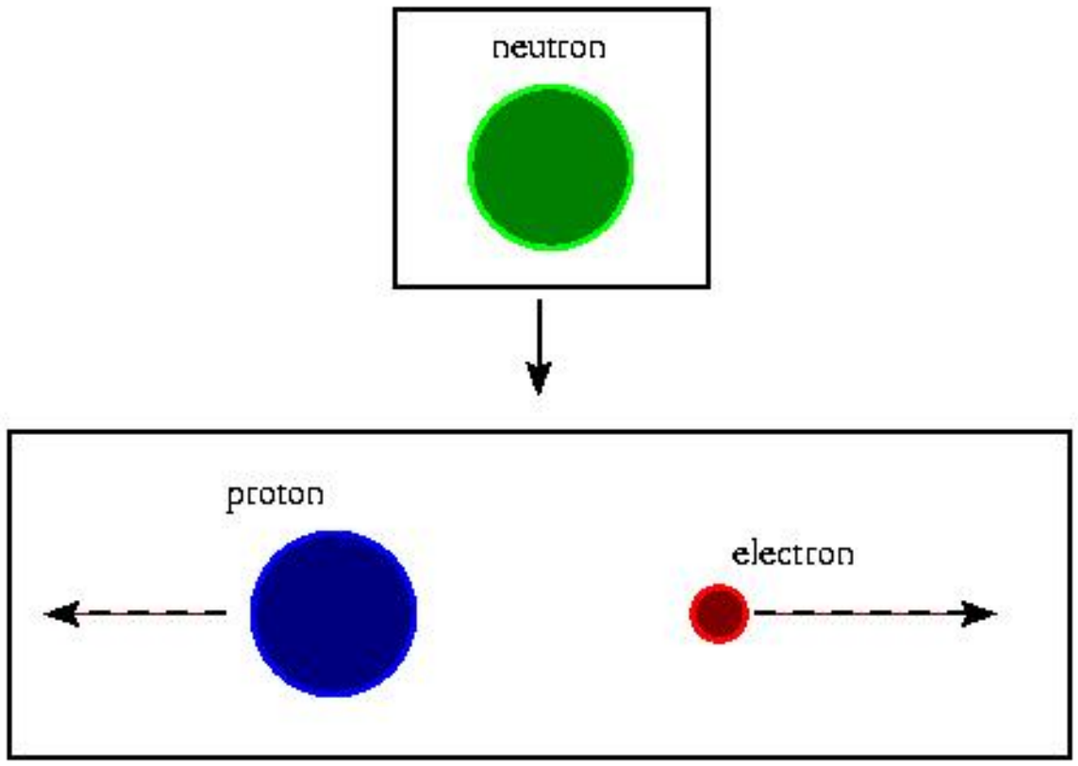
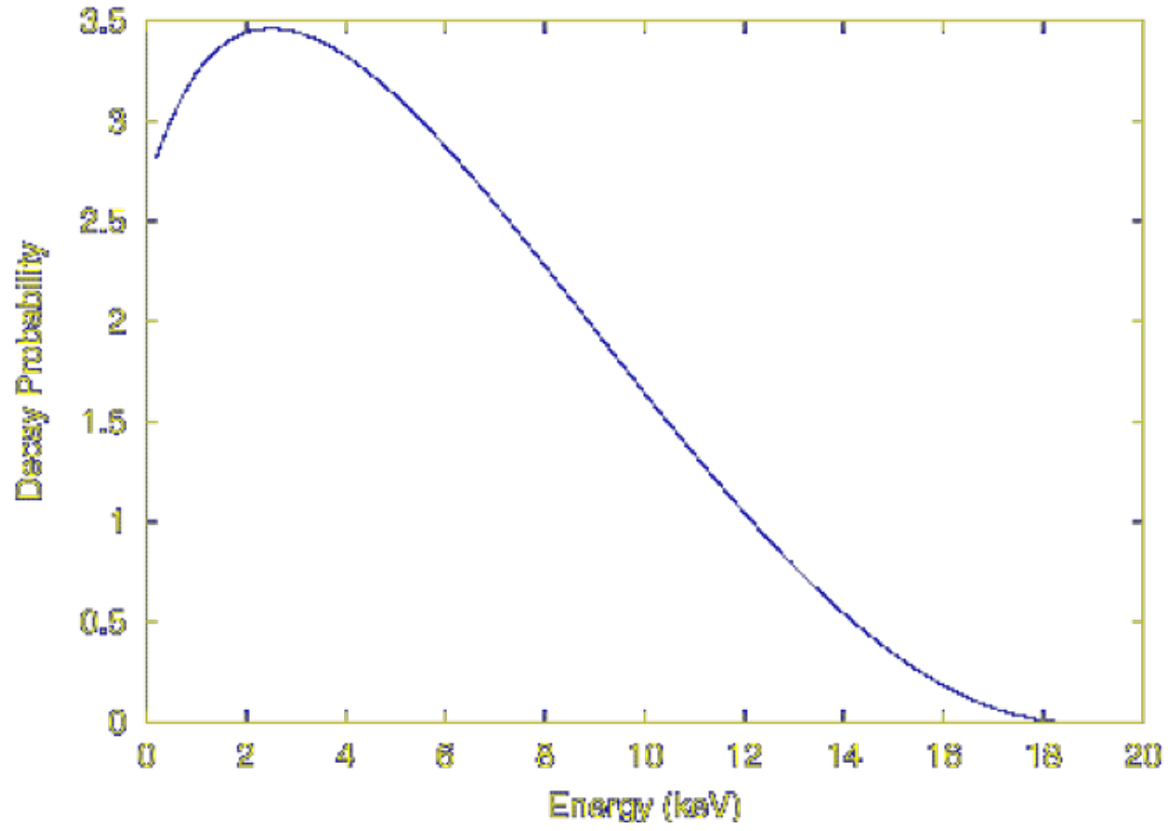
Beta decay spectrum - Necessity of a neutrino

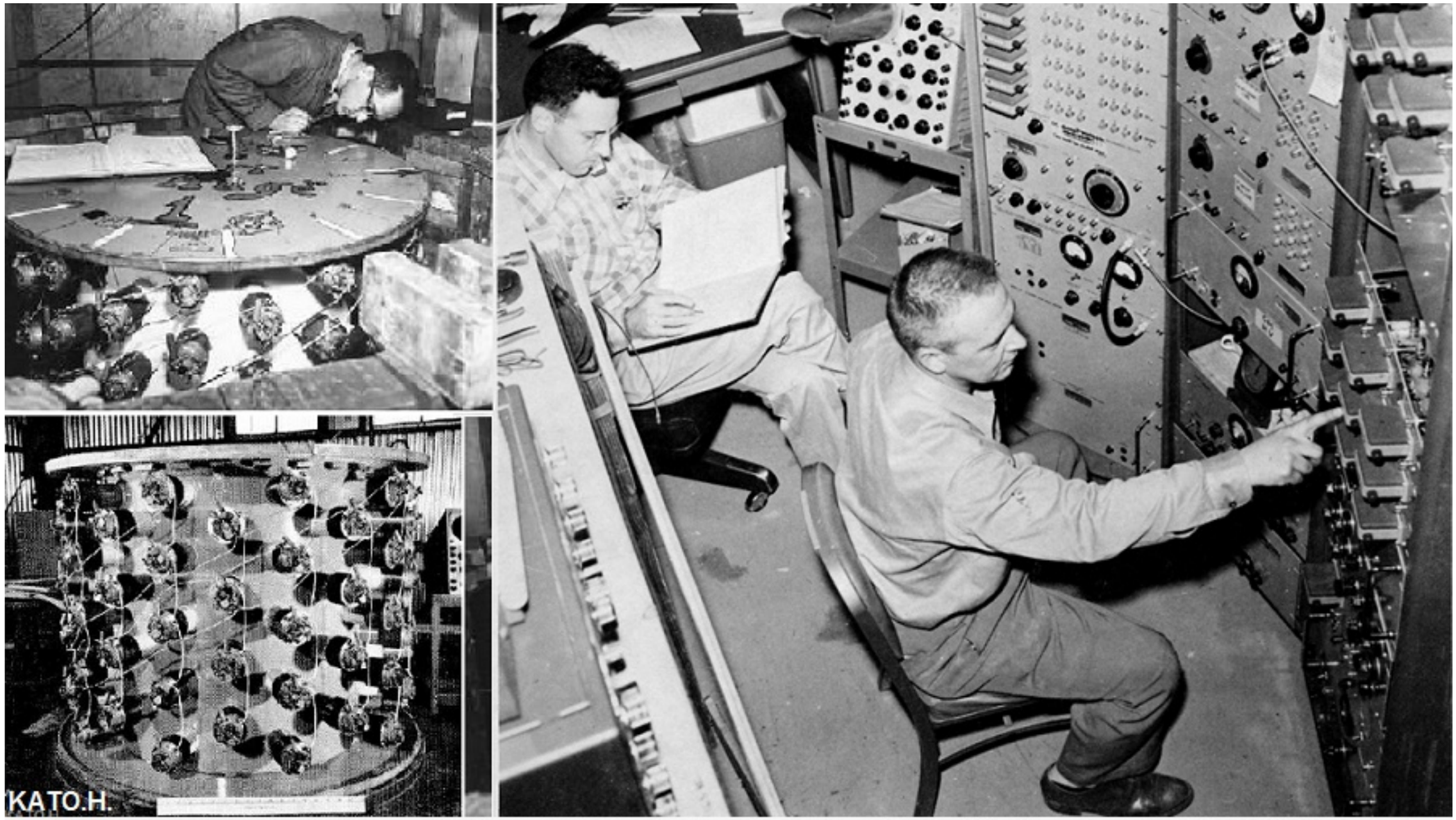
2-body decay should give mono-energetic electron



