Neutrino Physics

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PIRE/GEMADARC Summer School — May 2023

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3: Breaking Things

Symmetries and Conservation Laws

- "Symmetries" play key role in physics
- Symmetry — Transformation of a system
- **Noether's Theorem (1918)**: "every differentiable (continuous) symmetry of the action of a physical system with conservative forces has a corresponding conservation law."
- Ie. If equations describing system doesn't change with some symmetry transformation, then there is a corresponding conserved quantity:
  - Translational — Conservation of Linear Momentum
  - Rotational —Conservation of Angular Momentum
  - U(1) Gauge — Conservations of Electric Charge
  - Lorentz Invariance: particle mass, space-time interval, etc…
  - …

Brittanica

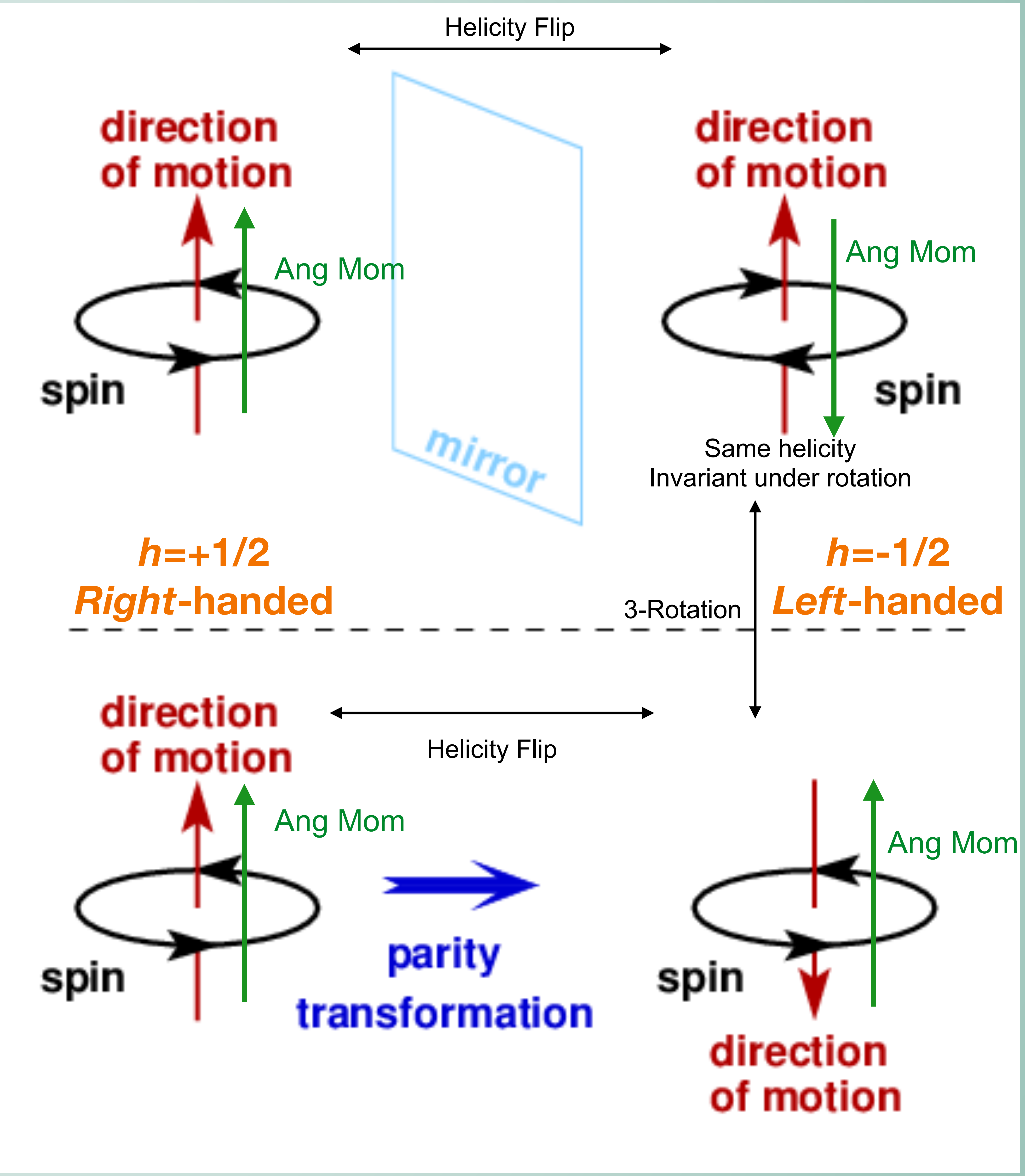
Parity and Helicity

- Parity is *discrete* symmetry: $\mathbf{x} \to -\mathbf{x}$
- 1950's — Physicists believe all physical processes invariant under *parity*:

$$\psi(\mathbf{x}) \leftrightarrow \pm\psi(-\mathbf{x})$$

- Particles have intrinsic parity: ± 1
- Parity state of particle can be determined by *helicity*:

$$h = \frac{\mathbf{S}\cdot\mathbf{p}}{p}$$



1957: Neutrino Helicity Measured

Phys Rev. 109 (1957) 1015

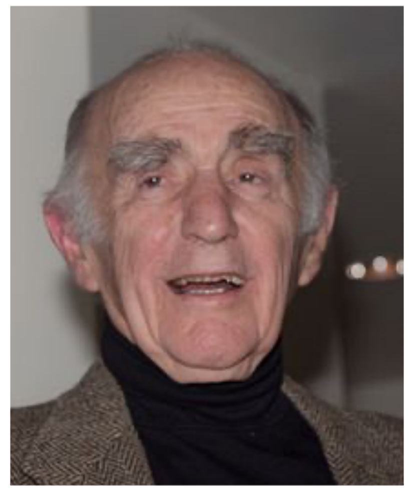
Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

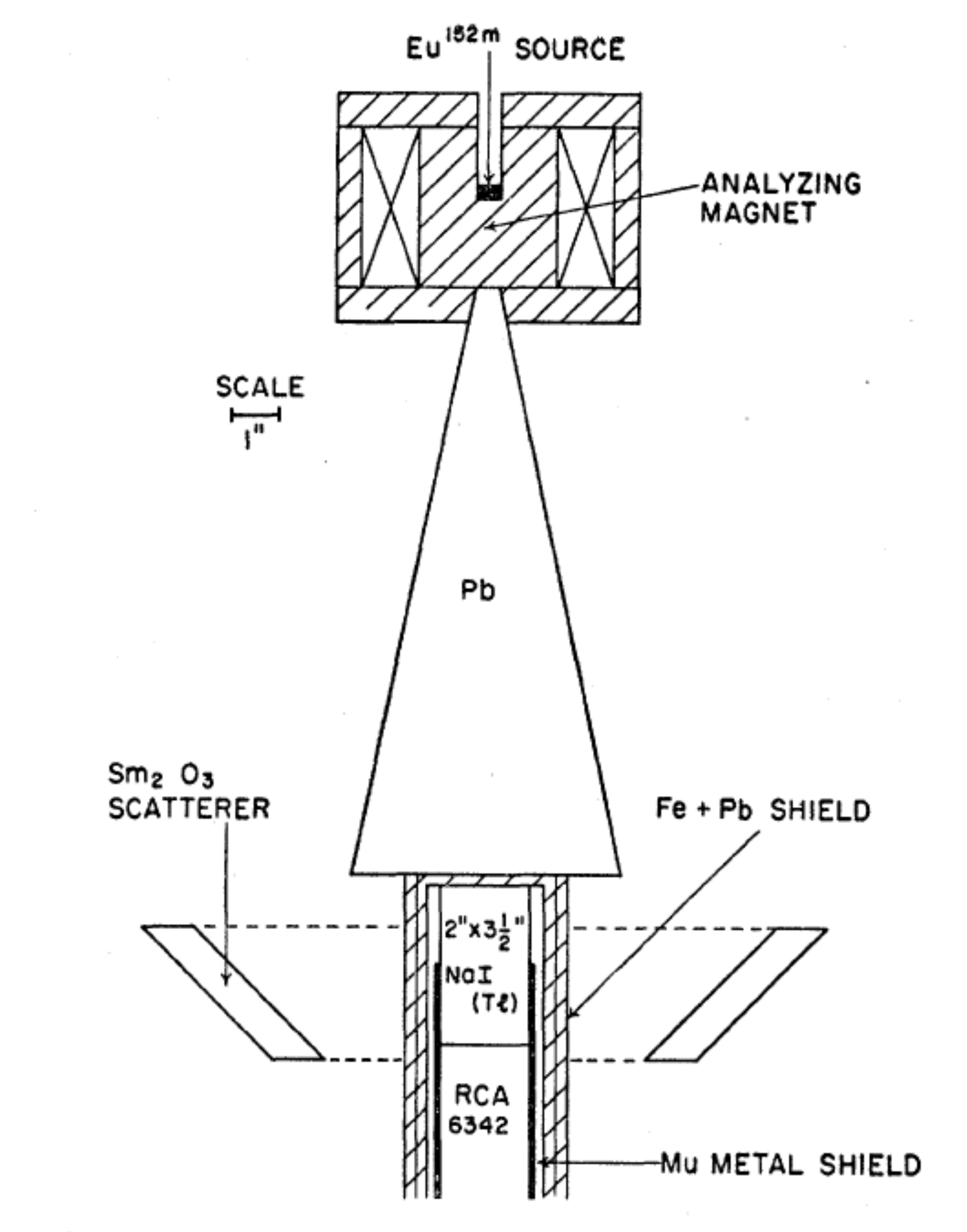
Thus, a measurement of the circular polarization of the γ rays which are resonant-scattered by the nucleus B, yields directly the helicity of the neutrino, if one assumes only the well-established conservation laws of momentum and angular momentum.

Wikipedia



Wikipedia

AIP



- Inferred Neutrino Helicity before Neutrinos were detected!

1956: Evidence of Parity Conservation Evaluated

- "Tau-theta" puzzle — same particle appeared to decay into different parity states.
- Lee and Yang found no existing experimental evidence for parity consideration in Weak interaction.
- Many skeptics:
  - Pauli "Ich glaube aber nicht, daß der Herrgott ein schwacher Linkshänder ist." (I do not believe that the Lord is a weak left-hander.)
- Proposed several test, including using nuclear beta decay
- Yang in his Nobel acceptance speech: "This prospect did not appeal to us. Rather we were, so to speak, driven to it through frustration."

The Nobel Prize in Physics 1957

Photo from the Nobel Foundation archive.

Chen Ning Yang

Prize share: 1/2

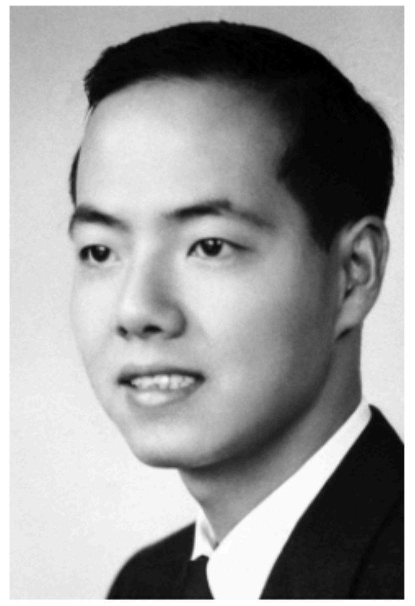


Photo from the Nobel Foundation archive.

Tsung-Dao (T.D.) Lee

Prize share: 1/2

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee "for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles."

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

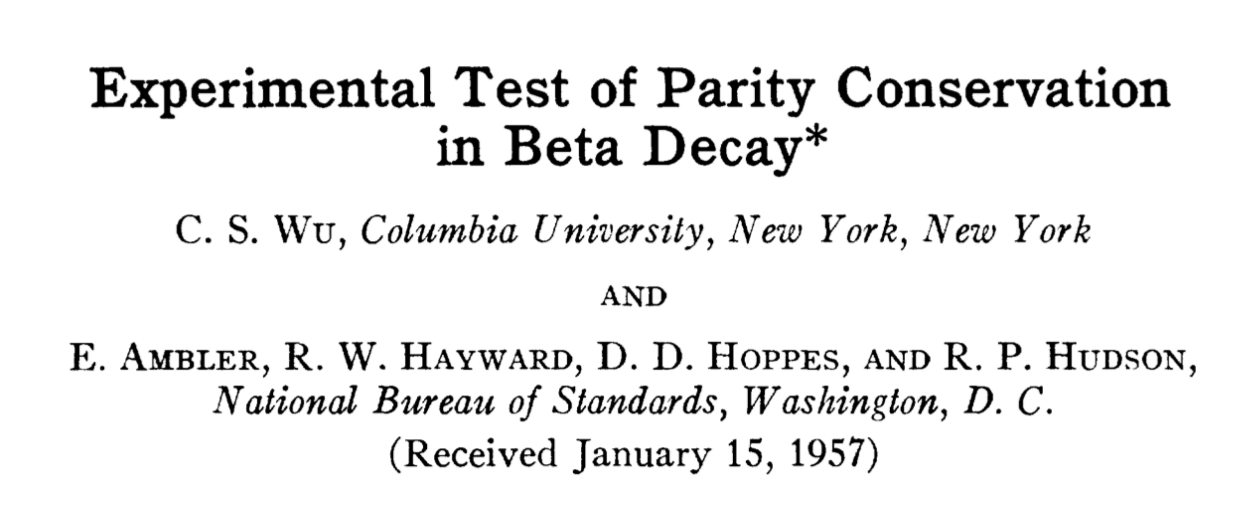
C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

1957: "Wu" Experiment Confirms Parity Violation

- ${}^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$
- Polarized spin of ^{60}Co nucleus using magnet and low temperatures.
- Gamma-rays served as control
- "A large beta asymmetry was observed."
- Later found to be *maximal*
  - Weak interaction only "sees" LH ν and RH $\bar{\nu}$



Experimental Test of Parity Conservation in Beta Decay*

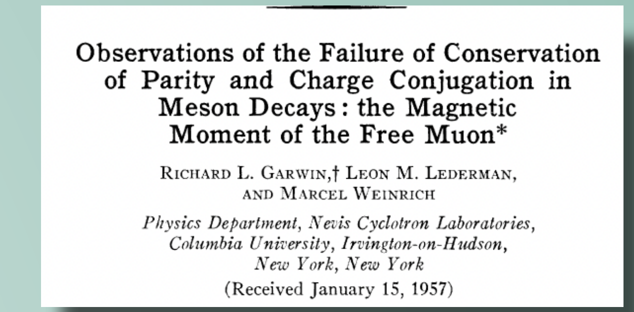
C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

Next Paper in Journal

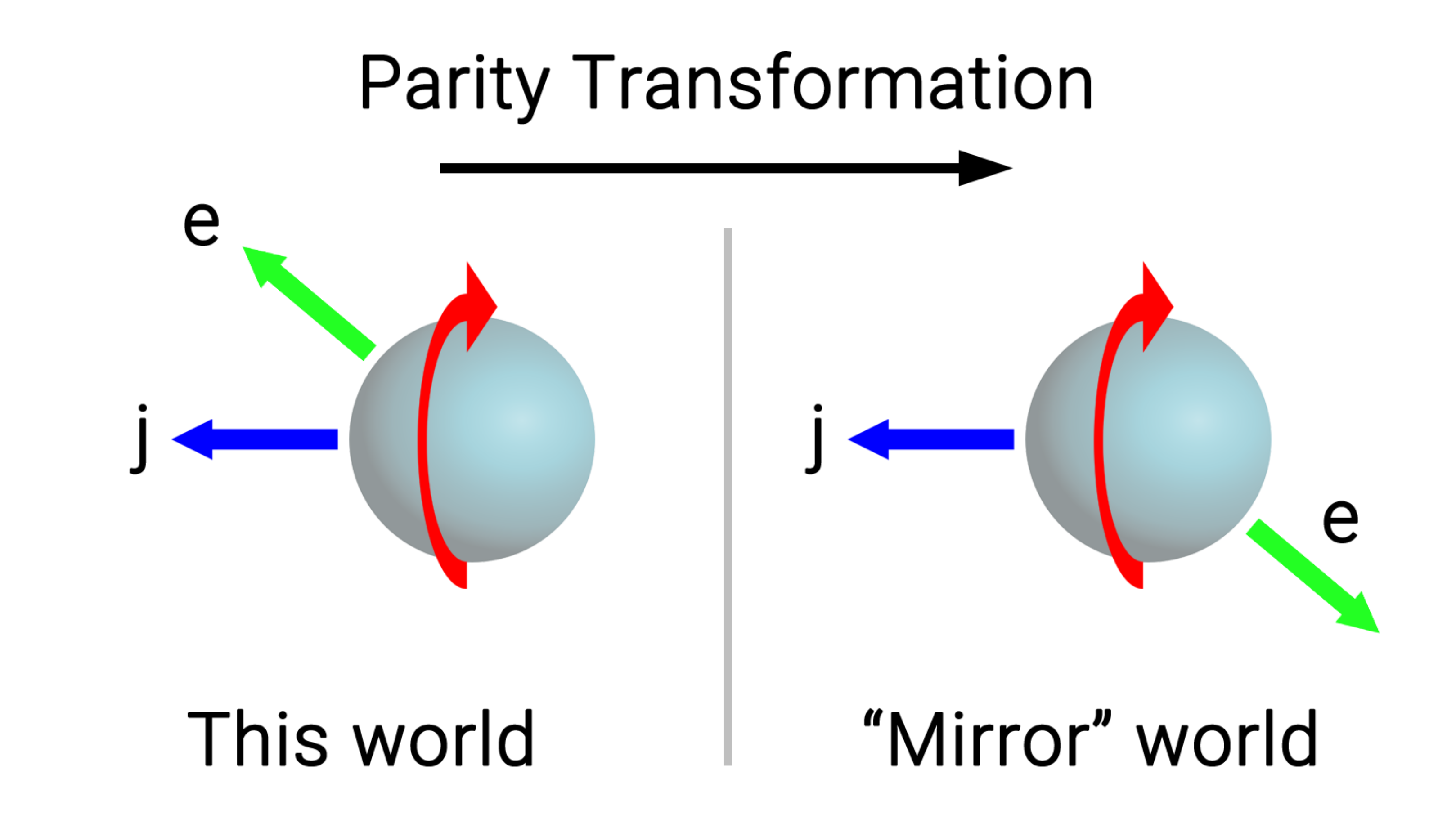


Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

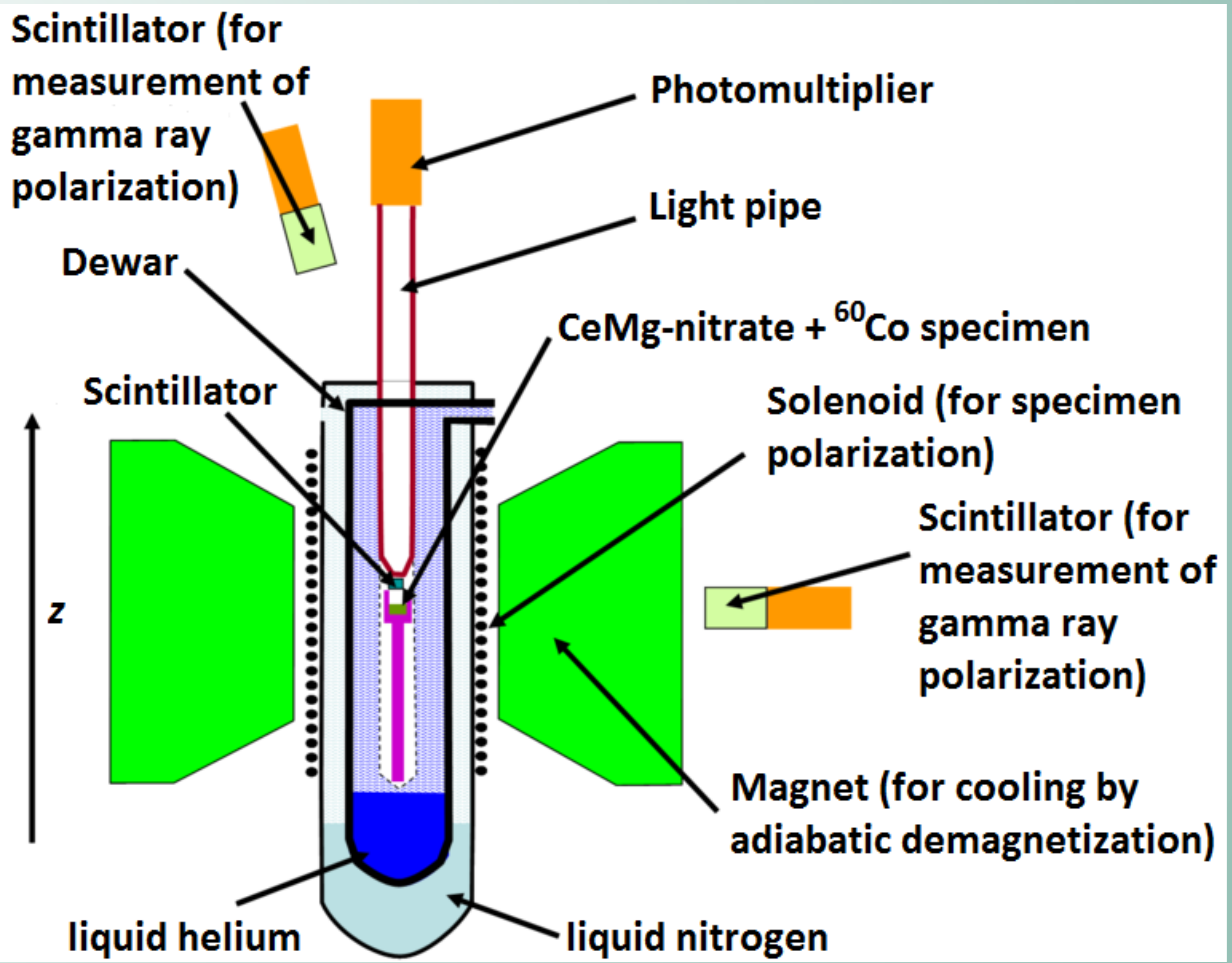
Richard L. Garwin,† Leon M. Lederman, and Marcel Weinrich

