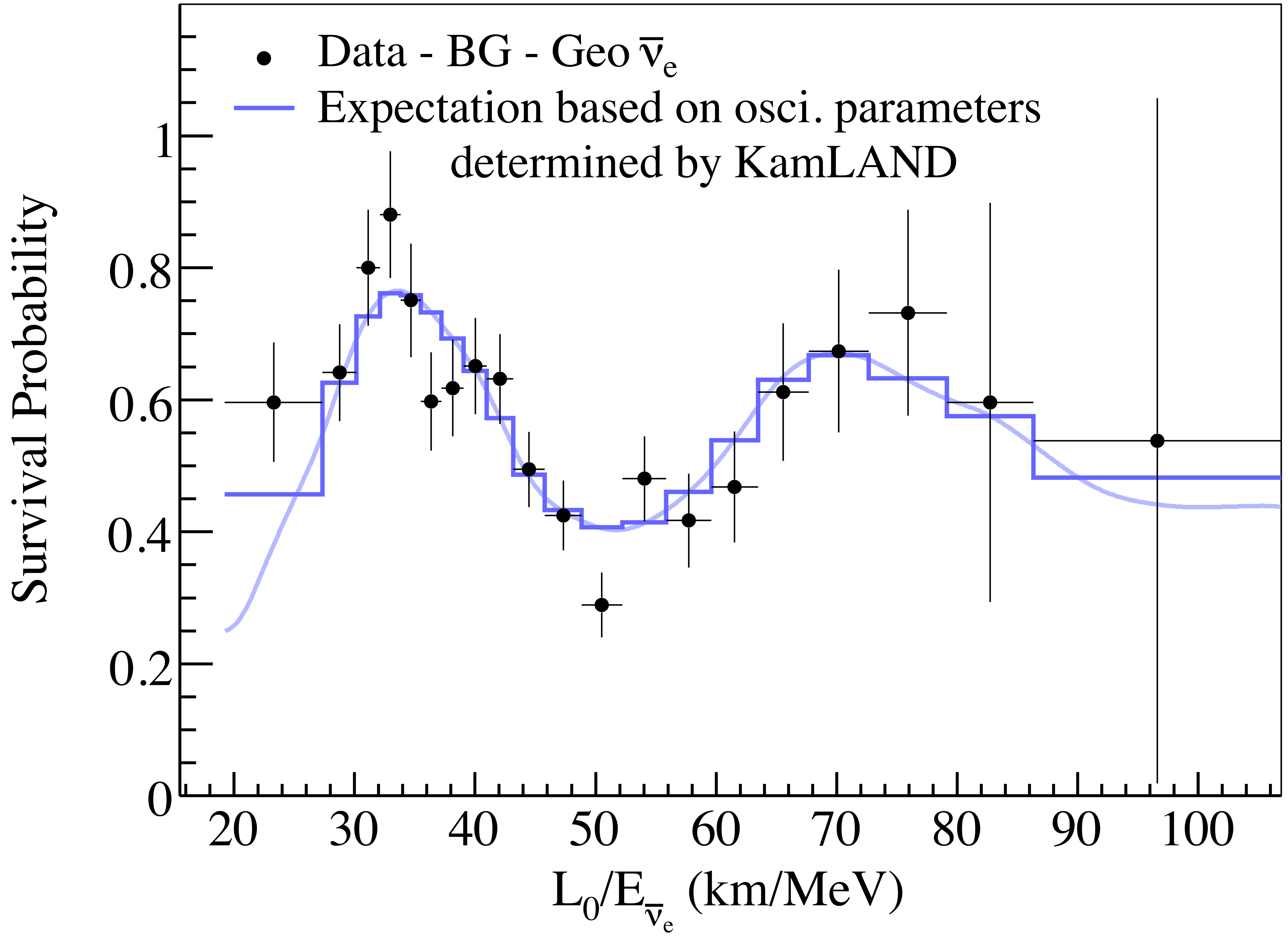


- Known distances to reactors allow $\bar{\nu}_e$ disappearance vs. L/E to be measured

RESULTS

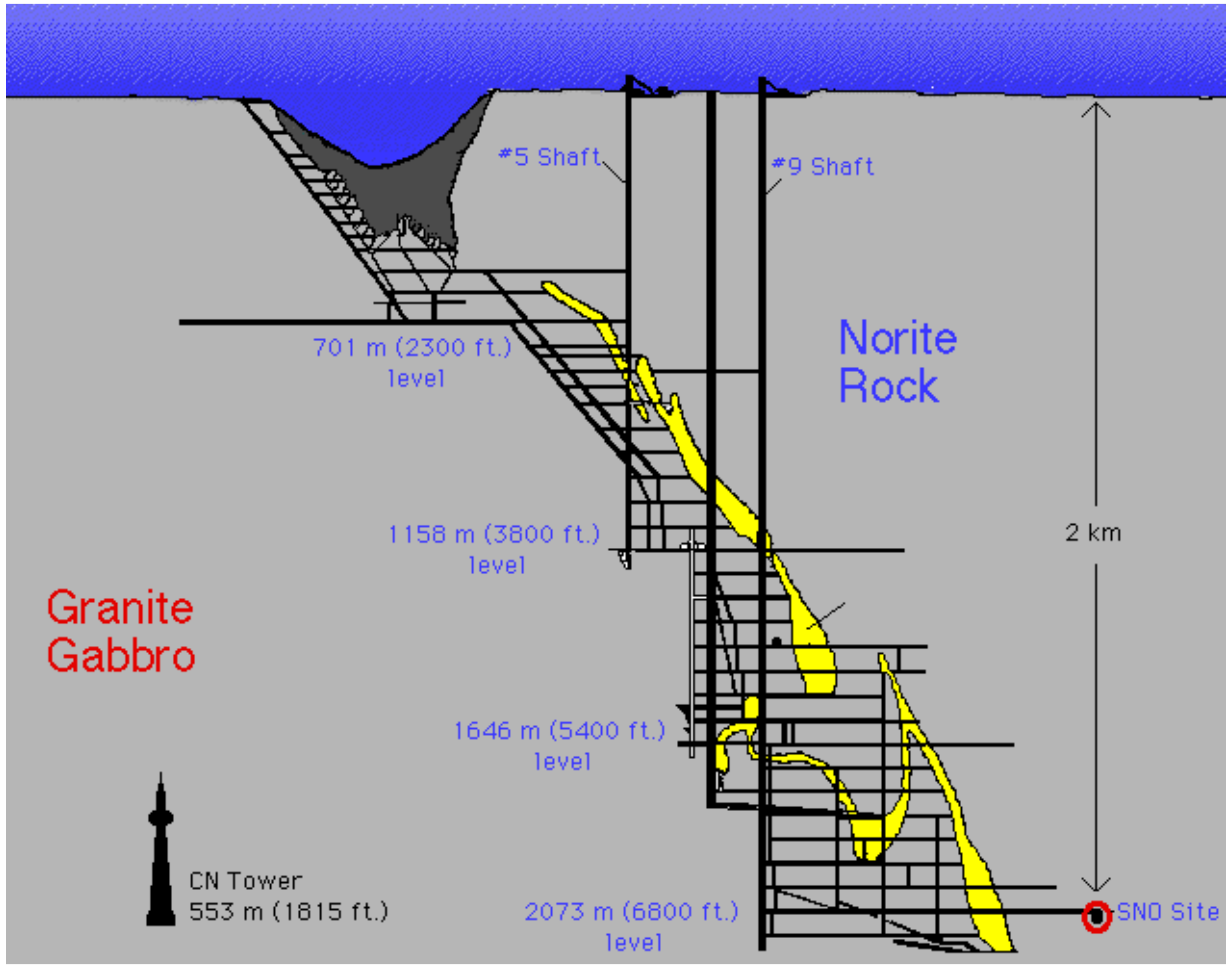
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \times \sin^2 \left[1.27\Delta m^2 \frac{L(\text{km})}{E(\text{GeV})}\right]$$

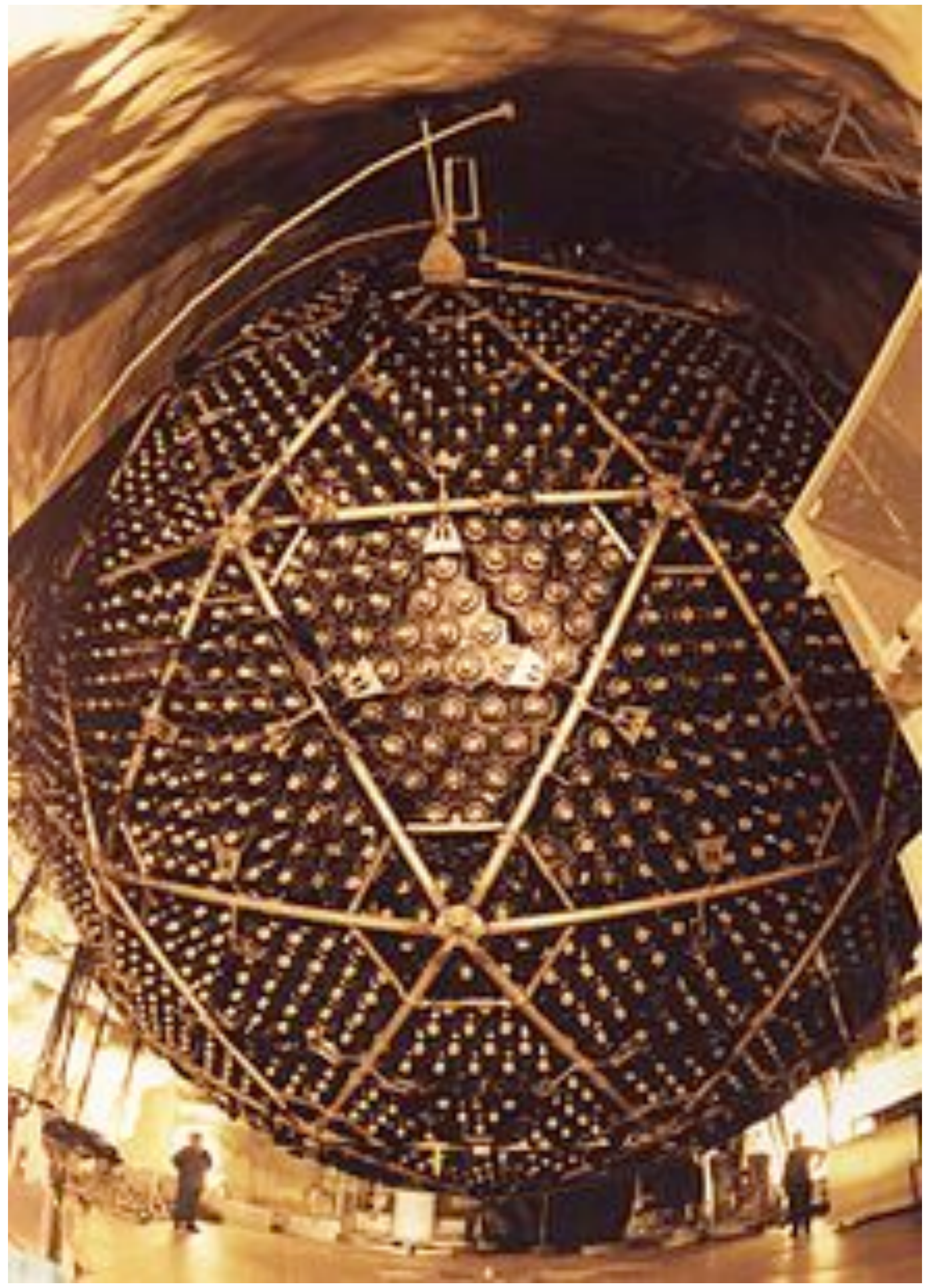




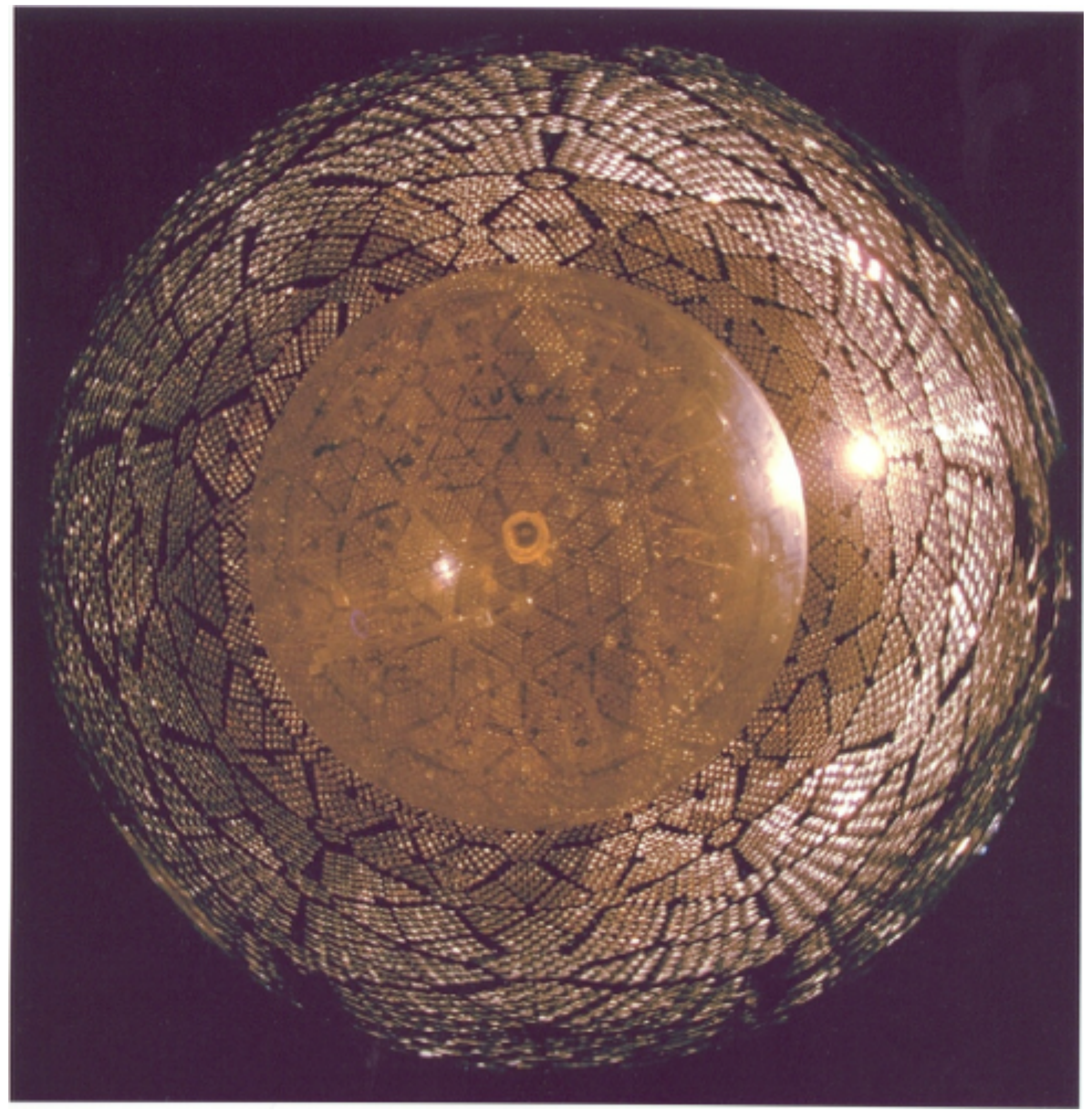
- Energy-dependent deficit of $\bar{\nu}_e$ measured
- Plotting deficit (ratio to expectation without oscillations) versus L/E shows oscillation pattern
    - large amplitude: $\sin^2 2\theta_{12} \sim 0.85$
    - 1st maximum of oscillation at L/E ~16000 km/GeV: mass splitting of $\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV^2

