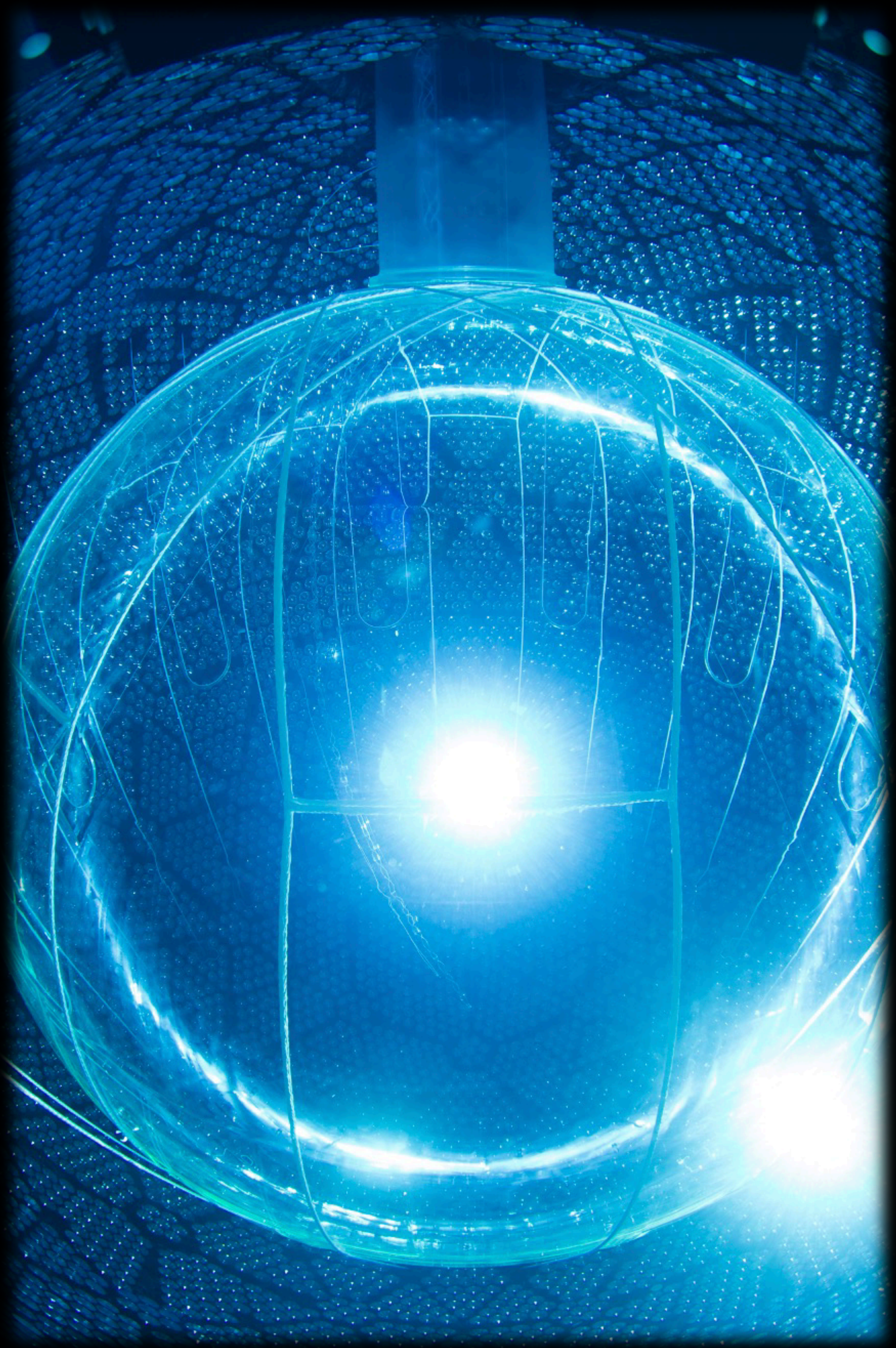

NEUTRINO SCIENCE 3

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SNOLAB UNDERGROUND SCIENCE INSTITUTE
JULY 22 - AUGUST 2, 2024 SUDBURY, CANADA

OVERALL PLAN OF THE 5 LECTURES

1. Neutrinos in the Standard Model.
2. Neutrino interactions, detectors. Solar and atmospheric neutrino problems.
3. Neutrino oscillations in 2 flavors. SNO and SK.
4. Neutrino oscillations in 3 flavors. Future experiments.
5. Theory and search for neutrino masses. Neutrinoless double-beta decay. Neutrinos in Cosmology and Astrophysics.

- Theory and experiment will be strongly mingled.
- Every lecture will have some of both.

PLAN FOR LECTURE 3

- Two-neutrino oscillations
  - History of the oscillation hypothesis
  - Derivation of the 2-ν vacuum oscillations formula
  - Matter effects
- Finding evidence for oscillations
  - with solar neutrinos: Sudbury Neutrino Observatory
  - … and early confirmations with terrestrial sources: KamLAND
-

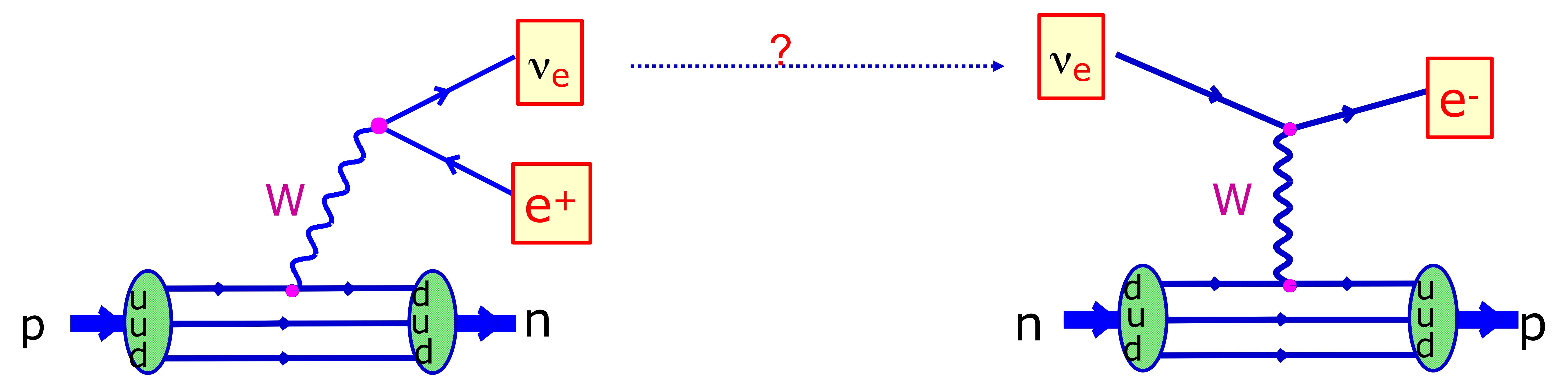
OSCILLATIONS

THE DAWN OF OSCILLATIONS

- 1957 Pontecorvo suggests $\nu \leftrightarrow \bar{\nu}$ oscillations, following an analogy with $K^0 \leftrightarrow \bar{K}^0$
  - apparently he heard rumors that Davis' Chlorine reactor experiment had seen events…
- 1962 Maki, Nakagawa, Sakata suggest mixing between massive neutrino states ν_1, ν_2 and massless ν_e, ν_μ but without referring oscillations
- 1967 Pontecorvo suggests $\nu_e \leftrightarrow \nu_\mu$ oscillations
  - mentions the Sun as the ideal source to test the idea
- 1969 Gribov, Pontecorvo: first survival probability calculation
- 1976 Bilenky, Pontecorvo: quark lepton analogy, "modern" formulation
- 1978 Wolfenstein describes matter effects in oscillation
- 1985 Mikheyev, Smirnov describe resonance of matter effects in media with large densities (e.g. Sun) → MSW effect

NEUTRINO FLAVORS

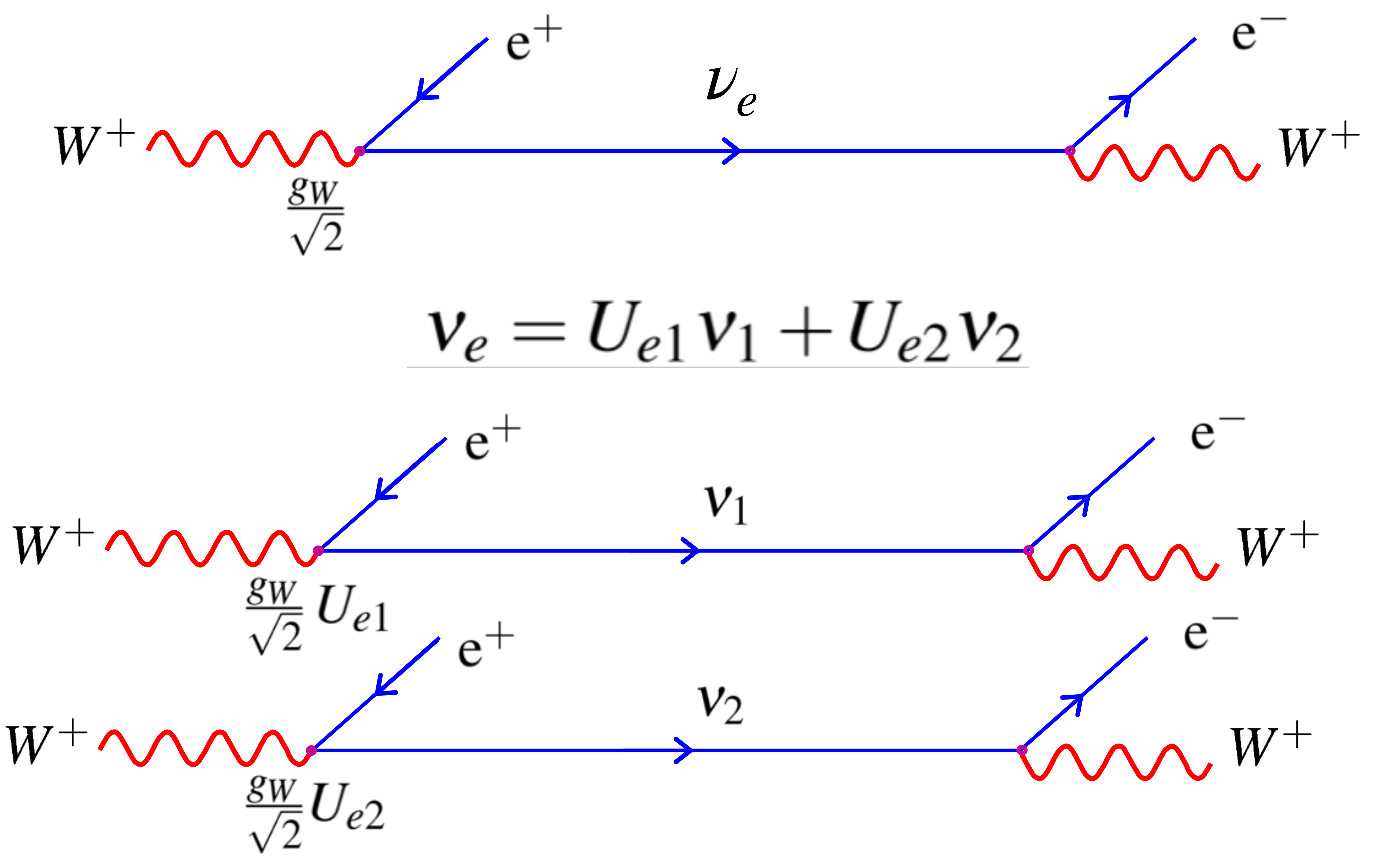
- Neutrinos only interact weakly. So our only handle to identify their states is through their weak interaction:
- By **definition**, ν_e is the state that is produced along with an electron
    - Similarly for the other flavors: ν_e, ν_μ, ν_τ are weak eigenstates
- Are these fundamental states?
- Experimentally, the neutrinos produced along with a flavor produced the same flavor when detected



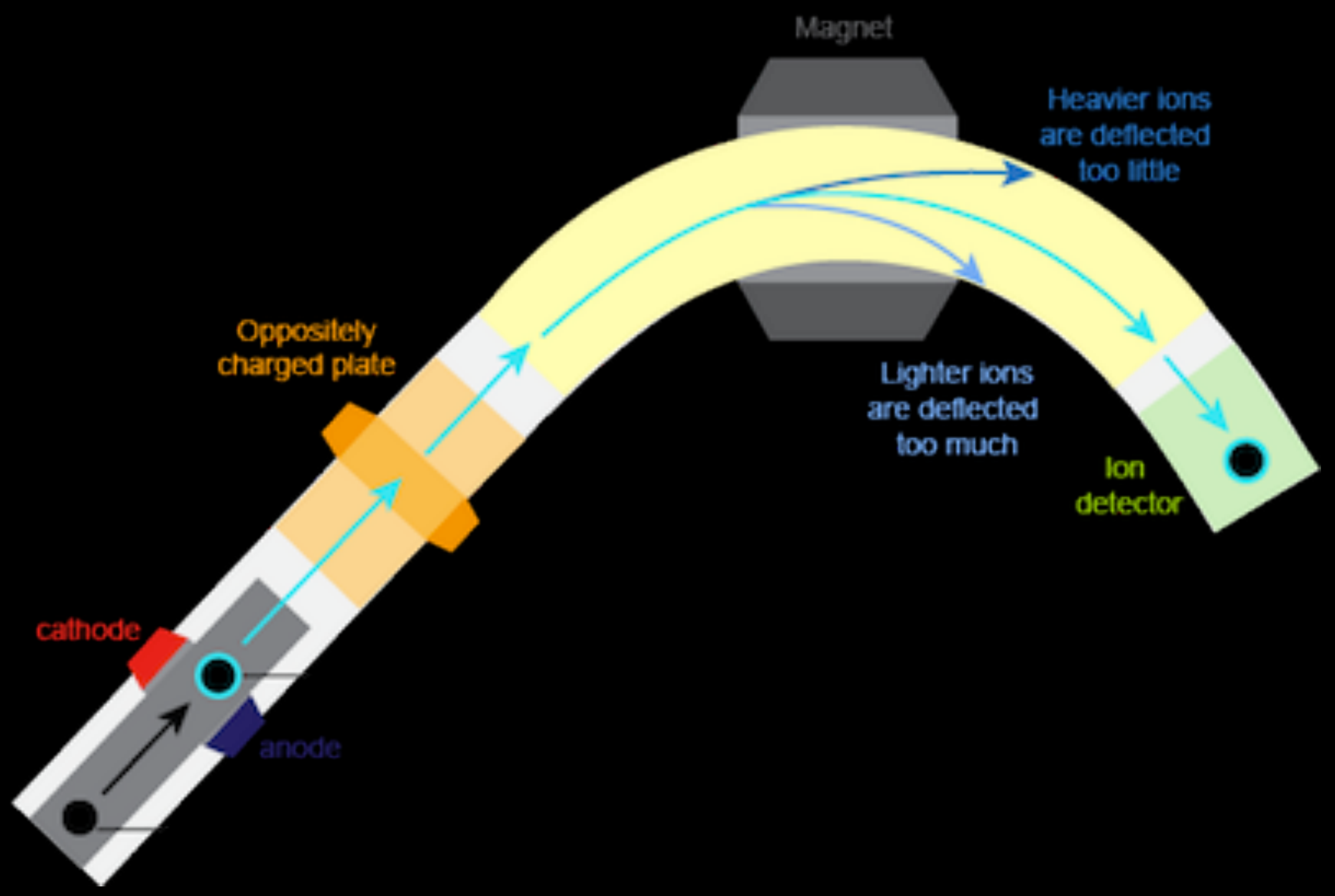
Except for the "two clouds" of solar and atmospheric neutrinos…

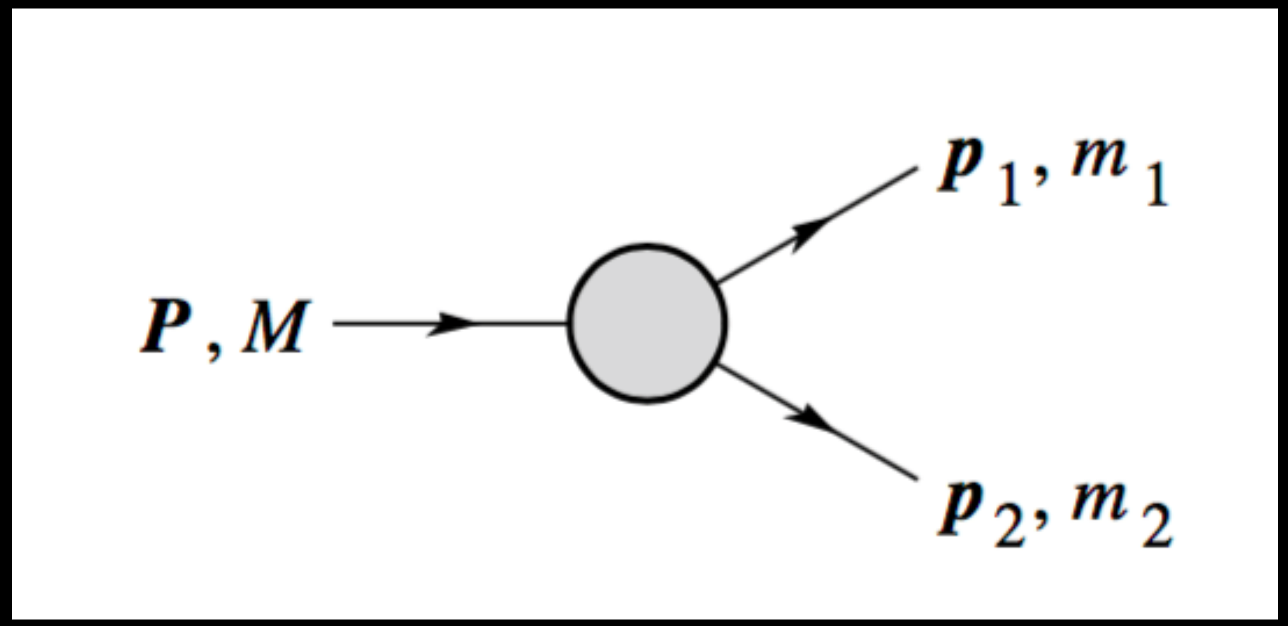
MASS AND WEAK EIGENSTATES

- Neutrino oscillations are based on the superposition of states.
  - States ν_e, ν_μ that couple to the weak bosons, the weak (or flavor) eigentstates
  - States ν_1, ν_2 with definite masses, the eigenstates of the free Hamiltonian

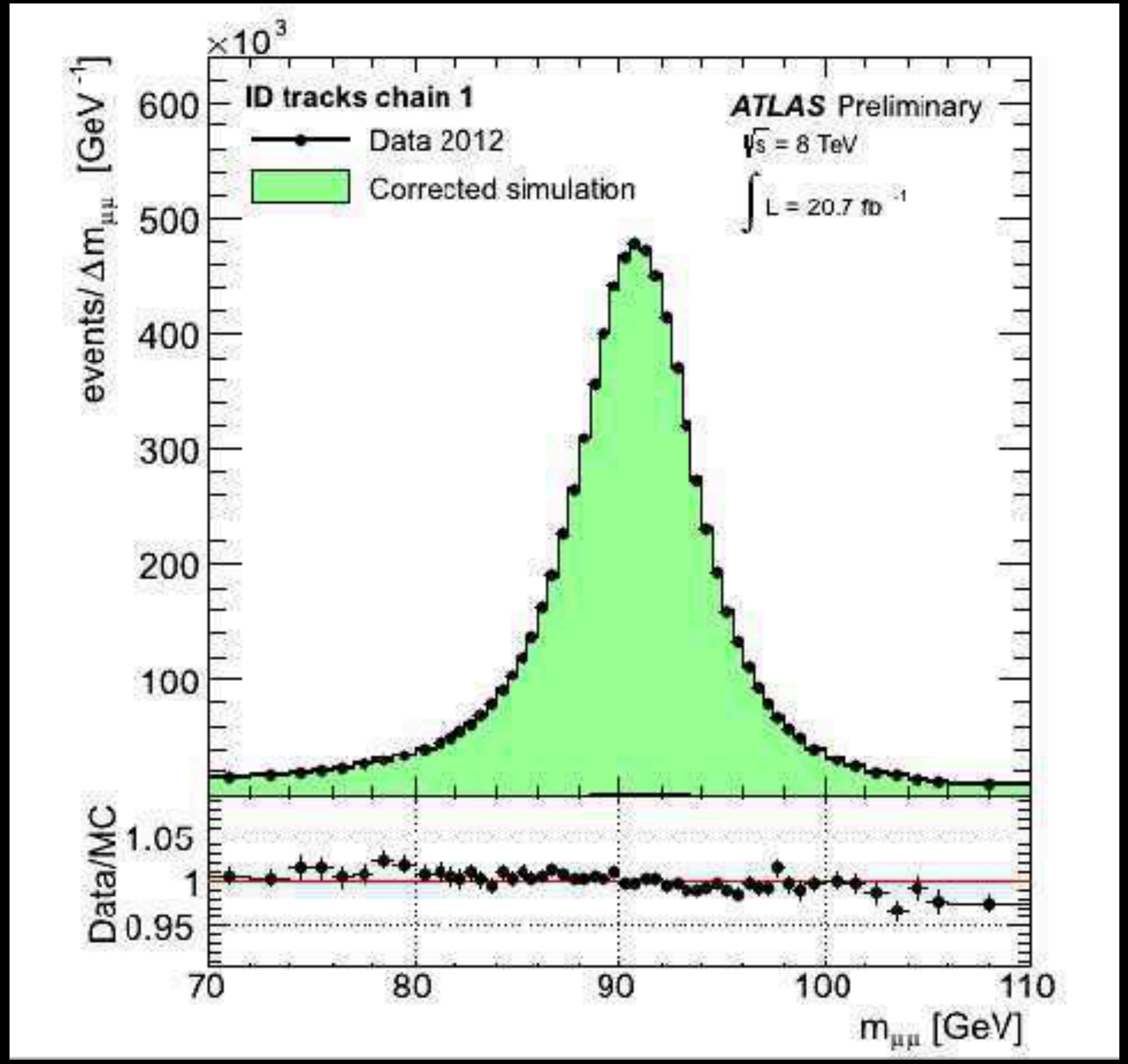


NEUTRINO MASS IS HARD TO MEASURE



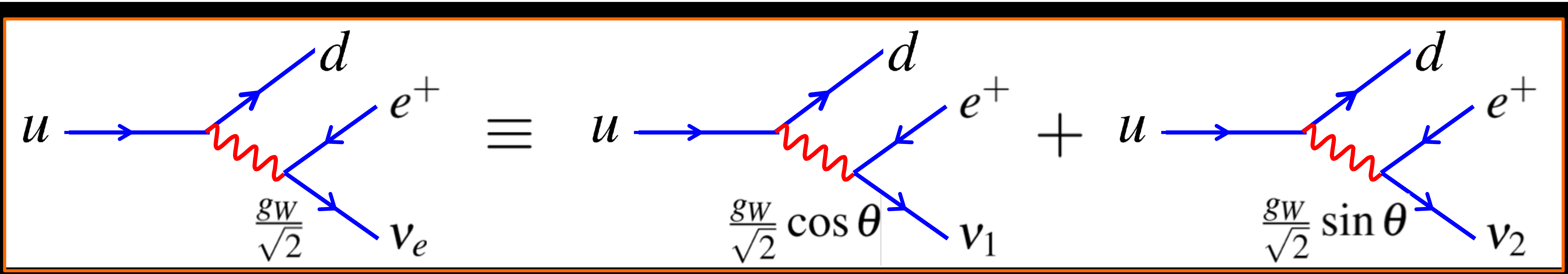


$$M^2=(E_1+E_2)^2-(\vec{p}_1+\vec{p}_2)^2$$



- Usual techniques don’t work…
- Measure their track curvature in a magnetic field
  - neutrinos are neutral, not affected by EM fields ✗
- Measure energy and momentum of daughter particles ?
  - Neutrinos are the lightest particles, don’t decay in others ✗
- Use quantum interference to probe neutrino mass ✓

OSCILLATIONS IN 2 FLAVOURS



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

$$|\nu_1(t)\rangle = |\nu_1\rangle e^{i\vec{p}_1.\vec{x} - iE_1 t}$$

$$|\nu_2(t)\rangle = |\nu_2\rangle e^{i\vec{p}_2.\vec{x} - iE_2 t}$$

- The gist of it:
  - Neutrino produced in a weak eigenstate
  - … that is a superposition of two mass eigenstates
  - … but phases change with time so the mass composition may be different at detection
  - Neutrino detected in a weak eigenstate that may not be the initial one

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

OSCILLATIONS IN 2 FLAVOURS

- At time t=0, neutrino produced in a pure ν_e state along z axis

$$|\psi(0)\rangle = |\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

- Wave function time evolution: mass eigenstates as plane waves

$$p_i.x = E_i t - \vec{p}_i.\vec{x} = E_i t - |\vec{p}_i|z$$

$$|\psi(t)\rangle = \cos\theta|\nu_1\rangle e^{-ip_1\cdot x} + \sin\theta|\nu_2\rangle e^{-ip_2\cdot x}$$

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

- Plugging in the mass states as a function of weak states

$$|\psi(t)\rangle = \cos\theta\left(\cos\theta|\nu_e\rangle - \sin\theta|\nu_\mu\rangle\right)e^{-ip_1\cdot x} + \sin\theta\left(\sin\theta|\nu_e\rangle + \cos\theta|\nu_\mu\rangle\right)e^{-ip_2\cdot x}$$

- Grouping the terms for each weak state

$$|\psi(t)\rangle = |\nu_e\rangle\left(\cos^2\theta e^{-ip_1\cdot x} + \sin^2\theta e^{-ip_2\cdot x}\right) + |\nu_\mu\rangle\sin\theta\cos\theta\left(\underbrace{-e^{-ip_1\cdot x} + e^{-ip_2\cdot x}}_{=0}\right)$$

if $p_1=p_2$ (i.e. if $m_1=m_2$)

so $|\psi(t)\rangle = |\nu_e\rangle e^{-ip_1\cdot x}$

OSCILLATIONS IN 2 FLAVOURS

$$|\psi(t)\rangle = |\nu_e\rangle\left(\cos^2\theta e^{-ip_1\cdot x} + \sin^2\theta e^{-ip_2\cdot x}\right) + |\nu_\mu\rangle\sin\theta\cos\theta\left(-e^{-ip_1\cdot x} + e^{-ip_2\cdot x}\right)$$

- If the masses are different $m_1 \neq m_2$, then the different flavour component is non-zero!
- What's the probability of seeing it? (QM recap: amplitude^2)

$$\begin{aligned} P\left(\nu_e \to \nu_\mu\right) &= |\langle\nu_\mu|\psi(t)\rangle|^2 \\ &= \cos^2\theta\sin^2\theta\left(-e^{-ip_1\cdot x} + e^{-ip_2\cdot x}\right)\left(-e^{ip_1\cdot x} + e^{ip_2\cdot x}\right) \\ &= \frac{1}{4}\sin^2 2\theta\left(2 - 2\cos\left(p_1\cdot x - p_2\cdot x\right)\right) \\ &= \sin^2 2\theta\sin^2\left(\frac{p_1\cdot x - p_2\cdot x}{2}\right) \end{aligned}$$

Assuming

$$|\vec{p_1}| = |\vec{p_2}| = p$$

and t~L

$$\begin{aligned} p_1\cdot x - p_2\cdot x &= (E_1 - E_2)t \\ &= \left(\sqrt{p^2 - m_1^2} - \sqrt{p^2 - m_2^2}\right)L \\ &= \left(\sqrt{1 - \frac{m_1^2}{p^2}} - \sqrt{1 - \frac{m_2^2}{p^2}}\right)pL \\ &\approx \frac{m_1^2 - m_2^2}{2E}L = \frac{\Delta m^2 L}{2E} \end{aligned}$$