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

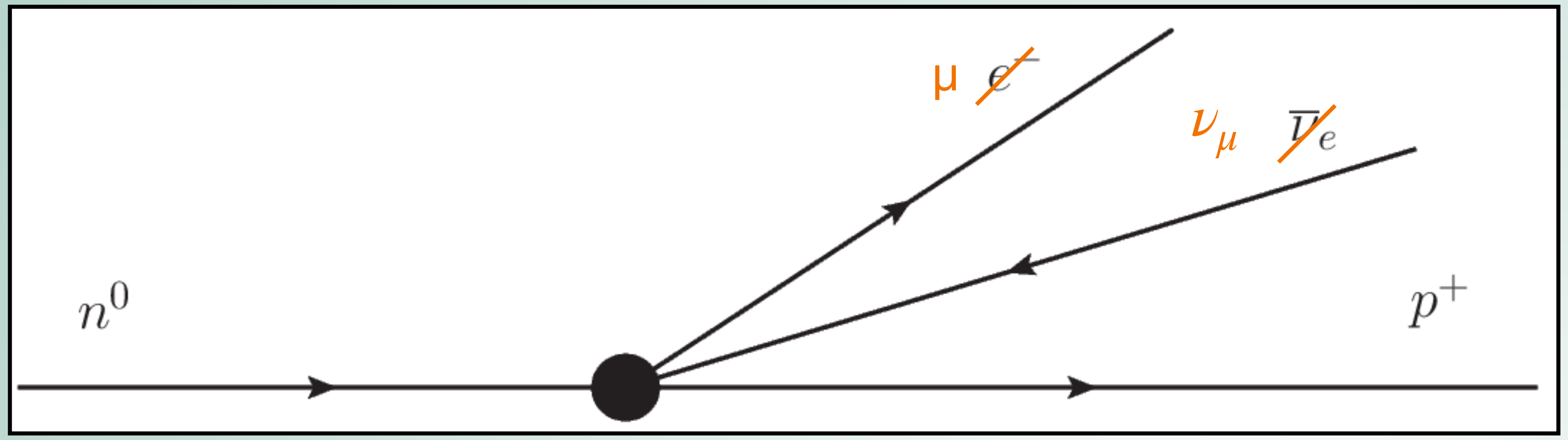


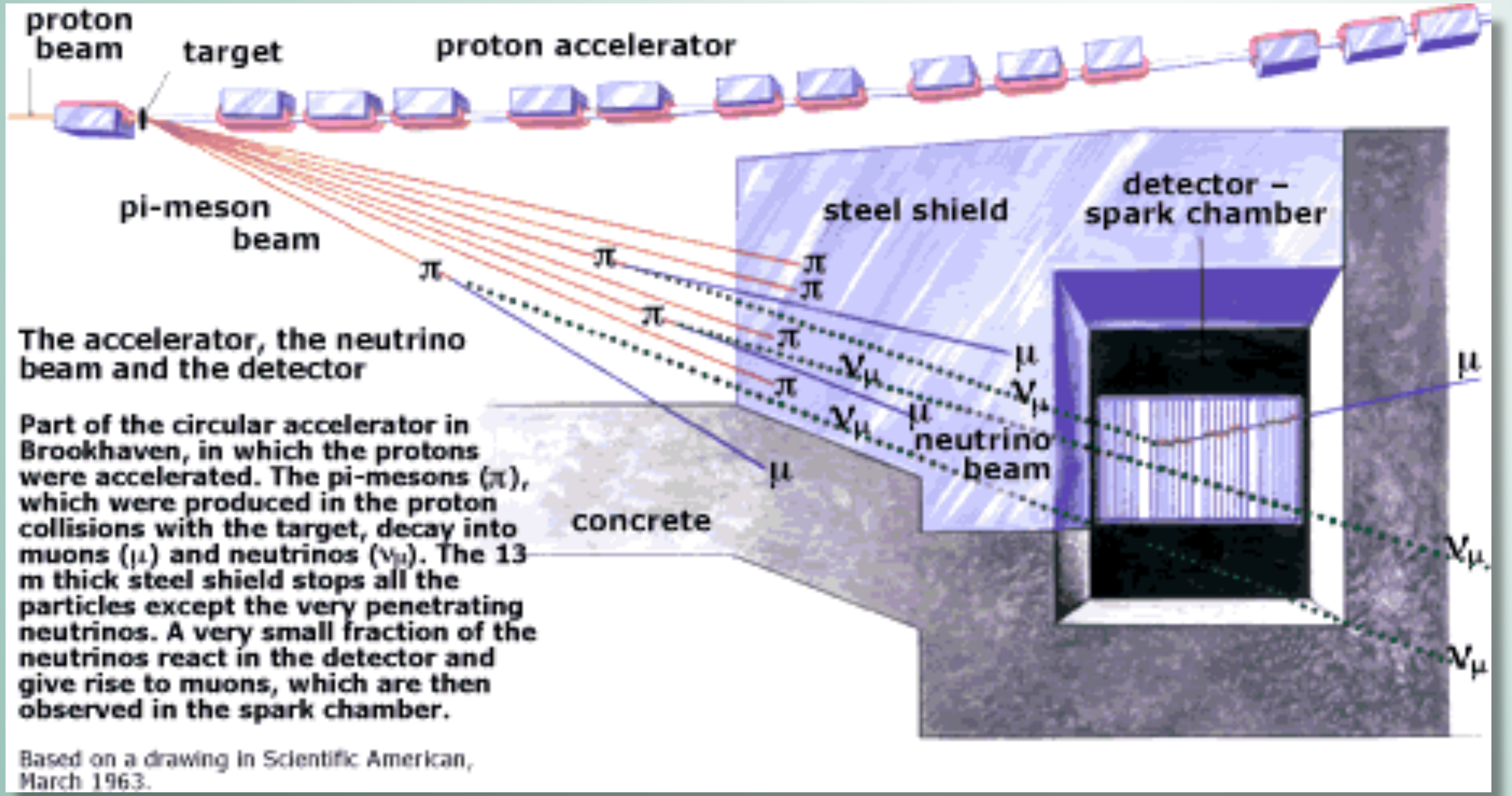
Images Courtesy Wikipedia

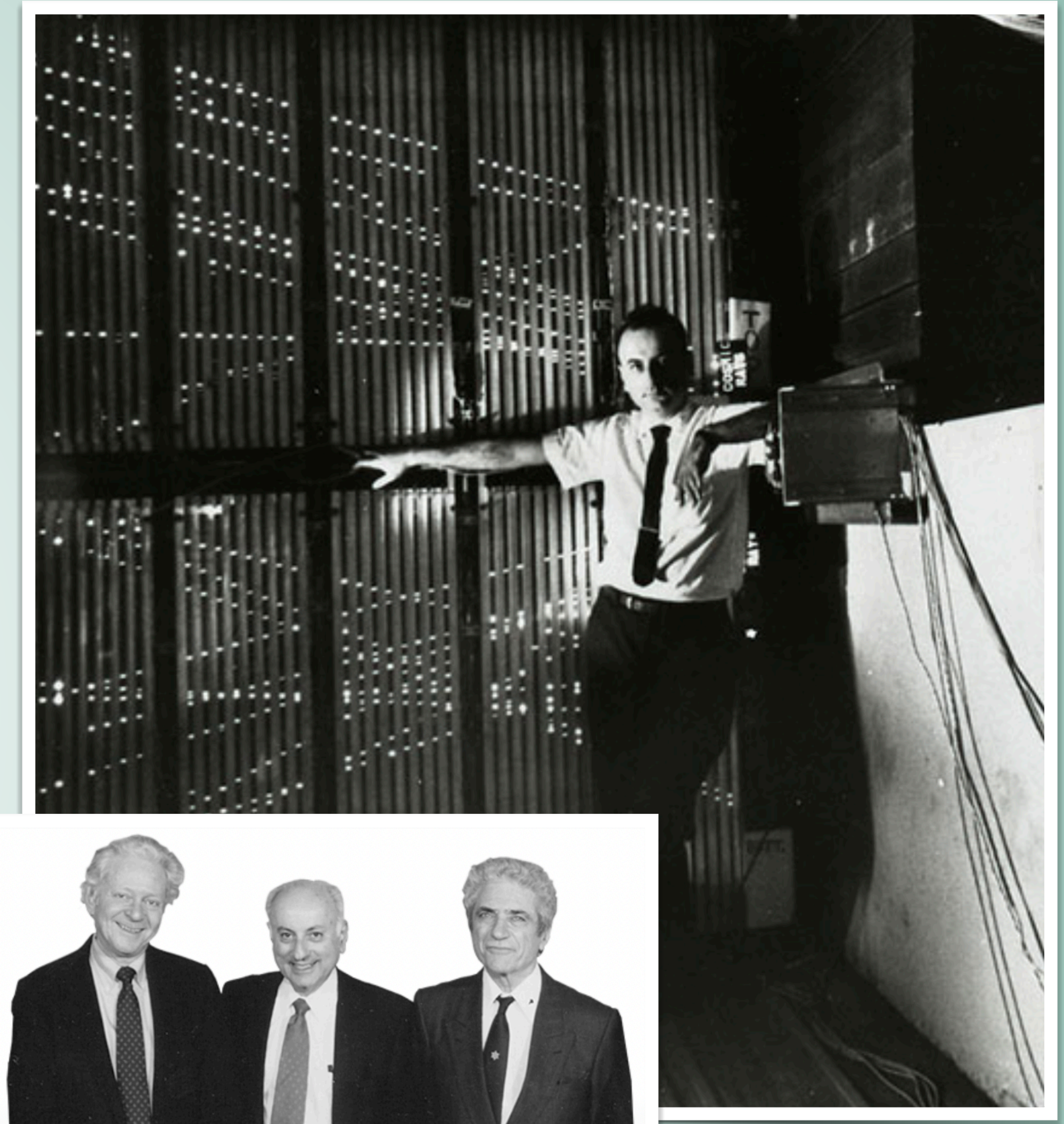


1962: Muon Neutrino Discovered

- New type of neutrino associated with muon

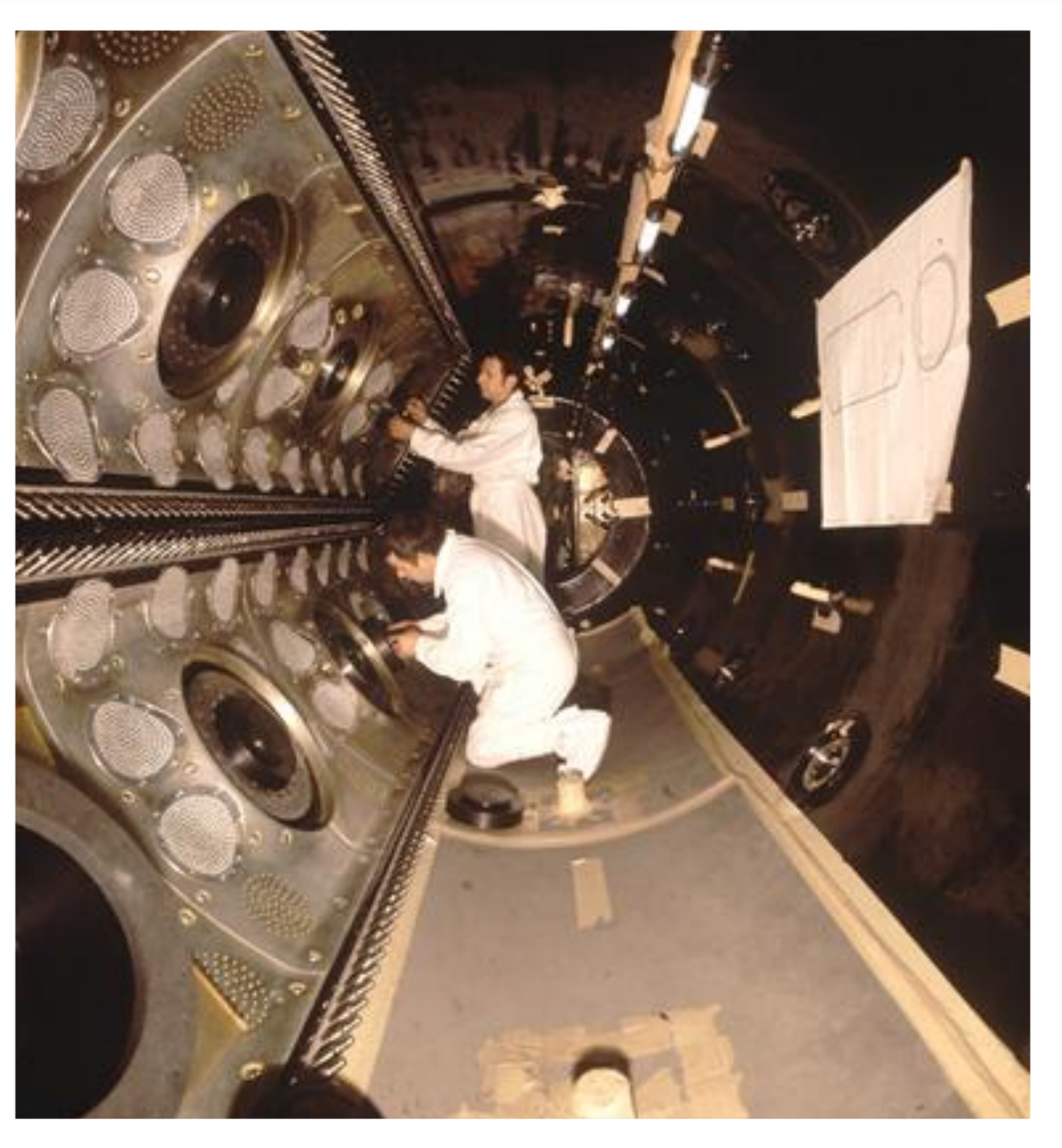






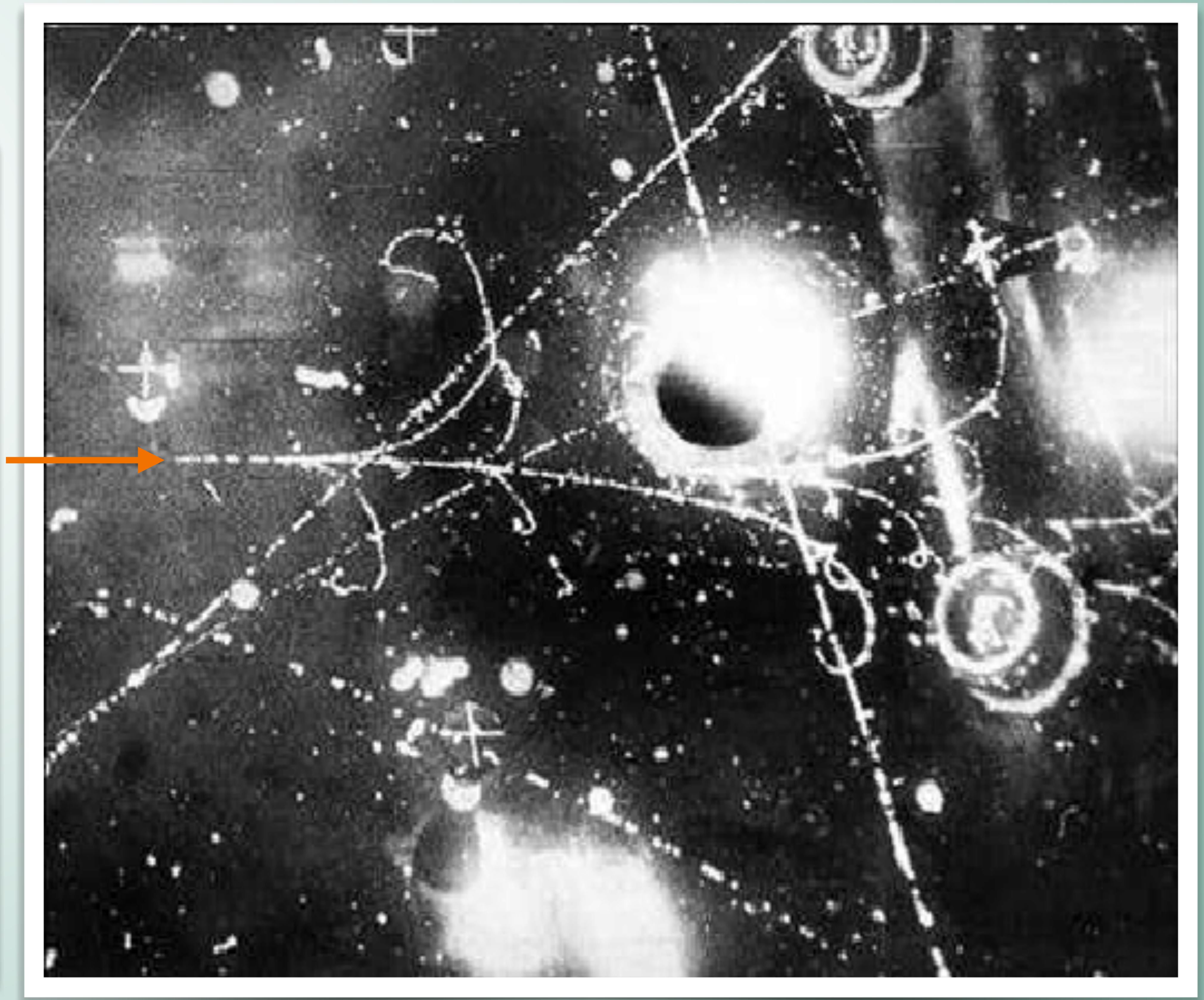
1970: Electroweak Model

- Late 1960's Electroweak Model developed by Glashow, Salam, Weinberg, Ward…
- 1973: Weak current discovery by Gargamelle experiment at CERN
- 1983: Z,W Bosons Discovered at CERN



Wikipedia

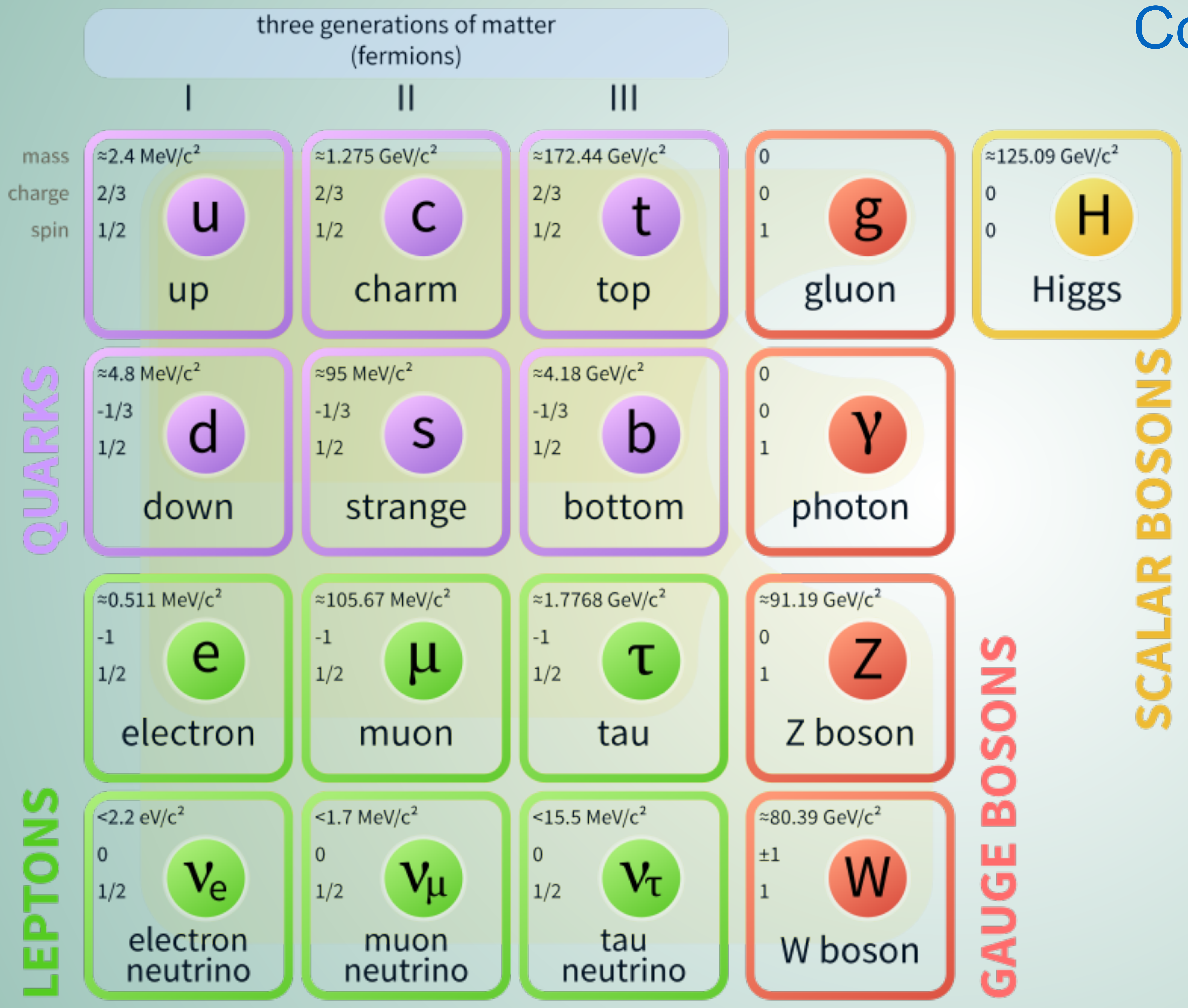
CERN



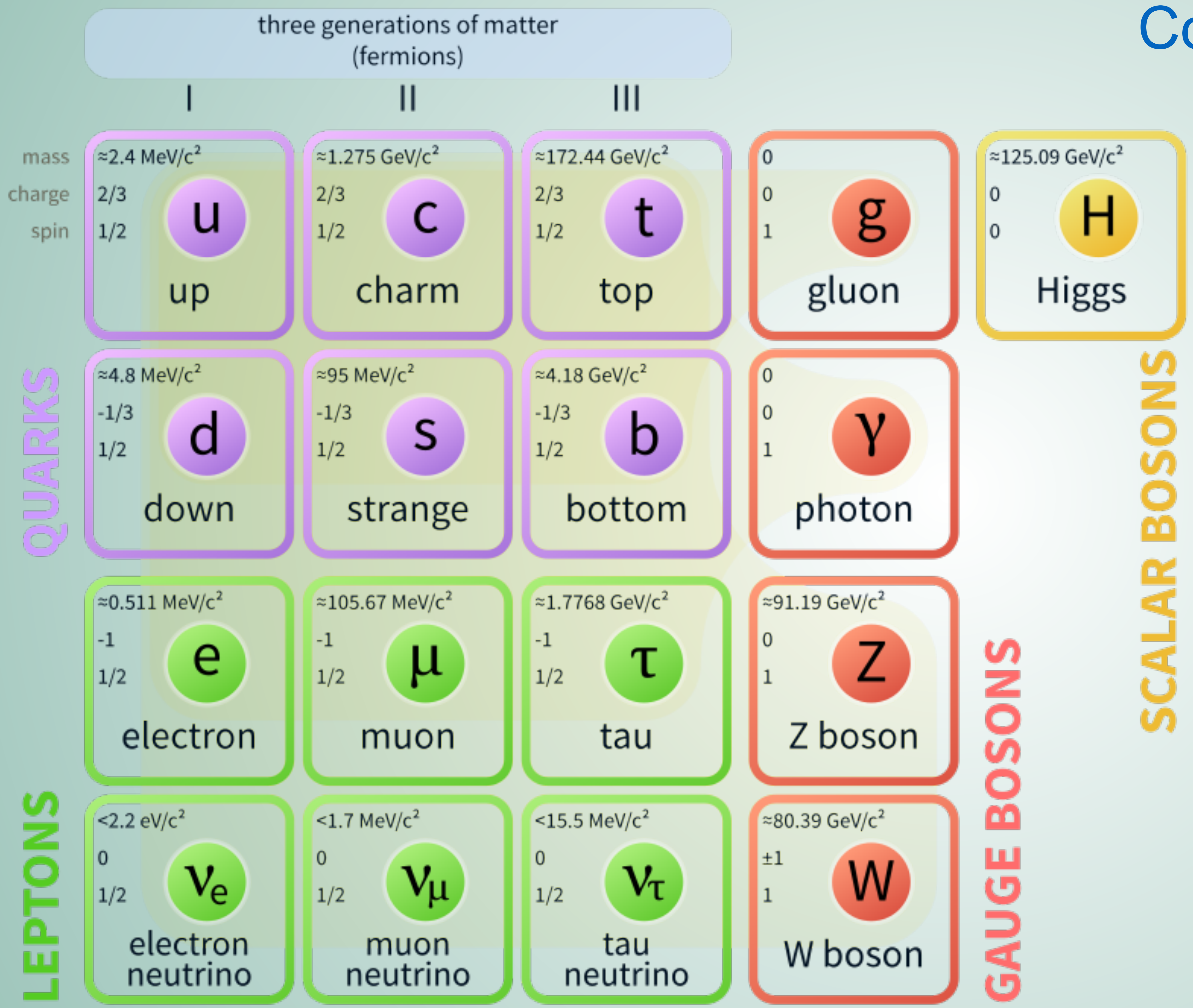
Duchesneau

Standard Model of Elementary Particles

Columns -> “Flavors”



Standard Model of Elementary Particles



Columns -> “Flavors”

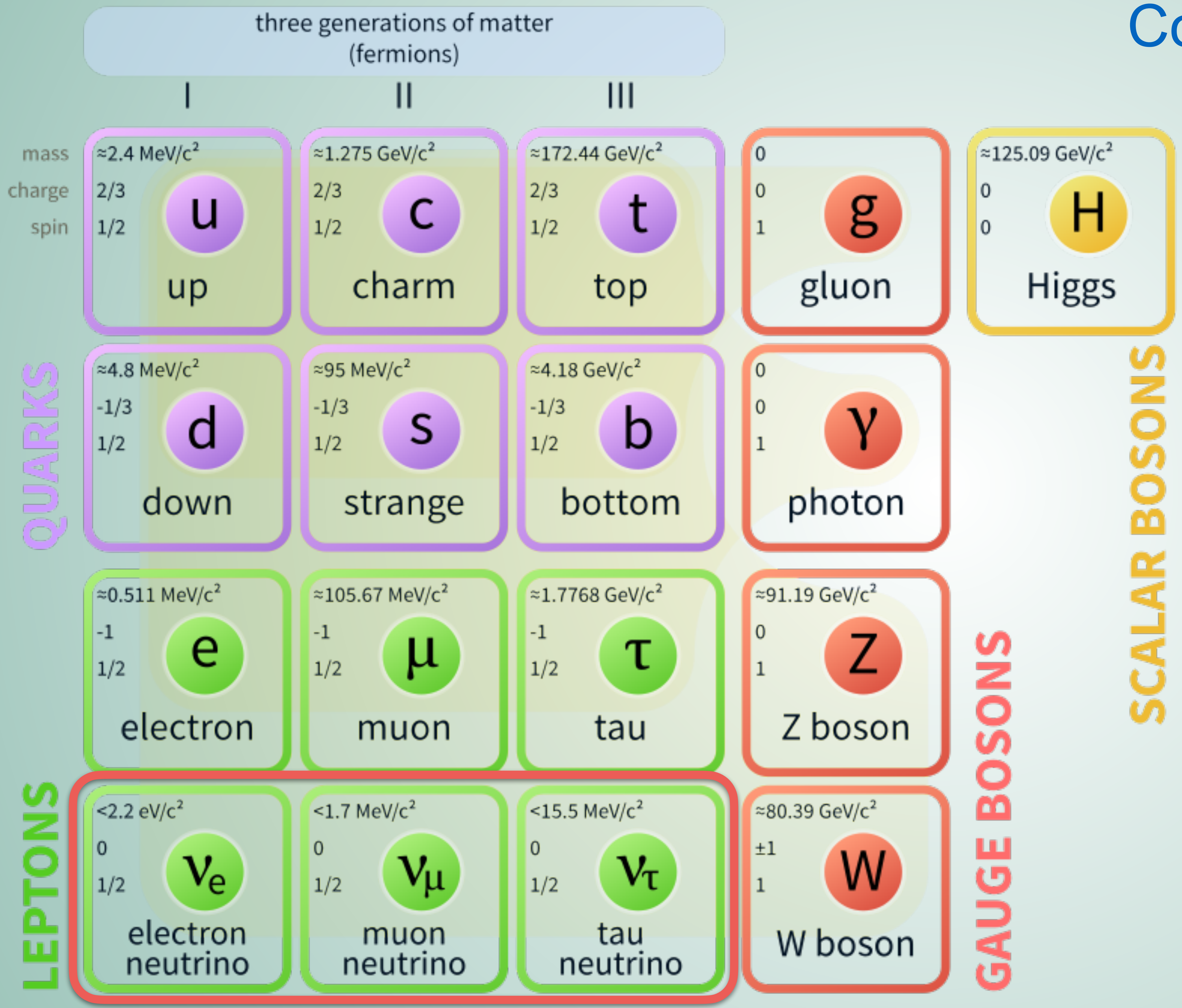
Force Carriers

Particle Physics “Force” is more than just push or pull

A Force can change a particle type

It describes how particles ***interact.***

Standard Model of Elementary Particles



Columns -> “Flavors”

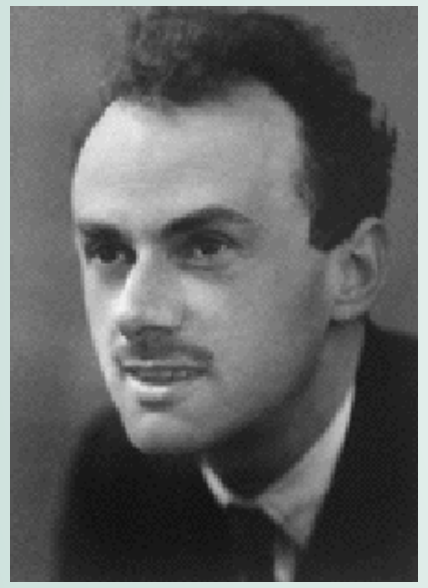
Blackboard Time

More about Majorana vs. Dirac

Note: Only valid if neutrinos are massive.

Lorentz Boost

ν_L $\overline{\nu_R}$



ν_R $\overline{\nu_L}$

CPT

$\nu \neq \overline{\nu}$

CPT

Lorentz Boost

ν_R^M

ν_L^M

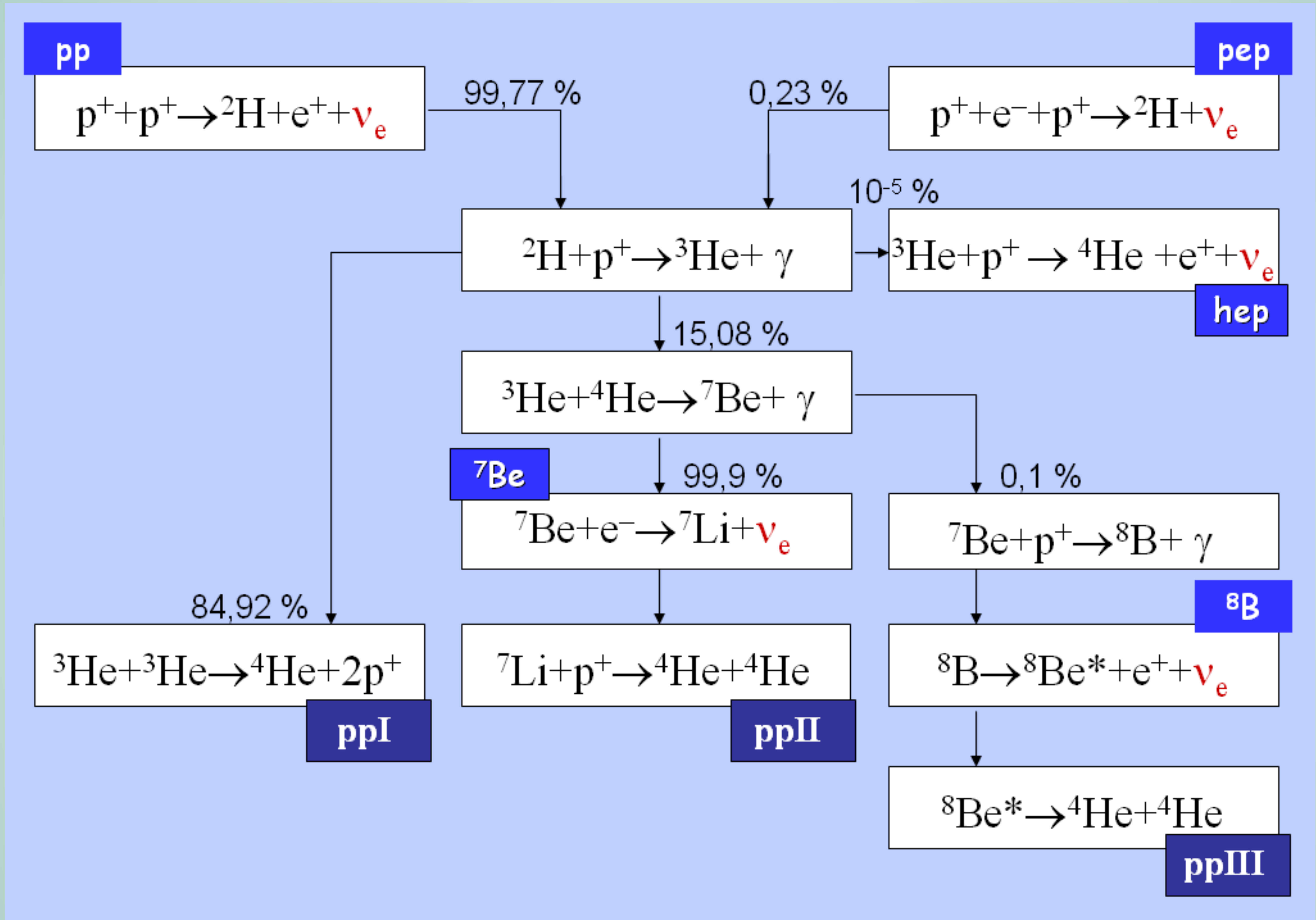
CPT

$\nu = \overline{\nu} = \nu^M$

Original argument by Kayser, 1985

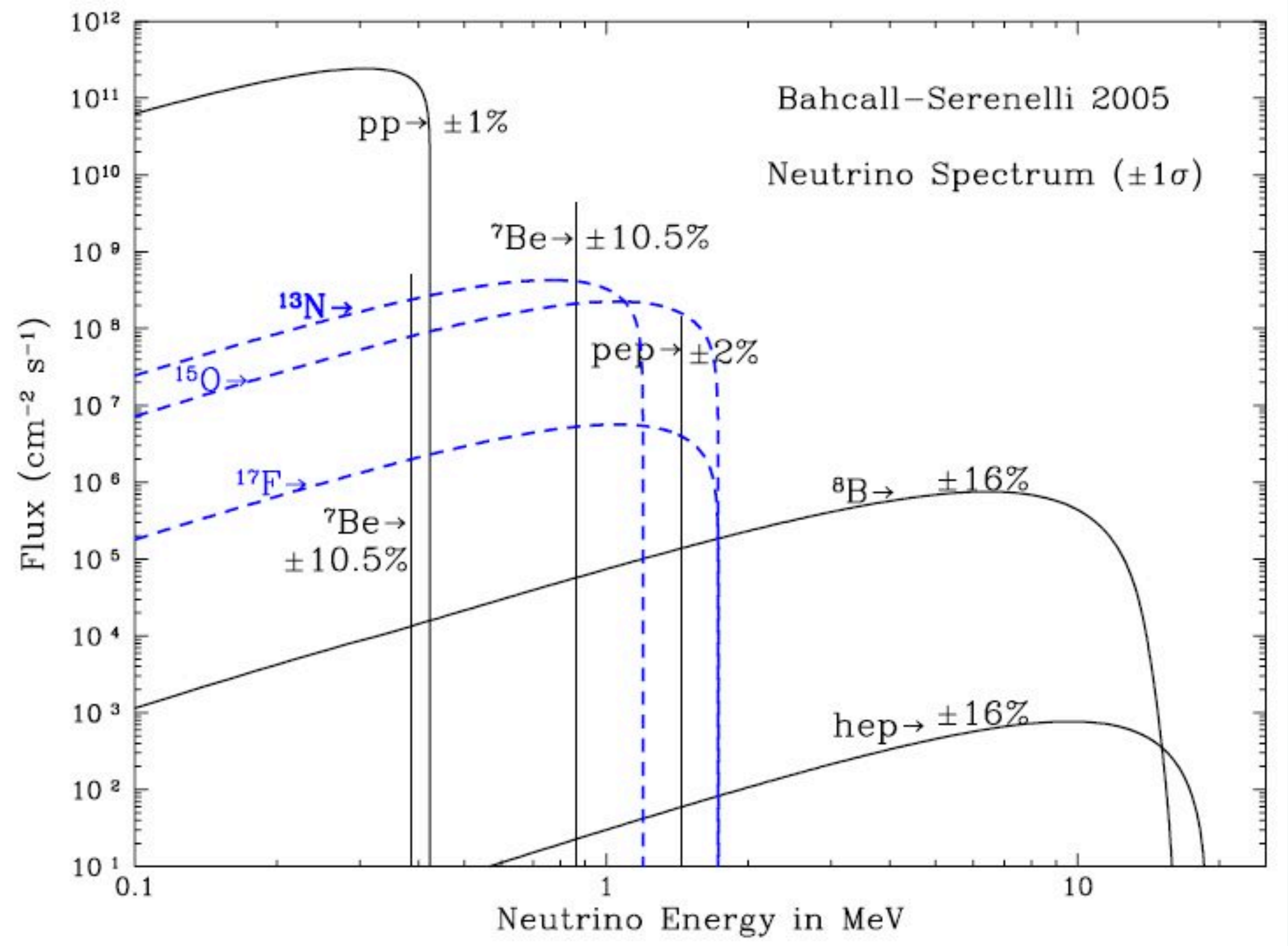
4: Strange Case of Missing Neutrinos

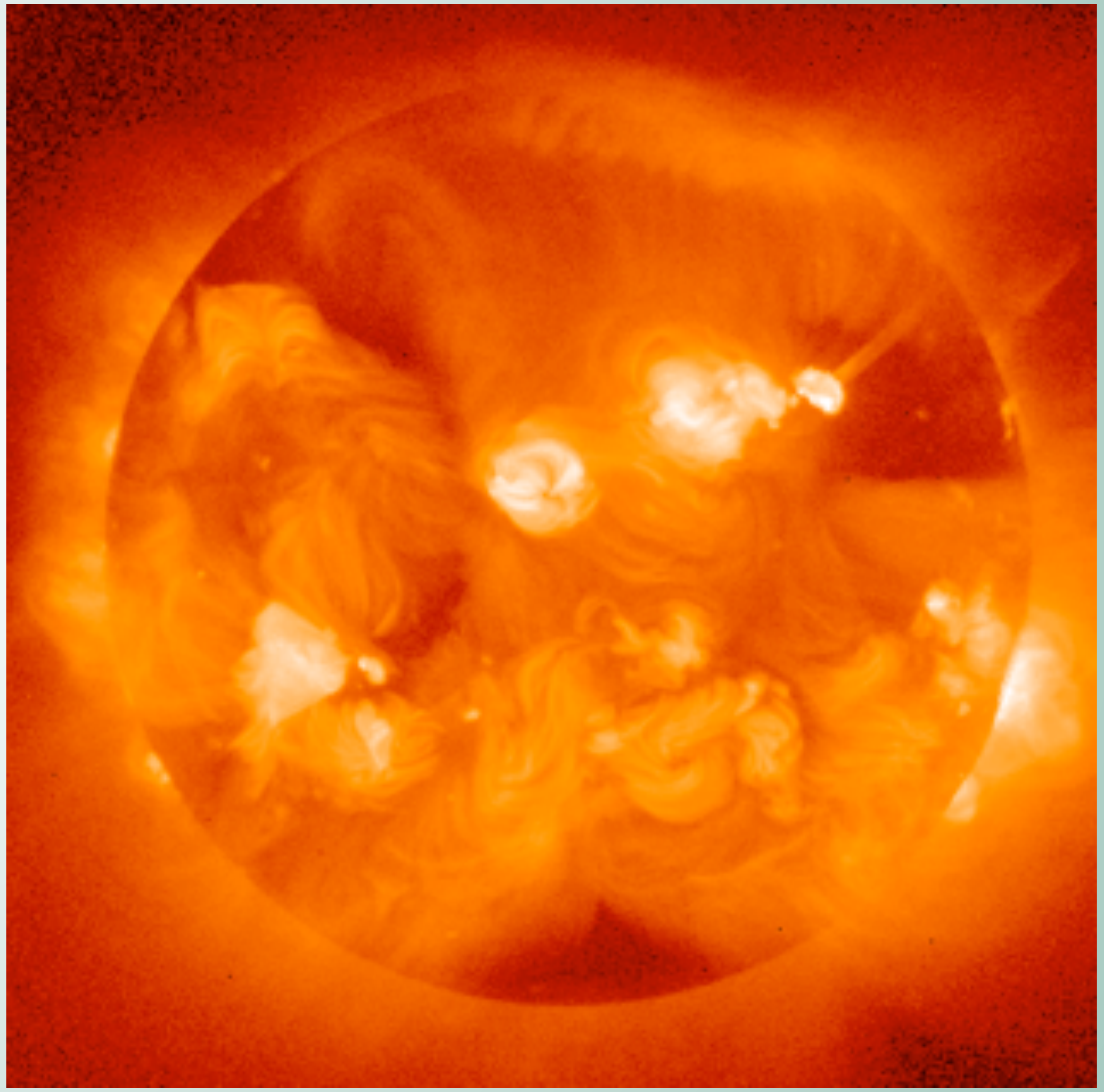
Segue: Neutrinos from the Sun



CNO Cycle contributes as well

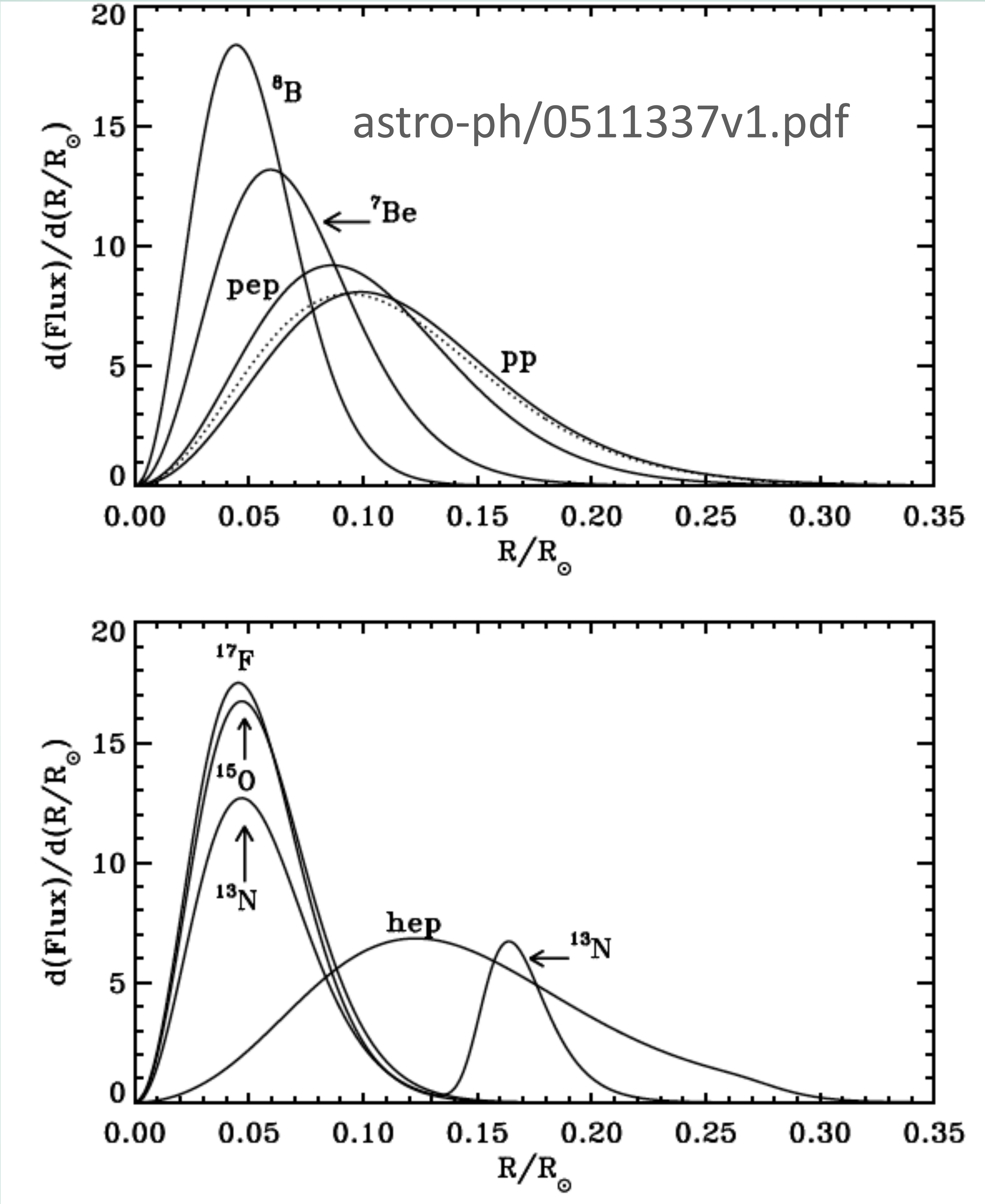
Solar Neutrino Flux



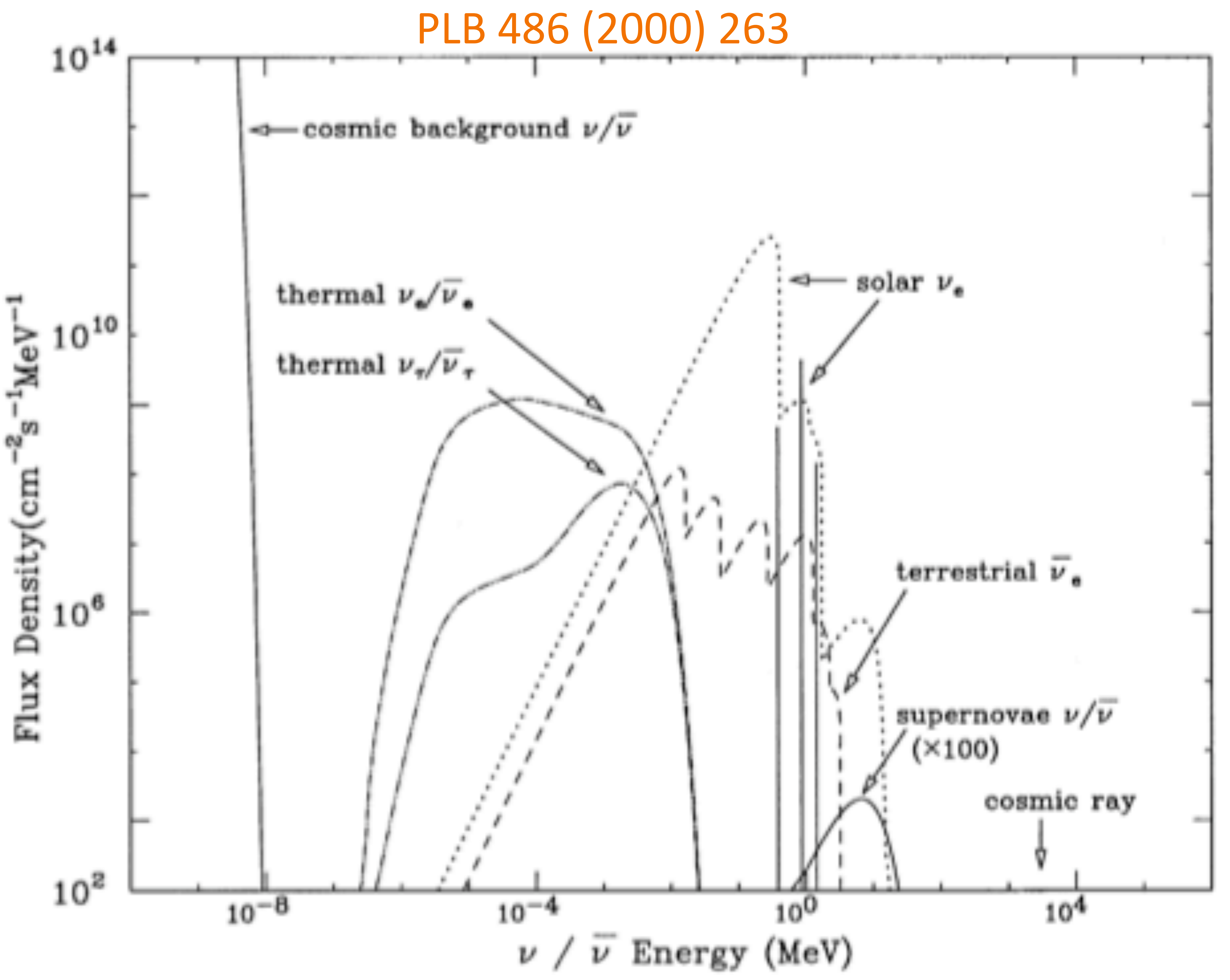


Production Location

Can Probe Core of Sun!