SNO



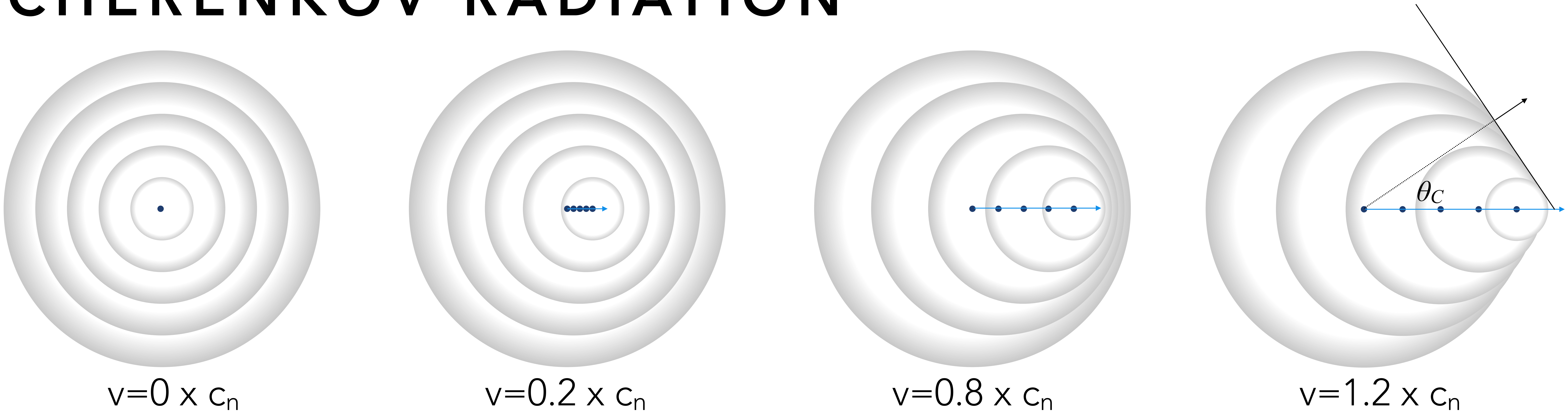


- Operated in three phases
  - "D2O"
  - "Salt"
  - "NCD"



- Large (heavy) water Cherenkov detector 2 km underground in Sudbury, ON
  - "Sudbury Neutrino Observatory"
- 1 kton of heavy water (D_2O) in an acrylic vessel suspended in light water (H_2O)
- viewed by 9456 20 cm photomultiplier tubes

CHERENKOV RADIATION



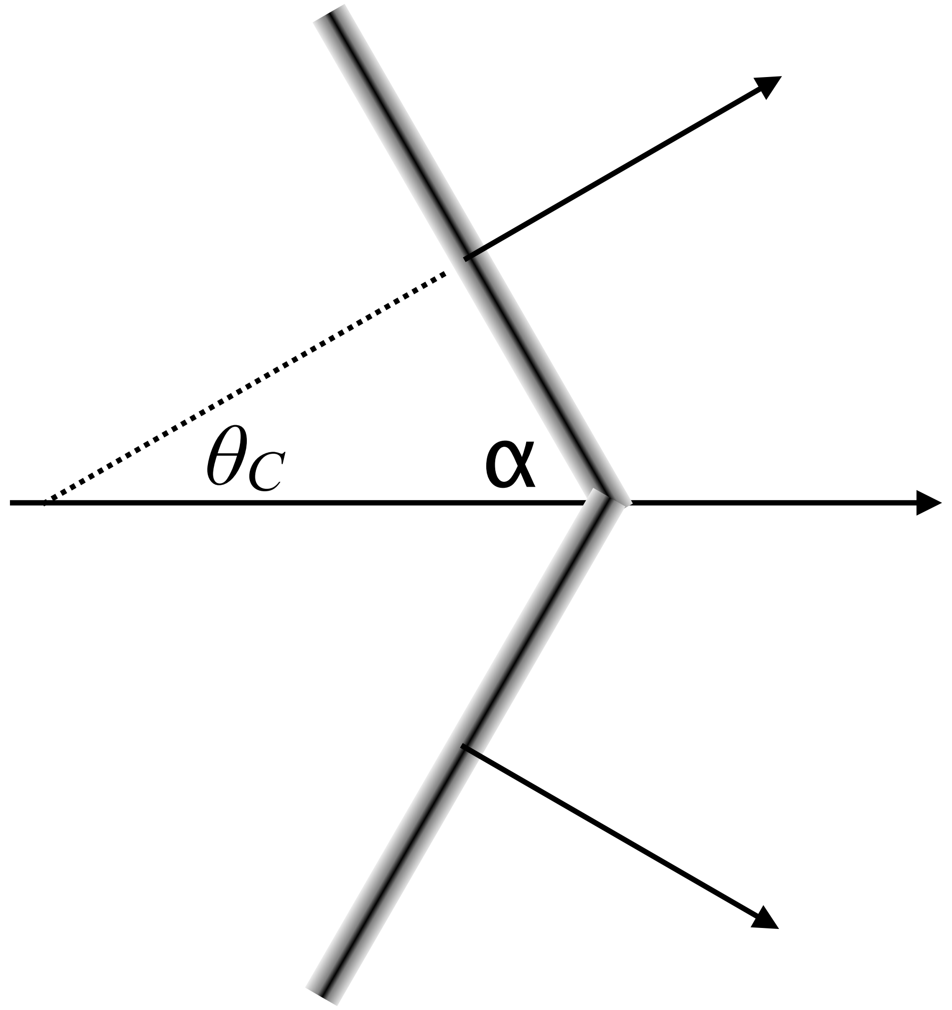
- Charged particle passing through a dielectric medium (n > 1) induces a EM disturbance that propagates at speed c_n=c/n
- If v >c_n, the disturbance piles up
  - electromagnetic "shock wave" emitted with angle θ_C

$$\cos\theta_C = \frac{c}{nv} = \frac{1}{n\beta}$$

- This is Cherenkov (Č) radiation

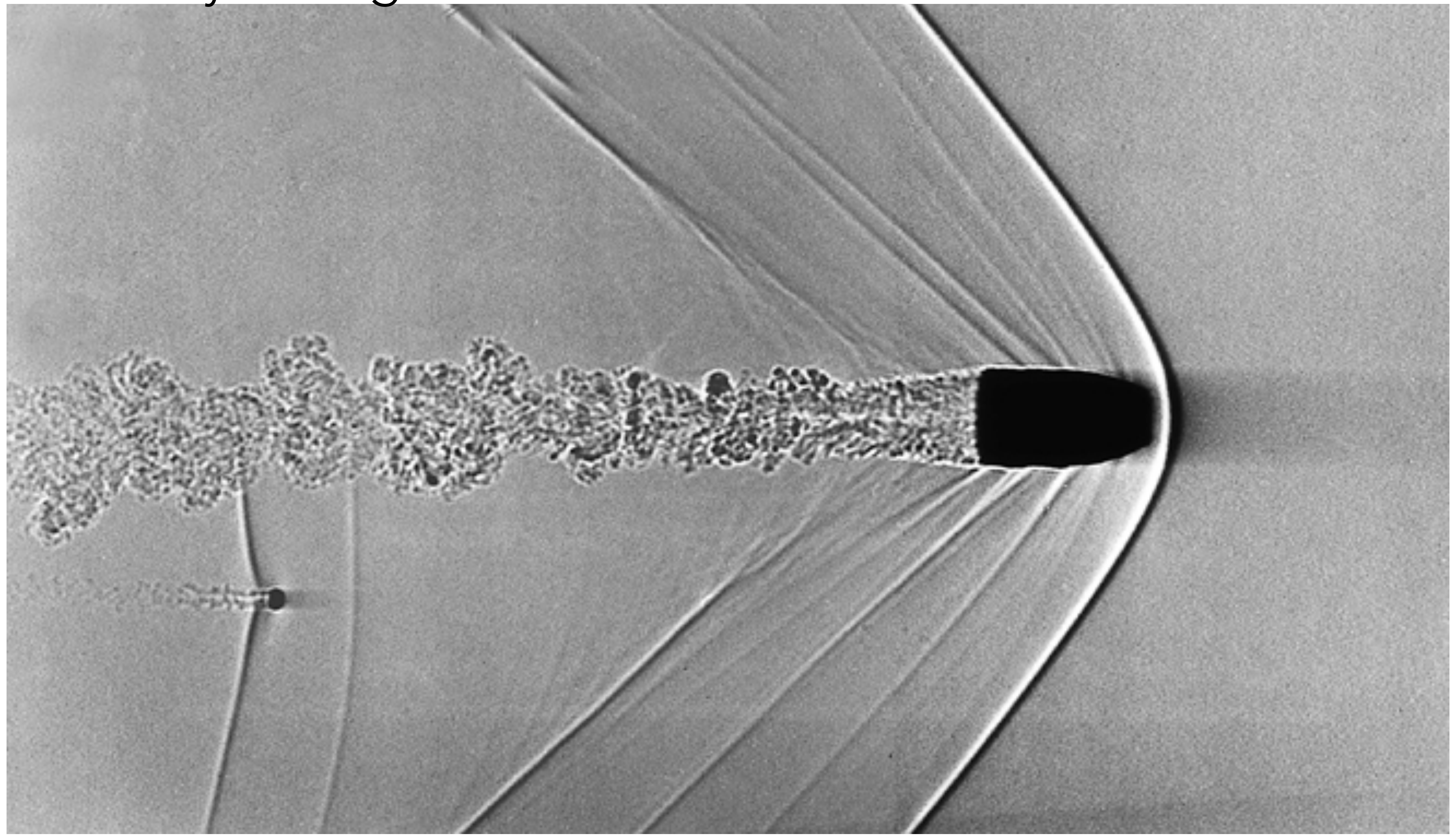
SONIC ANALOGY

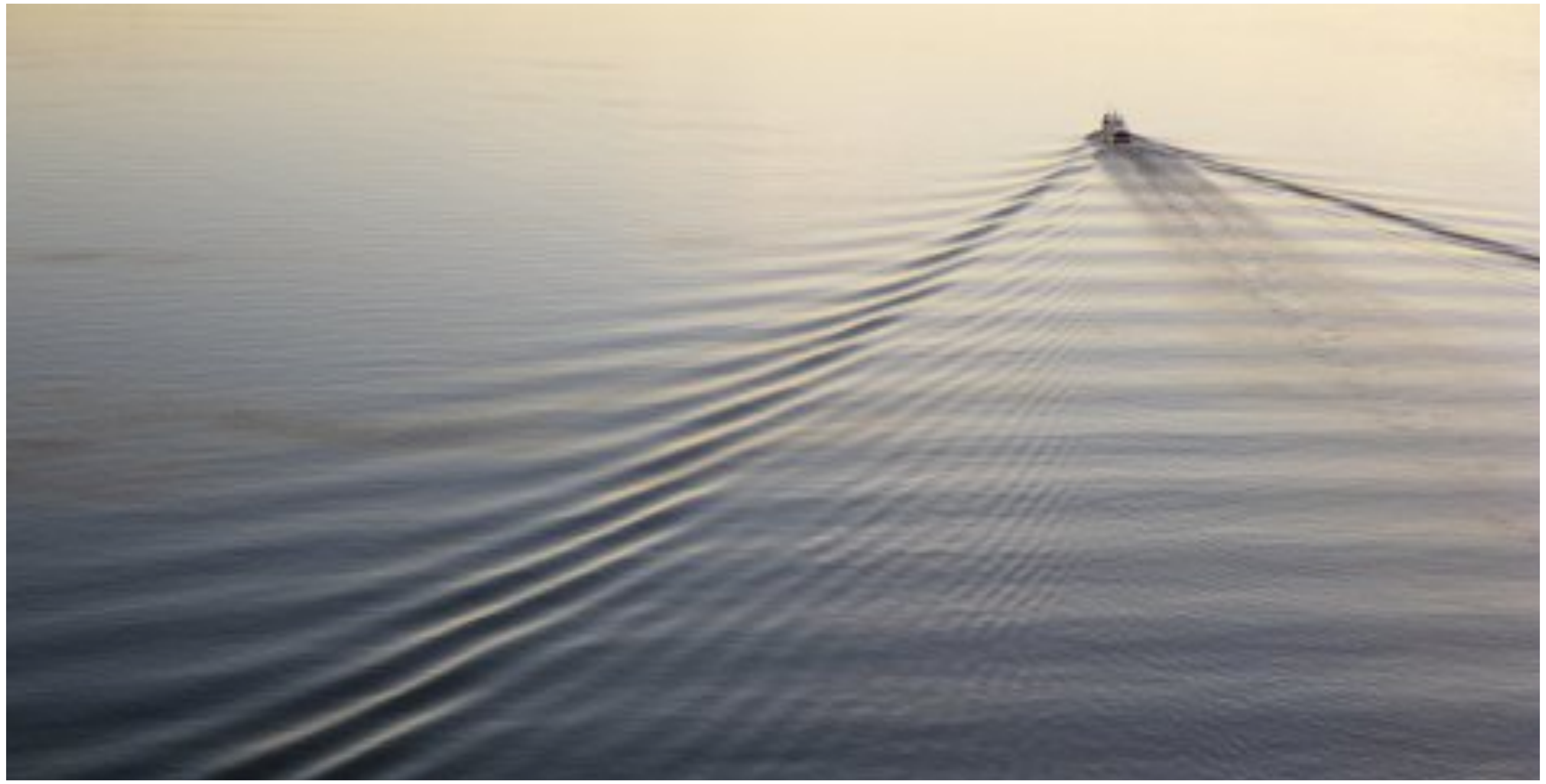
courtesy findagrave.com



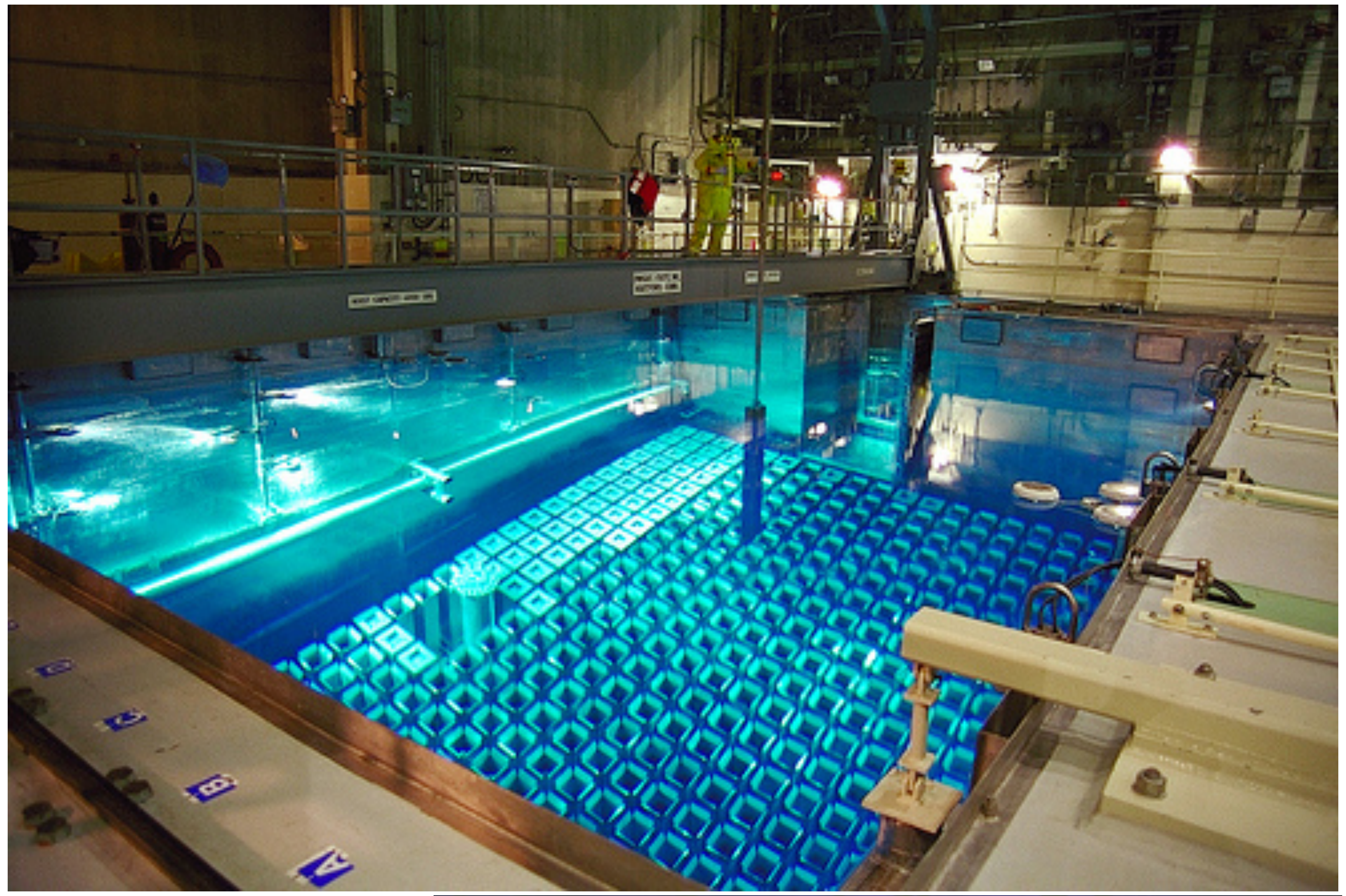
- Analogous to other (mechanical) systems where a disturbance exceeds the propagation velocity
  - e.g. "sonic boom" from supersonic object

