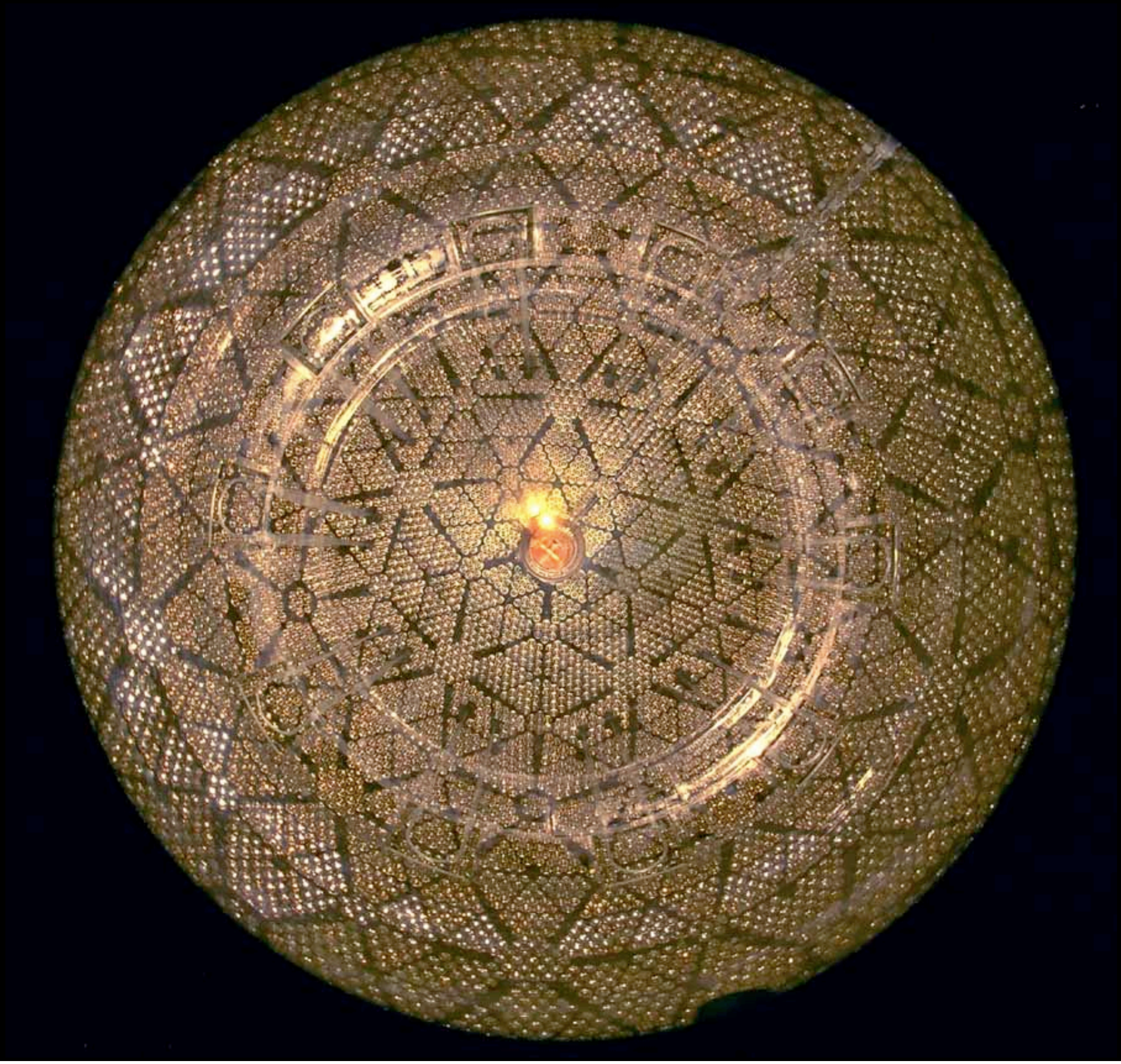
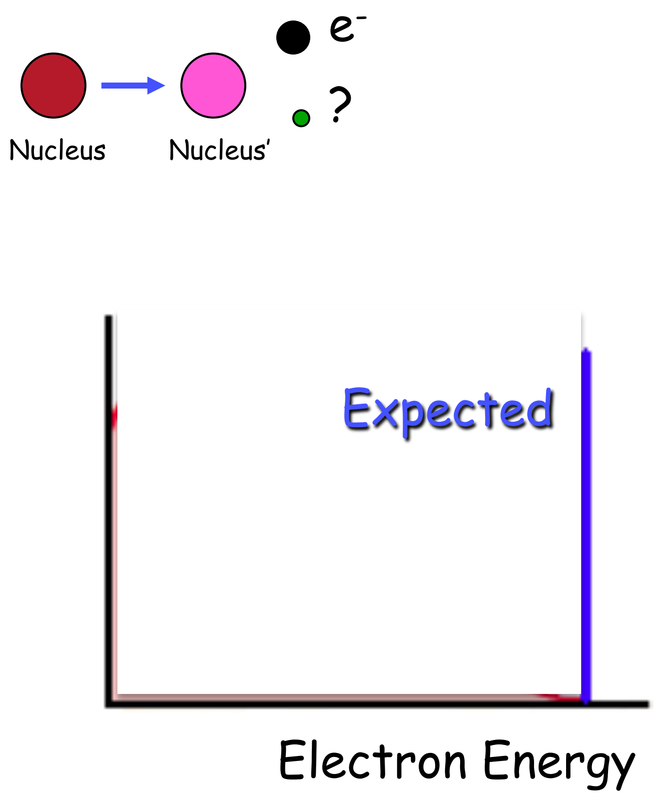


Neutrinos from heaven and hell

Nikolai Tolich, University of Washington

What Are Neutrinos?



- In 1930 Pauli postulated the particle we now call the neutrino.
- Pauli's particle would have almost zero mass and be almost impossible to observe.
- In 1956 the impossible happened as Reines and Cowan observed neutrinos from a nuclear reactor, for which they got the 1995 Nobel prize in physics.

Beta-decay

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

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

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

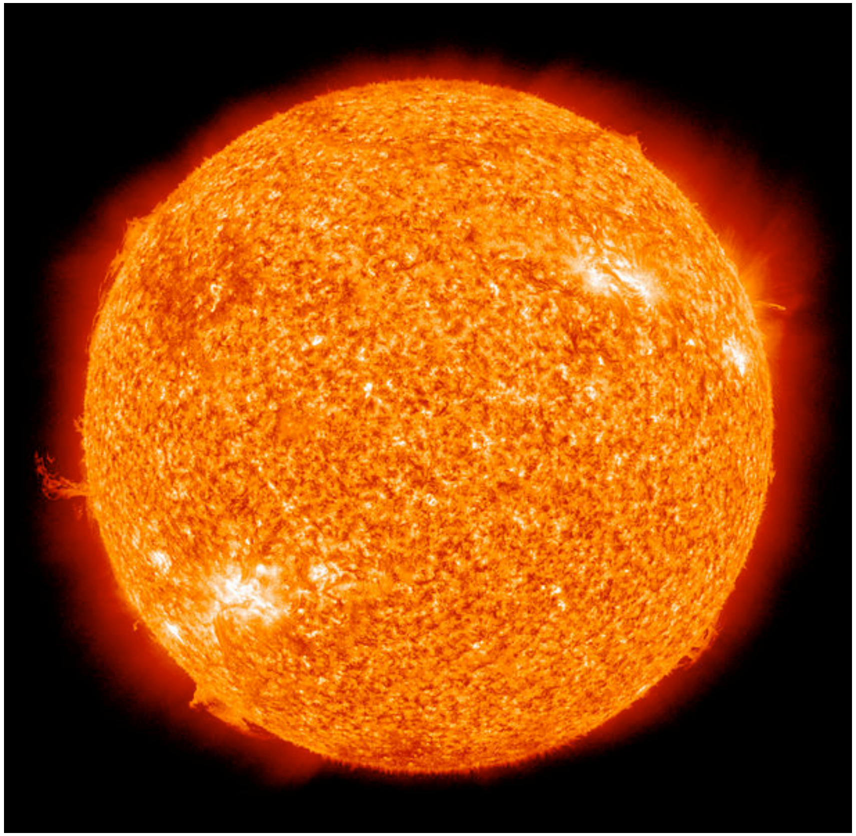
$$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + e^+ + \nu_e$$