Low energy solar neutrinos
Produced by plasma interactions



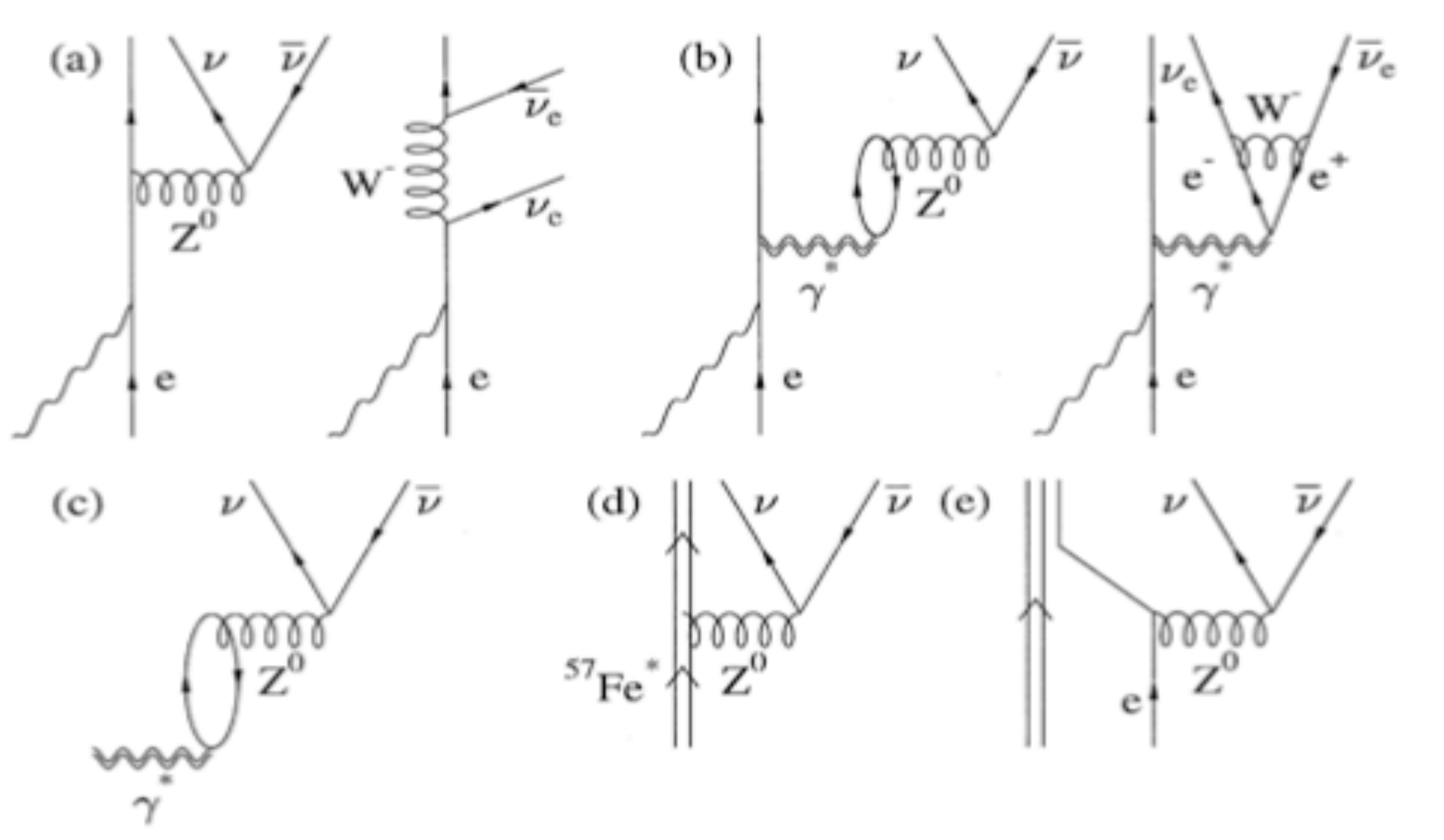
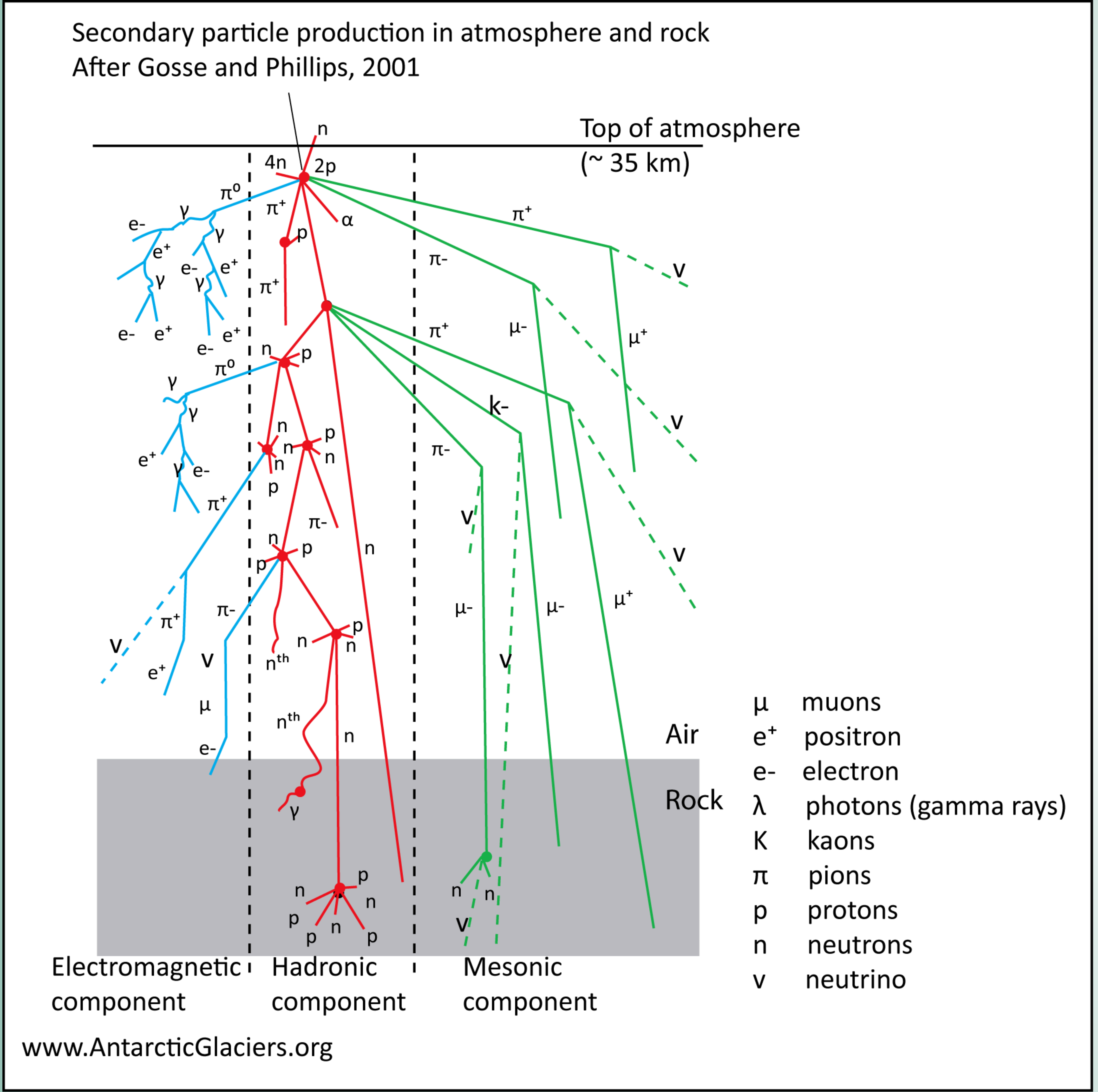
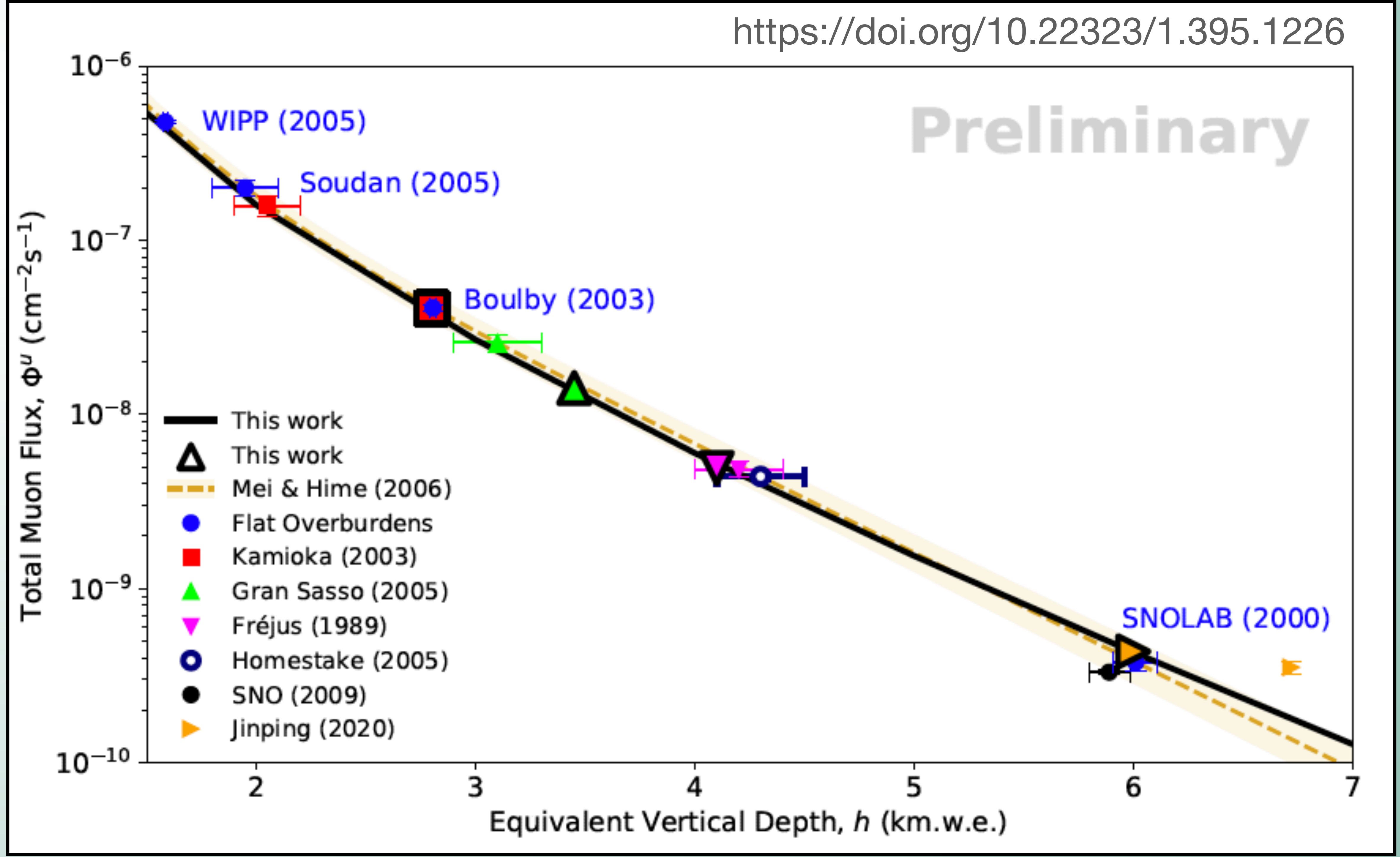


Fig. 1. Representative diagrams for the various thermal neutrino pair processes considered here: a) Compton process; b) plasmon pole contribution to the Compton process; c) transverse plasmon decay; d) nuclear Z^0 emission; and e) pair production in free-bound atomic transitions.

Why do physics underground?

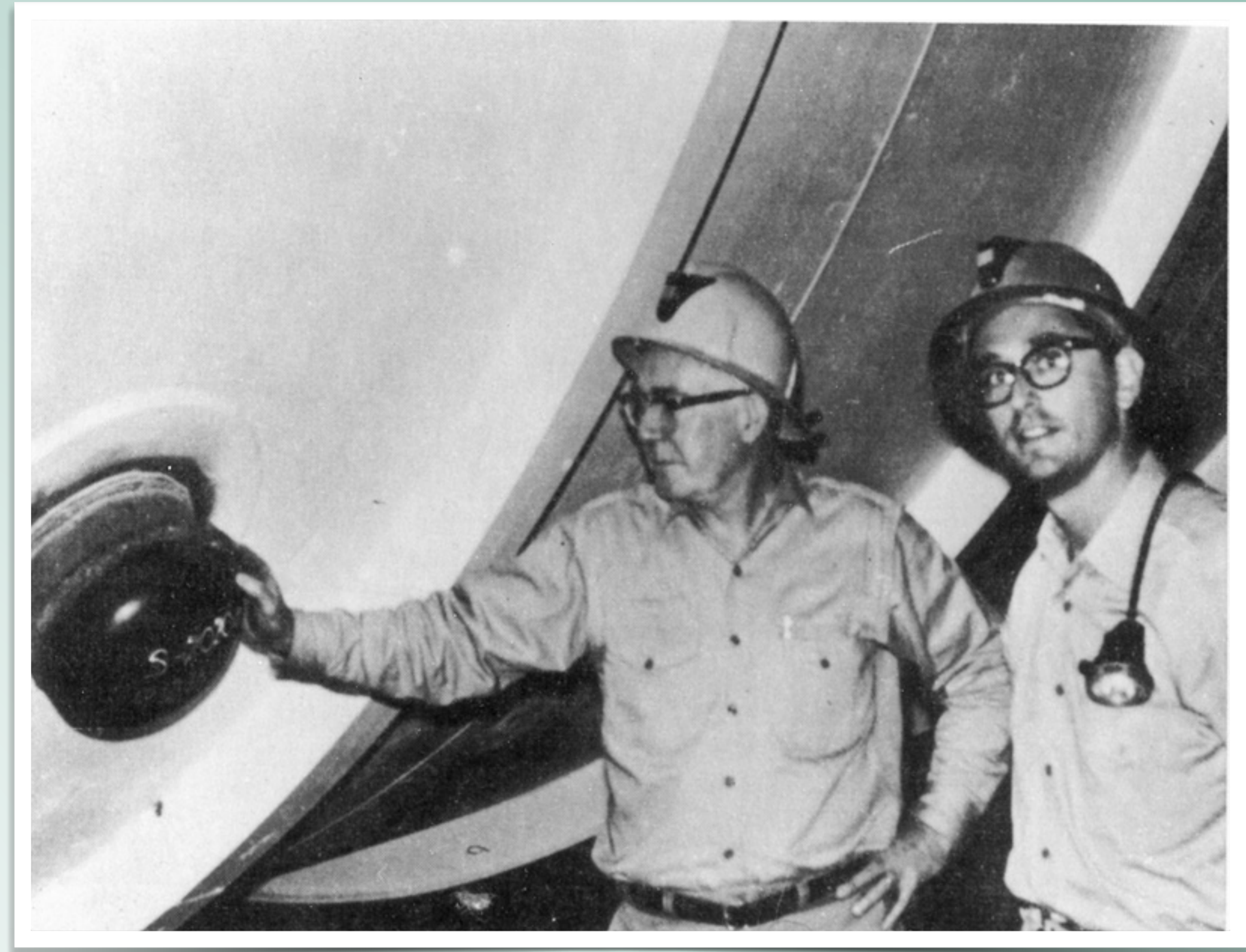


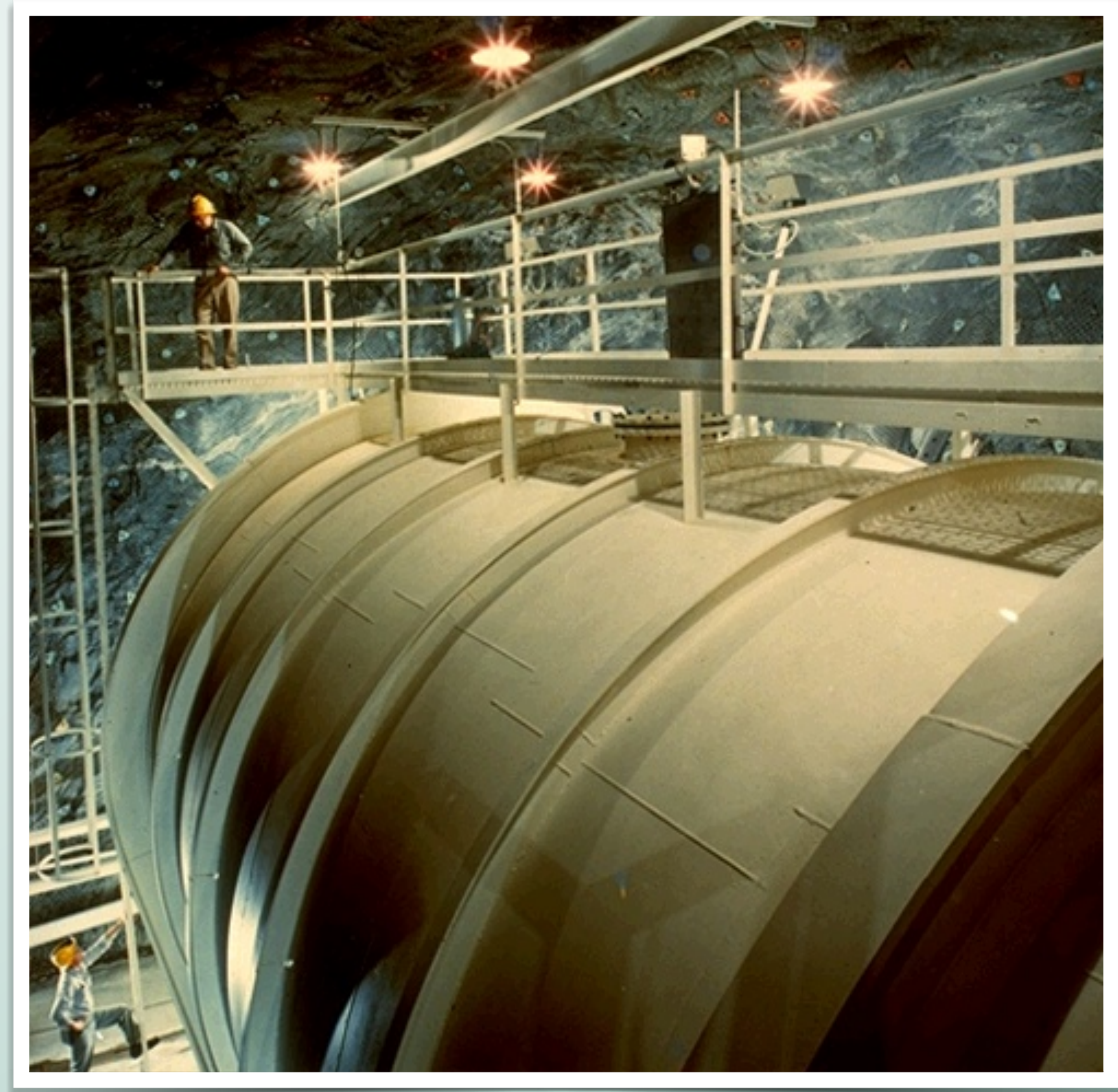
To escape from cosmic-rays that can travel through miles of rock.



Ray Davis Experiment

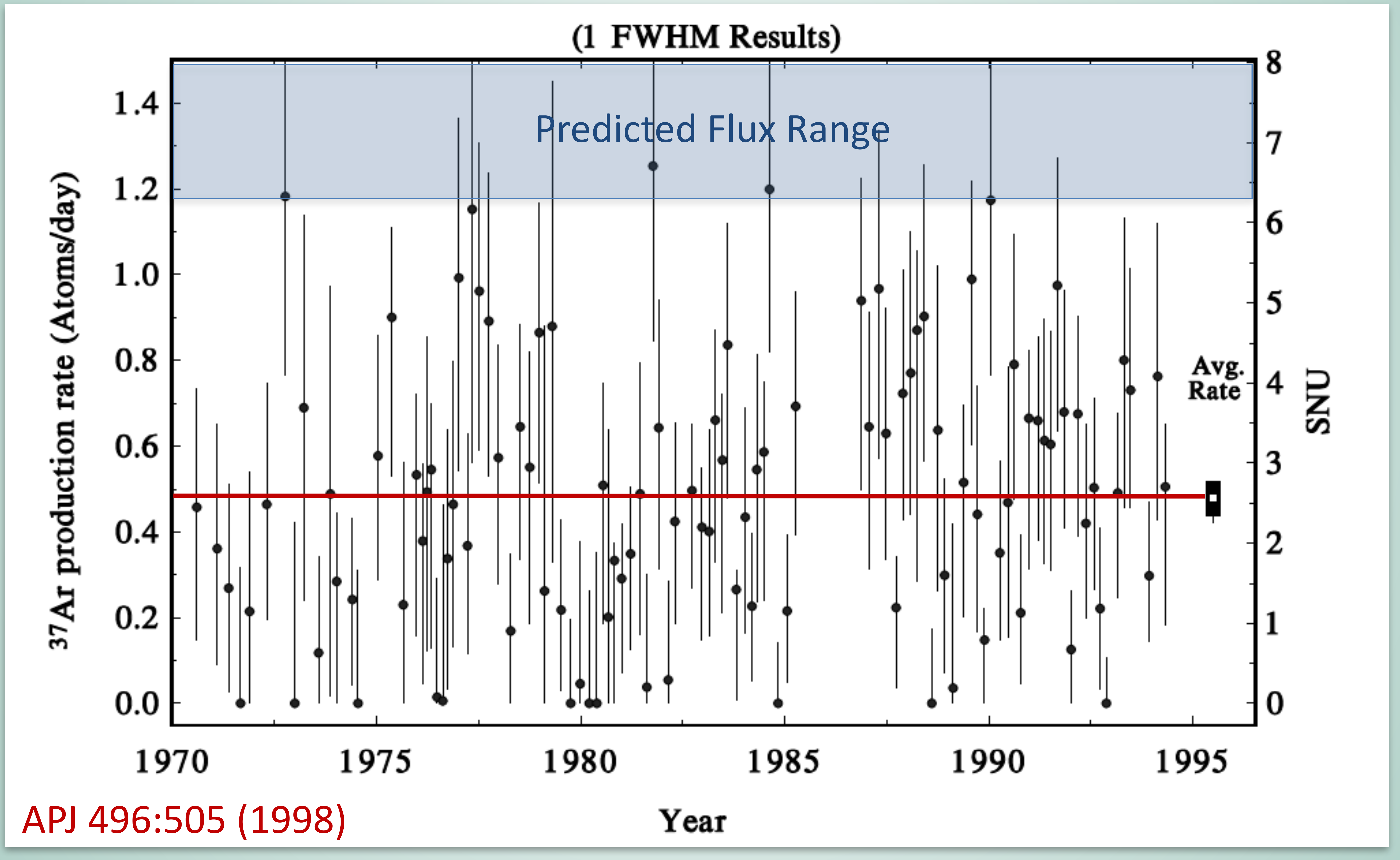
- $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$
- E_{th} = 0.814 MeV (no pp)
- 615 t of C_2Cl_4
- Flush tank, look for ^{37}Ar decay
- Only 0.5 atoms of ^{37}Ar per day!
- **Sensitive to ν_e flavor only**





Davis experiment results

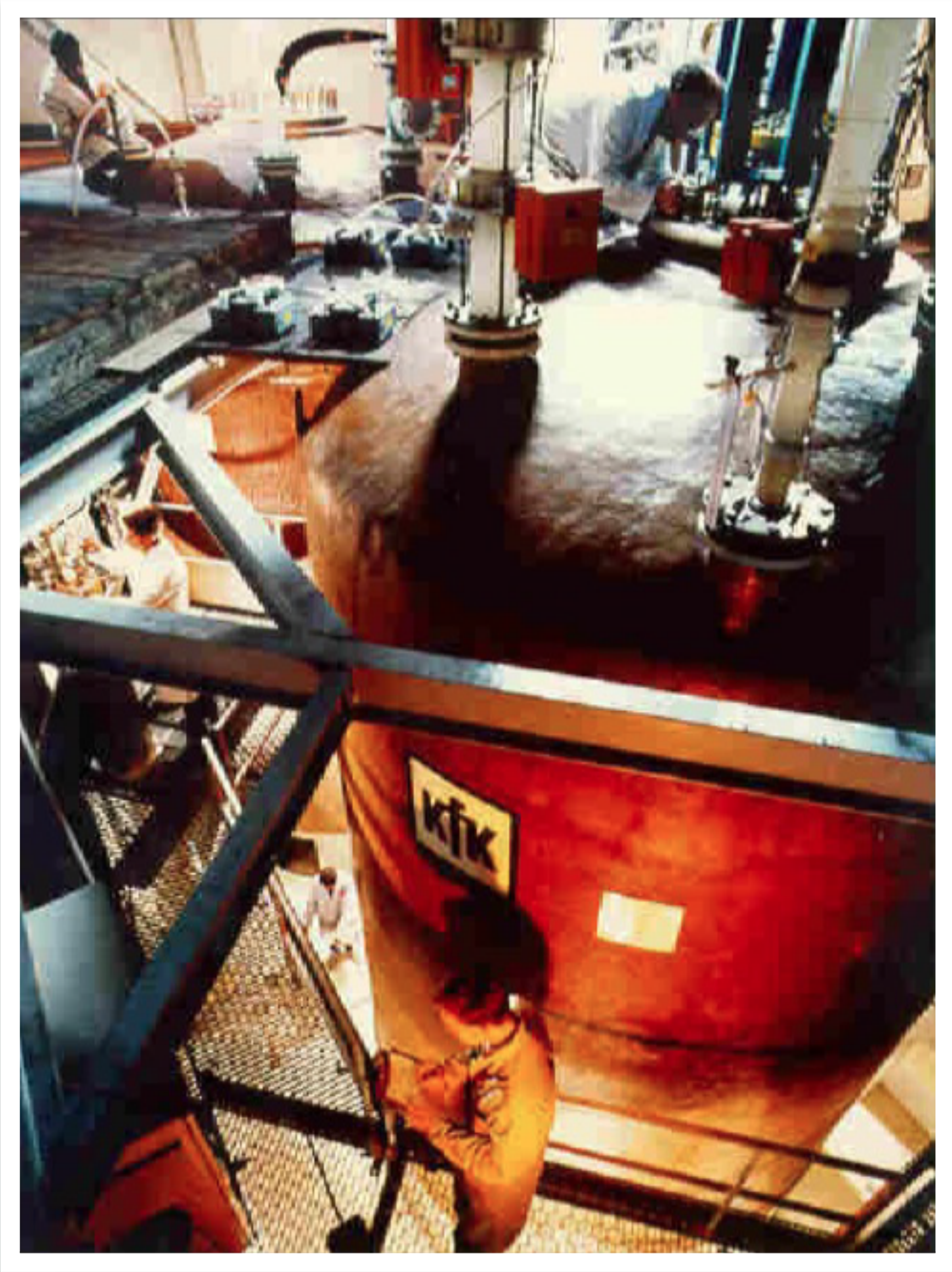
Only 1/3 of expected flux!



SAGE/GALLEX

- $\nu_e + {}^{71}Ga \rightarrow {}^{17}Ge + e^-$
- E_{th} = 0.233 MeV
- **Sensitive to pp neutrinos**
- SAGE: 60t metallic Ga
- GALLEX/GNO 30t $GaCl_3$-HCl
- Measured 70 SNU, expected 130 SNU
- Experiments disagreed initially. Resolved with source calibration (more later)

SAGE/Gran Sasso



GNO/
GALLEX
Baksan

^{51}Cr Electron Capture Sources

GALLEX: 1.5 Mci; 1 ton

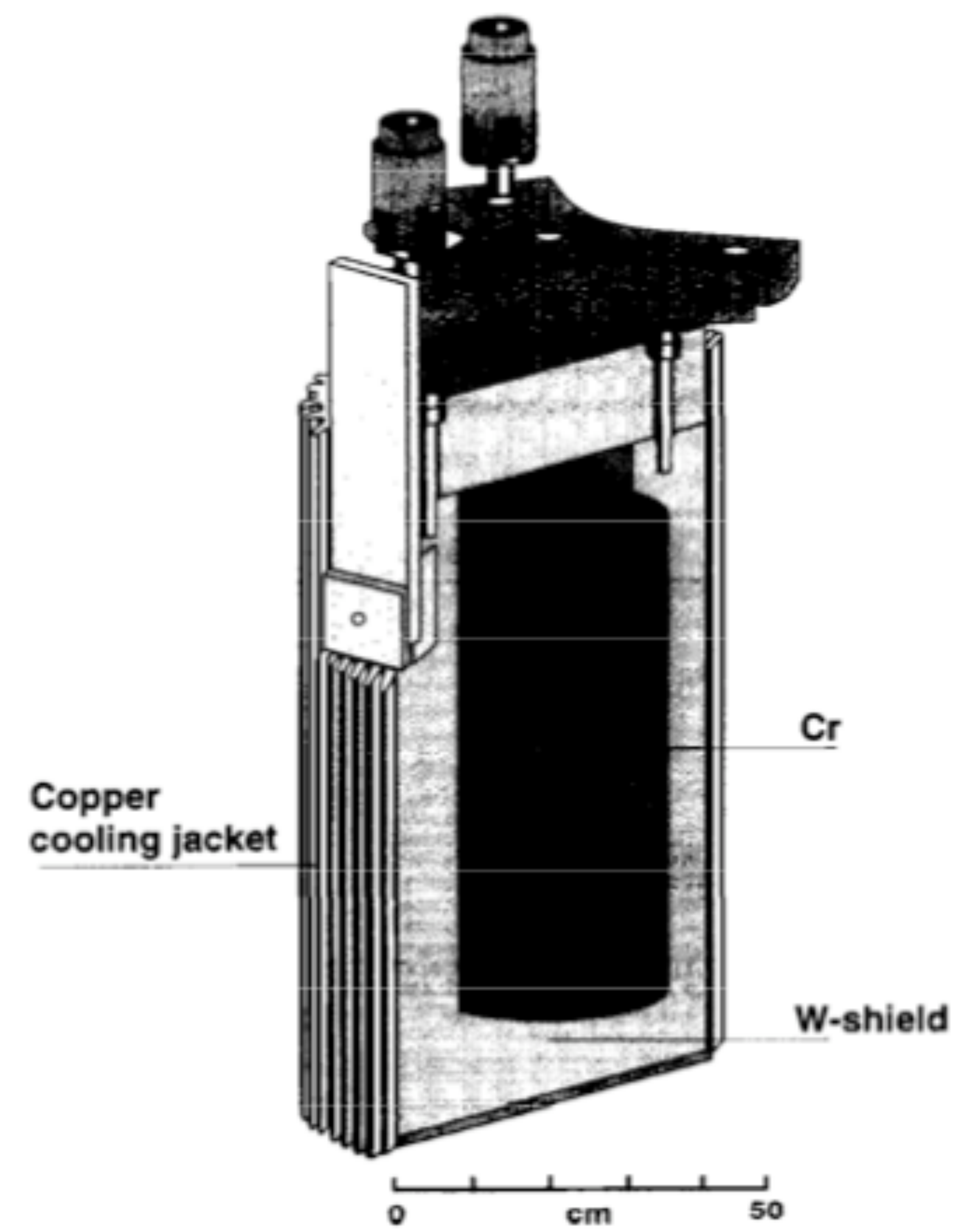


Fig. 11. Schematic drawing of the Cr-source inside the W-shield.

