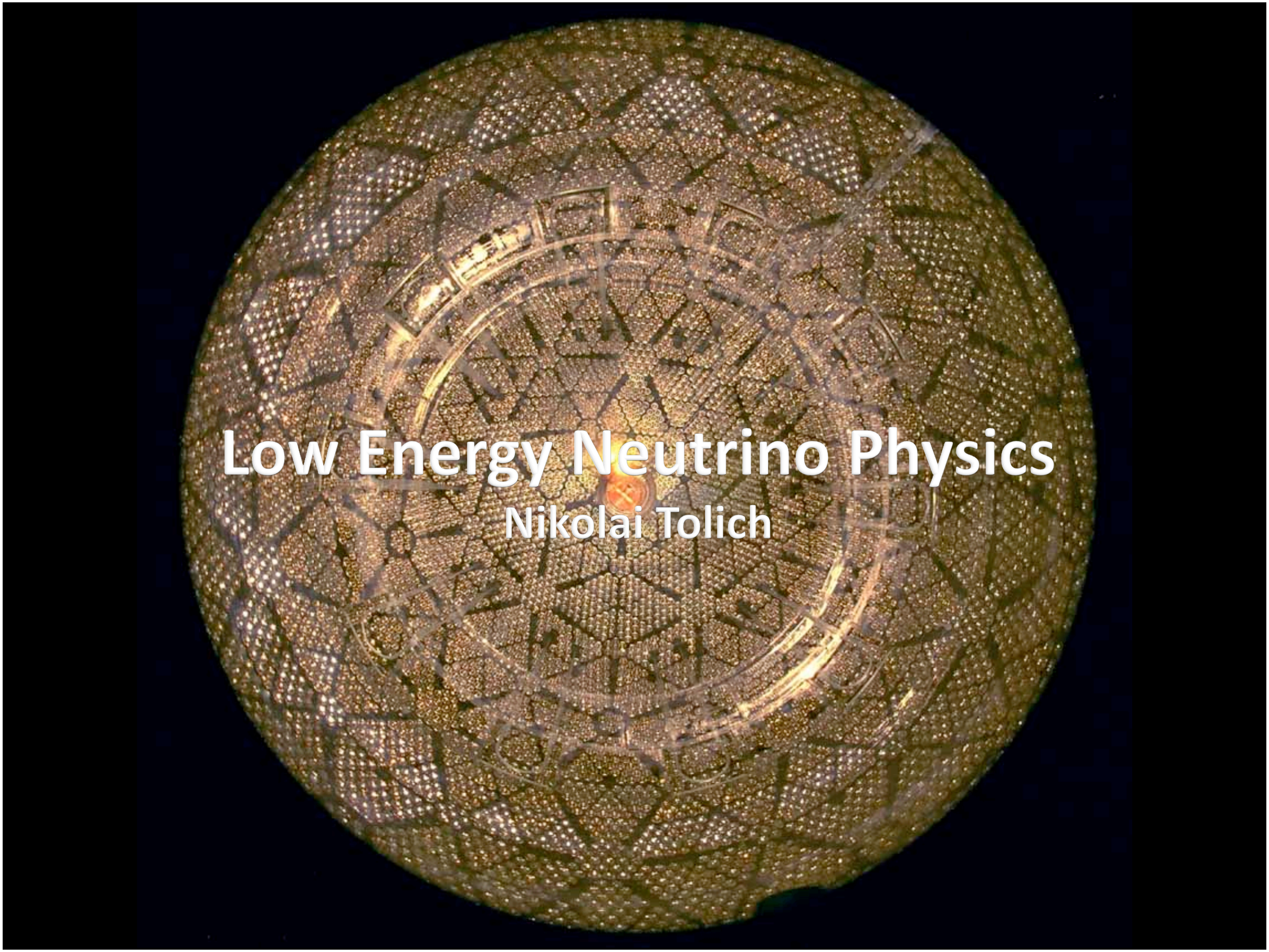


# Low Energy Neutrino Physics

Nikolai Tolich

# Outline

- Double-beta-decay
- Geoneutrinos
- Solar neutrinos

# Beta-decay

- $\beta^-$-decay is the conversion of a bound neutron into a proton with the emission of an electron and an electron anti-neutrino

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \overline{\nu}_{e} $$

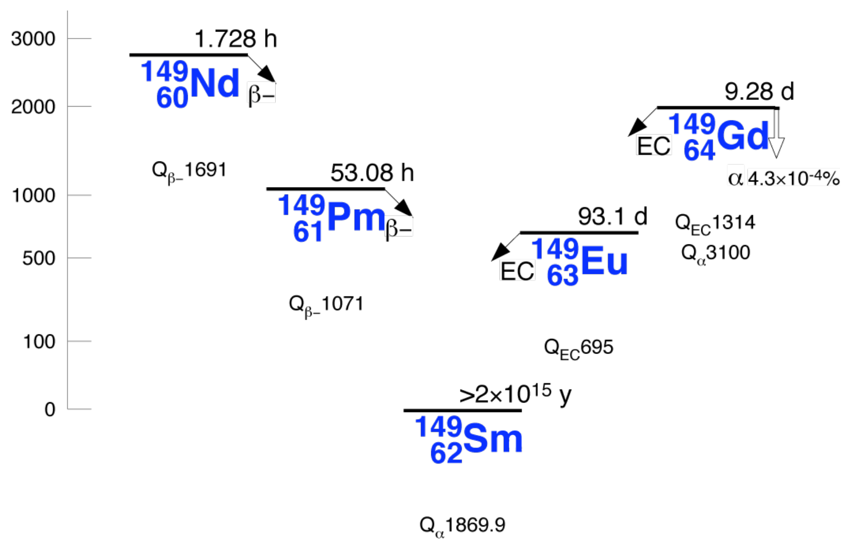
- $\beta^+$-decay is the conversion of a bound proton into a neutron with the emission of a positron and an electron neutrino

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \nu_{e} $$

- Electron-capture is similar to $\beta^+$-decay but instead of producing a positron, an electron is captured

$$ {}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y + \nu_{e} $$

# Conservation of energy

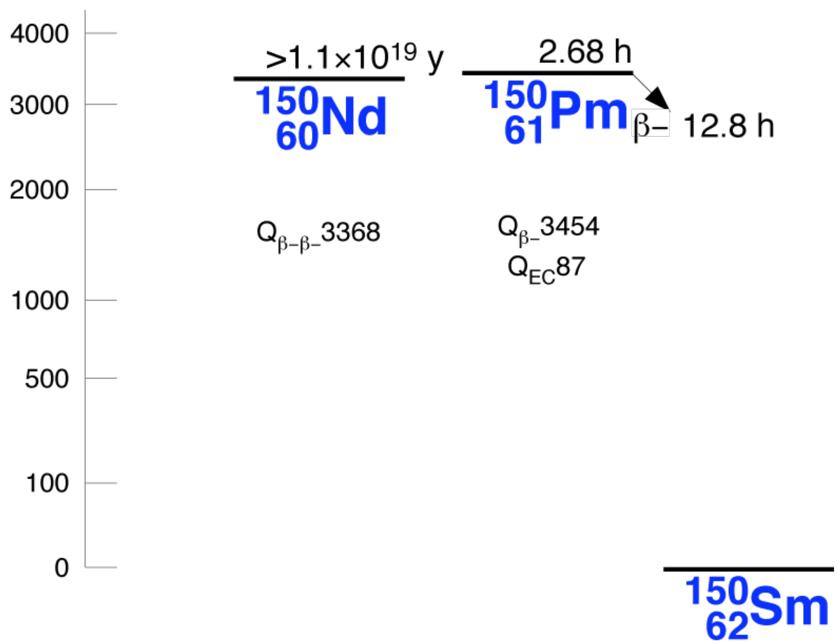



- Conservation of energy tells us that for
  - β-decay:

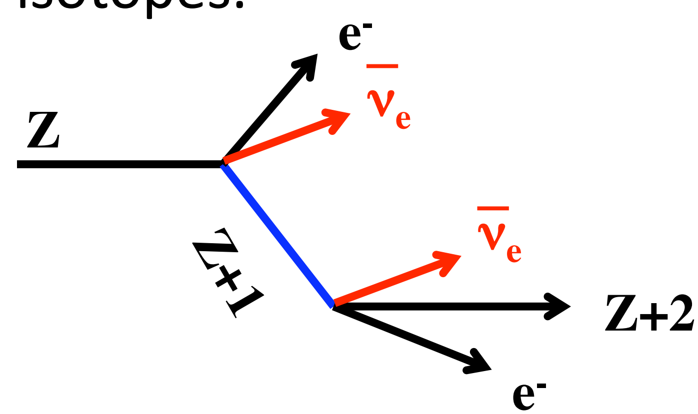
    mass of the X is greater than the sum of the mass of Y, the electron, and neutrino
  - Electron-capture:

    mass of the X plus electron is greater than the mass of Y plus the neutrino
- Nuclear physicists often draw energy level diagrams for a particular atomic mass, like that on the left

# Double-beta-decay

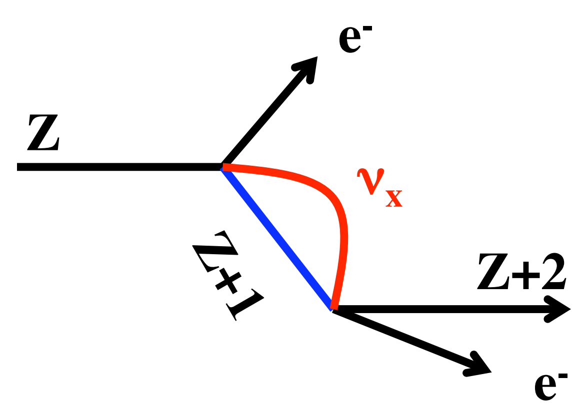



- Double-beta-decay occurs when the single beta-decay is energetically forbidden.
- It is an extremely rare process, but has been observed in numerous isotopes.