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

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

Astrophysical energy sources

Sun luminosity 384×10^{24} W



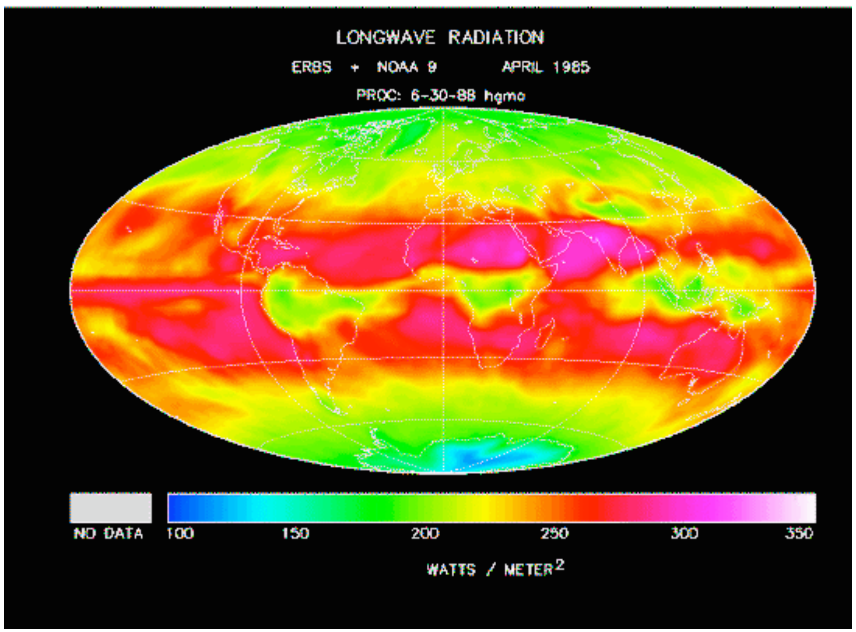
Earth luminosity 46×10^{12} W

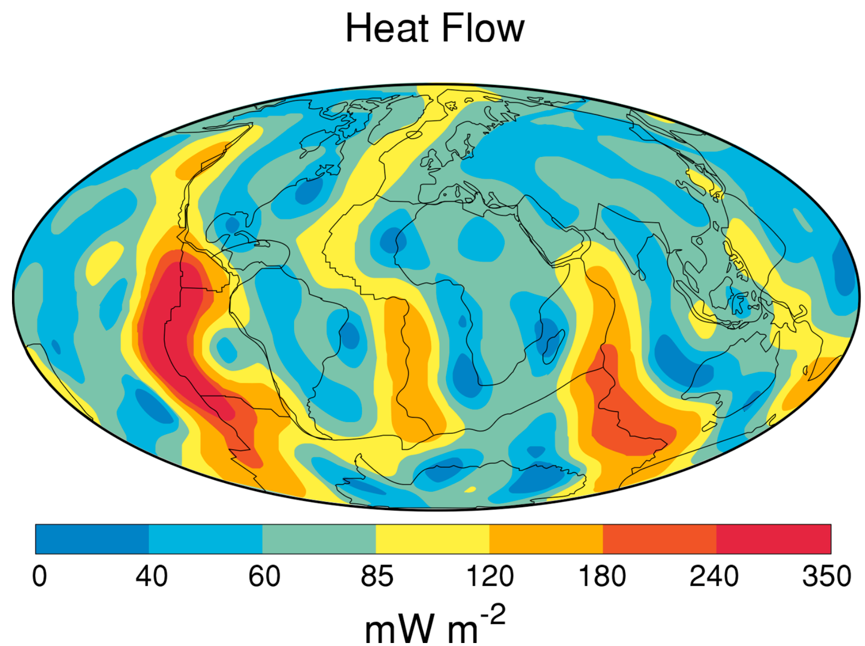
Mount St. Helens

Power density at Earth's surface

Solar average 240 Wm^{-2}

Earth average 90×10^{-3} Wm^{-2}

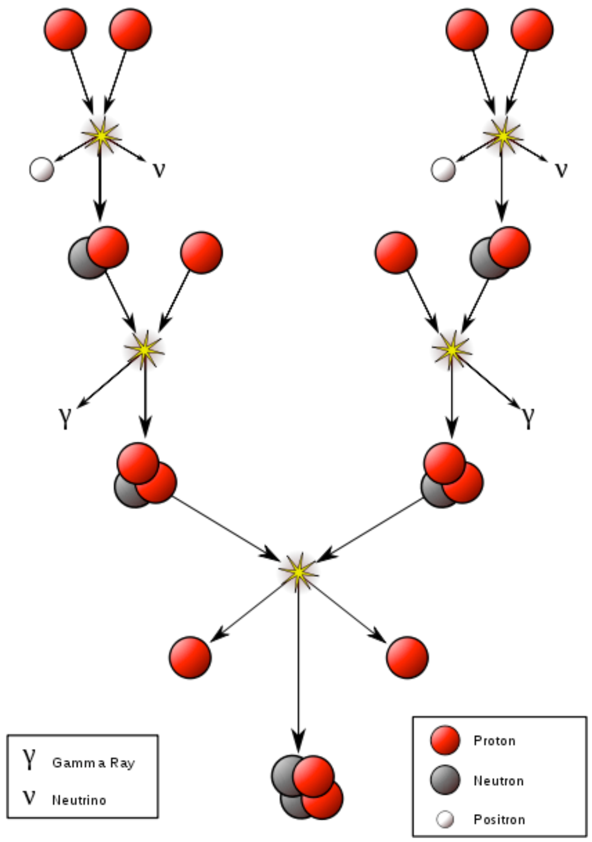




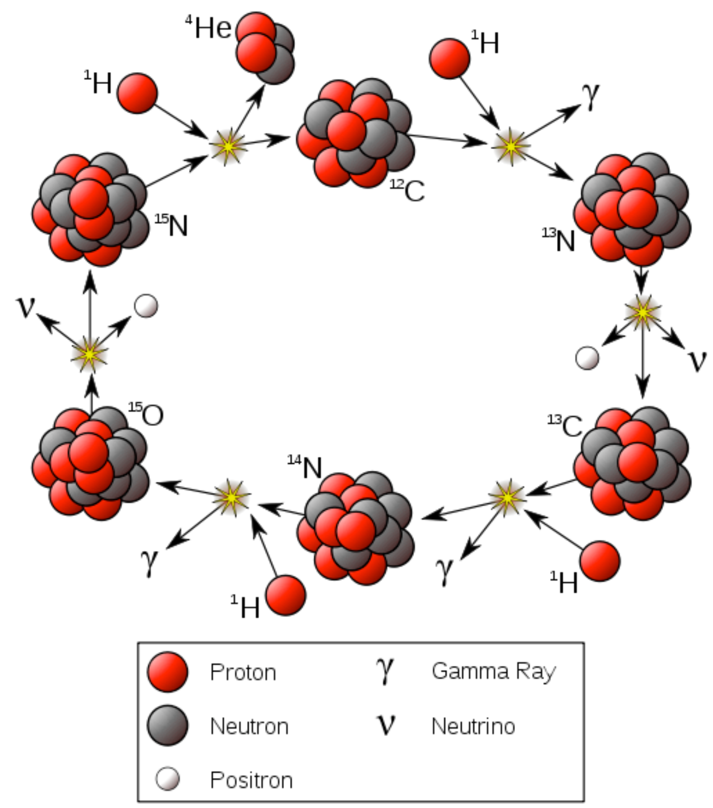
The Sun

Solar fusion ($4\,^1H \rightarrow ^4He + 2e^+ + 2\nu_e$)