SAGE: 0.6 MCi

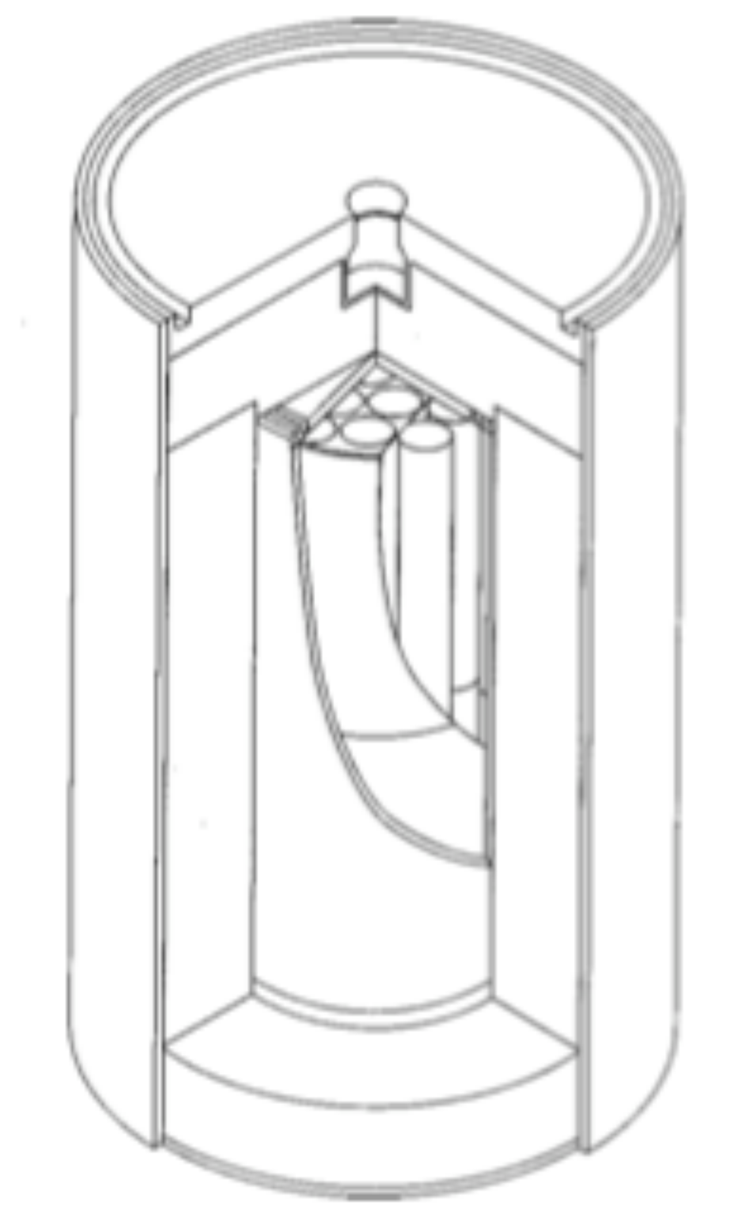
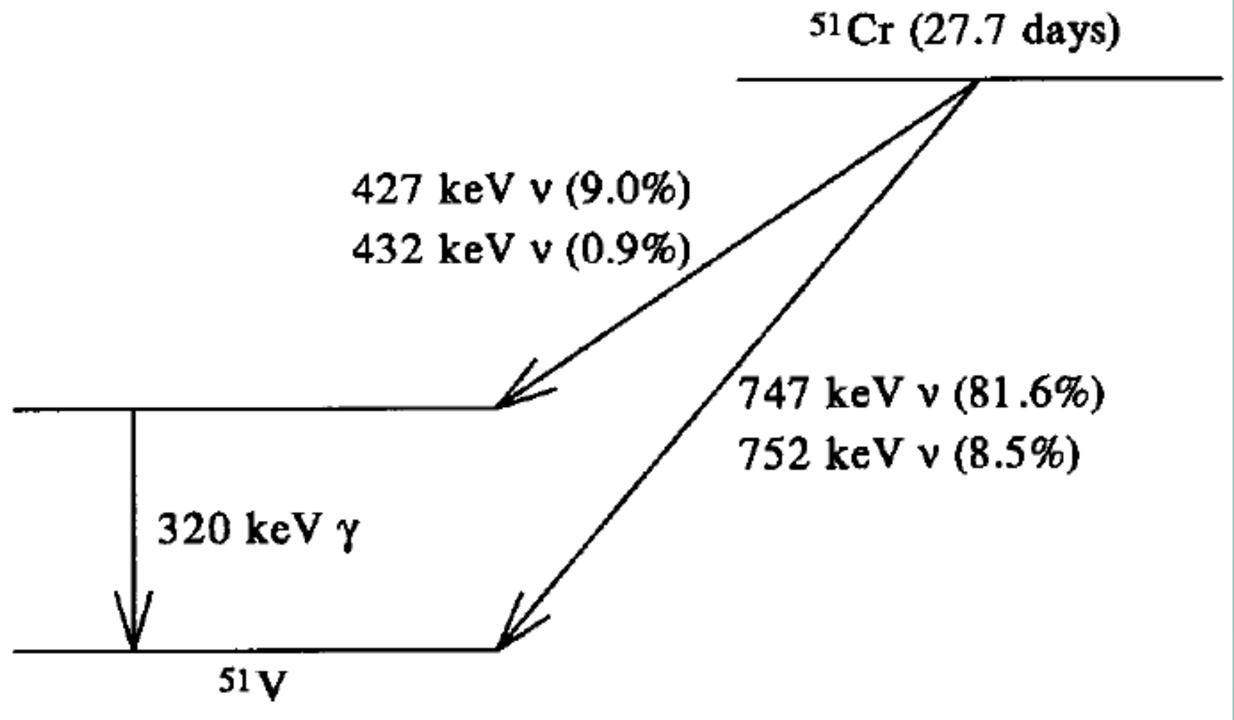


FIG. 4. Cutaway drawing of the source. The Cr rods were placed within the inner cylinders.

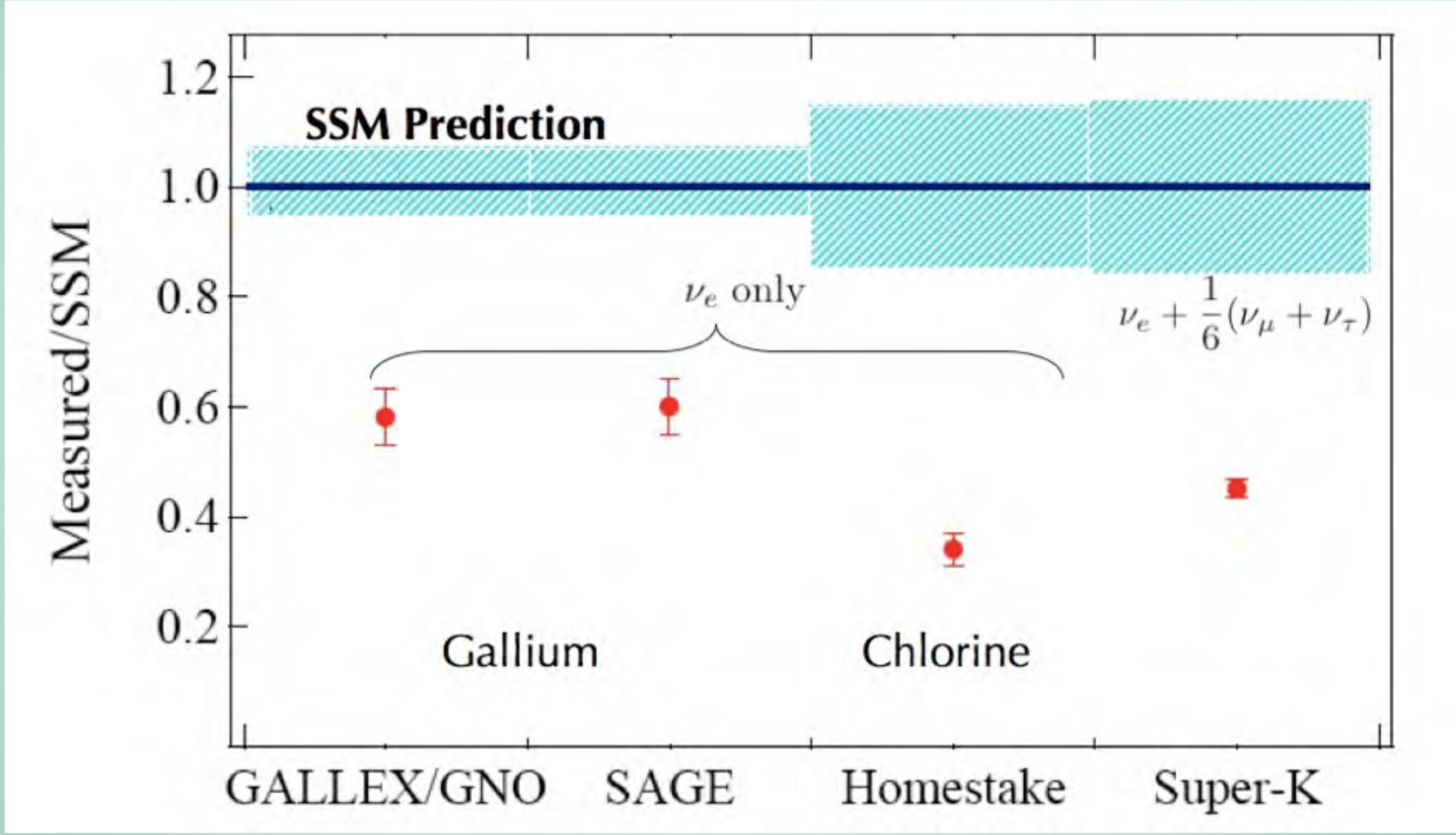
$$e^- + p \rightarrow n + \nu_e$$



Decay scheme of ^{51}Cr to ^{51}V through electron capture.

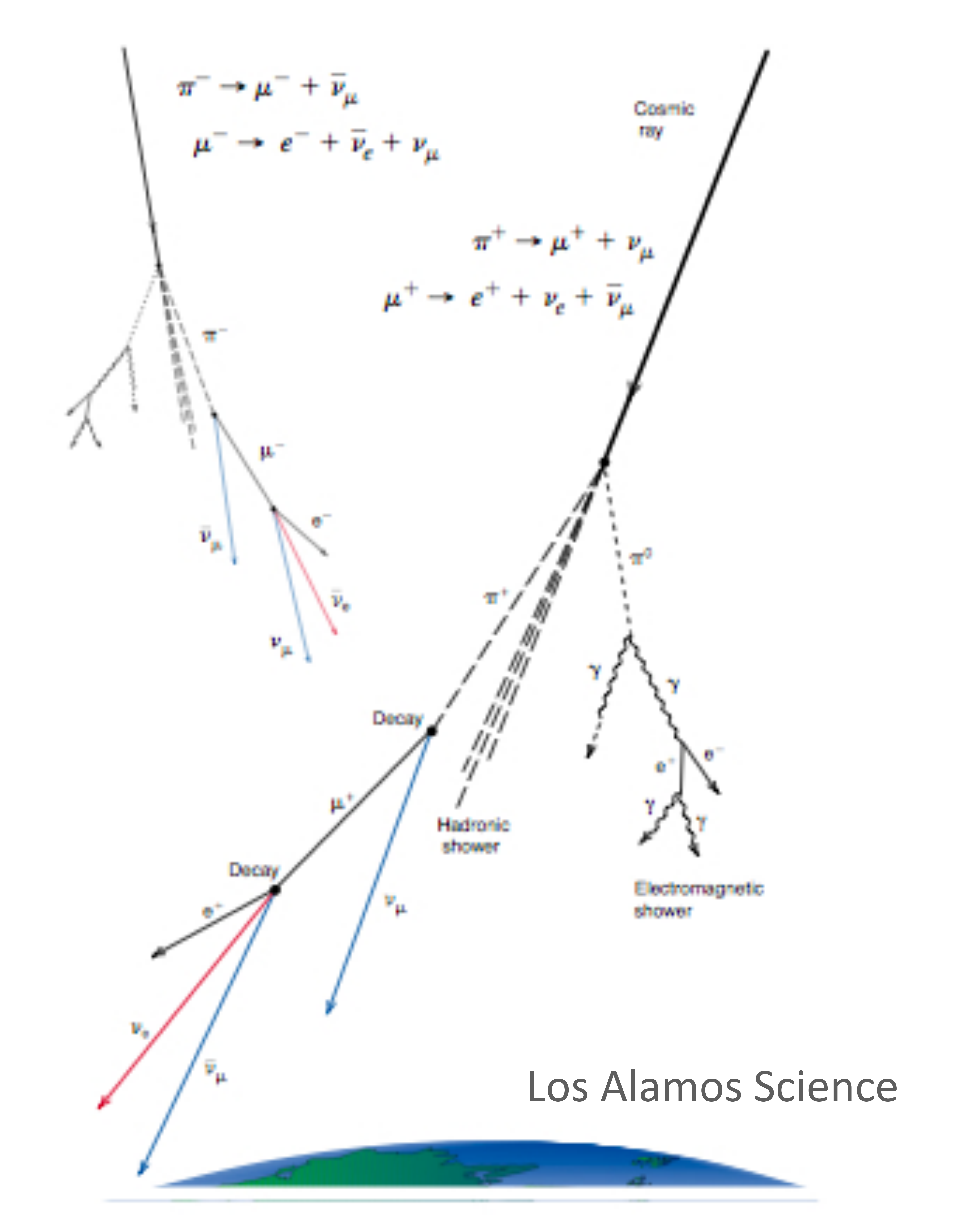
Gallex ^{51}Cr Source

The Solar Neutrino Problem ~2000

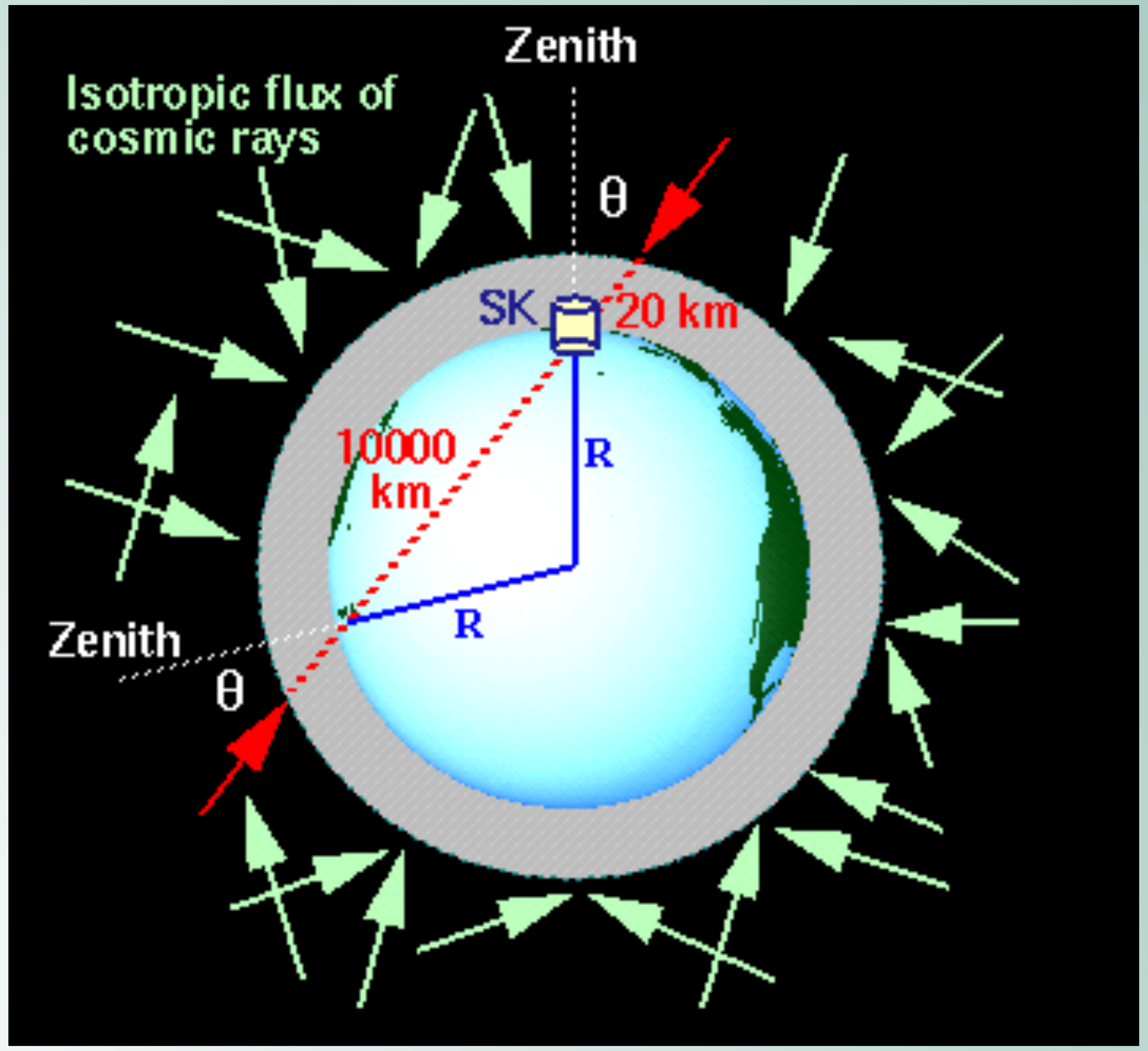


A. Poon

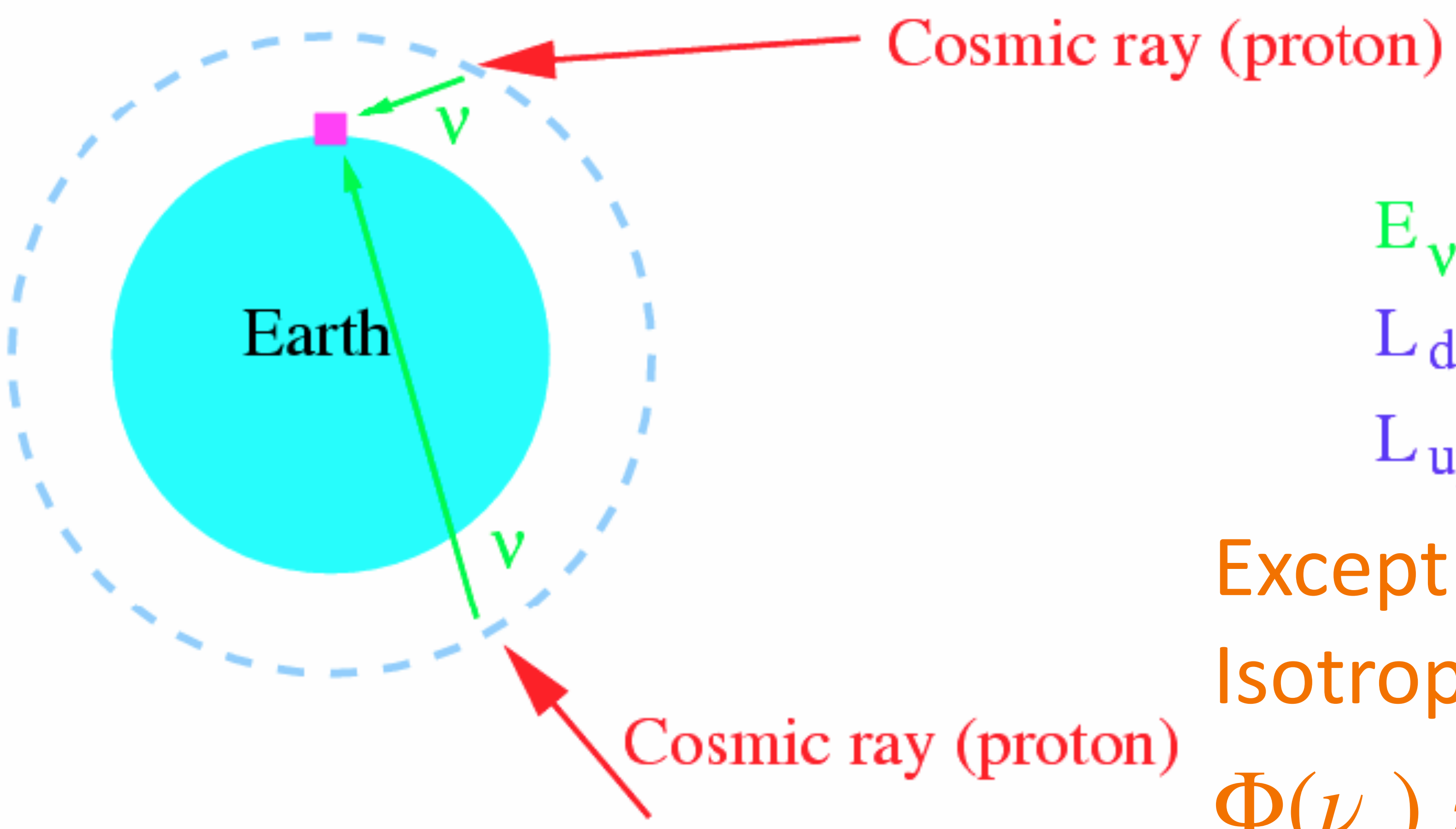
Atmospheric Neutrino Anomaly



Los Alamos Science



http://hep.bu.edu/~superk/atmnu/



$E_\nu \sim 0.5 - 5$ GeV

$L_{down} \sim 100$ km

$L_{up} \sim 10{,}000$ km

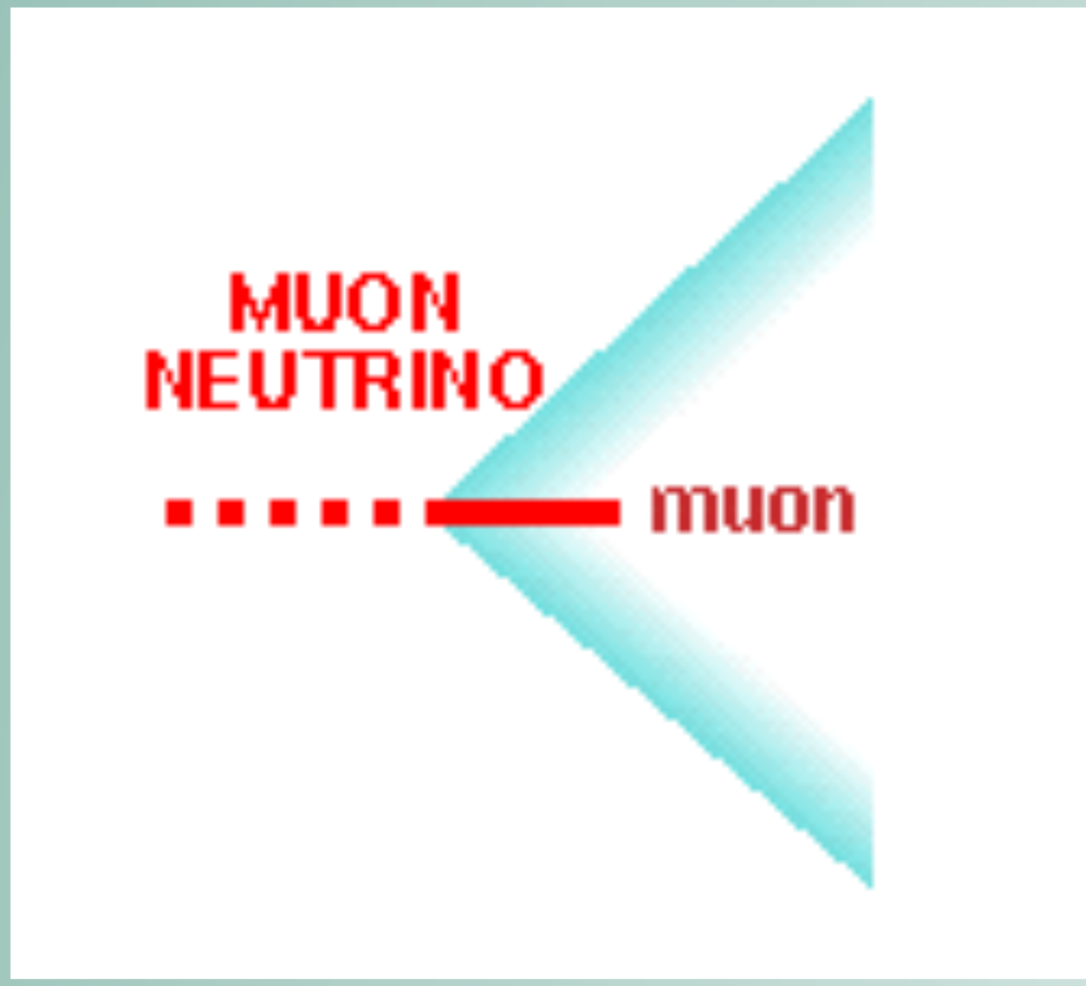
Except:

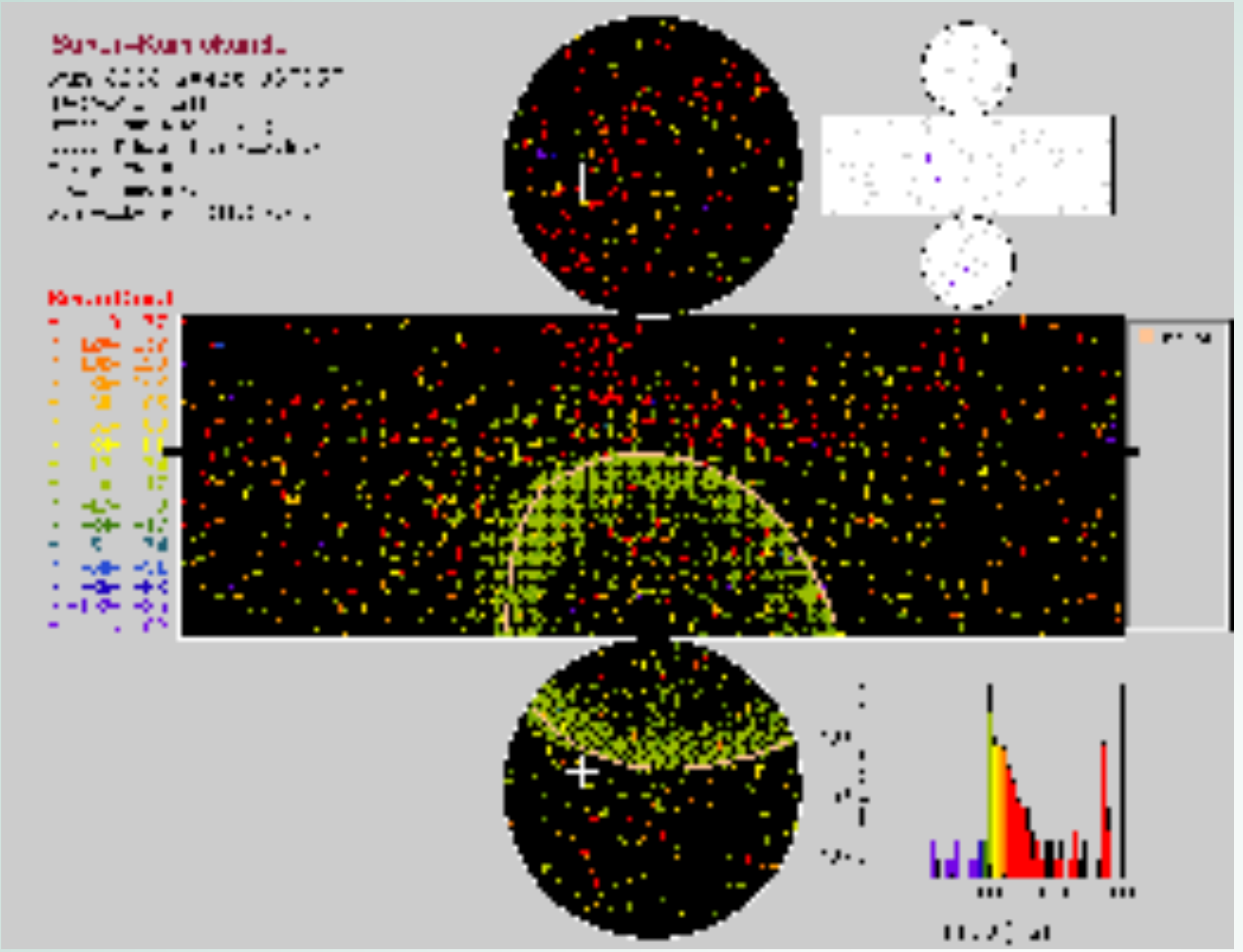
Isotropic Flux of ν_μ

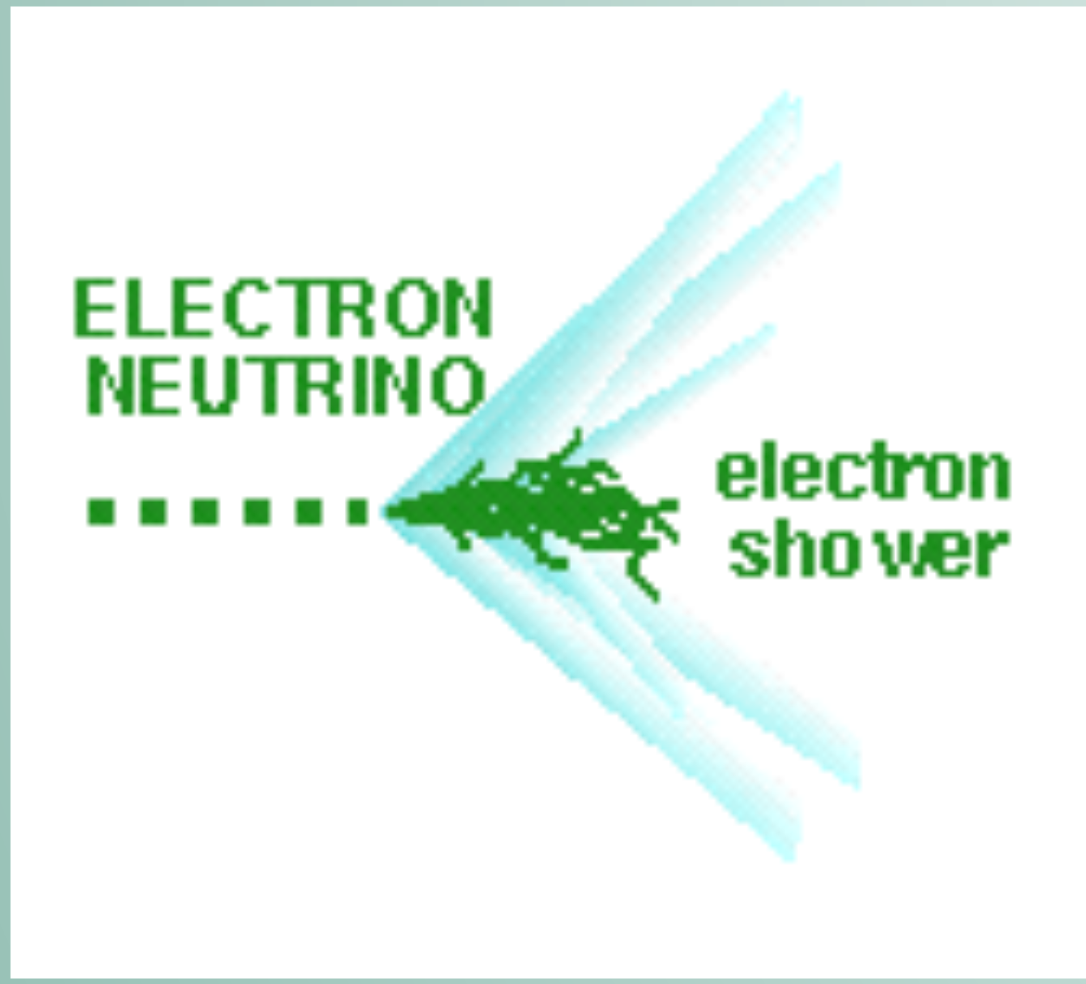
$\Phi(\nu_e) \approx \Phi(\nu_\mu)$

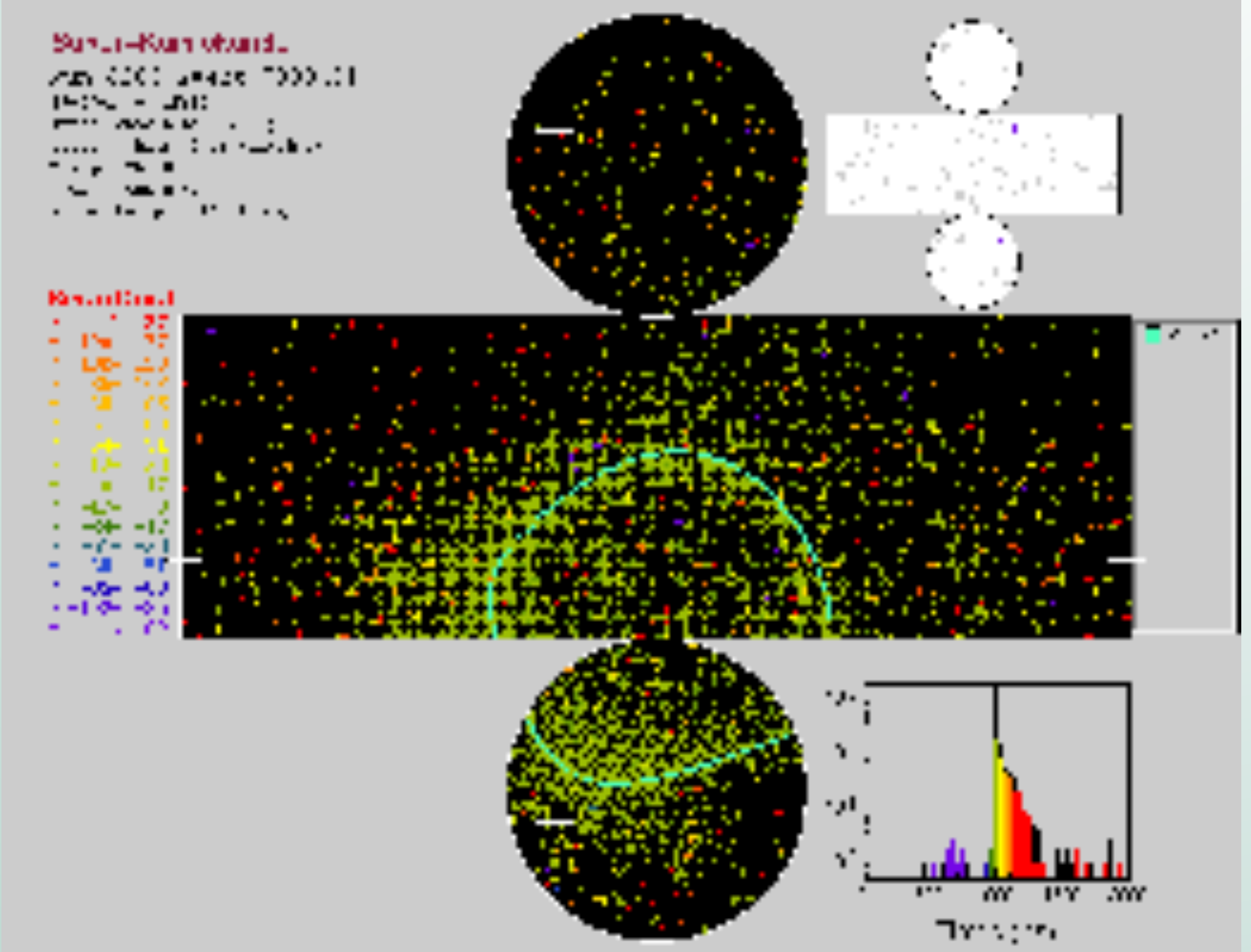
Water Cerenkov Detectors
Particle ID

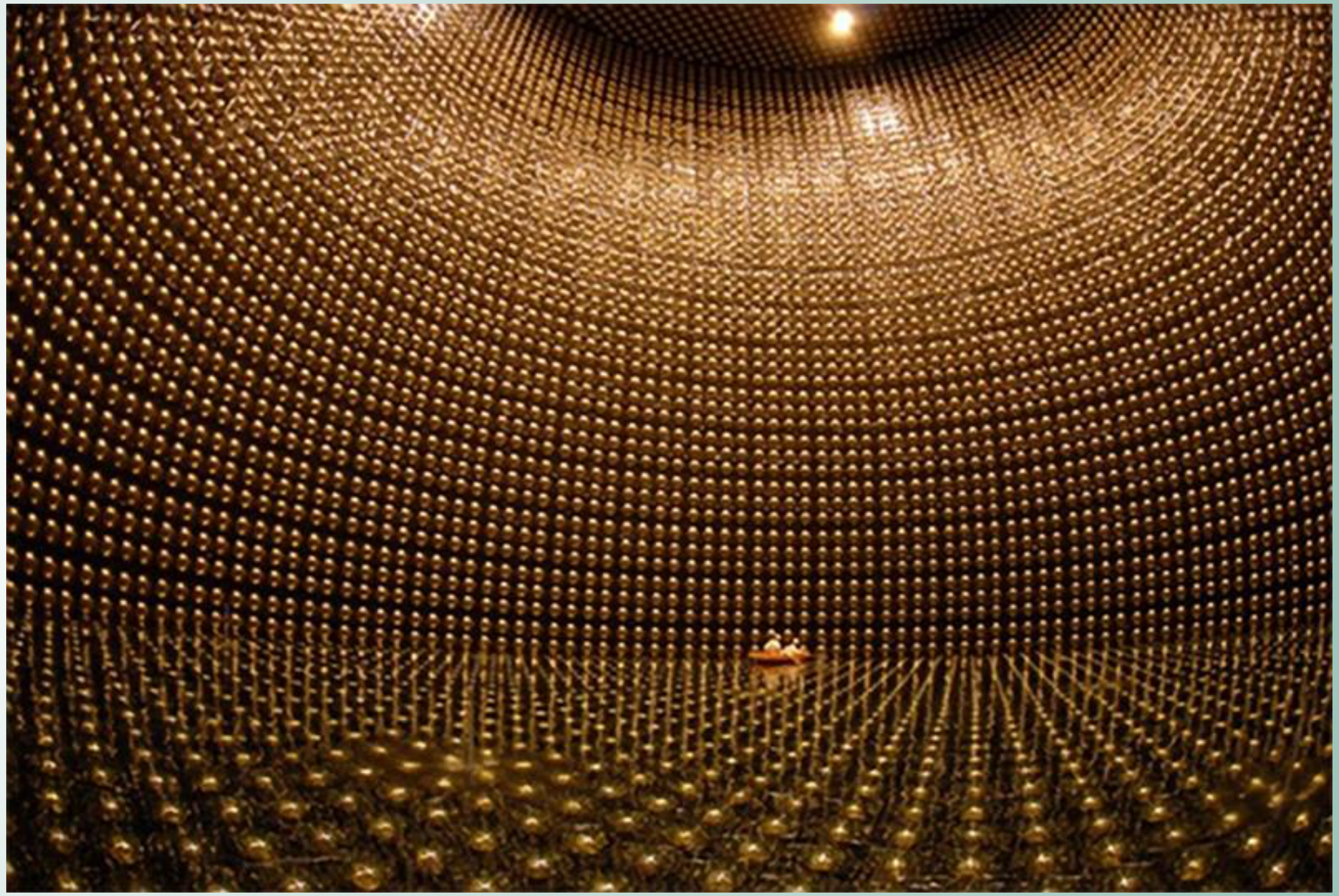
Super-K



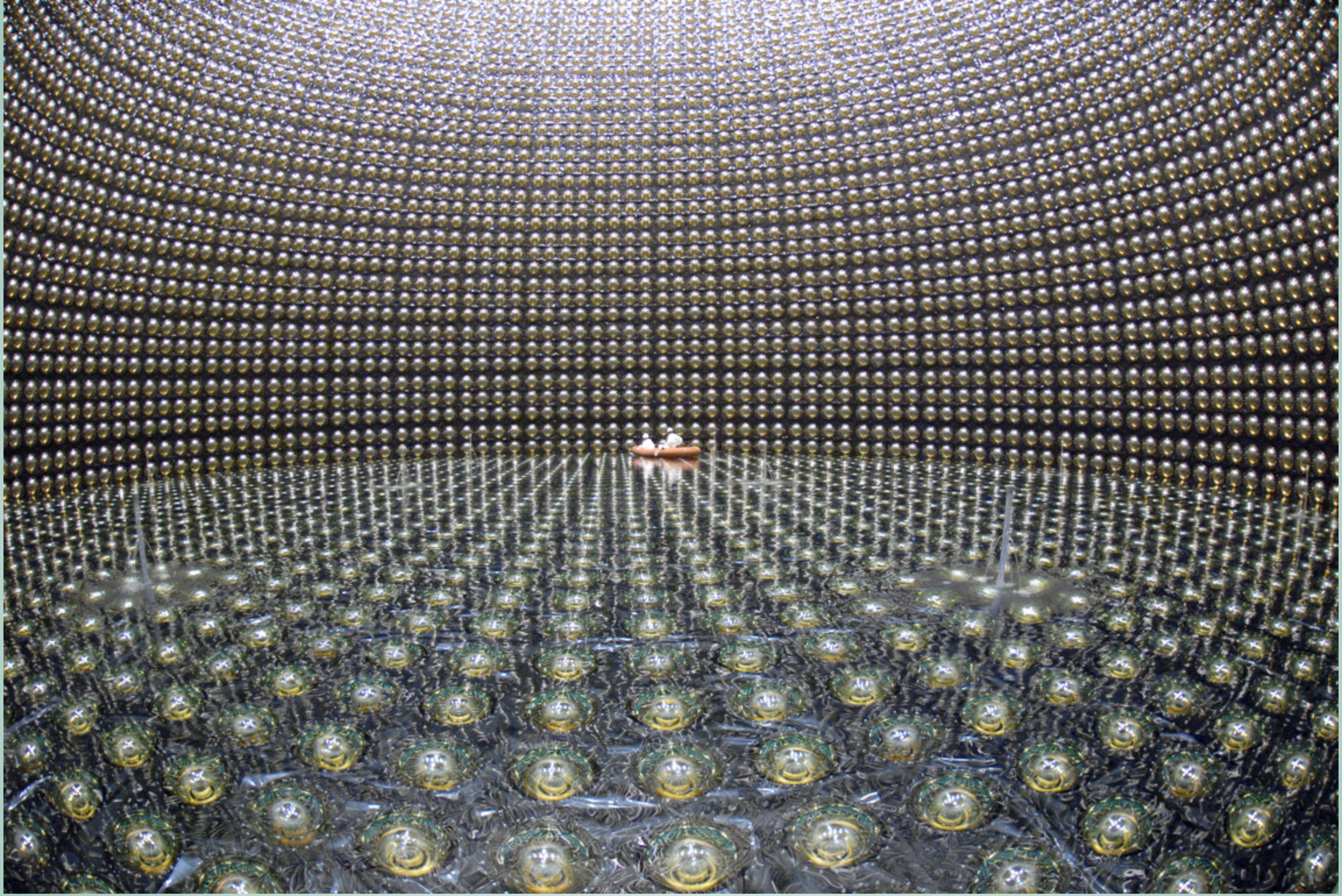




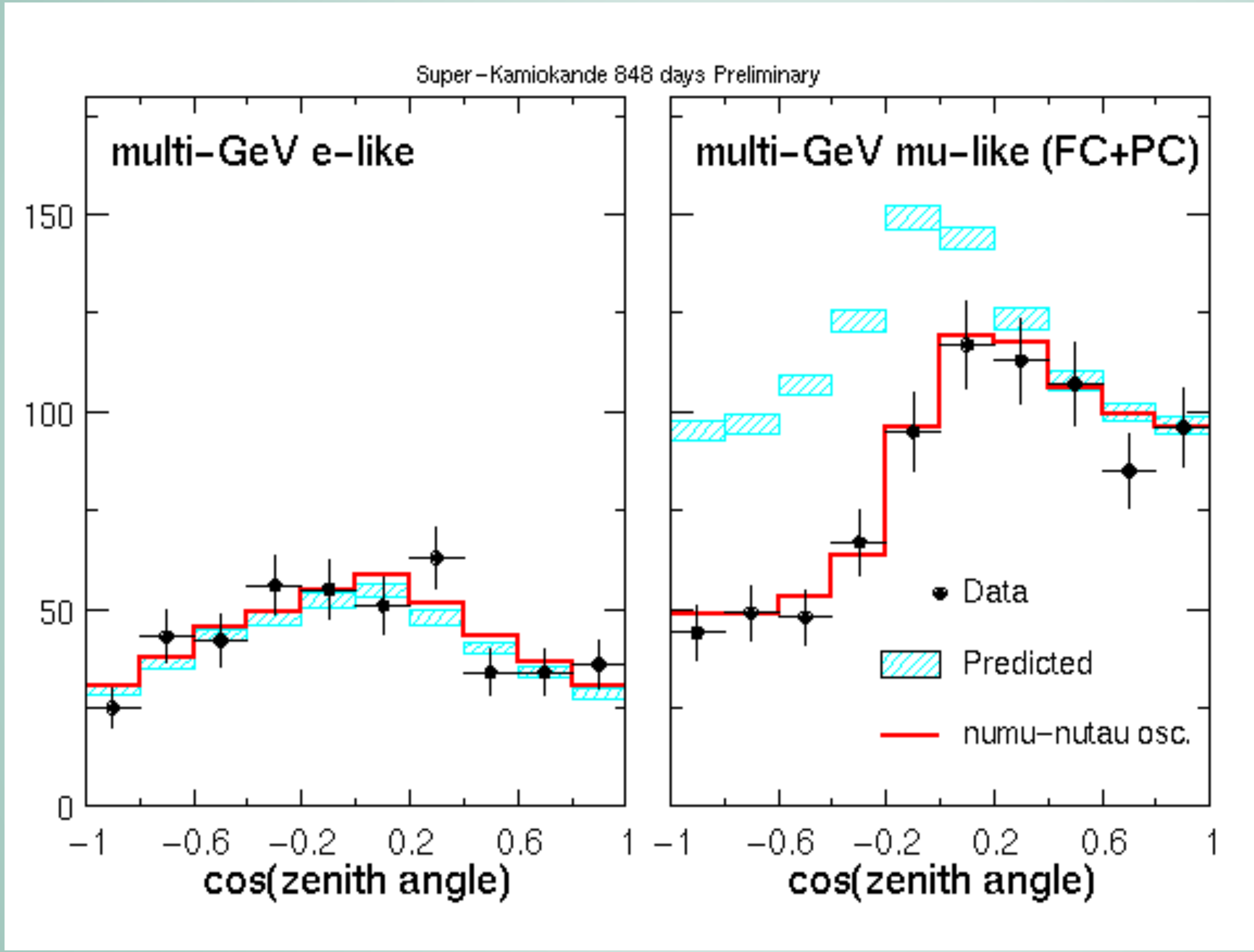




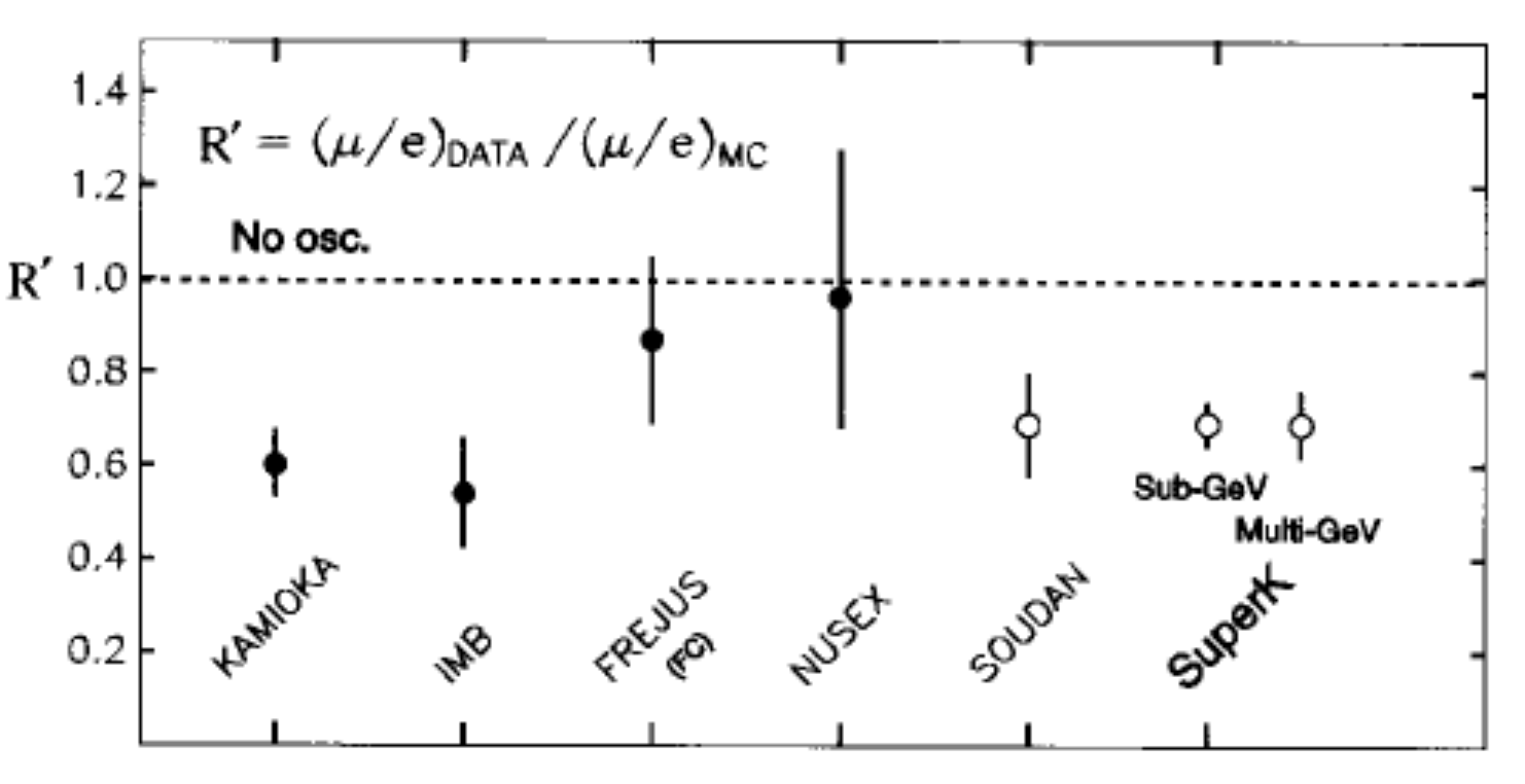
Initially built for
proton decay searches



Up-down Asymmetry Observed



Results



Mixing Angle quite large (consistent with maximal)

$\Delta m^2 = 2.5\text{x}10^{-3}\ \text{eV}^2$

Verified by Accelerator Experiments

So what happened to the neutrinos?

1958-67: Lepton / Neutrino Oscillations Predicted

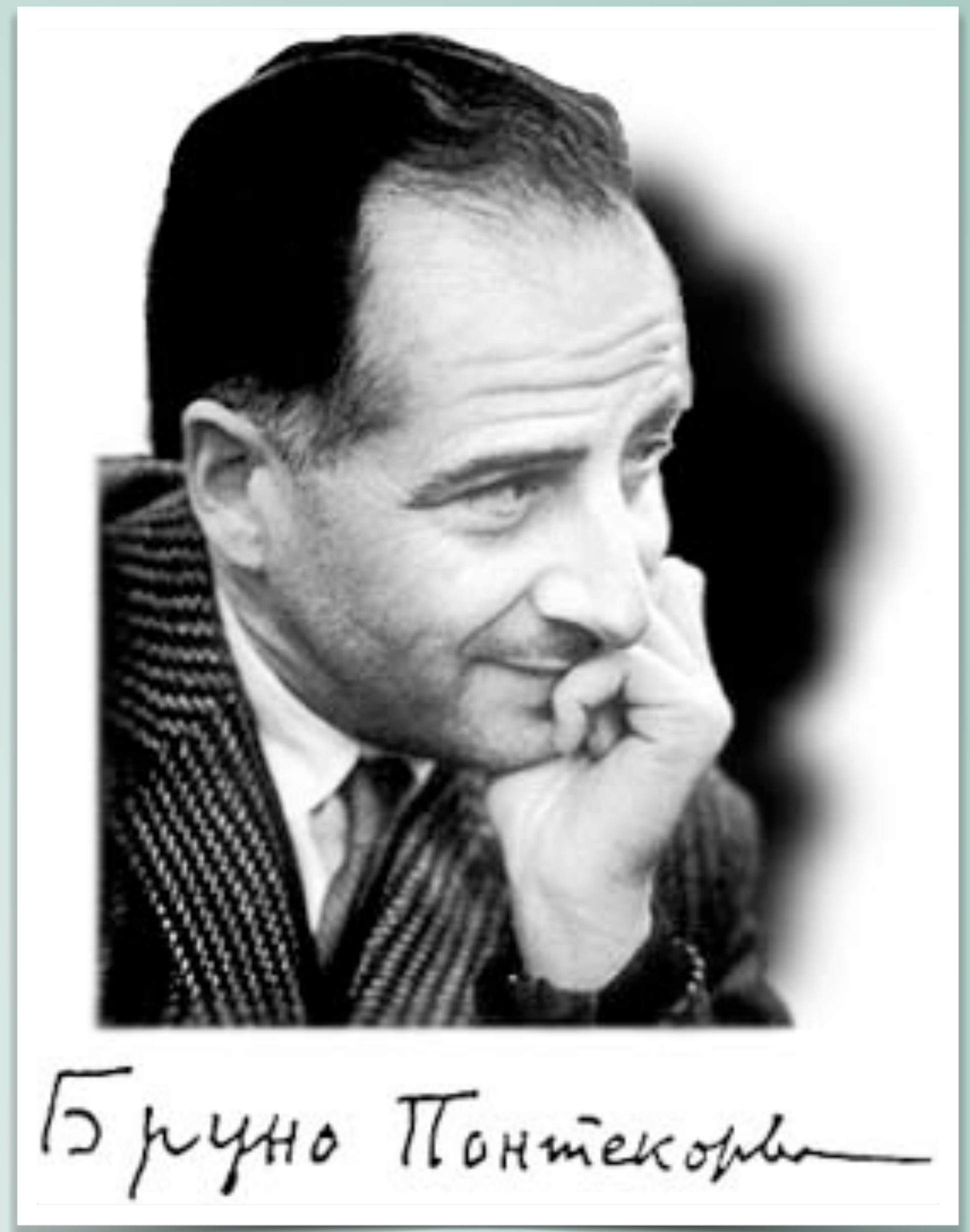
- **1958:** Pontecorvo, inspired by K-meson oscillations studied lepton flavor-violating “mesonium and antimesonium” oscillations: $e^+\mu^- \leftrightarrow e^-\mu^+$.

Sov. Phys. JETP. 26: 984

- Oscillation timescale too long to detect (muon decays)

- **1967:** Proposed 2-state neutrino oscillations:
  - $\nu_e \leftrightarrow \nu_\mu$
  - $\nu \leftrightarrow \overline{\nu}$

Zh. Eksp. Teor. Fiz. 53, 1717



- Provided first limit of mixing parameters based on Cowan and Reines Experiment (10m baseline)

- Postulated Sun as Source of neutrinos, but (!)

Unfortunately the weight of the various thermonuclear reactions in the sun, and the central temperature of the sun are insufficiently well known in order to allow a useful comparison of expected and observed solar neutrinos, from the point of view of this article [1)].

Also (!)

OSCILLATIONS AND ASTRONOMY

If the oscillation length is large (>10 km) it will be impossible to observe the transitions $\nu \rightleftarrows \overline{\nu}$, $\nu_\mu \rightleftarrows \nu_e$ in neutrino beams from reactors or accelerators. However, significant astrophysical effects might be possible.

Neutrino Oscillations Concept

- QM: **Superposition Principle:** *Particles can exist in more than one state at a time (superposition of states)*
- Neutrino *flavor* is a state
- Consider only 2 states: $|\nu_e\rangle$, $|\nu_\mu\rangle$
- QM says this is *also* a valid neutrino state: $|\nu_x\rangle = \alpha|\nu_e > + \beta|\nu_\mu\rangle$
- This is known as *neutrino mixing.* It is also observed in quarks (CKM mixing)
- Charge Current interaction determines flavor, e.g. electrons create $|\nu_e\rangle$

Toy Model: 2-Flavor Mixing

- Not required for *mass* eigenstates to be same as *flavor* eigenstates
  - $|\nu_e\rangle$, $|\nu_\mu\rangle$ do not have well-defined mass. Must use *effective masses*

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

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_1\rangle = \cos\theta|\nu_e\rangle - \sin\theta|\nu_\mu\rangle \ \ldots$$

Neutrinos interact as *flavor* eigenstates.

Propagate as *mass* eigenstates

A ν_e from a beta decay will *mix or oscillate* between a ν_e and ν_μ as it propagates. QM Gives:

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

E : Energy of neutrino

L: Distance Travelled

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

3 - Flavor Mixing

$$\theta_{12} \approx 30^\circ \quad \delta = ?$$
$$\theta_{23} \approx 45^\circ \quad \alpha_i = ?$$
$$\theta_{13} \approx 10^\circ$$

Pontecorvo–Maki–Nakagawa–Sakata matrix (PMNS matrix)

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

e.g. $|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

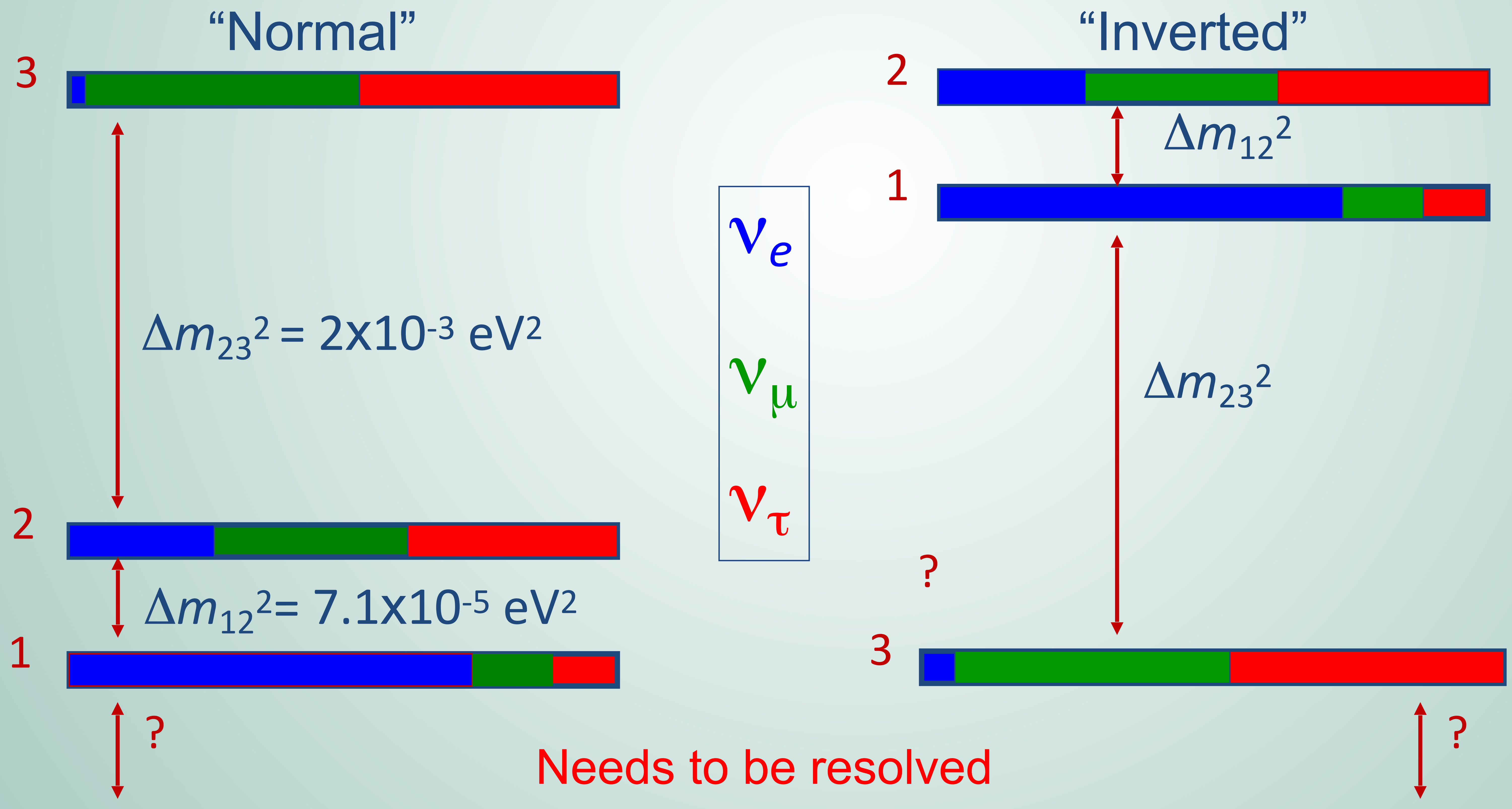
$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

Neutrino Masses

Absolute masses weakly constrained, < 1eV.

Relative mass-squared differences known.

Three possible scenarios: Quasi-degenerate, also:



Needs to be resolved

Current parameters values

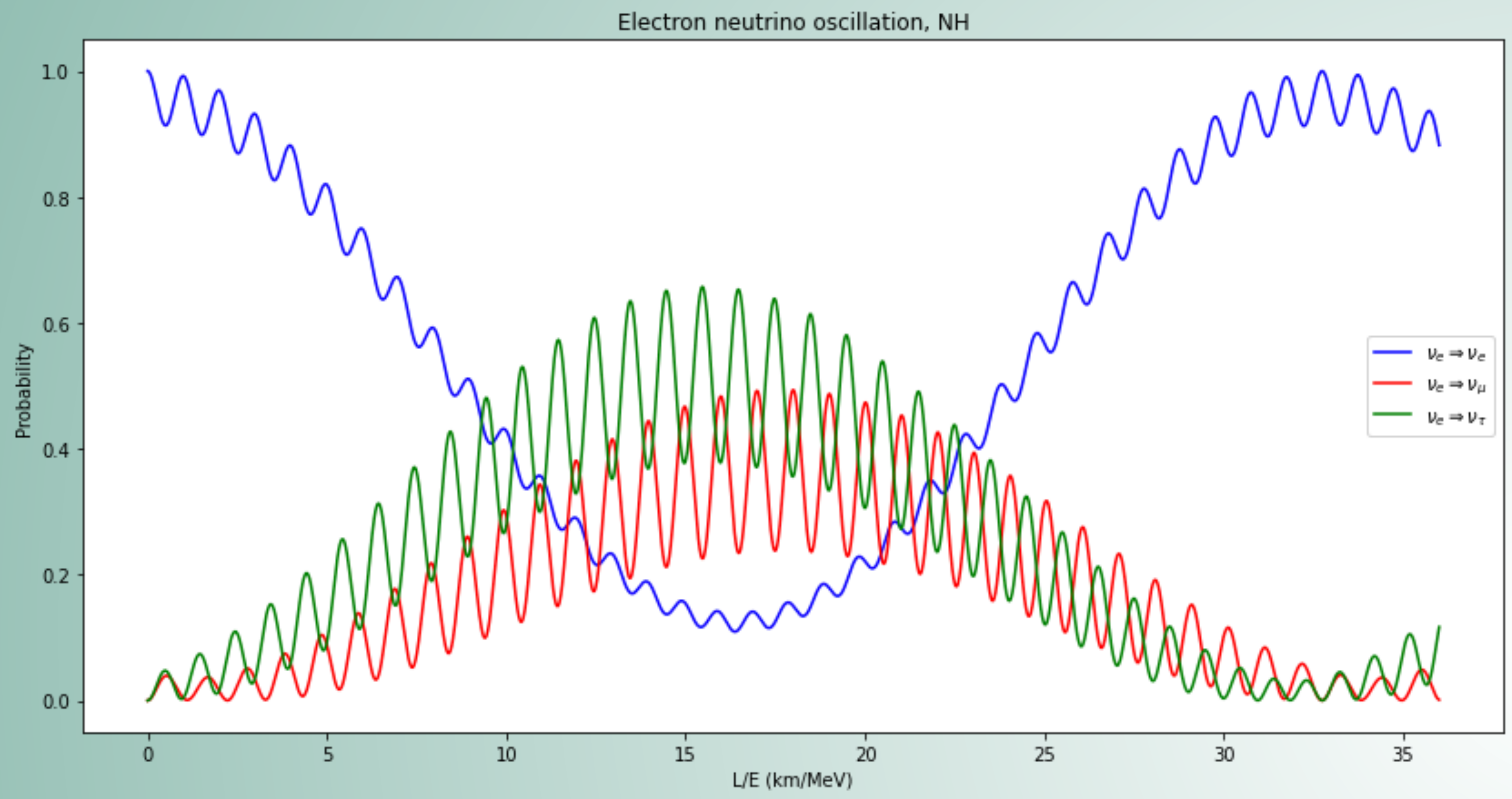
https://pdg.lbl.gov/2020/reviews/rpp2020-rev-neutrino-mixing.pdf

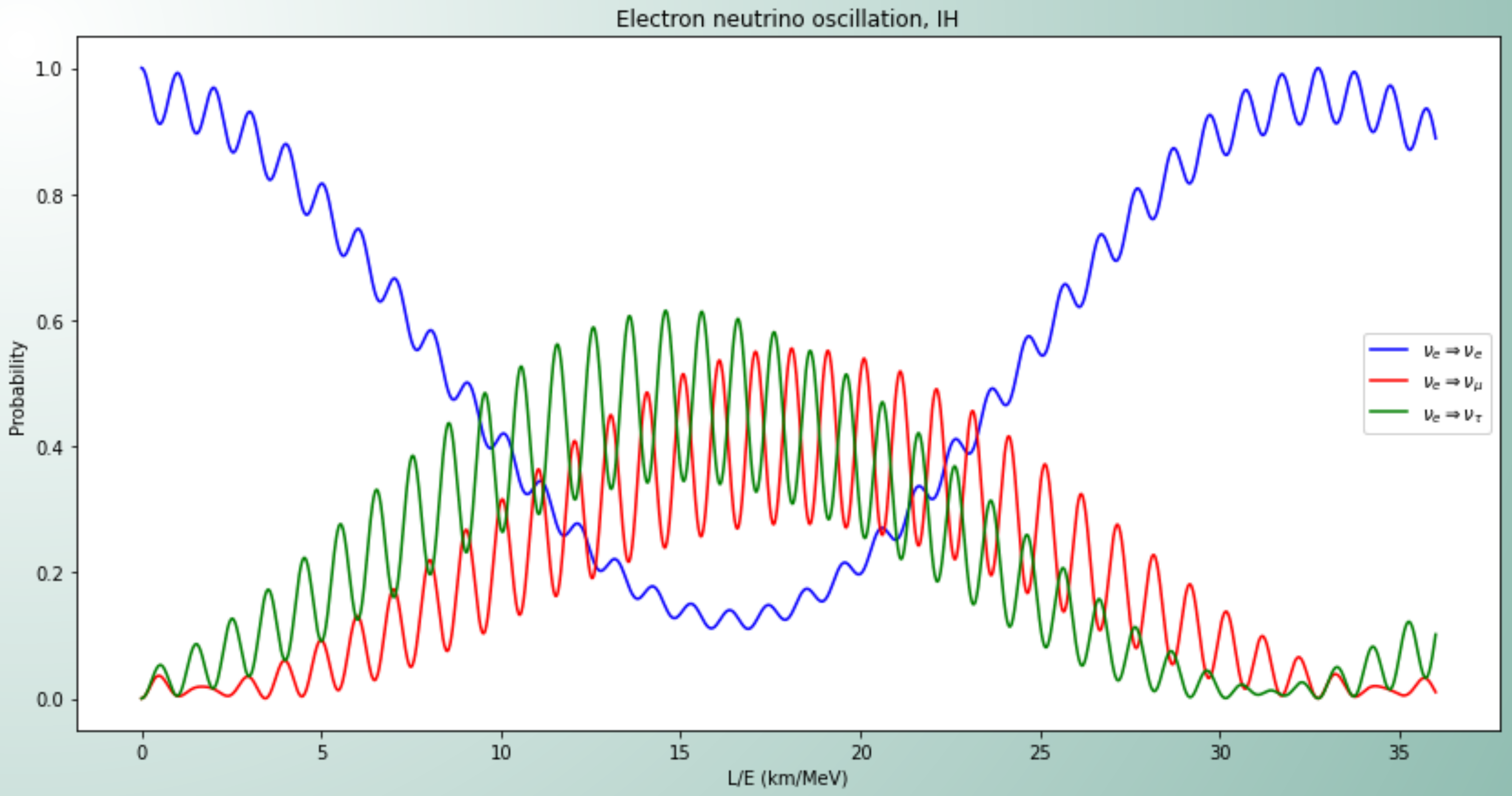
~50 years of work

Table 14.7: 3ν oscillation parameters obtained from different global analysis of neutrino data. In all cases the numbers labeled as NO (IO) are obtained assuming NO (IO), *i.e.*, relative to the respective local minimum. SK-ATM makes reference to the tabulated χ^2 map from the Super-Kamiokande analysis of their data in Ref. [94].