But observed spectrum is continuous

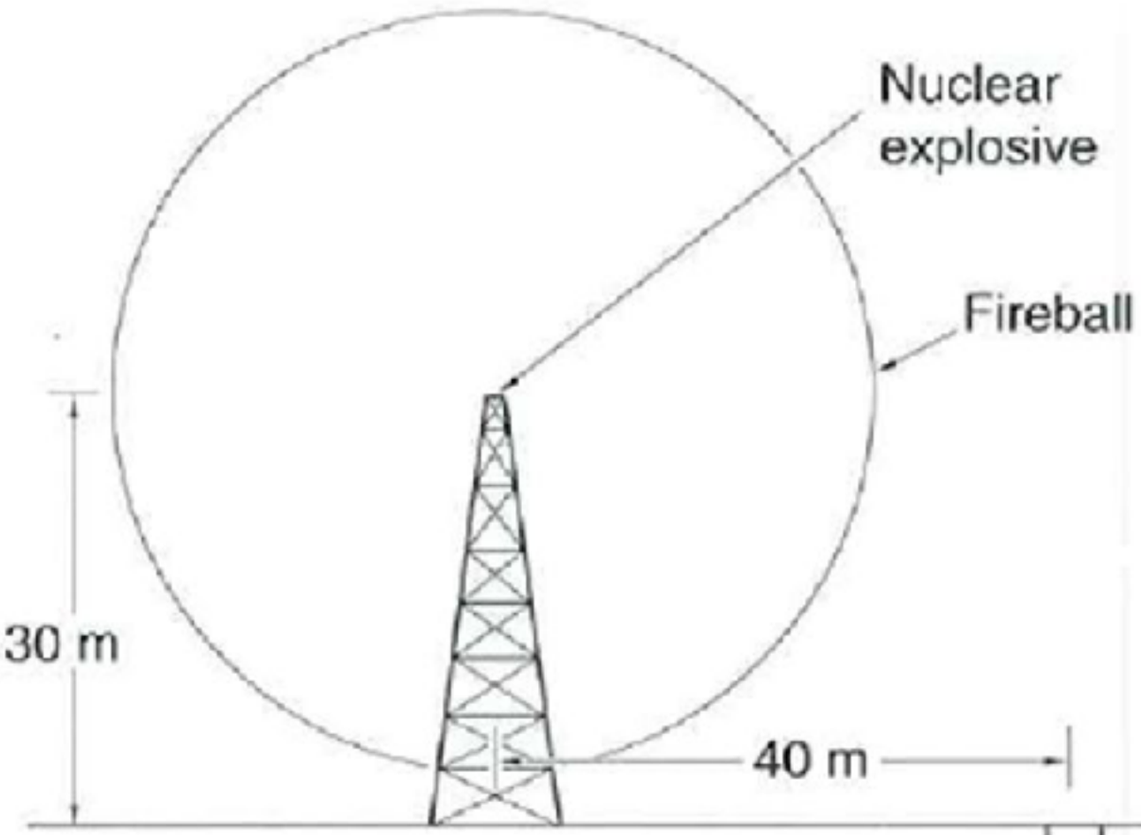


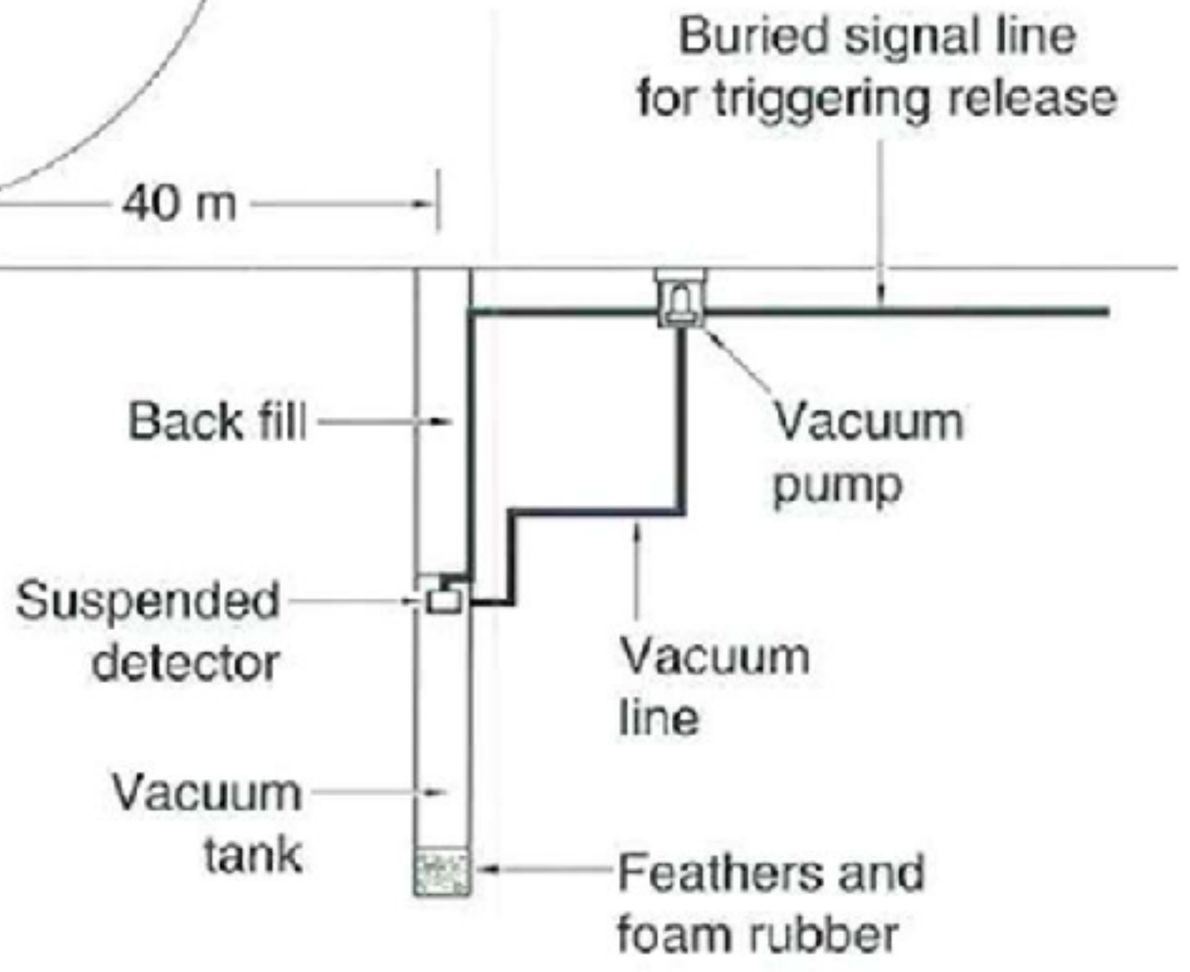
Detecting neutrinos



Frederick Reines (left) and Clyde L. Cowan, Jr. with the control equipment used in their first tentative observations of the neutrino at Hanford, Washington, in 1953. Their definitive detection of the (anti) neutrino was performed at Savannah River, Georgia, three years later.

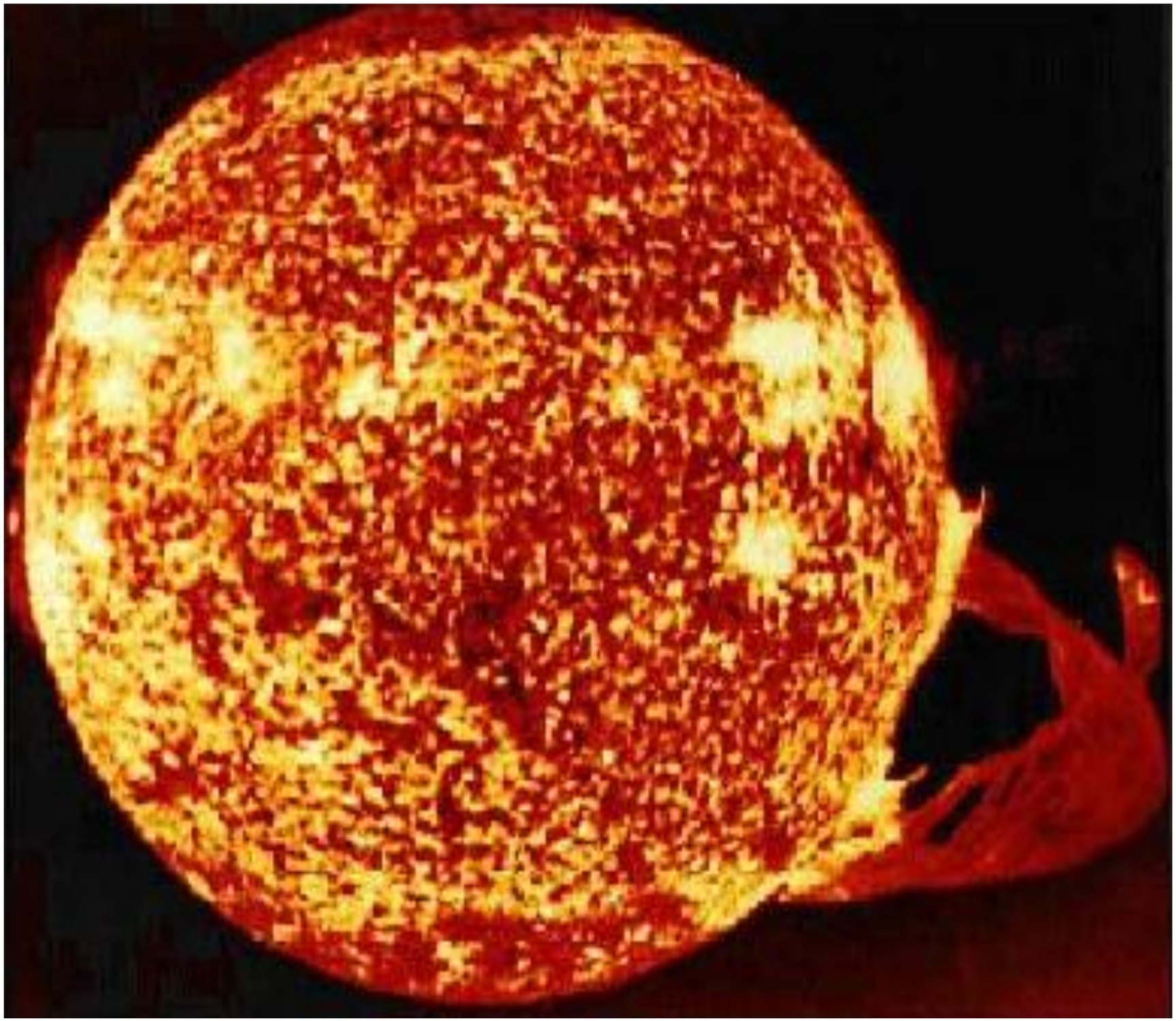
Reines‘ first idea to detect neutrinos …



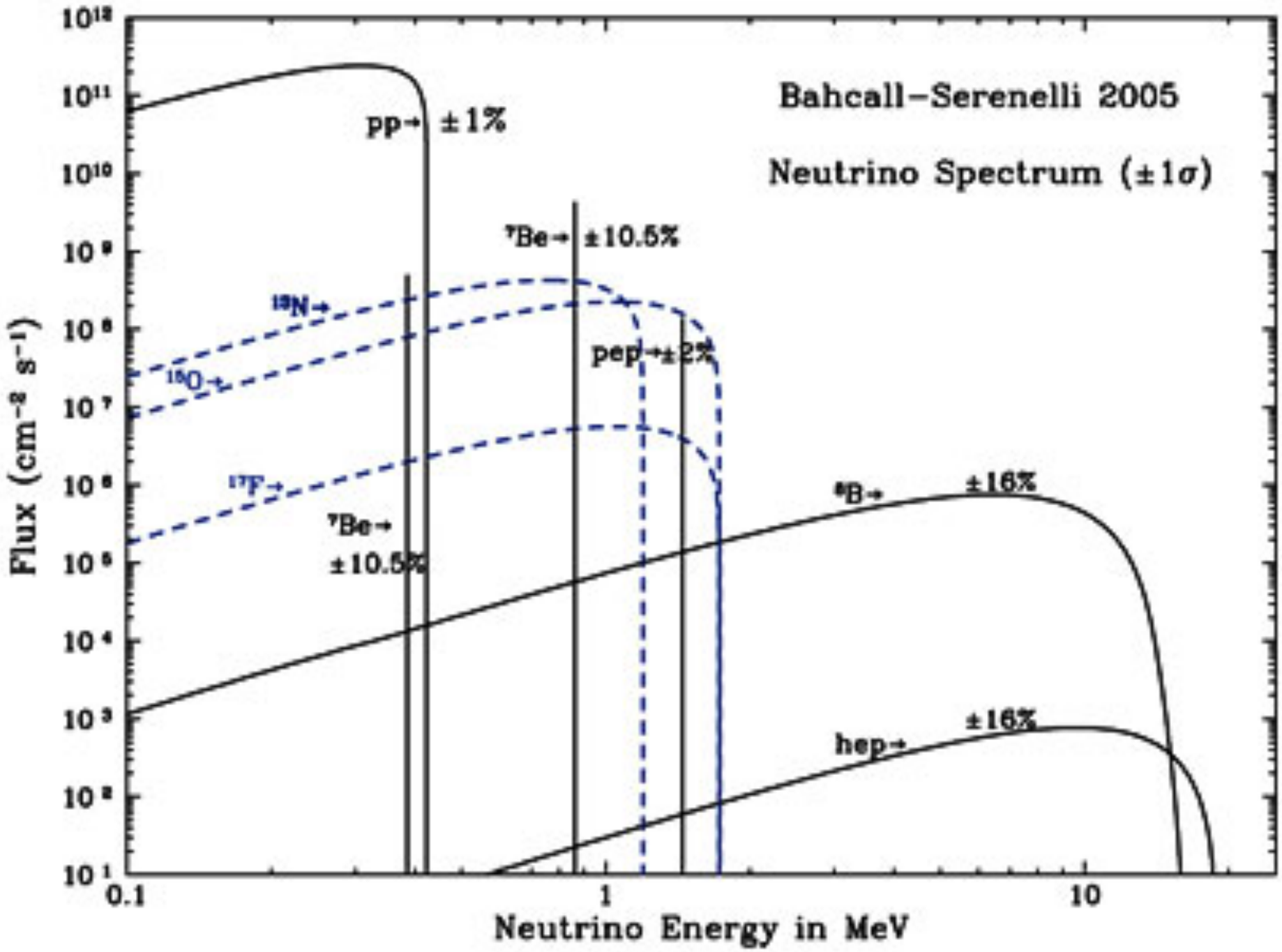


… from the explosion of a nuclear bomb !