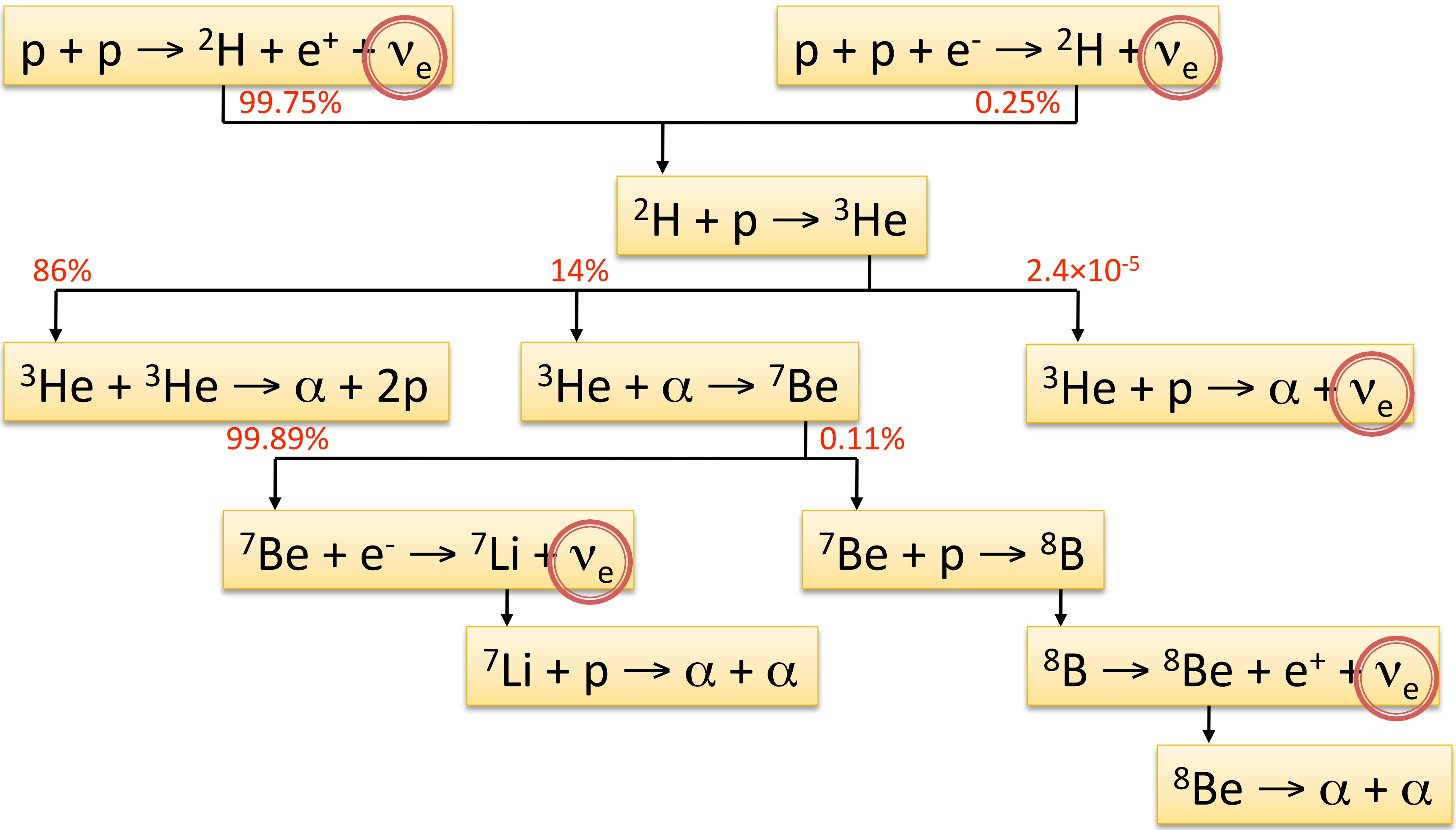
PP fusion



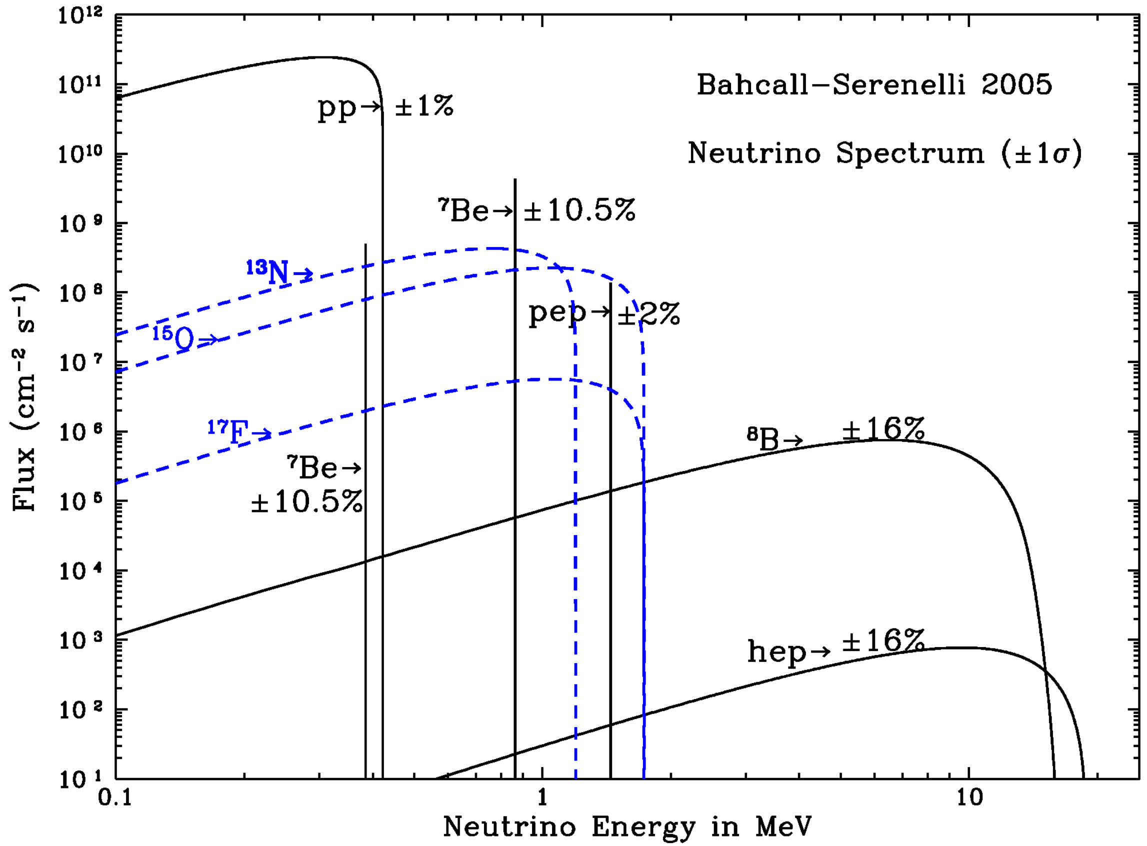
CNO cycle



Solar pp chain reactions