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

OSCILLATION IN 2 FLAVORS

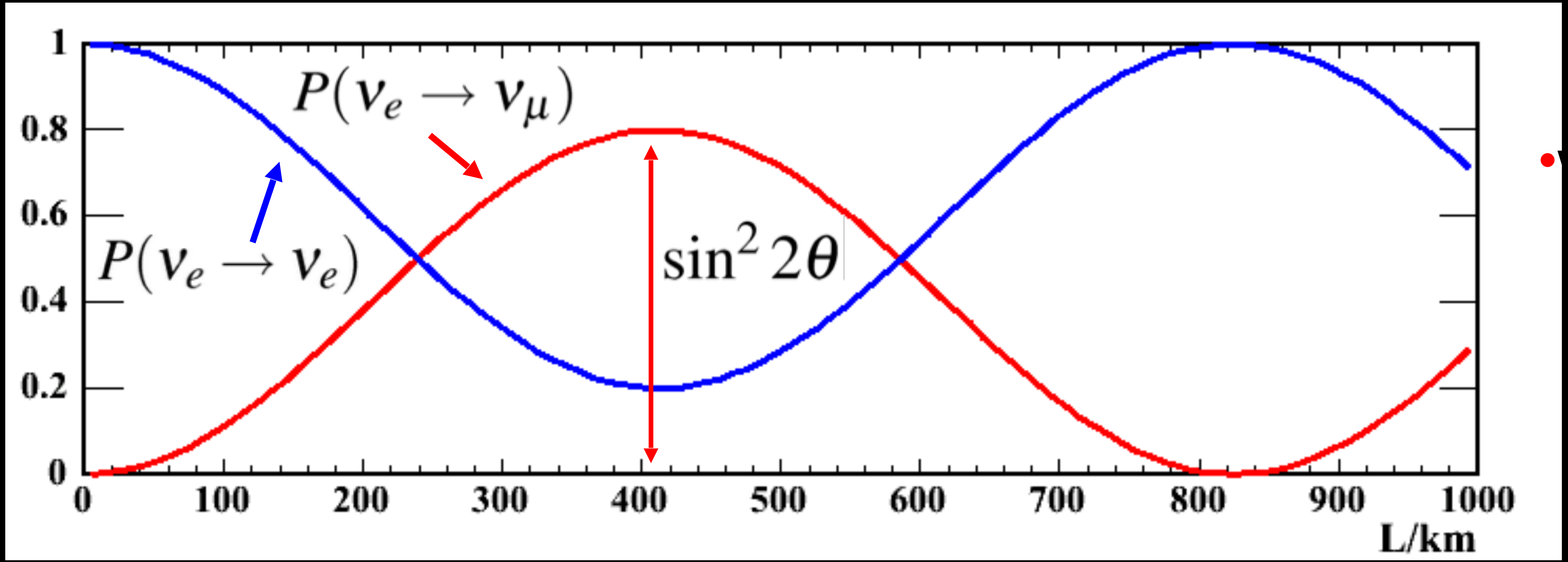
$$\Delta m^2_{21} = m^2_2 - m^2_1$$

- Oscillation probability $P\left(\nu_e \to \nu_\mu\right) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$
- Survival probability $P\left(\nu_e \to \nu_e\right) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$

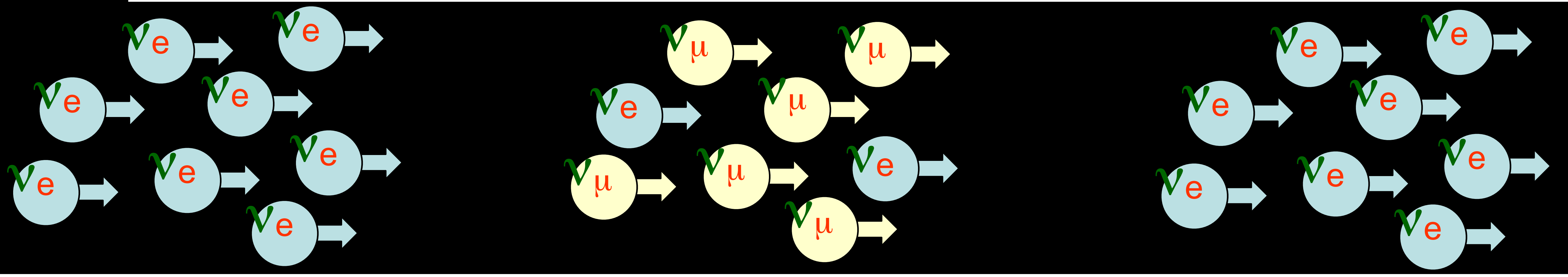
$$1.27\frac{\Delta m^2_{21}[eV^2]L[km]}{4E[GeV]}$$

Example

$$\Delta m^2 = 0.003\,\mathrm{eV}^2$$
$$\sin^2 2\theta = 0.8$$
$$E_\nu = 1\,\mathrm{GeV}$$

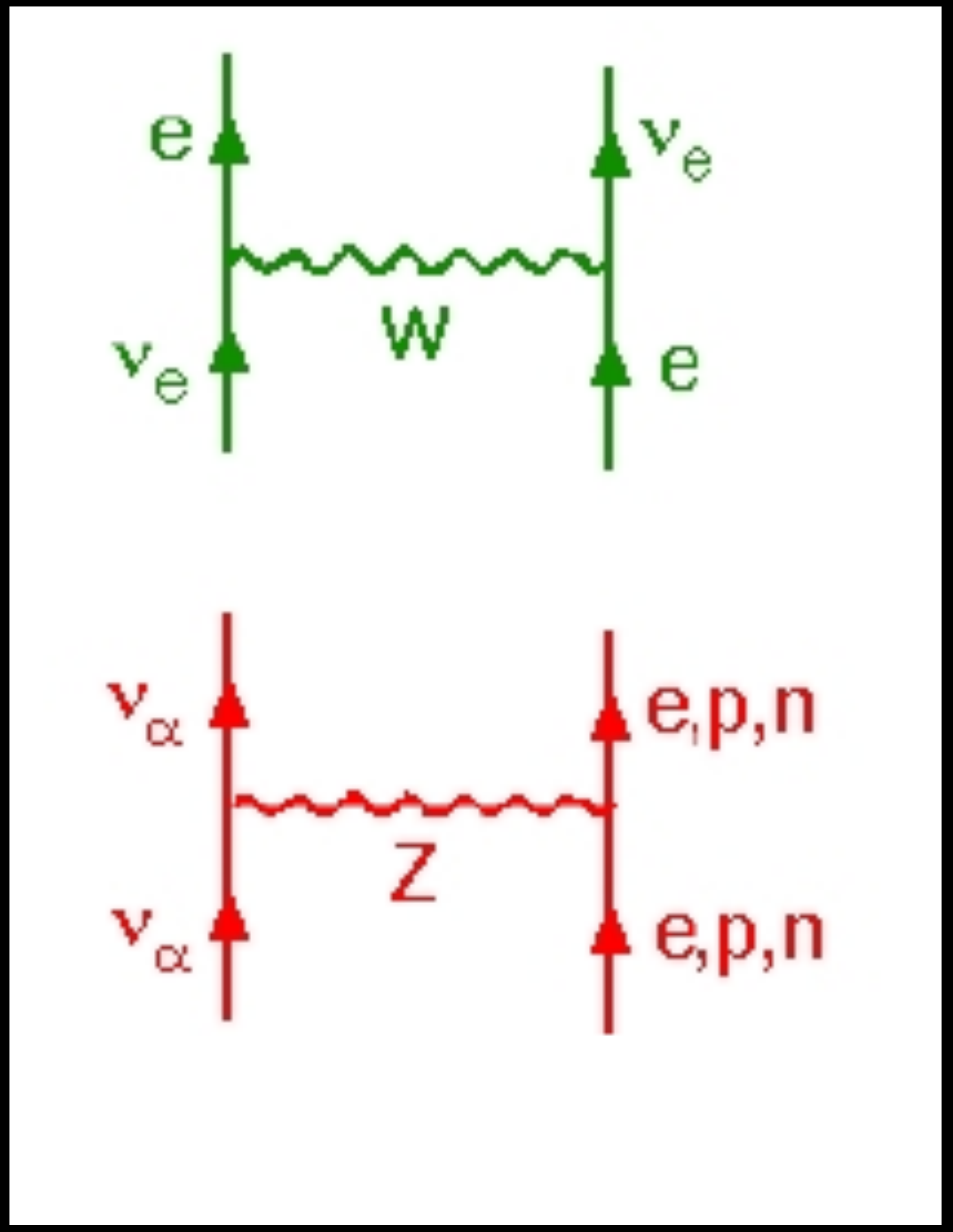


$$\lambda_{\rm osc} = \frac{4\pi E}{\Delta m^2}$$



MATTER EFFECTS

NEUTRINO POTENTIAL IN MATTER



- Coherent forward scattering gives rise to extra potential energy
  - ν_e (and only ν_e) can exchange a W boson with electrons in matter
    - $V_W = \pm\sqrt{2}G_F N_e$. + for ν_e, − for $\bar{\nu}_e$, N_e is the density of electrons.
  - all neutrinos can exchange a Z boson with electrons, neutrons, protons
    - the term for electrons and protons cancels out
    - $V_Z = \mp\frac{\sqrt{2}}{2}G_F N_n$. − for ν, + for $\bar{\nu}$, N_n is the density of neutrons.

MIXING IN MATTER

$$i\frac{d}{dx}\begin{bmatrix}\nu_e\\ \nu_\mu\end{bmatrix}=\frac{1}{2E}M^2\begin{bmatrix}\nu_e\\ \nu_\mu\end{bmatrix}=\frac{1}{2E}\left[U\begin{bmatrix}m_1^2 & 0\\ 0 & m_2^2\end{bmatrix}U^\dagger+\begin{bmatrix}A & 0\\ 0 & 0\end{bmatrix}\right]\begin{bmatrix}\mu_e\\ \nu_\mu\end{bmatrix}$$

$$=\frac{1}{4E}\left[(\Sigma+A)+\begin{bmatrix}A-\Delta C_{2\theta} & \Delta S_{2\theta}\\ \Delta S_{2\theta} & -A+\Delta C_{2\theta}\end{bmatrix}\right]\begin{bmatrix}\nu_e\\ \nu_\mu\end{bmatrix}$$

$$\Sigma=m_2^2+m_1^2$$

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

$$S_{2\theta}=\sin 2\theta$$

$$C_{2\theta}=\cos 2\theta$$

$$\begin{bmatrix}\nu_1^m\\ \nu_2^m\end{bmatrix}=\begin{bmatrix}\cos\theta_m & -\sin\theta_m\\ \sin\theta_m & \cos\theta_m\end{bmatrix}\begin{bmatrix}\nu_e\\ \nu_\mu\end{bmatrix}$$

$$A\equiv 2\sqrt{2}G_F N_e E=2\sqrt{2}G_F(Y_e/m_n)\rho E$$

(change sign for antineutrinos)

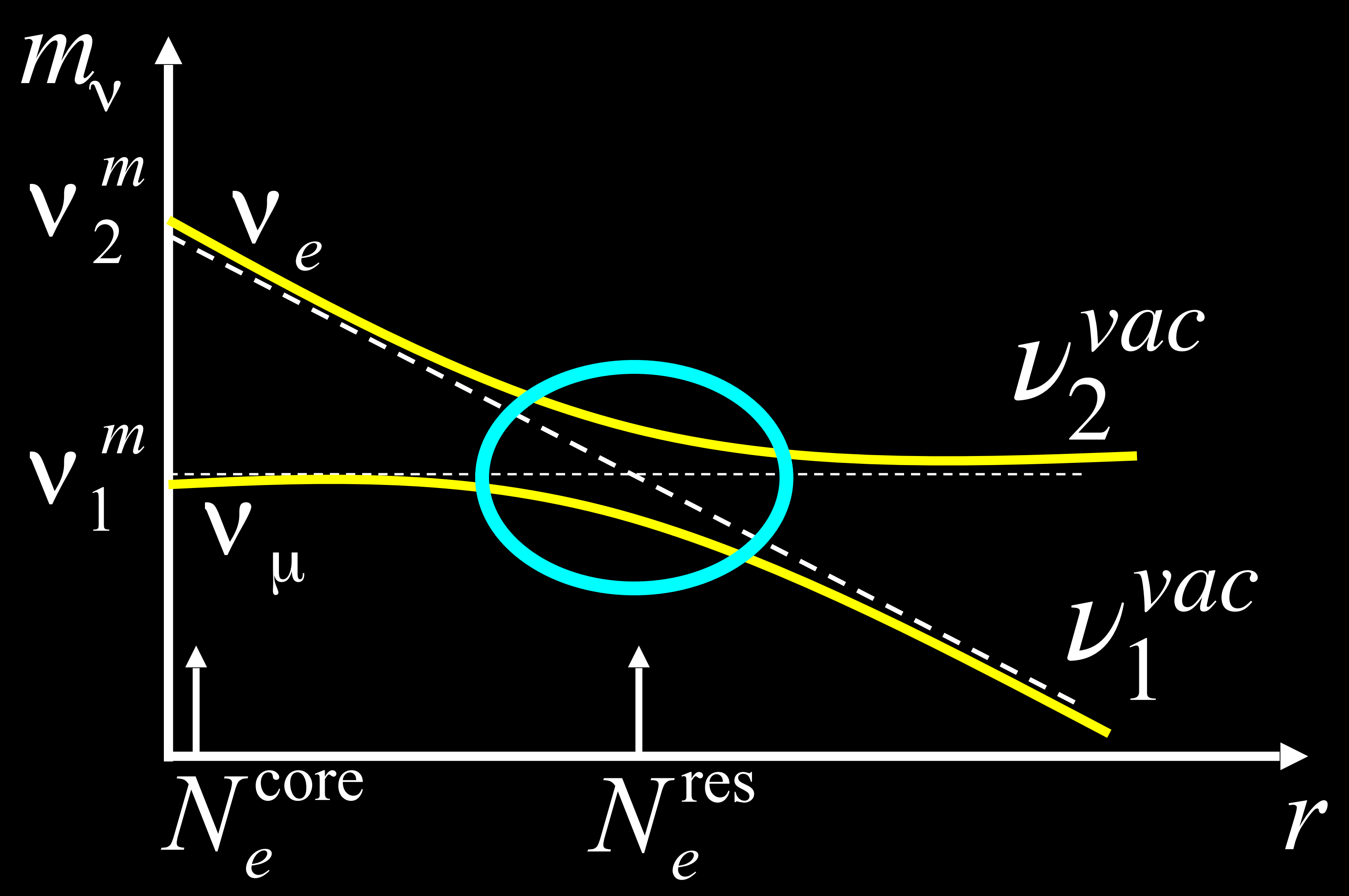
$$M_{2,1}^2=\{(\Sigma+A)\pm[(A-\Delta C_{2\theta})^2+(\Delta S_{2\theta})^2]^{1/2}\}/2\ .$$

$$\sin^2 2\theta_m=(\Delta\sin 2\theta)^2/[(A-\Delta\cos 2\theta)^2+(\Delta\sin 2\theta)^2]$$

Resonant for: $A=\Delta\cos 2\theta$

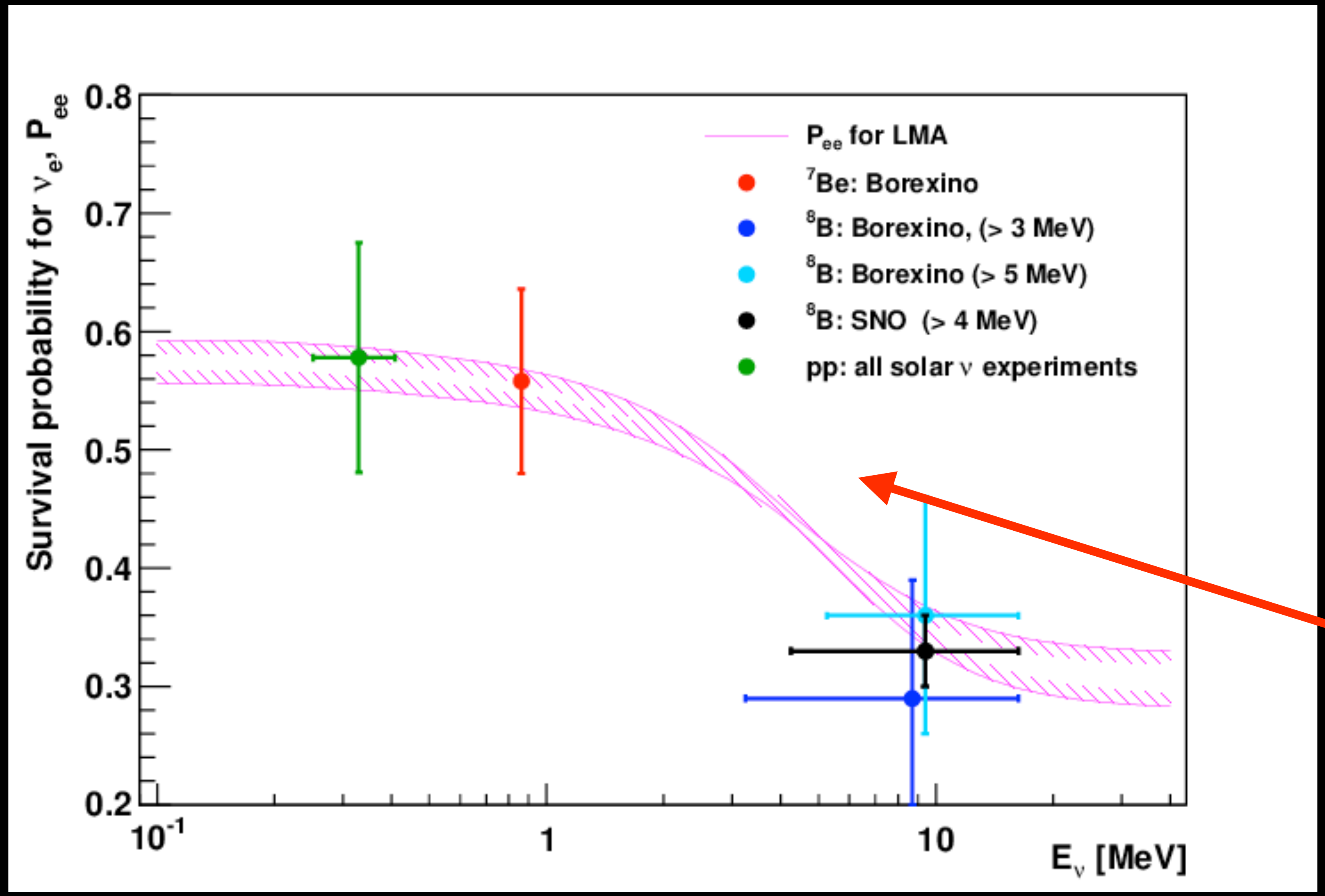
- Equations formally equal to oscillations in vaccuum, but with parameters dependent on density
- θ_m depends on sign of Δ

MSW EFFECT IN THE SUN



$$\Delta m^2 \cdot \frac{\sin^2 2\theta}{\cos 2\theta} \geq 2E_\nu \frac{d \ln N_e}{dr}$$

- Adiabatic condition:
  - slow density gradient
  - neutrinos stay in the same mass eigenstate, as its mass and flavor evolves



- Large densities in the core of the Sun
- Neutrinos produces as ν_e, which are pure ν_2^m
- Emerge as $\nu^{vac} = \sin\theta\nu_e + \cos\theta\nu_\mu$
- Partial conversion

Note expected rise of Pee at low energies. This is a prediction of the MSW effect.

MSW EFFECT IN THE EARTH

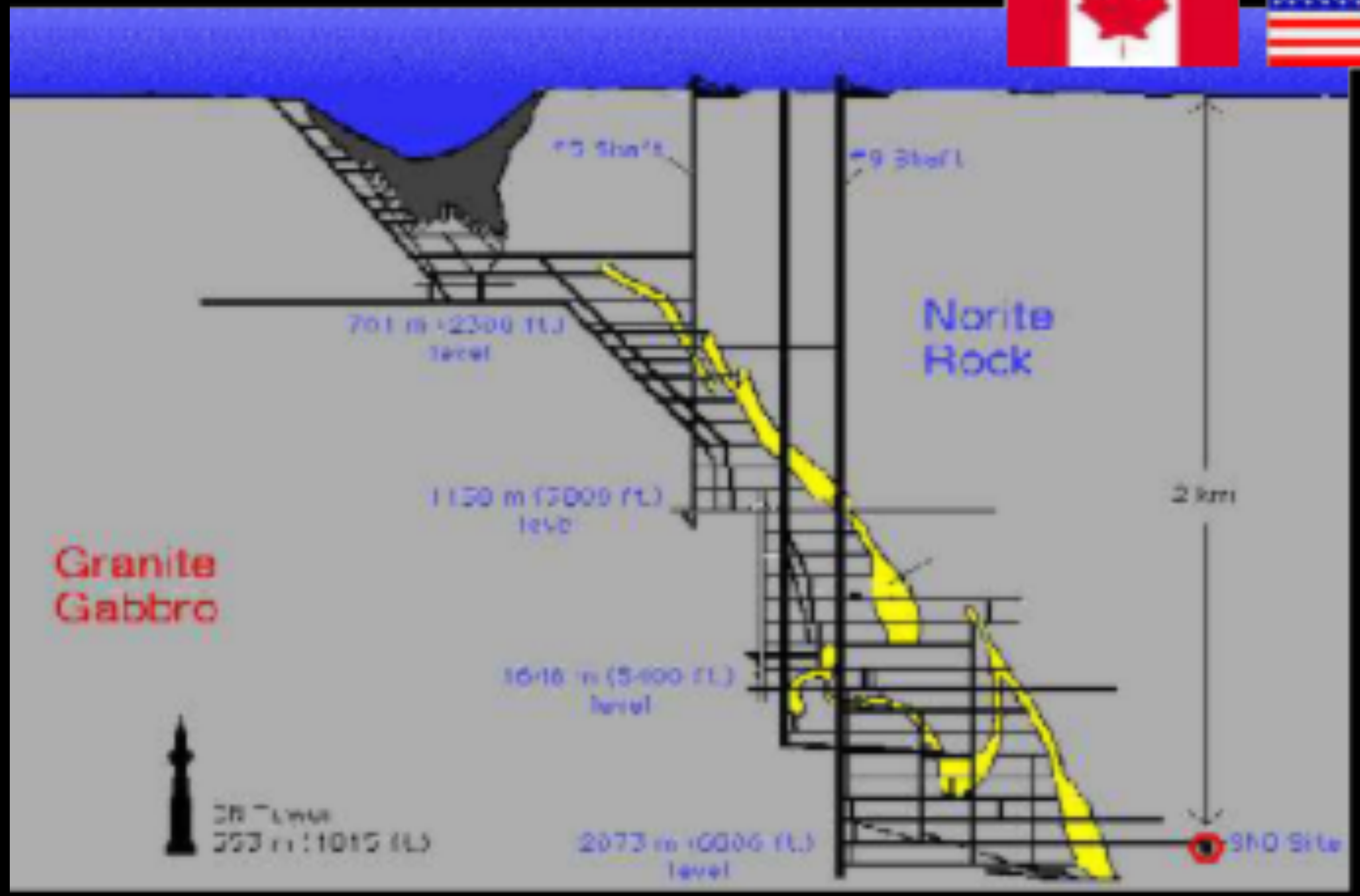
- Solar neutrinos
  - cross the whole Earth, large path and varying density
  - regenerate some of the neutrinos converted to ν_μ in the Sun
  - Day-night effect: Sun is actually "brighter" at night in neutrinos!

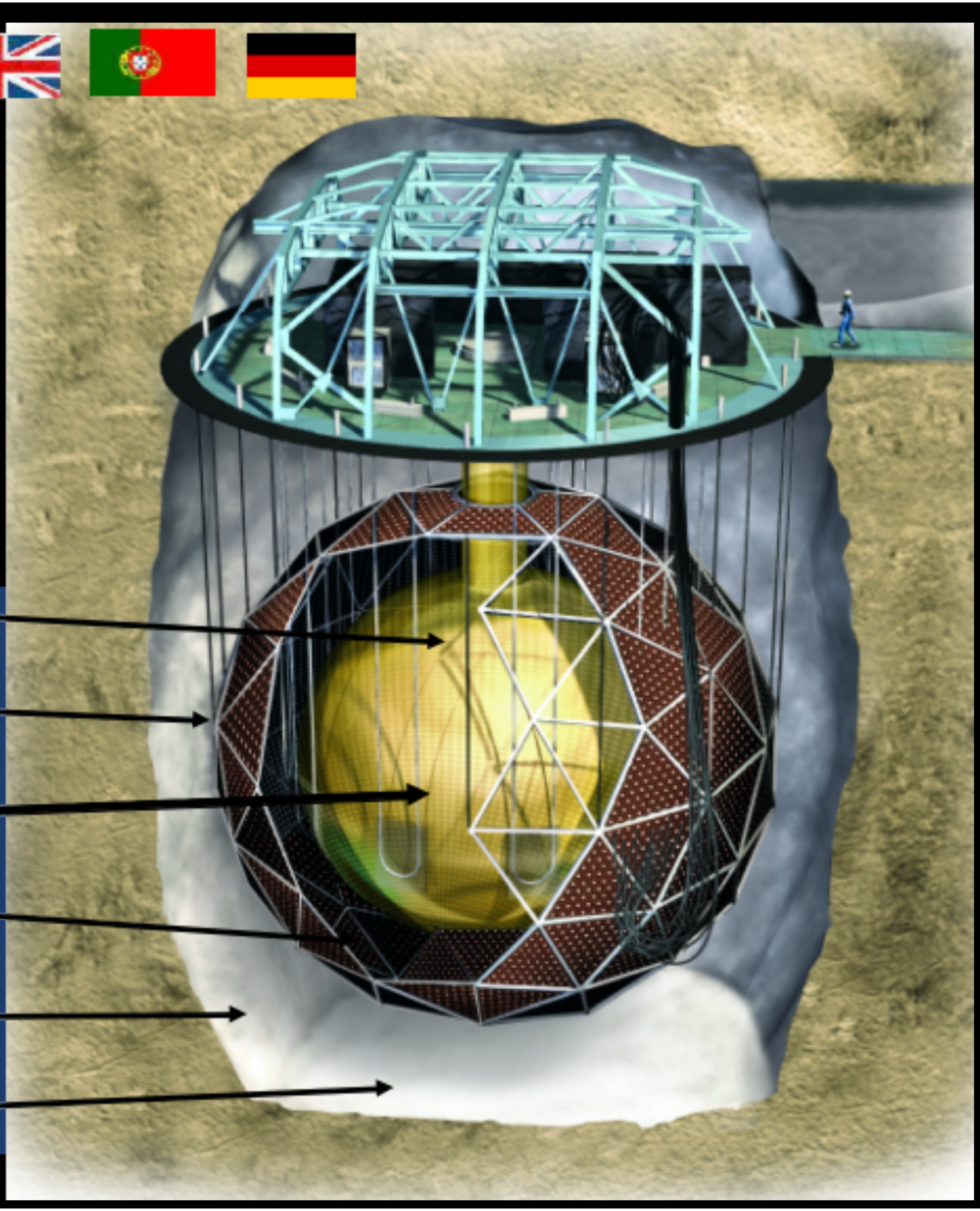
- Reactor neutrinos
  - Short path and low density
  - Small effect

- Accelerator (and atmospheric) neutrinos
  - Effect changes sign for antineutrinos
  - Mimics CP violation (more next lecture)
  - Dependence on sign of Δm^2 useful to measure that sign!