Determine the temperature of the core of the sun



Neutrinos in the sun



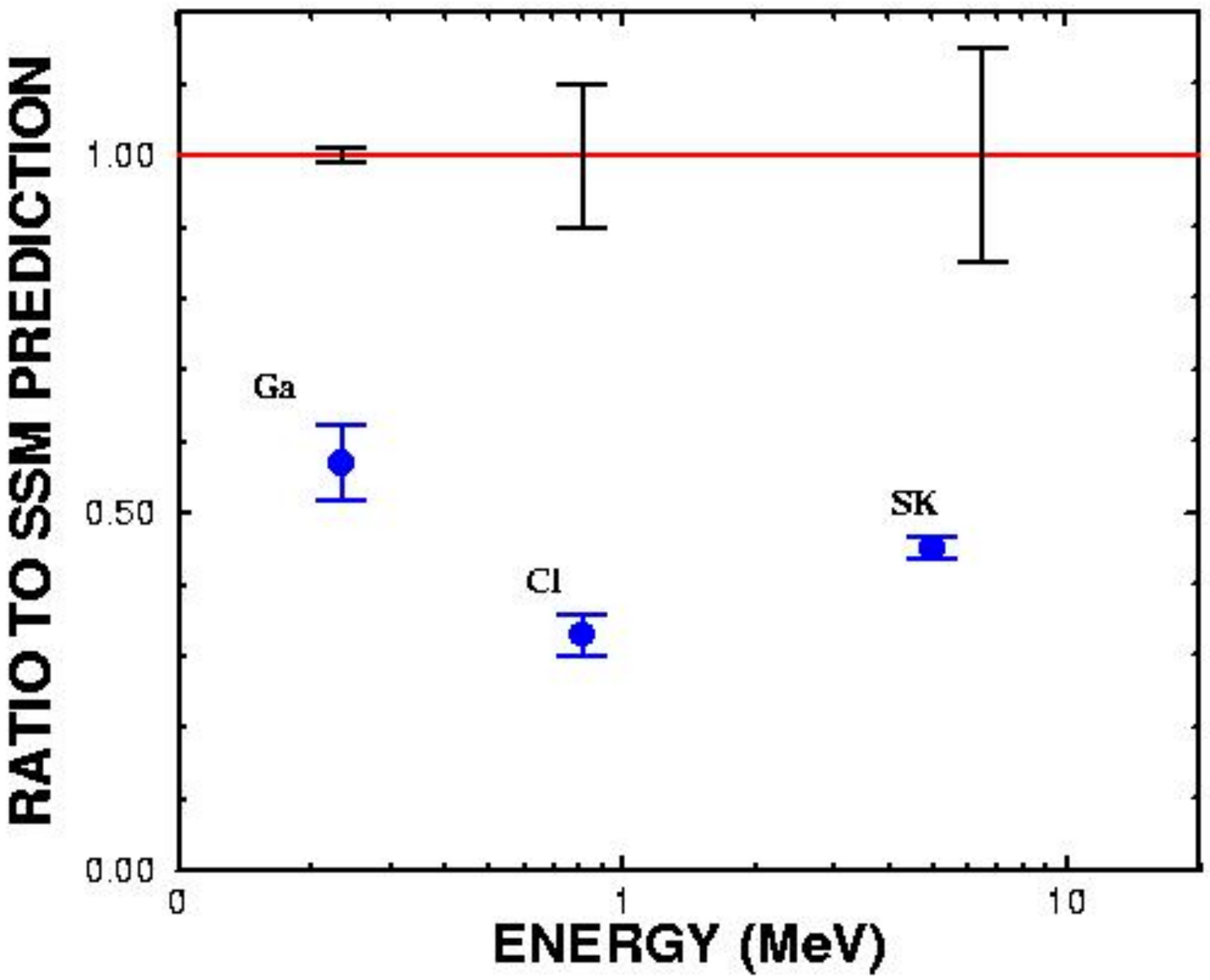
Homestake mine experiment

$$\nu_e + {}^{37}_{17}\mathrm{Cl} \rightarrow {}^{37}_{18}\mathrm{Ar} + e^-.$$

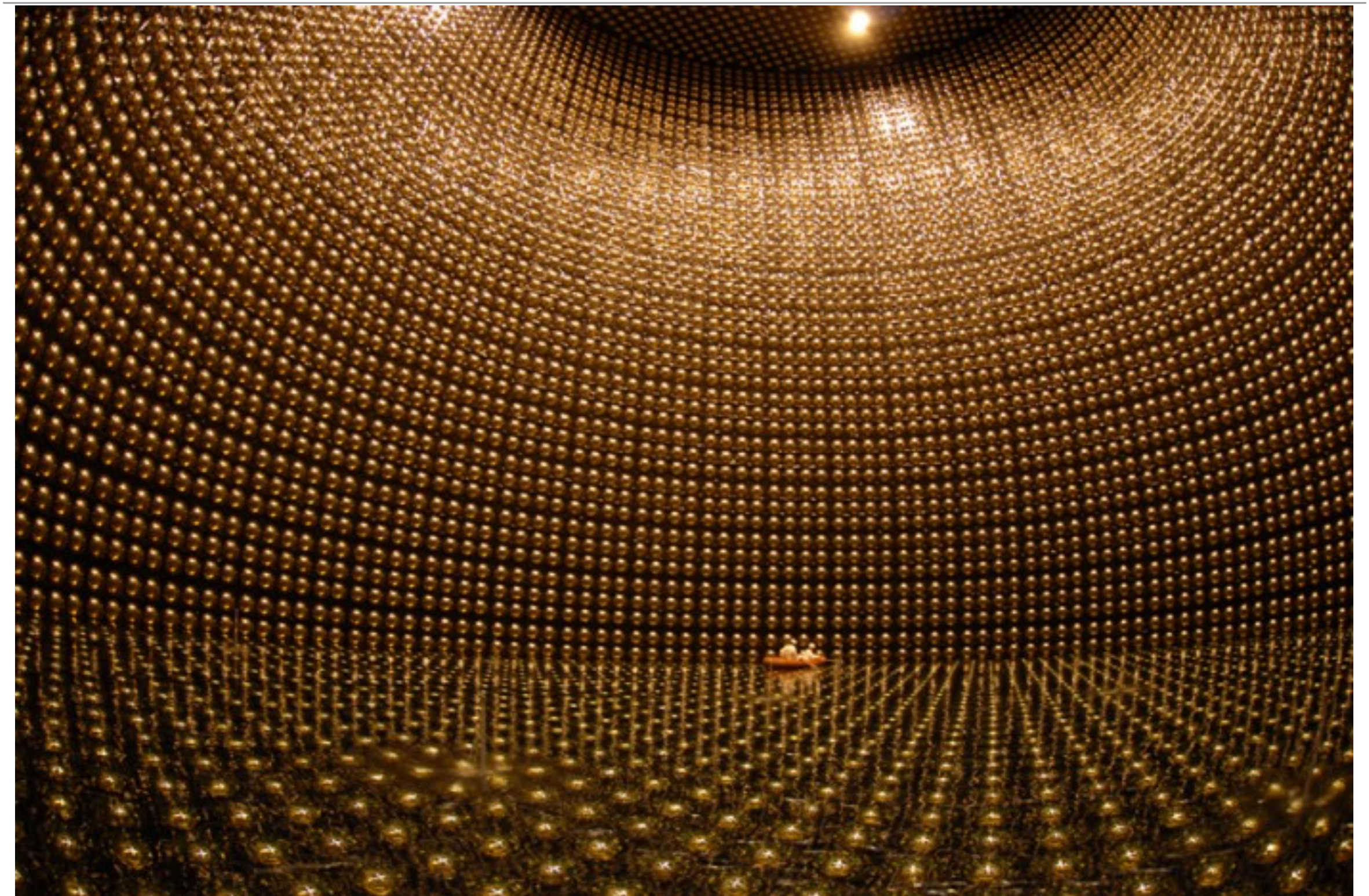
Chemically extracted the Argon and counted it