# Neutrinoless double-beta-decay

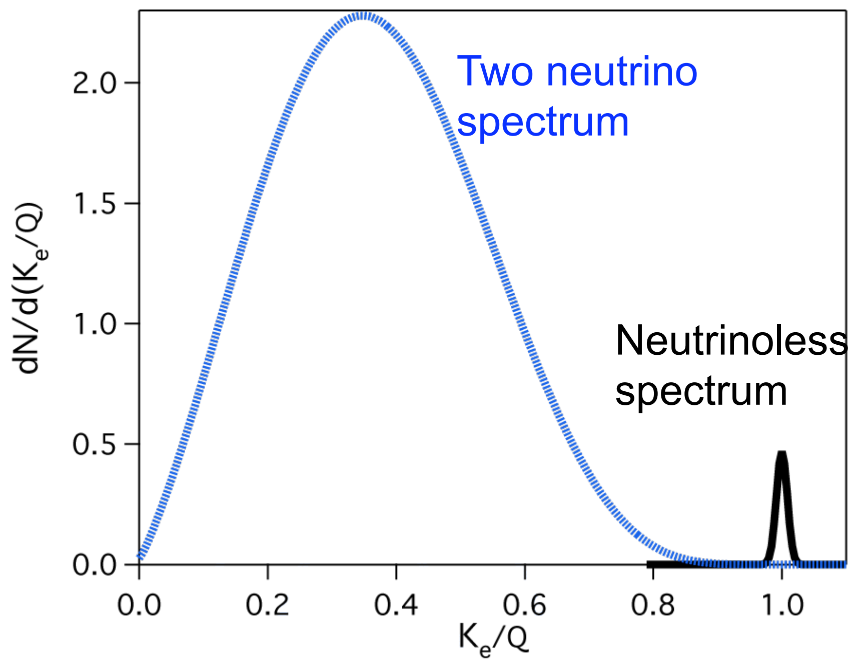
- If neutrinos are Majorana particles (an anti-neutrino is equivalent to a neutrino) then we do not need to emit any neutrinos in a double-beta-decay.
- Neutrinoless double-beta-decay is the best probe we have to test if neutrinos are Majorana particles.



# Majorana neutrinos?

- So-called “seesaw” models, which explain the lightness of the neutrino, require the neutrino to be a Majorana particle.
- Leptogenesis, which could explain the apparent matter dominance of the universe also requires neutrinos to be a Majorana particle.
- **All other particles are Dirac particles.**

# Observing neutrinoless double-beta-decay

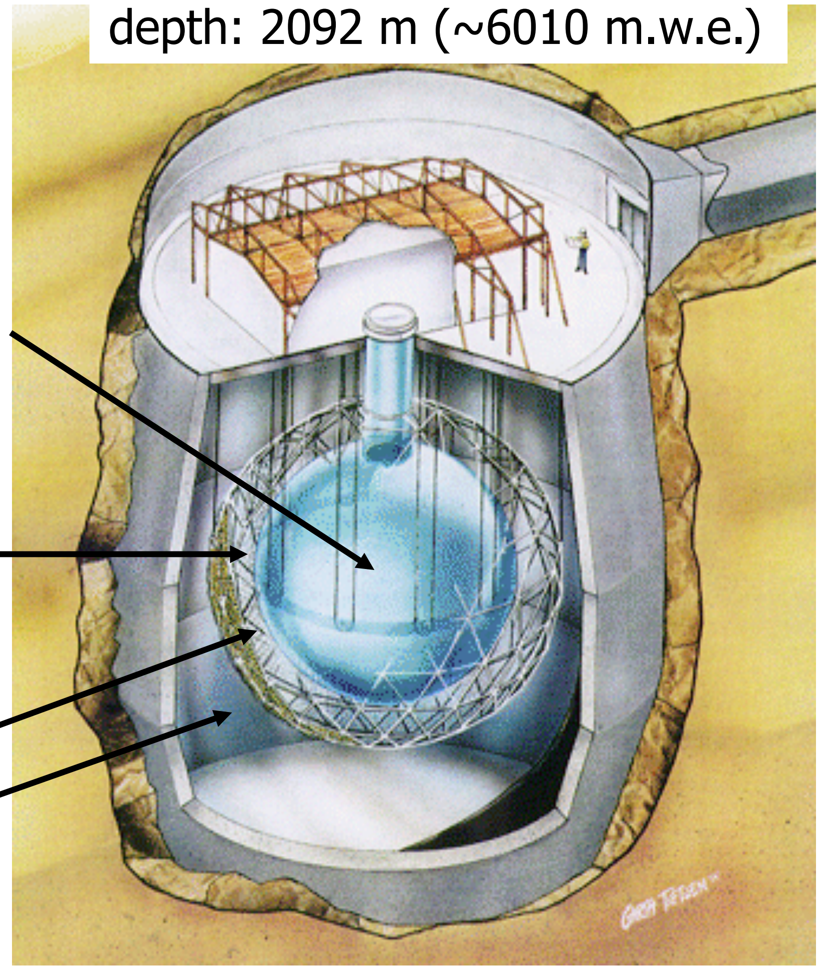



arXiv:hep-ph/0611243

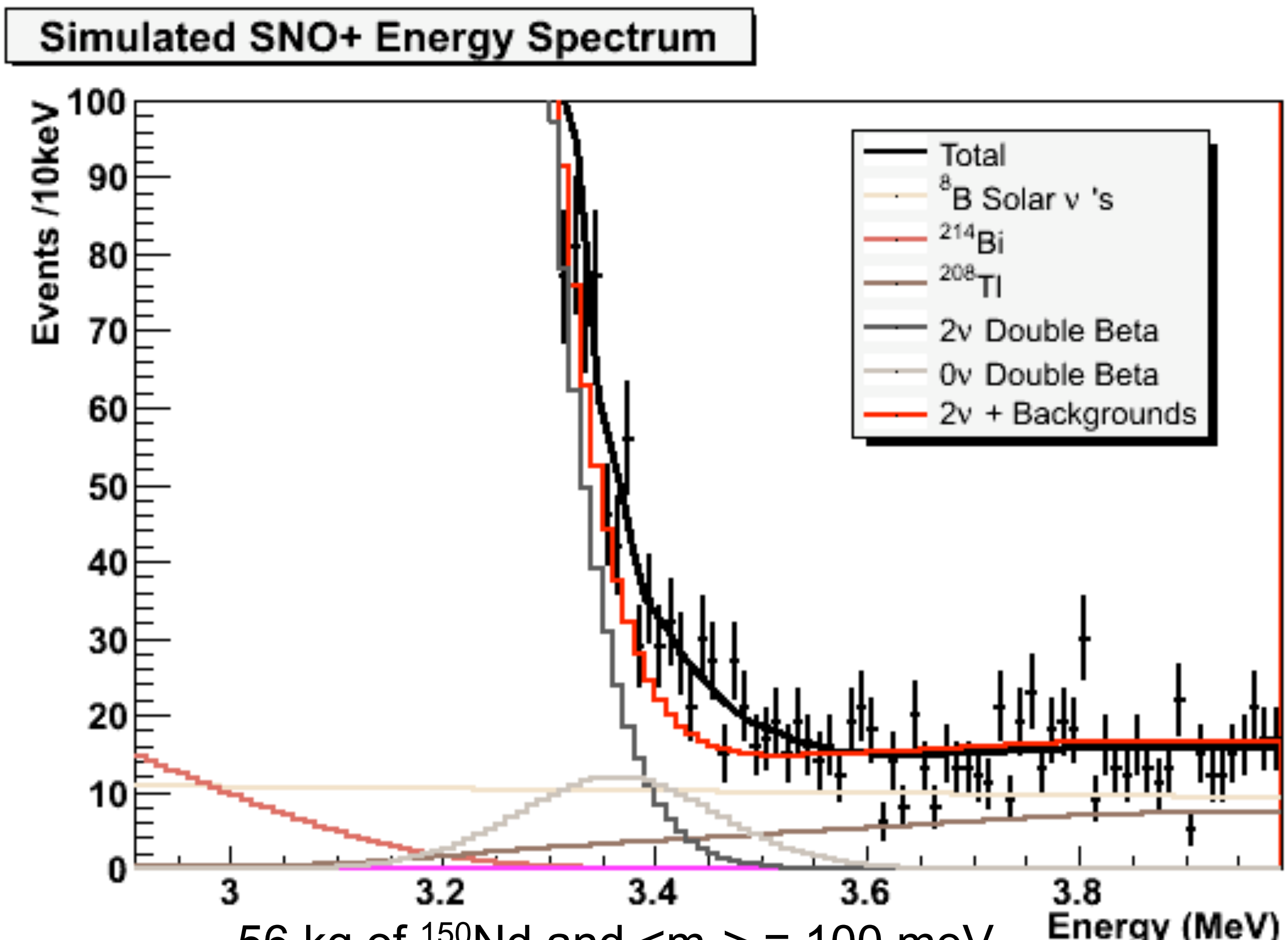
- Because there are no neutrinos to take away energy, the total electron energy in neutrinoless double-beta-decay is equal to the decay energy.
- We can recognize neutrinoless double-beta-decay by observing a peak at the end of the total electron energy spectrum.