	Ref. [188] w/o SK-ATM		Ref. [188] w SK-ATM		Ref. [189] w SK-ATM		Ref. [190] w SK-ATM	
NO	Best Fit Ordering		Best Fit Ordering		Best Fit Ordering		Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.04^{+0.14}_{-0.13}$	$2.65 \to 3.46$	$3.20^{+0.20}_{-0.16}$	$2.73 \to 3.79$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.46^{+0.87}_{-0.88}$	$30.98 \to 36.03$	$34.5^{+1.2}_{-1.0}$	$31.5 \to 38.0$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	$4.27 \to 6.09$	$5.63^{+0.18}_{-0.24}$	$4.33 \to 6.09$	$5.51^{+0.19}_{-0.80}$	$4.30 \to 6.02$	$5.47^{+0.20}_{-0.30}$	$4.45 \to 5.99$
$\theta_{23}/^\circ$	$48.3^{+1.2}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$47.9^{+1.1}_{-4.0}$	$41.0 \to 50.9$	$47.7^{+1.2}_{-1.7}$	$41.8 \to 50.7$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	$2.046 \to 2.440$	$2.237^{+0.066}_{-0.065}$	$2.044 \to 2.435$	$2.14^{+0.09}_{-0.07}$	$1.90 \to 2.39$	$2.160^{+0.083}_{-0.069}$	$1.96 \to 2.41$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.41^{+0.18}_{-0.14}$	$7.9 \to 8.9$	$8.45^{+0.16}_{-0.14}$	$8.0 \to 8.9$
$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	221^{+39}_{-28}	$144 \to 357$	238^{+41}_{-33}	$149 \to 358$	218^{+38}_{-27}	$157 \to 349$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.34^{+0.17}_{-0.14}$	$6.92 \to 7.91$	$7.55^{+0.20}_{-0.16}$	$7.05 \to 8.24$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$2.449^{+0.032}_{-0.030}$	$2.358 \to 2.544$	$2.454^{+0.029}_{-0.031}$	$2.362 \to 2.544$	$2.419^{+0.035}_{-0.032}$	$2.319 \to 2.521$	2.424 ± 0.03	$2.334 \to 2.524$
IO	$\Delta\chi^2 = 6.2$		$\Delta\chi^2 = 10.4$		$\Delta\chi^2 = 9.5$		$\Delta\chi^2 = 11.7$	
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.03^{+0.14}_{-0.13}$	$2.64 \to 3.45$	$3.20^{+0.20}_{-0.16}$	$2.73 \to 3.79$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$	$33.40^{+0.87}_{-0.81}$	$30.92 \to 35.97$	$34.5^{+1.2}_{-1.0}$	$31.5 \to 38.0$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.63^{+0.19}_{-0.26}$	$4.30 \to 6.12$	$5.65^{+0.17}_{-0.22}$	$4.36 \to 6.10$	$5.57^{+0.17}_{-0.24}$	$4.44 \to 6.03$	$5.51^{+0.18}_{-0.30}$	$4.53 \to 5.98$
$\theta_{23}/^\circ$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$	$48.2^{+1.0}_{-1.4}$	$41.8 \to 50.9$	$47.9^{+1.0}_{-1.7}$	$42.3 \to 50.7$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.261^{+0.067}_{-0.064}$	$2.066 \to 2.461$	$2.259^{+0.065}_{-0.065}$	$2.064 \to 2.457$	$2.18^{+0.08}_{-0.07}$	$1.95 \to 2.43$	$2.220^{+0.074}_{-0.076}$	$1.99 \to 2.44$
$\theta_{13}/^\circ$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$	$8.49^{+0.15}_{-0.14}$	$8.0 \to 9.0$	$8.53^{+0.14}_{-0.15}$	$8.1 \to 9.0$
$\delta_{CP}/^\circ$	285^{+24}_{-26}	$205 \to 354$	282^{+23}_{-25}	$205 \to 348$	247^{+26}_{-27}	$193 \to 346$	281^{+23}_{-27}	$202 \to 349$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.34^{+0.17}_{-0.14}$	$6.92 \to 7.91$	$7.55^{+0.20}_{-0.16}$	$7.05 \to 8.24$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$-2.509^{+0.032}_{-0.032}$	$-2.603 \to -2.416$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$	$-2.478^{+0.035}_{-0.033}$	$-2.577 \to -2.375$	$-2.50\pm^{+0.04}_{-0.03}$	$-2.59 \to -2.39$

3-flavor Oscillation Example





Resolution

SNO
Sudbury Neutrino Observatory

1 kton ($300M!) D_2O

3 Channels:

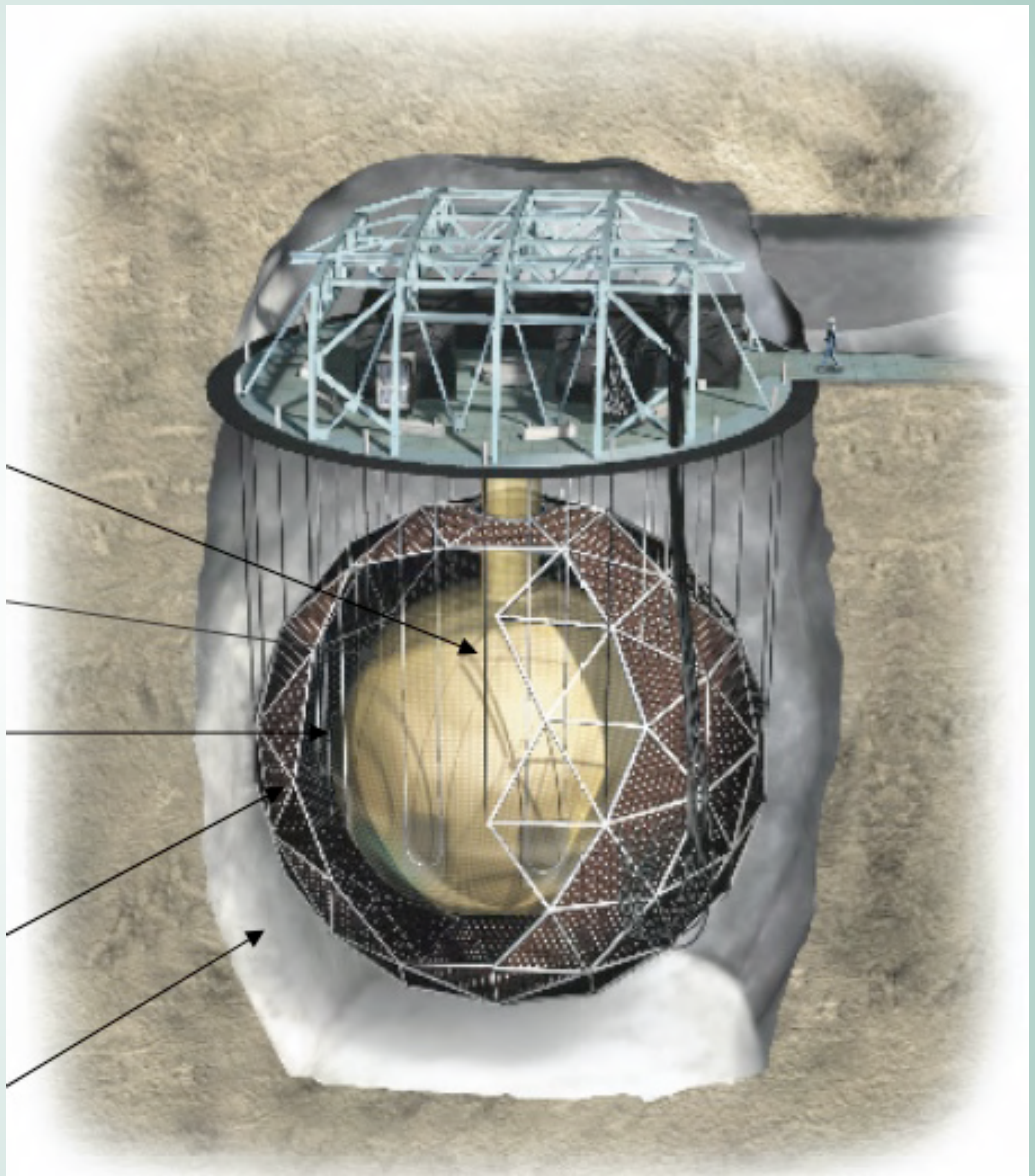
- Elastic Scattering (ES)
  - $\nu_{e\tau\mu}+e^- \rightarrow \nu_{e\tau\mu}+e^-$
- Neutral Current (NC)
  - $\nu_{e\tau\mu}+d \rightarrow \nu_{e\tau\mu}+p^+ +n$
- Charged Current
  - $\nu_e+d \rightarrow \nu_e +p^+ +p^+ +e^-$

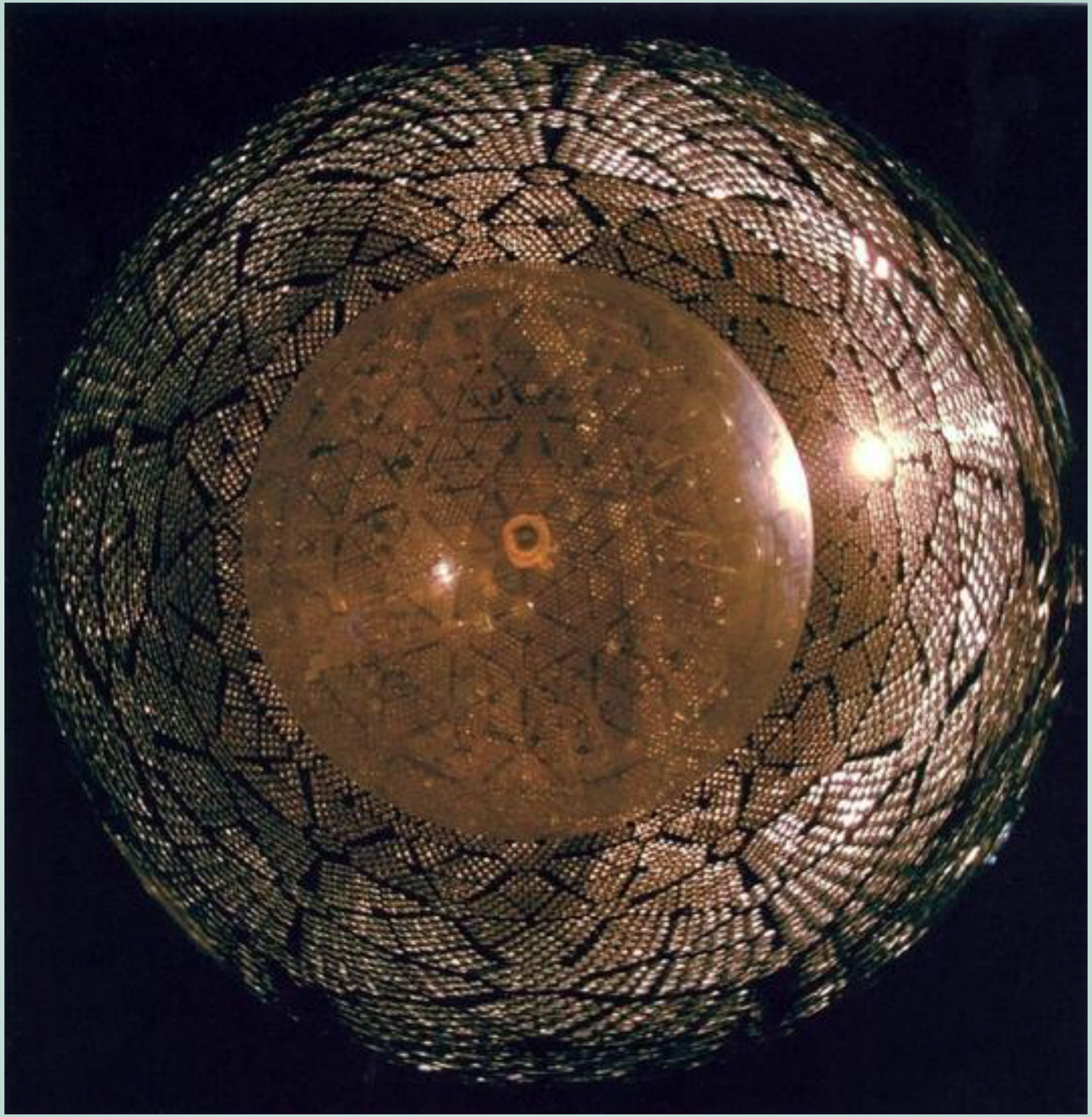
3 Phases:

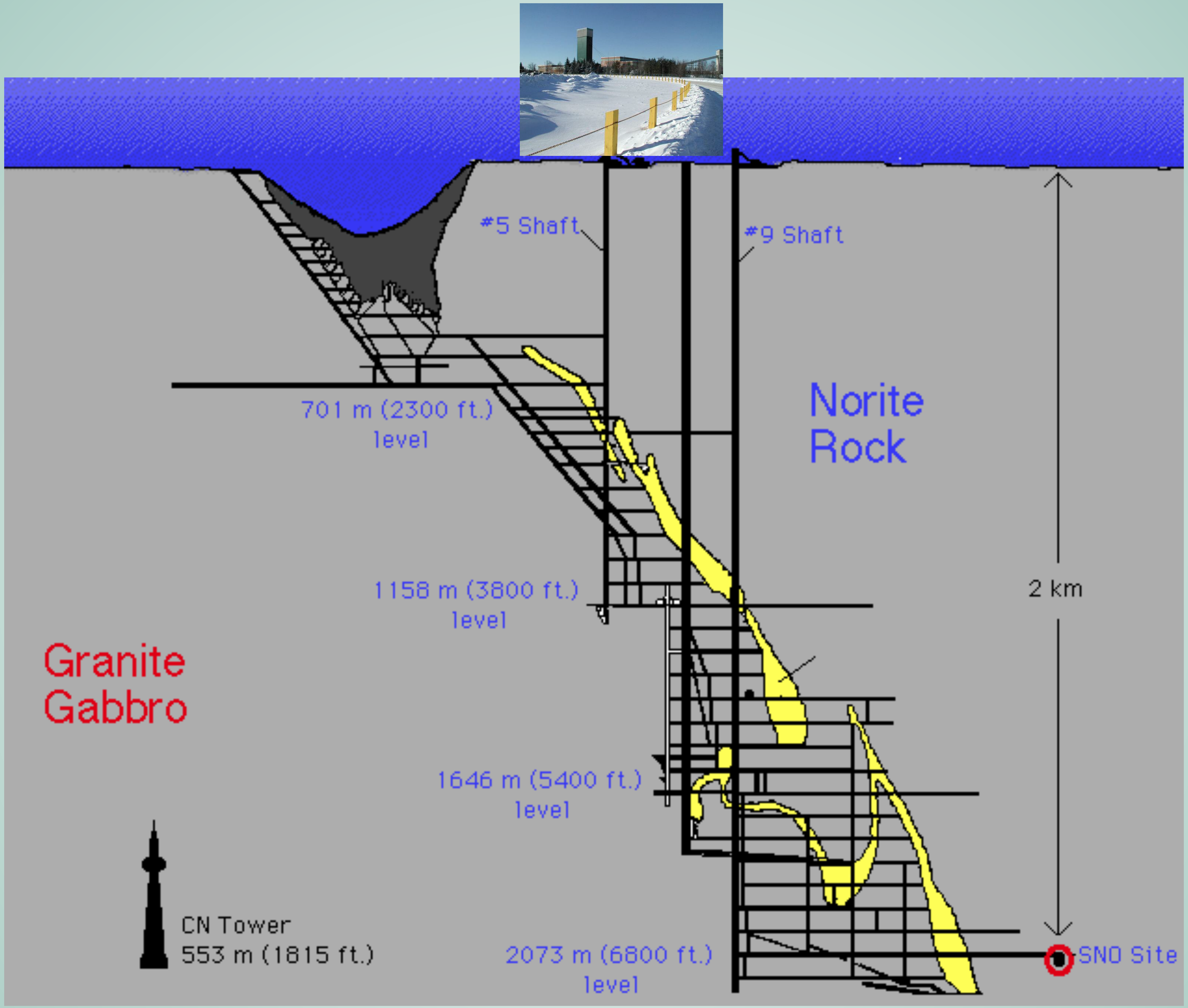
I: $n + d \rightarrow {}^3H + \gamma + 6.3$ MeV

II: $n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6$ MeV

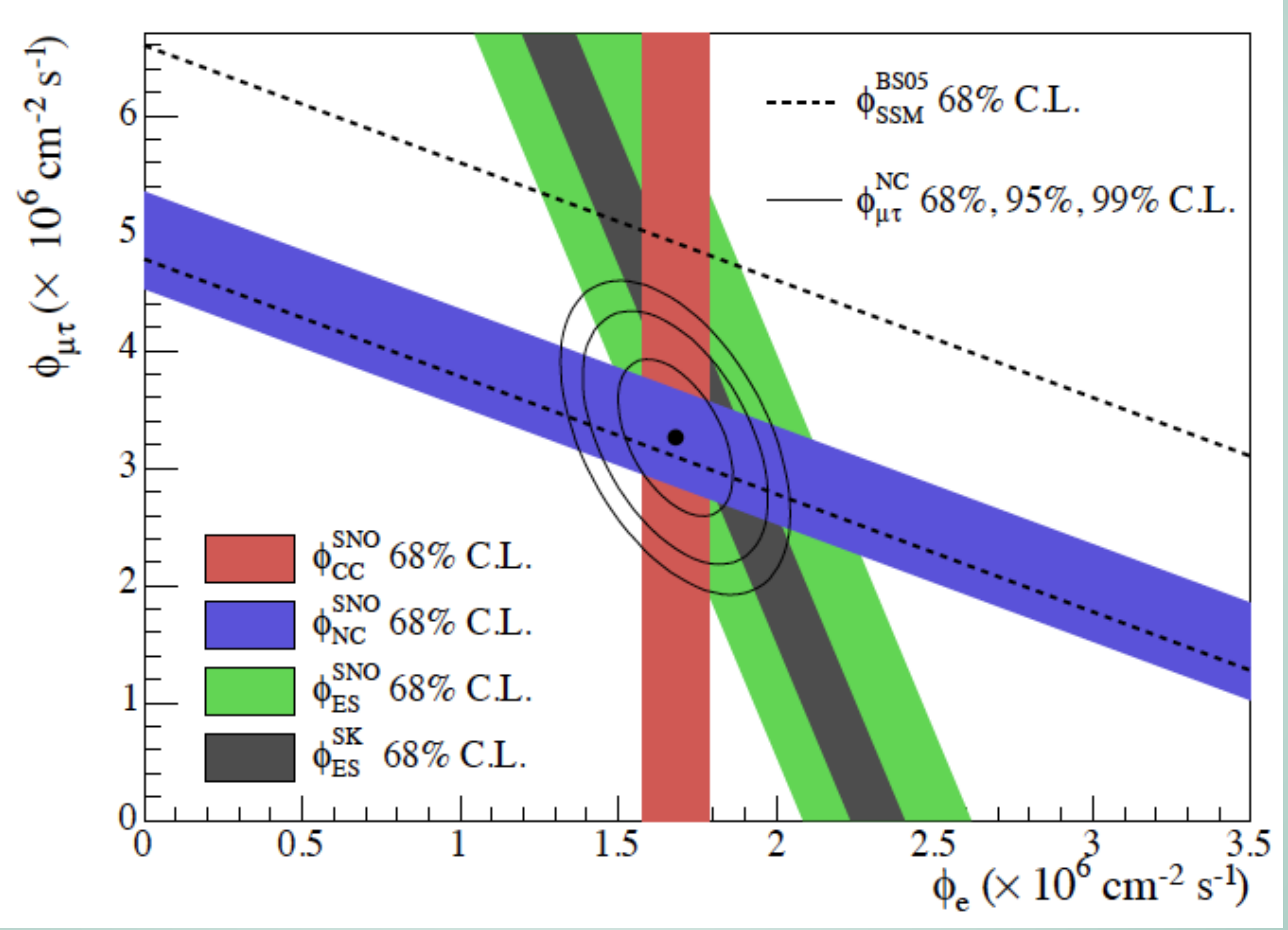
III: $n + {}^3He \rightarrow {}^3H + p + 0.76$ MeV

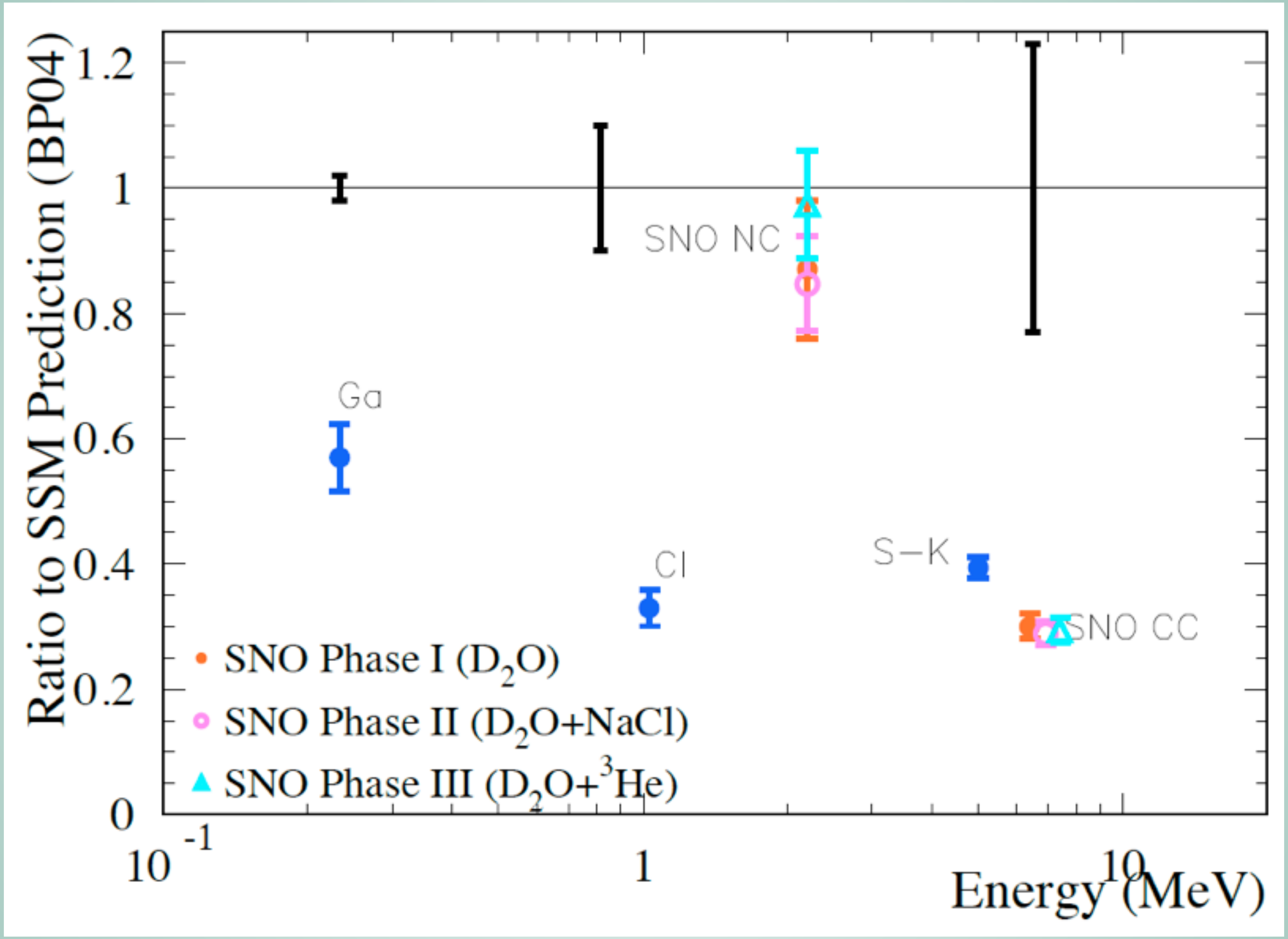





#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
1158 m (3800 ft.) level
2 km
Granite Gabbro
1646 m (5400 ft.) level
CN Tower
553 m (1815 ft.)
2073 m (6800 ft.) level
SNO Site

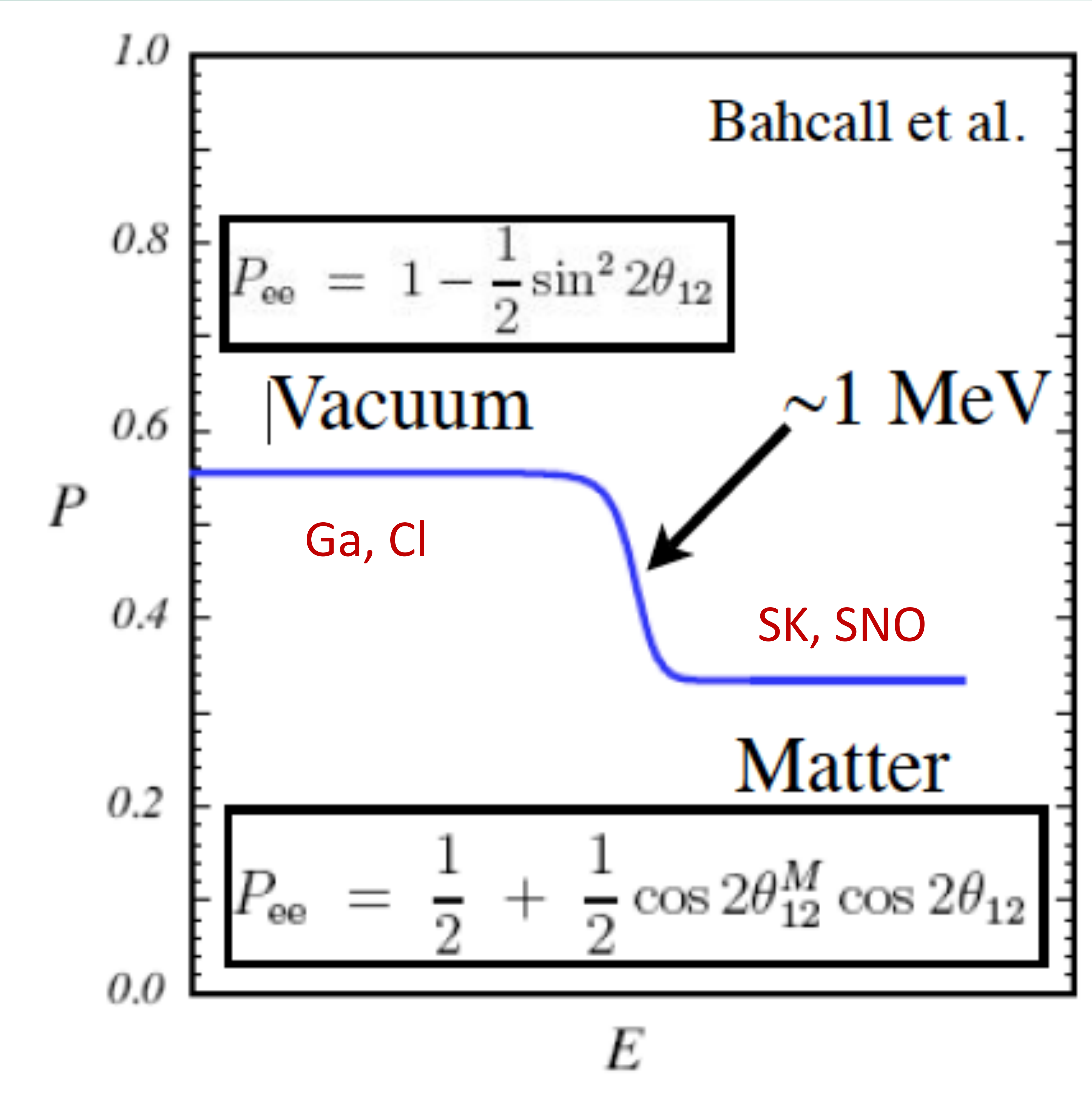
Solar Neutrino Problem Solved!