Saw 1/3 of what was expected

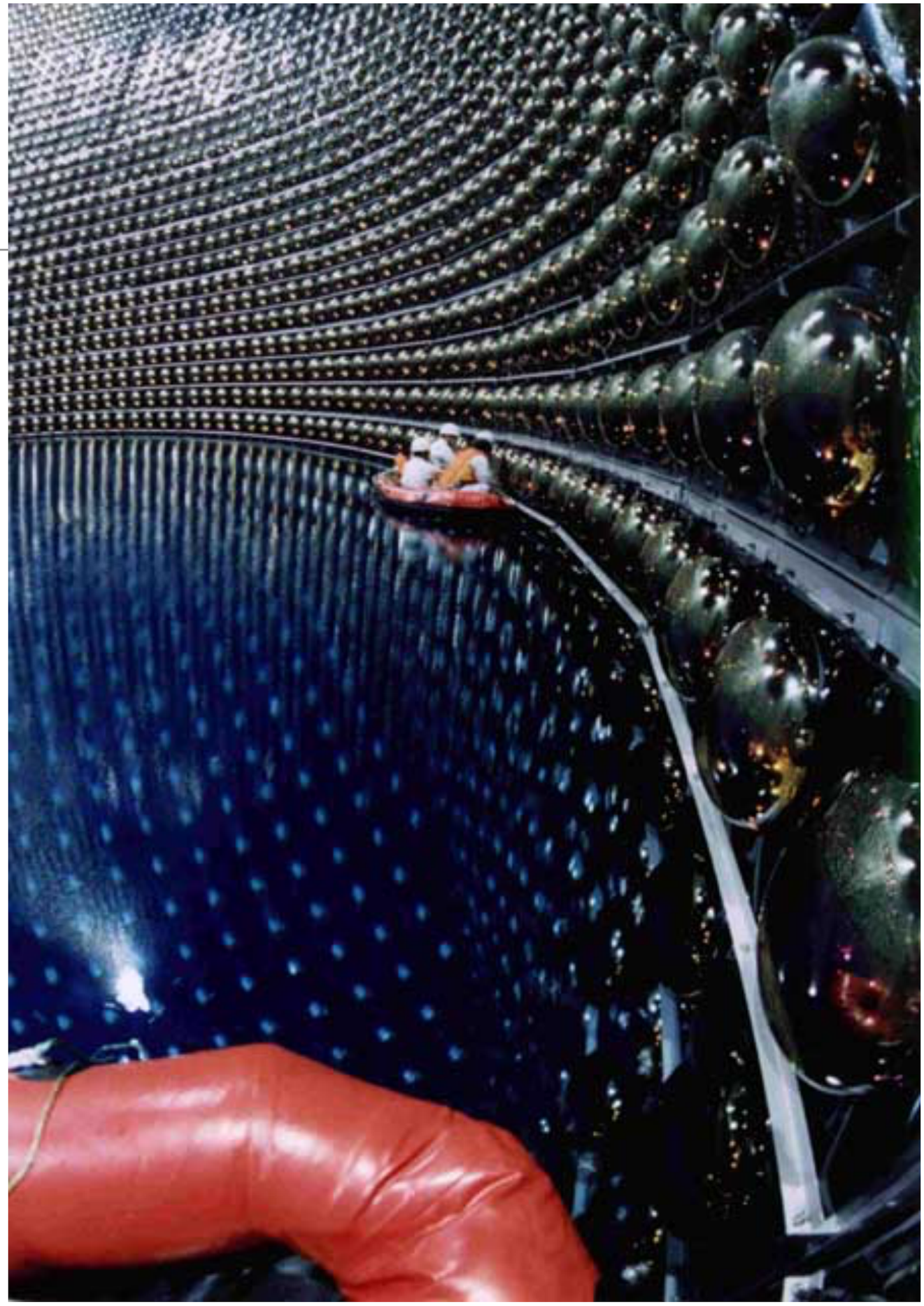
The solar neutrino problem



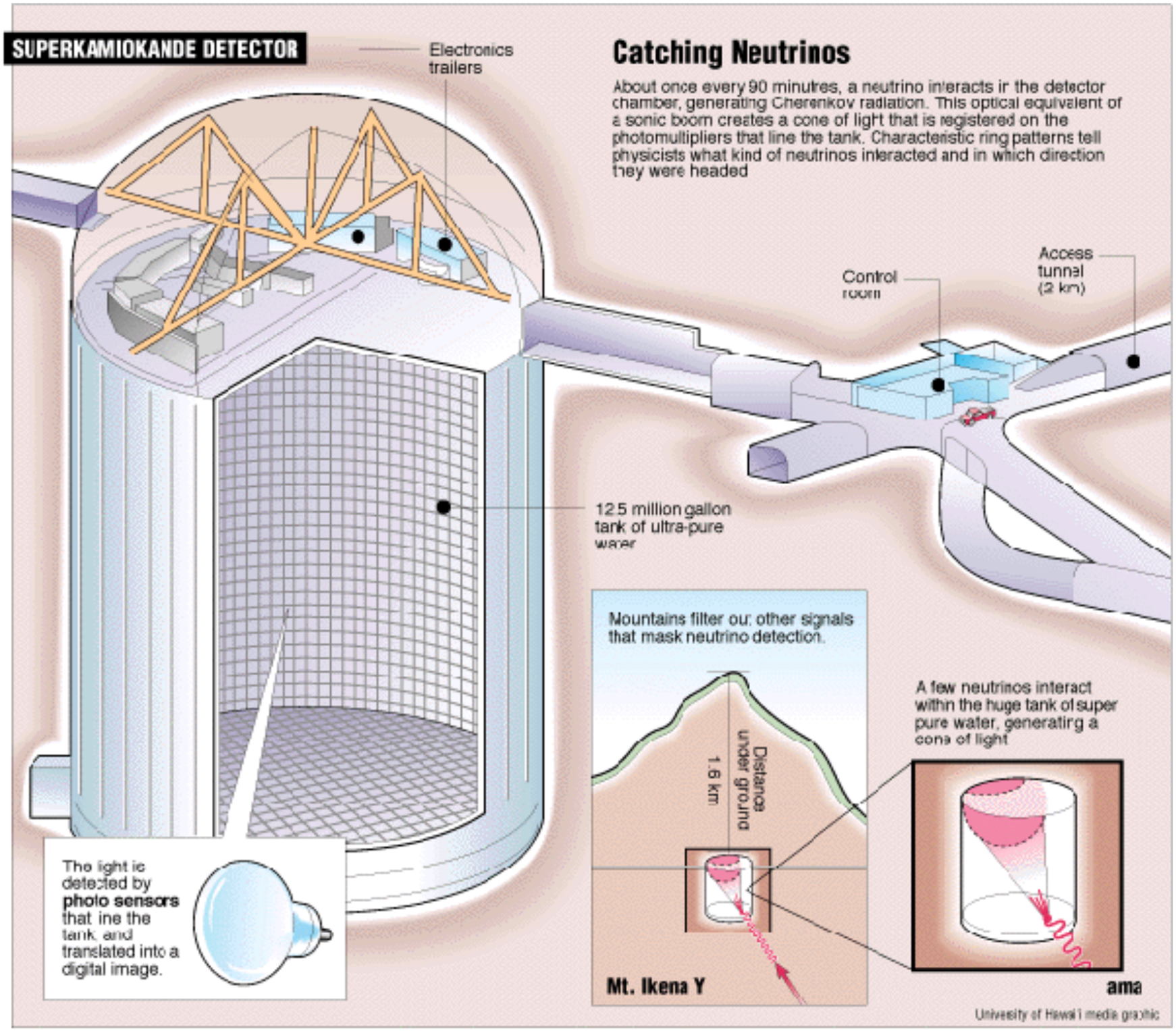
More data - Super Kamiokande



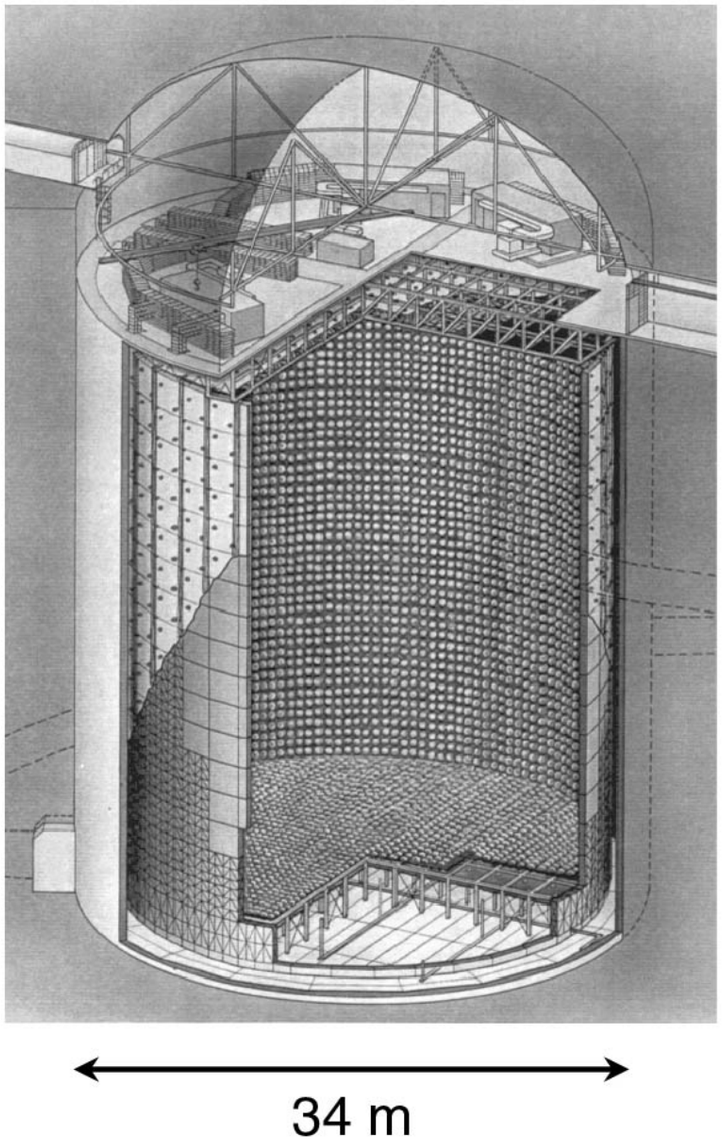
Super-K



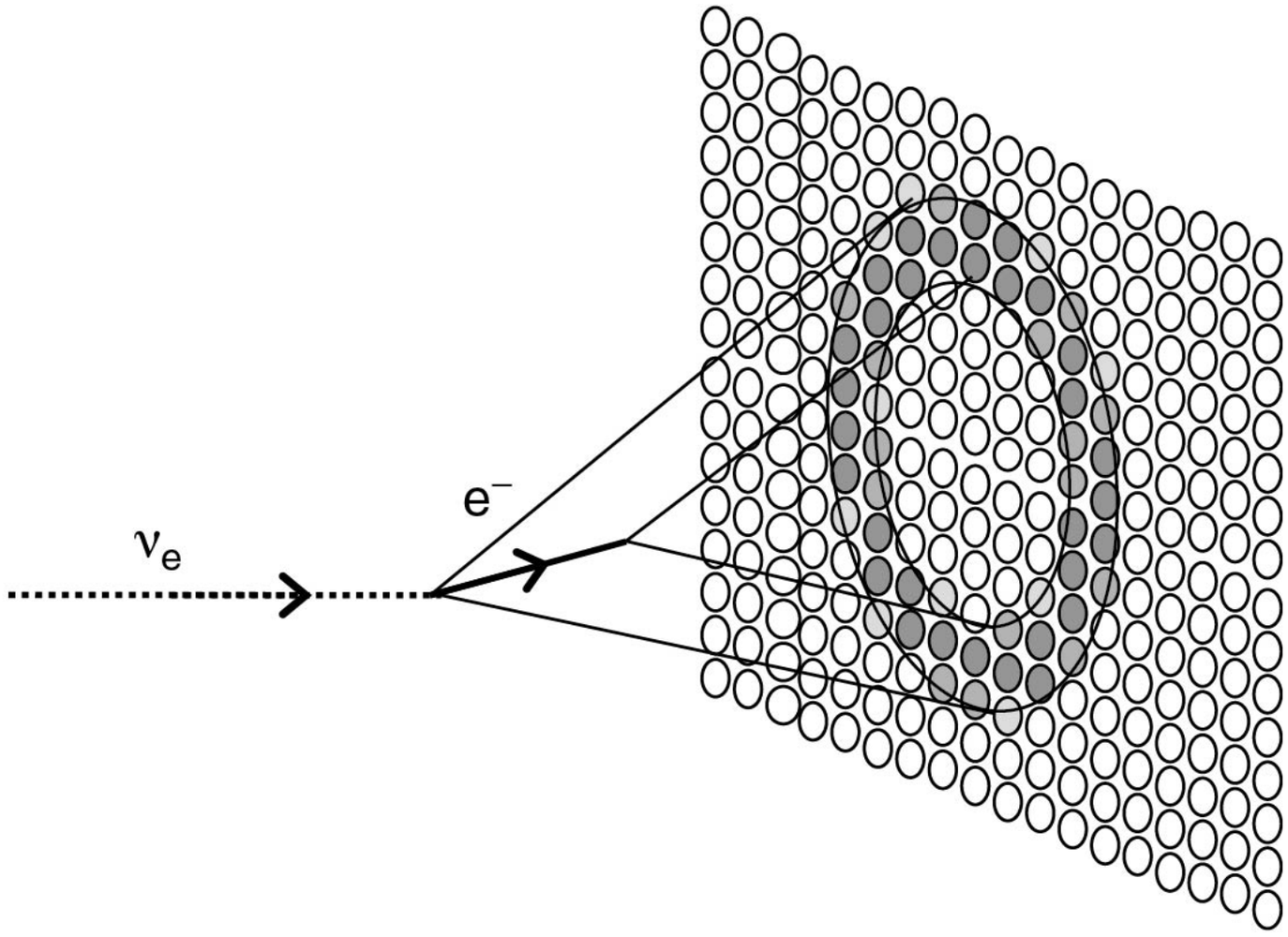
Concept


SUPERKAMIOKANDE DETECTOR
Electronics trailers
Catching Neutrinos
About once every 90 minutes, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed
Control room
Access tunnel (2 km)
12.5 million gallon tank of ultra-pure water
The light is detected by photo sensors that line the tank, and translated into a digital image.
Mountains filter out other signals that mask neutrino detection.
Distance underground 1.6 km
Mt. Ikena Y
A few neutrinos interact within the huge tank of super pure water, generating a cone of light
ama
University of Hawai'i media graphic

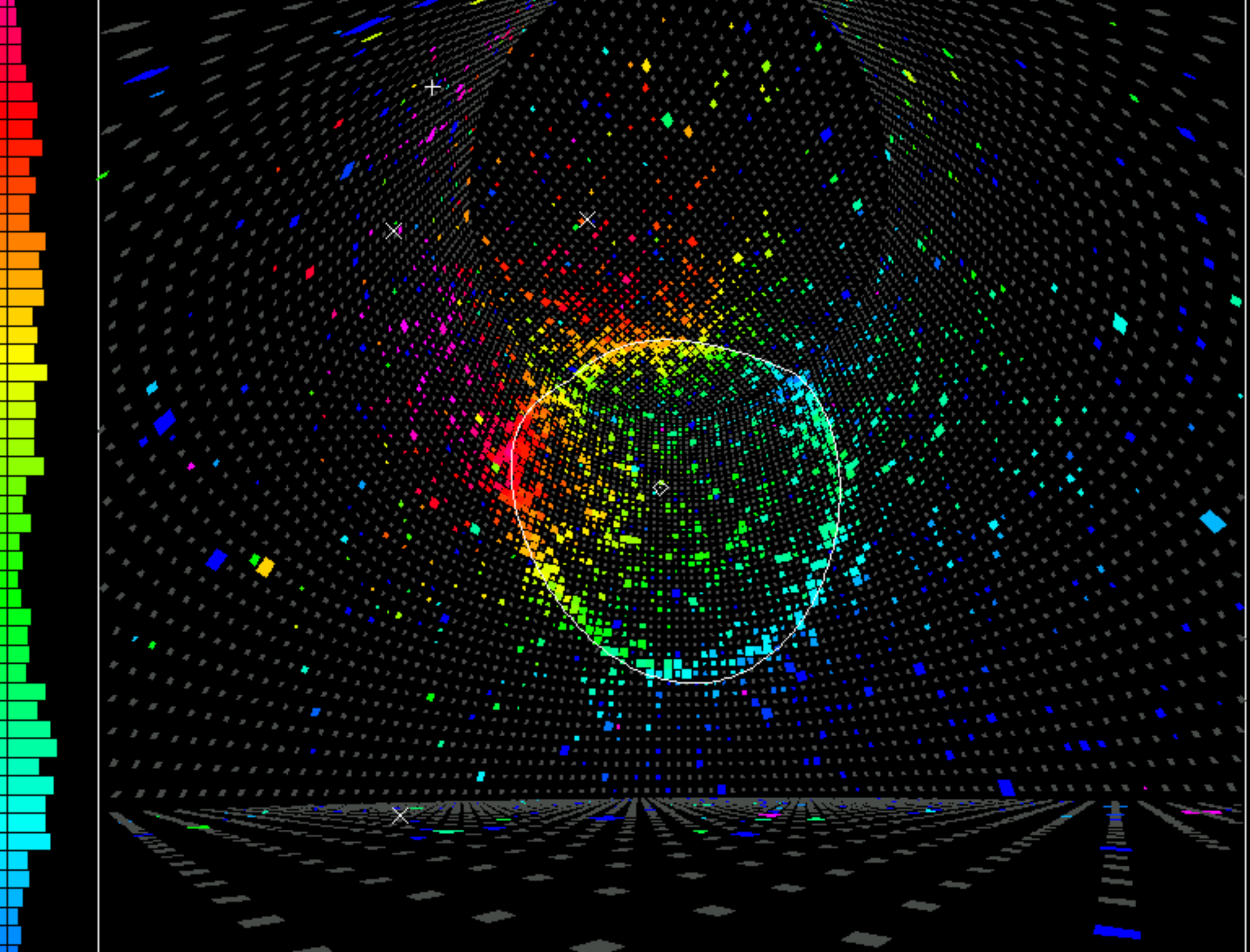
(a)

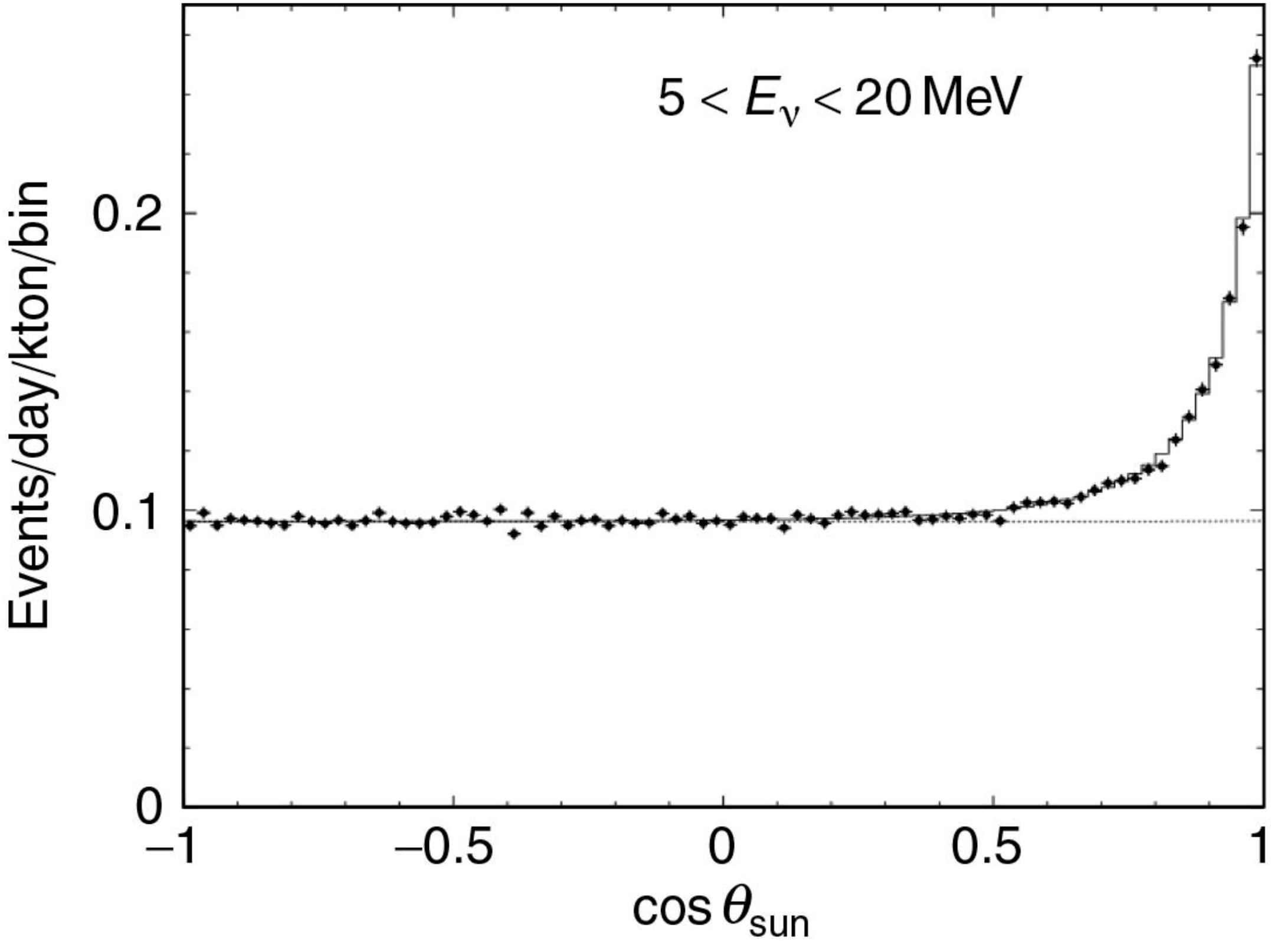


(b)