SUDBURY NEUTRINO OBSERVATORY

THE SNO DETECTOR





D_2O (heavy water) : 1000 ton

PMT Support structure: 9500 PMTs

Acrylic Sphere: 12 m diameter

Internal H_2O layer: 1700 ton

External H_2O layer: 5300 ton

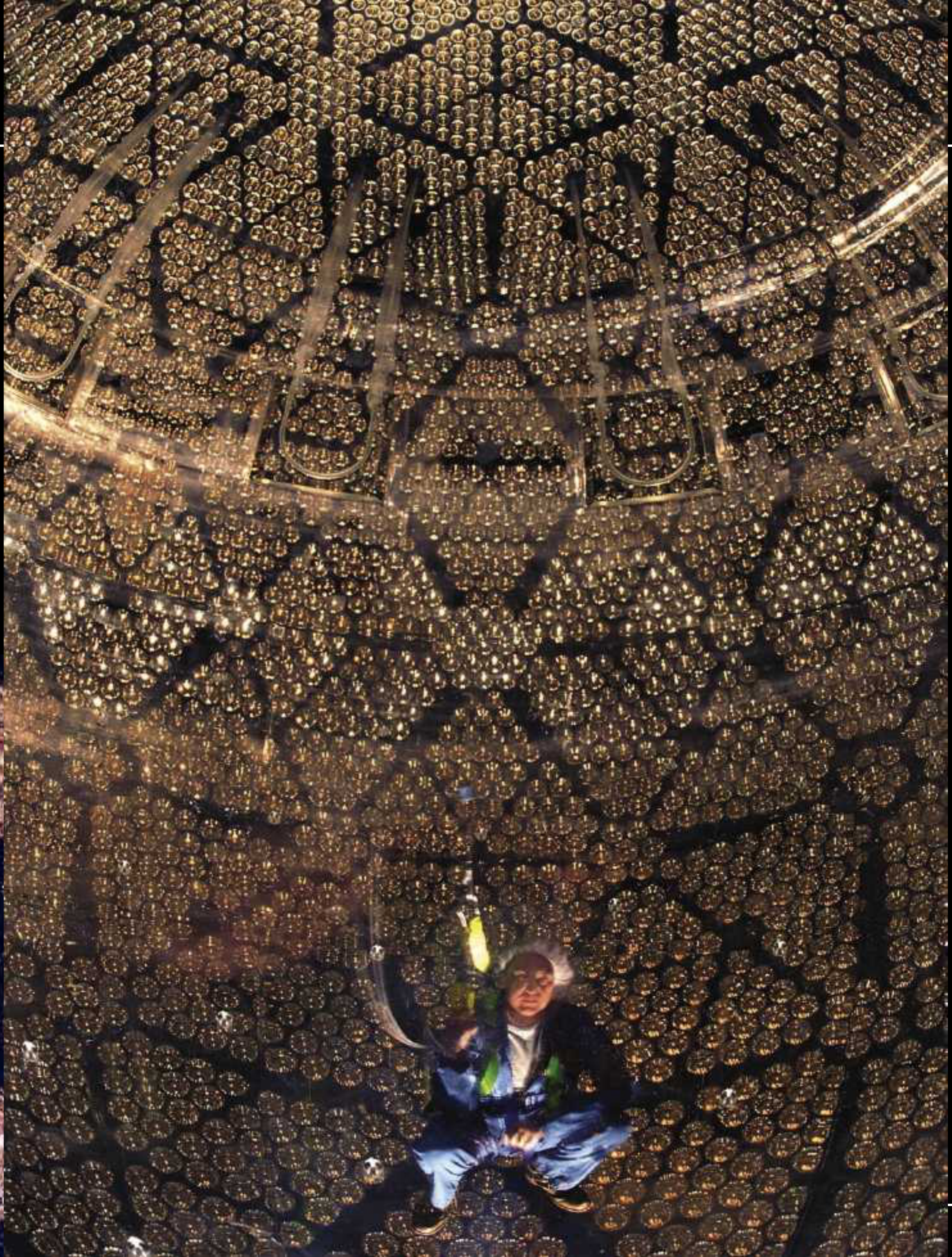
Urylon liner: Radon seal

CONSTRUCTION

SNO was built in the active Creighton mine (INCO, now VALE), close to Sudbury

The experimental cavities were dug on purpose for SNO, at 6800 ft (2 km) depth

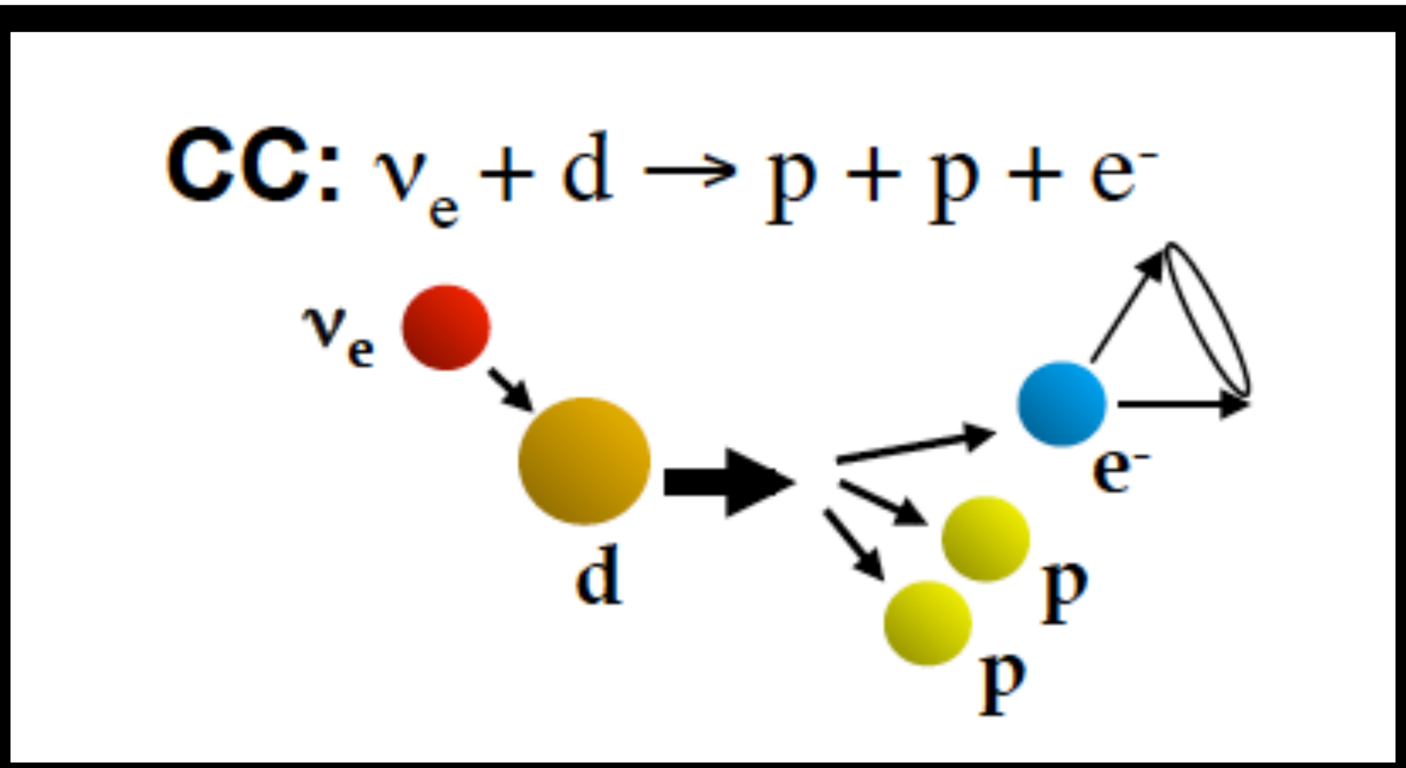
PMTS



REACTIONS ON DEUTERIUM

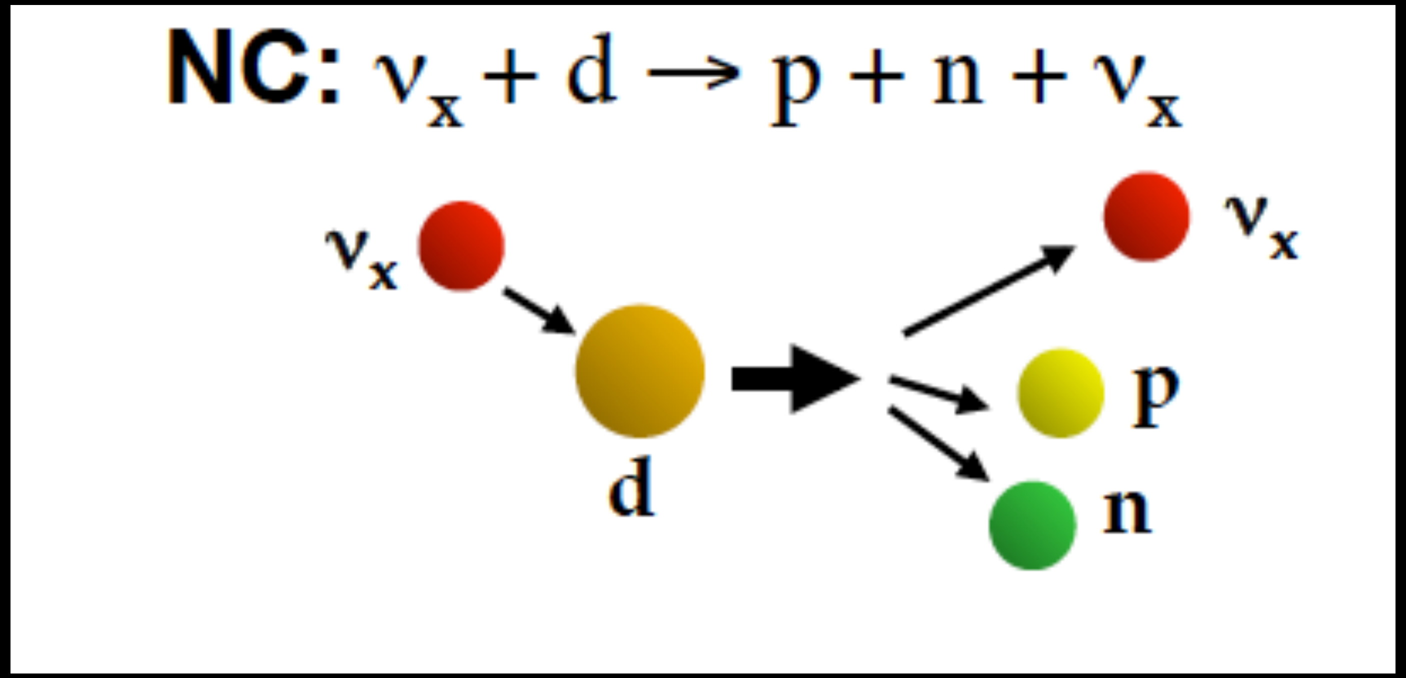
$$\nu_e + d \rightarrow p + p + e^-$$

Charged Current reaction
W boson exchange
Only electron neutrinos
Detect electron in final state



$$\nu_x + d \rightarrow p + n + \nu_x$$

Neutral Current reaction
Z boson exchange
All neutrino flavors
Detect neutron in final state



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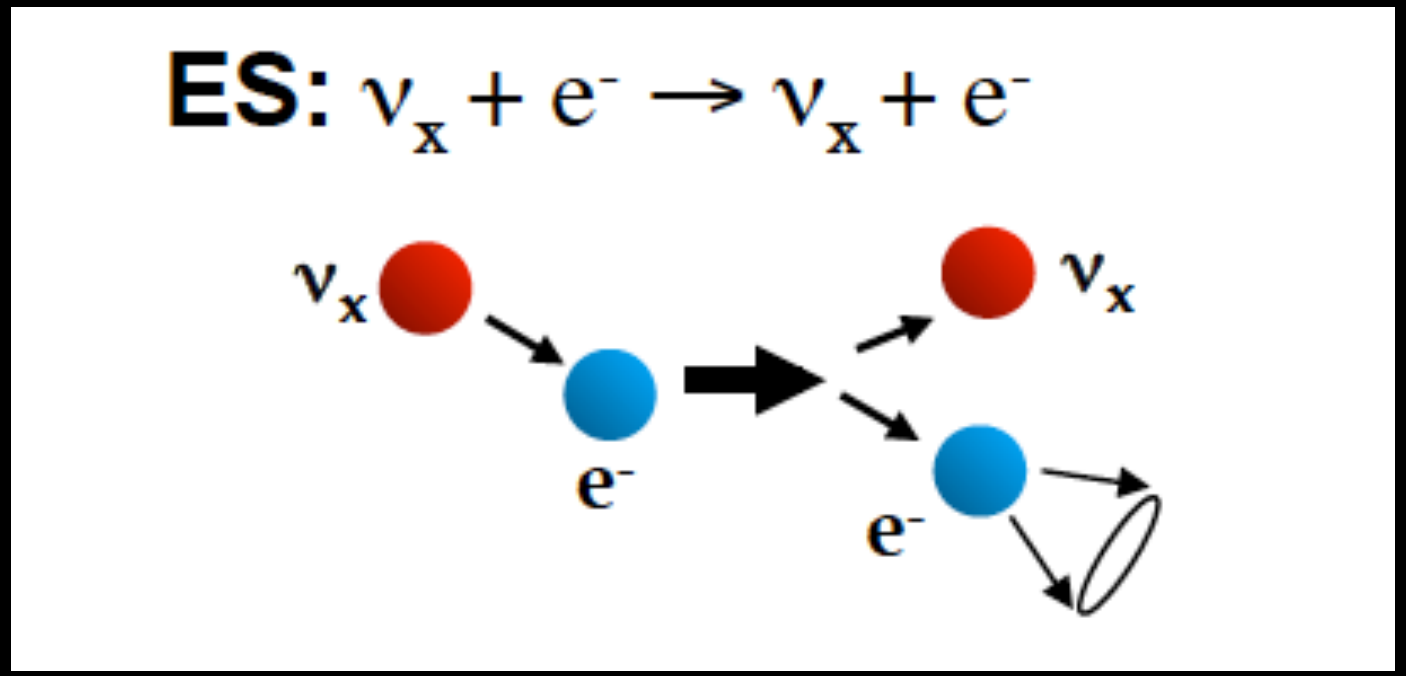
also:

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

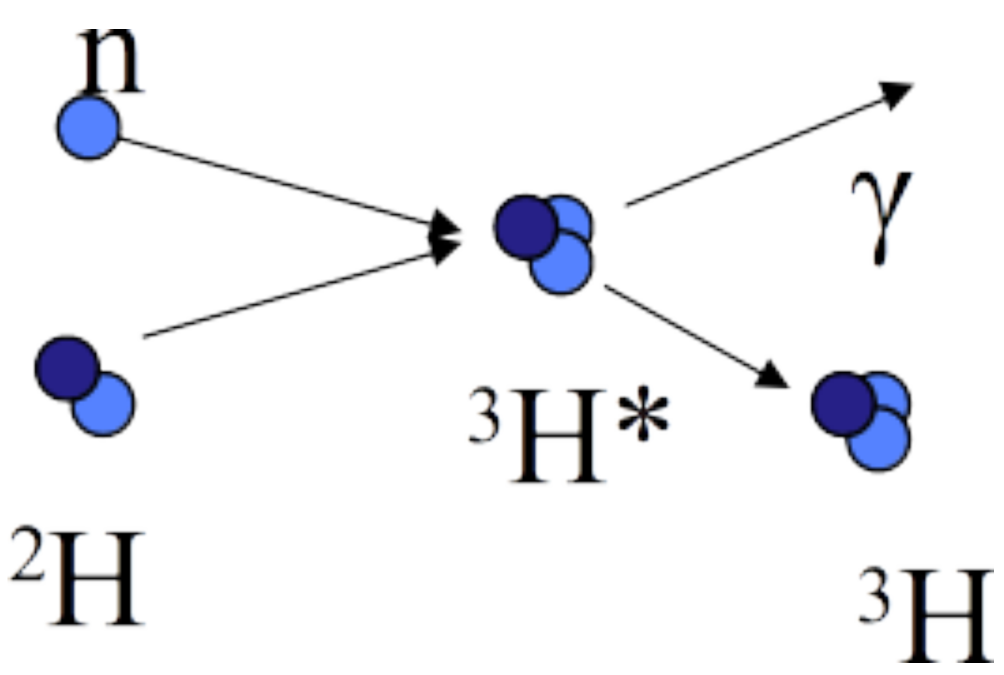
Elastic Scattering reaction
W or Z boson exchange
Lower cross section for ν_μ, ν_τ
Directional
Lower statistics



THE 3 PHASES OF SNO

Phase I (D_2O)

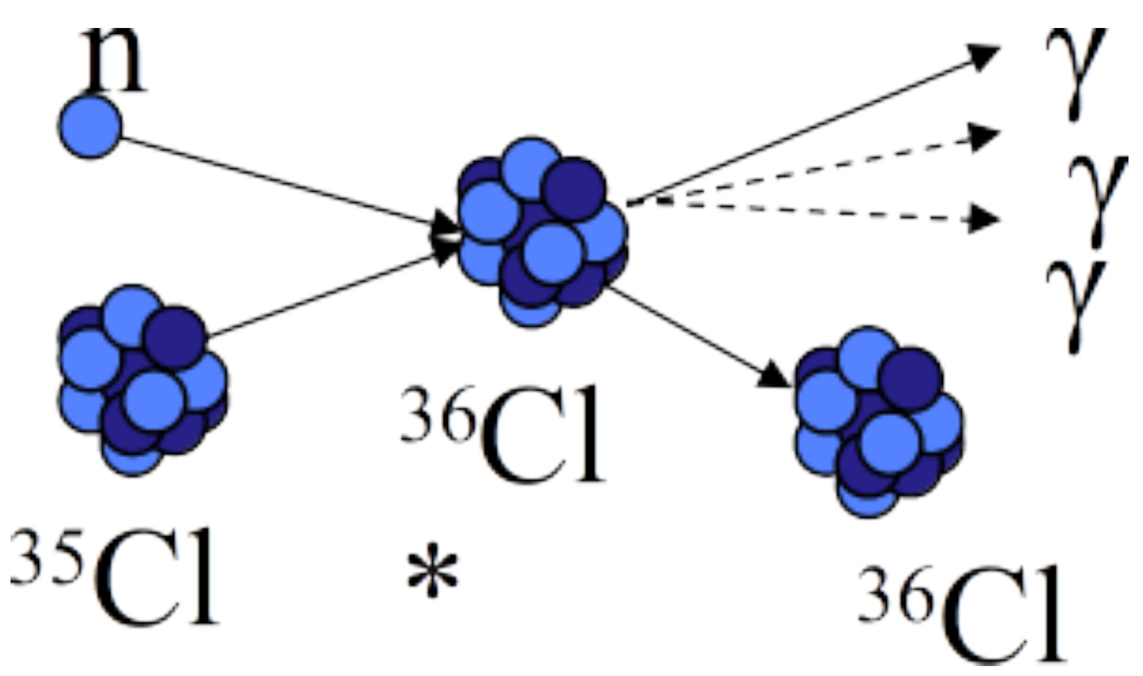
Nov. 99 - May 2001



neutrons captured
by deuterons
$E(\gamma) = 6.25$ MeV

Phase II (salt)

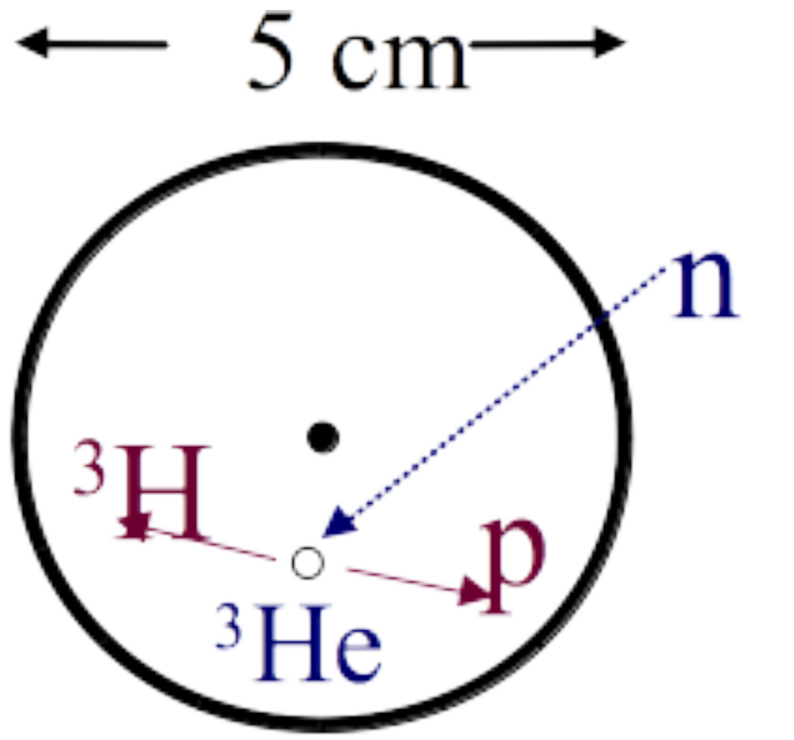
July 2001 - Sept. 2003



neutrons captured
by chlorine
$\Sigma(E(\gamma)) = 8.6$ MeV

Phase III (NCD)

Nov. 2004 - Dec. 2006



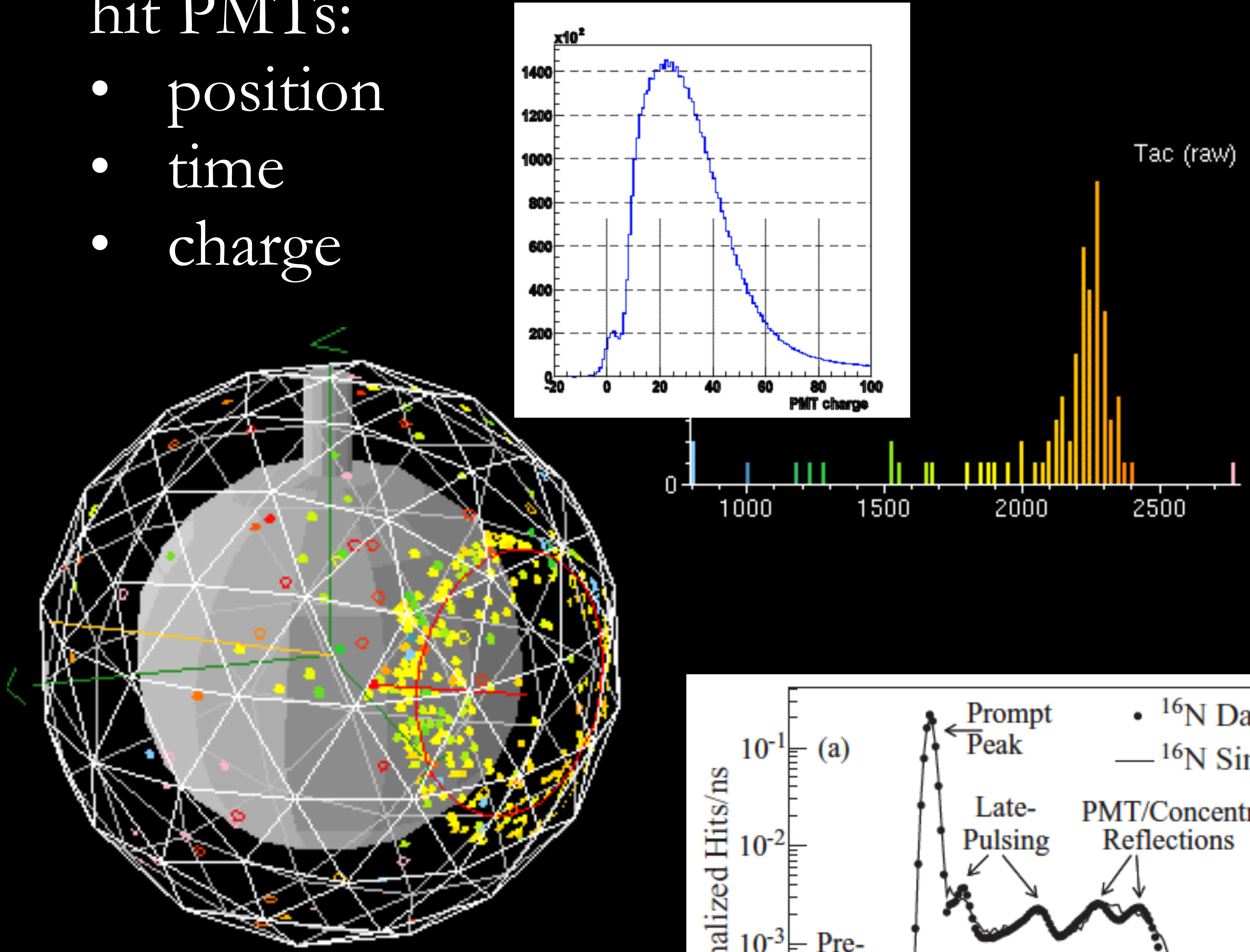
$n + {}^3He \rightarrow p + {}^3H$

neutrons captured
by ^3He
array of 40
proportional counters

EXPERIMENTAL OBSERVABLES

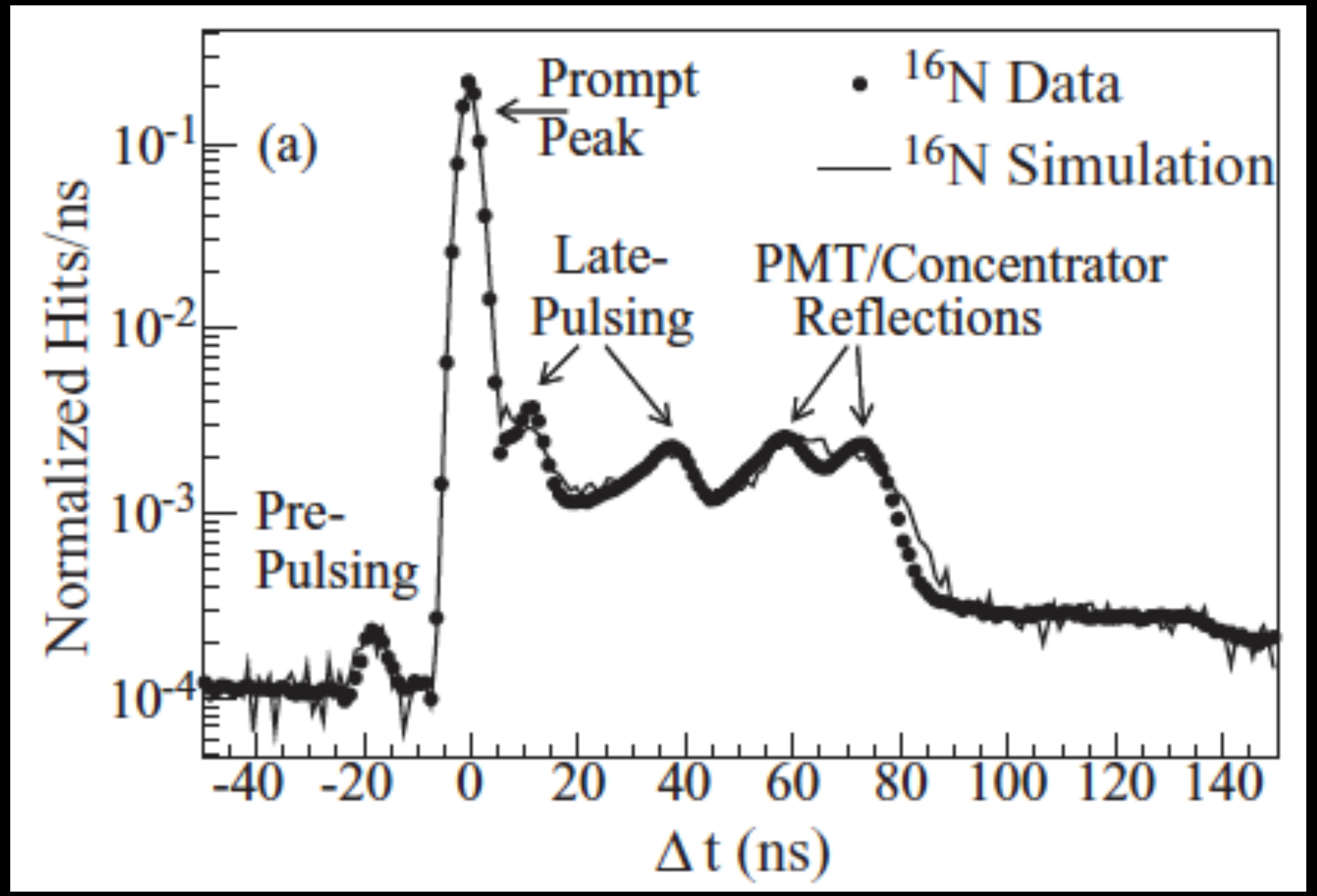
hit PMTs:

- position
- time
- charge



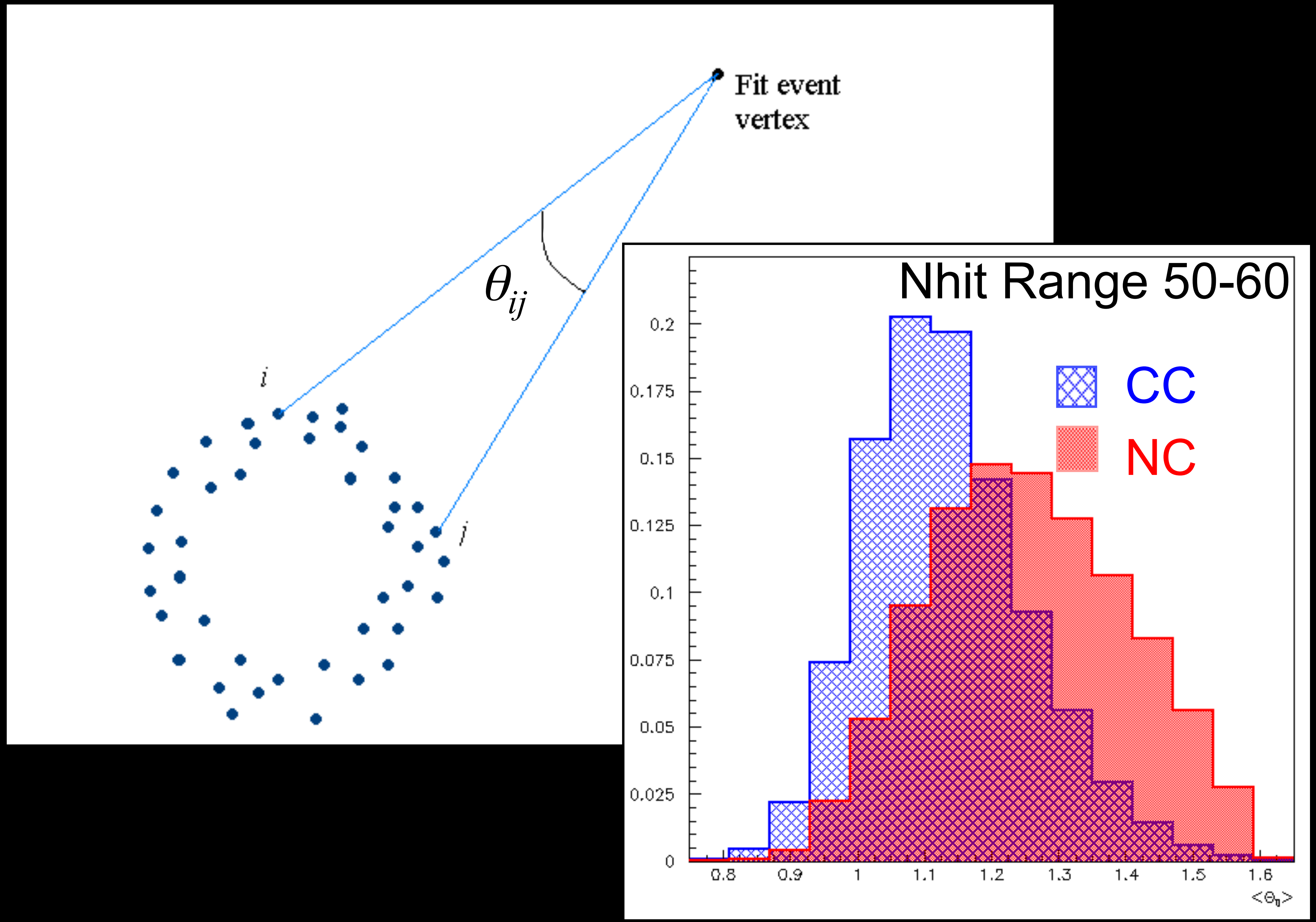
From these we calculate:

- event position
- direction
- energy
- isotropy

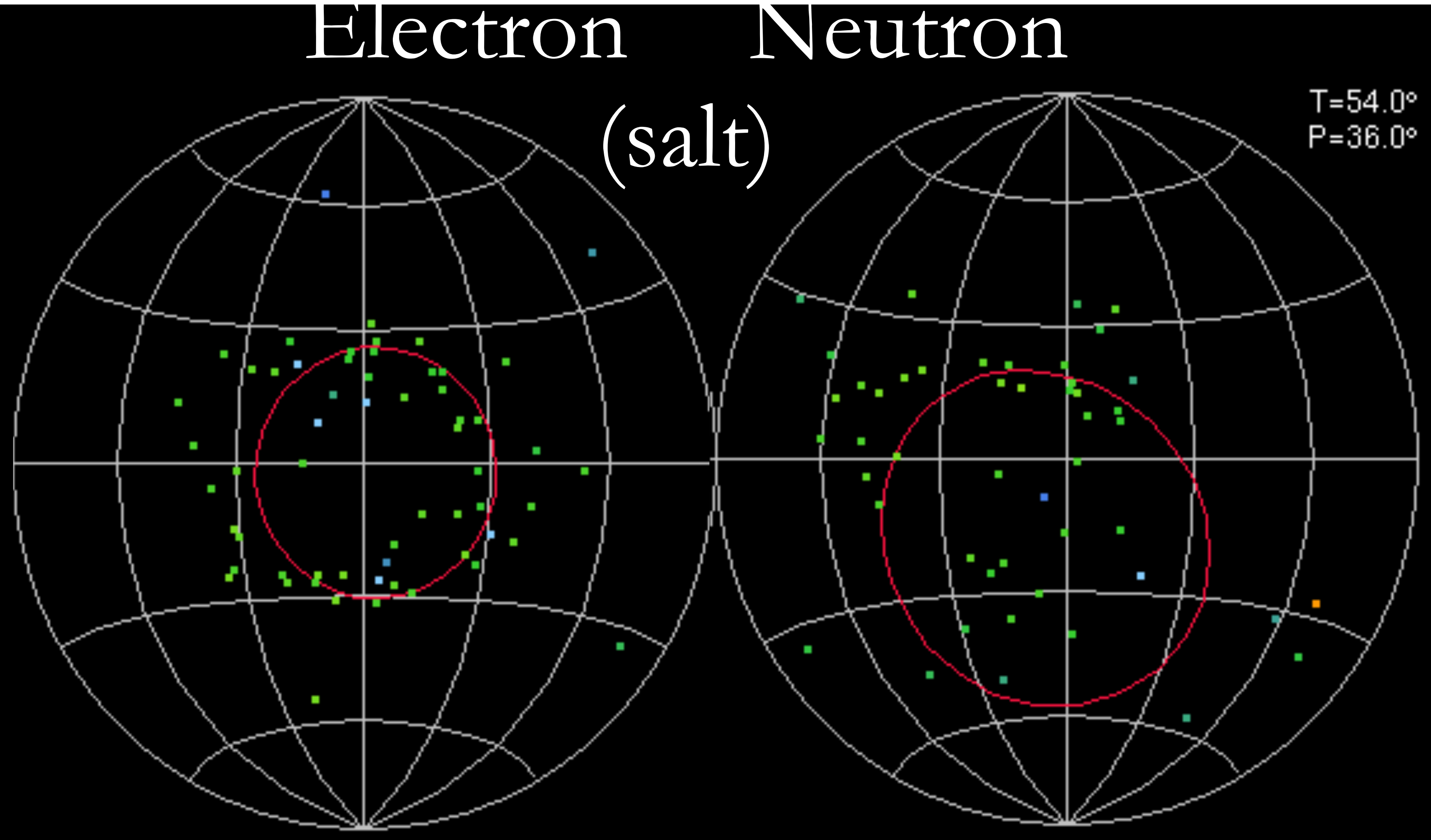


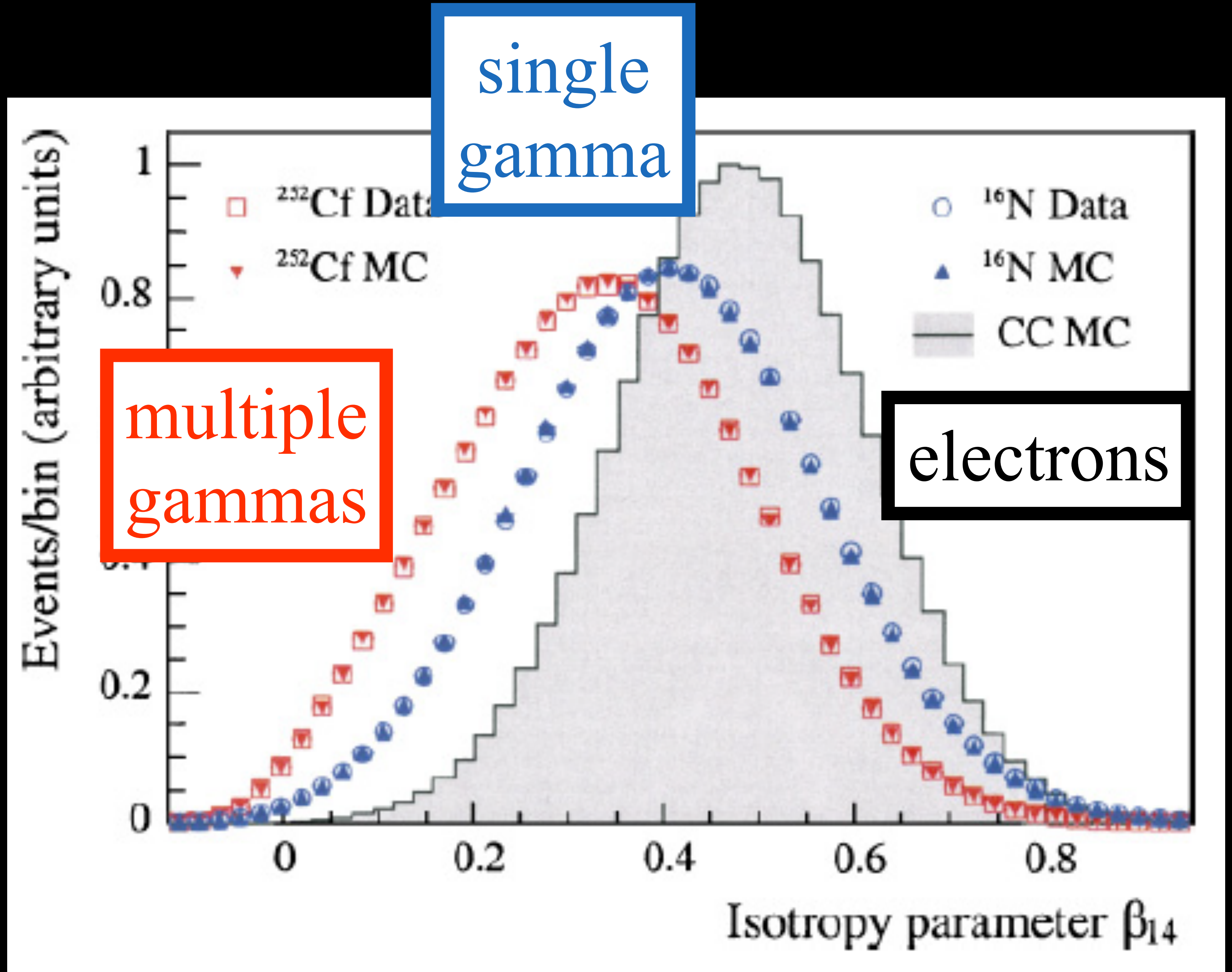
SNO used extensive calibrations to tune response models and determine systematics

ISOTROPY



$<\theta_{ij}>$ average
over all PMT pairs

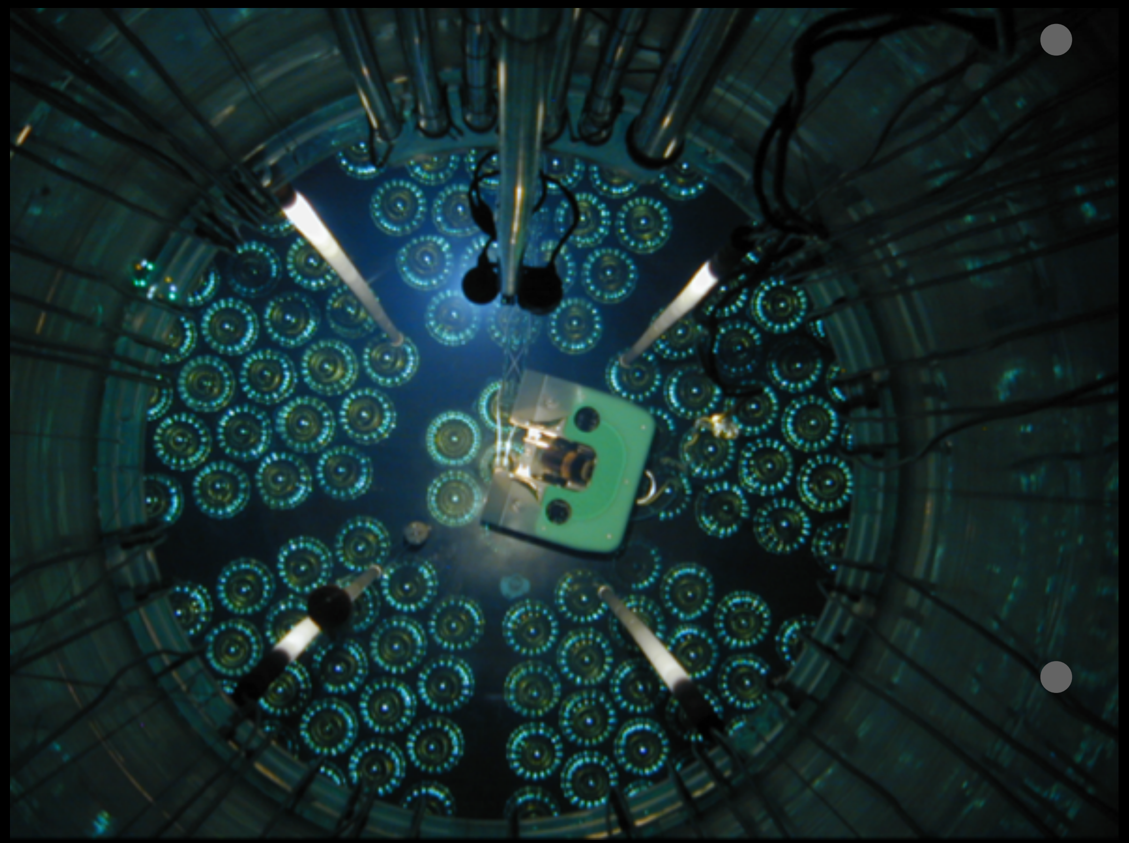




$$\beta_l \approx \left\langle P_l\left(\cos\theta_{ij}\right)\right\rangle_{i\neq j}$$

P_l = l_{th} order Legendre polynomial
best separation found with $\beta_{14} = \beta_1 + 4\beta_4$

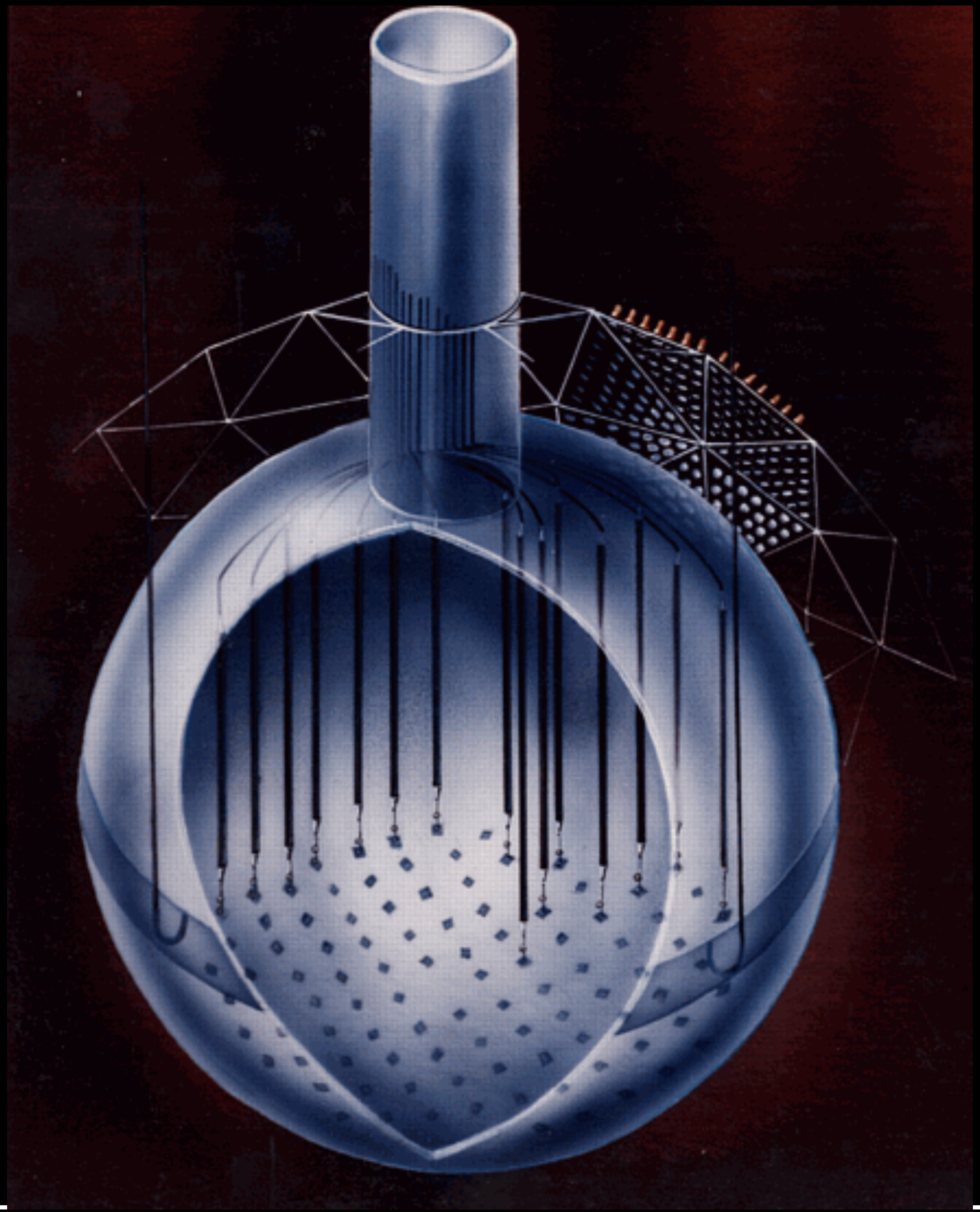
NEUTRAL CURRENT DETECTORS



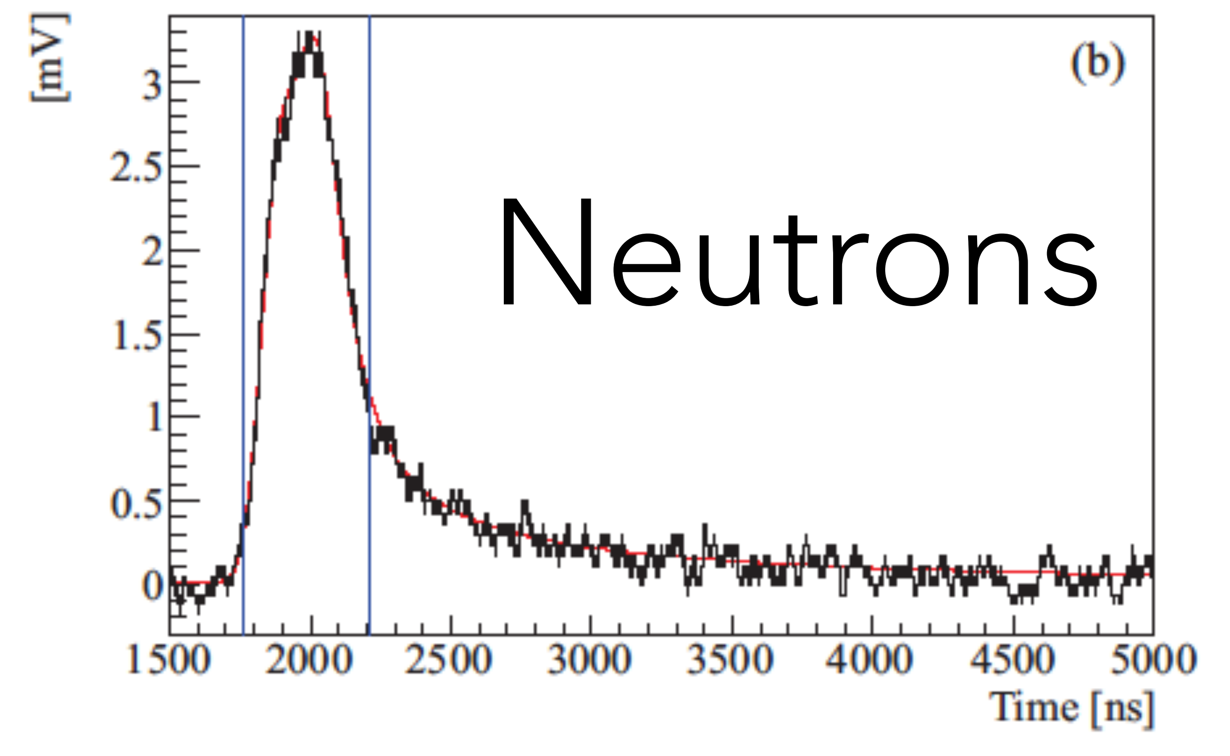
- Array of ^{3}He-filled proportional counters deployed in the AV

$$n + {}^3He \rightarrow p + {}^3H$$

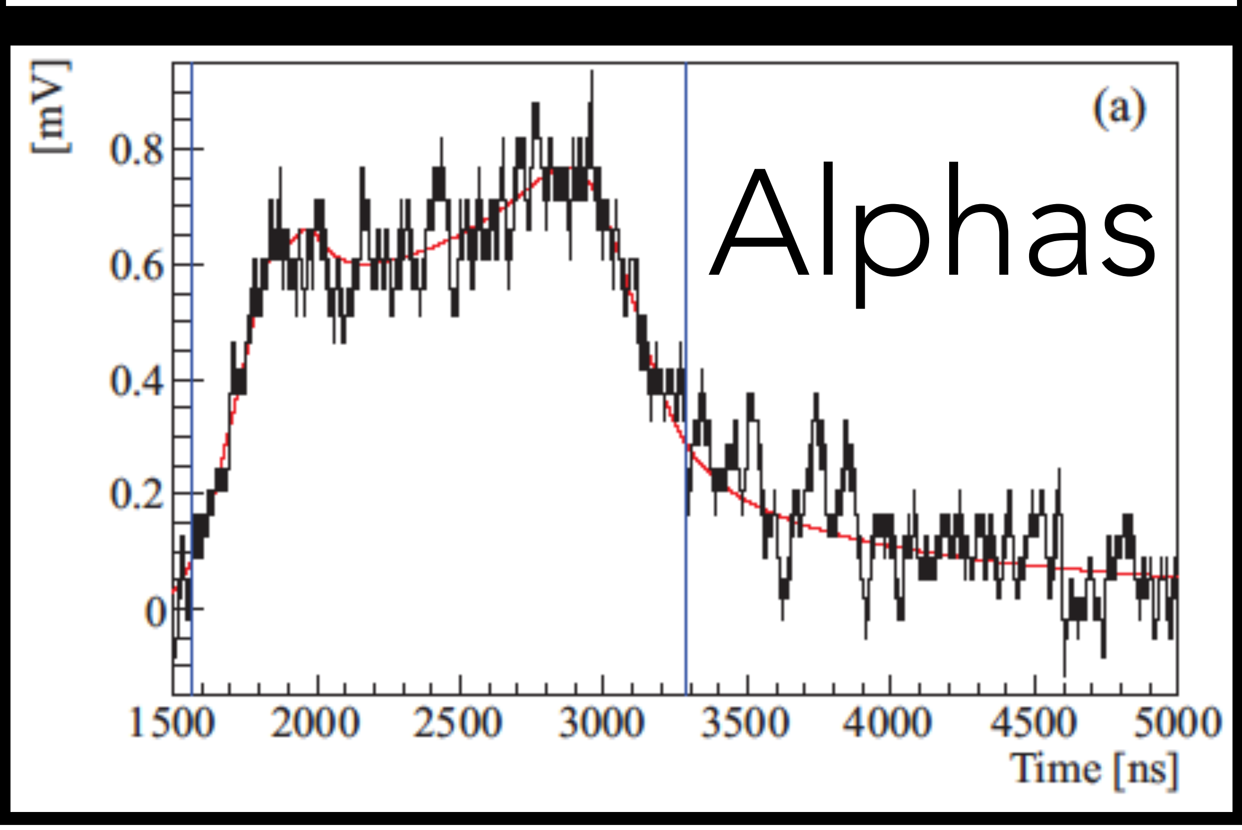
- Neutron capture efficiency: 21.5%
- Pulse-shape allows background discrimination



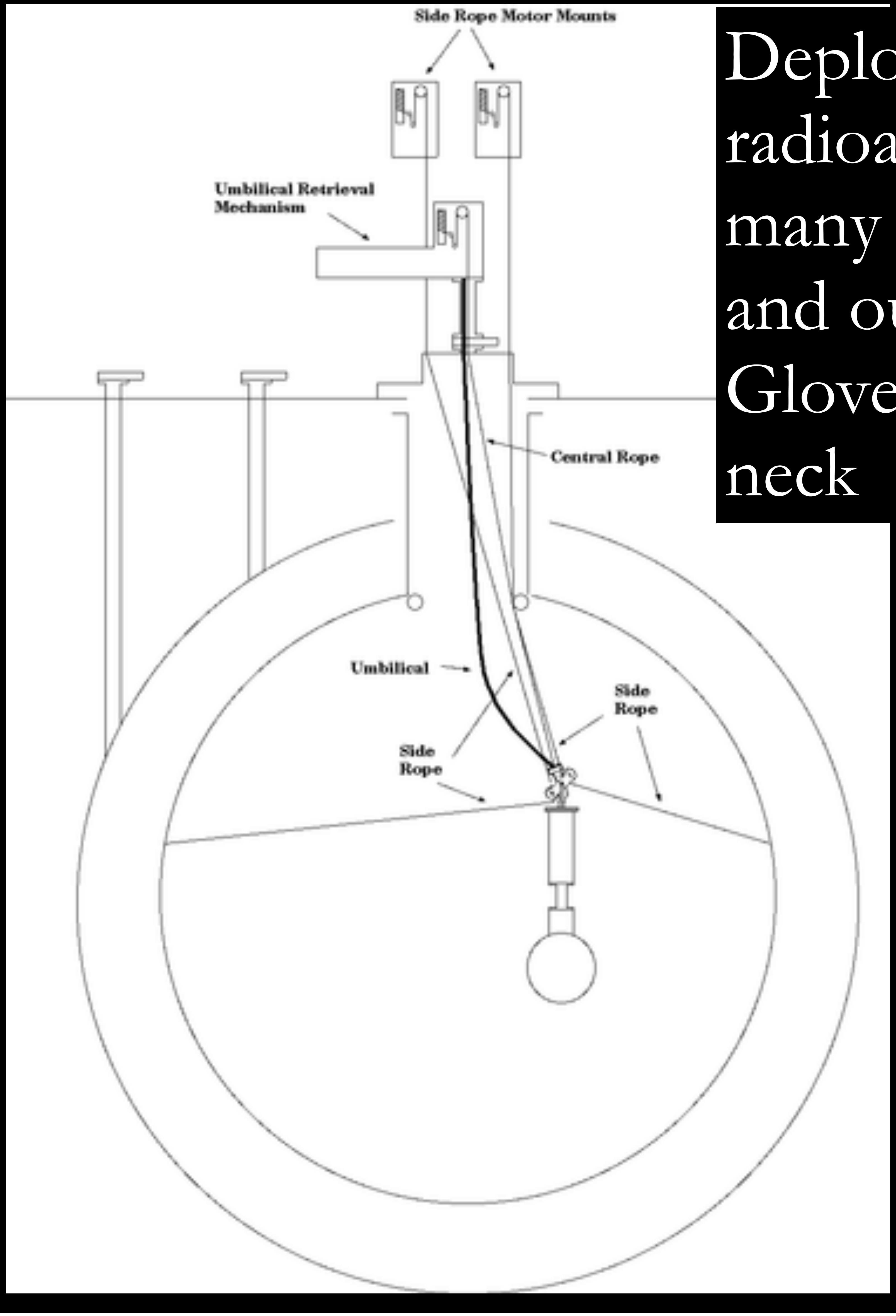
- neutron pulses, obtained from calibrations