Solar neutrino energy spectrum



The Earth

Radioactivity in the earth

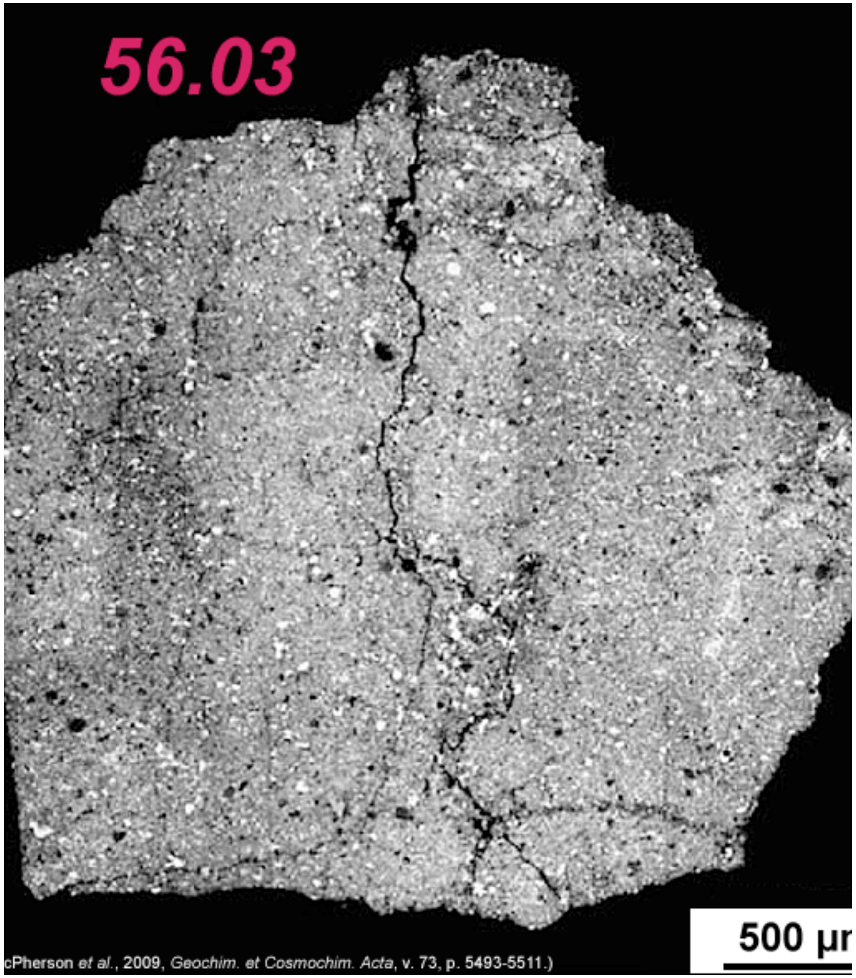
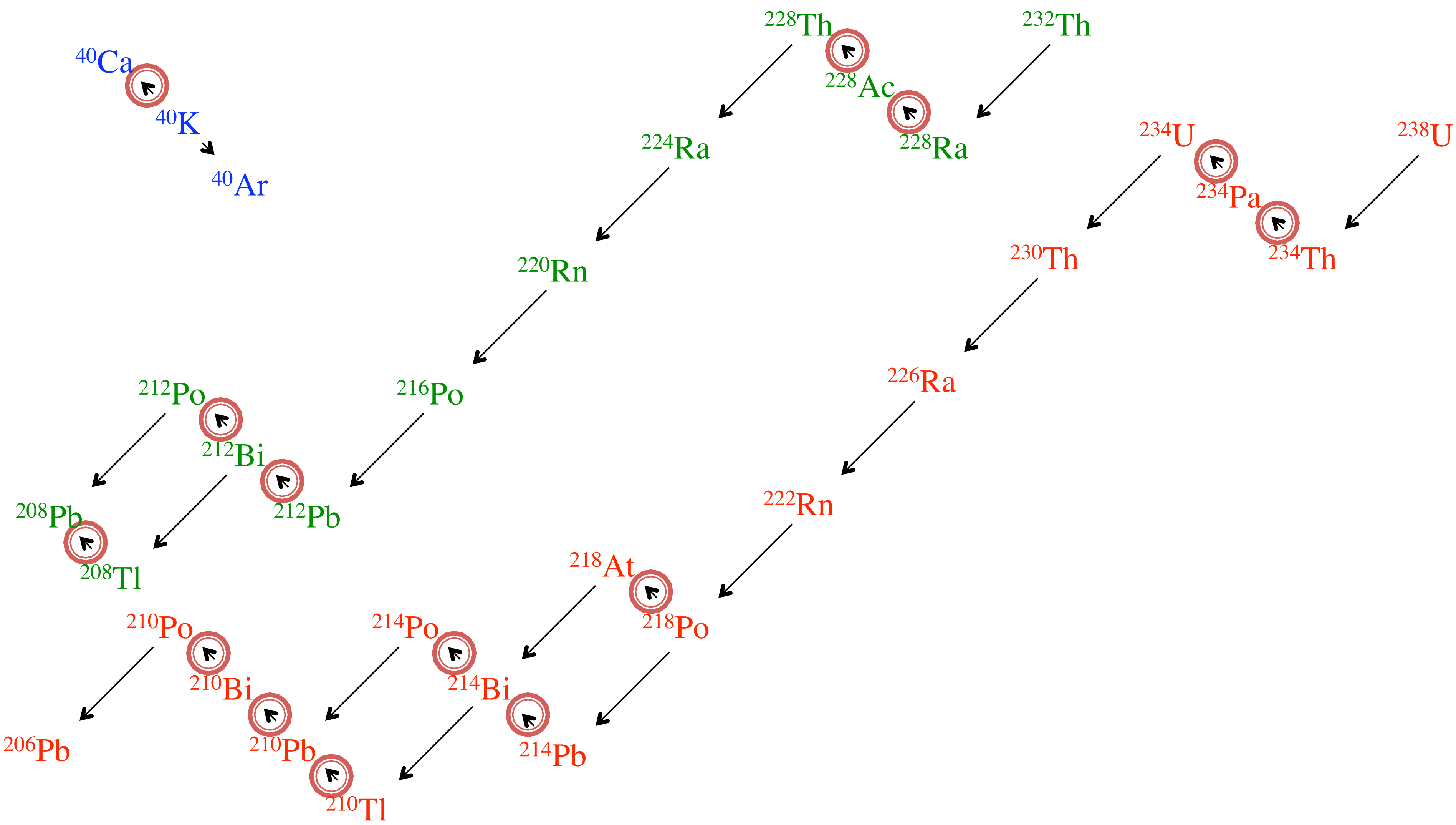