M. Thomson, Modern Particle Physics
© Cambridge University Press 2013





M. Thomson, Modern Particle Physics
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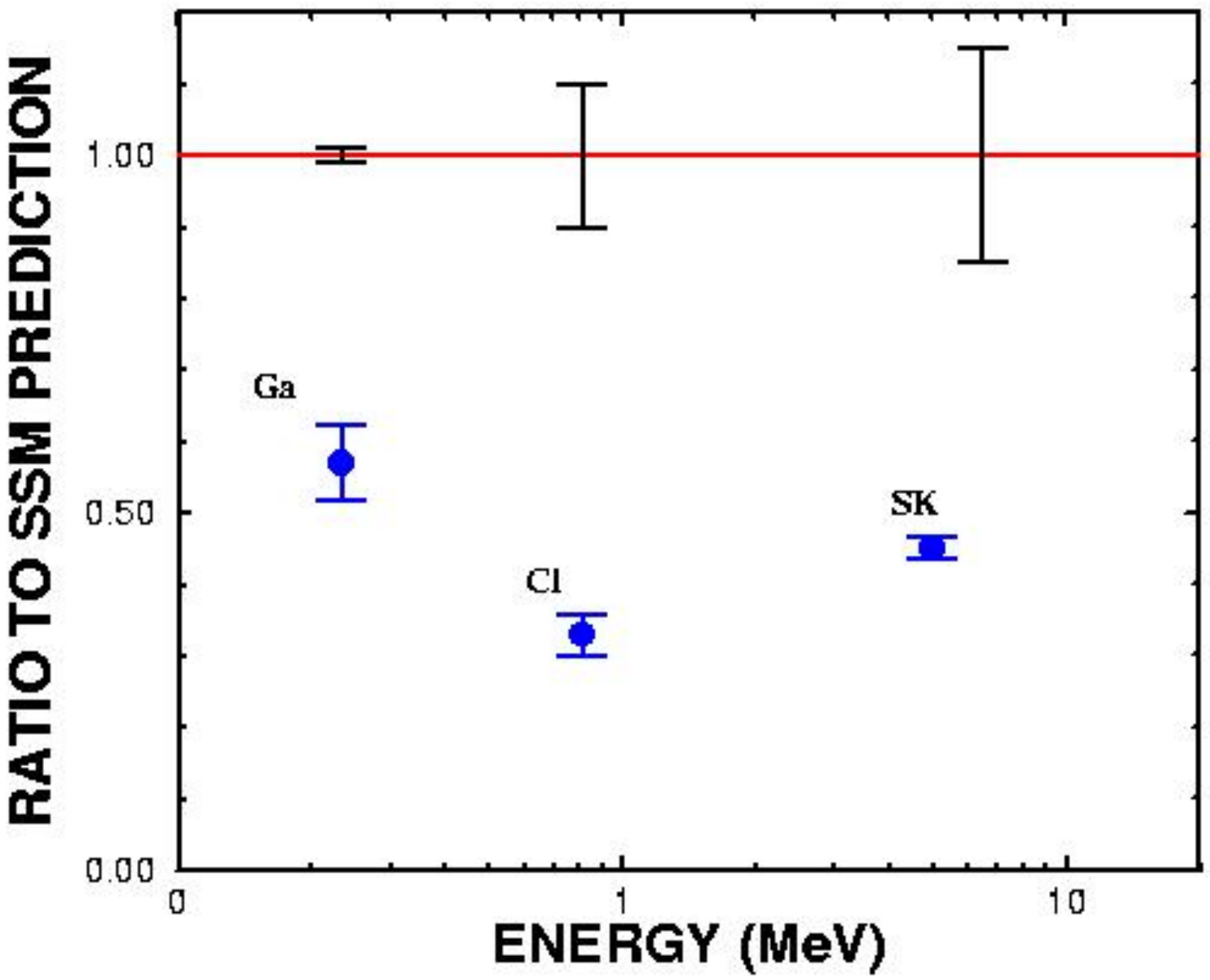
The solar neutrino problem