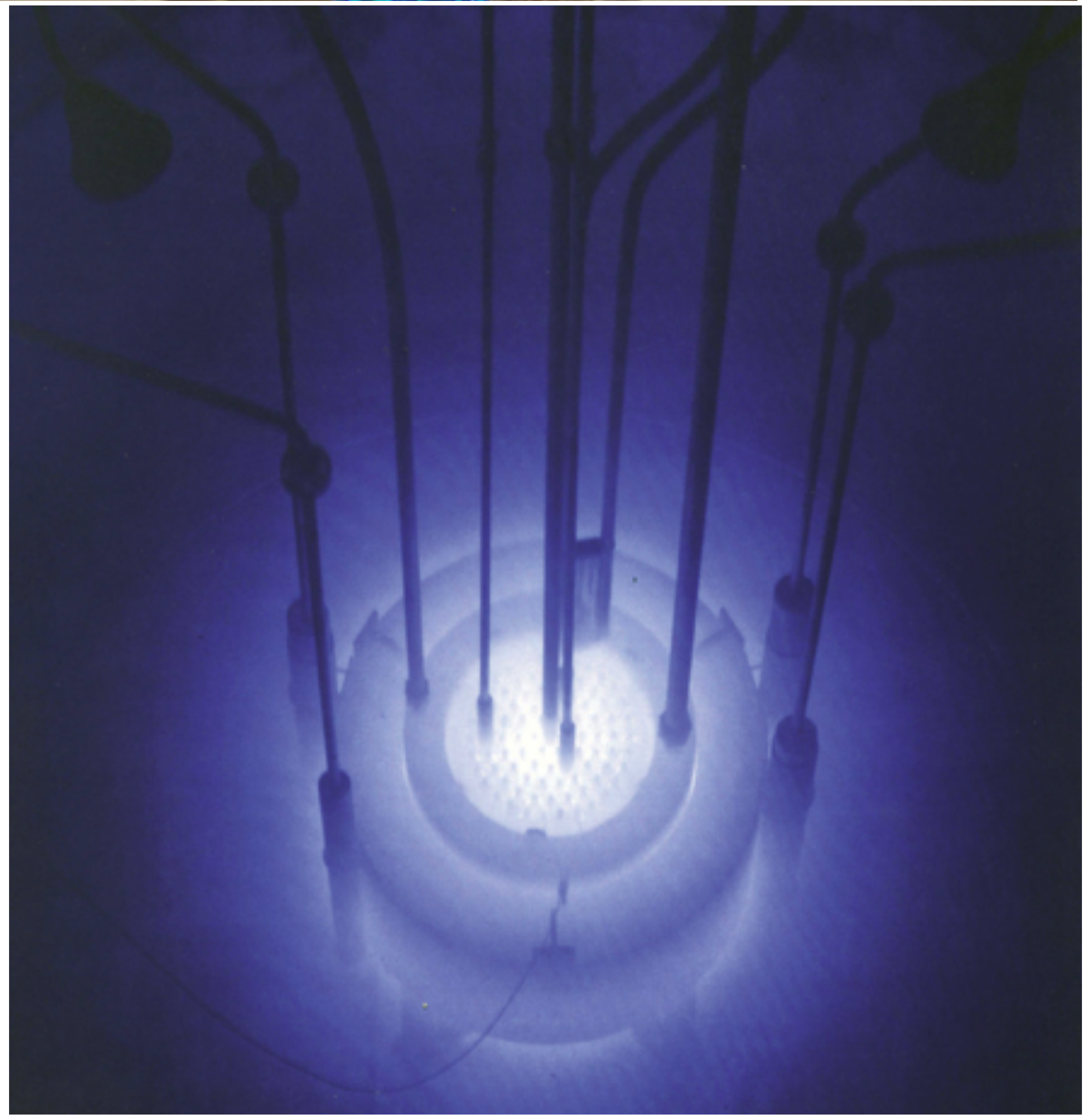
$$\sin\alpha = \frac{v_s}{v} \qquad \alpha = \frac{\pi}{2} - \theta_C$$





PROPERTIES OF CHERENKOV RADIATION





- Considerations of "spatial singularity":
  - k = wavenumber, so that $p = \hbar k$
  - expect light to be emitted "flat" in k

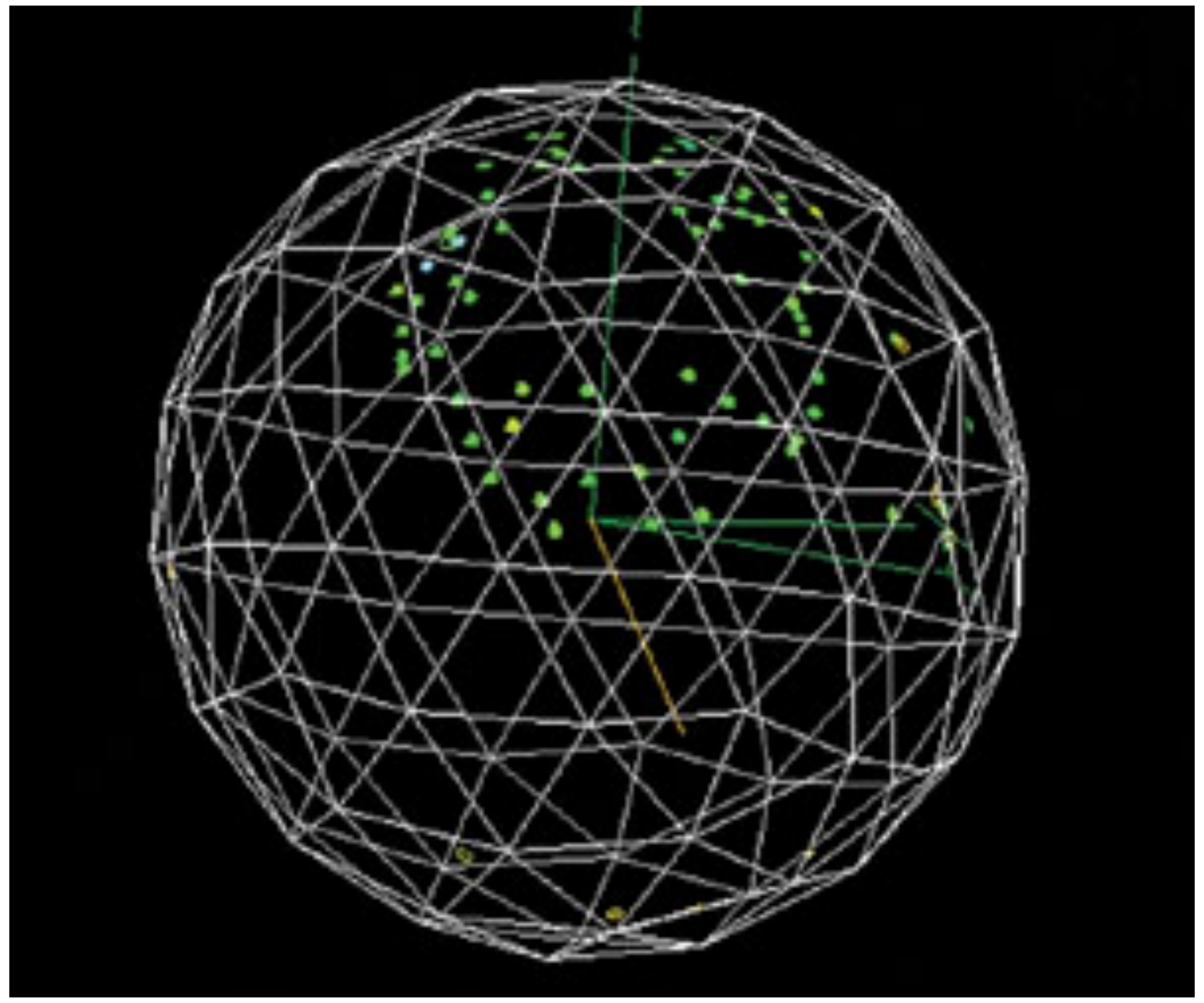
$$k = \frac{2\pi}{\lambda} \qquad dk = -\frac{2\pi}{\lambda^2} d\lambda$$

  - wavelength spectrum is $1/\lambda^2$
- Frank-Tamm Equation

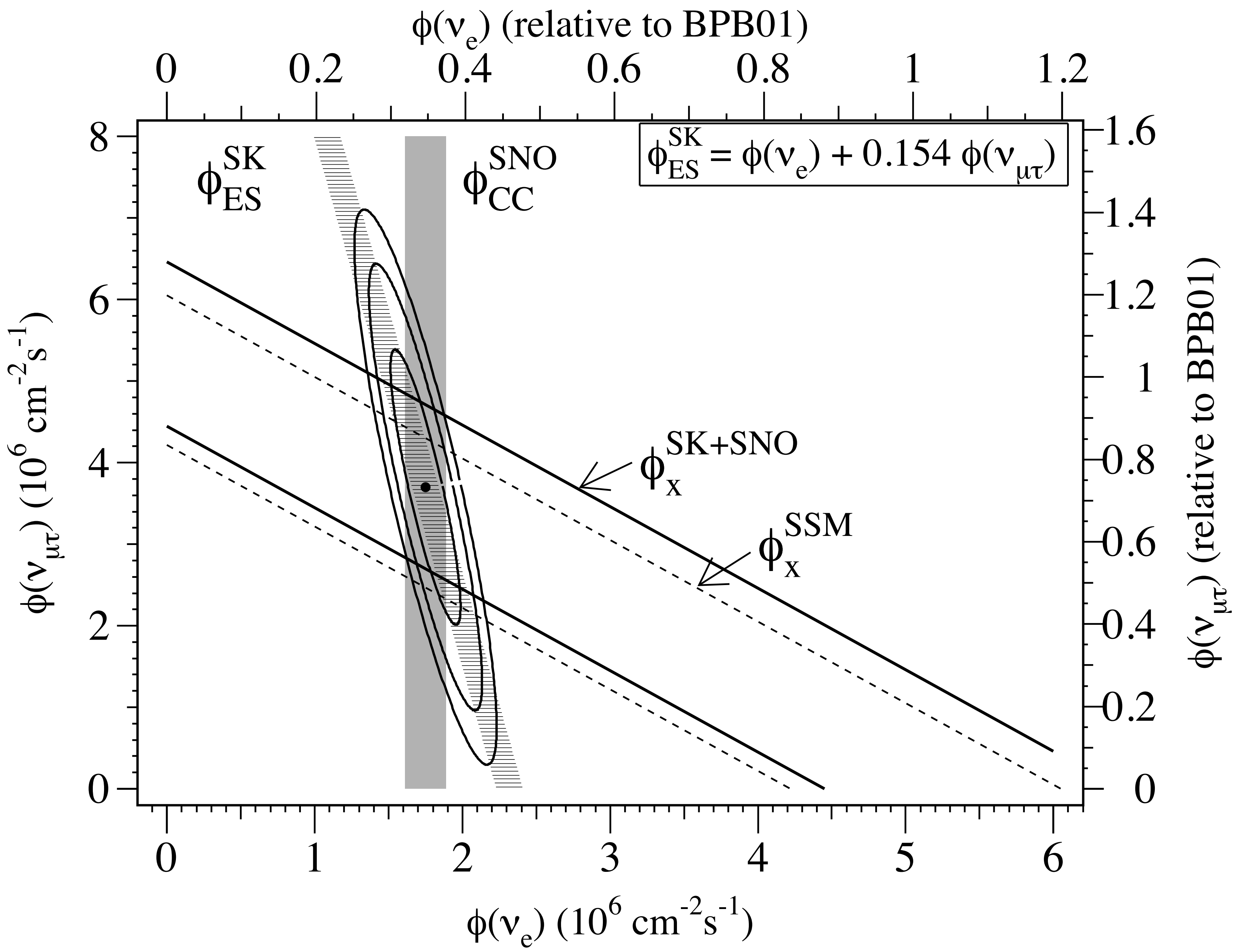
$$\frac{d^2N}{dE\,dx} = \frac{\alpha z^2}{\hbar c} \sin^2\theta_C \sim 370 \sin^2\theta_C \ \mathrm{eV}^{-1}\mathrm{cm}^{-1}$$

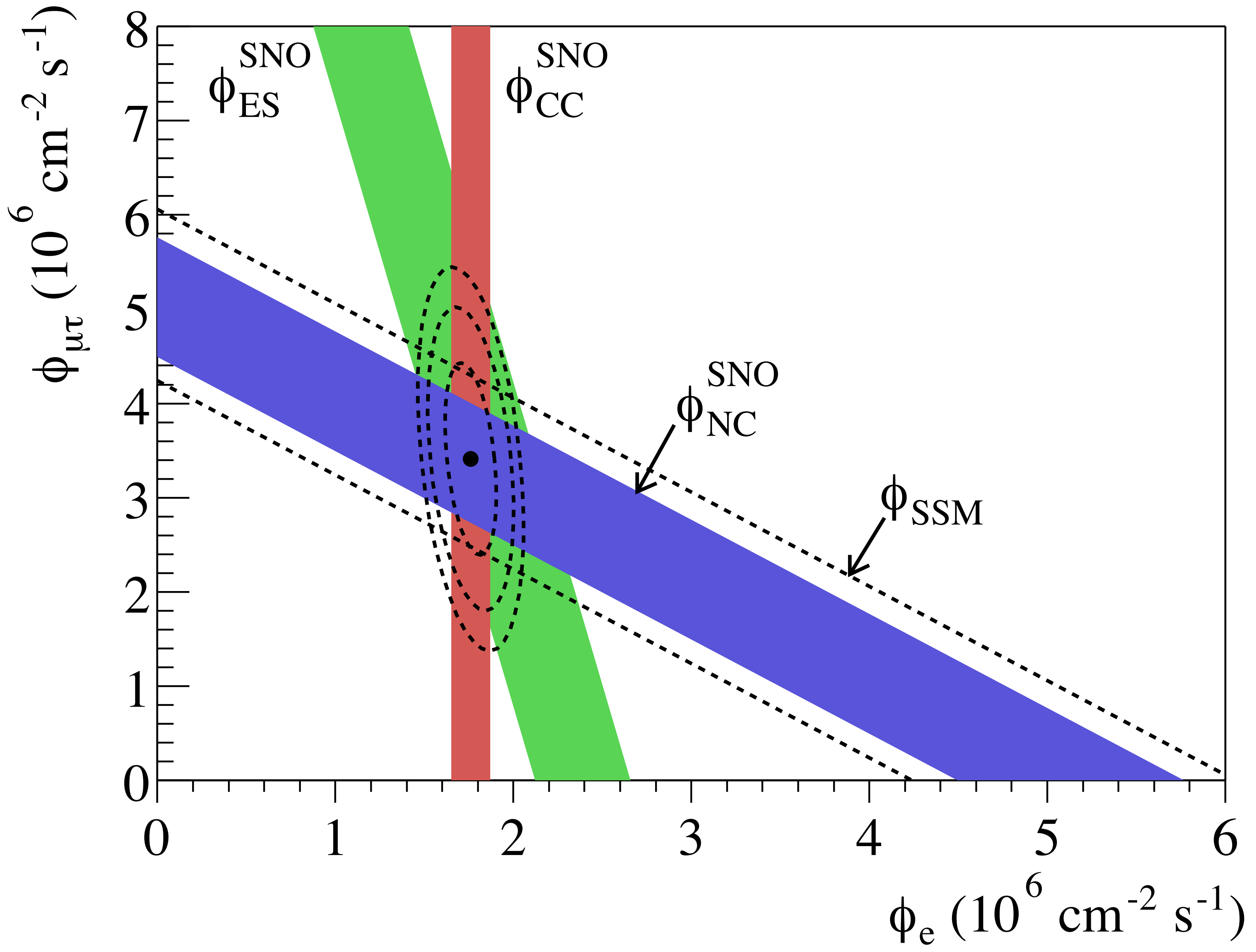
- For water, n ~1.34, $\sin^2\theta_C = 0.44$
  - "~160 photons/cm for β=1 particle in 1 eV interval of photon energy"
  - ~250 photons emitted/cm in the visible light region
  - "Collapse" of Č cone: as $v \sim c_n$ (threshold), θ_C and $\sin^2\theta_C$ goes to zero