Ratio to SSM Prediction (BP04)
1.2
1
0.8
0.6
0.4
0.2
0
SNO NC
Ga
Cl
S−K
SNO CC
SNO Phase I (D$_2$O)
SNO Phase II (D$_2$O+NaCl)
SNO Phase III (D$_2$O+^{3}He)
10^{-1}
1
10
Energy (MeV)

Interpretation



2002: Discovery of Reactor Neutrino Oscillations

- Late 90s: Evidence for neutrino oscillations become compelling from solar neutrino and atmospheric neutrinos.
- Not observed in reactor neutrinos yet, though

Probability of ν_e disappearance:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

KamLAND

2800 mwe in Kamioka mine in Japan

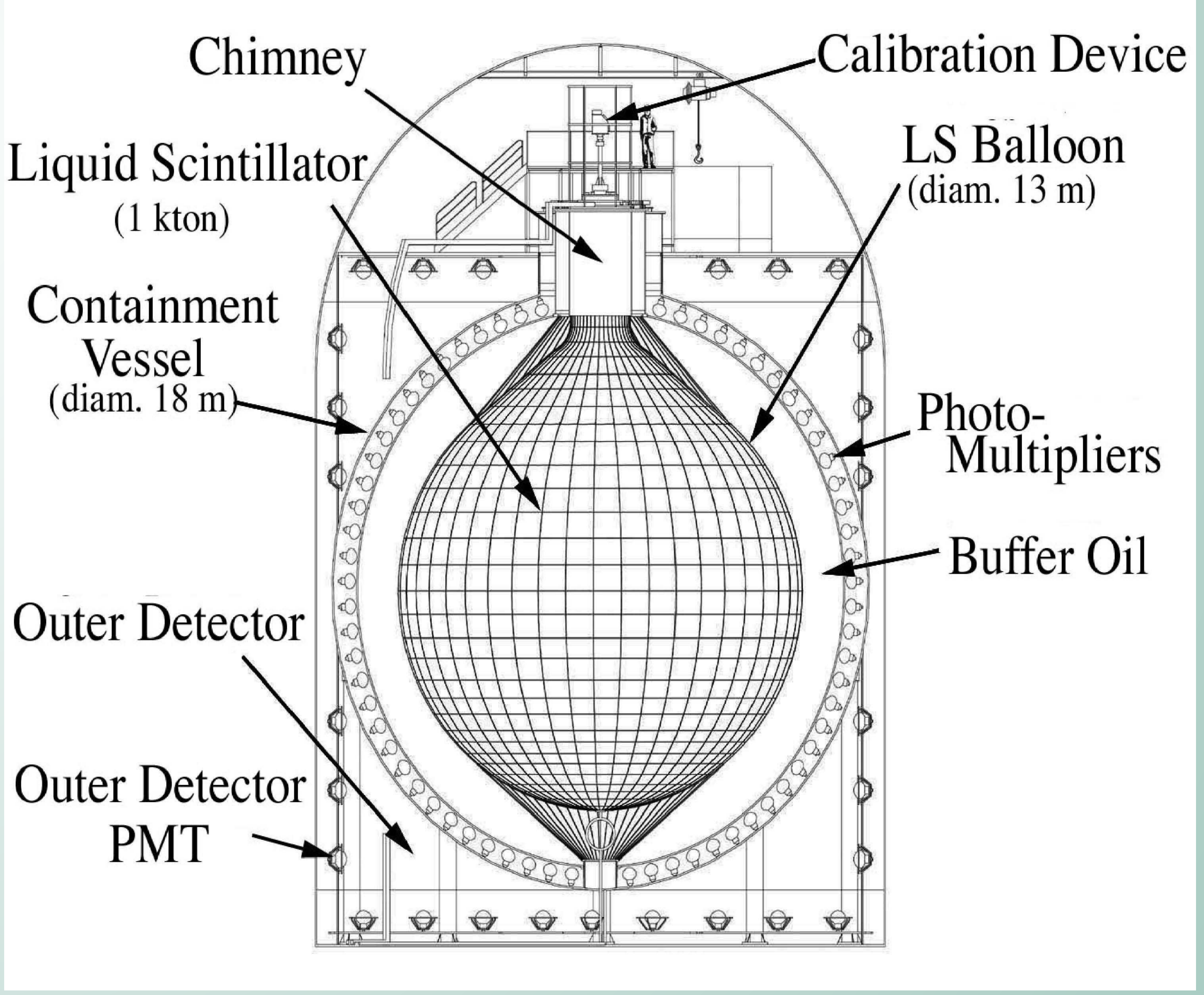
~ 200km from reactors

1 kton ultra pure liquid scintillator (80% dodecane, 20% pseudocumene) doped with fluor (2,5-Diphenyloxazole)

1900 PMTs

Muon veto and buffer shield

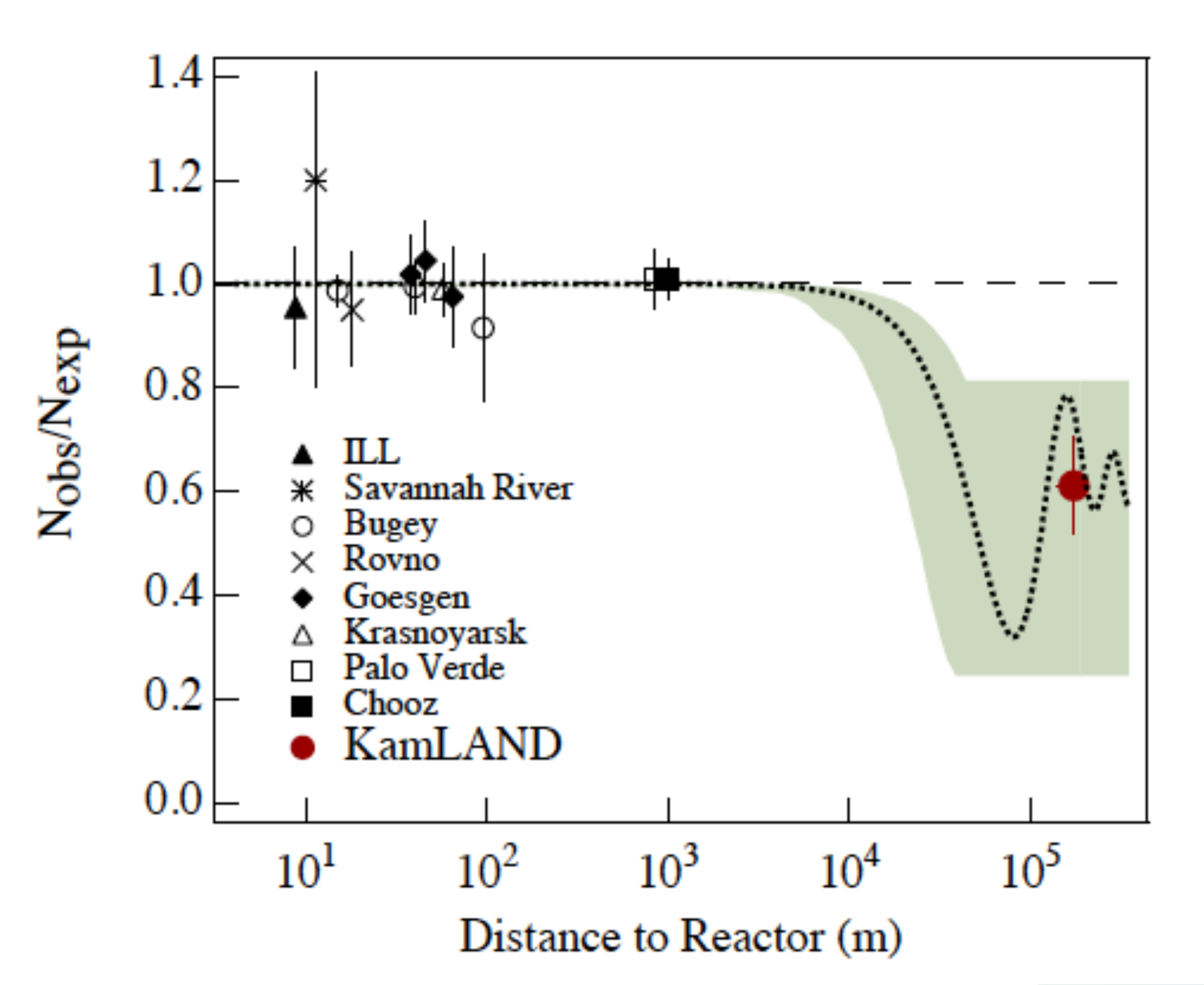
(add map)

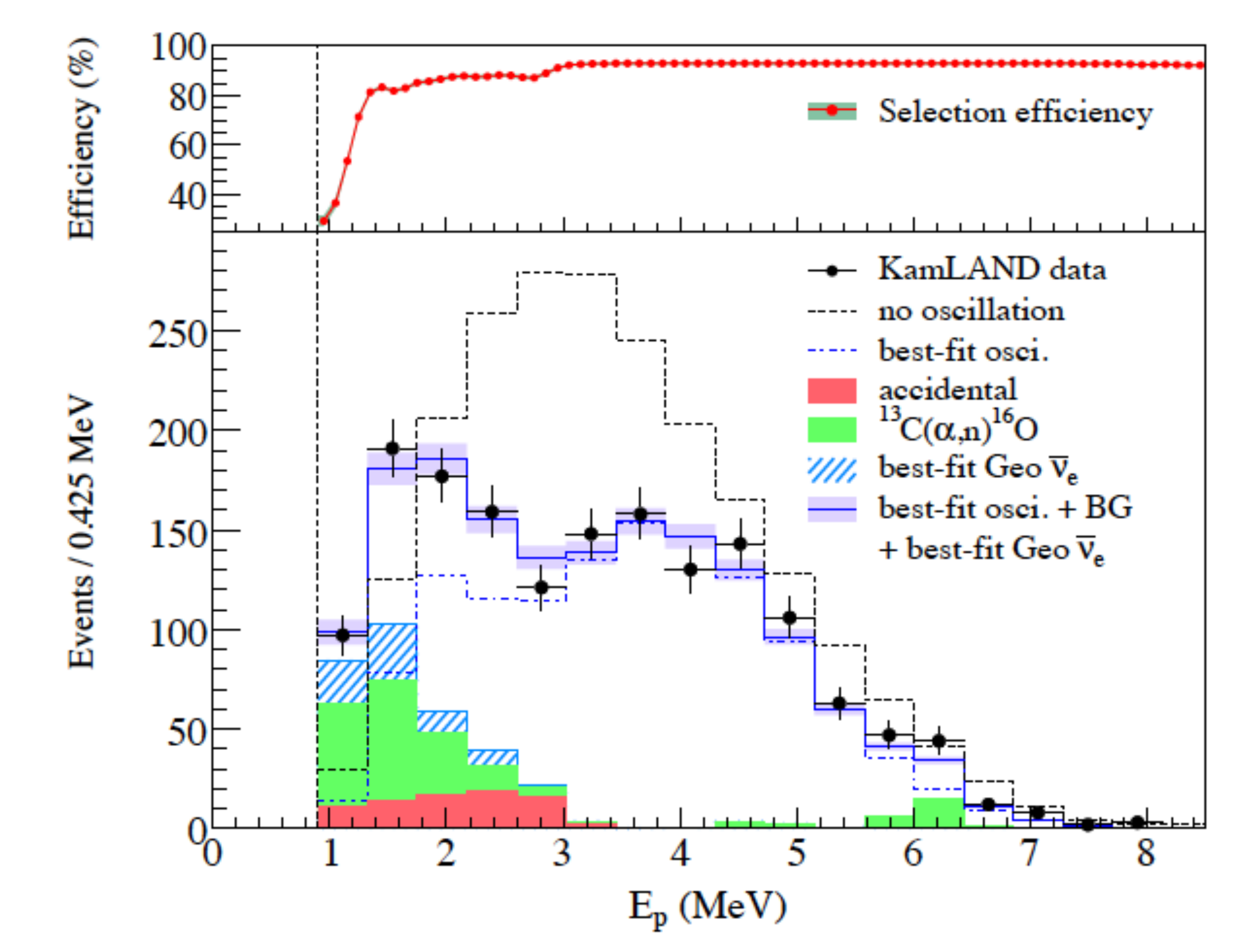


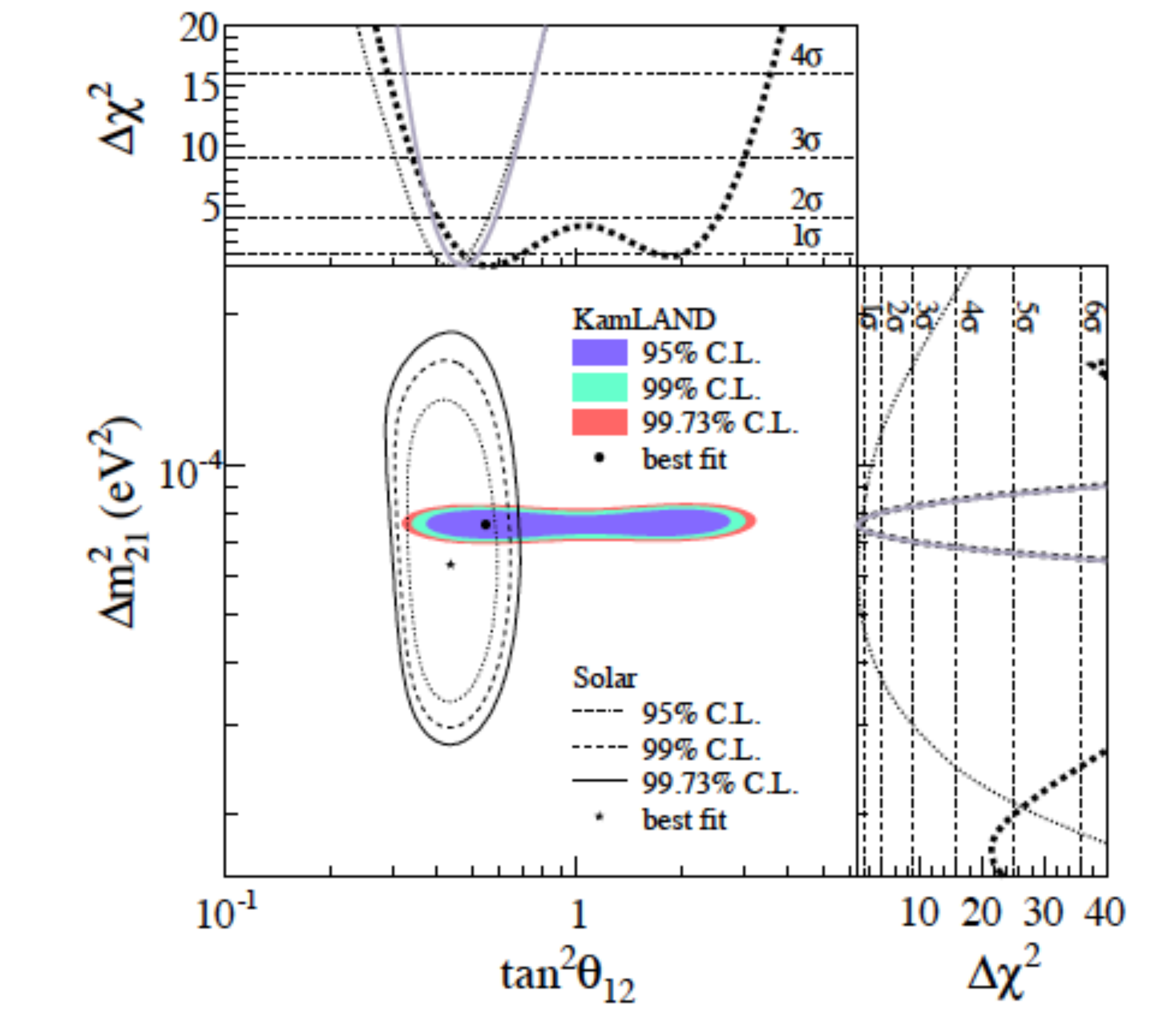
Main KamLAND Results

2002: First observation of ν_e disappearance at very long baselines

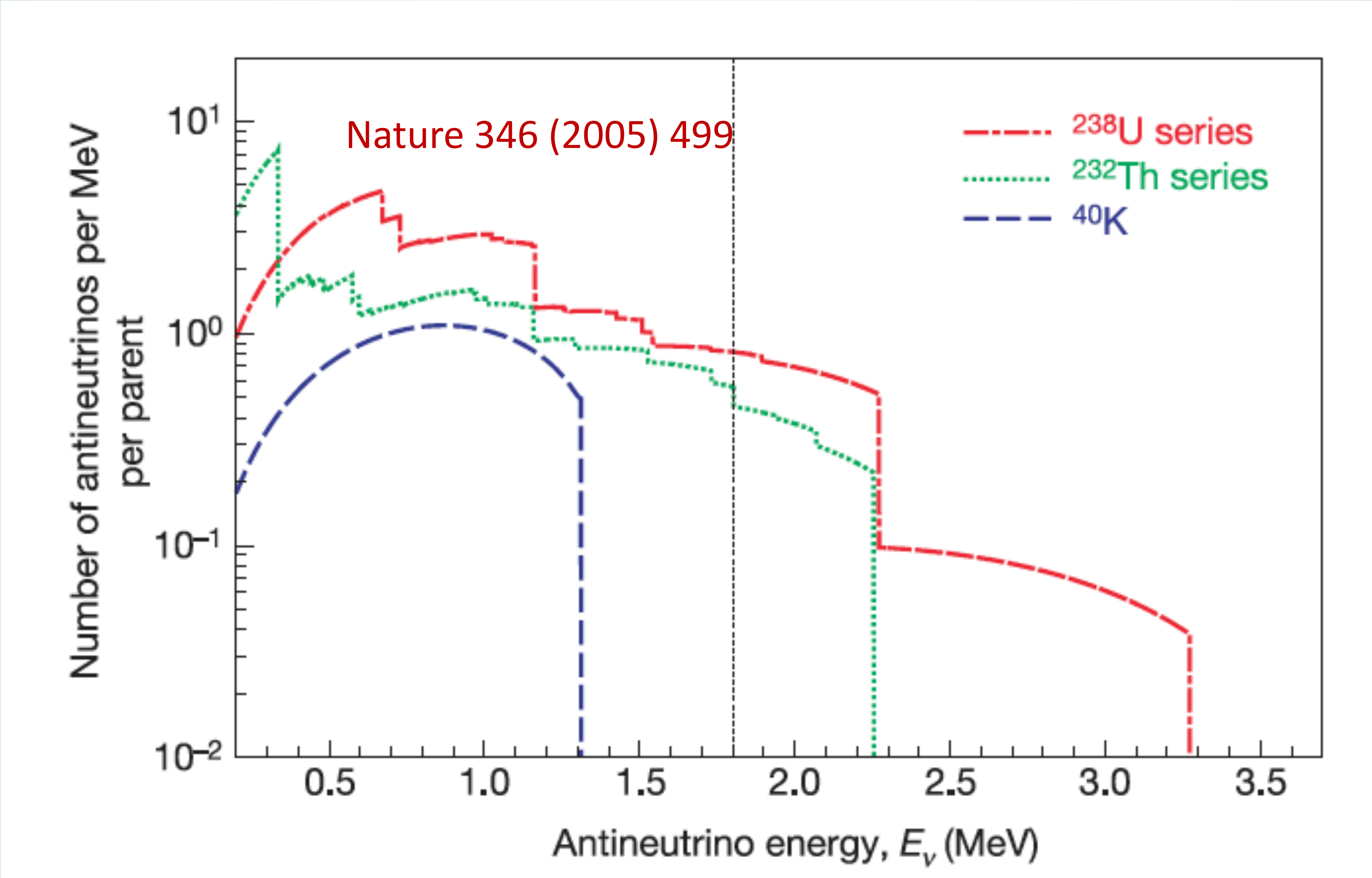
Precision measurements of mixing parameters consistent with solar experiments



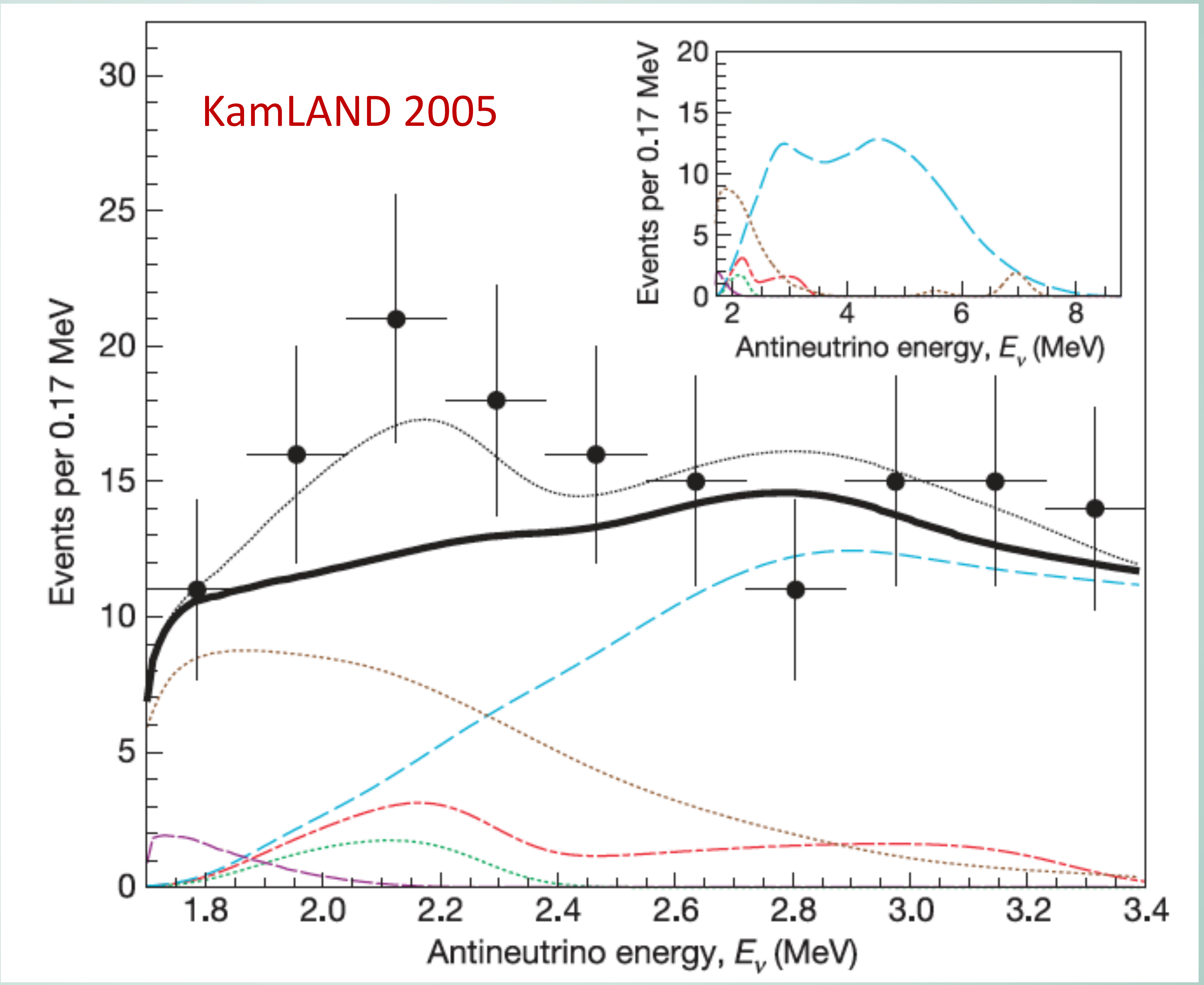




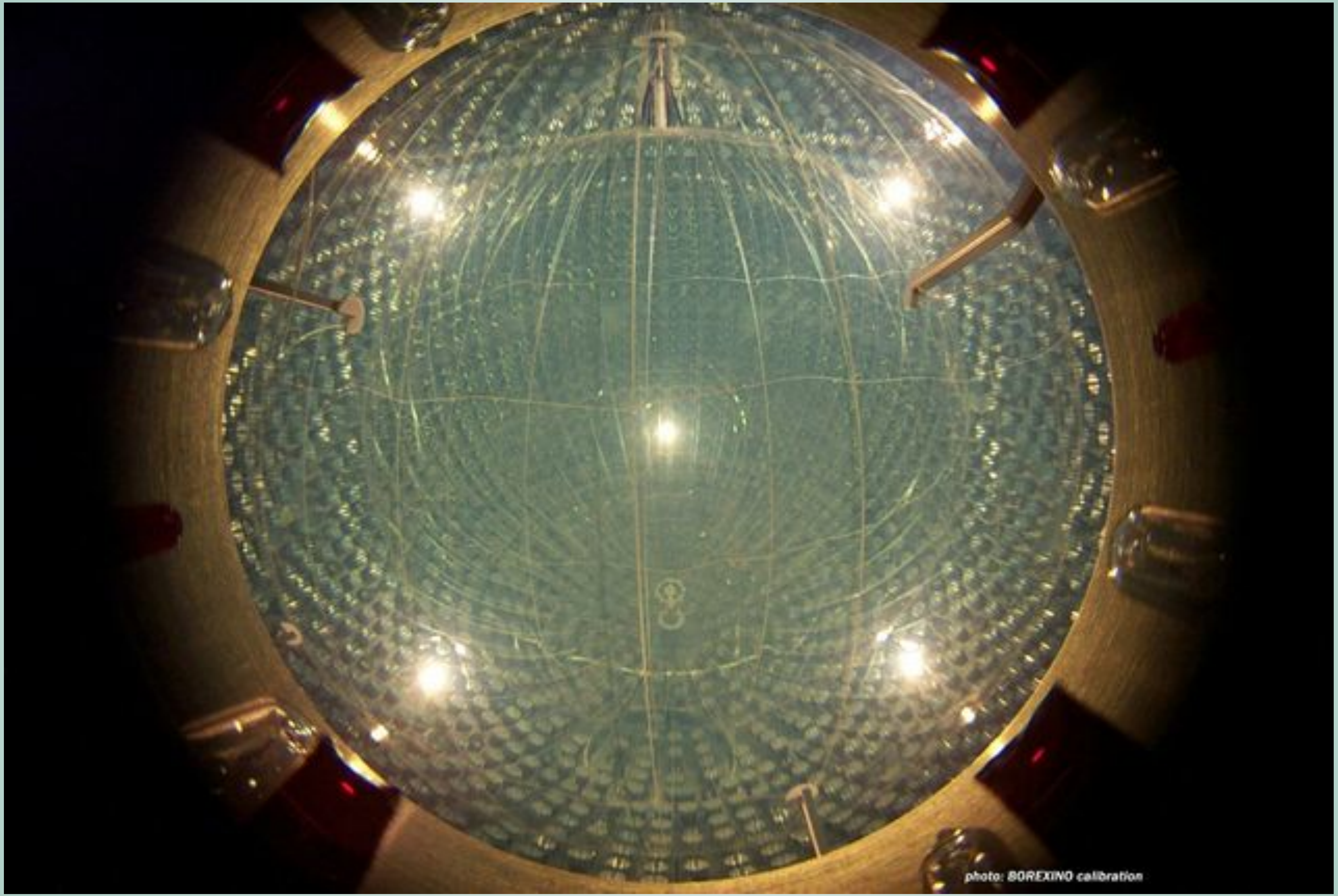
2005: Discover of Geoneutrinos



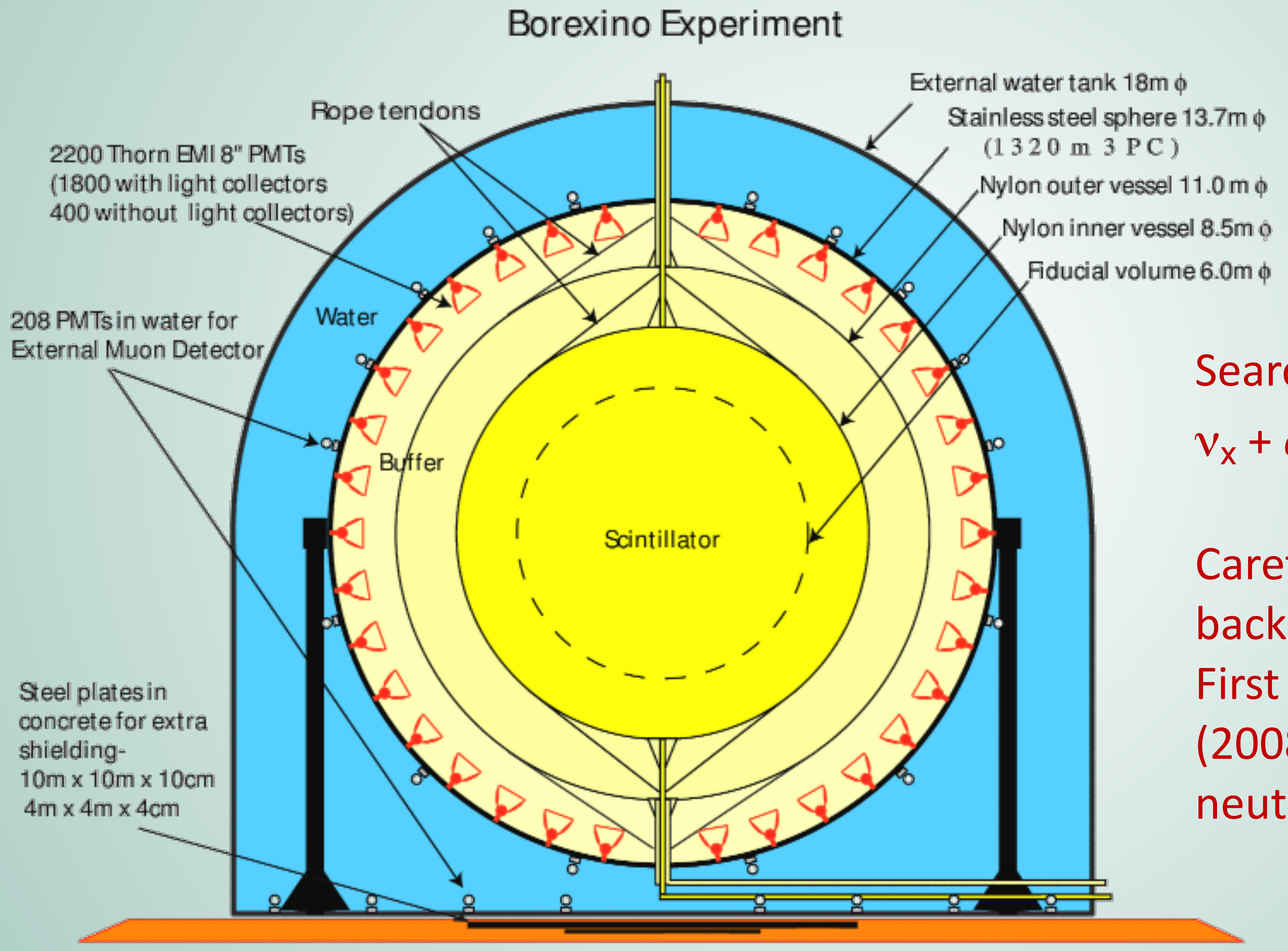
Geoneutrinos Initial Hints



BOREXINO



BOREXINO



Search for ^{7}Be neutrinos via

$\nu_x + e^- \rightarrow \nu_x + e^-$

Careful control of backgrounds

First measurements of ^{7}Be (2008) and pep (2011) neutrinos

Geoneutrino Discovery

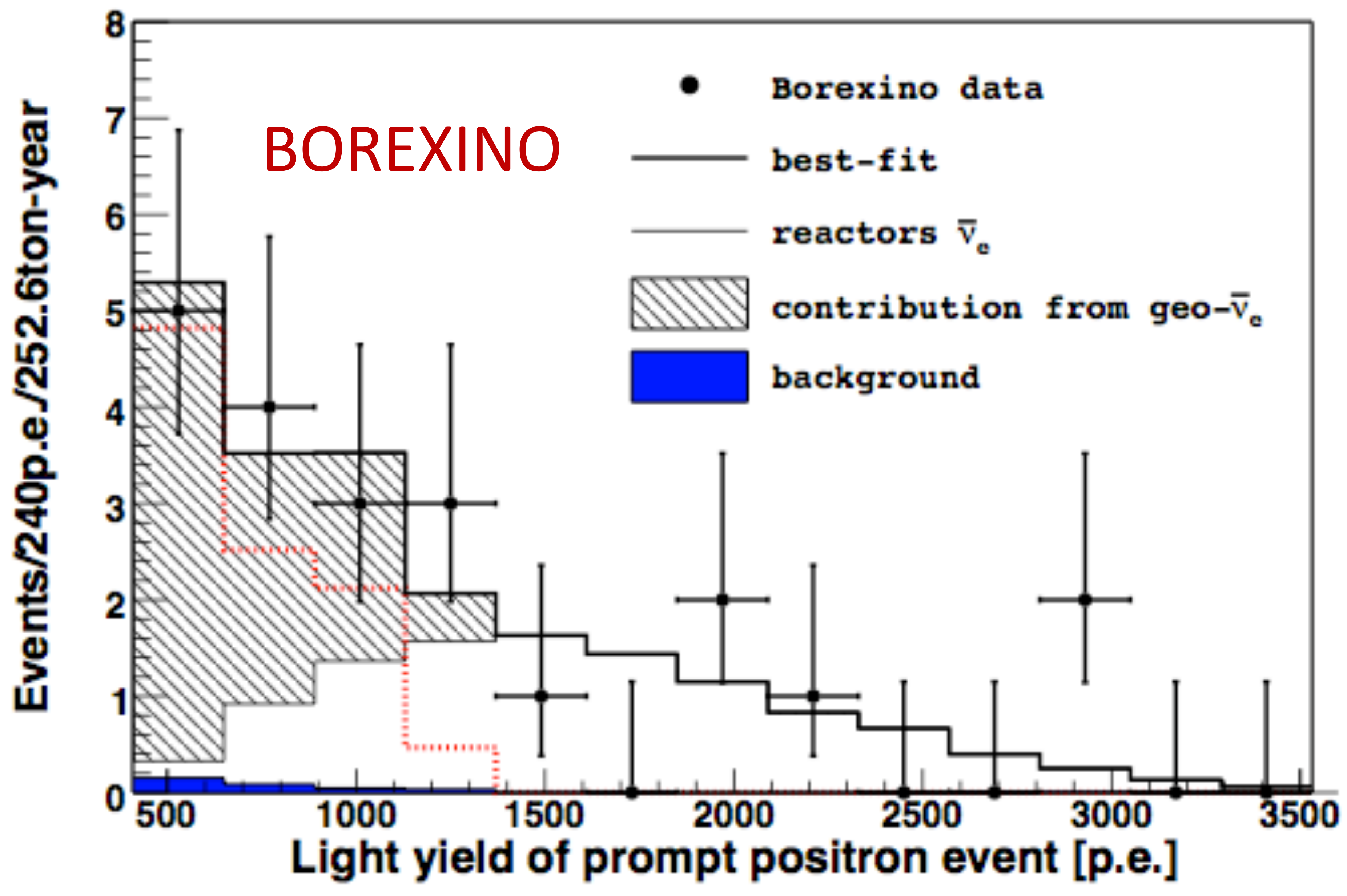
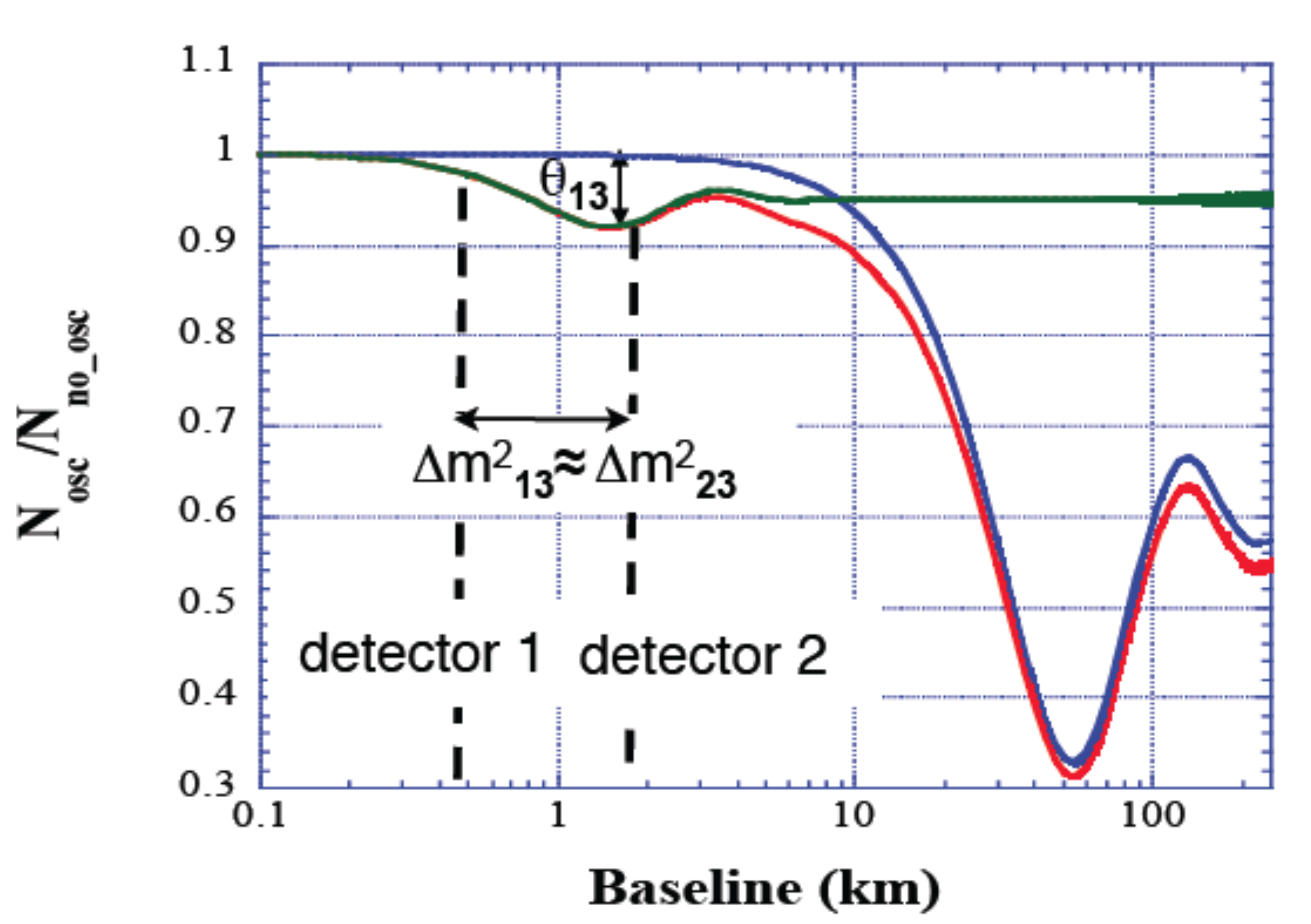


Figure 3: Light yield spectrum for the positron prompt events of the 21 $\bar{\nu}_e$ candidates and the best-fit with Eq. (5) (solid thick line). The horizonal axis shows the number of p.e. detected by the PMTs. The small filled area on the lower left part of the spectrum is the background. Thin solid line: reactor–$\bar{\nu}_e$ signal from the fit. Dotted line (red): geo–$\bar{\nu}_e$ signal resulting from the fit. The darker area isolates the contribution of the geo–$\bar{\nu}_e$ in the total signal. The conversion from p.e. to energy is approximately 500 p.e./MeV.