A great idea

Ask Canada to loan you its reserve of heavy water

The Sudbury Neutrino Observatory

Located on the 6800ft Level in Creighton Mine, Sudbury ON

1000 tonnes D_2O

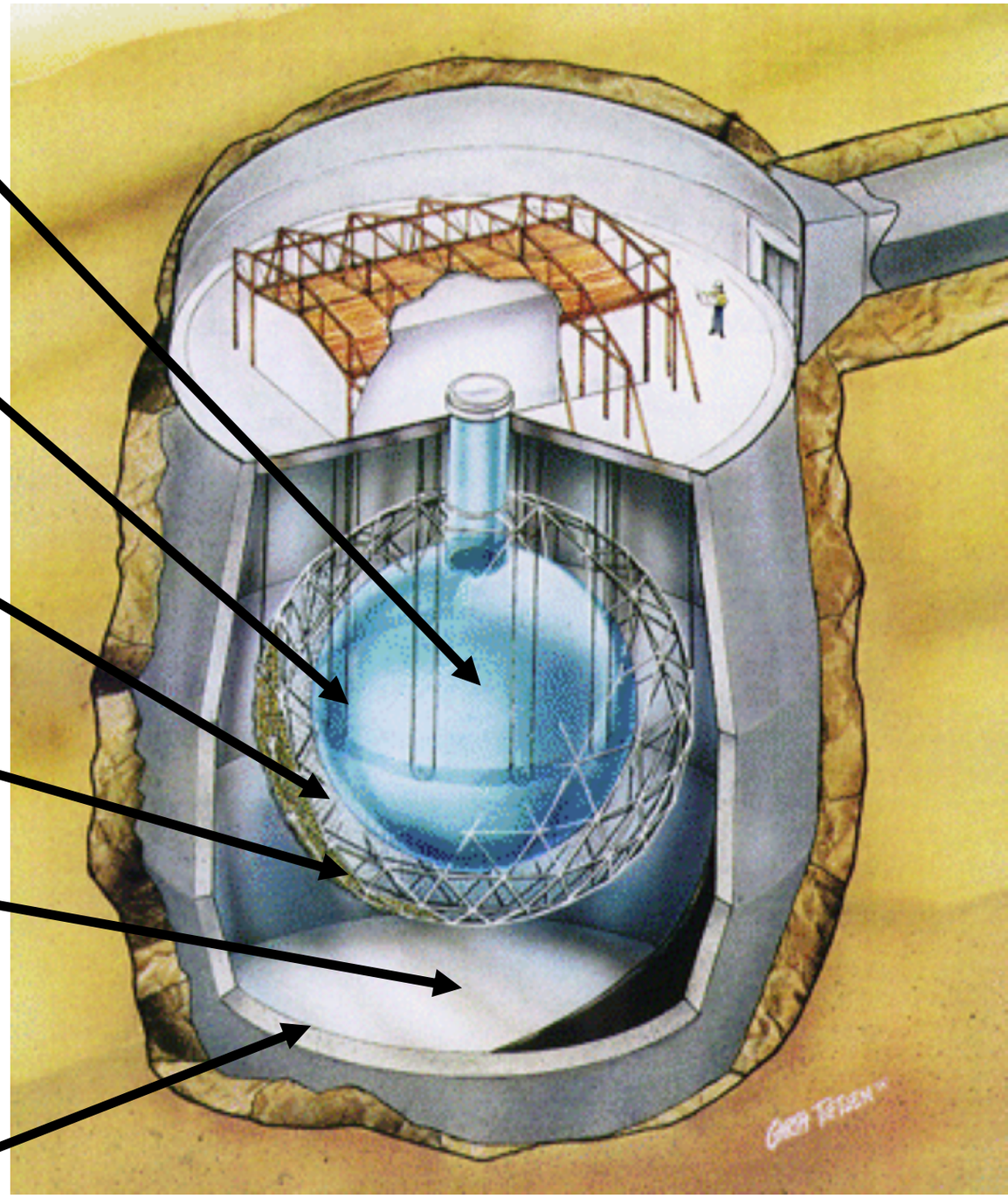
12m Diameter Acrylic Vessel

1700 tonnes Inner H_2O Shield

PMT Support Structure
9500 PMTs w/ 55% coverage

5300 tonnes Outer H_2O Shield

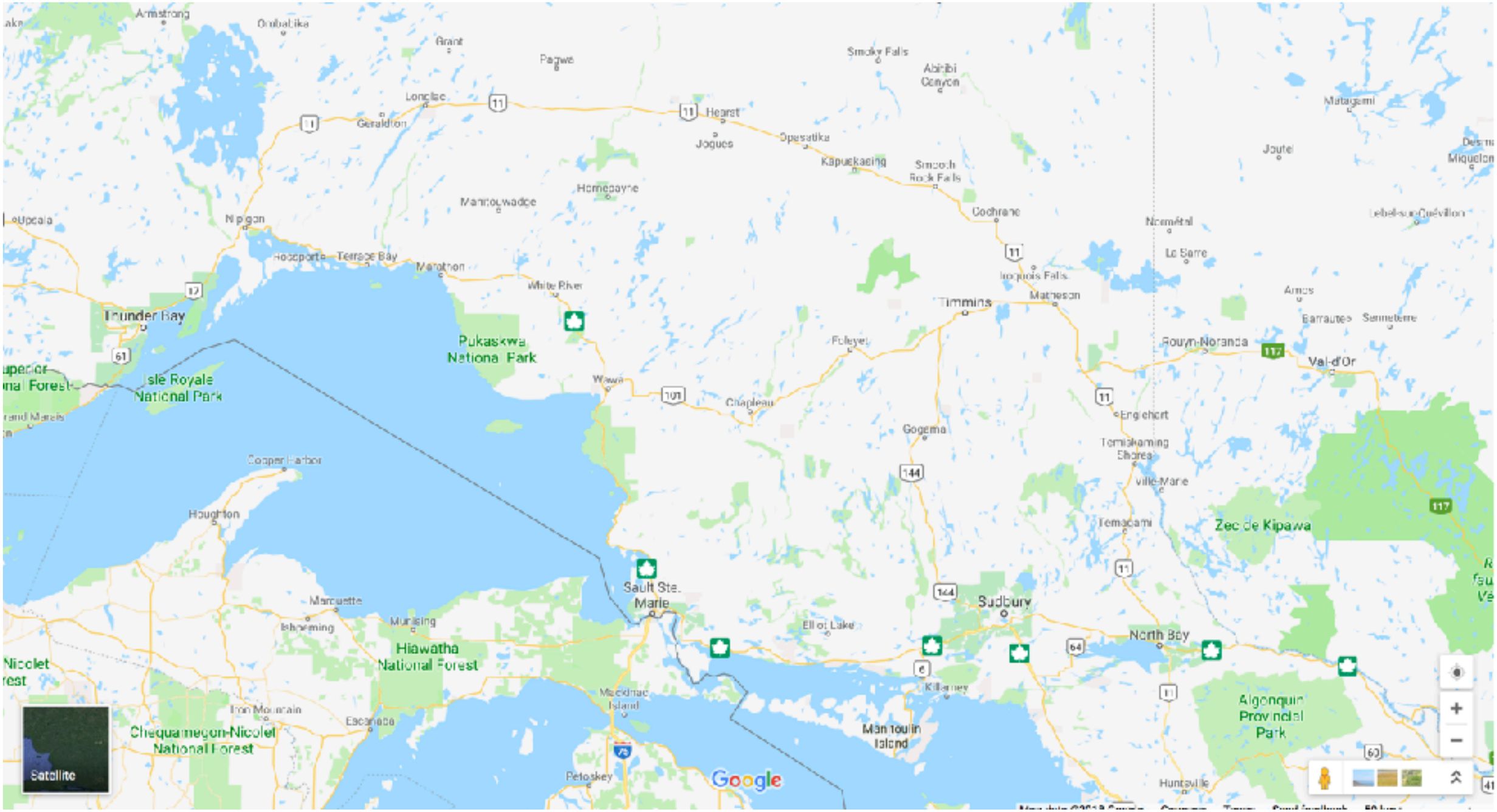
Urylon Liner and Radon Seal



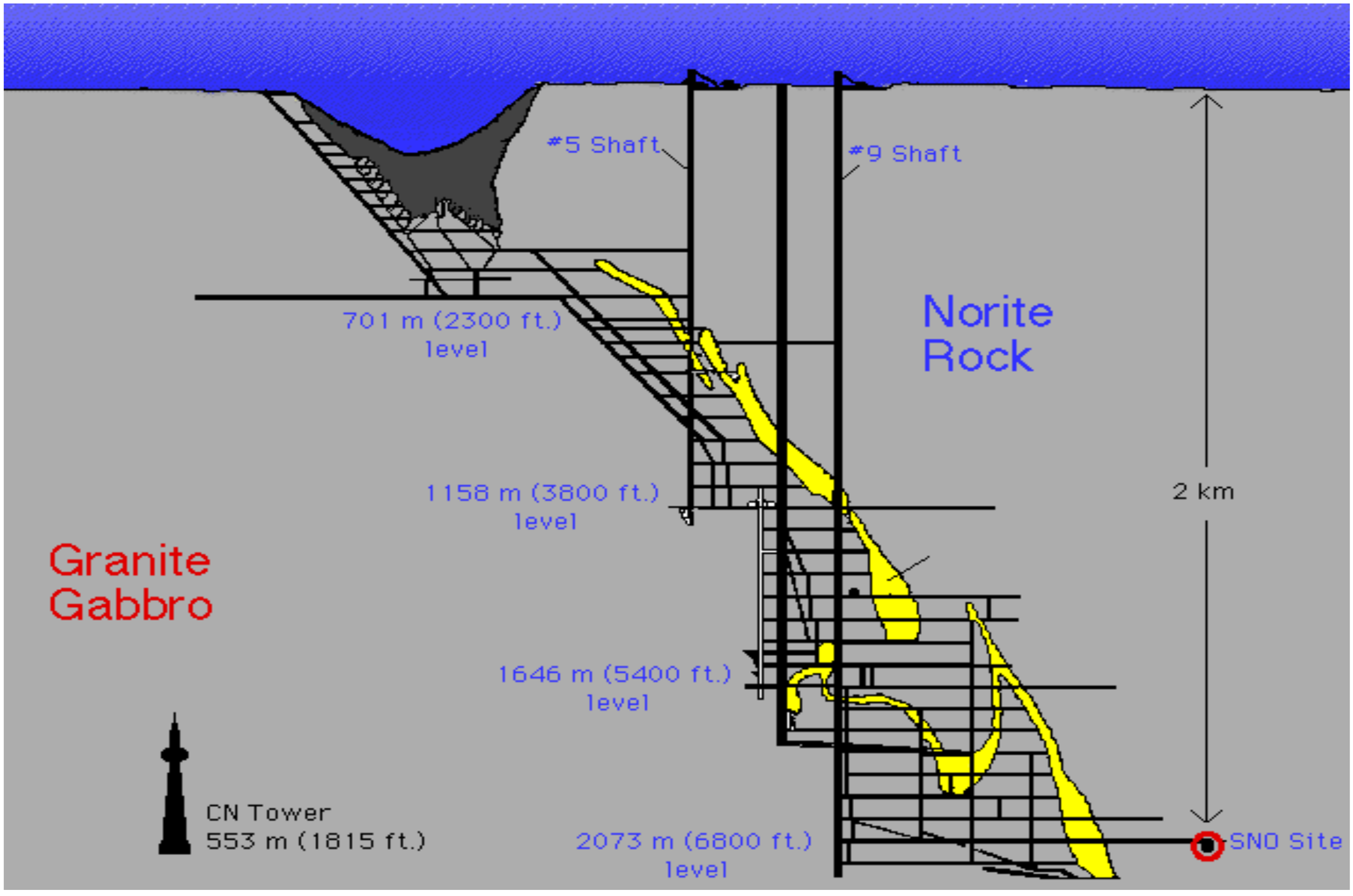
Sudbury


Hudson Bay
Canada
ALBERTA
MANITOBA
SASKATCHEWAN
ONTARIO
QUEBEC
NEWFOUNDLAND
AND LABRADOR
NORTH
DAKOTA
MONTANA
MINNESOTA
SOUTH
DAKOTA
WISCONSIN
MICHIGAN
IDAHO
WYOMING
NEBRASKA
IOWA
ILLINOIS
INDIANA
OHIO
PENN
NEVADA
UTAH
COLORADO
KANSAS
MISSOURI
WEST
VIRGINIA
KENTUCKY
VIRGINIA
NORTH
CAROLINA
SOUTH
CAROLINA
TENNESSEE
OKLAHOMA
ARKANSAS
MISSISSIPPI
ALABAMA
GEORGIA
ARIZONA
NEW MEXICO
TEXAS
NEW YORK
MAINE
VT
NH
MA
CT RI
NB
PE
NOVA SCOTIA
MD
DE
NJ
Ottawa
Montreal
Toronto
Chicago
Philadelphia
Las Vegas
Los Angeles
San Diego
Dallas
United States

Sudbury


Armstrong
Ombabika
Nipigon
Geraldton
Longlac
Pagwa
Grant
Hearst
Jogues
Opasatika
Kapuskasing
Smooth Rock Falls
Smoky Falls
Abitibi Canyon
Cochrane
Matagami
Joutel
Homepayne
Manitouwadge
Hoodsport
Terrace Bay
Marathon
White River
Thunder Bay
Timmins
Iroquois Falls
Matheson
Lebel-sur-Quévillon
Amos
Barraute
Senneterre
Rouyn-Noranda
Val-d'Or
Englehart
Temiskaming Shores
Ville-Marie
Témiscami
Zec de Kipawa
Gogama
Chapleau
Foleyet
Wawa
Pukaskwa National Park
Isle Royale National Park
Cooper Harbor
Houghton
Marquette
Ishpeming
Munising
Hiawatha National Forest
Escanaba
Iron Mountain
Chequamegon-Nicolet National Forest
Sault Ste. Marie
Mackinac Island
Petoskey
Elliot Lake
Sudbury
North Bay
Killarney
Manitoulin Island
Algonquin Provincial Park
Huntsville
Satellite
Google

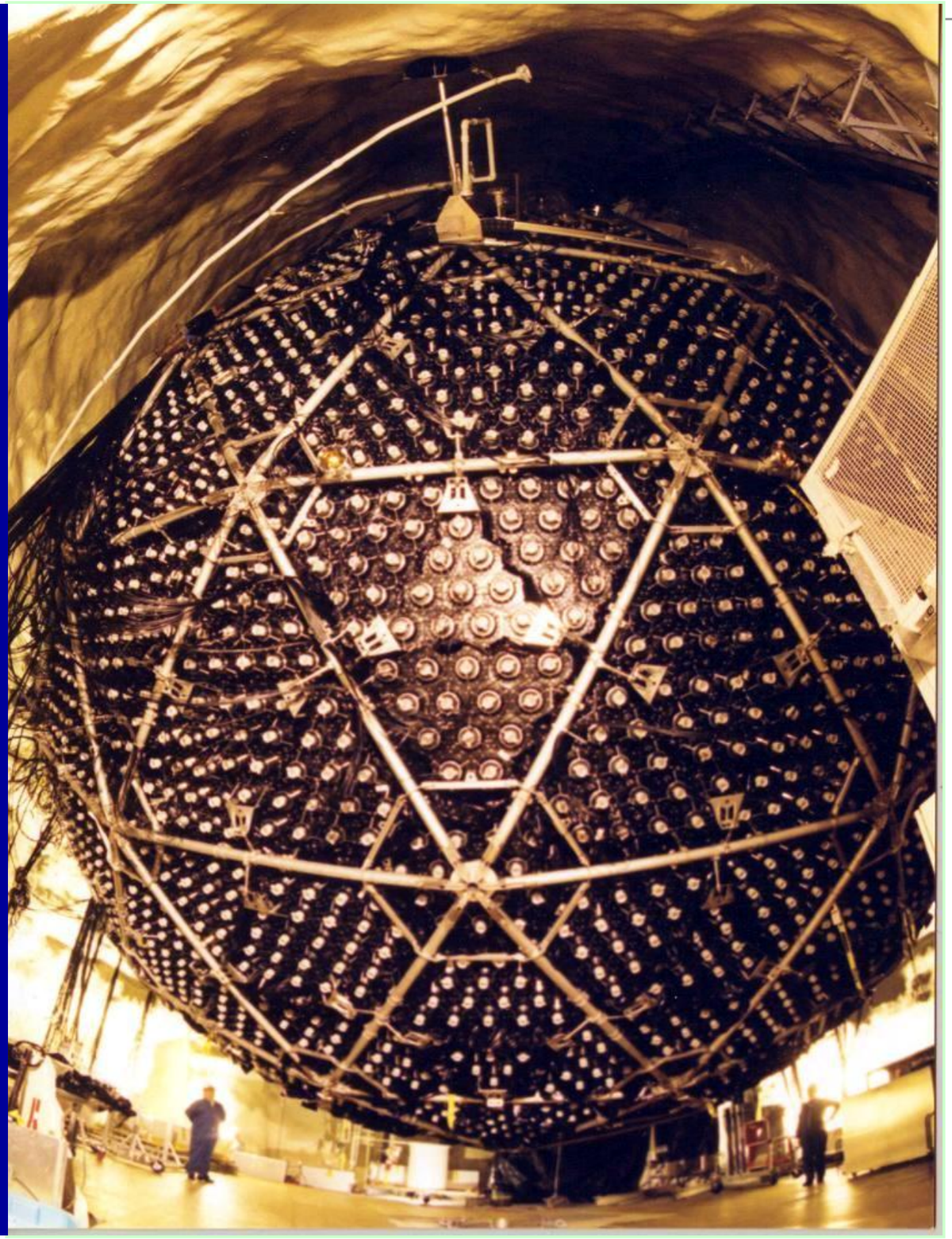
The mine

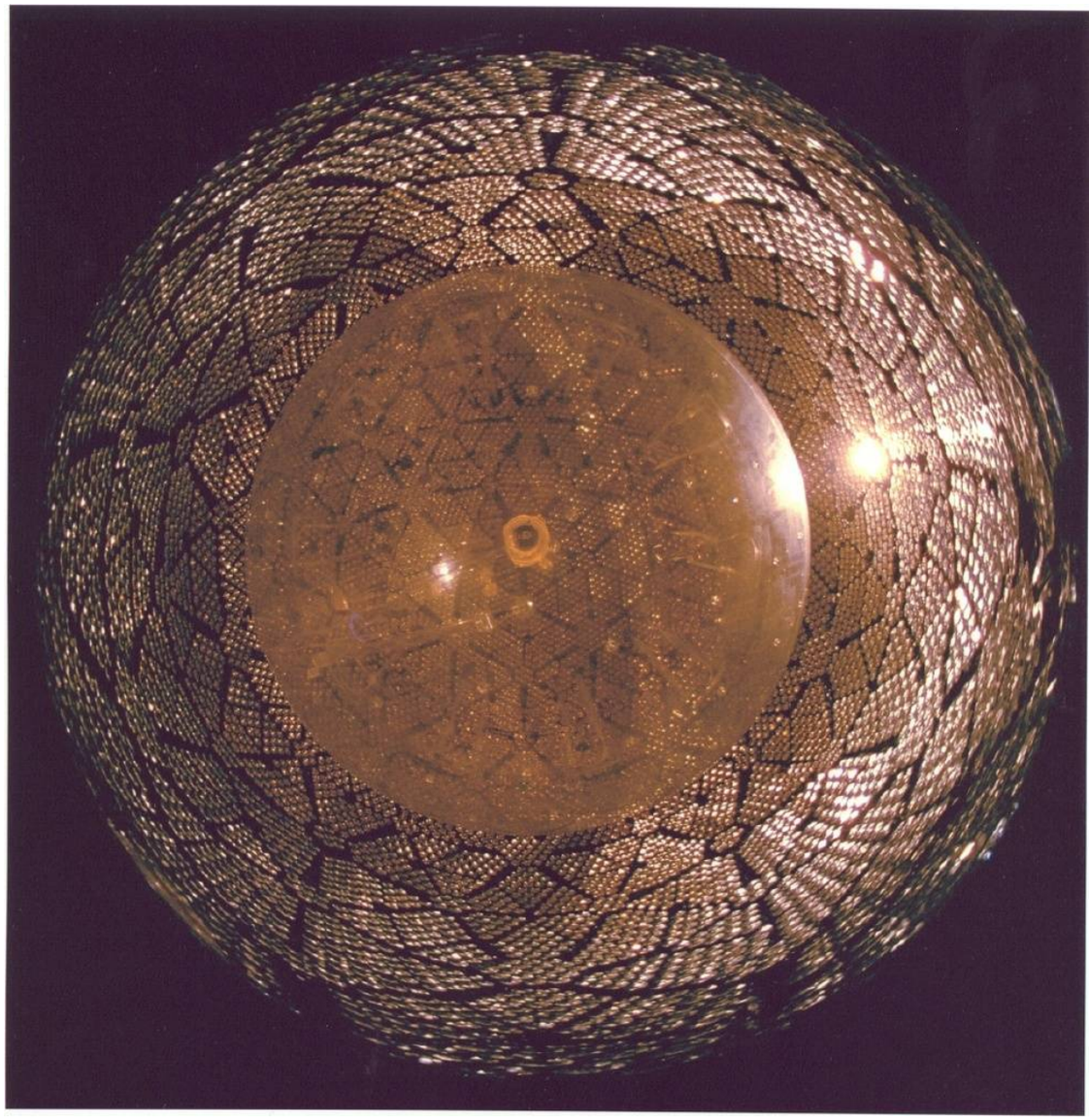

#5 Shaft
#9 Shaft
701 m (2300 ft.) level
Norite Rock
1158 m (3800 ft.) level
2 km
Granite Gabbro
1646 m (5400 ft.) level
CN Tower
553 m (1815 ft.)
2073 m (6800 ft.) level
SNO Site