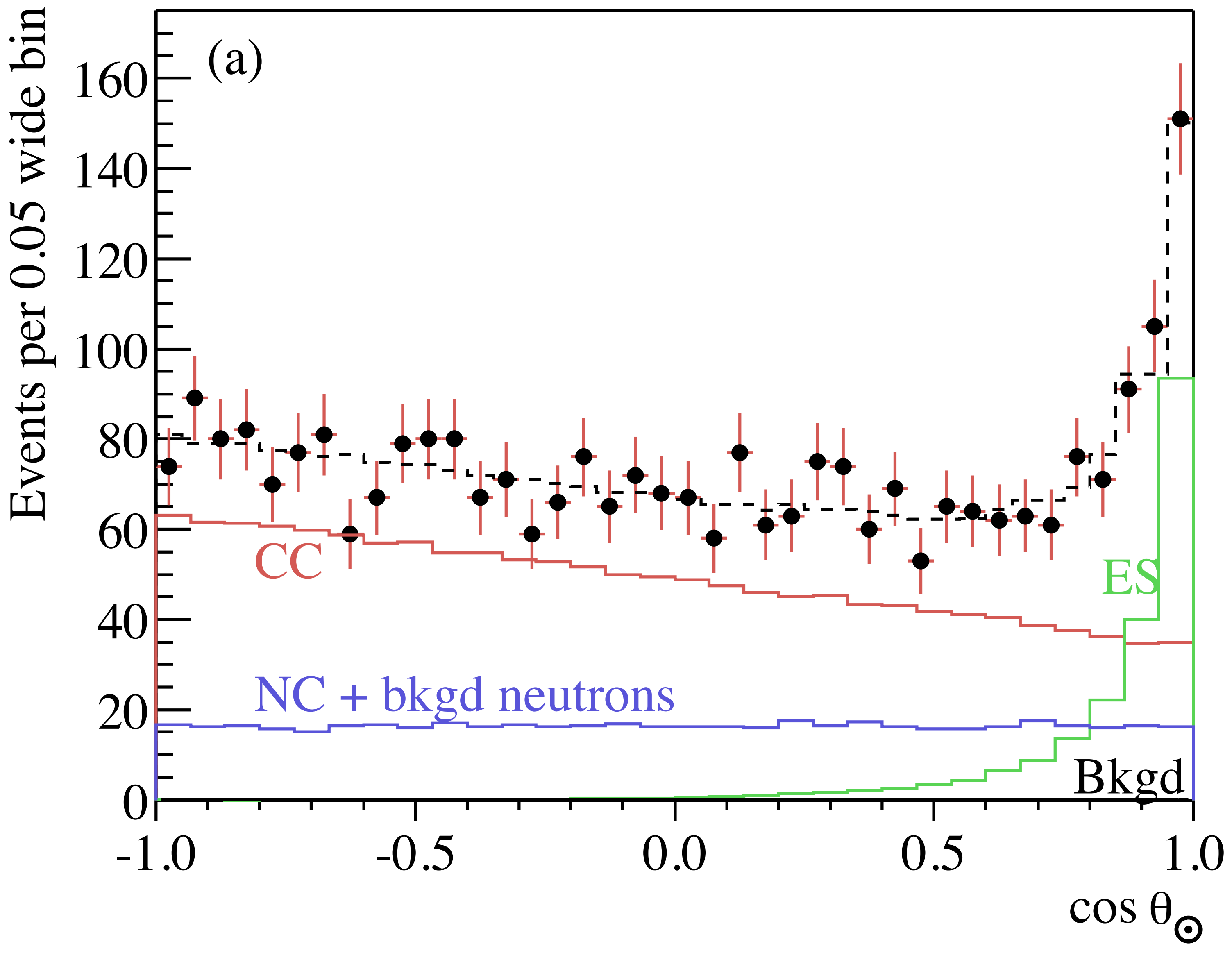
NEUTRINO INTERACTIONS AT SNO



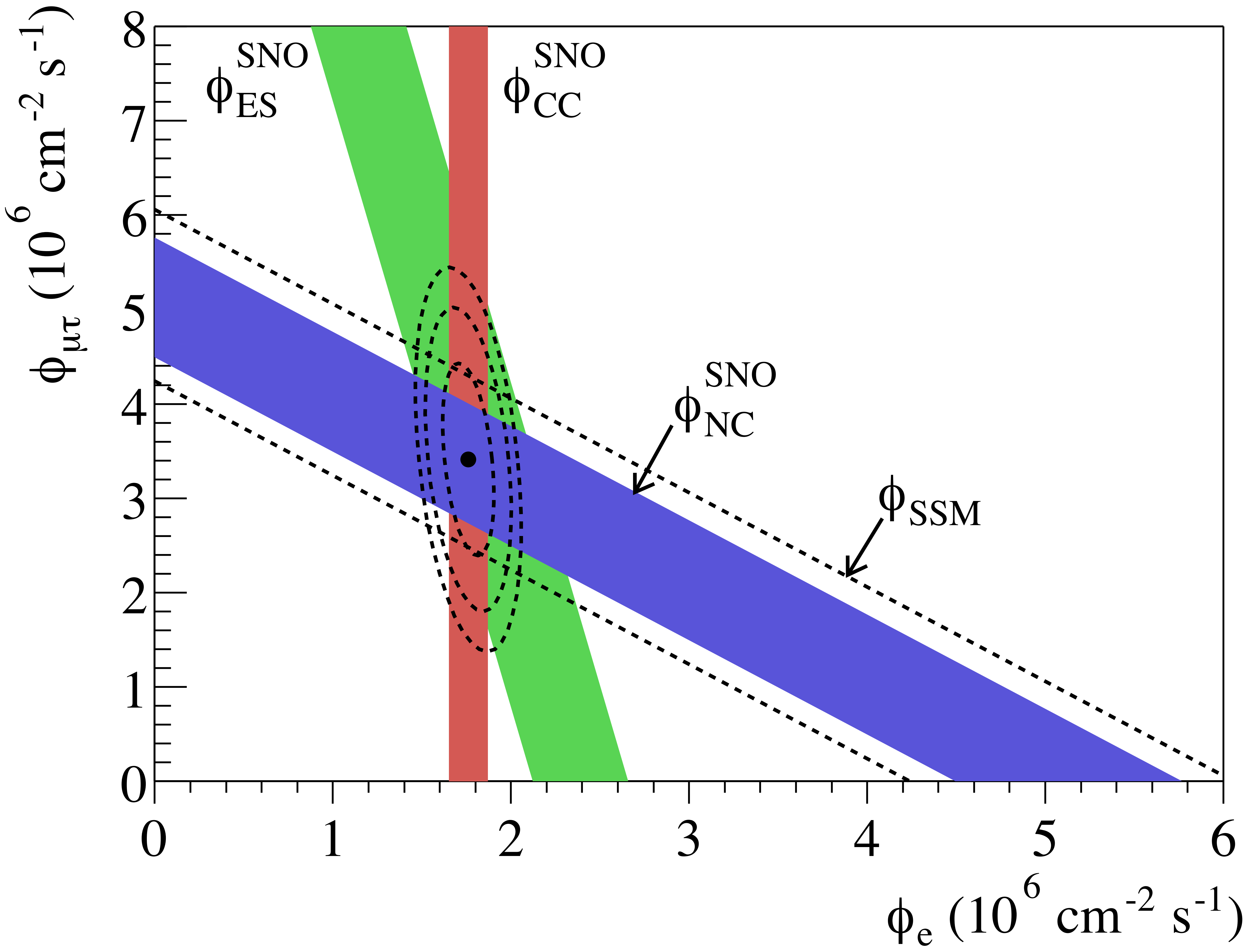
- Three channels observed:
- "CC": $\nu_e + d \rightarrow e^- + p + p$
  - sensitive only to ne from the sun
- "NC": $\nu_x + d \rightarrow \nu_x + n + p$ ($n + d \rightarrow t + \gamma$(6.25 MeV))
  - equally sensitive to all neutrino flavours (ν_e, ν_μ, ν_τ)
- "ES": $\nu_x + e^- \rightarrow \nu_x + e^-$
  - interactions in all neutrino flavors, but higher for ν_e ($\sigma(\nu_e) \sim 6.5 \times \sigma(\nu_\mu)$ or $\sigma(\nu_\tau)$)







BOTTOM LINE FROM SNO



- Total neutrino flux from the sun is consistent with expectation (10^6/cm^2/sec)

$$\phi_{\rm NC}^{\rm SNO} = 6.42^{+1.57}_{-1.57}(\text{stat.})^{+0.55}_{-0.58}\ (\text{syst.})$$

$$\phi_{\rm SSM} = 5.05^{+1.01}_{-0.81}.$$

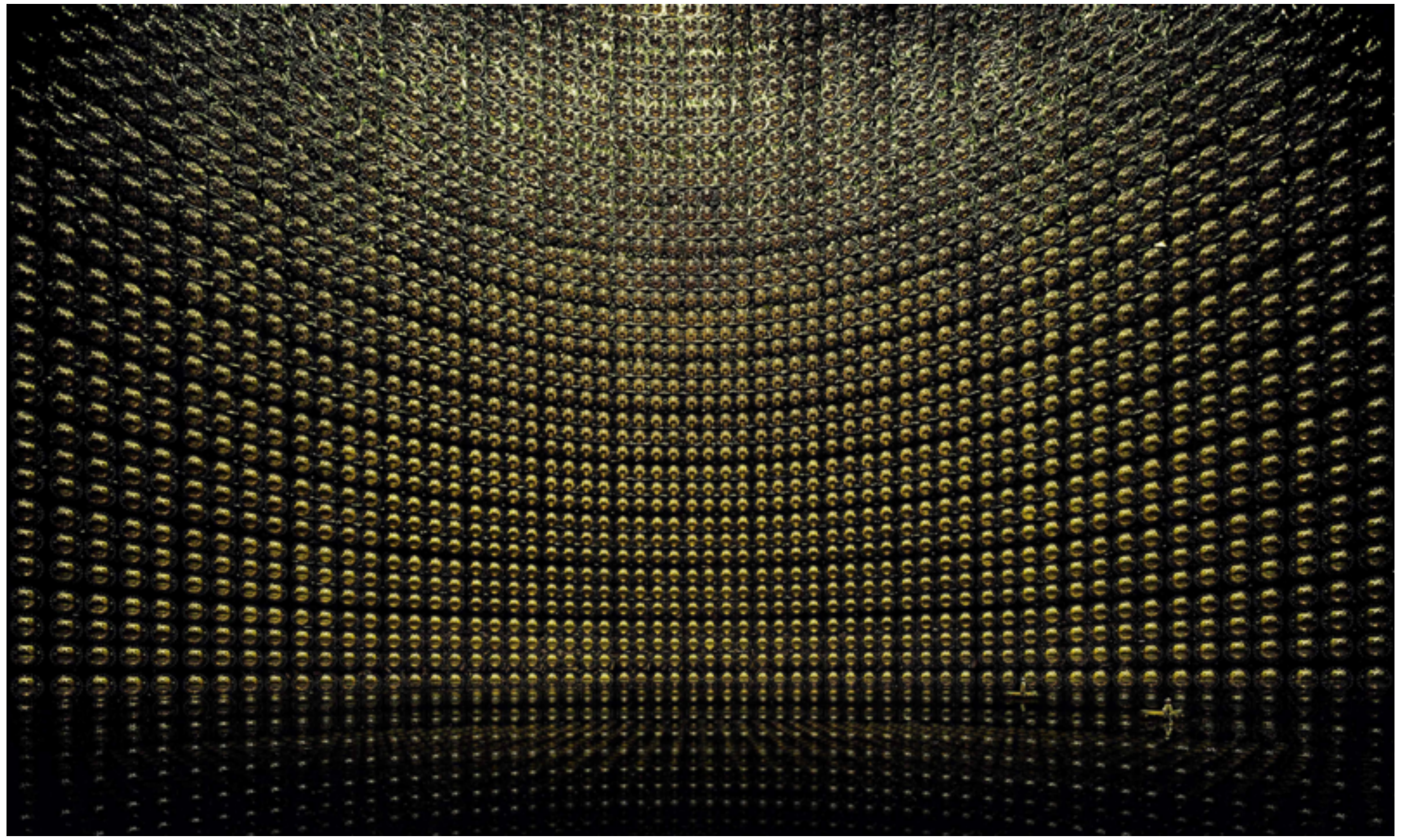
- Only a fraction of this is ν_e, the rest ν_μ,ν_τ

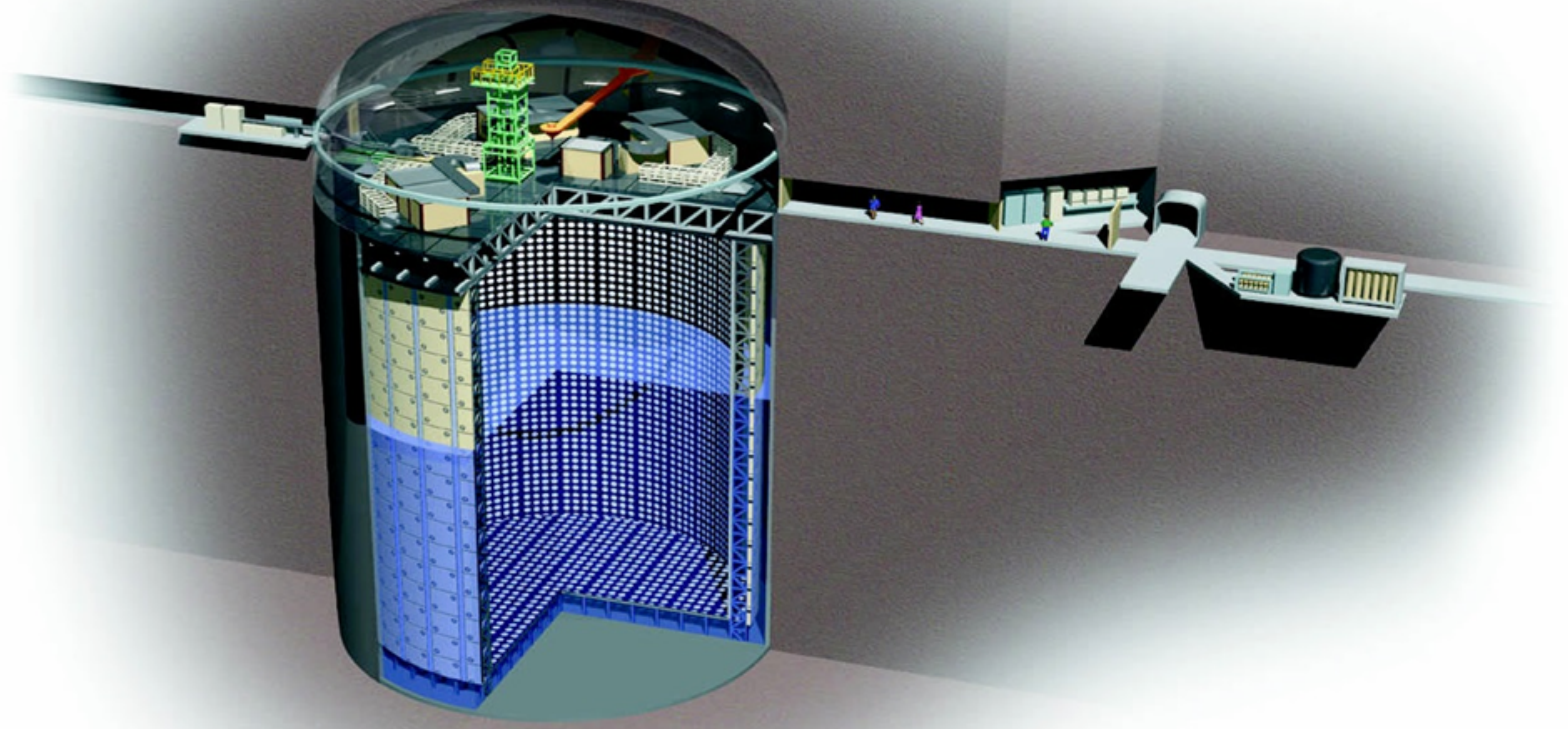
$$\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$

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

- Solution to the solar neutrino problem:
  - experiments sensitive to only ν_e observe only a small fraction (1/3) of the total neutrinos
  - SNO showed that the other 2/3 are there in the form of ν_μ and ν_τ