- alpha pulses, obtained from ^{4}He-filled counters



CALIBRATIONS



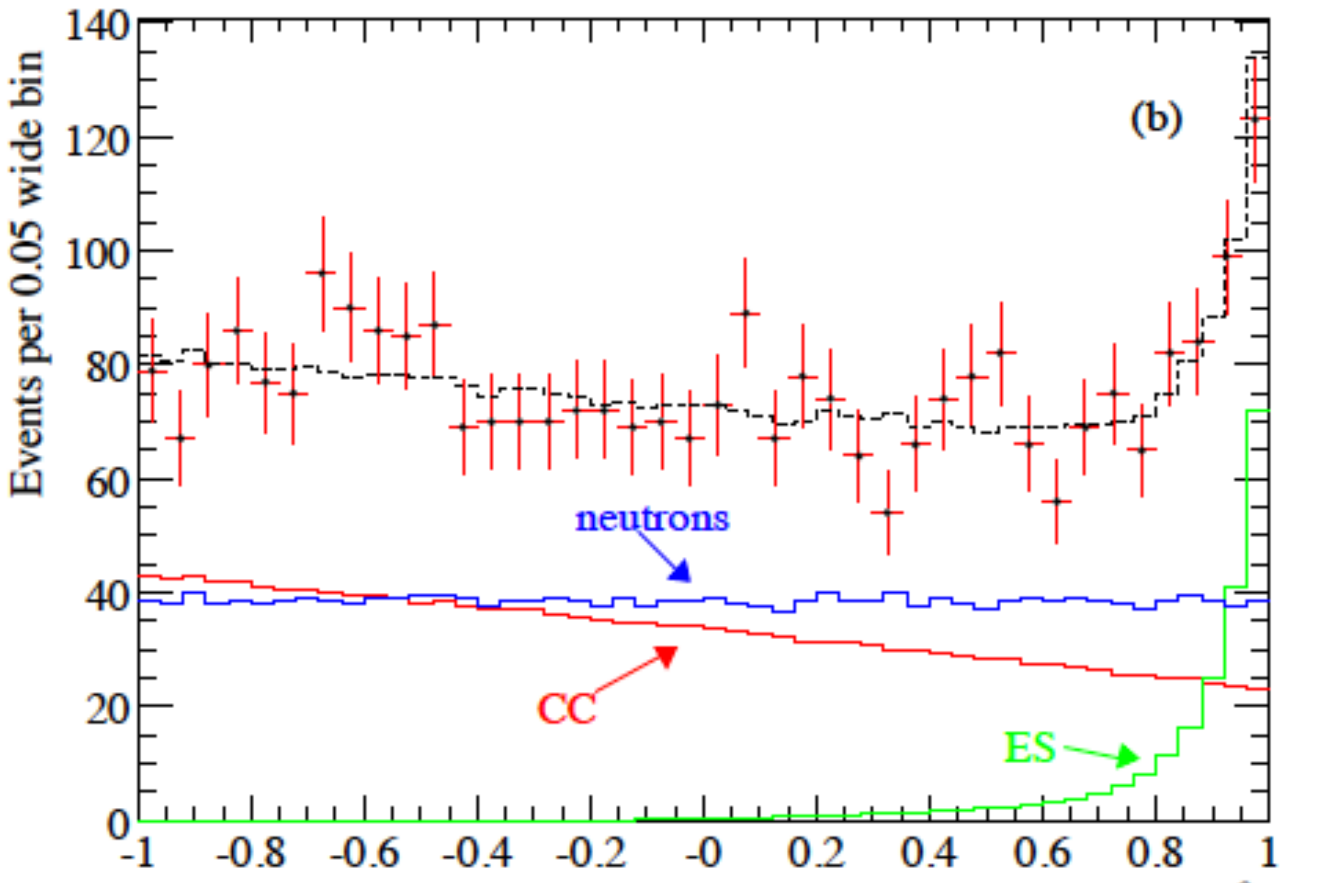
Deploy optical and radioactive sources in many positions inside and outside the AV
Glove box on top of AV neck

Also: radioactivity spikes uniformly distributed in the heavy water: ^{222}Rn, ^{24}Na

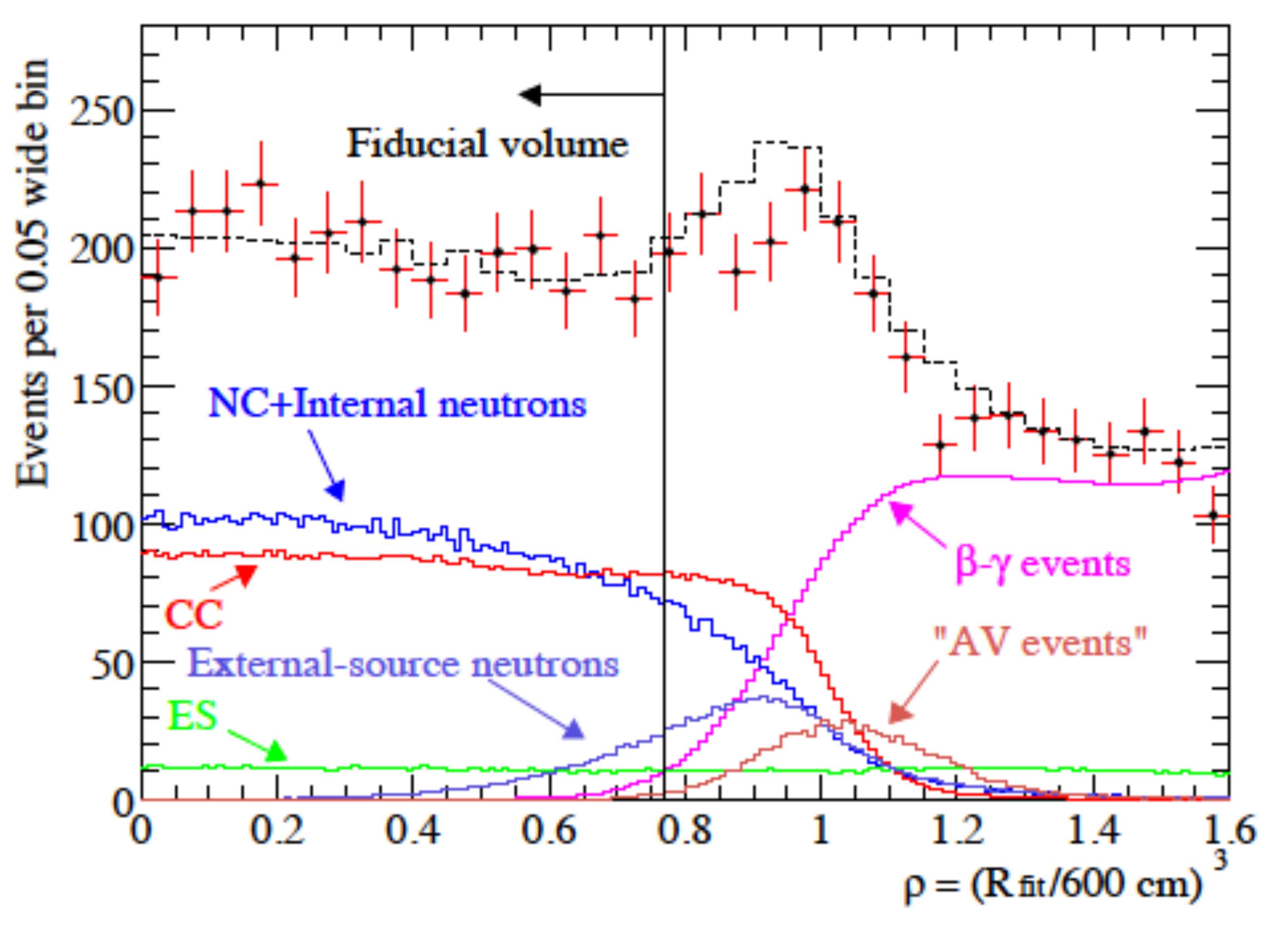
SUDBURY NEUTRINO OBSERVATORY SOLAR NEUTRINO RESULTS

SIGNAL EXTRACTION

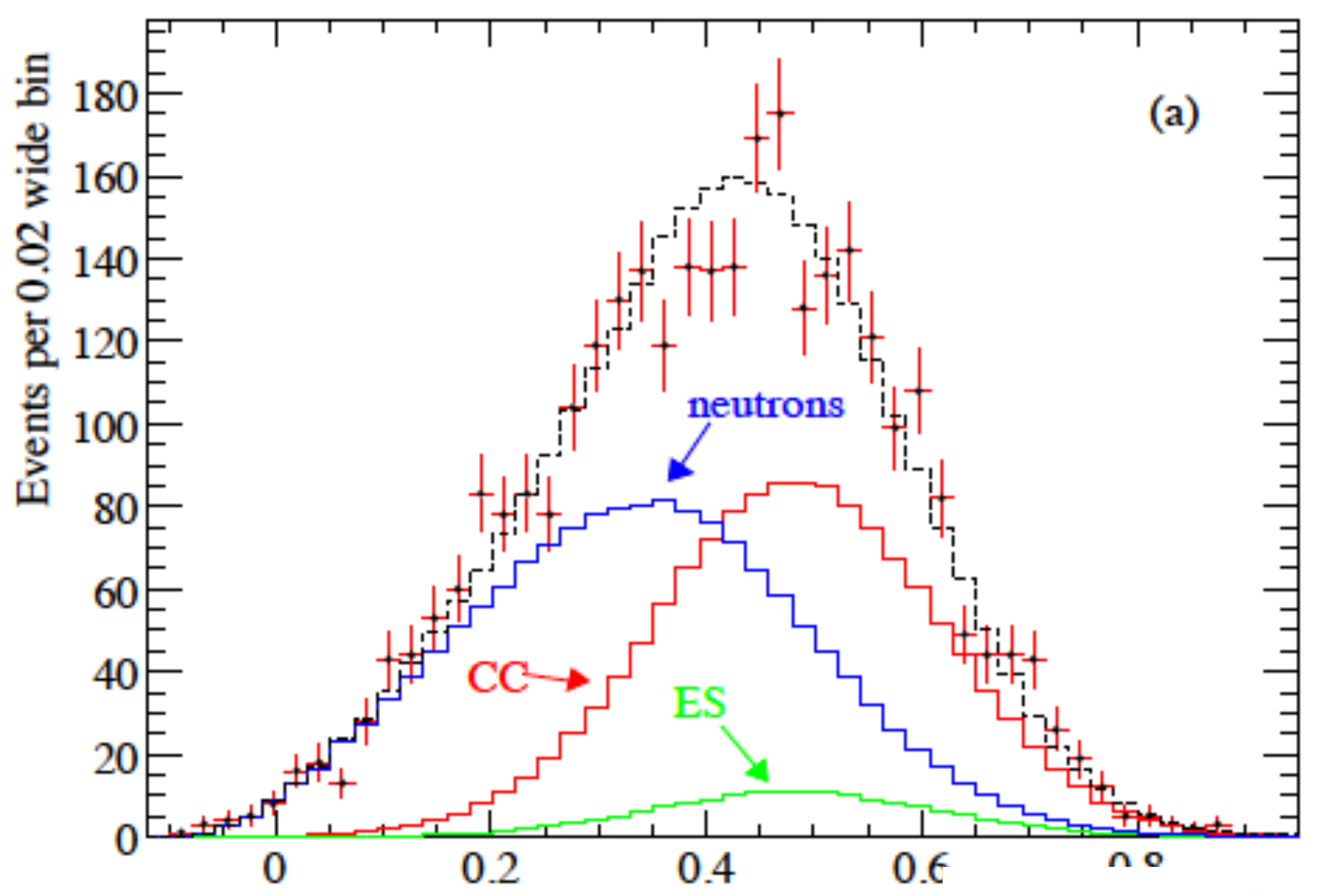
- Fit distributions of direction, position, isotropy
- Measure number of events and energy spectrum of CC, NC, ES
- (Energy fixed in phase I result)



Direction w/r Sun



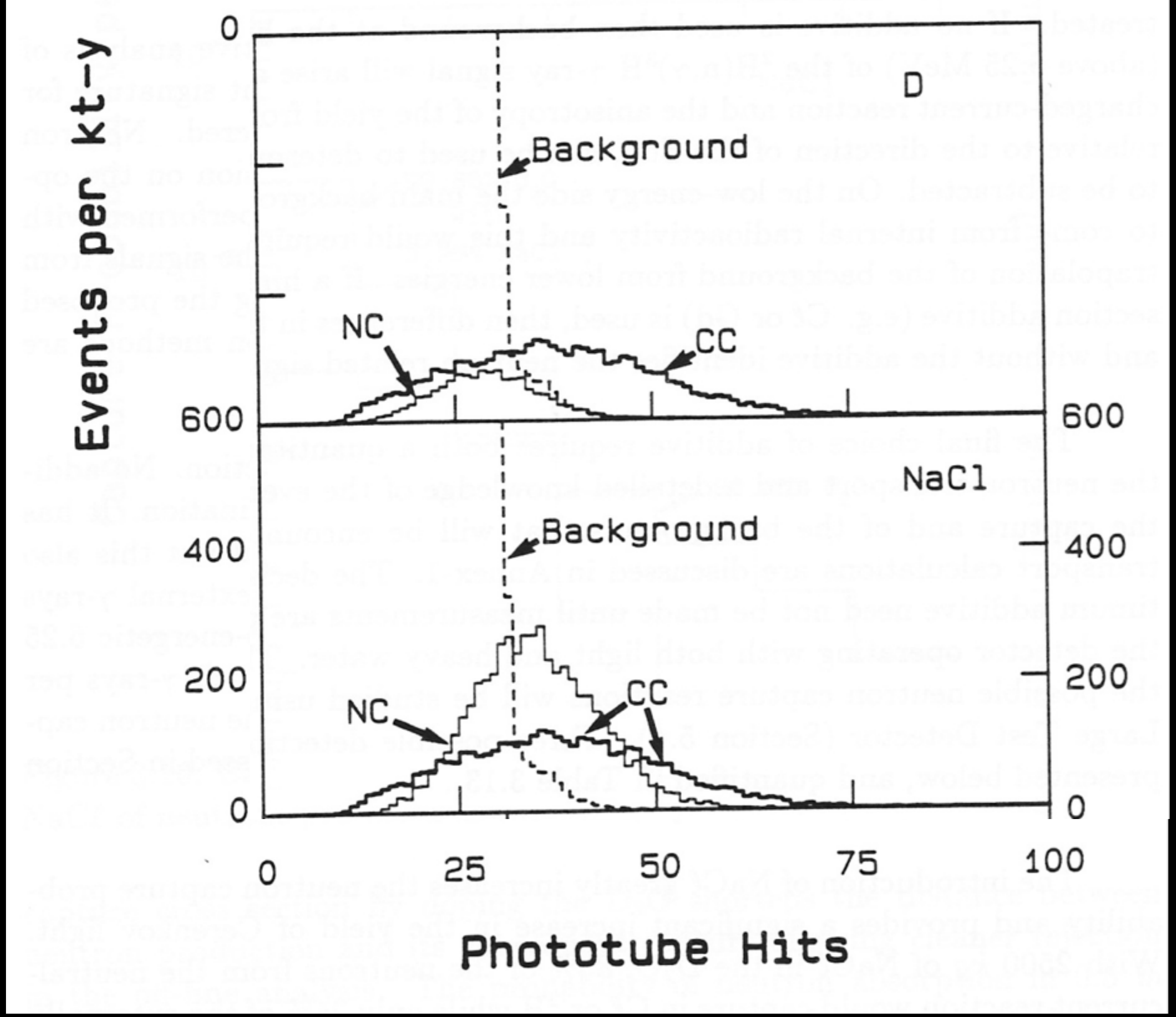
Radial position



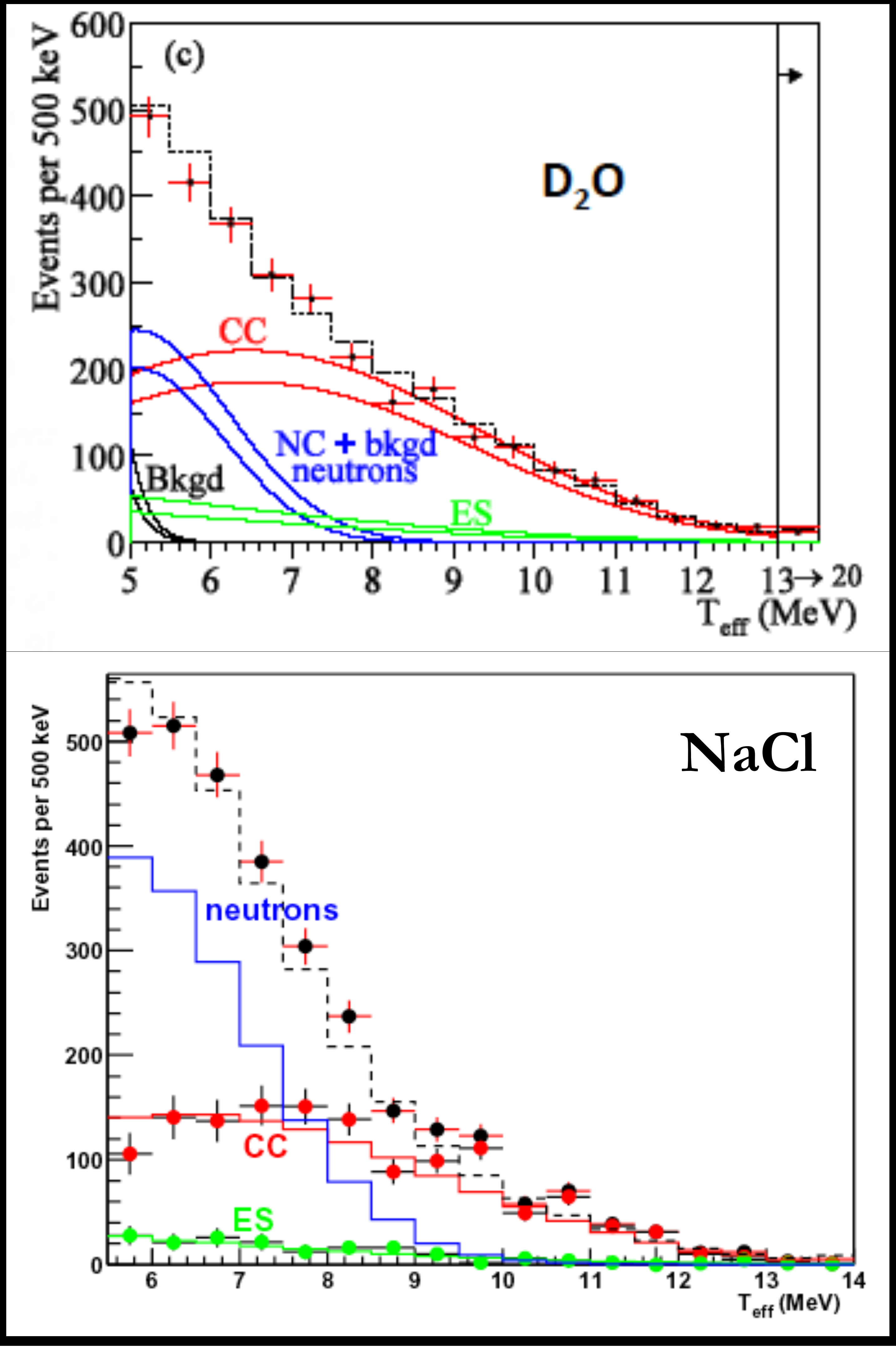
Isotropy β_{14}

ENERGY SPECTRA

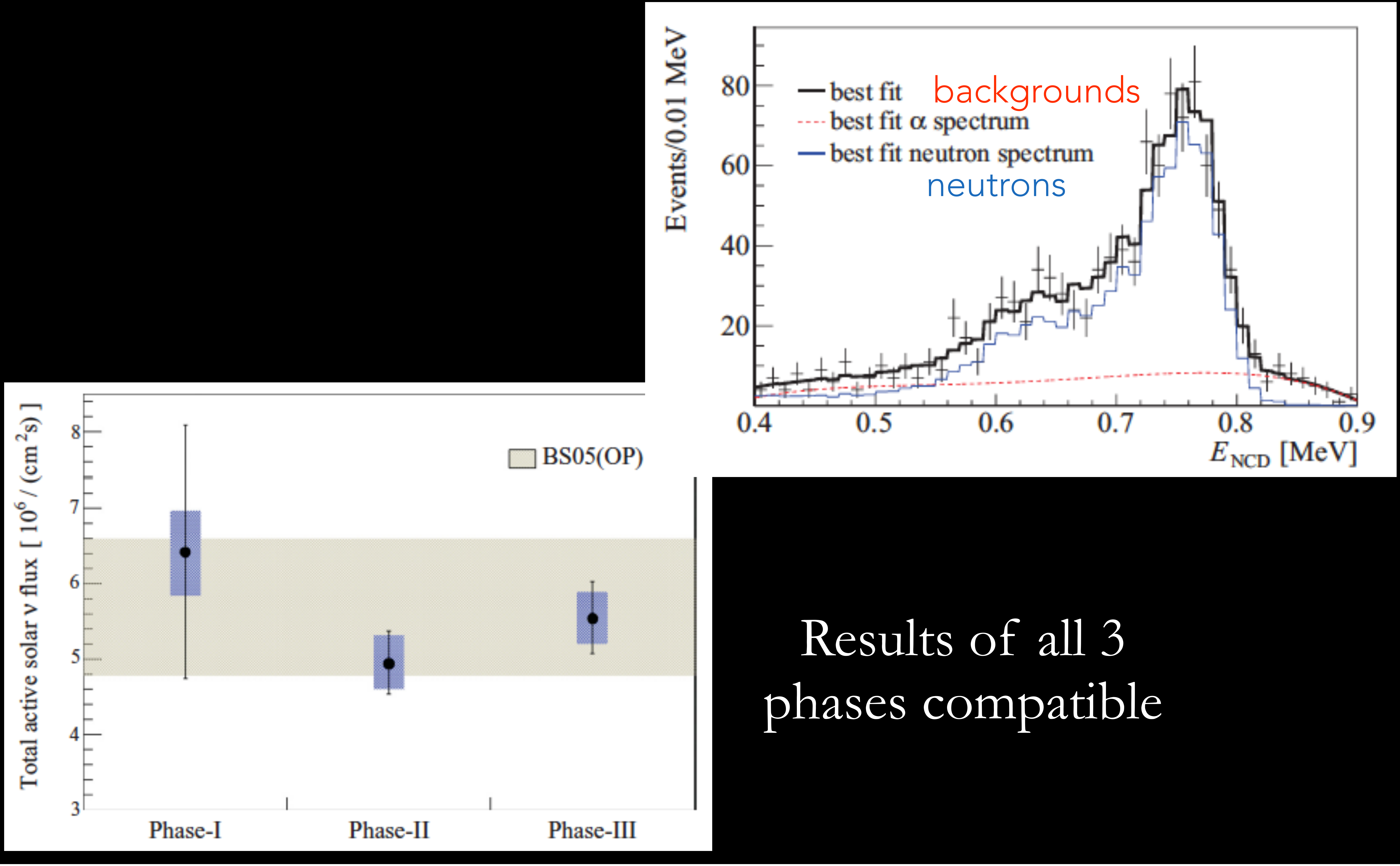
simulated in 1987



measured 1999-2003

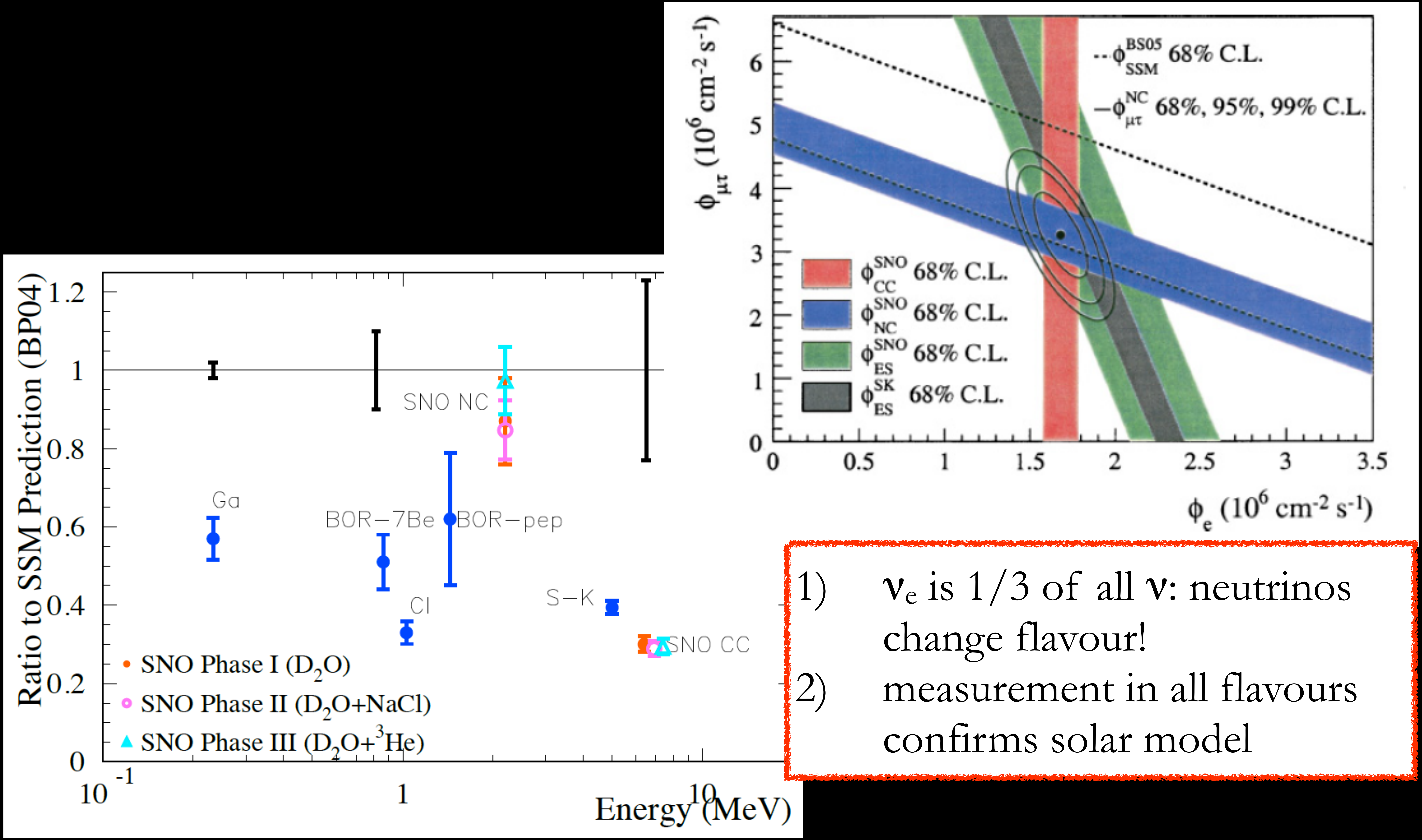


NEUTRAL CURRENT DETECTORS



Results of all 3
phases compatible

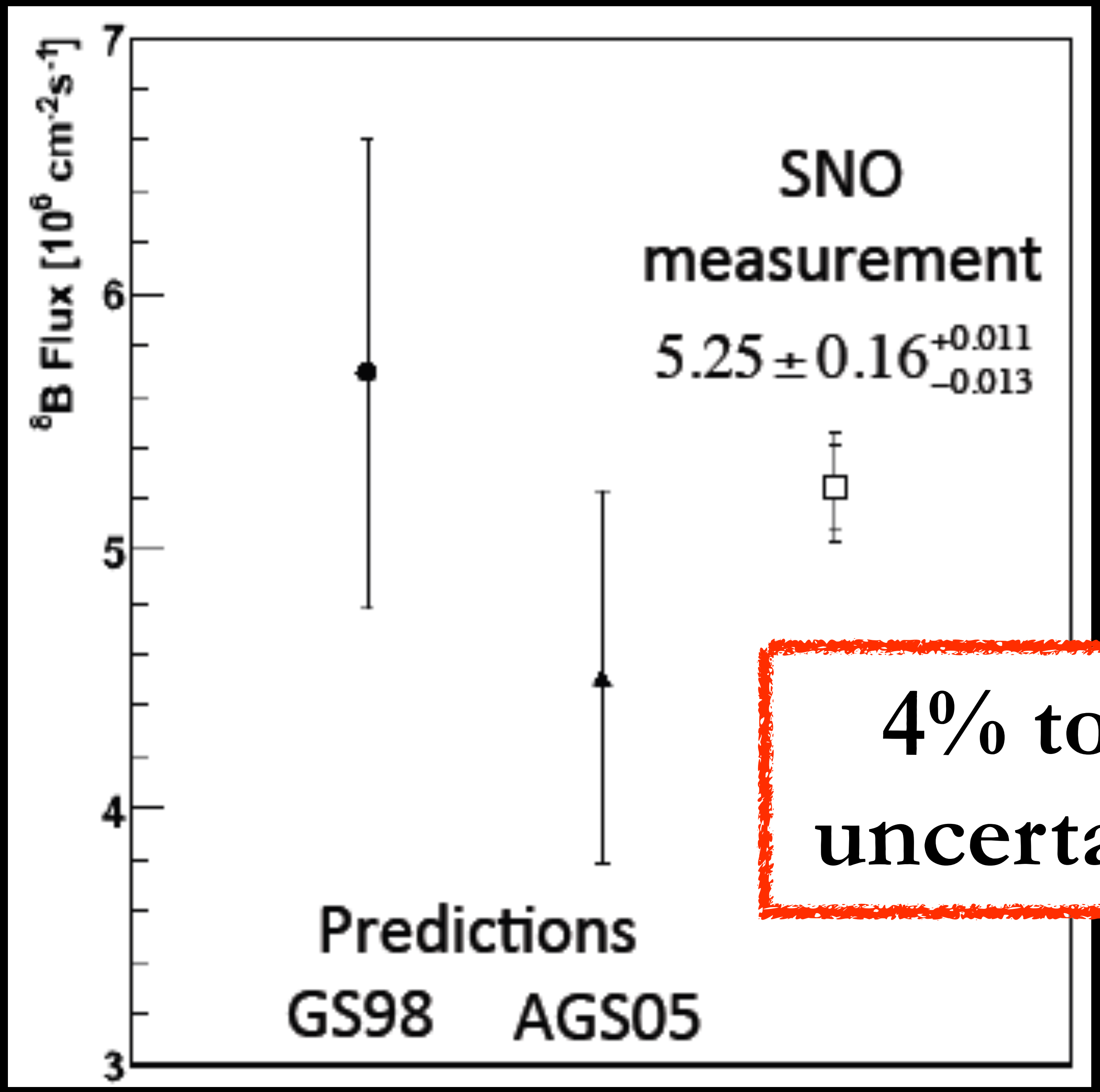
SOLAR NEUTRINO PROBLEM, SOLVED!