# SNO (SNO+) detector

- Located in the Vale Inco Ltd. Creighton Mine near Sudbury, Canada
  - 1 kton $D_2O$ held in 12 m diameter acrylic vessel, **to be replaced with Nd doped liquid scintillator**
  - 18 m diameter support structure holds 9500 PMTs (~60% photocathode coverage)
  - 1.7 kton inner shielding $H_2O$
  - 5.3 ktons outer shielding $H_2O$



# Expected energy spectrum in SNO+




56 kg of $^{150}$Nd and $<m_{\nu}>$ = 100 meV

# Geoneutrinos

# Convection in Earth

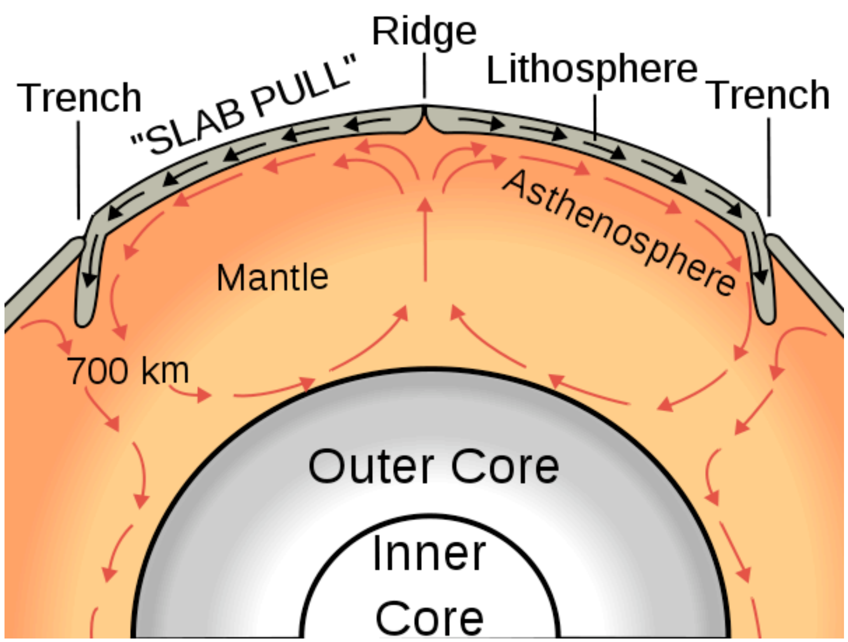



Image: by Surachit, http://en.wikipedia.org/wiki/File:Oceanic_spreading.svg

- Seismic data splits Earth into 5 basic regions:
  - inner core
  - outer core
  - mantle
  - oceanic crust
  - continental crust
- All these regions are solid except the outer core.
- The mantle convects even though it is solid.
- Oceanic crust is being renewed at mid-ocean ridges and recycled at trenches.

# Heat flow from the Earth

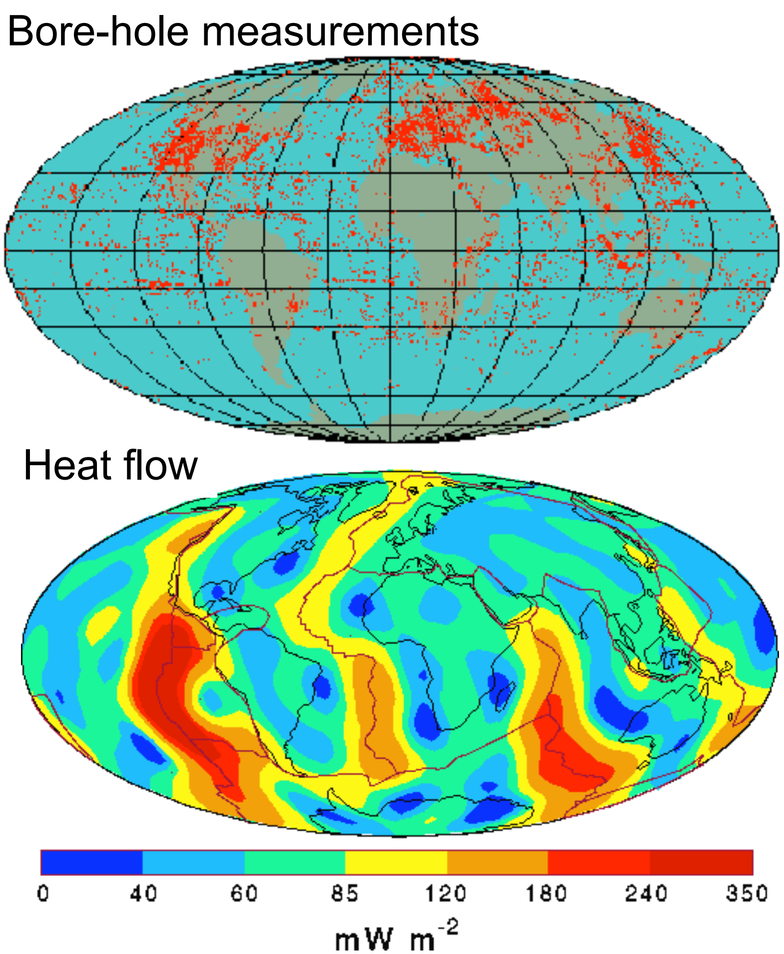



Image: Pollack *et. al*

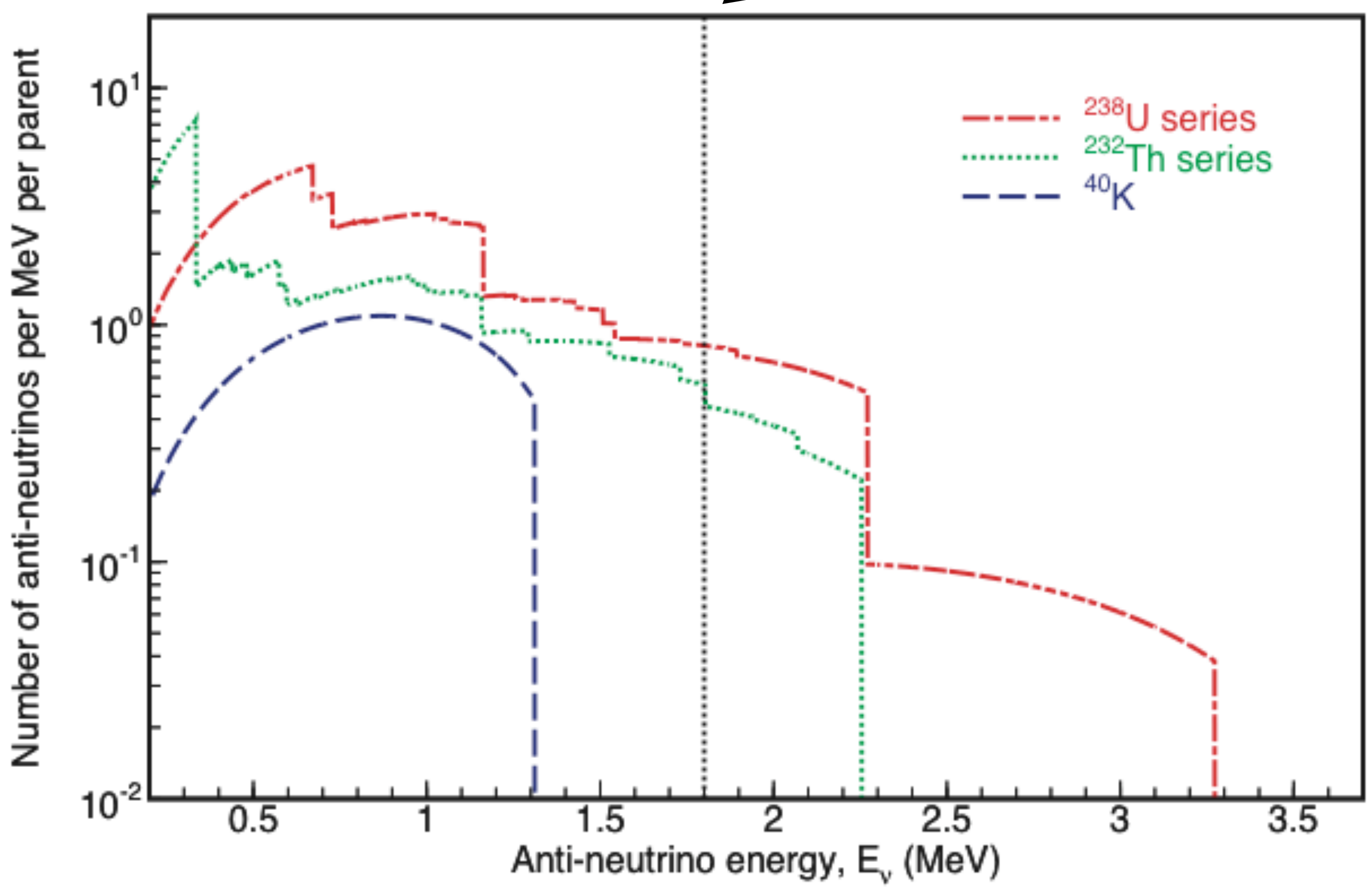
- Conductive heat flow measured from bore-hole temperature gradient and conductivity
- Total heat flow 46±2 TW
- Based on chondritic meteorites the heat production from U, Th, and K are 8 TW, 8 TW, and 3 TW, respectively.