2012: First measurement of θ_{13}

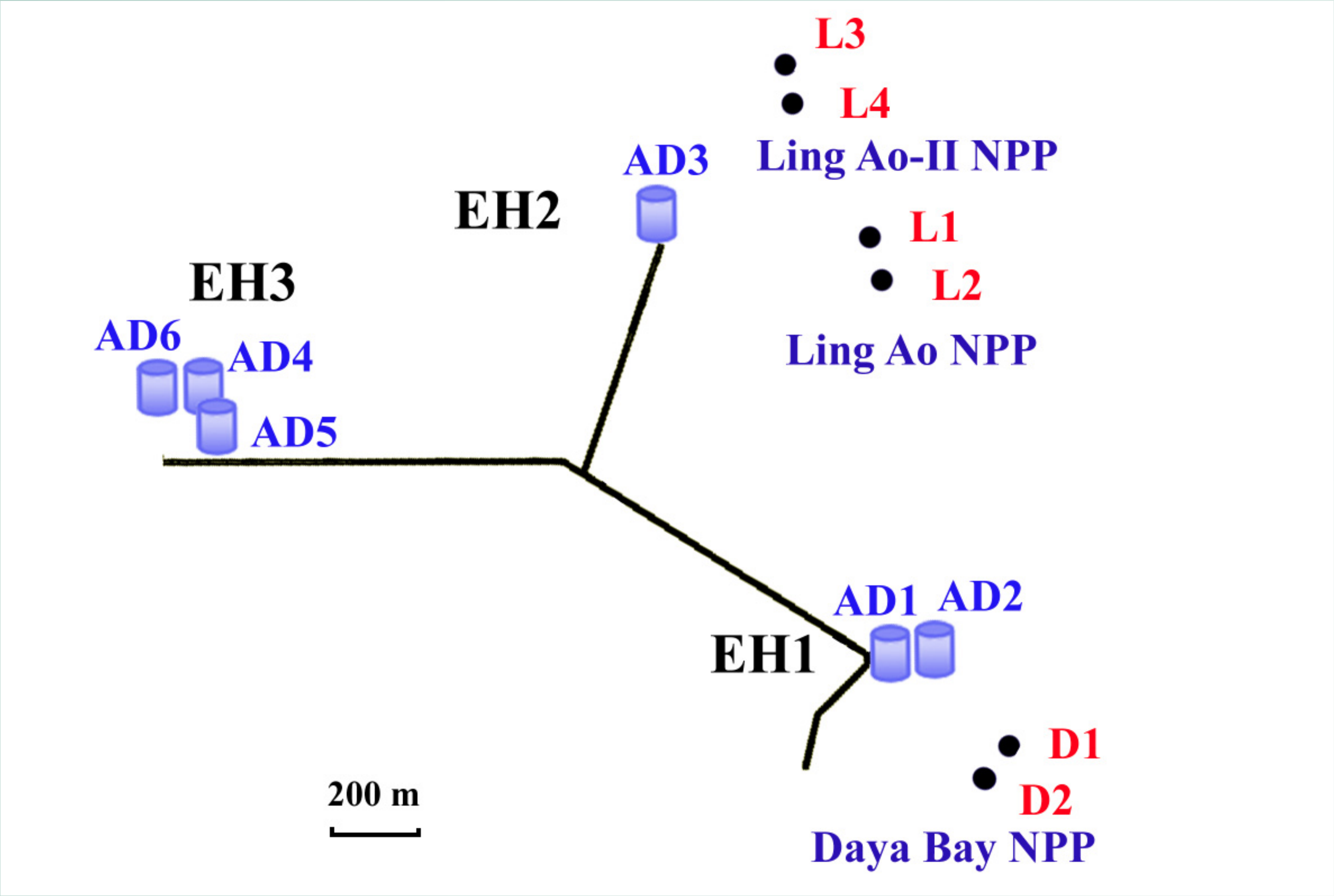
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

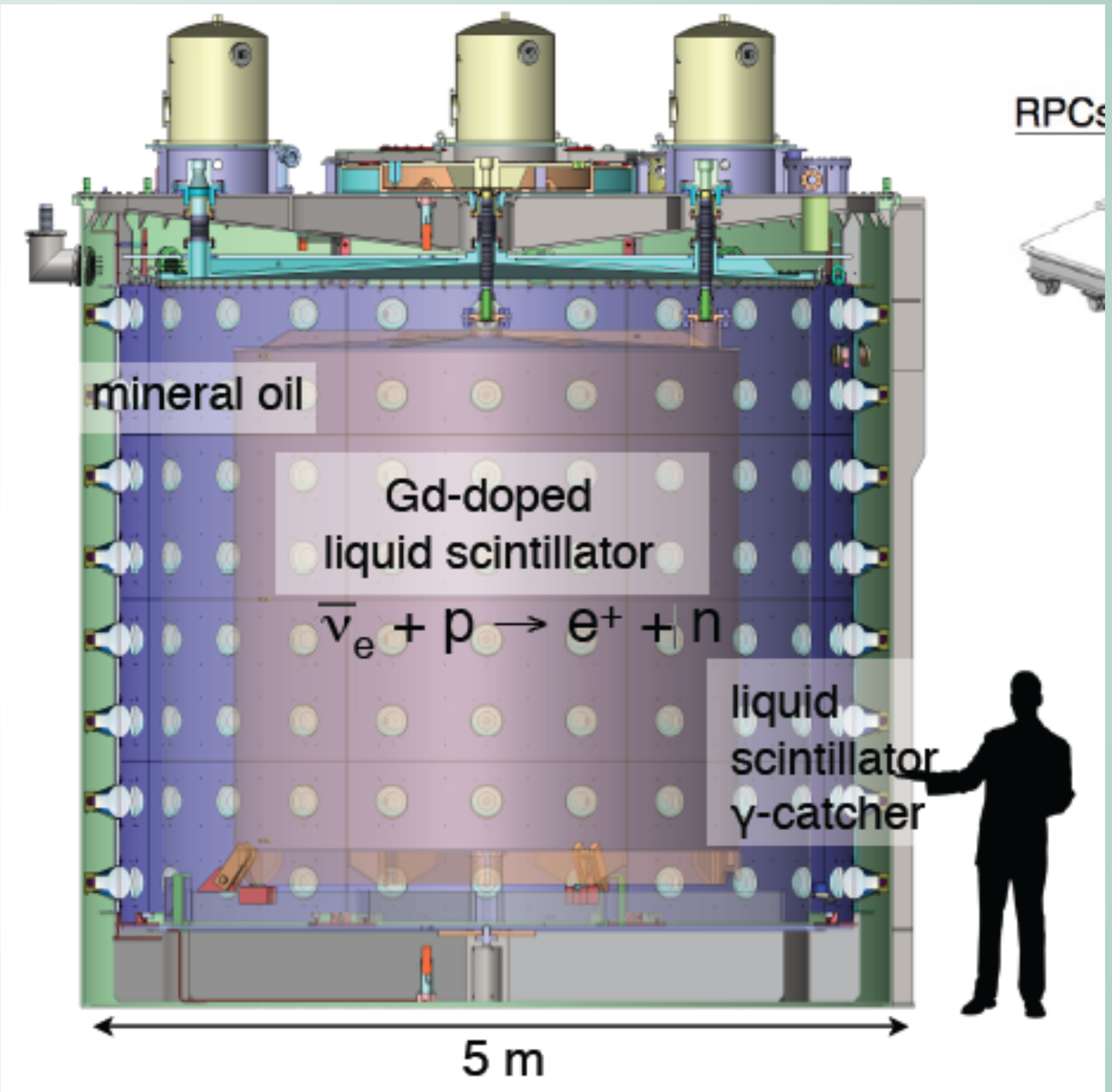
- Non-zero θ_1
- Important c
- ~ 1km baseline
- Exquisite control of systematic errors to ~1%
- Two, identical detector concept:
    - Near detector monitors reactor output
    - Far detector (1 ~km) searches for ν_e disappearance
    - Cancels many systematics



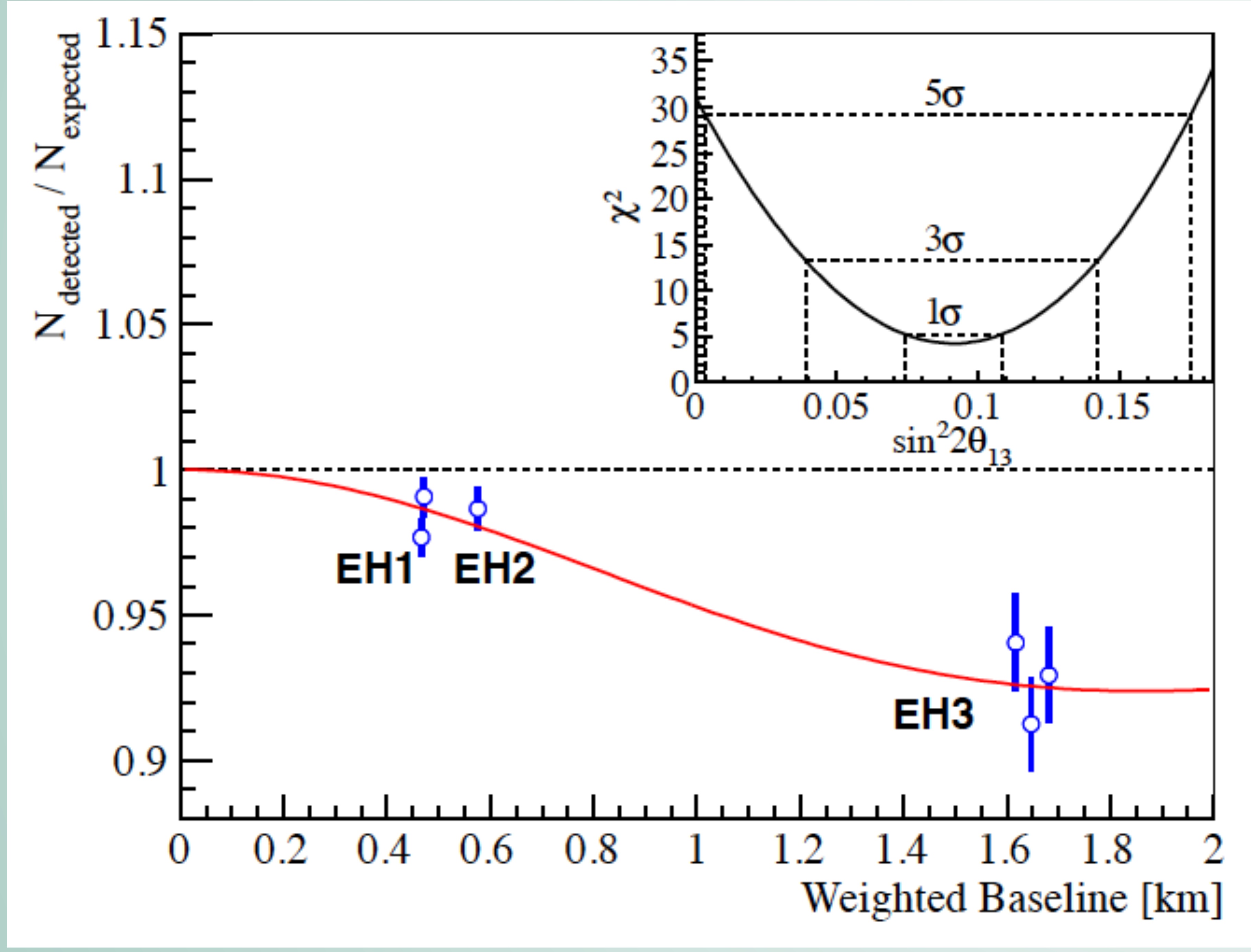
$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

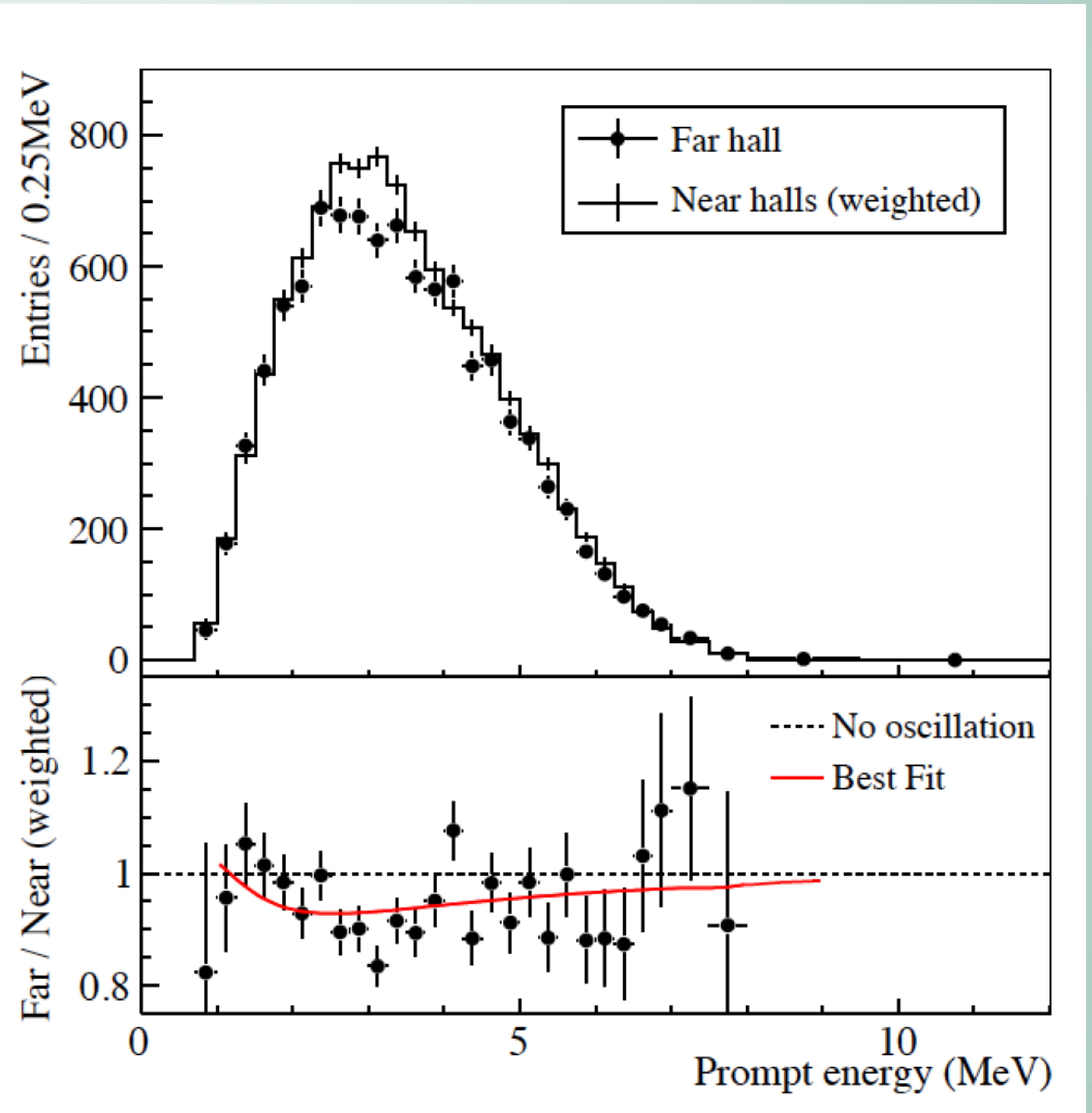
Three Experiments Realized :
Daya Bay





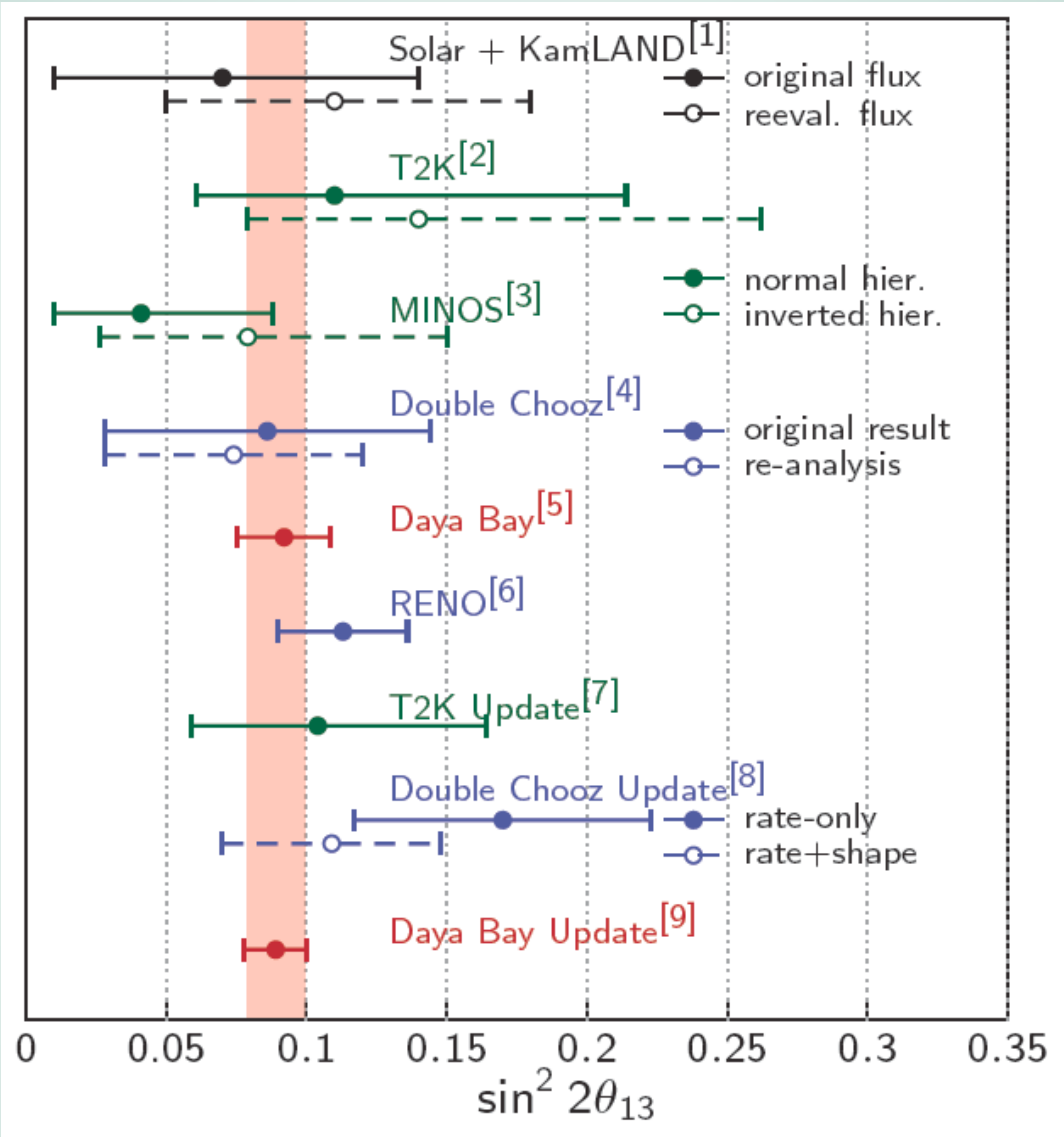
2012: Daya Bay does First measurement of θ_{13}





Pure rate. Shape measurement in progress

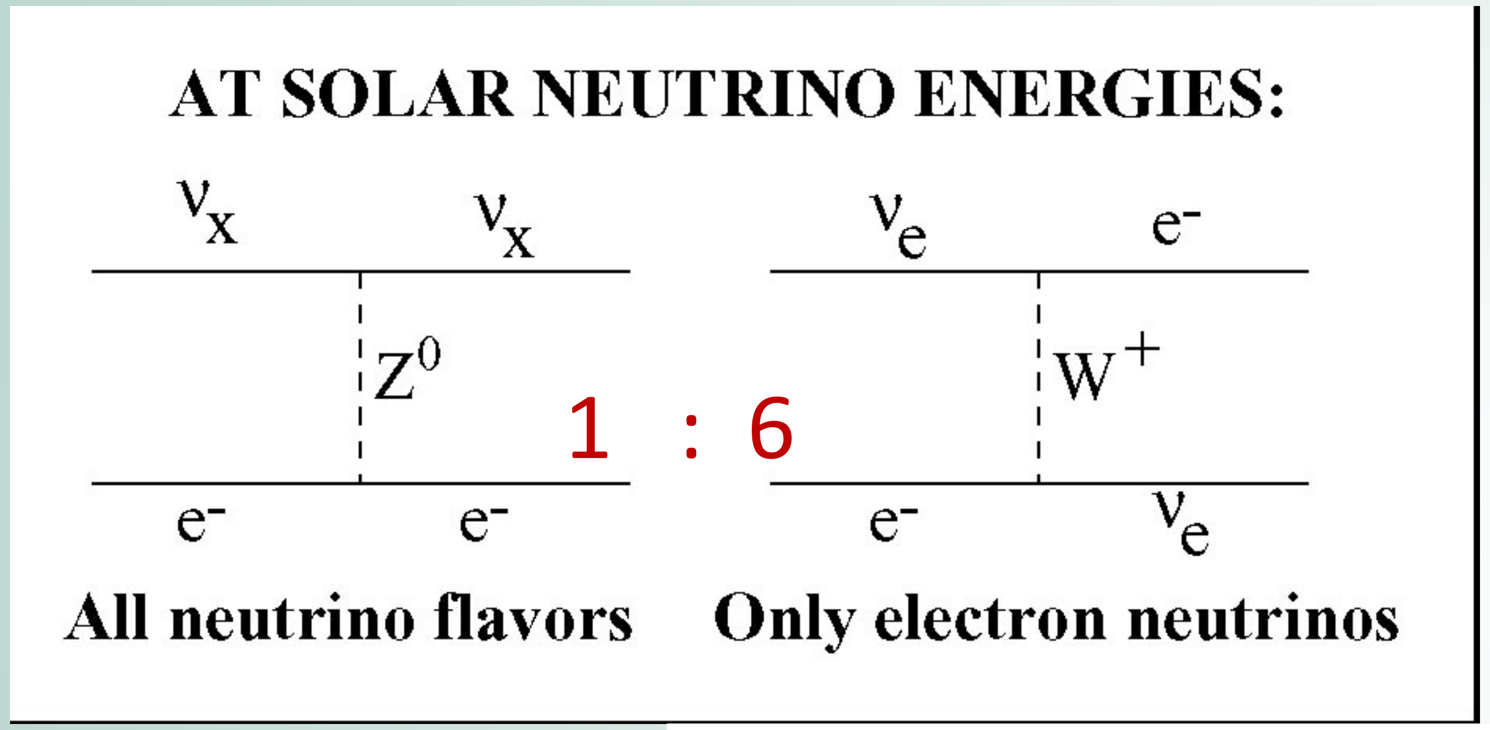
RENO, Double CHOOZ, and others follow.



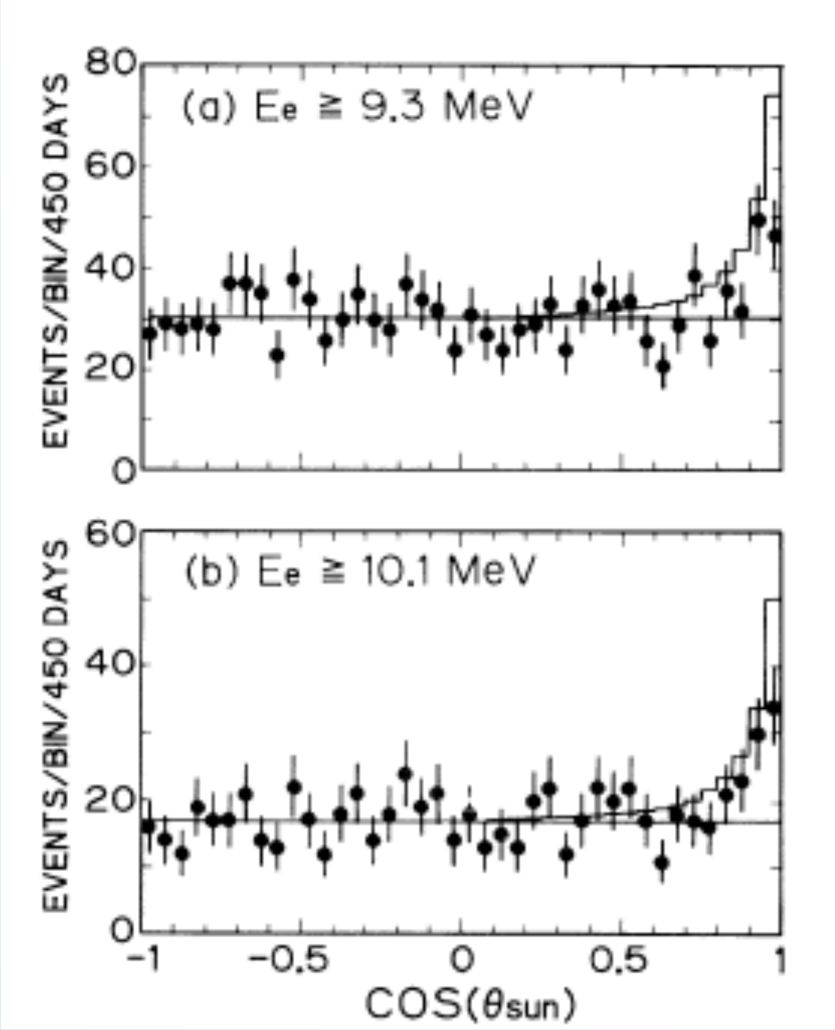
Kamiokande-II and Super-K

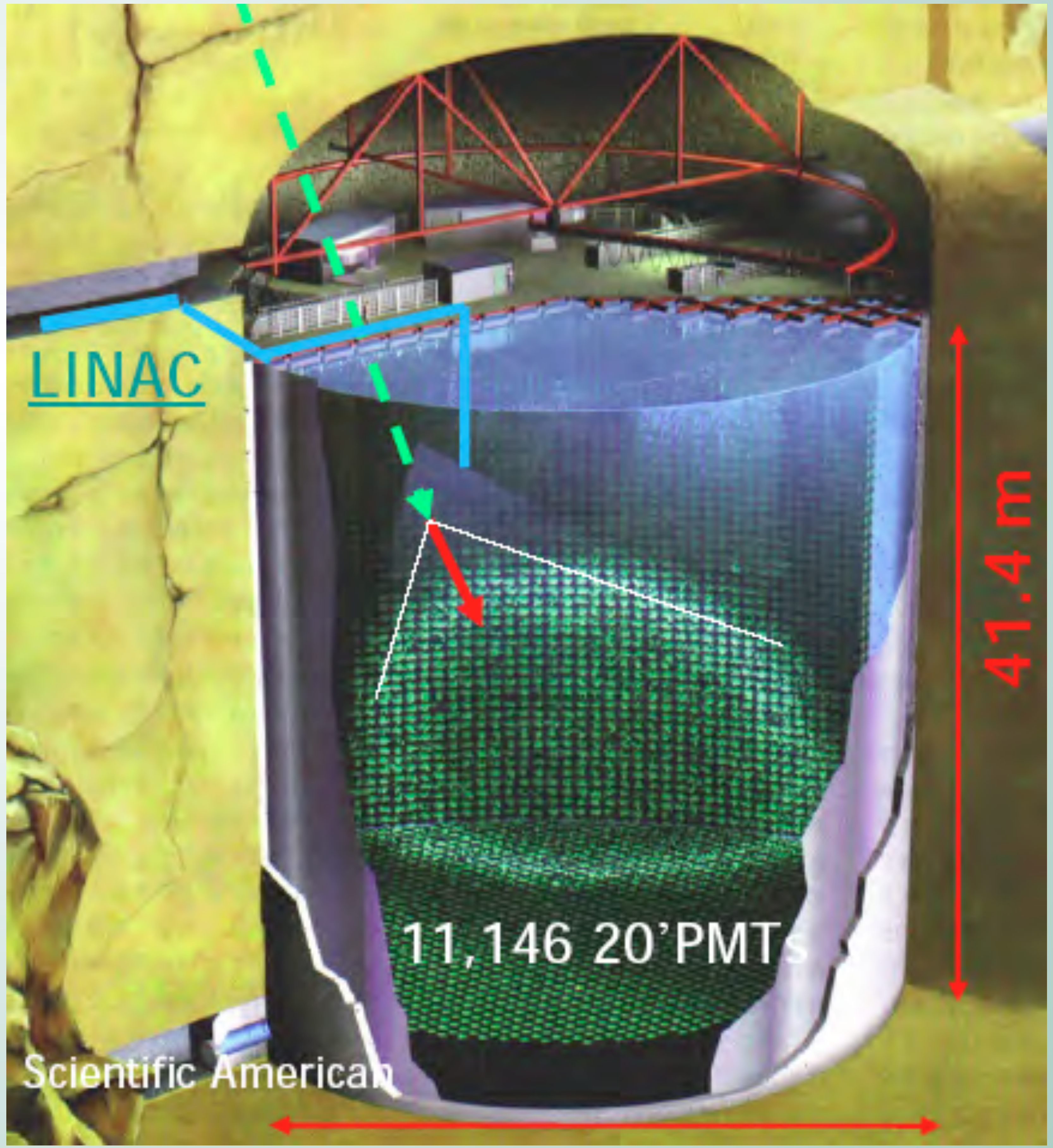
Detect High Energy ^{8}B neutrinos via neutrino electron elastic scattering:

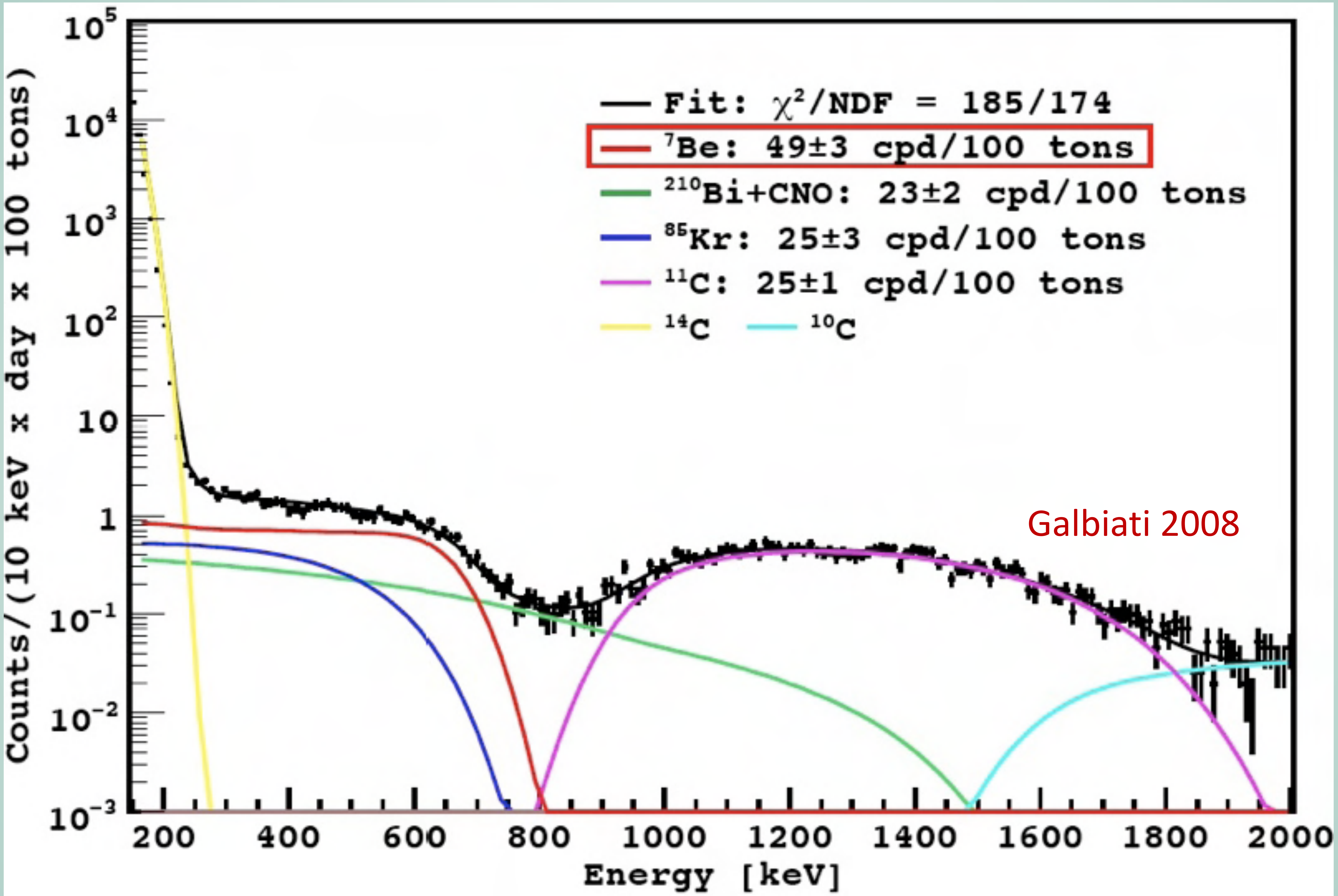
$$\nu_X + e^- \rightarrow \nu_X + e^-$$



1989: K-II shows Neutrinos are from sun!







Galbiati 2008

Solar neutrinos combined