SUPER-KAMIOKANDE

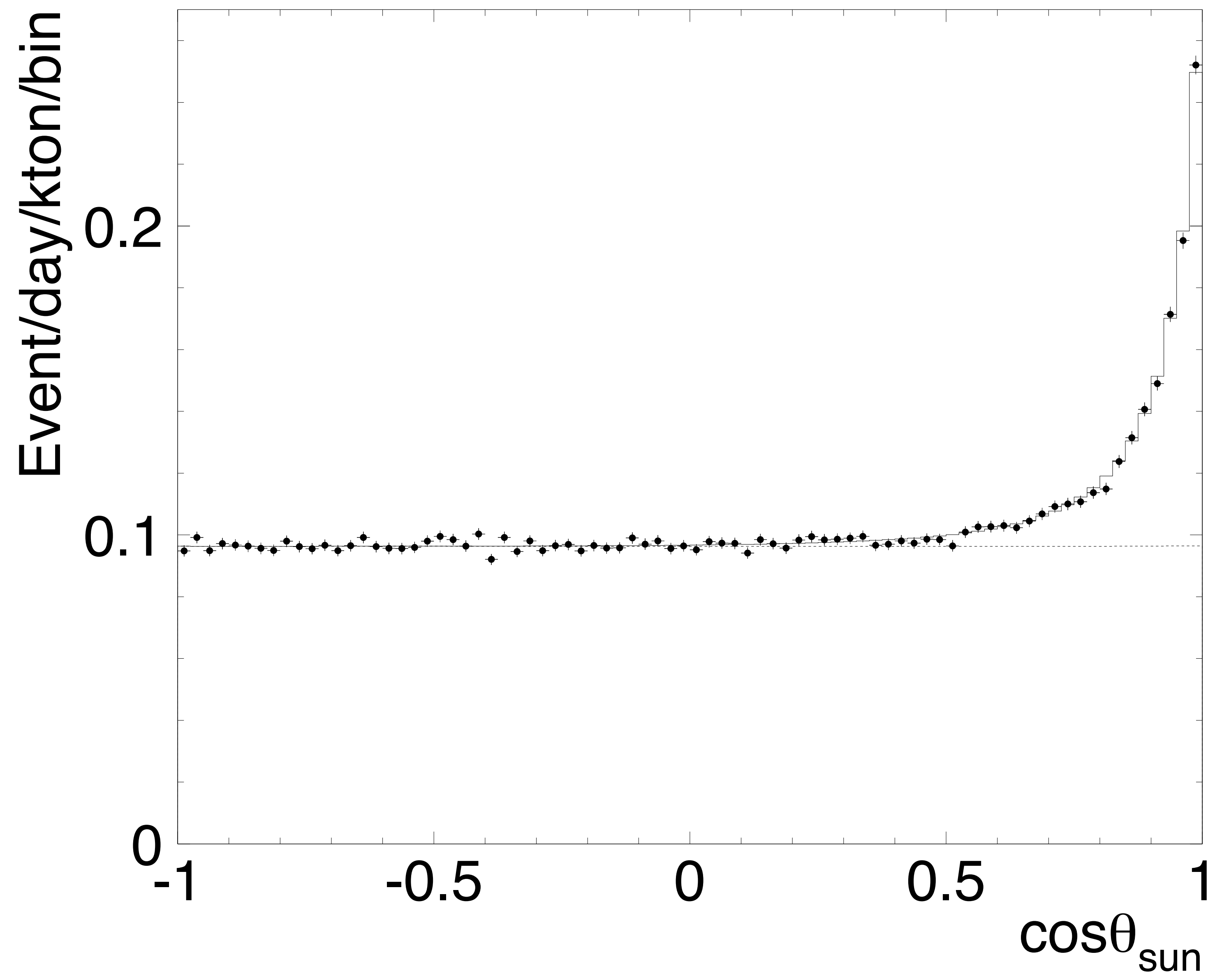




- 50 kt water Cherenkov detector with 1000 m of overburden
    - light water (no D_2O like SNO)
- 32 kt inner volume viewed by 11,129 50 cm PMTs
    - typically events at least 2 m from the PMTs are used in analysis. This defines a 22.5 kton “fiducial volume’.
- Outer “veto” volume viewed by 1,885 20 cm PMTs
    - tag particles entering from outside the detector or particles exiting the detector

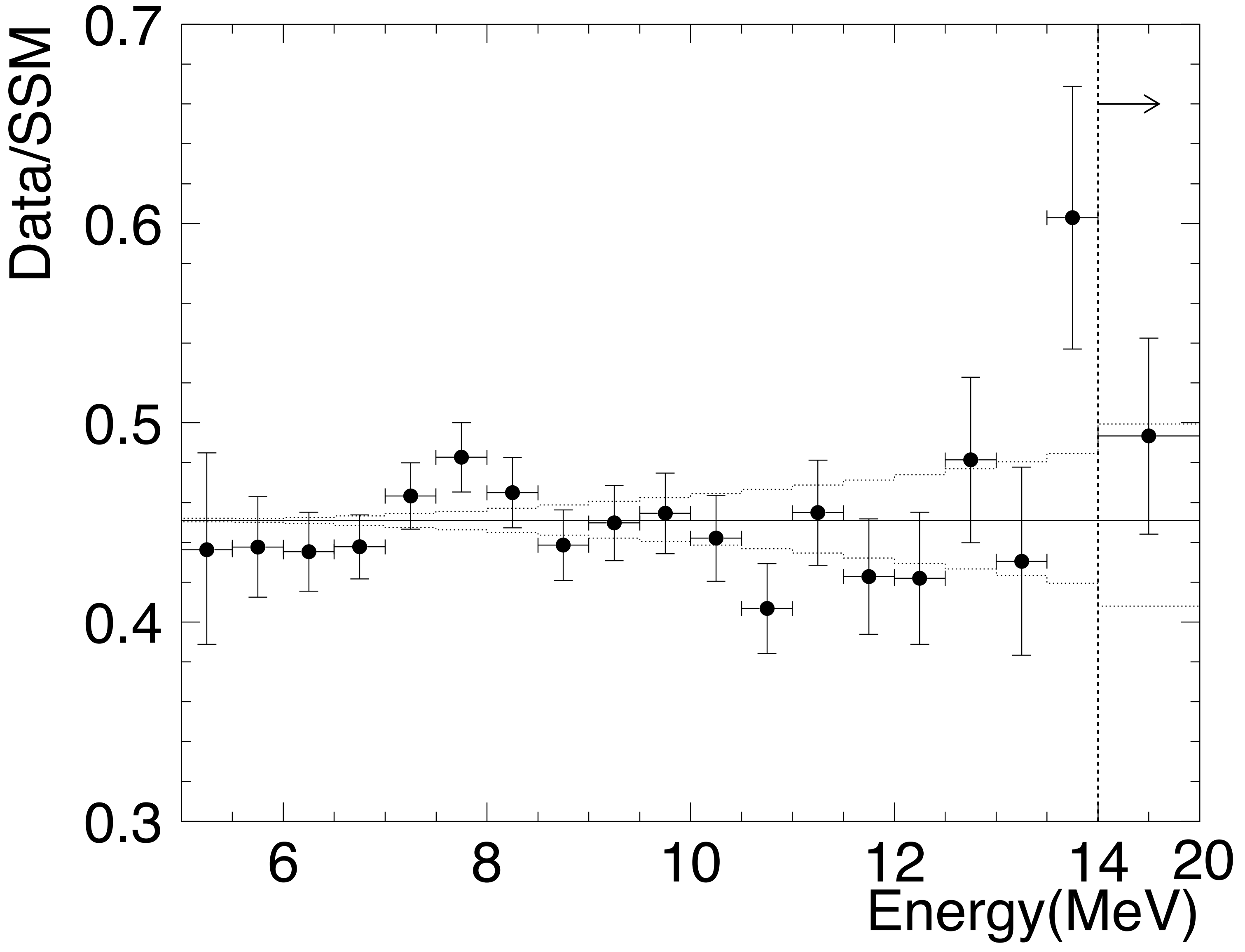
SOLAR DATA FROM SUPER-KAMIOKANDE

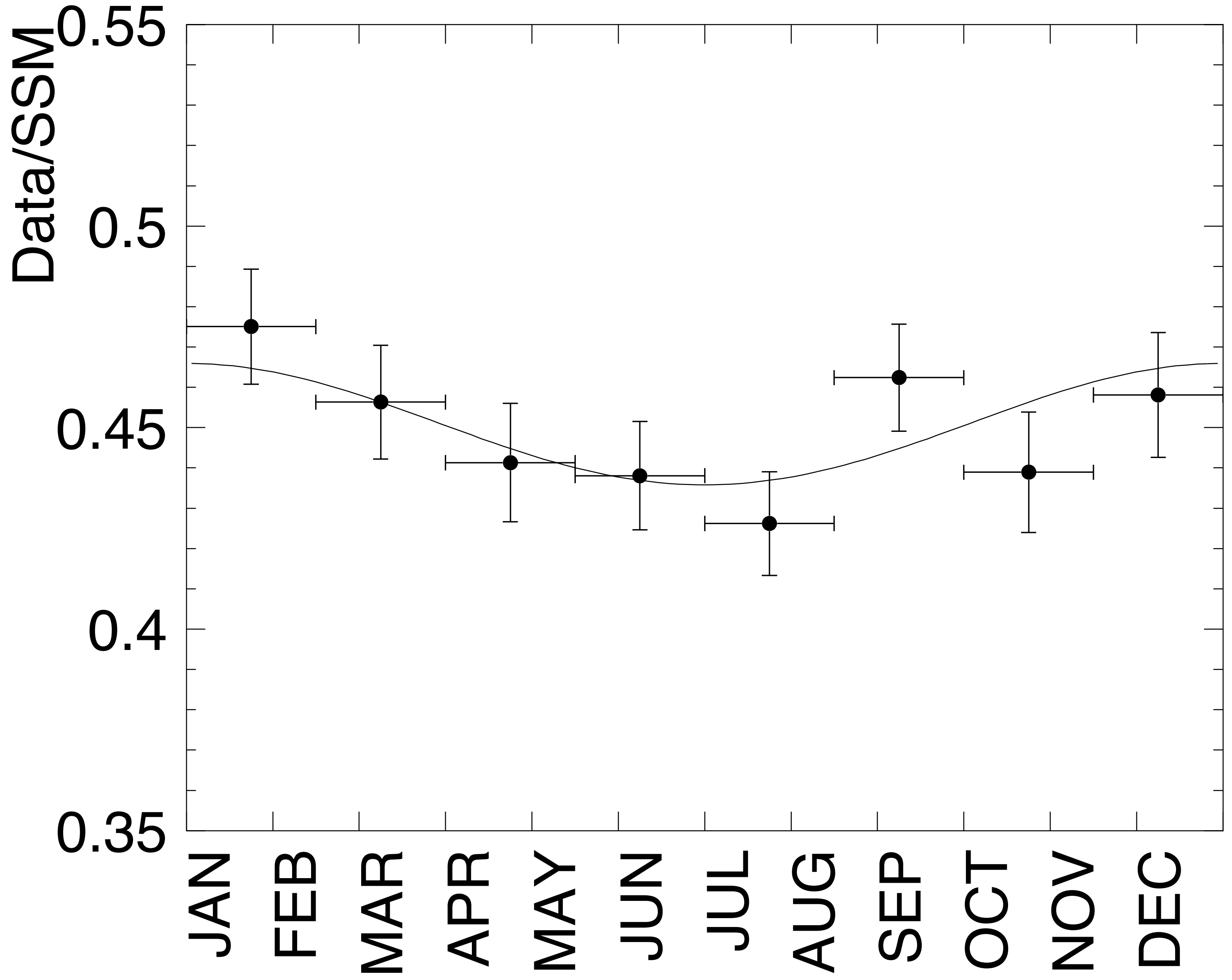
- Very high statistics of elastic scattering events due to large volume
  - ~20x SNO
- Allows detailed study of:
  - energy dependence of solar neutrino deficit
    - none observed . . . .
  - seasonal dependence
    - expected R^2 dependence observed . . . . .



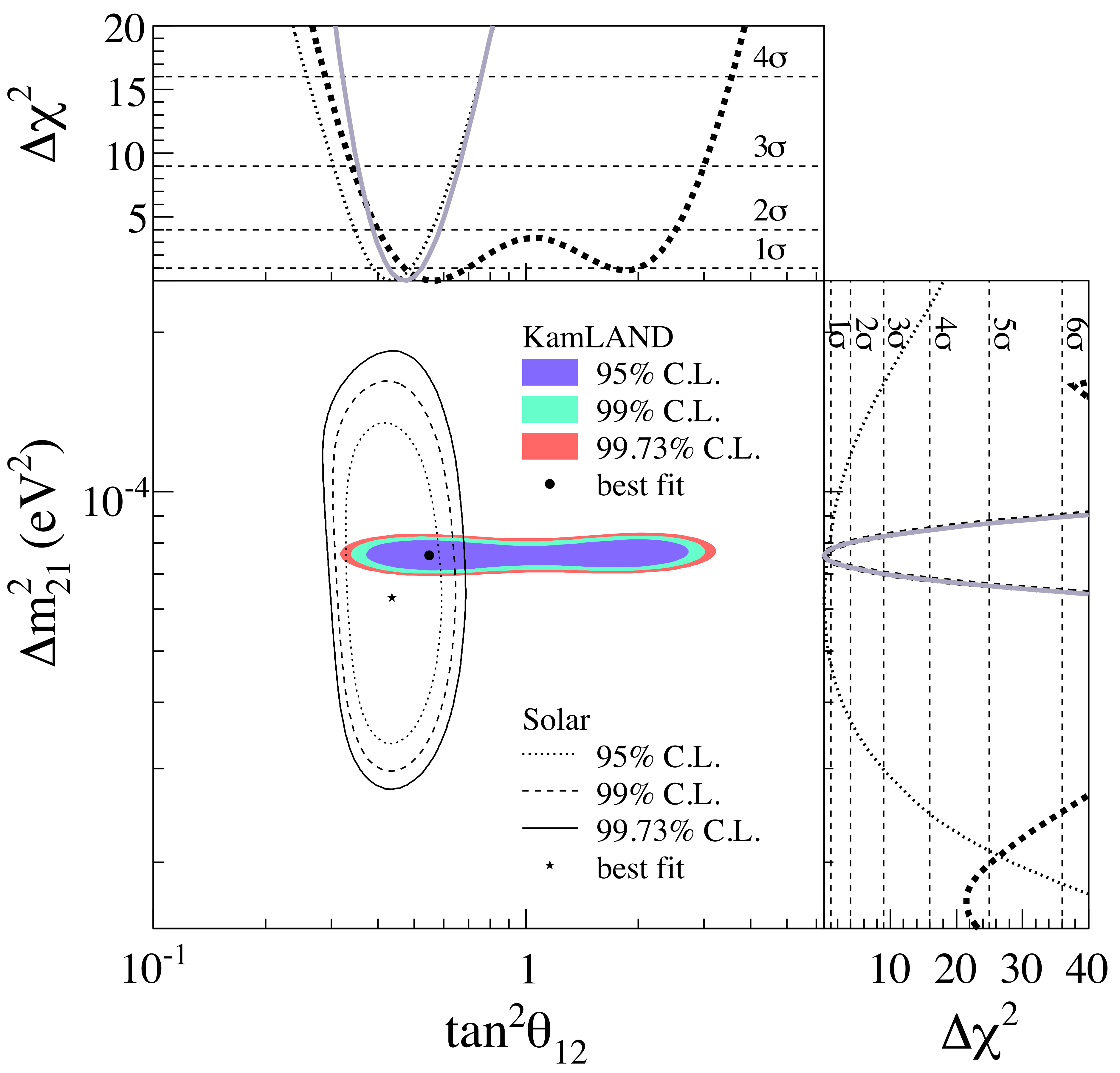
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \times \sin^2 \left[1.27\Delta m^2 \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

- No evidence of oscillatory behaviour in energy or distance . . .
- Just an overall deficit . . .





THE SOLUTION



- SNO observes that ~2/3 of ν_e from the sun have converted to $\nu_\mu,\ \nu_\tau$
- SK however observes that there is no energy dependence or distance dependence of the ν_e survival probability
- KamLAND, on the other hand, sees a very clear oscillatory behaviour with $\Delta m^2 = 7.6\text{x}10^{-5}$ eV^2

- The strong matter effects in the sun make ν_e (electron neutrinos) ~ energy eigenstate
- As the neutrino propagates through the sun and out into the vacuum of space, they stay as an energy eigenstate corresponding to ν_2 (the heavier of the mass eignestates)
- ν_2 is an energy eigenstate. It doesn't oscillate!
  - flavour content is "locked in" on its transit to earth
  - no E or L dependence . . . . .