# Discrepancy?

- The measured total heat flow is 44 TW.
- The estimated radiogenic heat produced is 19 TW.
- Models of mantle convection suggest that the radiogenic heat production rate should be a large fraction of the measured heat flow.
- Problem with
  - Mantle convection model?
  - Total heat flow measured?
  - Estimated amount of radiogenic heat production rate?
- Geoneutrinos can serve as a cross-check of the radiogenic heat production.

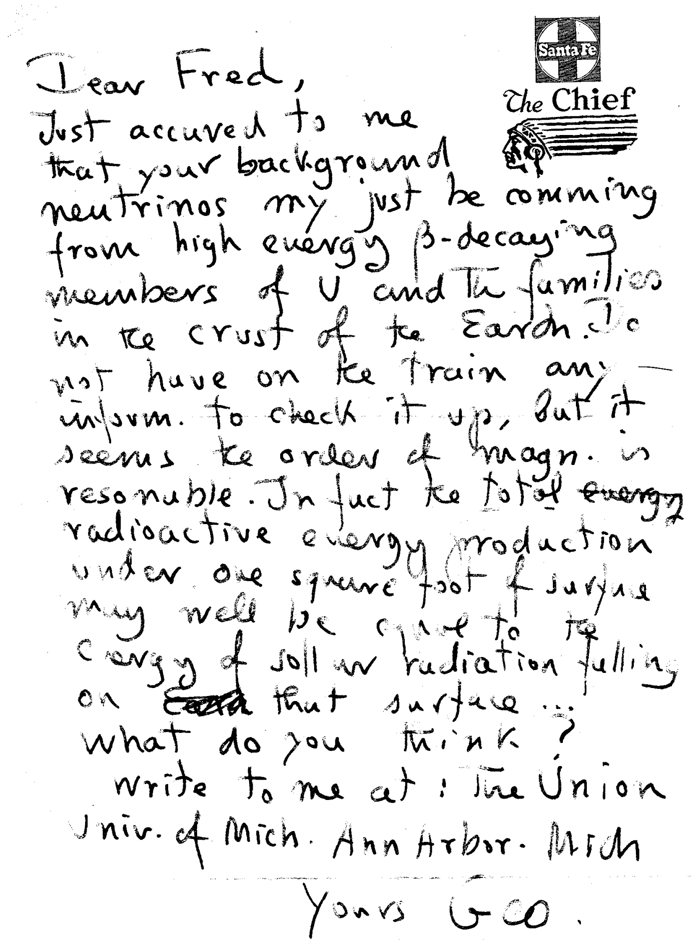
# Geo-neutrino signal

Neutron inverse beta decay threshold



# A little history

Fred Reines (circa 1953)



Santa Fe
The Chief

Dear Fred,
Just accured to me
that your background
neutrinos my just be comming
from high energy β-decaying
members of U and Th families
in the crust of the Earth. Do
not have on the train any
inform. to check it up, but it
seems the order of magn. is
resonable. In fact the total ~~energy~~
radioactive energy production
under one square foot of surface
may well be equal to the
energy of sollar radiation falling
on ~~Earth~~ that surface ...
what do you think?
write to me at: The Union
Univ. of Mich. Ann Arbor. Mich
Yours Geo.

# Were they geo-neutrinos?

TO: DR. GEORGE GAMOW
THE UNION
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

MESSAGE:

FROM NUMBERS IN UREY BOOK ON THE PLANETS, EQUILIBRIUM HEAT LOSS FROM EARTH'S SURFACE IS 50 ERGS/$CM^2$ SEC. IF ASSUME ALL DUE TO BETA DECAY THEN HAVE ONLY ENOUGH ENERGY FOR ABOUT $10^8$, 1 Mev NEUTRINOS PER $CM^2$ AND SEC. THIS IS LOW BY $10^5$ OR SO. SHORT HALF LIVES WOULD BE MADE BY COSMIC RAYS OR NEUTRONS IN EARTH. IN VIEW OF RARITY OF COSMIC RAYS: I.E. ABOUT EQUAL TO ENERGY OF STARLIGHT AND OF NEUTRONS IN EARTH THIS SOURCE OF NEUTRONS SEEMS EVEN LESS LIKELY AS A SOURCE OF OUR SIGNAL.