The SNO underground control room

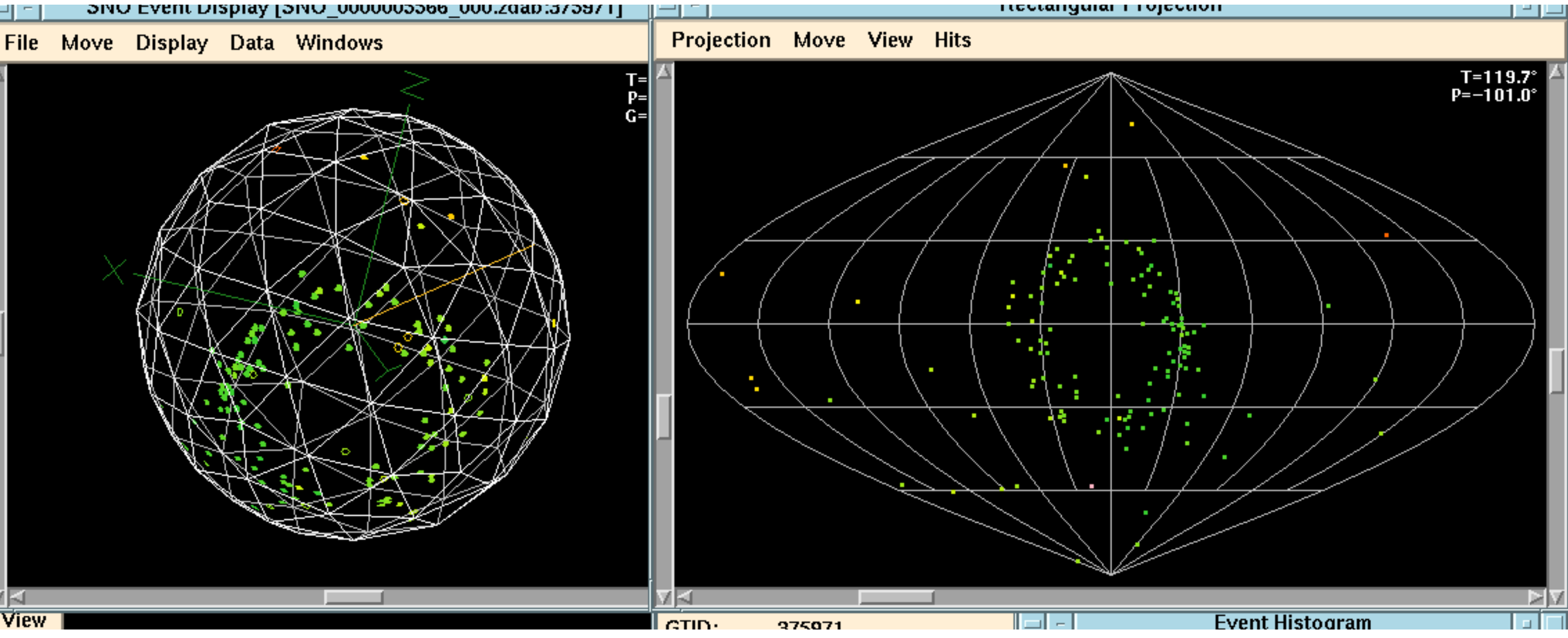

FIRE
Creighton Mine
VALE

The detector

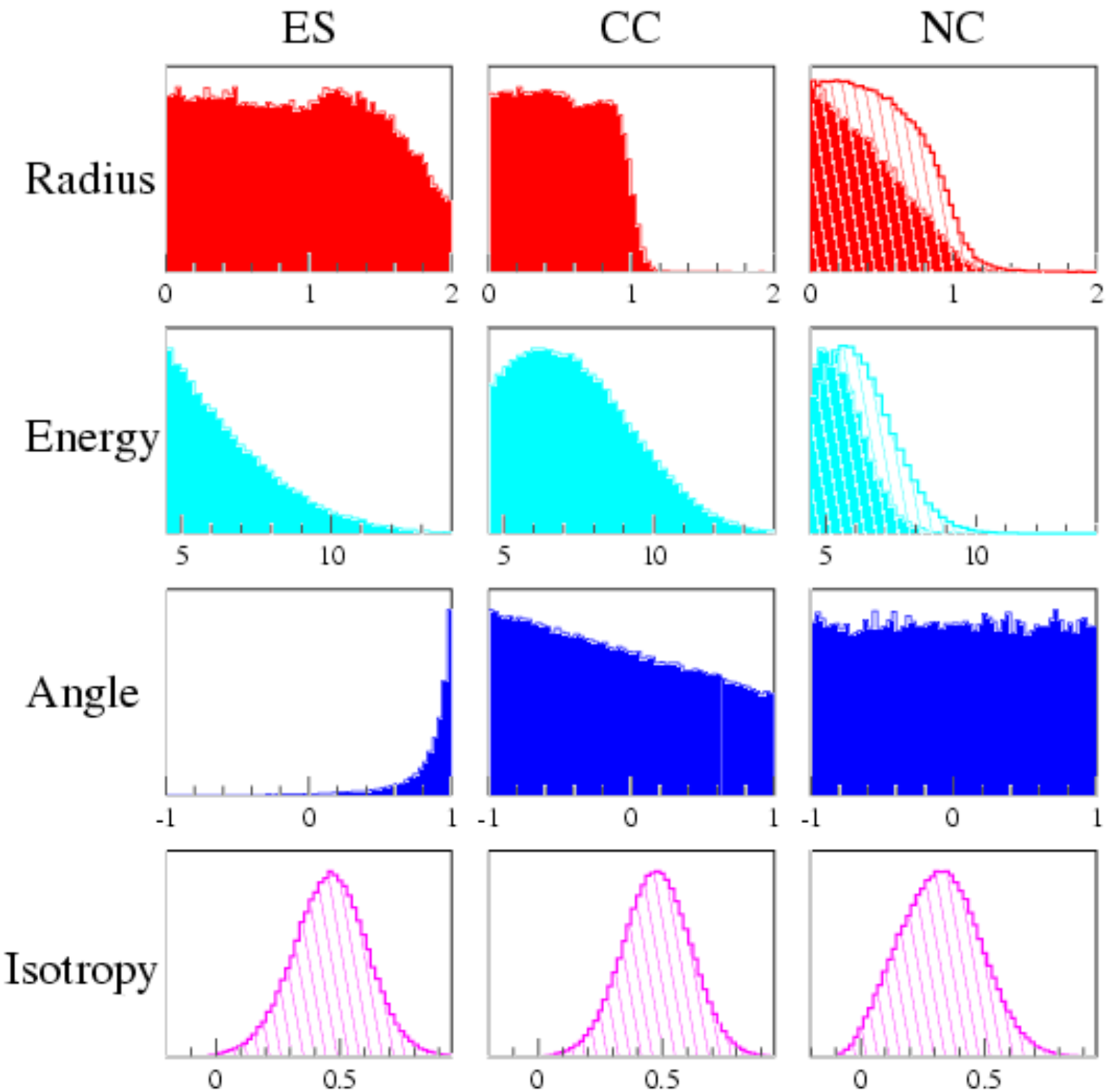




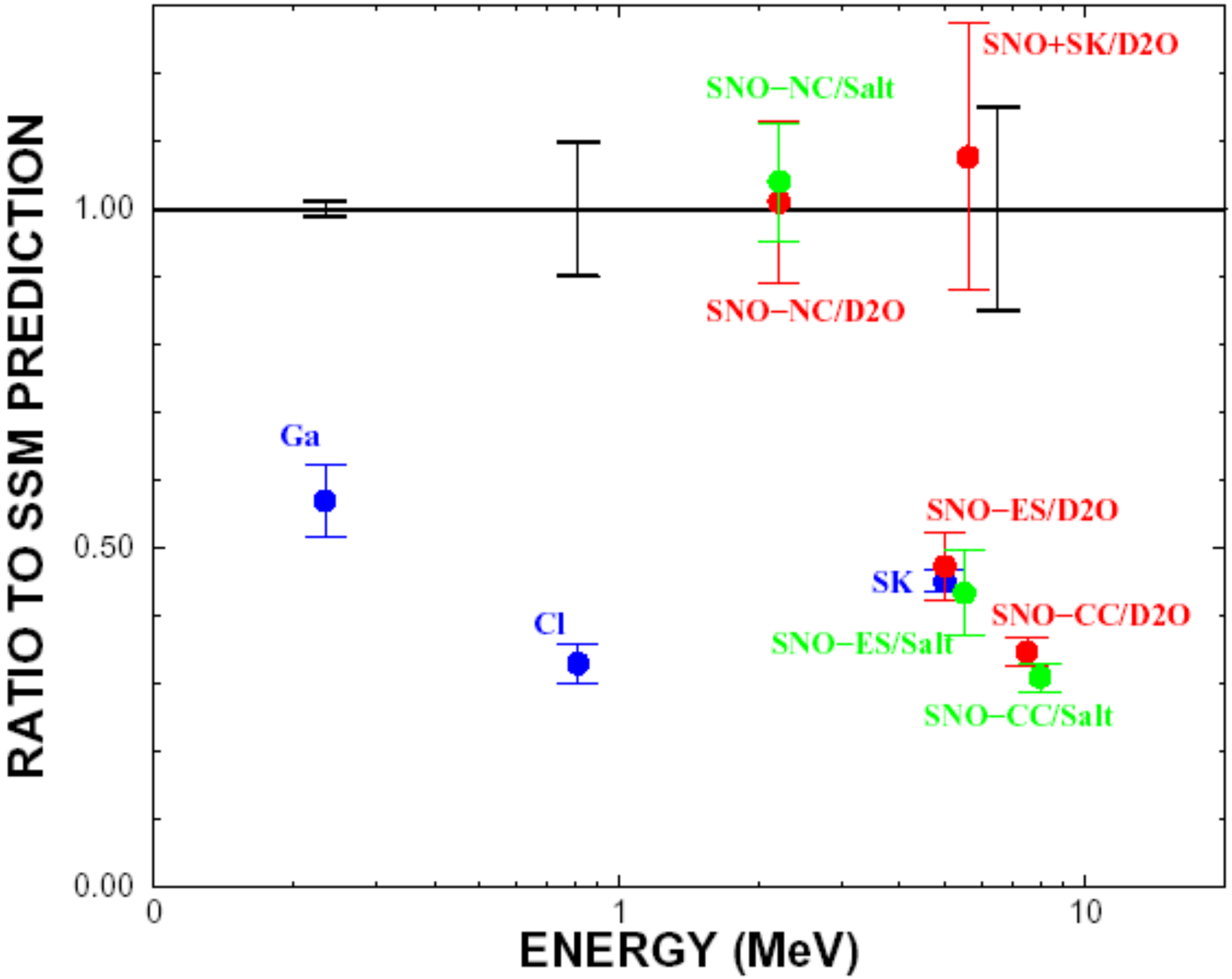
Neutrino event



Event separation



The overall results

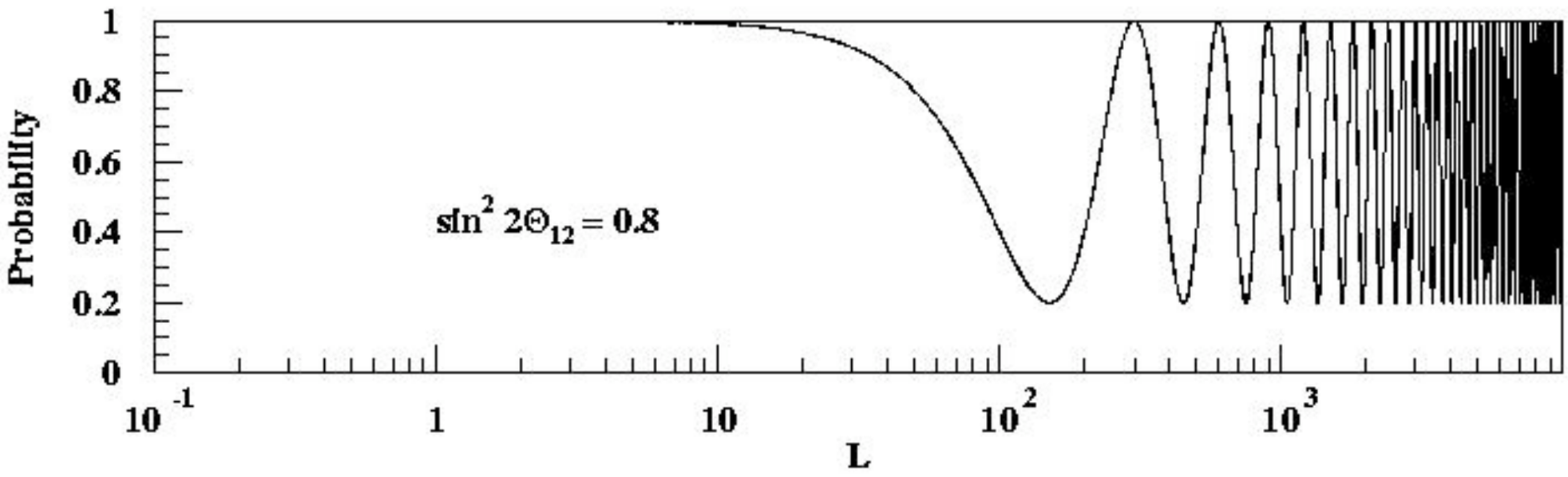


Neutrino oscillations

Two flavor survival probability

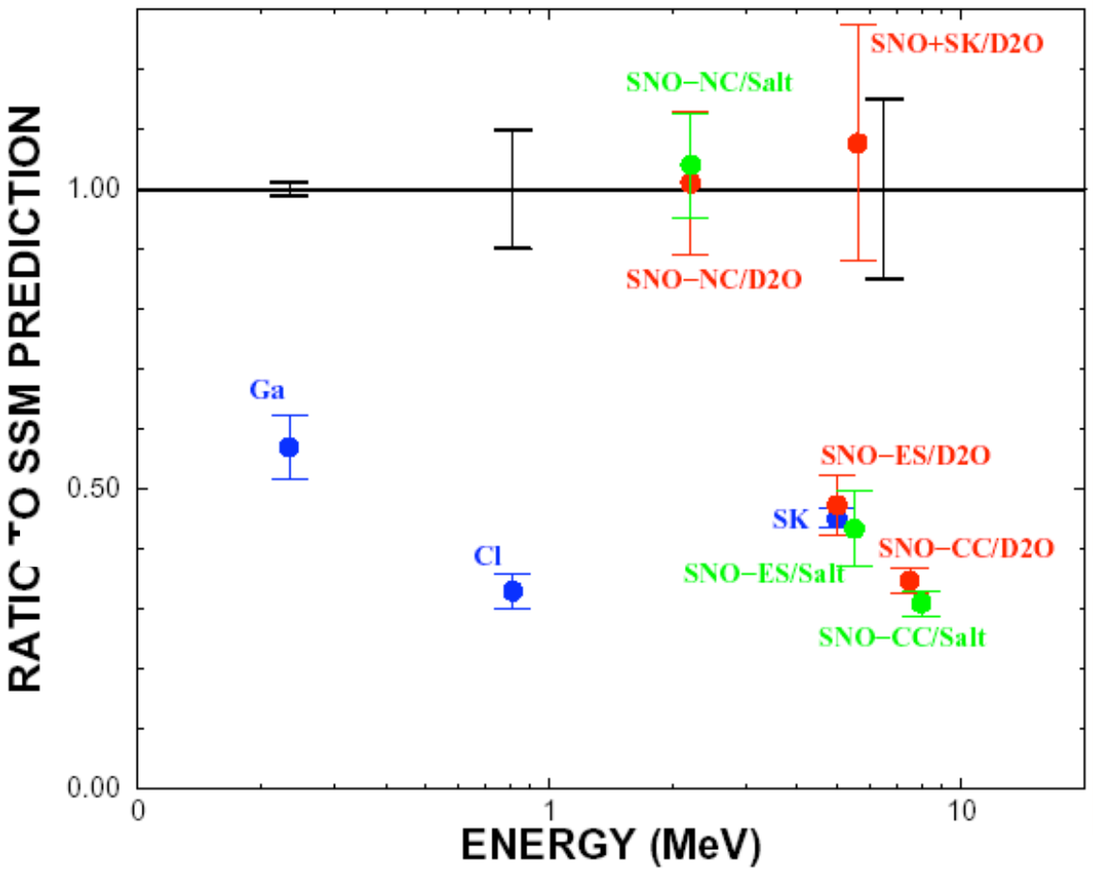
$$P_{\upsilon_x \to \upsilon_x} = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Vacuum Oscillations



Neutrino oscillations

$$P_{\upsilon_e \to \upsilon_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m_{12}{}^2 L}{E}\right)$$



For $\Delta m^2 >> E/L$,