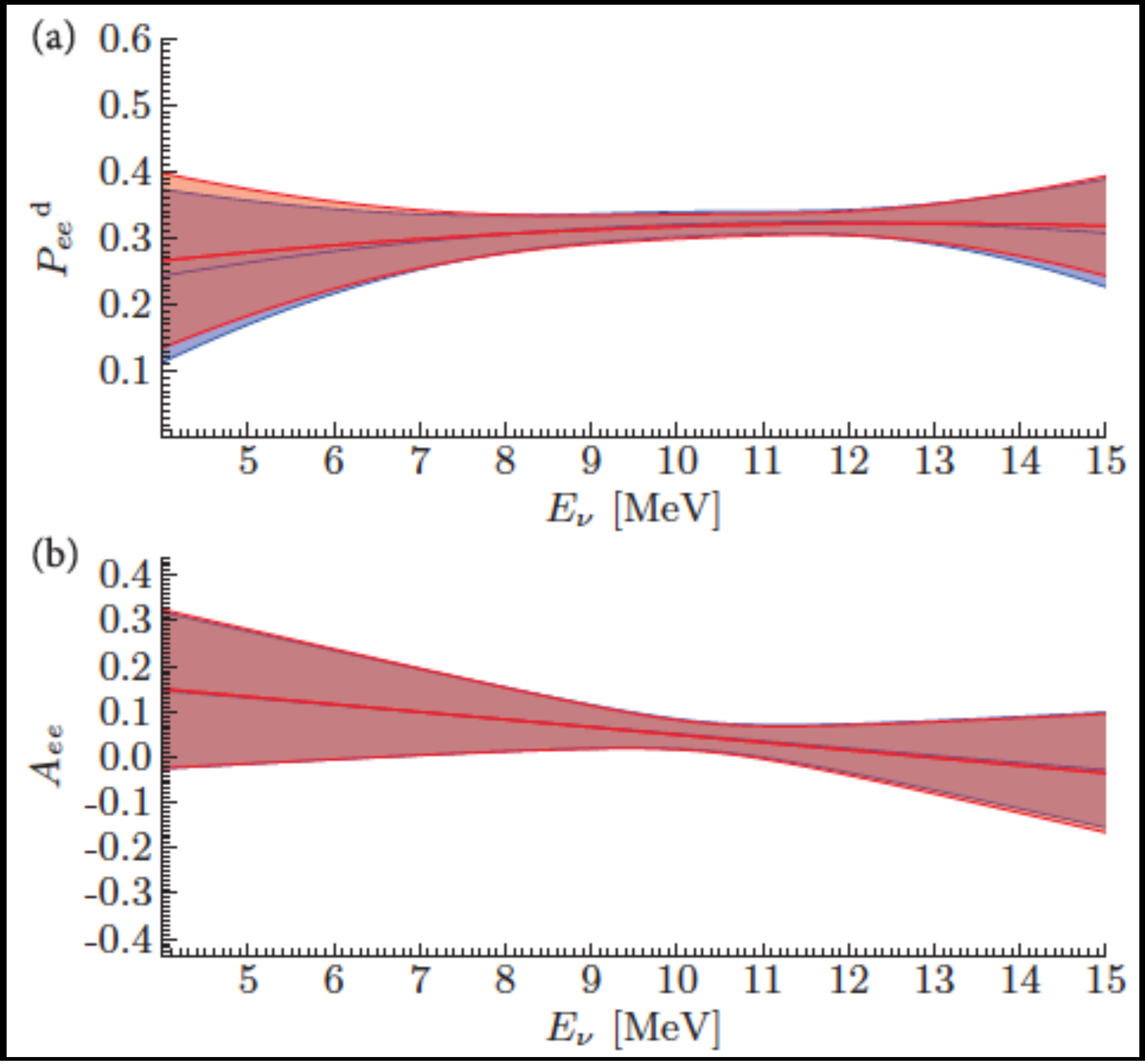
1) ν_e is 1/3 of all ν: neutrinos change flavour!
2) measurement in all flavours confirms solar model

FINAL COMBINATION ALL PHASES

- Lowered energy threshold to 3.5 MeV
  - better CC/NC precision
- Common fit of all phases, handle common systematics
- Fit common ^{8}B ν flux and survival probability
- E dependence compatible with flat (and MSW)

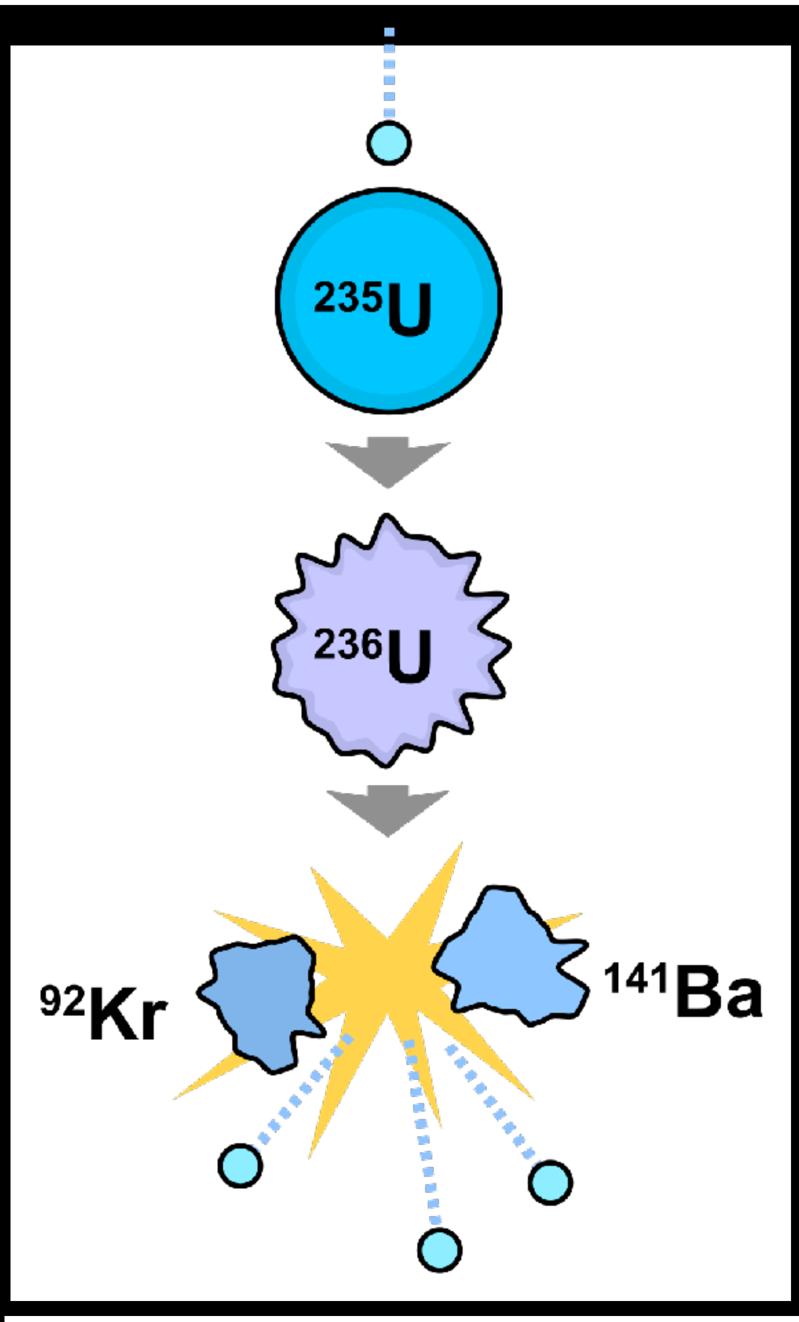


4% total uncertainty



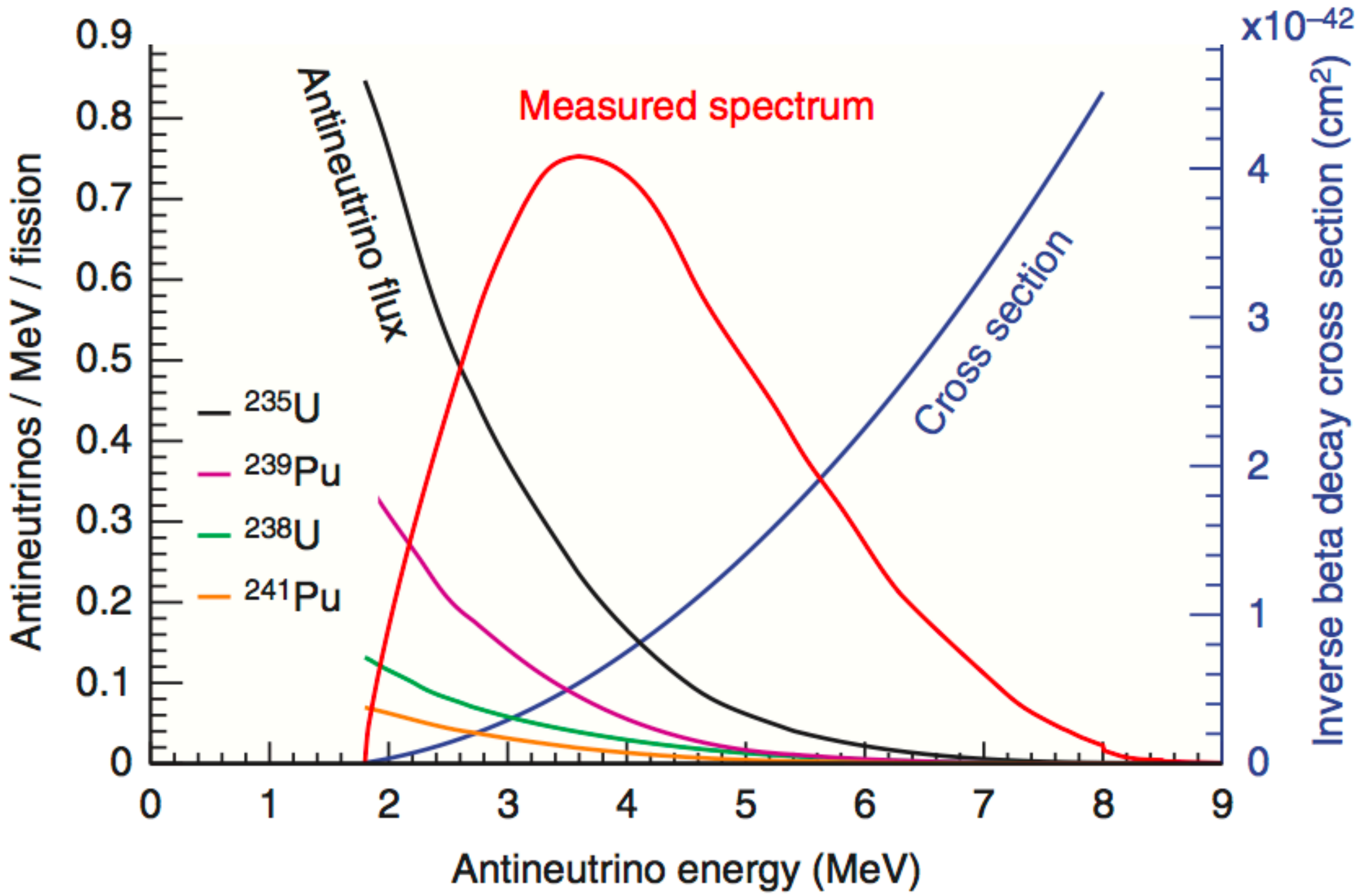
LONG-BASELINE REACTOR NEUTRINOS

NUCLEAR REACTORS

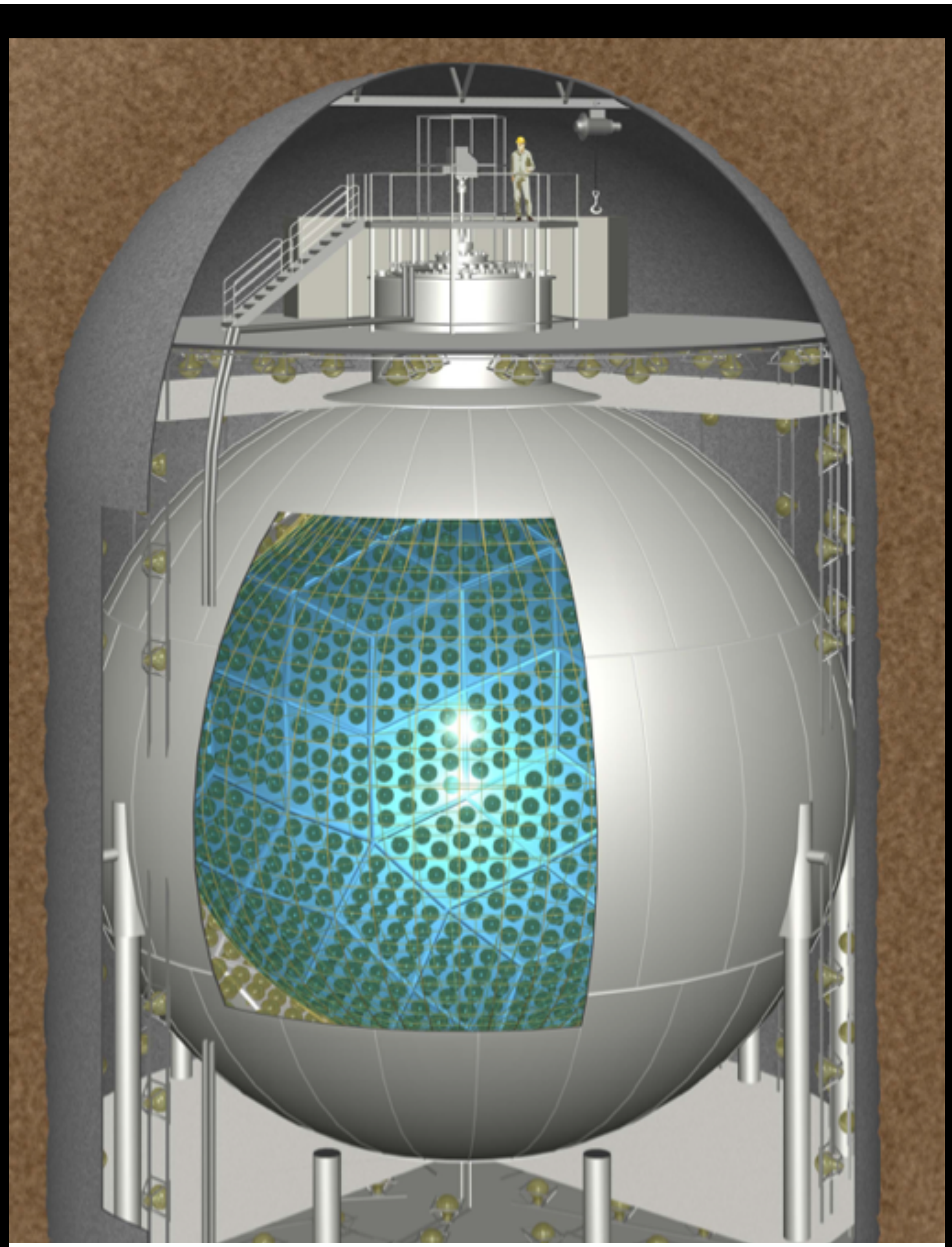


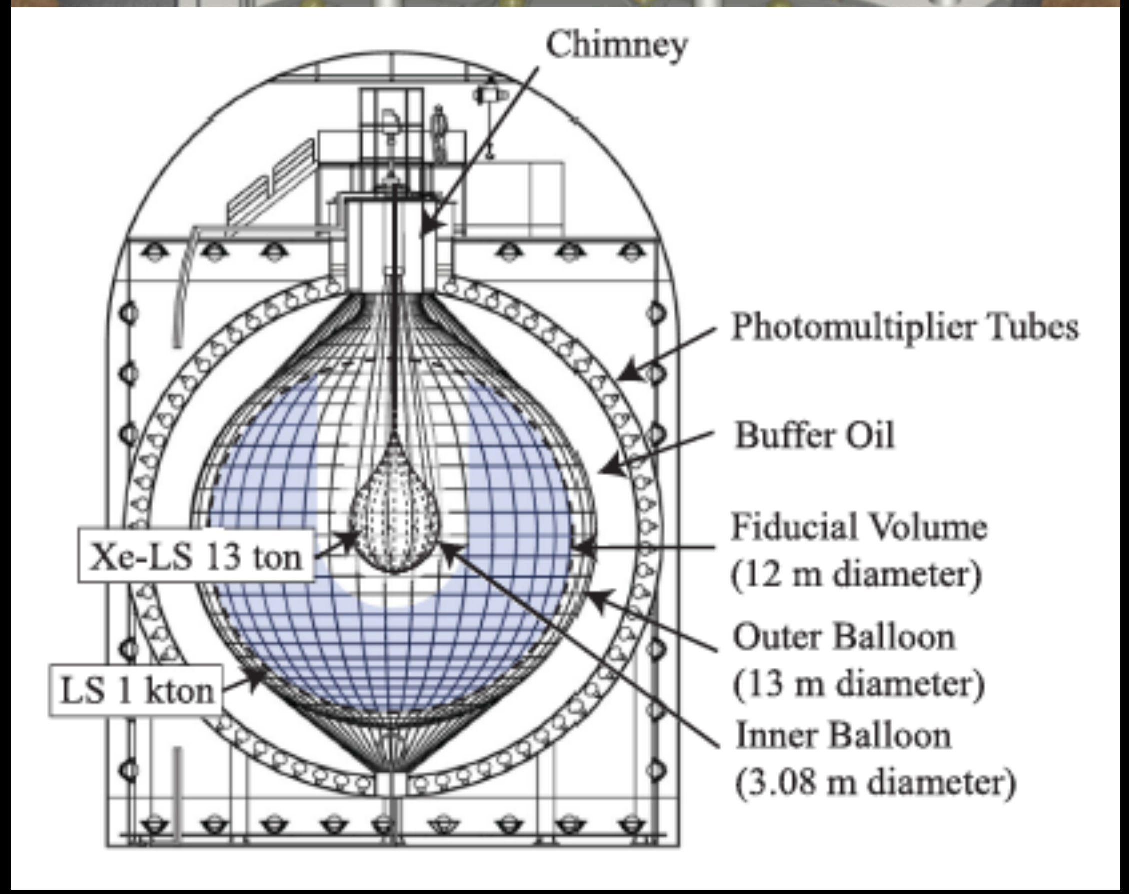
- In fission reactors, fragments of ^{235}U or ^{239}Pu break-up are neutron-rich, so they β^- decay, emitting $\bar{\nu}_e$, not ν_e (or other flavors).
- To go from ^{235}U to stable nuclei, on average 6 decays are needed, so 6 $\bar{\nu}$ are emitted per fission. Plus ~200 MeV.
- So, for a 3GW thermal power reactor (~Bruce Peninsula power plant), 6×10^{20} $\bar{\nu}$ are produced per second
- What's the flux at 300 m from the reactors?
  - **$F=5\times10^{10}\ \nu/\text{cm}^2/\text{s}$**

Energy: a few MeV

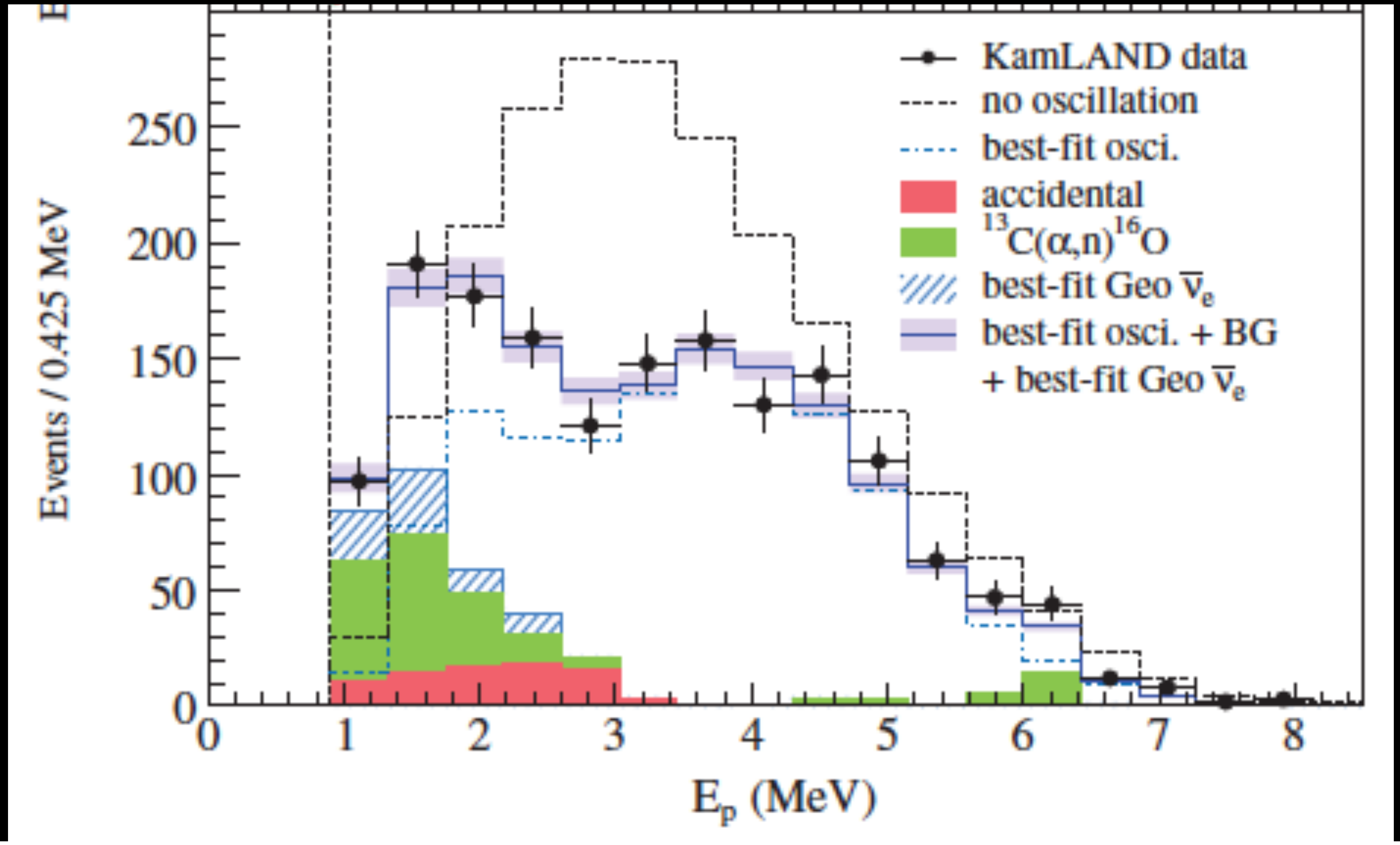


KAMLAND



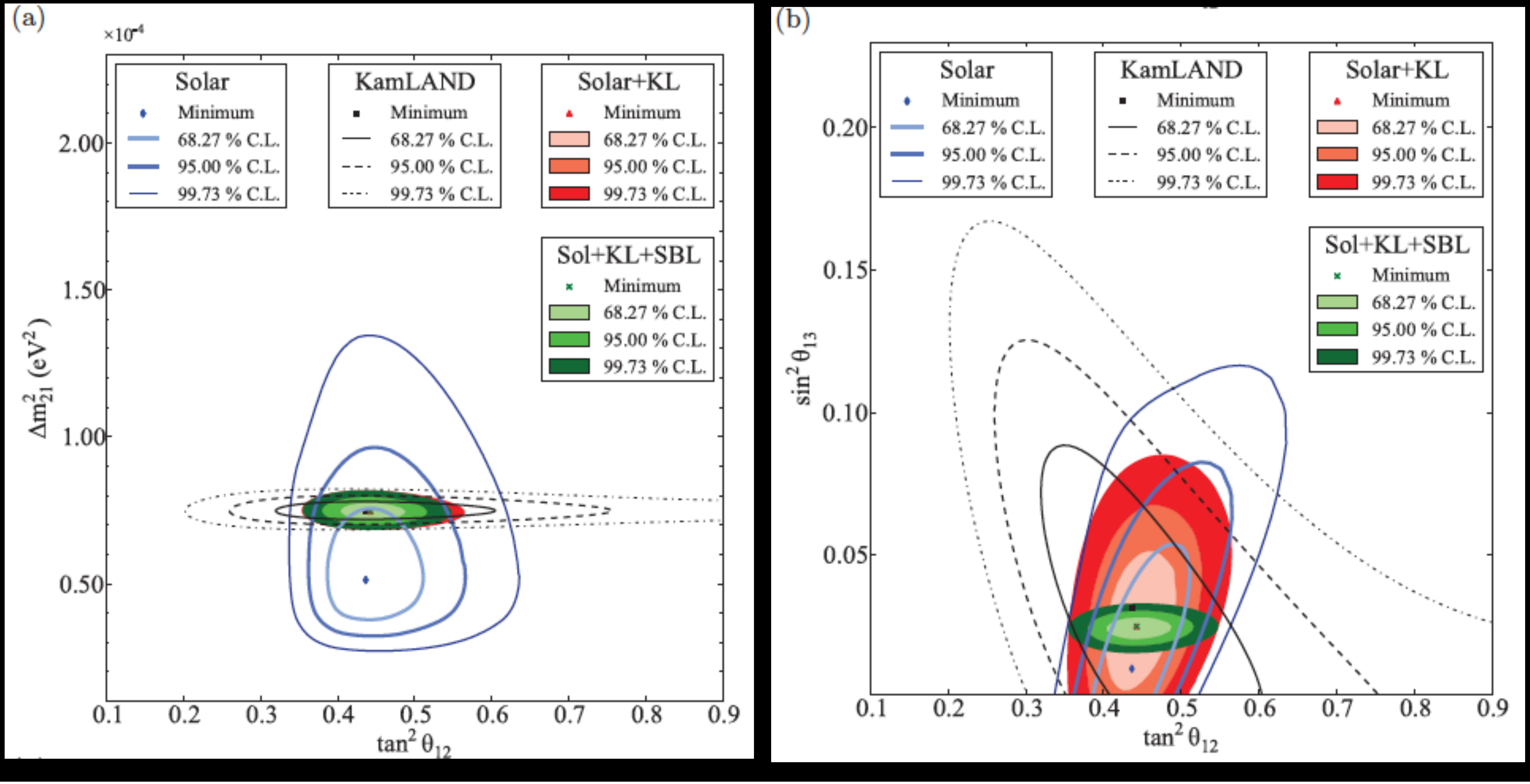


- Solar neutrino mixing in matter predicts oscillation suppression for reactor neutrinos, but only at long distances, ~50- 100 km
- Kamioka lab: average distance to reactors 180 km
- Low flux compensated by having the largest yet pure LS scintillator detector: 1 kton
- Solar neutrino mixing confirmed on Earth!