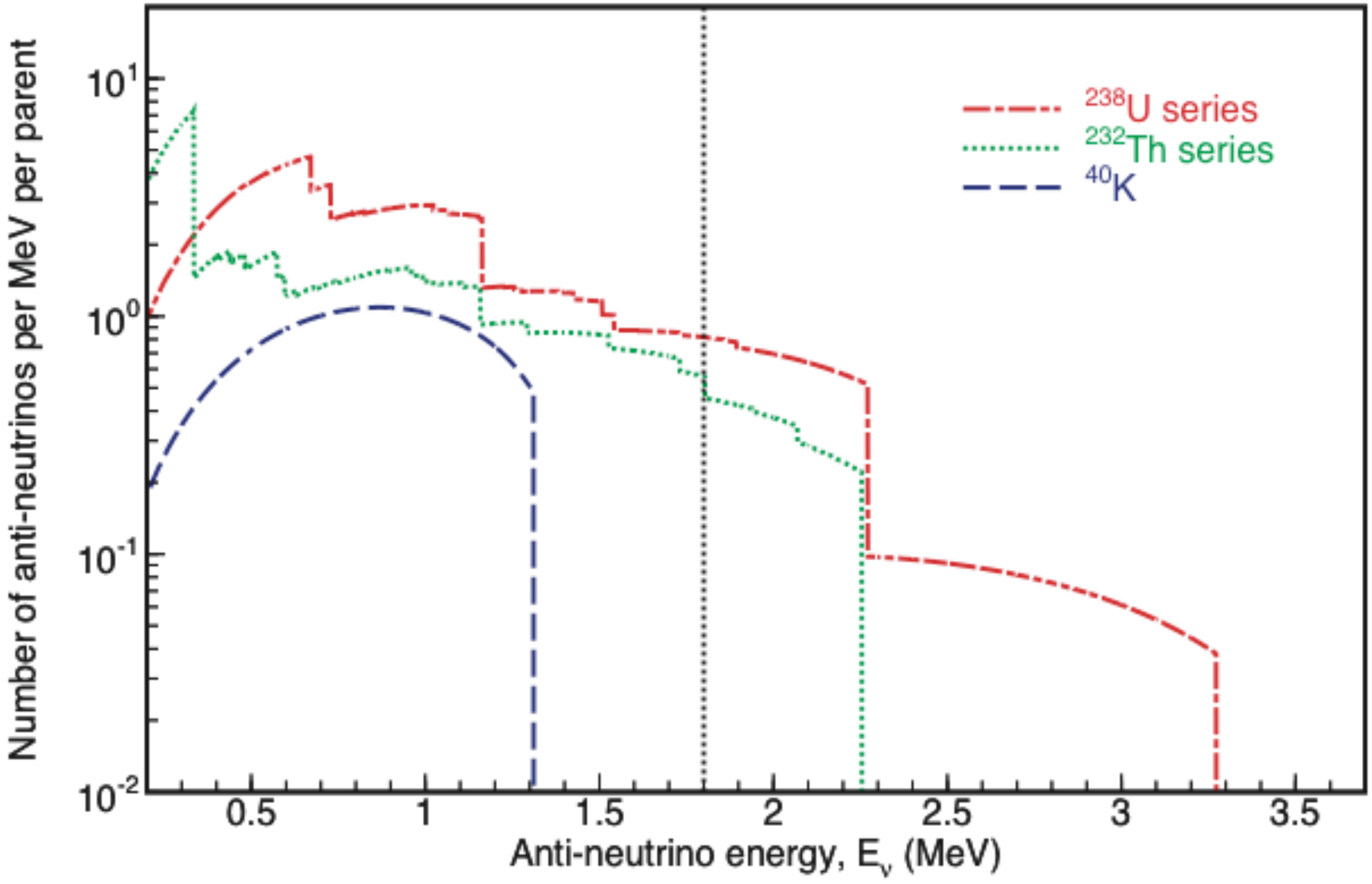
Image: http://www.psrd.hawaii.edu/

- Based on carbonaceous chondrites Lyubetskaya & Korenaga (2007) predict the following concentrations of radioactive isotopes in the earth's primitive mantle and crust
  - U (17±3) ng/g
  - Th (63±11) ng/g
  - K (23±5) μg/g
- The resulting heat production rate is $(16\pm3)\times10^{12}$ W

Radiogenic isotopes

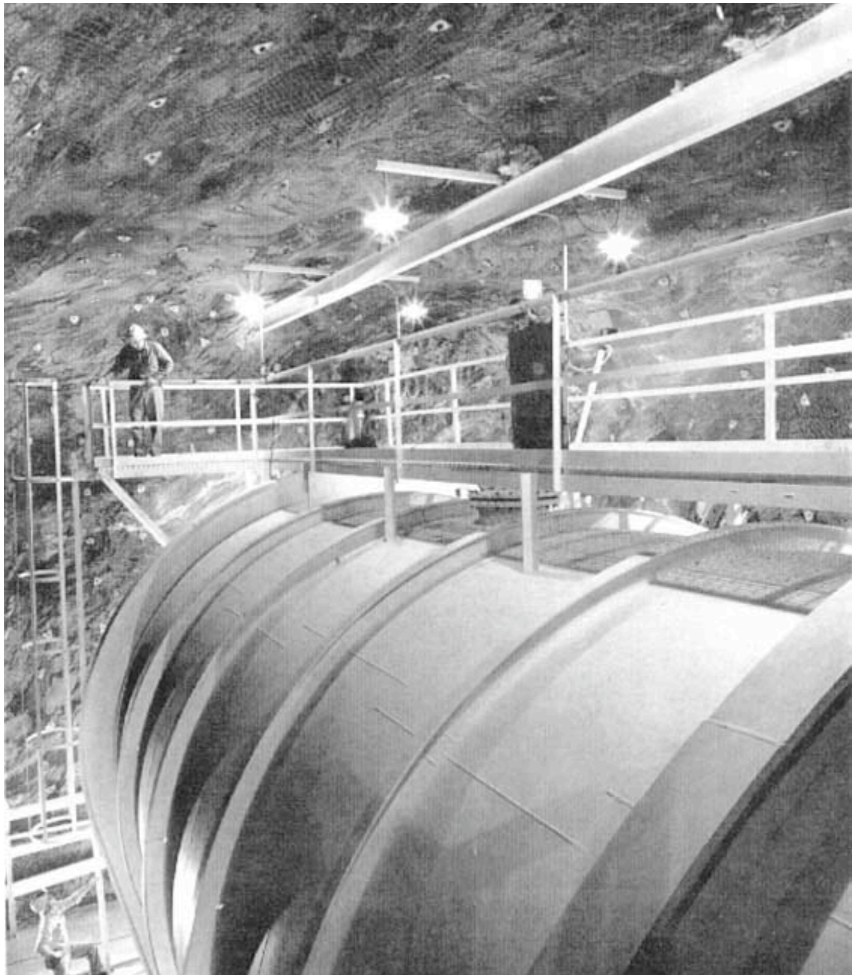


Geo-neutrino energy spectrum



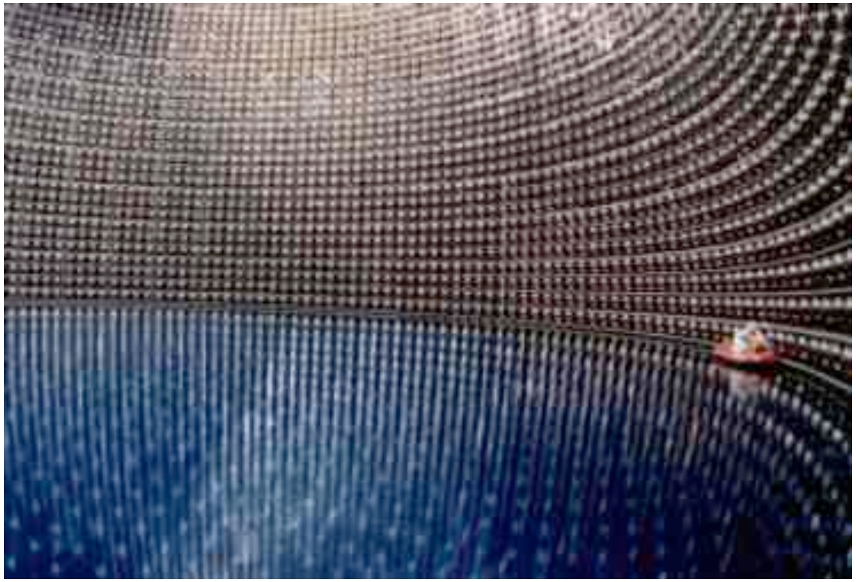
Solar neutrinos

Ray Davis

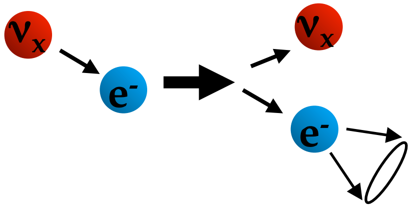


- $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$
- ^{37}Ar is a gas which is removed from detector with He carrier gas
- Outside the active volume the ^{37}Ar is detected via $^{37}Al + e^- \rightarrow {}^{37}Cl + \nu_e$ which has a half-life of 35 days