ATMOSPHERIC NEUTRINOS

- Atmospheric neutrinos are produced by the interaction of cosmic ray protons on nuclei in the atmosphere

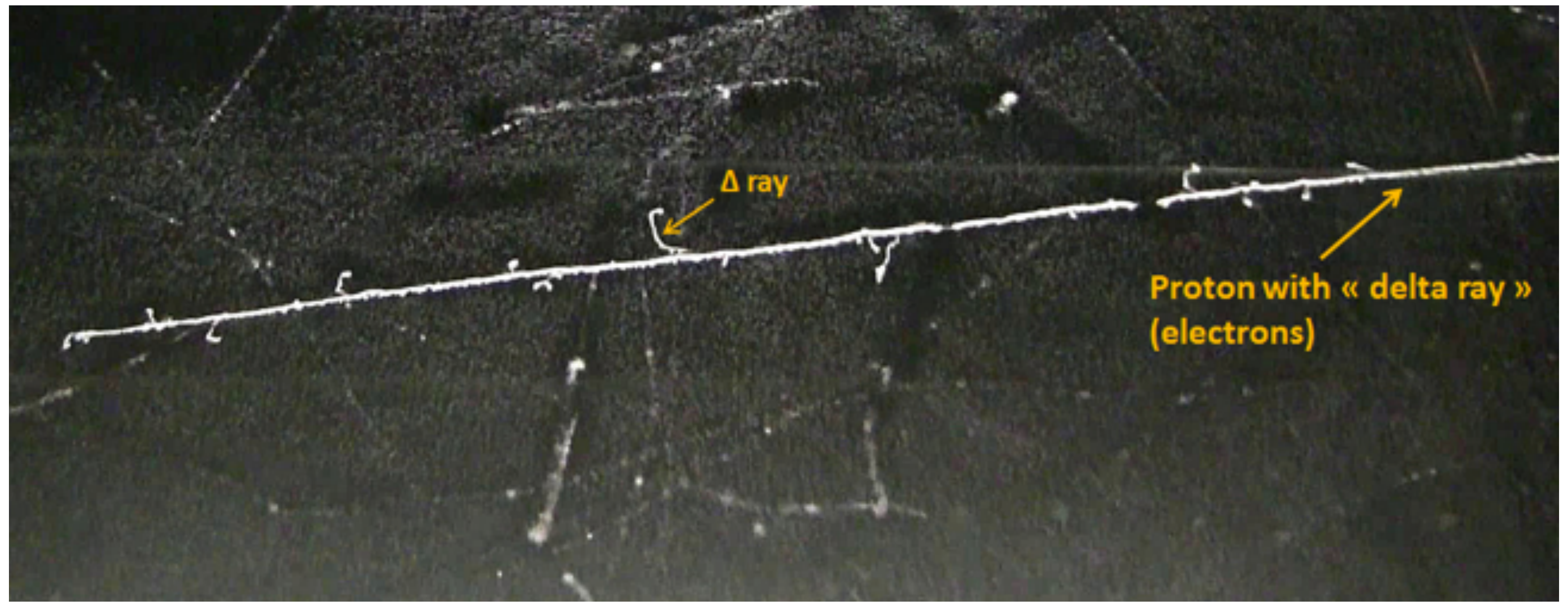
$$p + N \rightarrow \pi^{\pm} + X$$

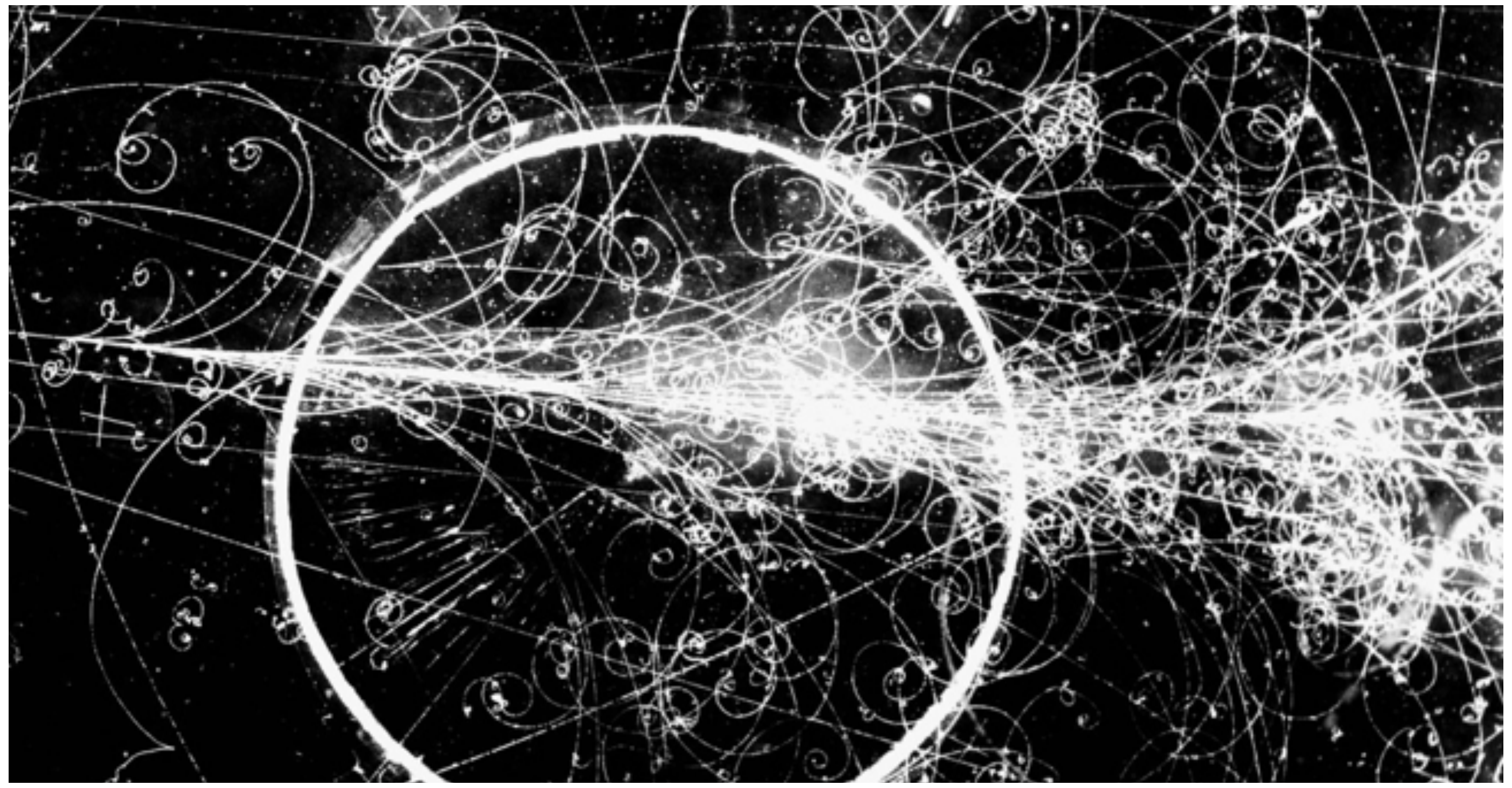
$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \boxed{\nu_\mu} \\ &\quad \hookrightarrow e^+ + \nu_e + \boxed{\bar{\nu}_\mu} \\ \pi^- &\rightarrow \mu^- + \boxed{\bar{\nu}_\mu} \\ &\quad \hookrightarrow e^- + \bar{\nu}_e + \boxed{\nu_\mu} \end{aligned}$$

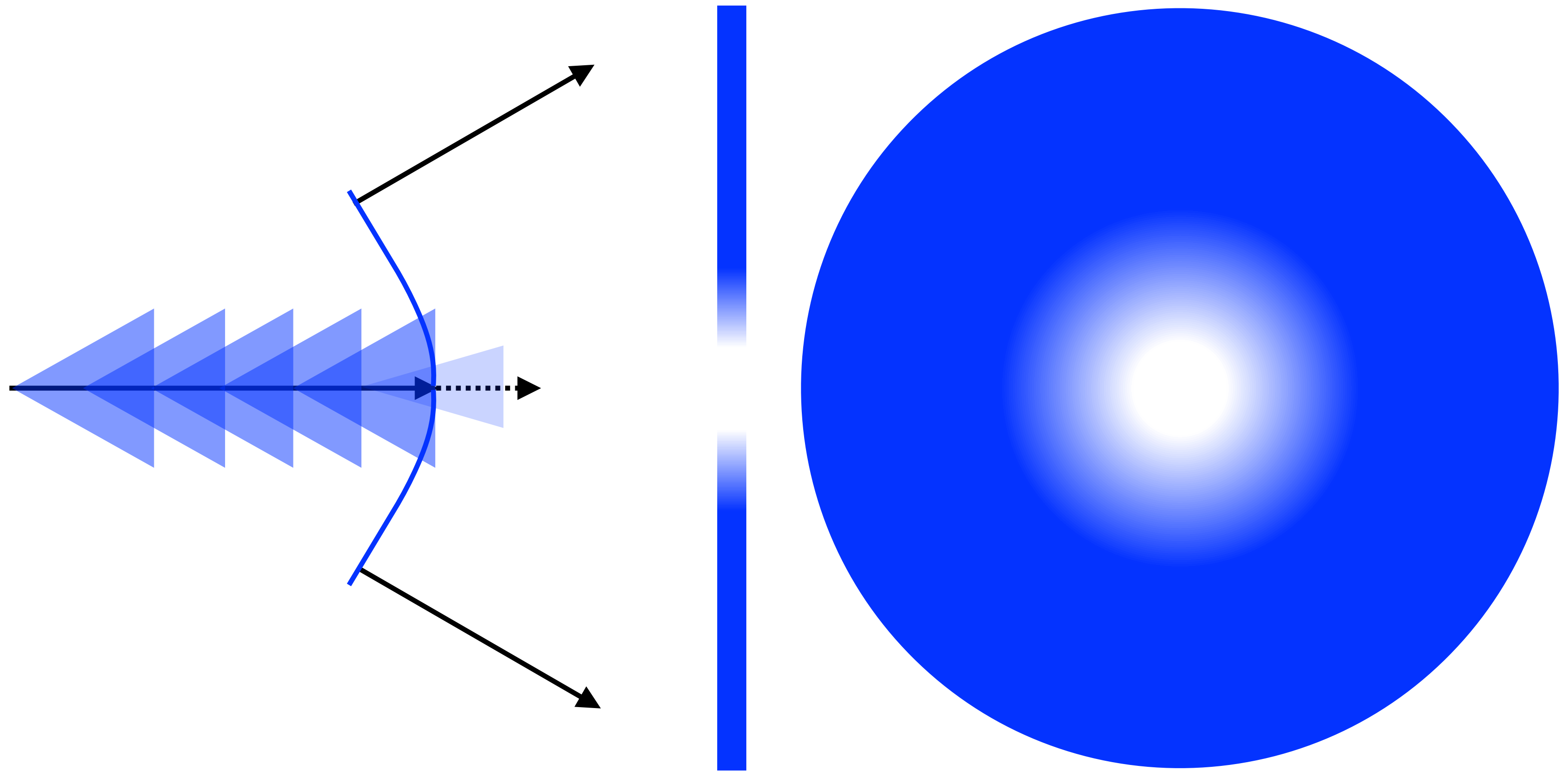
- Naively, expect a 2:1 ratio of muon (anti)neutrino to electron (anti)neutrino ratio in the absence of oscillations
  - can we test this by identifying muon neutrinos and electron neutrinos?
  - look for muon production (from ν_μ) and electron production (from ν_e).

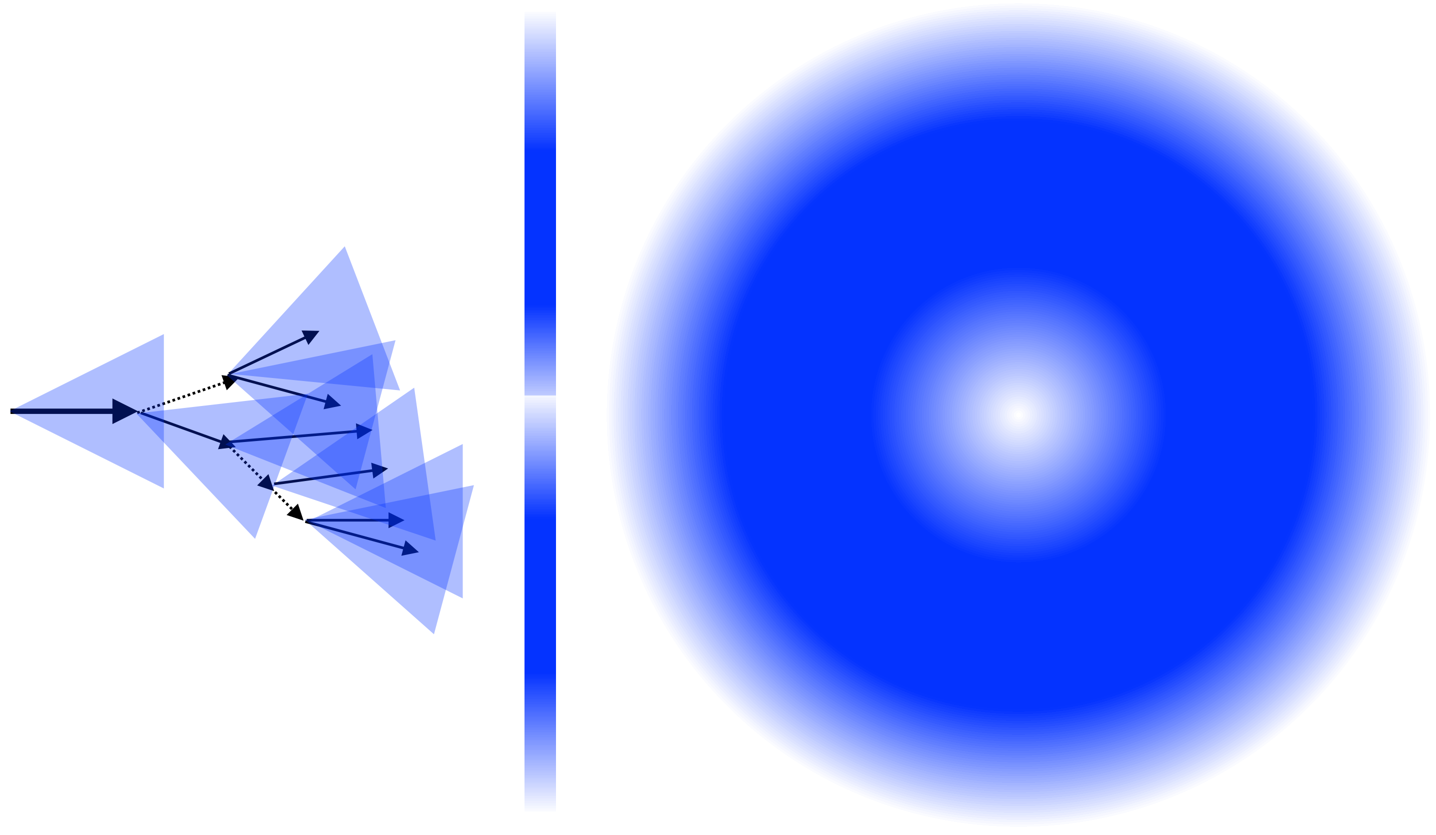
PARTICLE IDENTIFICATION

- Other processes as charged particles passes through media
- Ionization loss: steady energy transfer by ionizing atoms.
- Bremsstrahlung:
  - photon emission from acceleration of particle in field of atomic nucleus
    - Photon can then Compton scatter, pair produce
    - electrons/positrons from this can in emit more photons
    - “Electromagnetic shower”
- Č Ring can tell us:
  - position/direction/energy of the particle “track reconstruction”
  - identify the particle as non-showering (μ, π, p) vs. e/γ