# S/N crust and mantle

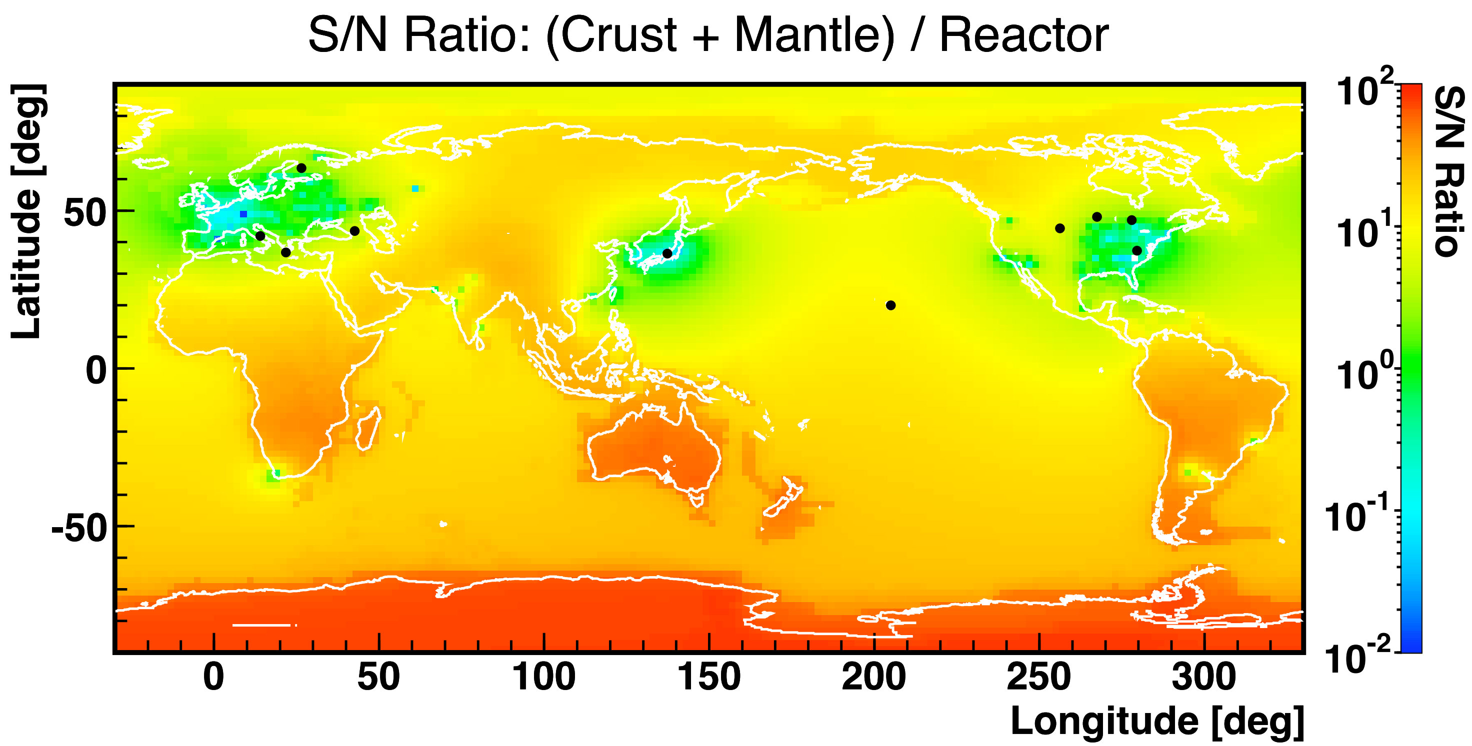



Image: S. Enomoto

# S/N Mantle

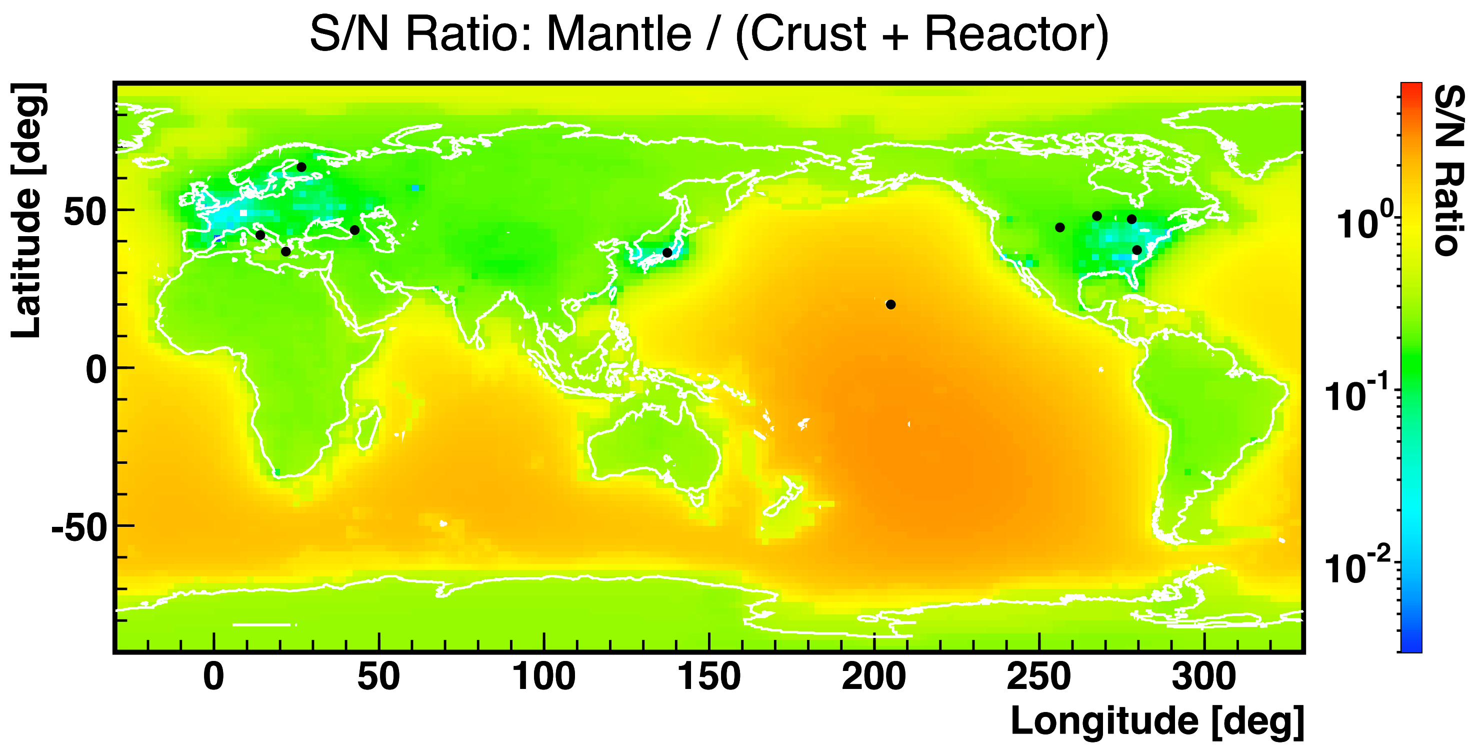
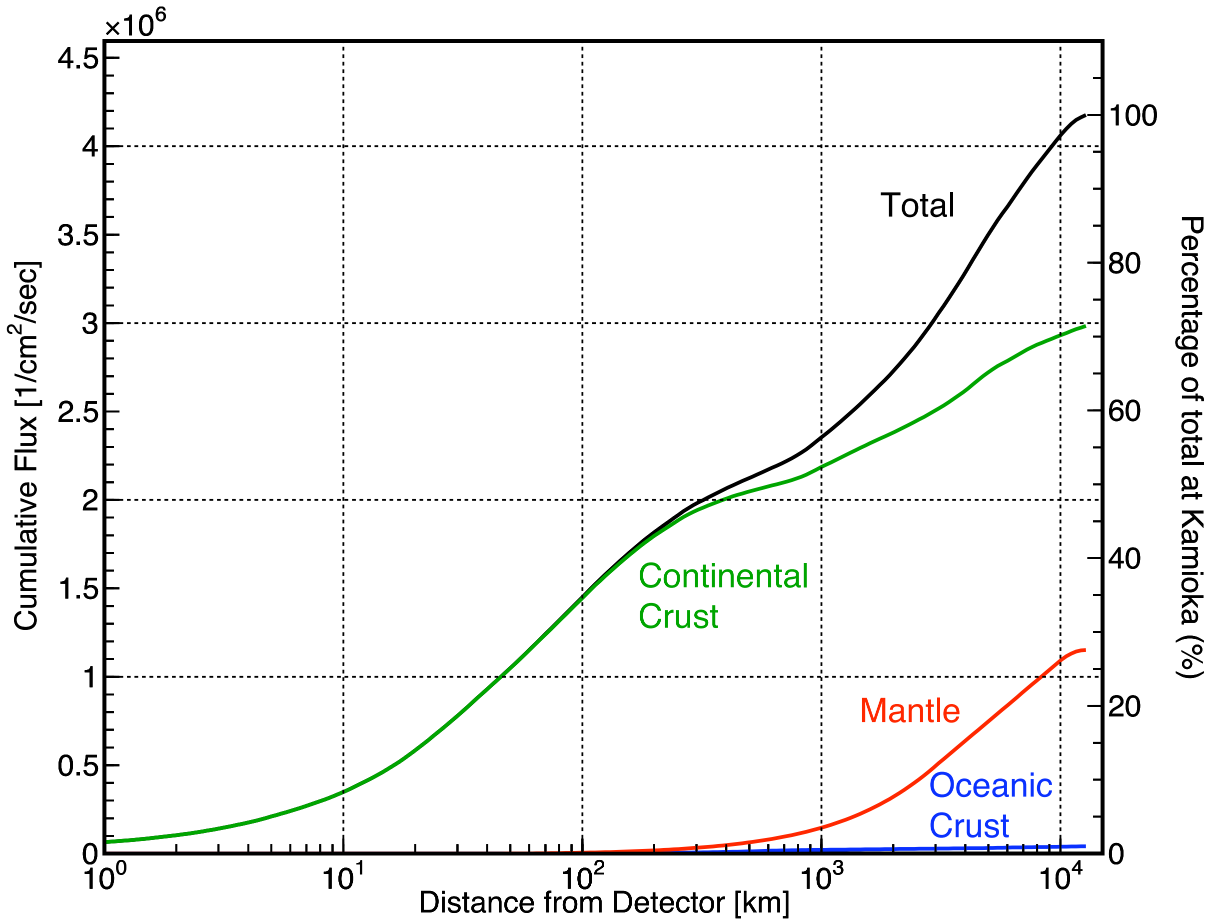


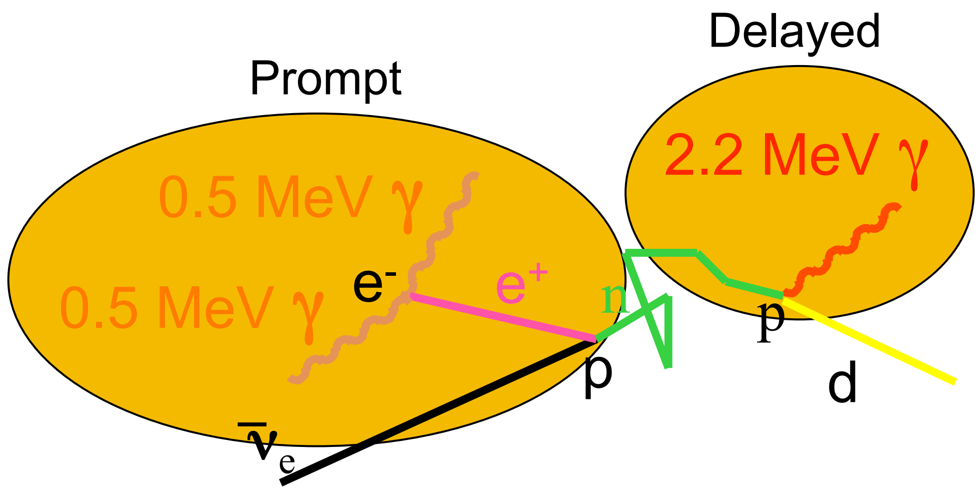

Image: S. Enomoto

# Where do the neutrinos come from?



# Detecting electron anti neutrinos

- $\overline{\nu}_e + p \rightarrow e^+ + n$
  The positron energy is related to the neutrino energy.
- The positron loses its energy then annihilates with an electron.
- The neutron first thermalizes then is captured by a proton with a mean capture time of ~200μs.