SuperK detector

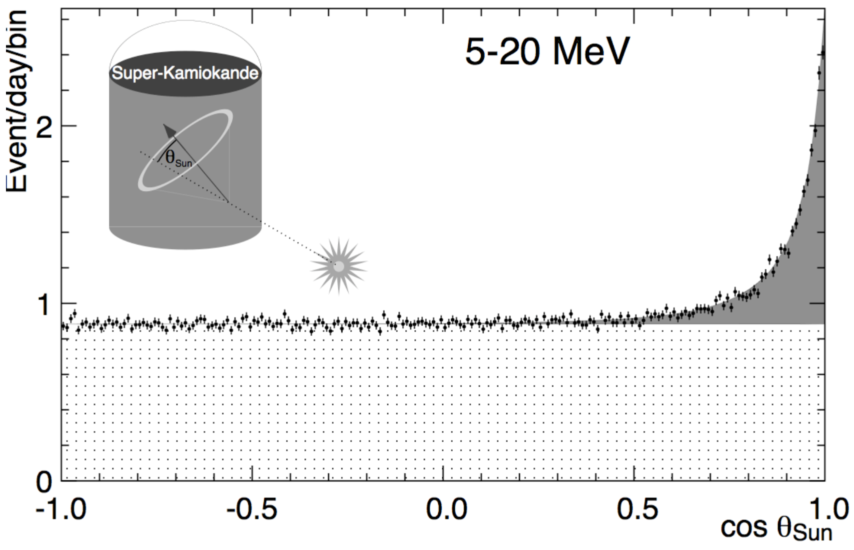


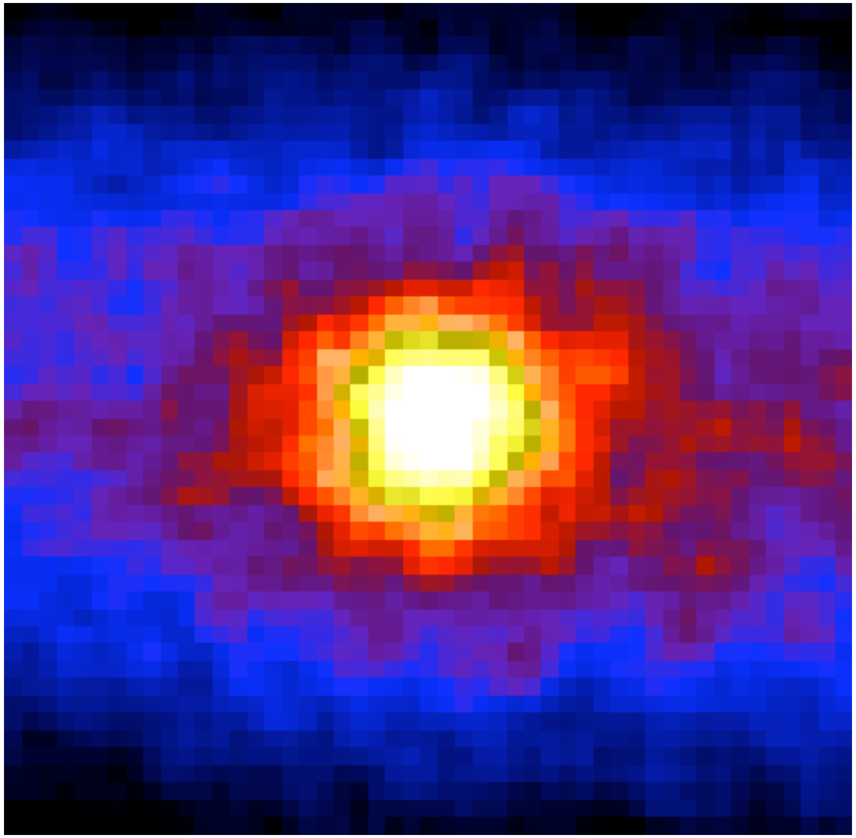
- 50,000 ton ring-imaging water Cherenkov detector
- SuperK detects solar neutrinos from electron elastic scattering



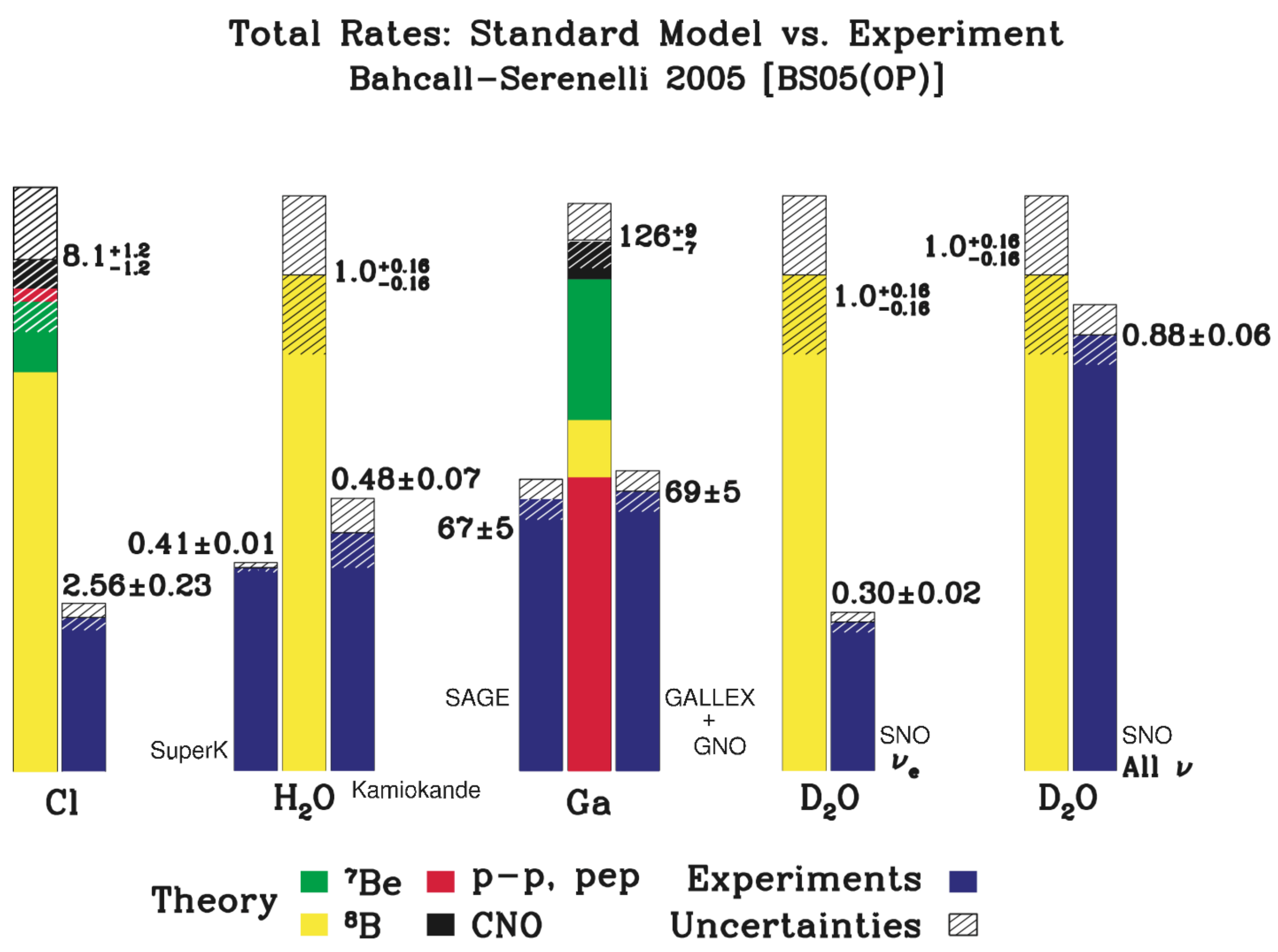
  - $\sigma(\nu_e) \approx 6\ \sigma(\nu_\mu) \approx 6\ \sigma(\nu_\tau)$
  - Strong directionality
- The scattered electron produces a Cherenkov ring