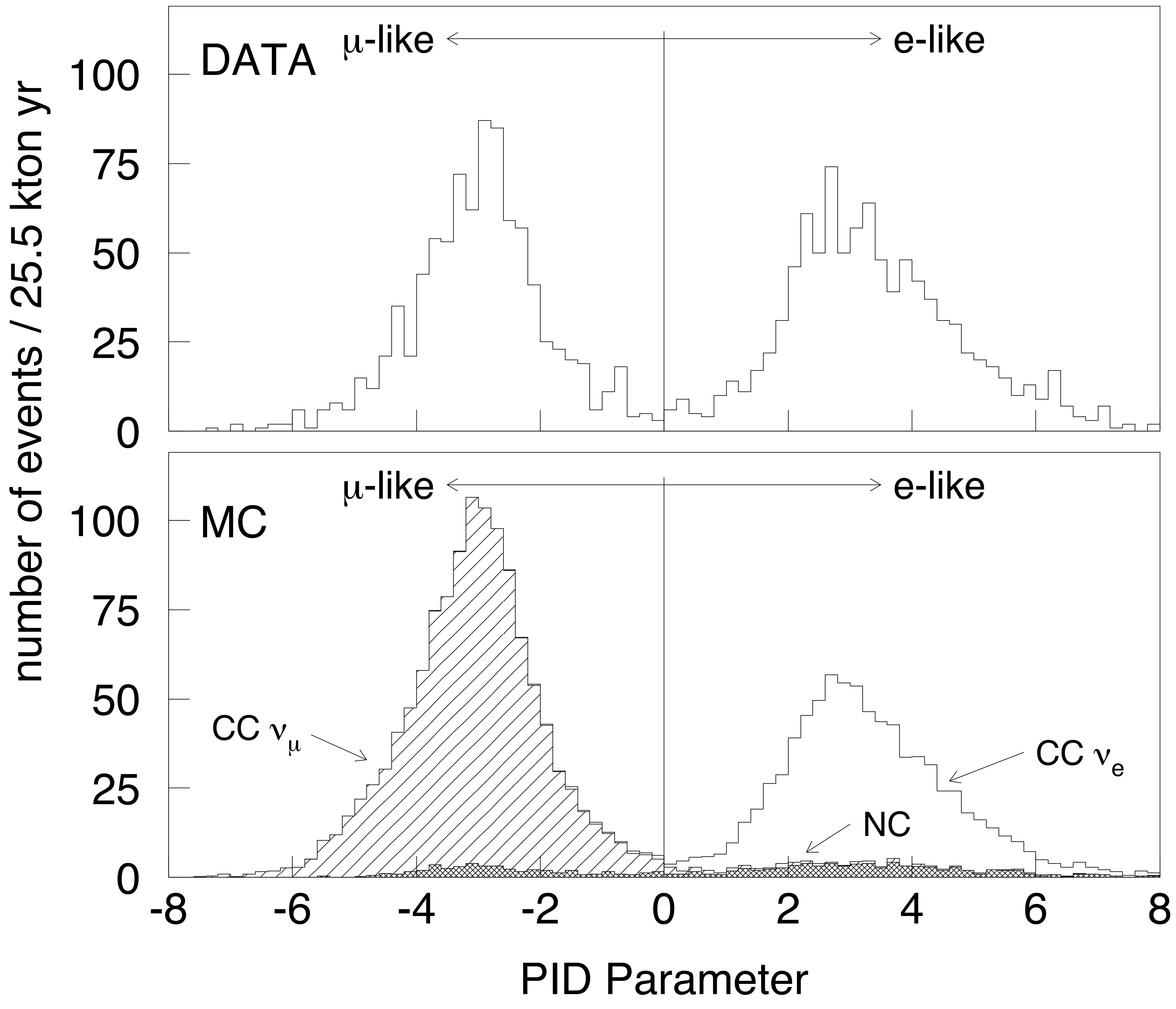


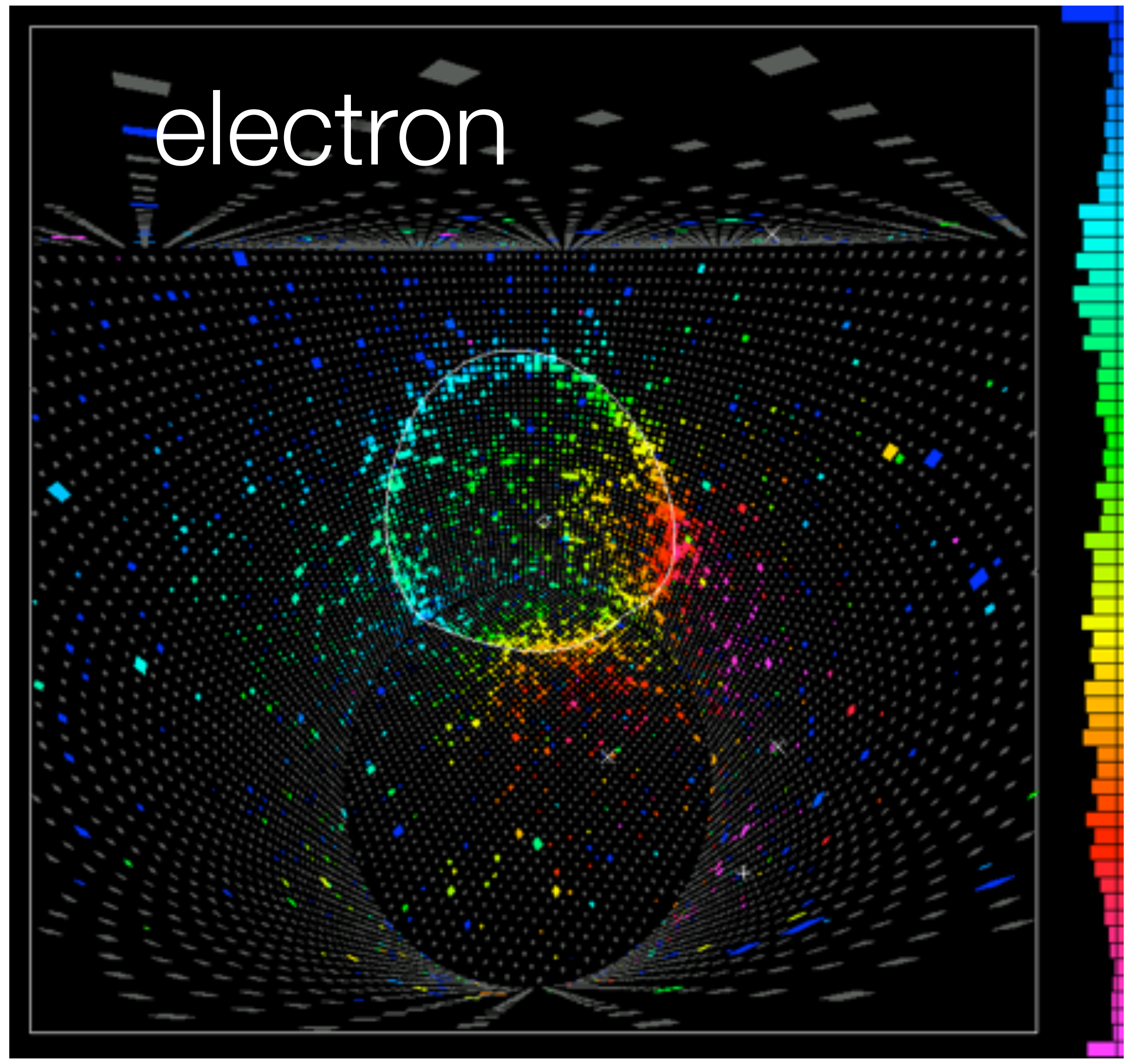


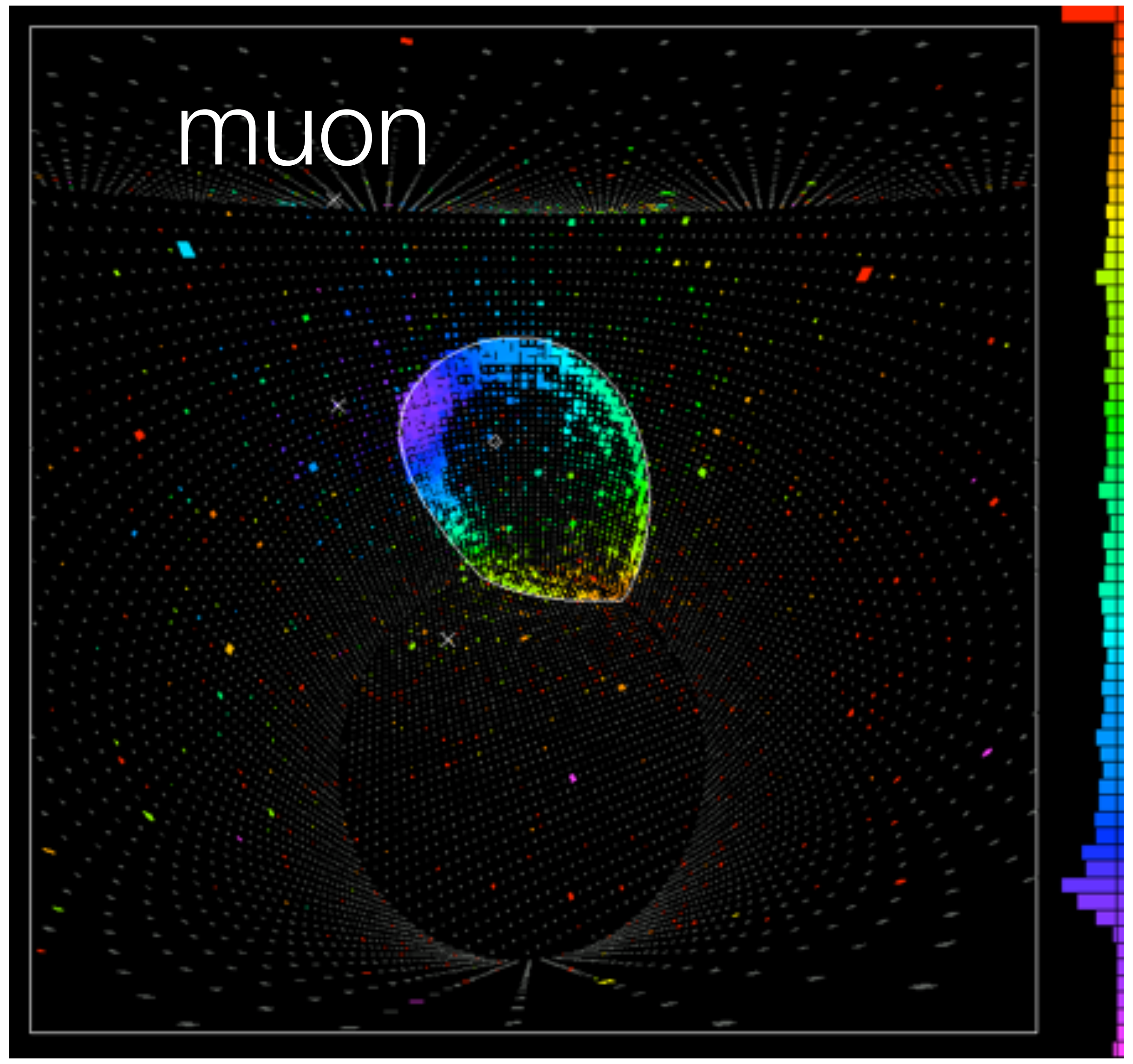


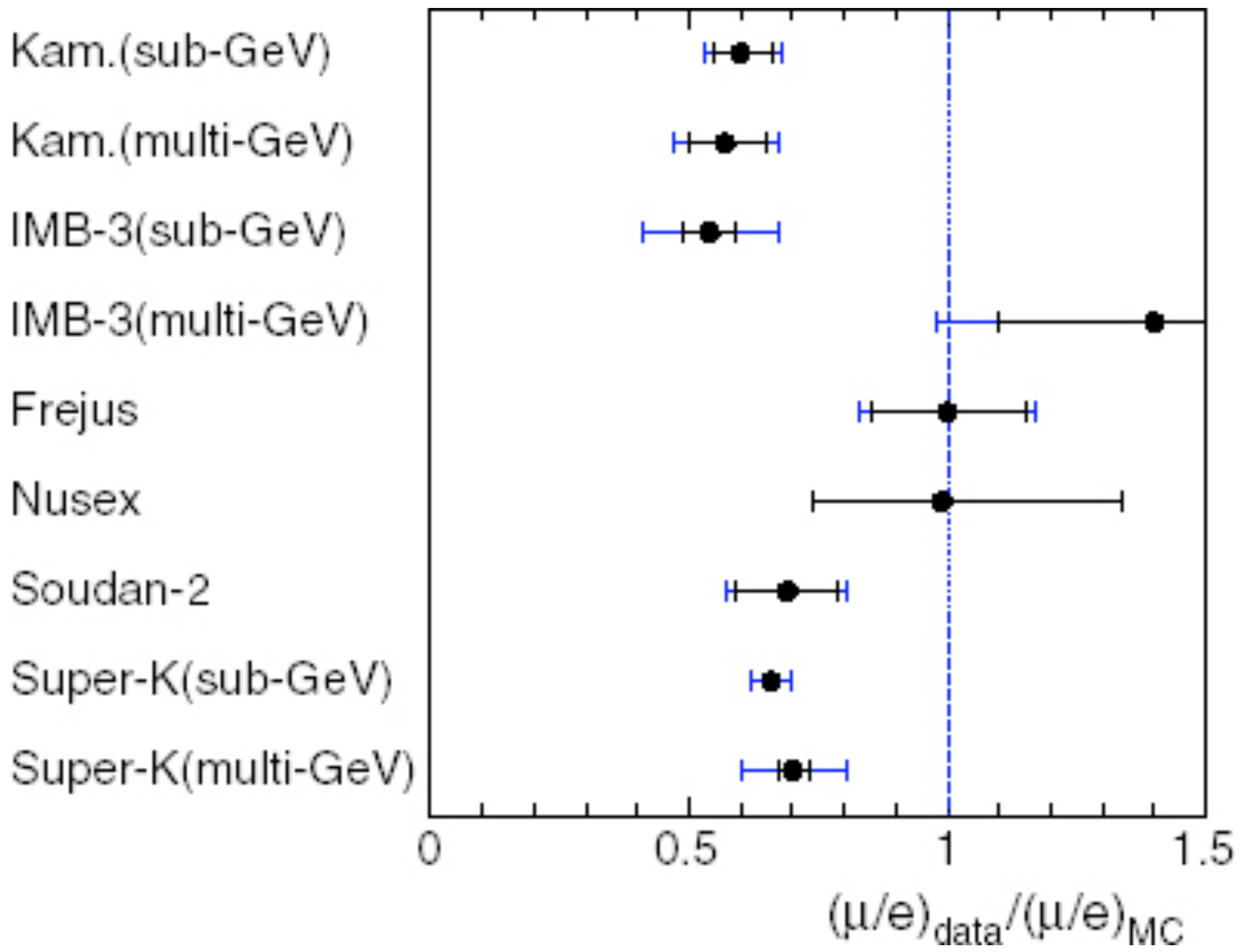


PARTICLE IDENTIFICATION IN SK



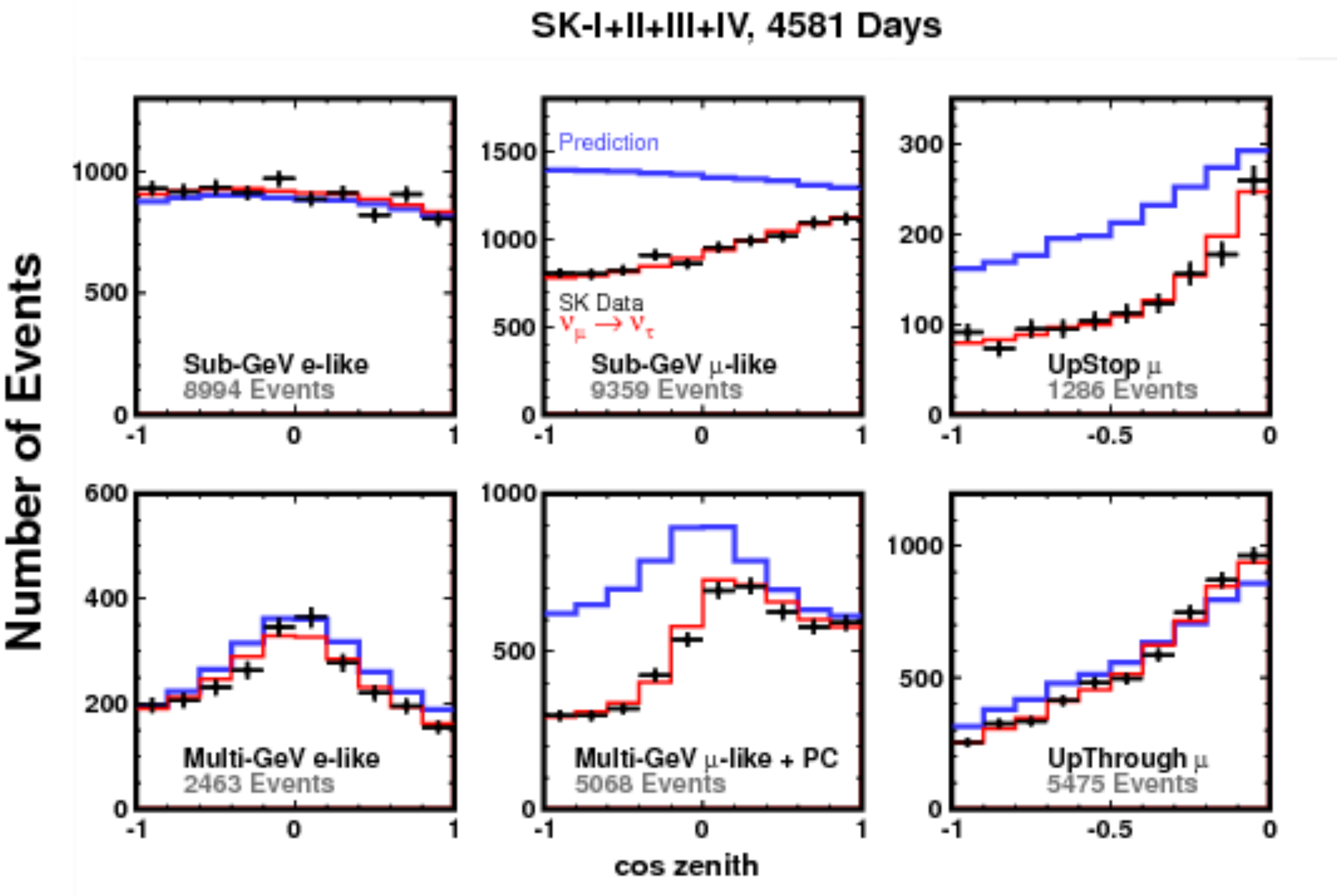






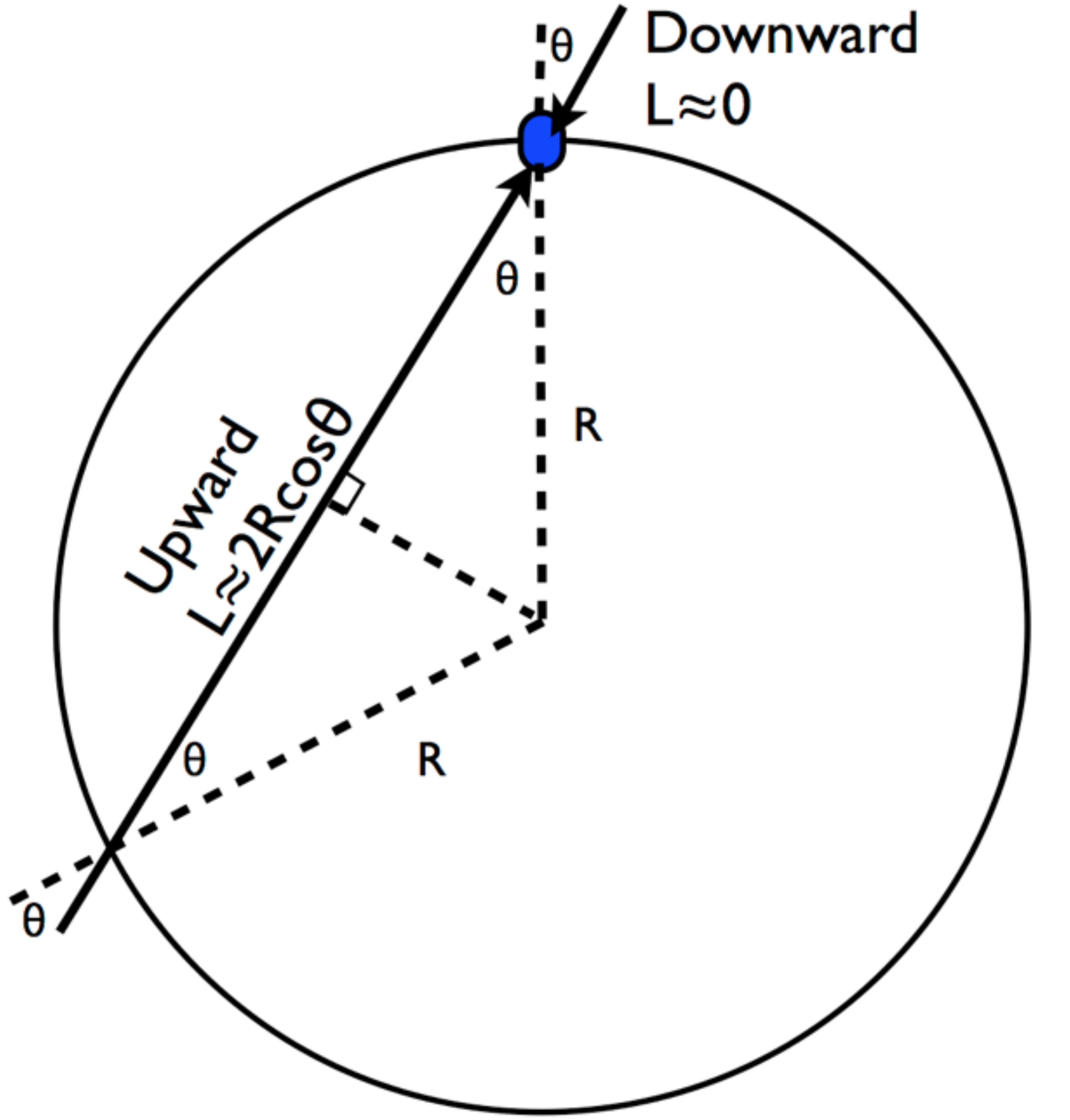
- particle identification variable to separate electron-like and muon-like Cherenkov rings in the Super-Kamiokande detector
- can separate electrons and muons (hence ν_e and ν_μ) at the 99% level

FURTHER EVIDENCE



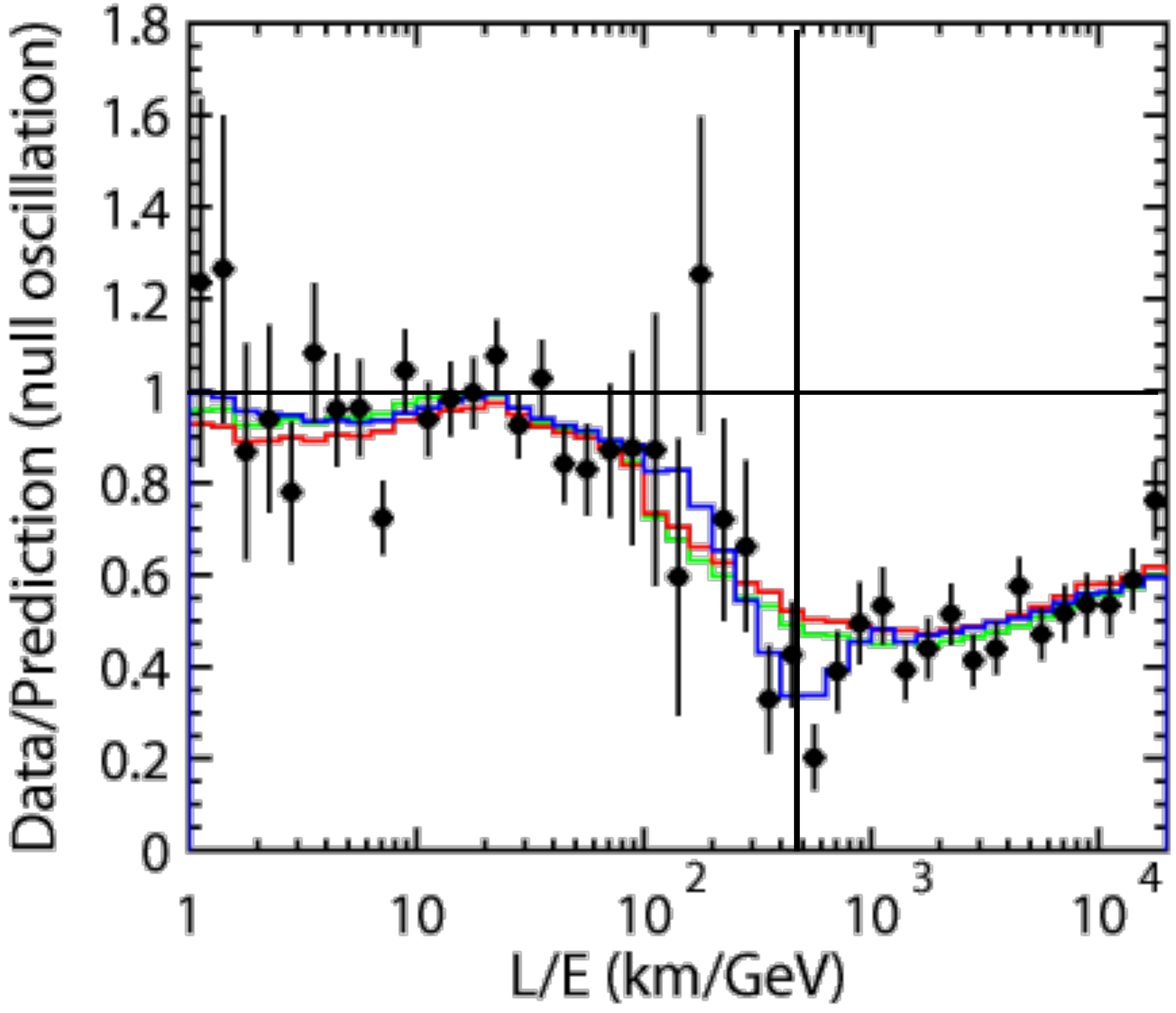
- Zenith angle distribution of deficit agrees with neutrino oscillations

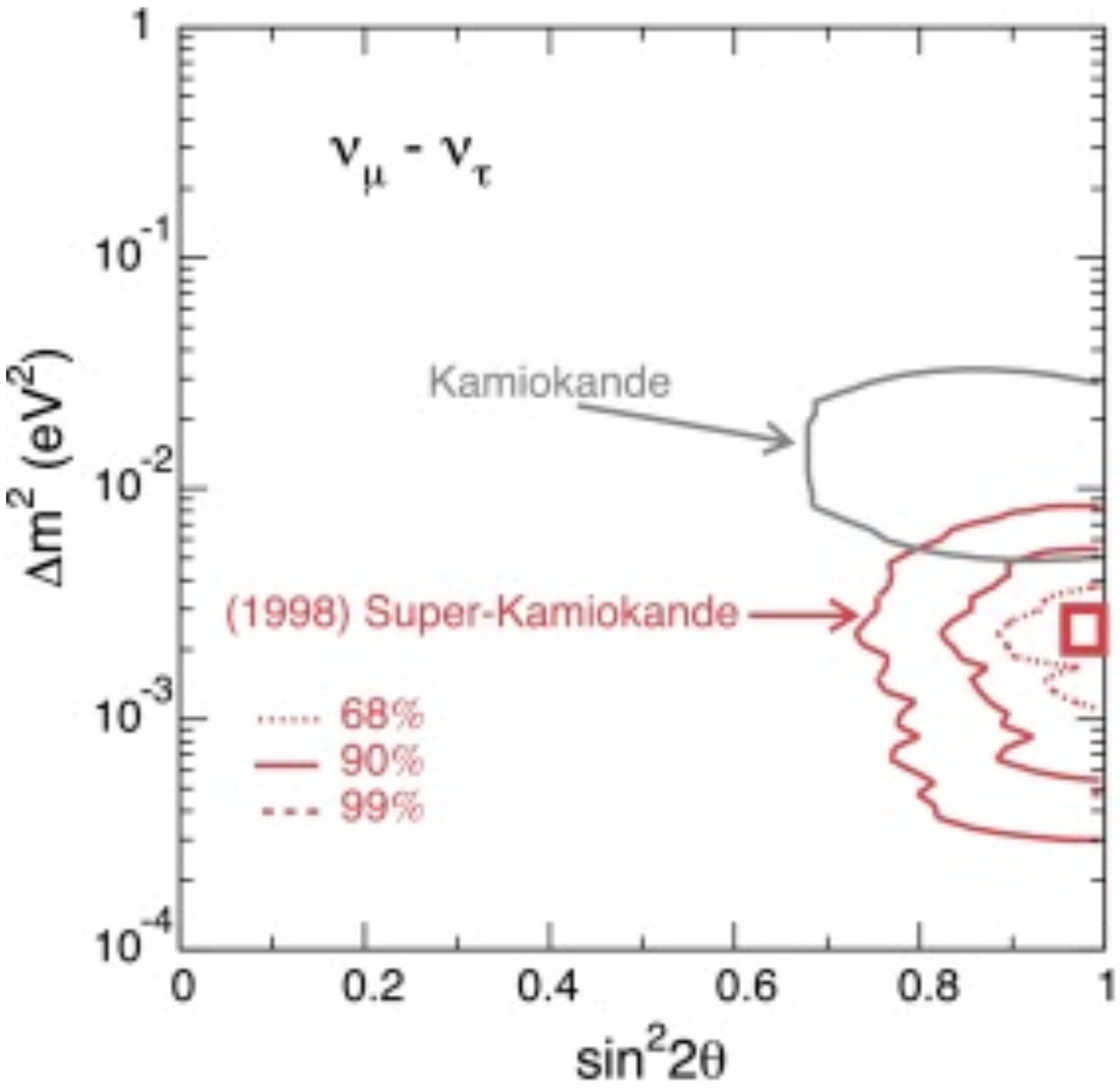
- Neutrino oscillations should have a dependence on the path length from production to detection.
- For atmospheric neutrinos, is related to the "zenith angle" of the neutrino



ANOTHER LOOK

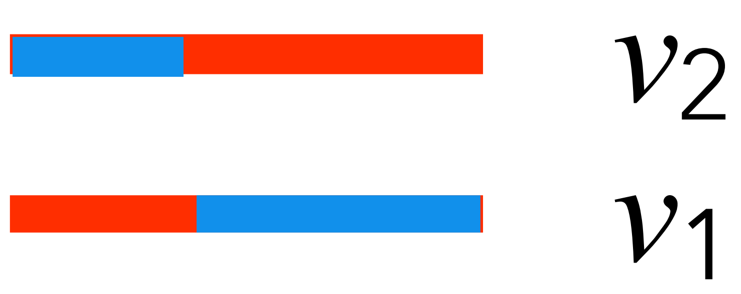
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \times \sin^2\left[1.27\Delta m^2 \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

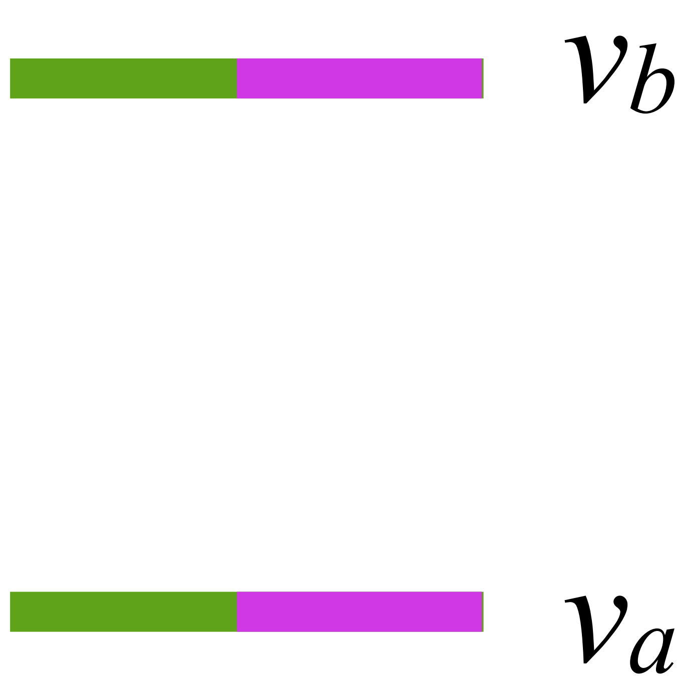




- Plot deficit directly as a function of L/E using subset of interaction where "pointing" accuracy is good.
- Location of minimum tells us Δm^2: $1.27 \times \Delta m^2(\mathrm{eV}^2) \times 600$ km/GeV = $\pi/2 \rightarrow \Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2
- "Depth" of minimum tells us $\sin^2 2\theta$: $\sin^2 2\theta \sim 1$ (maximal mixing)

WHAT DO WE KNOW?





$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{pmatrix} \nu_\mu \\ \nu_y \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix}$$

- From solar measurement:
  - ν_e component of ν_2 is ~1/3 → $\sin^2\theta_{12} = 1/3$
  - θ_{12} ~ 35 degrees
- From KamLAND
  - $\sin^2 2\theta_{12} = 0.85$ → θ_{12} ~34 degrees
  - Δm^2_{21} ~ 7.5x 10^{-5} eV^2

- From atmospheric measurment
  - ν_μ disappearance is ~maximal
  - θ_{23} ~ 45 degrees
  - Δm^2_{ba} ~ 2.5 x10^{-5} eV^2
  - excess of ν_e not observed:
    - ν_y is primarily ν_τ

The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita

Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald

Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"