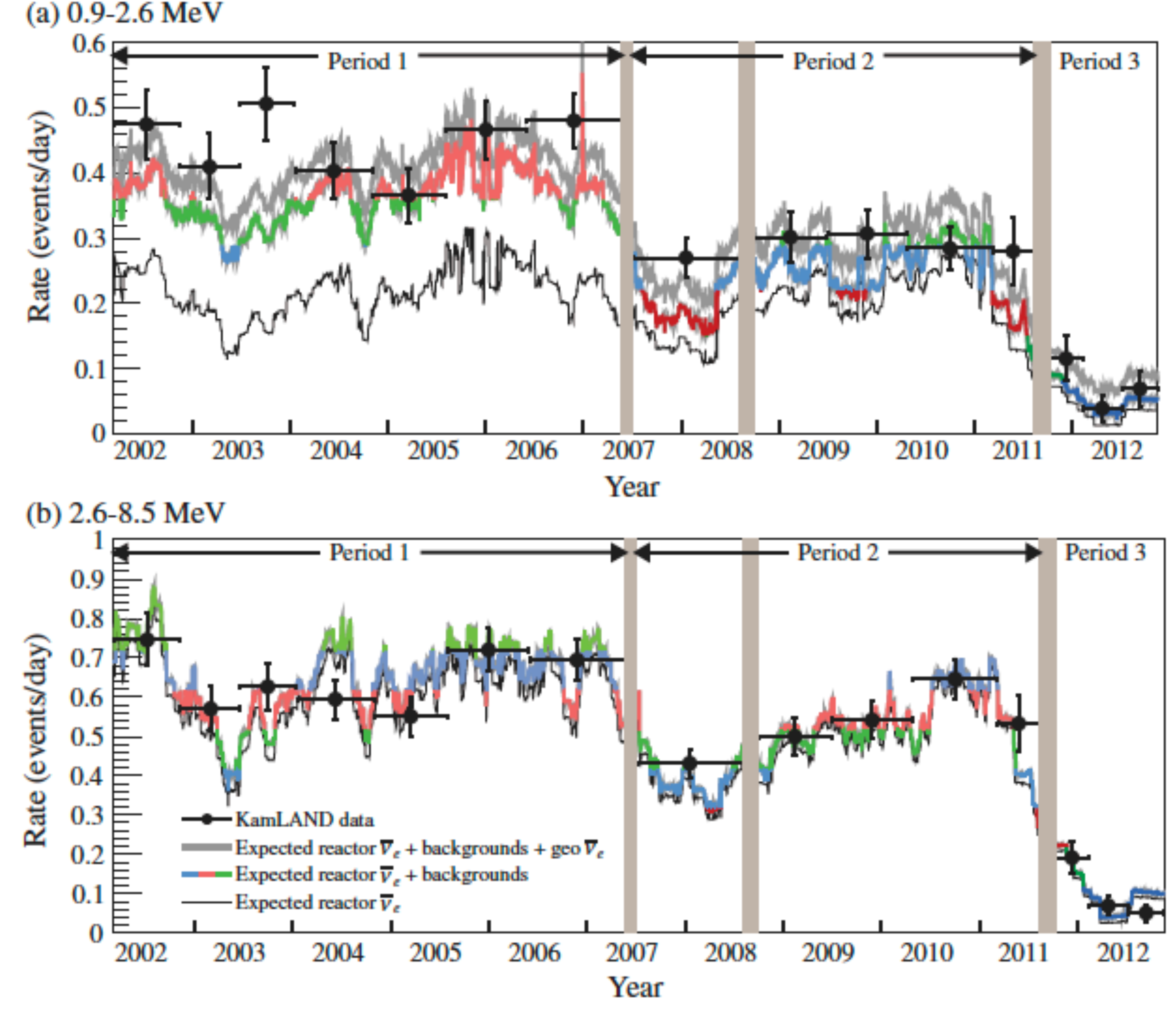
NEUTRINO OSCILLATIONS

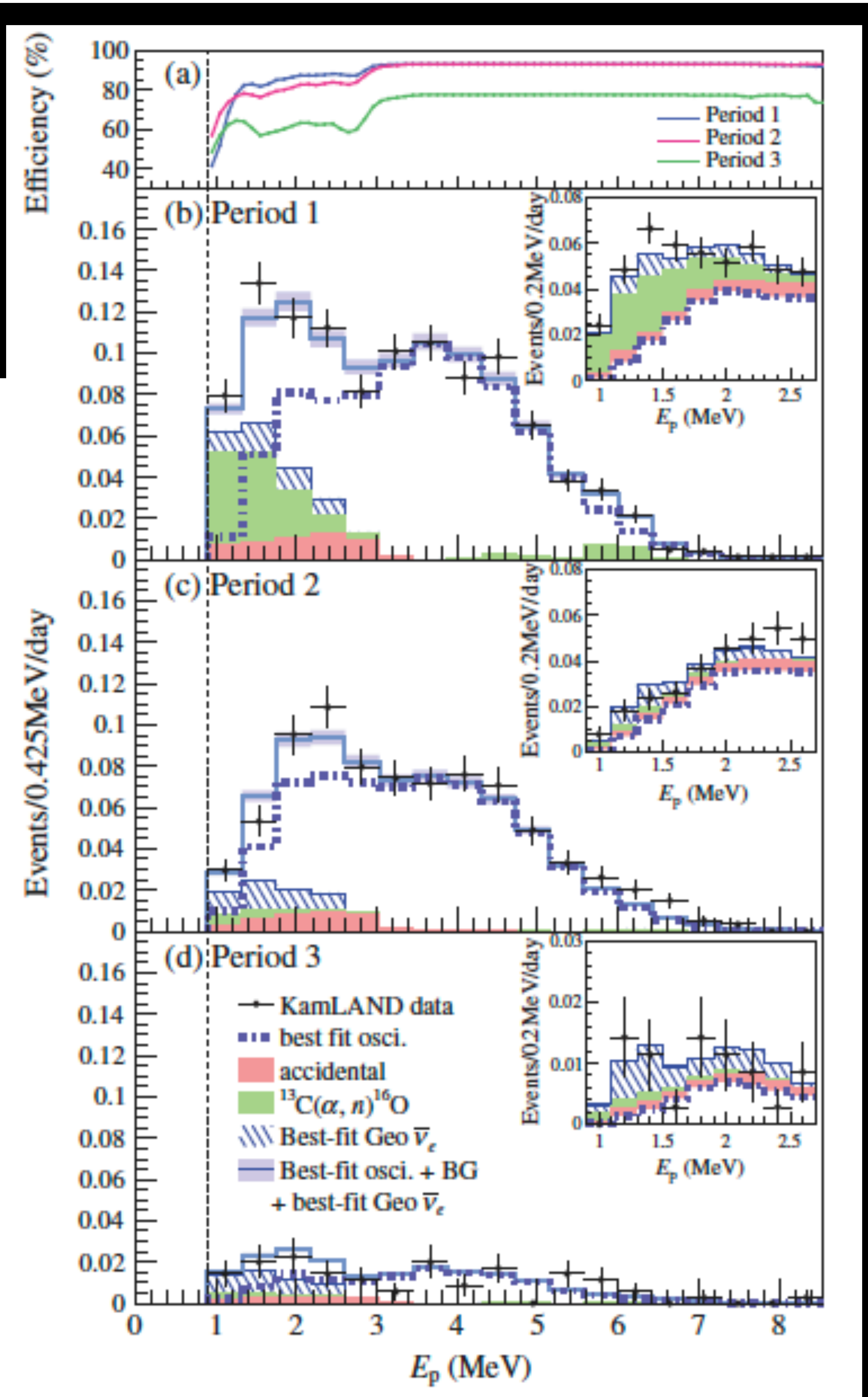
- SNO results crucial to good precision on θ_{12}
- Complementary with KamLAND's Δm^2_{12} sensitivity
- Tension led to early hints of non-zero θ_{13} , SBL experiments (Daya Bay, Reno, Double-Chooz, and also T2K, Minos) then measured it

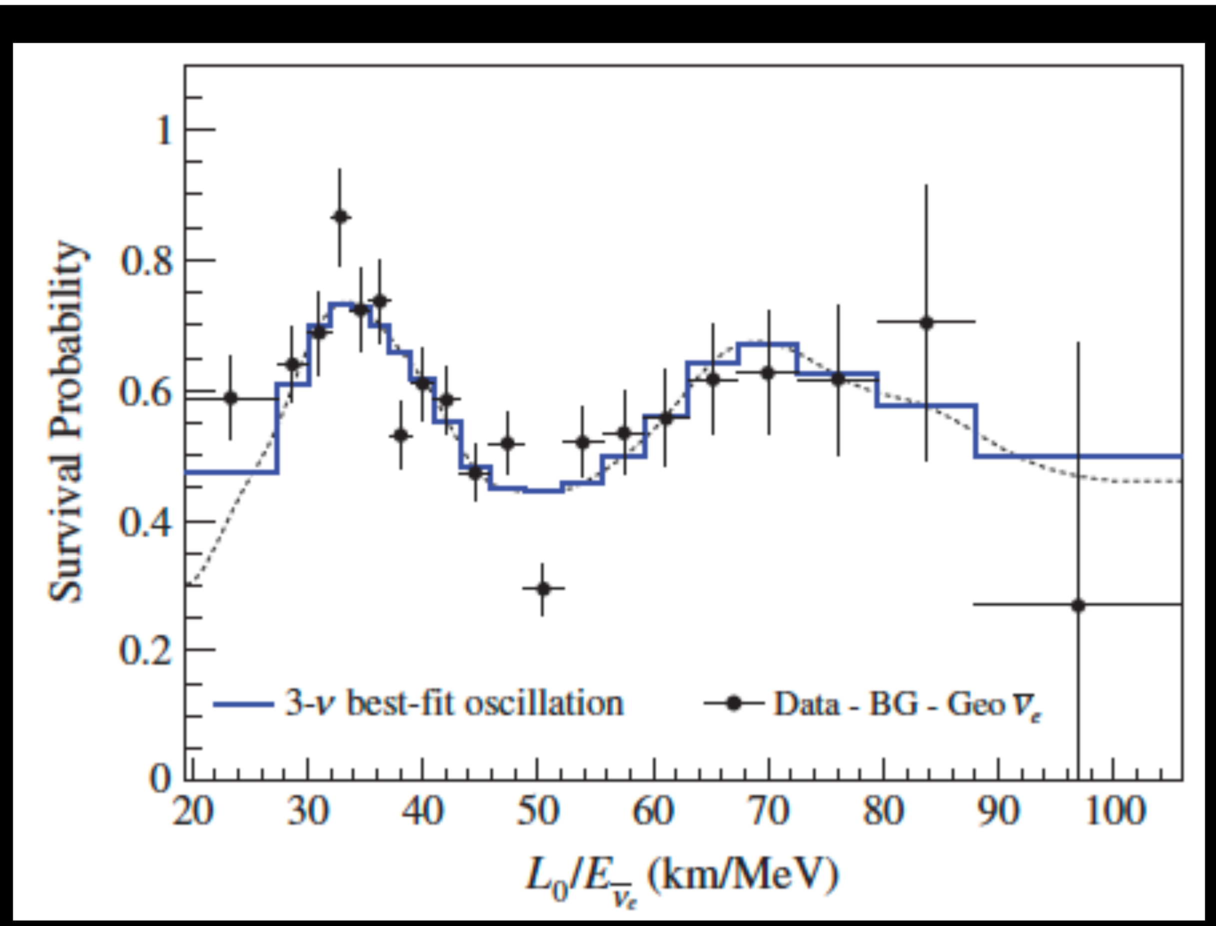


KAMLAND FINAL RESULTS

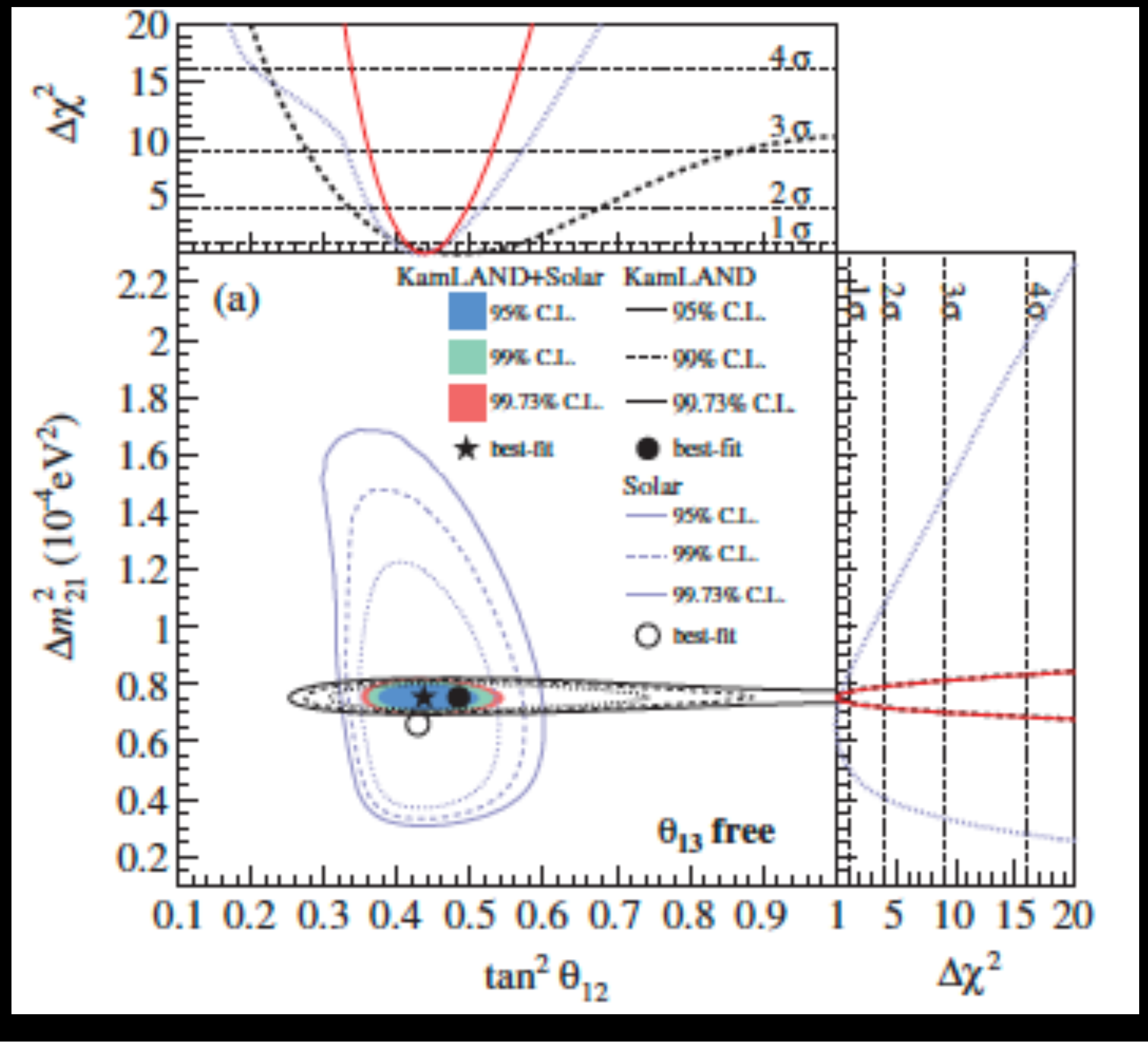
- Long-term shutdown of reactors in Japan following Fukushima
- Allowed better estimation of backgrounds at KamLAND





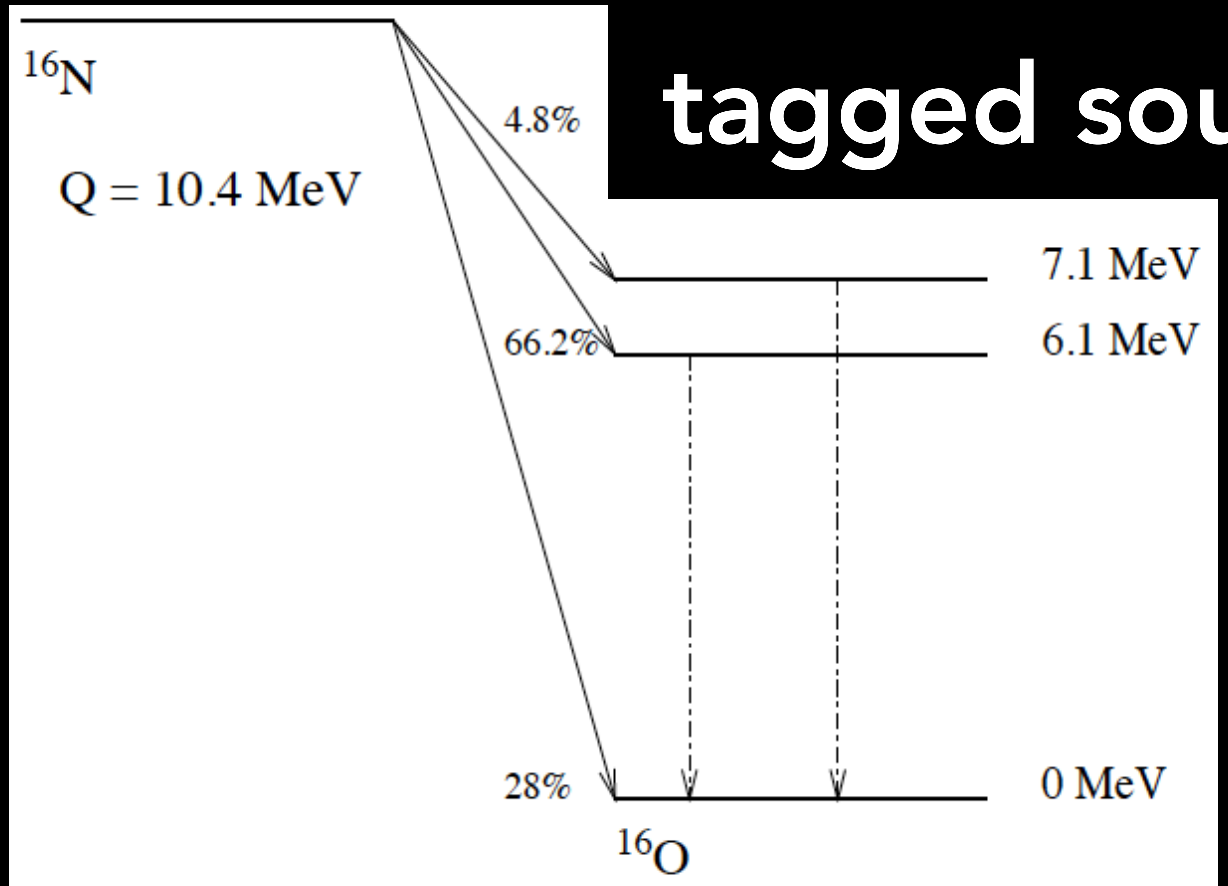


Most precise measurement of Δm^2_{12}

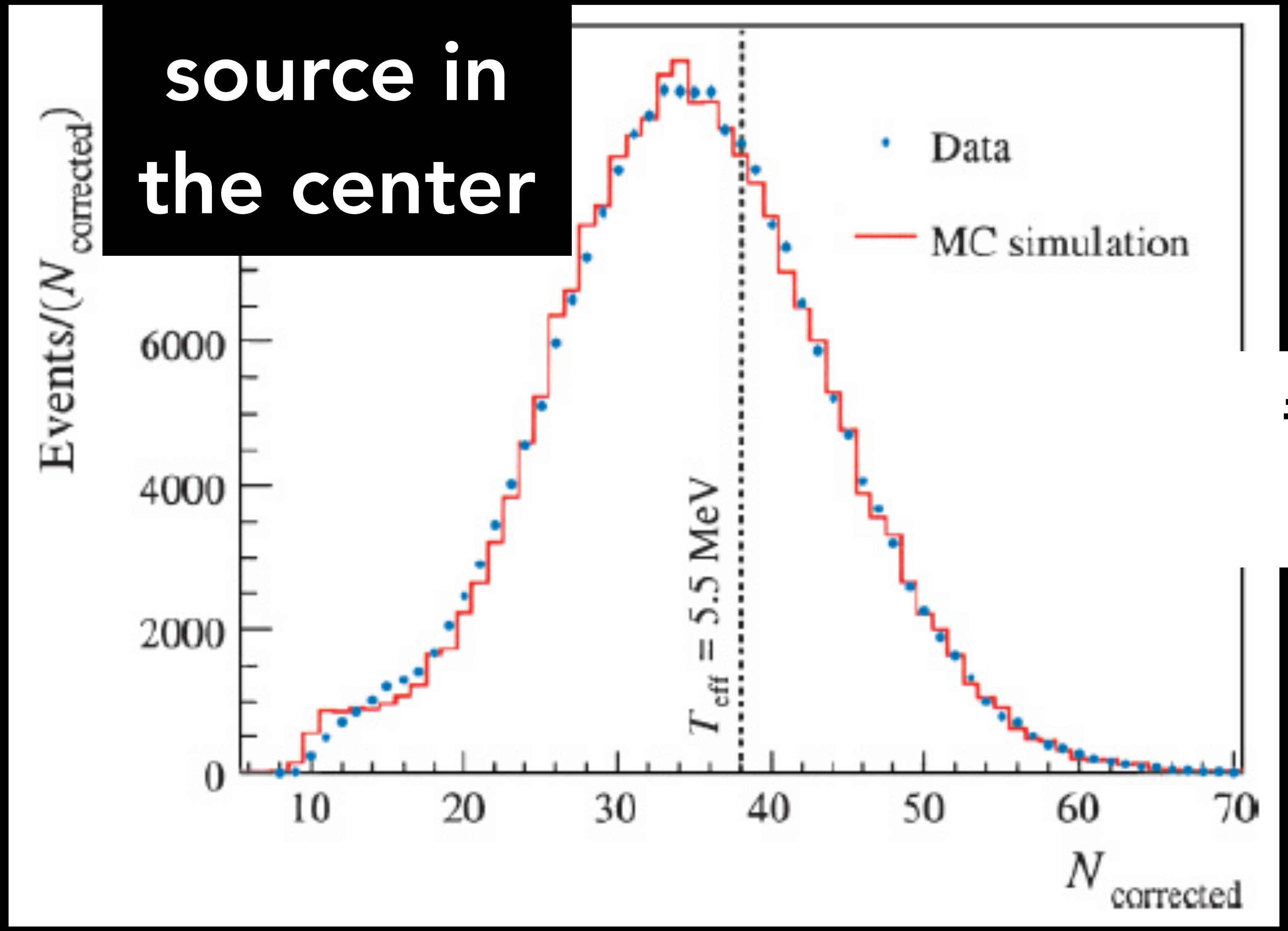


EXTRA SLIDES

N16 ENERGY CALIBRATION



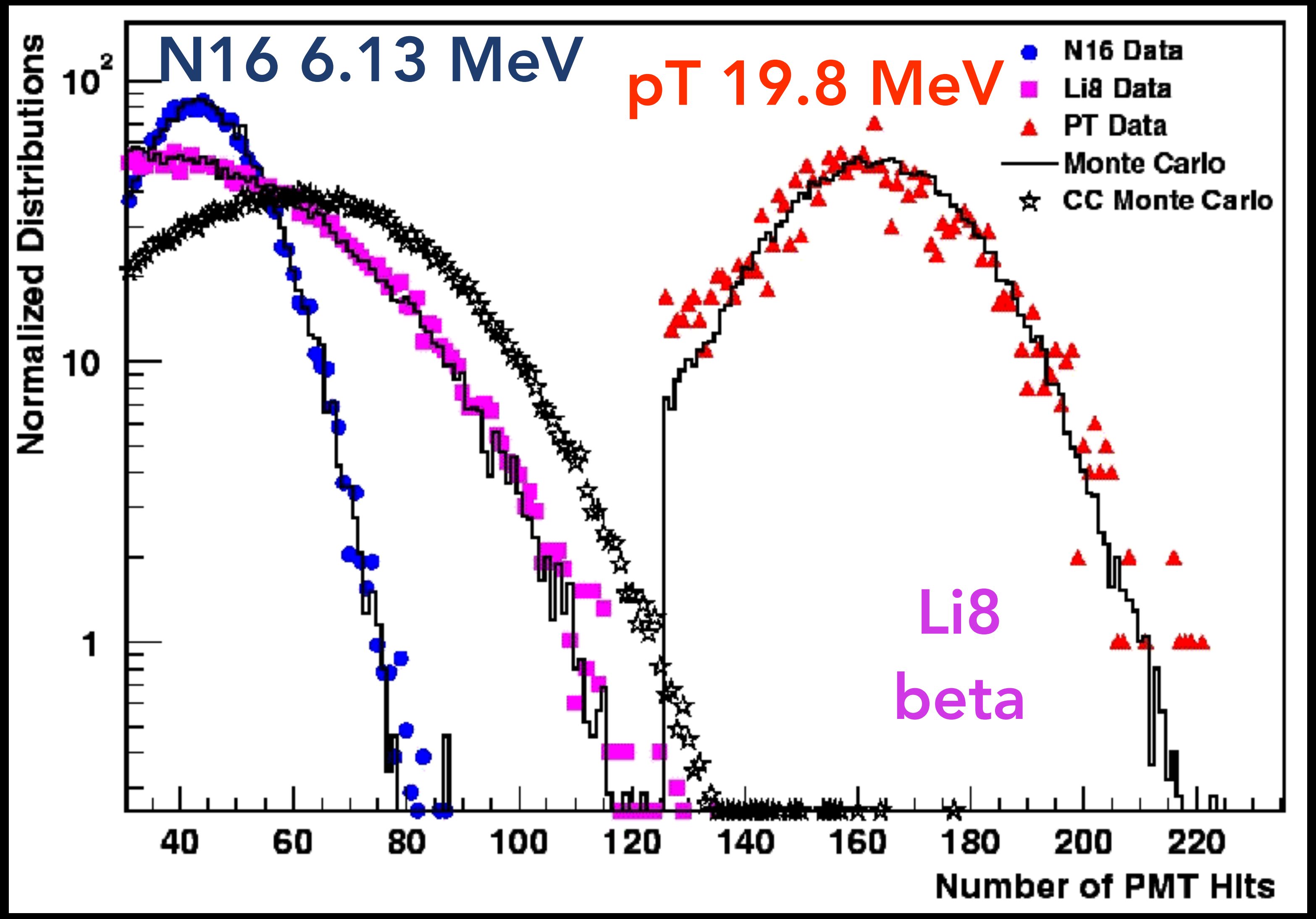
6.13 MeV γ tagged source



source in the center

hits corrected for optical response

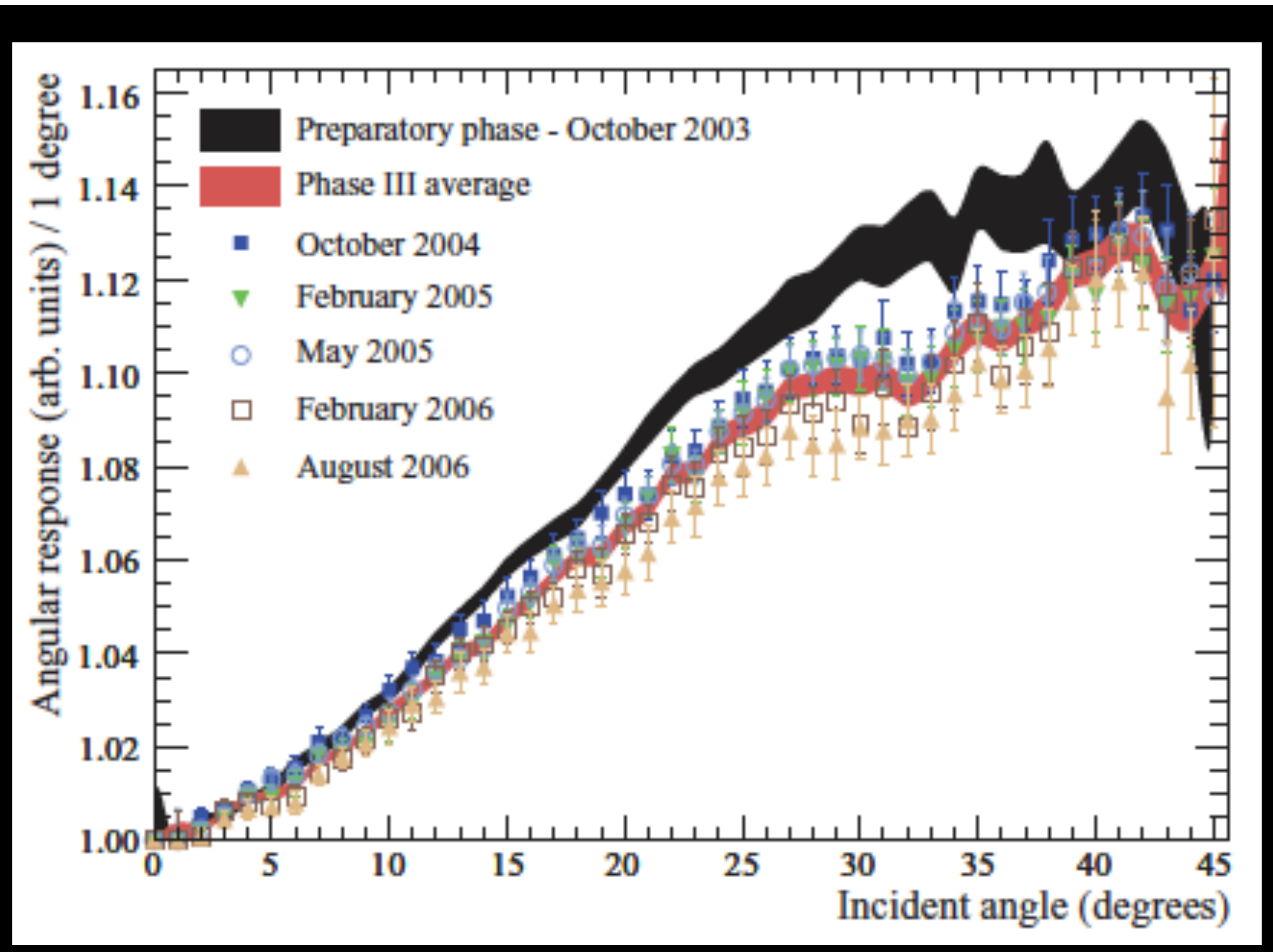
Other sources used to validate higher energies