SuperK solar neutrino results





Solar neutrino results



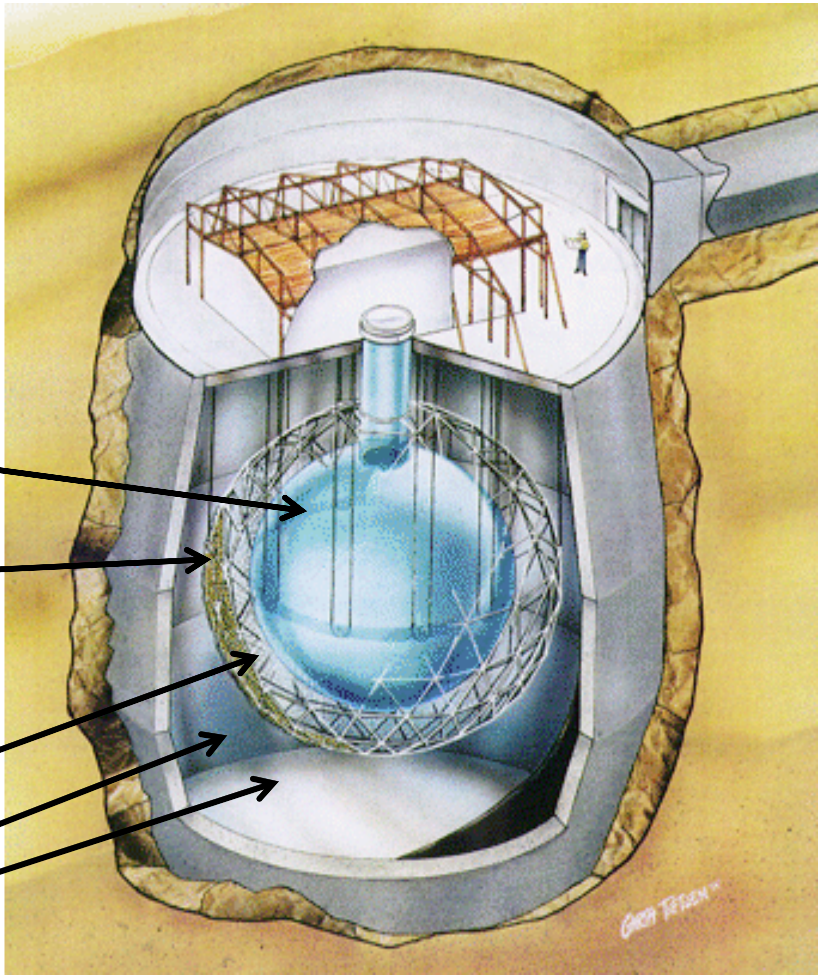
Neutrino oscillations

- The weak interaction neutrino eigenstates can be expressed as superpositions of definite mass eigenstates
- Mixing matrix is parameterized by three mixing angles, ϑ_{12}, ϑ_{13}, and ϑ_{23}, one CP violating phase δ, and two Majorana phases, α_1 and α_2.
- Assuming only two neutrino flavors the probability of the neutrino being detected in the same flavor as it was created after travelling a distance *L* is given by

$$P_{\nu_e \to \nu_e}\left(E_{\nu_e}, L\right) \approx 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_{\nu_e}}\right)$$

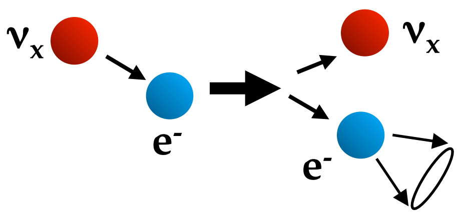
SNO detector

- Located 2 km underground (~70 muons/day) in the Vale Inco Ltd. Creighton Mine near Sudbury, Canada
  - 1 kton D_2O held in 12 m diameter acrylic vessel
  - 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
  - Urylon liner radon seal

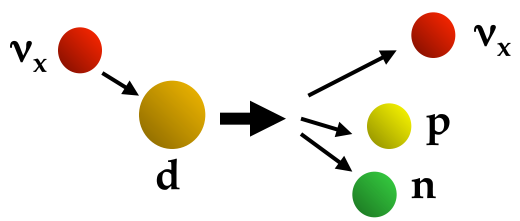


Three reactions

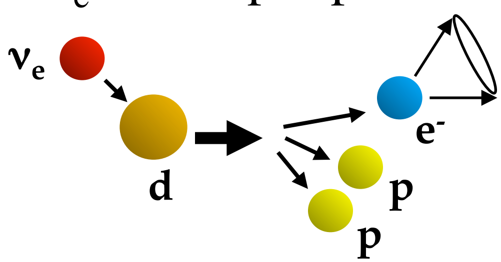
ES: $\nu_x + e^- \rightarrow \nu_x + e^-$