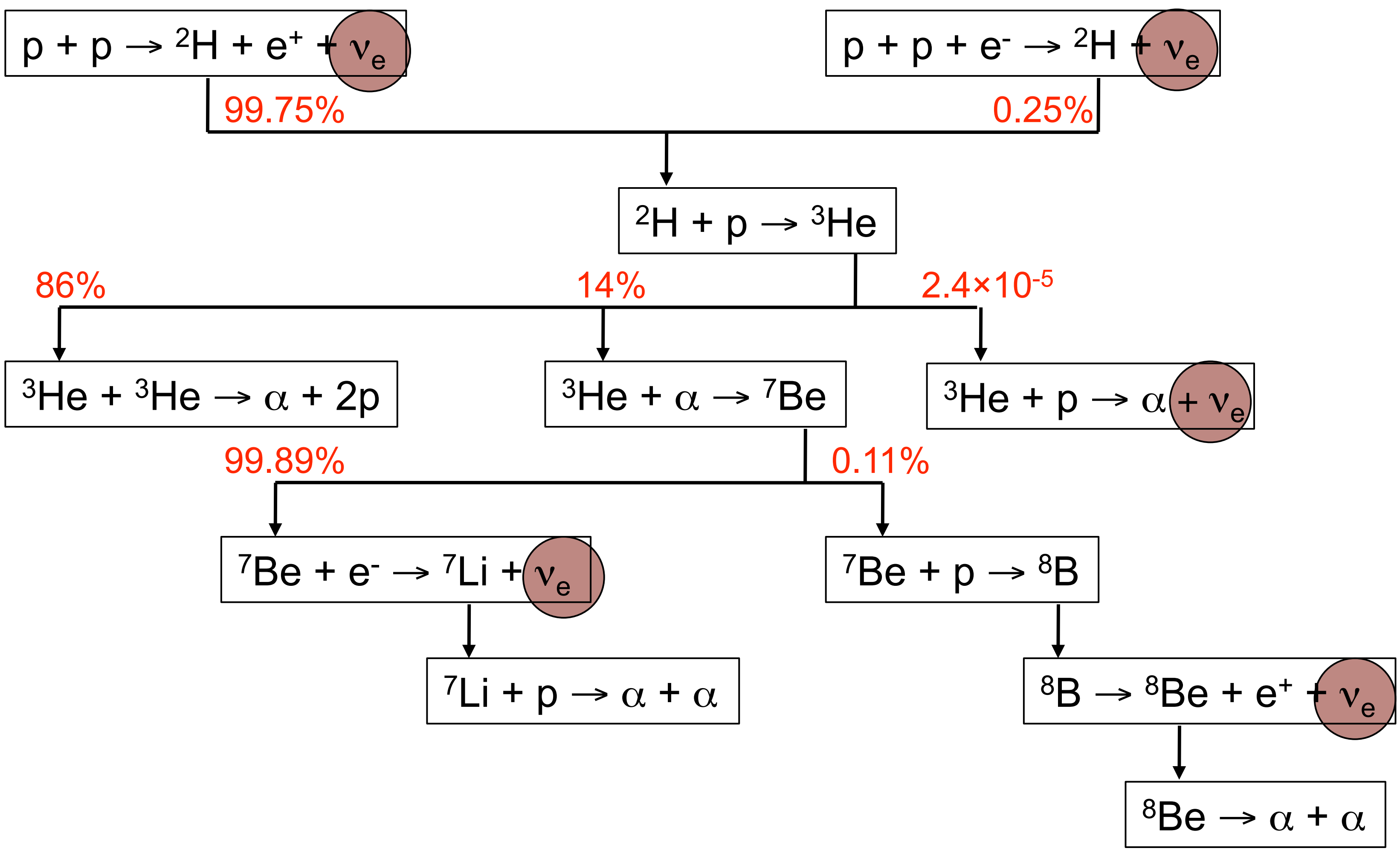


# Need for more detectors

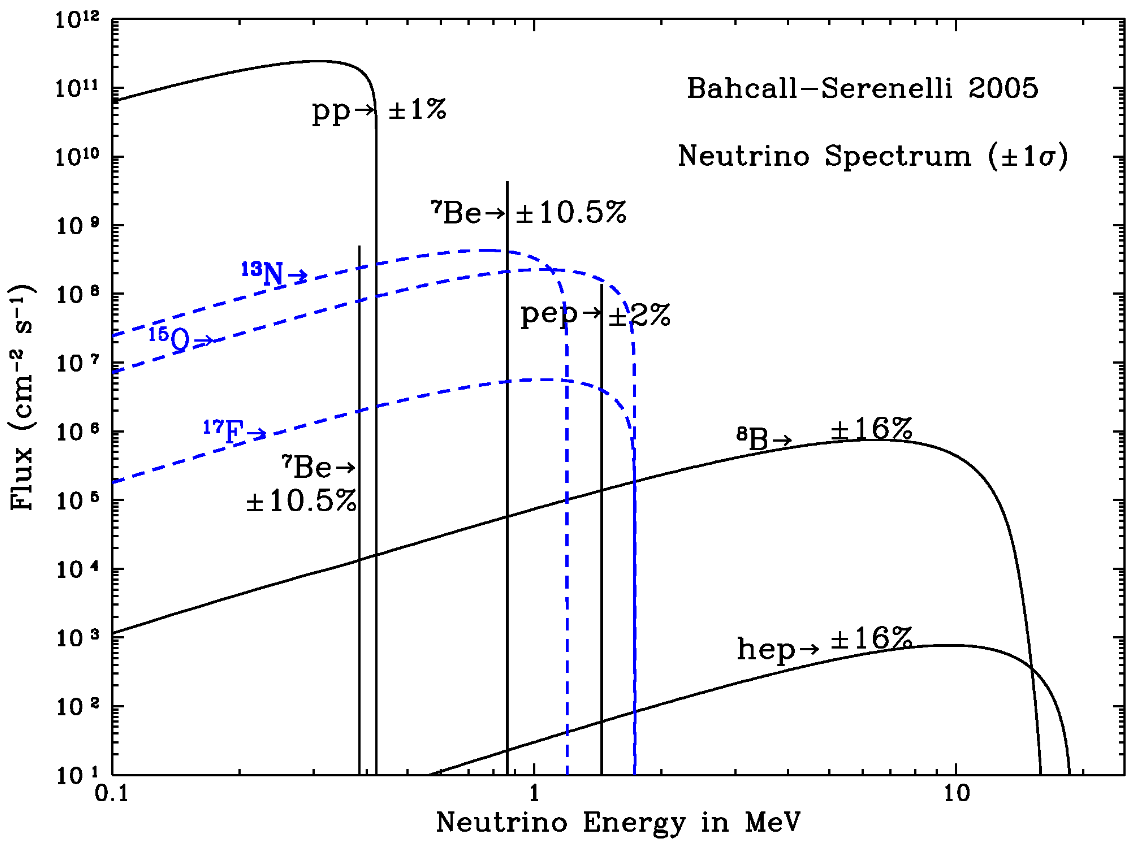
- Current geoneutrino flux measurements
  - KamLAND $\left(4.3^{+1.2}_{-1.1}\right)\times 10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - BOREXINO $\left(7.1^{+2.9}_{-2.4}\right)\times 10^{6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Ideally we would like to make a measurement in the ocean to probe the contribution from the mantle.
- However, with a precision measurement on the crust, and an accurate measurement of the local crustal contribution from heat flow measurements, could also obtain mantle contribution.
- Ideally we would like multiple measurements to probe local variations (despite our assumptions, the mantle is not uniform).