$P_{\upsilon_e \to \upsilon_e} \to \frac{1}{2}\sin^2 2\theta$ (`washed out')

For $\Delta m^2 << E/L$,

$P_{\upsilon_e \to \upsilon_e} \to 1$ (no sensitivity)

Need $\Delta m^2 \sim E/L$

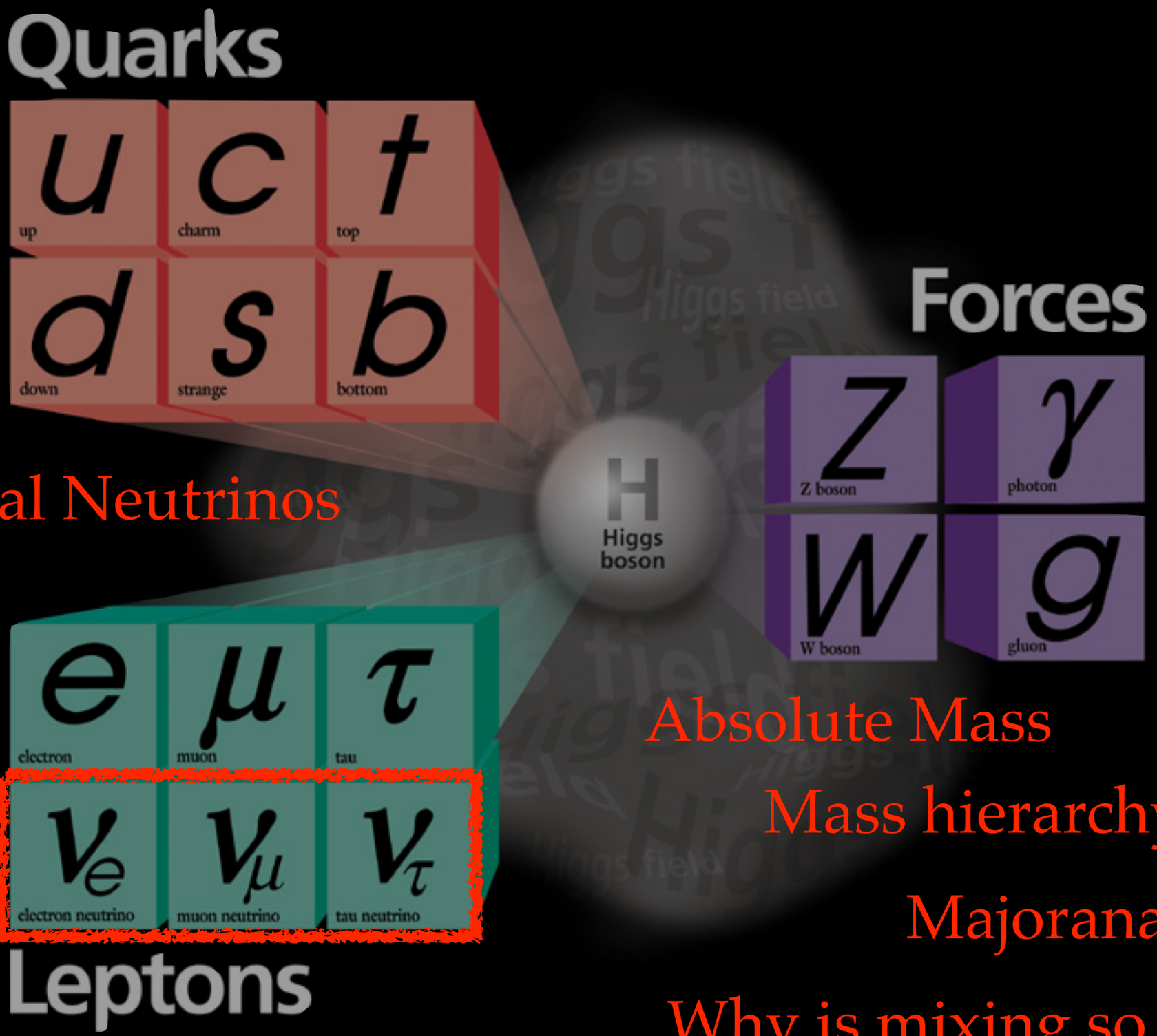
(roughly Earth - Sun distance)

The future

Maximal ~45° ?? Small <12° Large ~33°

$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Rector/Accelerator Solar



Additional Neutrinos

Absolute Mass

Mass hierarchy

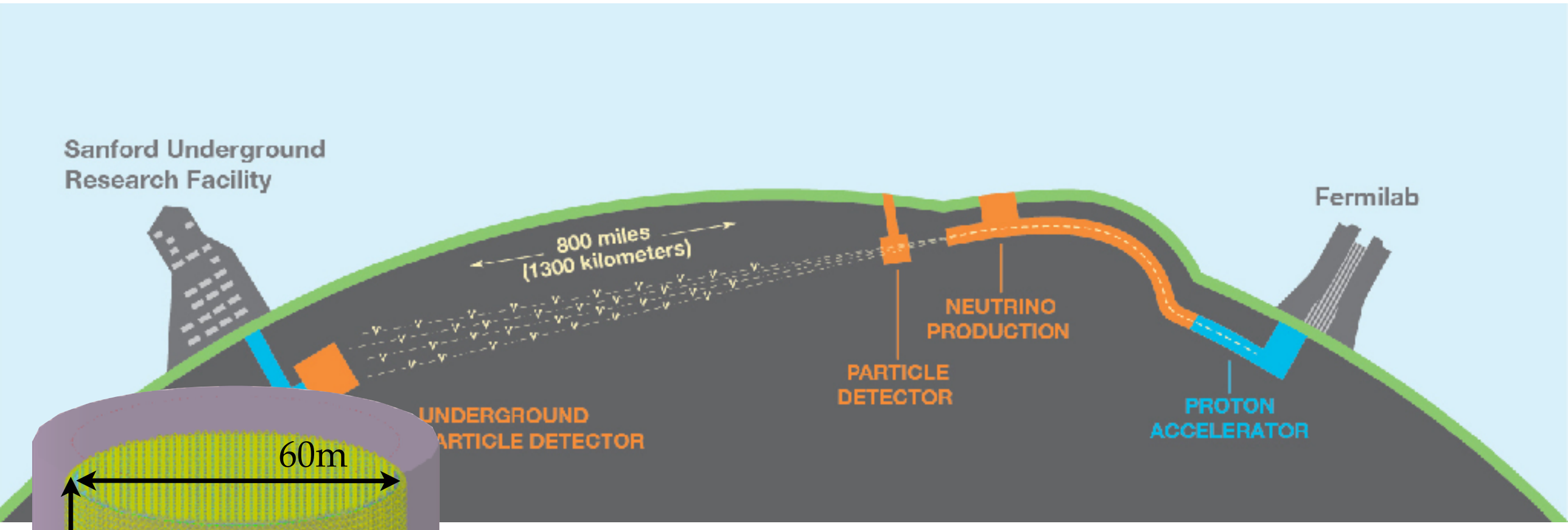
Majorana vs. Dirac

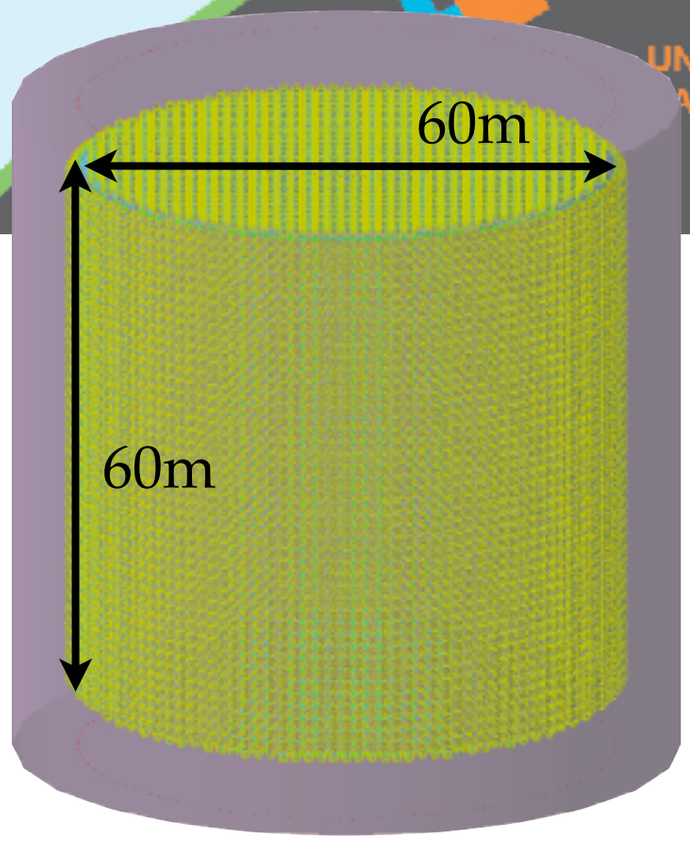
Why is mixing so large?

CP Violation

Why is θ_{13} so small?

The Nature of Matter/Anti-Matter





THEIA: Water-based liquid scintillator


SK