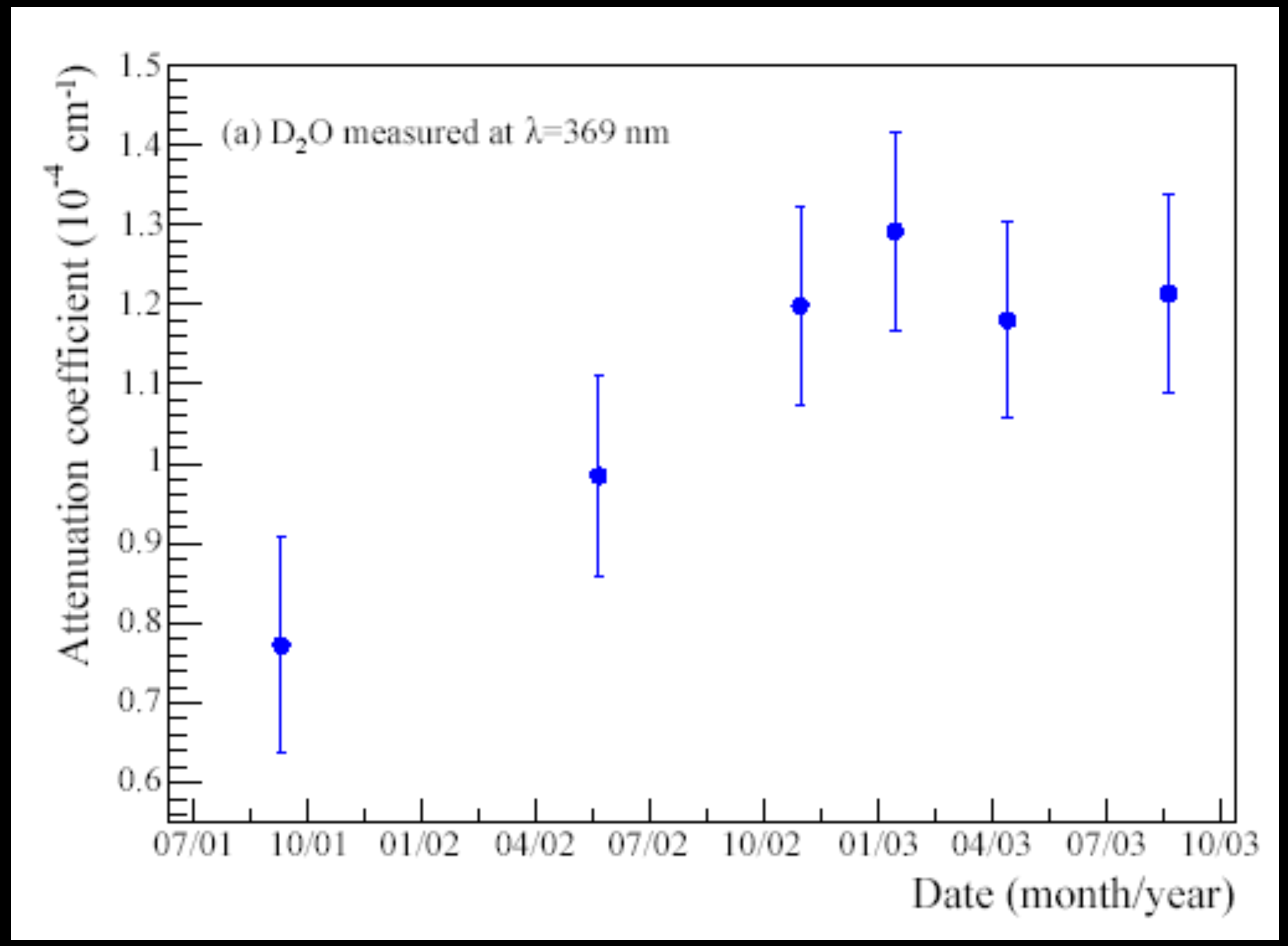
- Energy estimator using number of prompt hits
  - later using all PMT hits, including late times
- # of detected PMT hits varies with event position by up to 8% due to PMT angular response, attenuation in heavy and light water, and acrylic
  - Need to measure the optical properties *in-situ* -> optical calibration

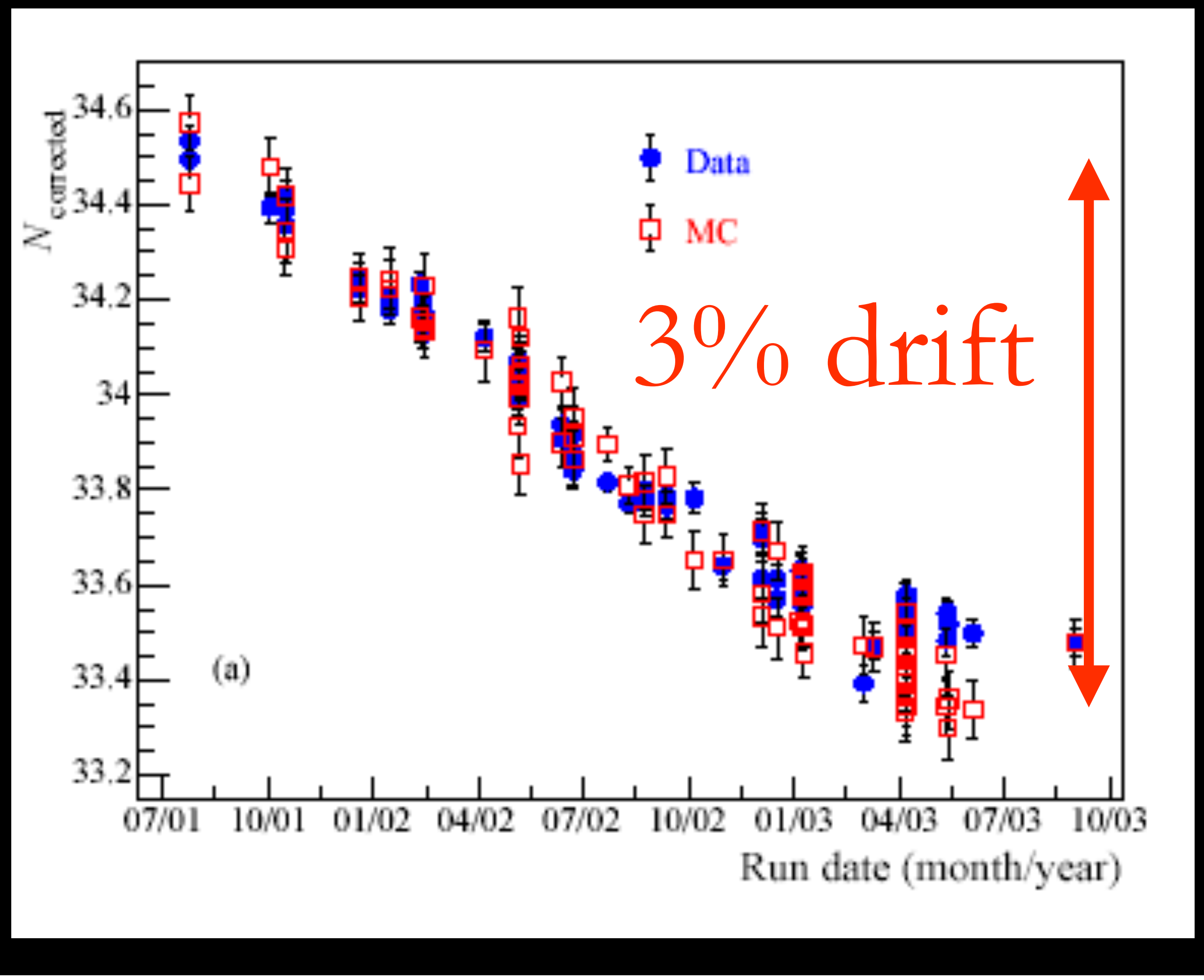
OPTICAL CALIBRATION

- PMT + reflector response versus incidence angle
- reflectivity degraded over time



- In salt phase, a drift in energy response was identified as caused by increasing attenuation of heavy water

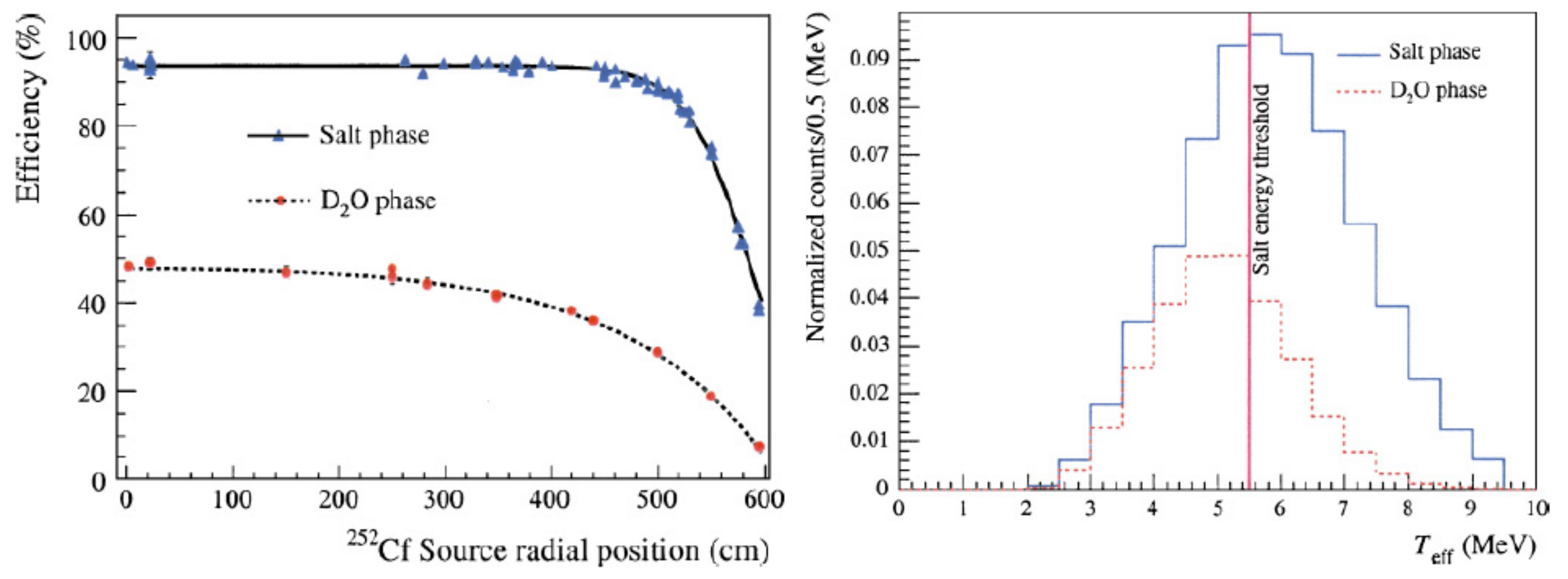




After all corrections, energy scale systematics were < 0.6%

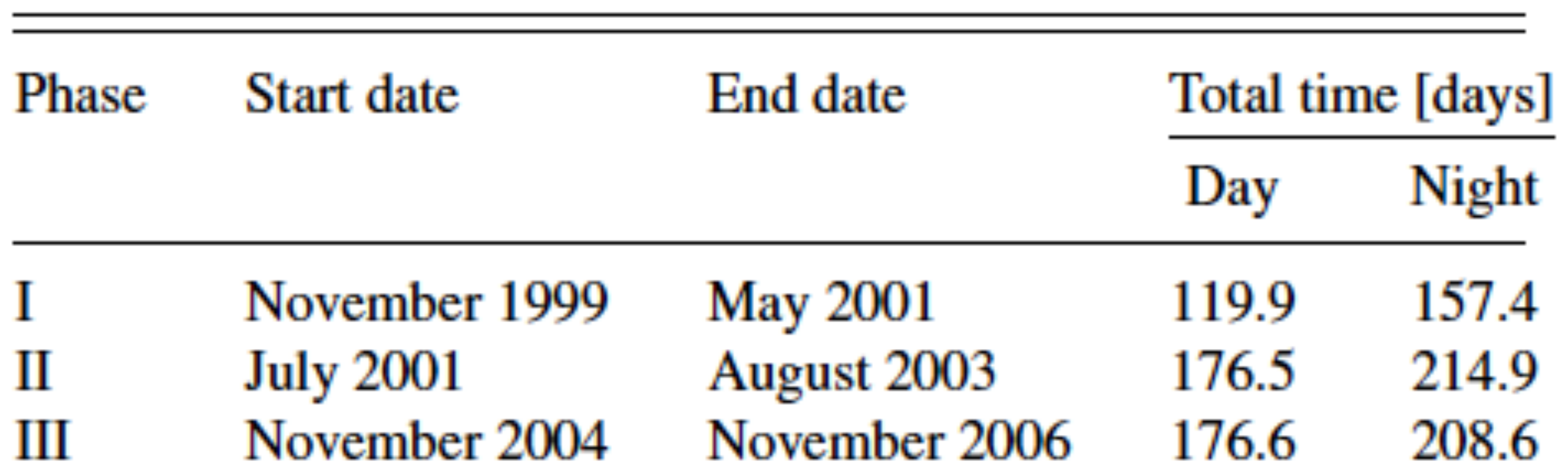
NEUTRON CALIBRATION

- AmBe and ^{252}Cf point sources
- Adding salt improved capture and detection efficiencies

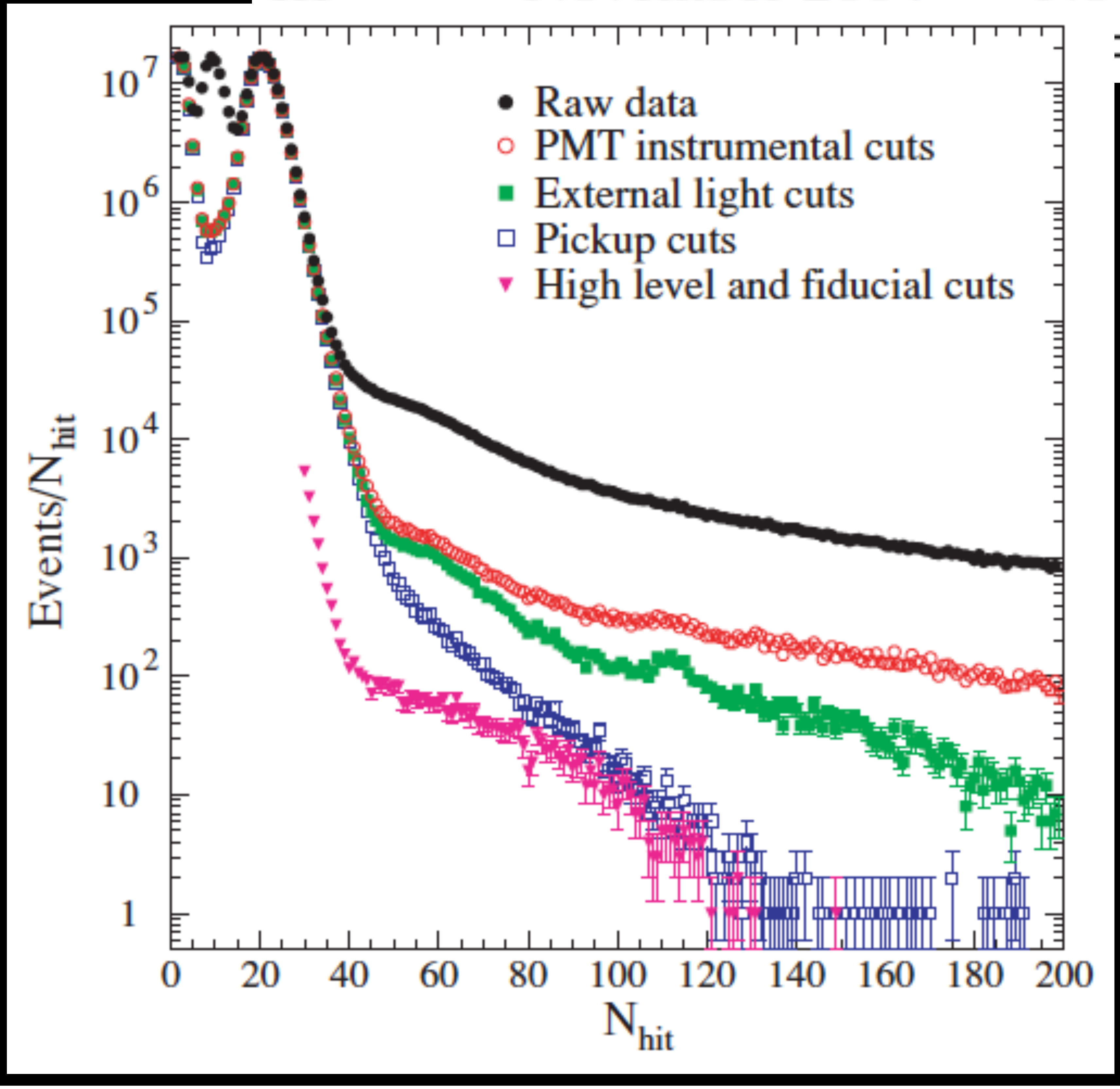


[ref. 14]

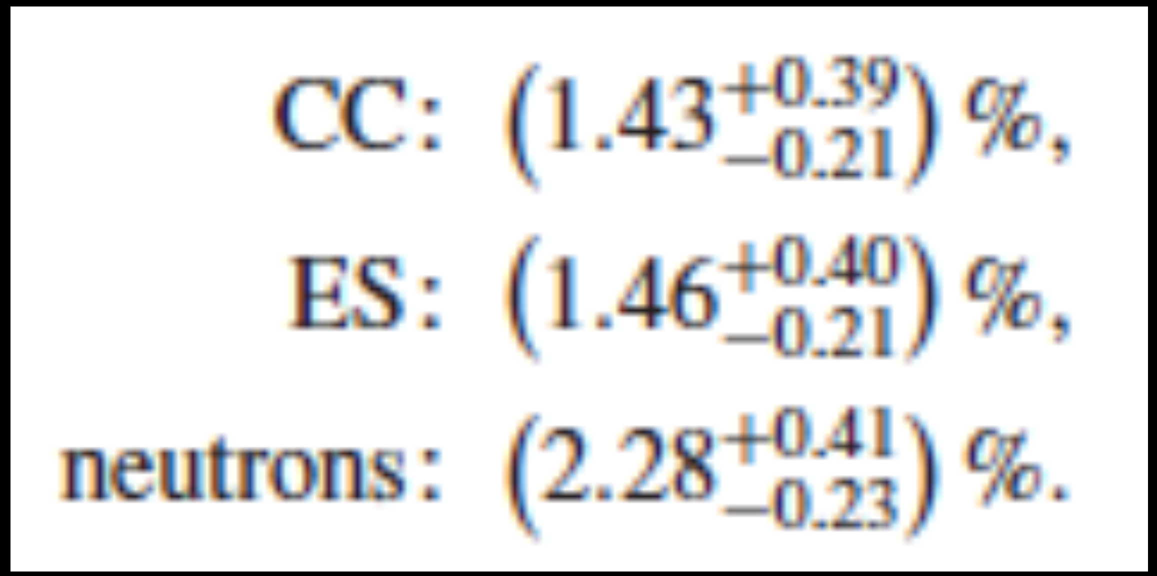
SNO DATA-TAKING



Phase	Start date	End date	Total time [days]	
			Day	Night
I	November 1999	May 2001	119.9	157.4
II	July 2001	August 2003	176.5	214.9
III	November 2004	November 2006	176.6	208.6



Large fraction of data-taking used in calibrations

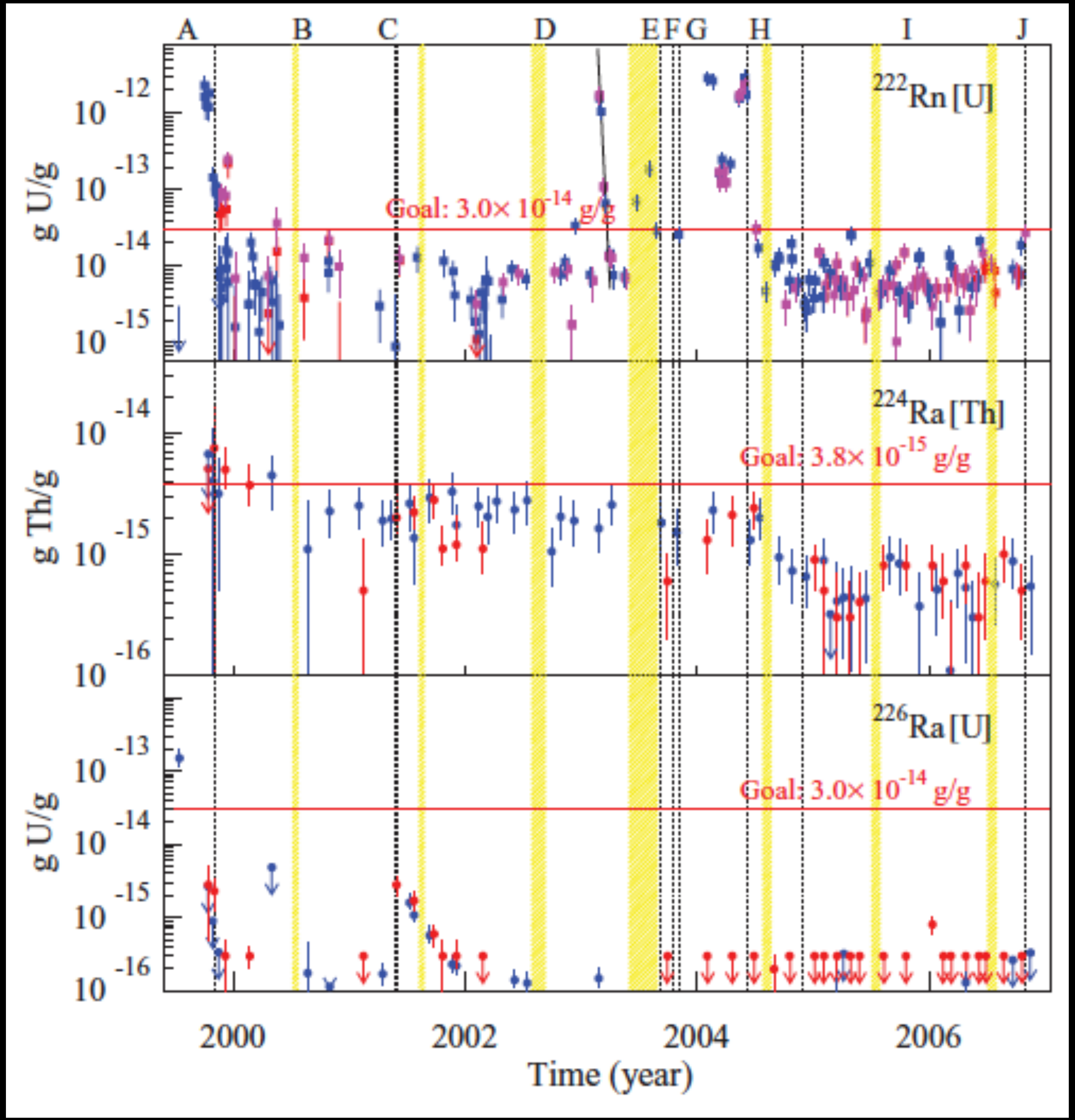


$$\text{CC}: \ (1.43^{+0.39}_{-0.21})\,\%,$$
$$\text{ES}: \ (1.46^{+0.40}_{-0.21})\,\%,$$
$$\text{neutrons}: \ (2.28^{+0.41}_{-0.23})\,\%.$$

Signal-loss from cuts, phase I

CHALLENGE: RADIOACTIVITY

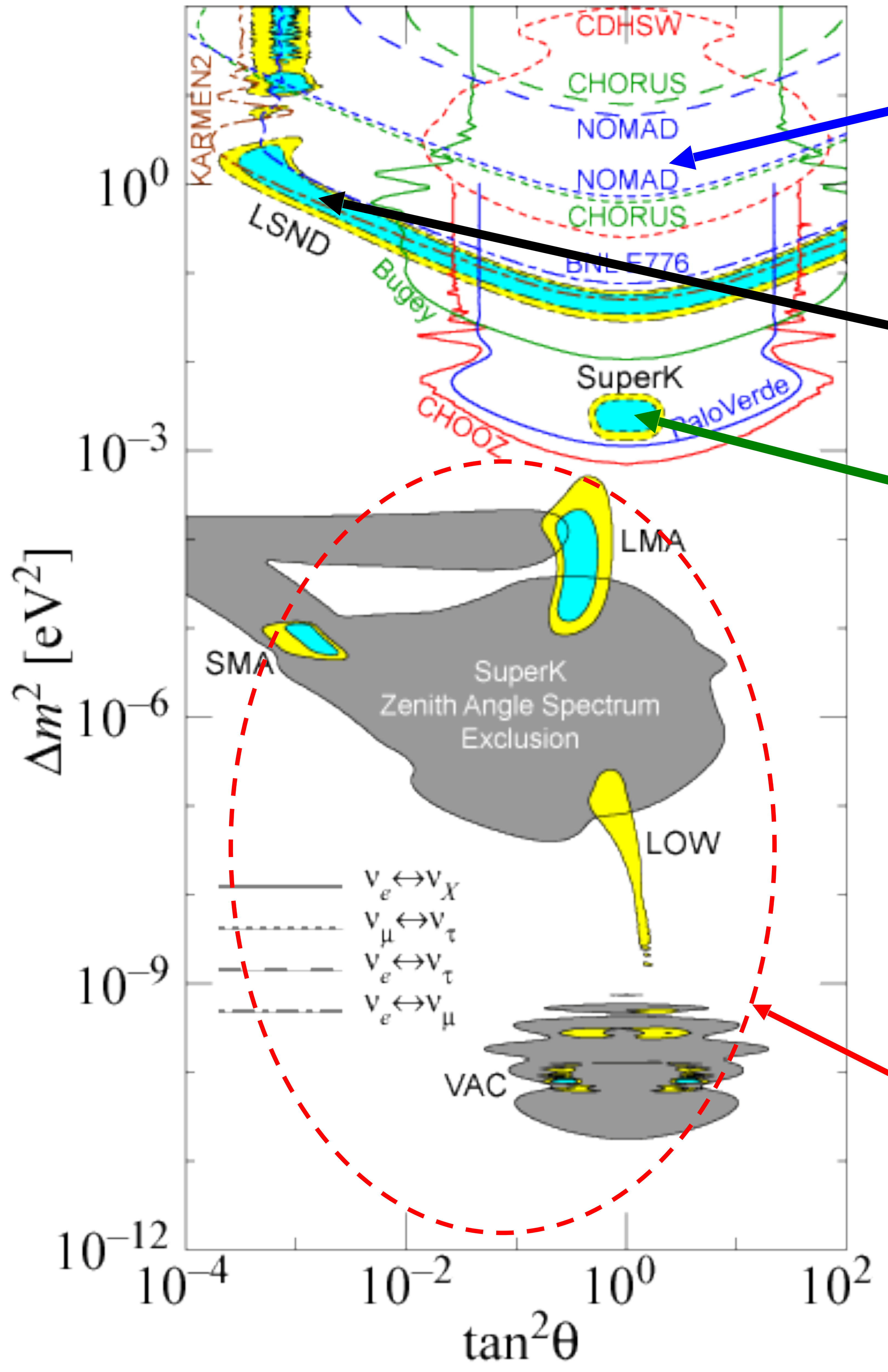

water purification plant



Heavy and light water regularly purified and assayed.
Well below target levels.

NEGATIVE OSCILLATION RESULTS

- oscillation hypothesis since late 1950s (nu/antinu), late 1960's (flavor).
- analogy with quark mixing
- short baseline reactor (Palo Verde, Bugey, etcc.)
- short baseline accelerator (CERN 1970's, chorus, nomad)



Excluded regions from other experiments

Possible oscillations from LSND (unconfirmed, being further checked by miniBoone)

Oscillations from "atmospheric neutrinos" (mainly $\nu_\mu \rightarrow \nu_\tau$)

Deficit of solar neutrinos can be interpreted as due to mixing with parameters in one of the regions here

Some of the solutions due to the fact that ν refractive index in the Sun different for ν_e and other flavors ("MSW effect")