# Solar neutrinos

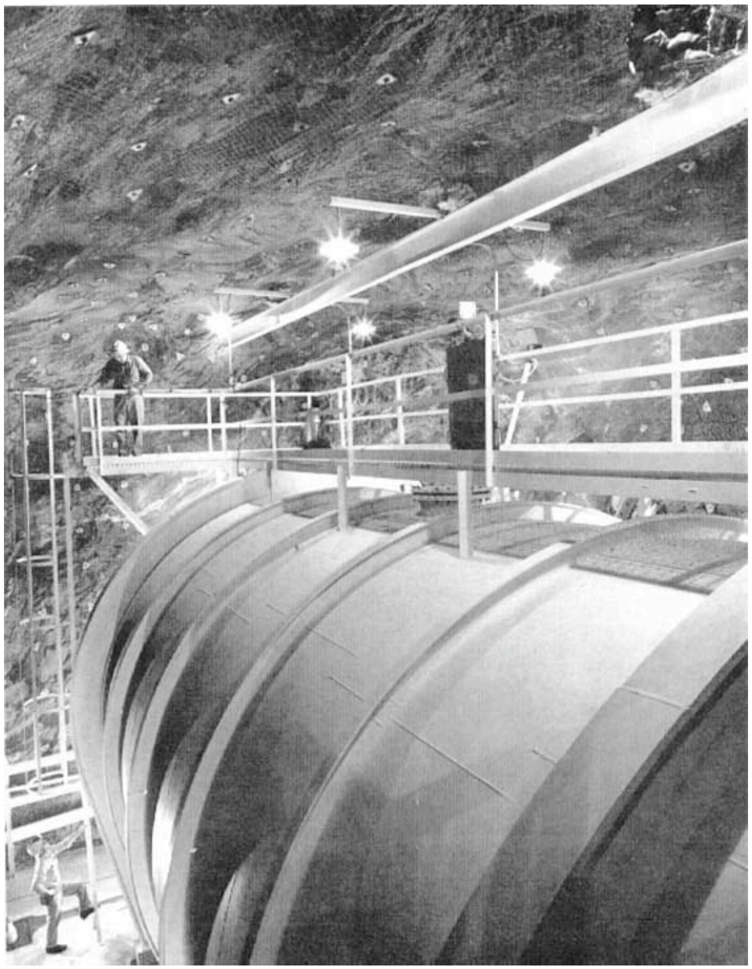
# Solar pp chain reactions



# Neutrino energy spectrum

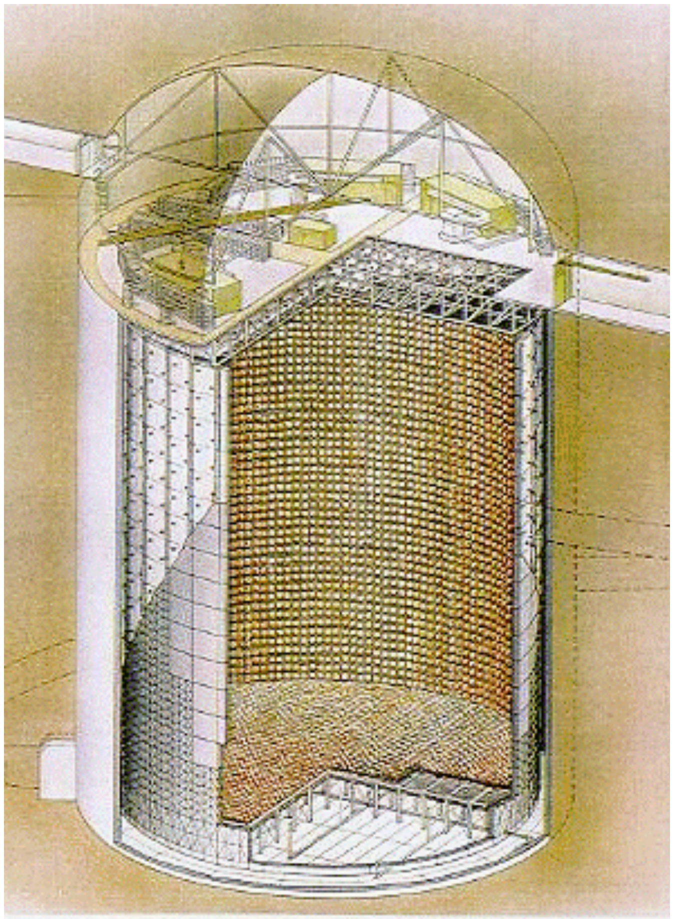


# Ray Davis

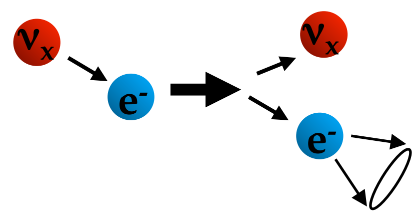


- $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$
- $^{37}Ar$ is a gas which is removed from detector with He carrier gas
- Outside the active volume the $^{37}Ar$ is detected via $^{37}Al + e^- \rightarrow {}^{37}Cl + \nu_e$ which has a half-life of 35 days

# SuperK



- 50,000 ton ring-imaging water Cherenkov detector
- SuperK detects solar neutrinos from electron elastic scattering

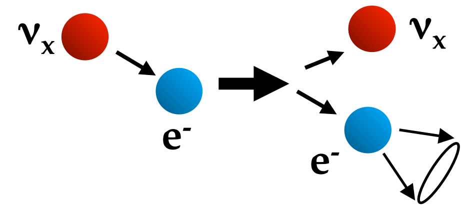



  - $\sigma(\nu_e) \approx 6\ \sigma(\nu_\mu) \approx 6\ \sigma(\nu_\tau)$
  - Strong directionality
- The scattered electron produces a Cherenkov ring

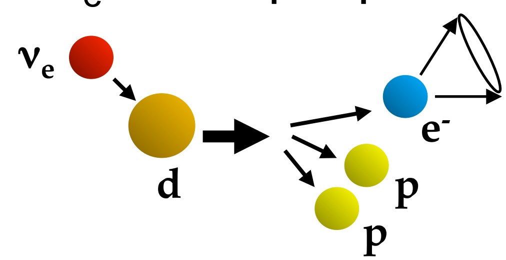
# SNO: 3 reactions and 3 phases

- Detected neutrons produced in NC reactions three ways
- Phase I:
  - Signal observed in PMT array via $n + {}^{2}H \rightarrow {}^{3}H + 6.25$ MeV
- Phase II:
  - Added salt
  - Signal observed in PMT array via $n + {}^{35}Cl \rightarrow {}^{36}Cl + 8.6$ MeV
- Phase III:
  - Removed salt and added an array of 40 $^{3}$He filled proportional counters "neutral-current detectors" (NCDs).
  - Signal observed in NCD array via $n + {}^{3}He \rightarrow {}^{3}H + p$

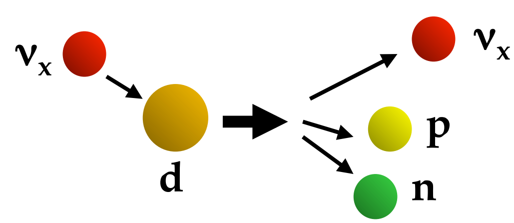
**ES:** $\nu_x + e^- \rightarrow \nu_x + e^-$



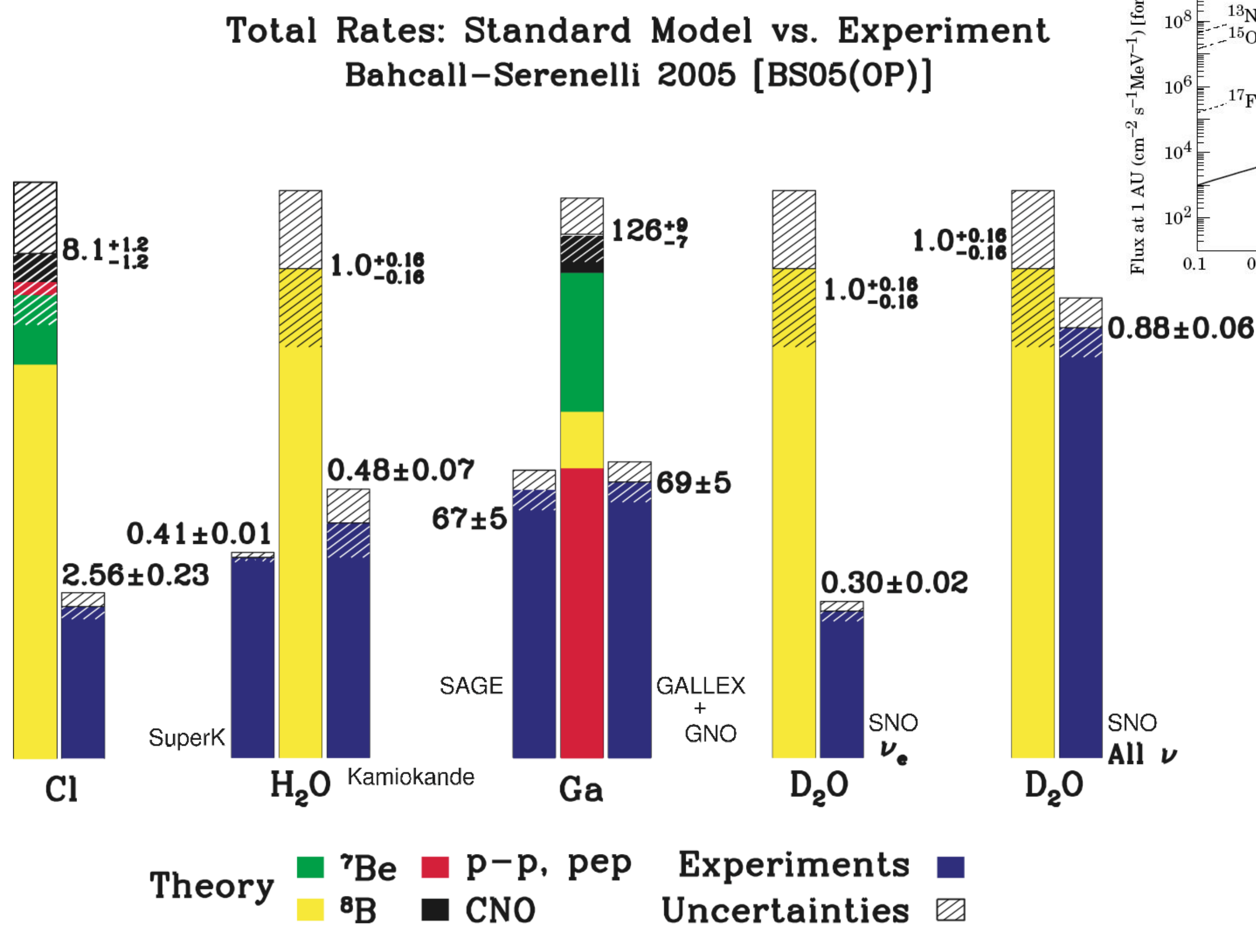

**CC:** $\nu_e + d \rightarrow p + p + e^-$

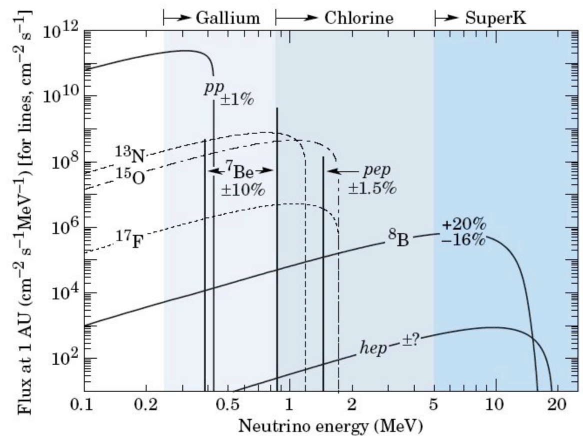



**NC:** $\nu_x + d \rightarrow p + n + \nu_x$



# Solar neutrino measurements

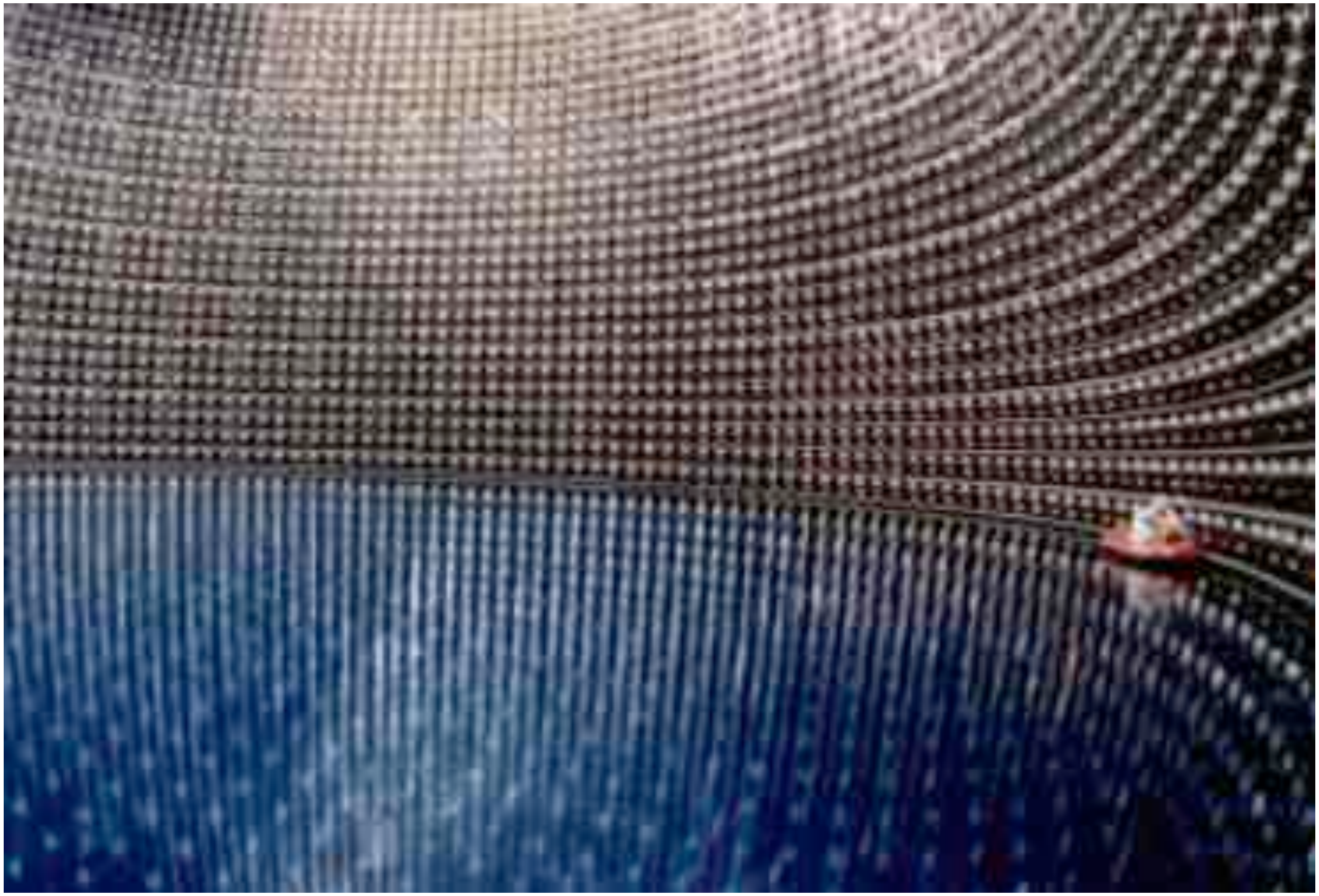


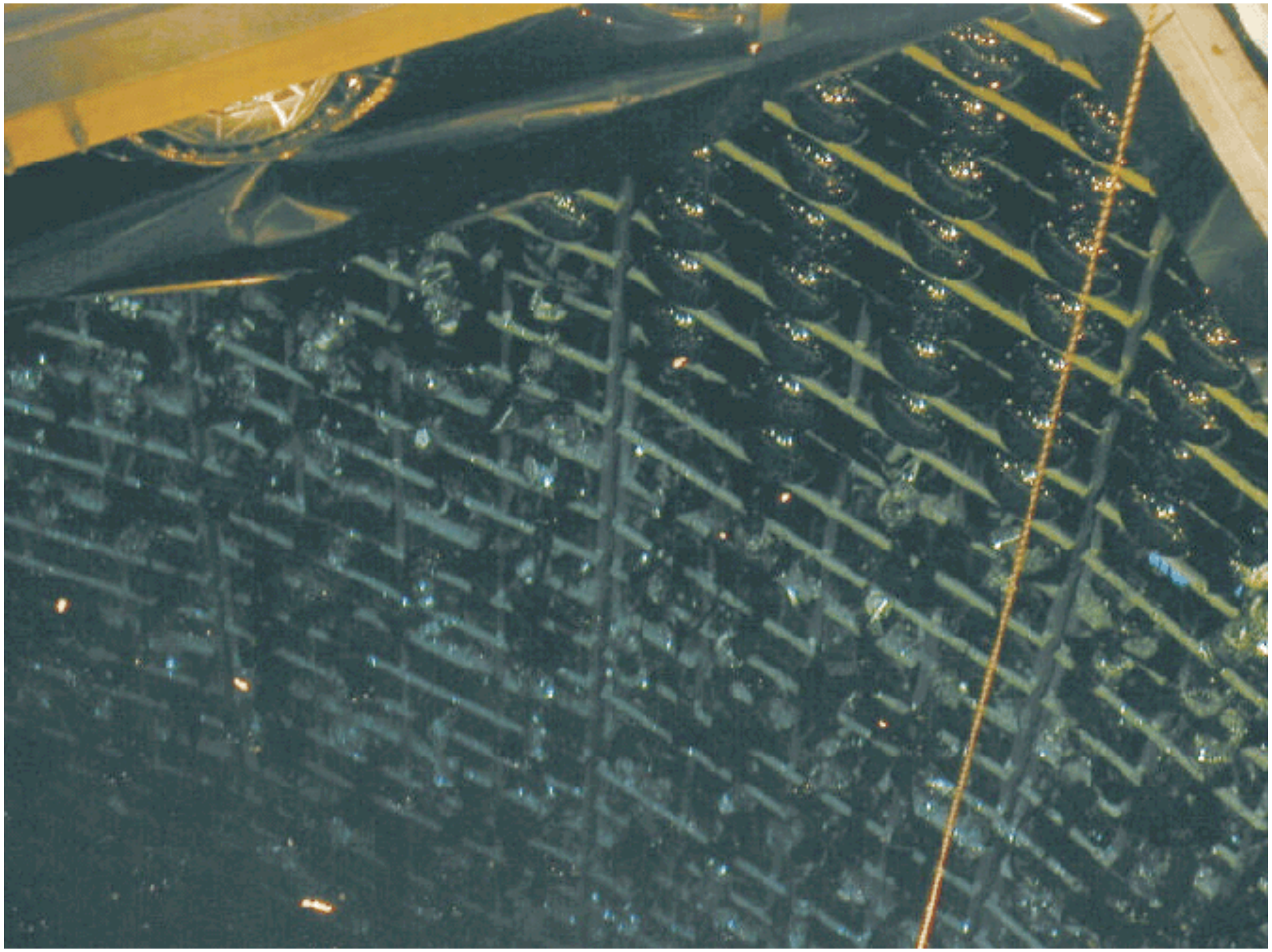
# Pretending to be miners


# Very clean miners


# Super-K cleaning



# Boating in Super-K, not likely again



# Questions?