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

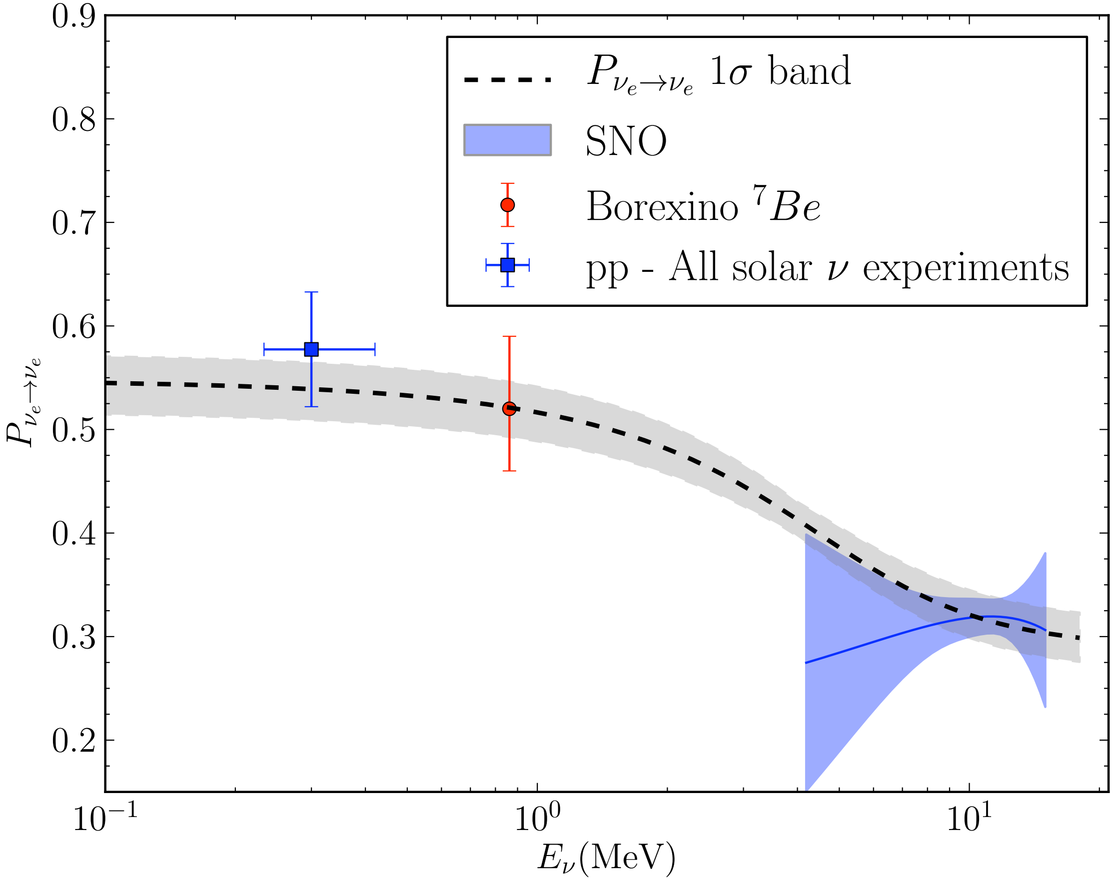


CC: $\nu_e + d \rightarrow p + p + e^-$



SNO Results

8B solar neutrino flux = $(5.25 \pm 0.21) \times 10^6$ cm^{-2}s^{-1}



Geo-neutrinos

Heat flow

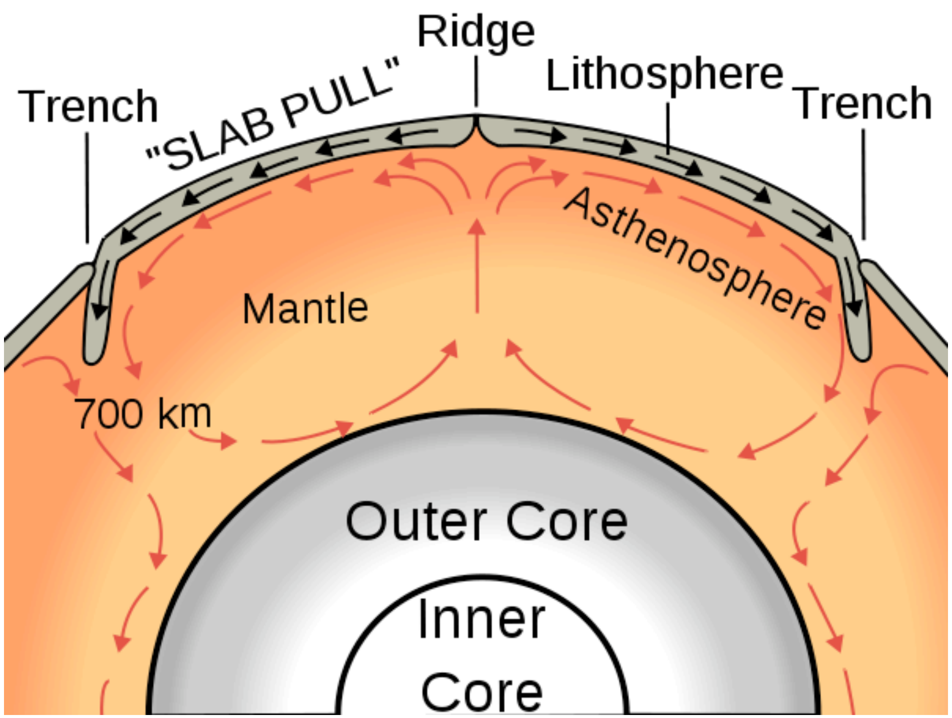
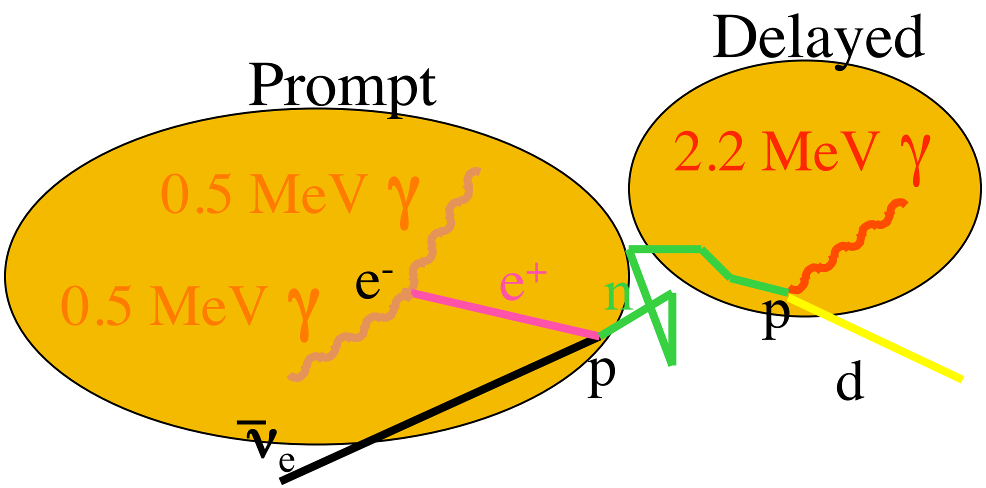


Image: by Surachit,
http://en.wikipedia.org/wiki/File:Oceanic_spreading.svg

Total heat loss	46 ± 3 TW
Total radiogenic heat production	16 ± 3 TW
Crust + lithosphere heat production	4.9 – 8.8 TW
Present Urey ratio	0.11 – 0.34

Neutron inverse-beta-decay

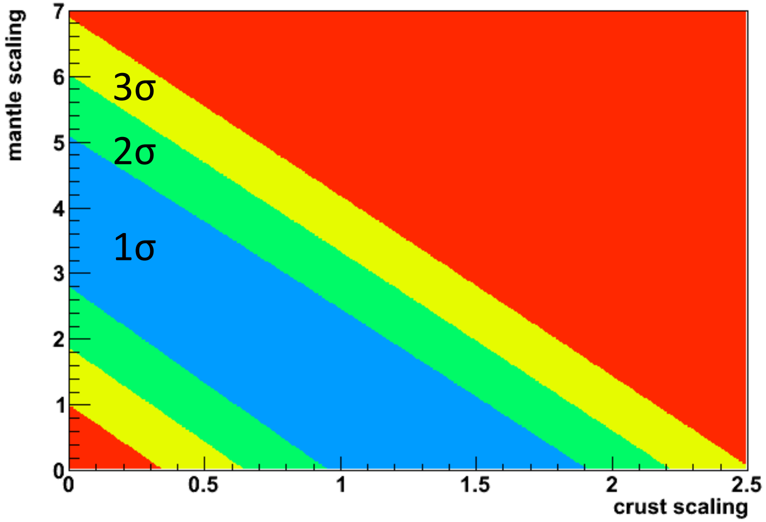
- $\overline{\nu}_e + p \rightarrow e^+ + n$
  The positron energy is related to the neutrino energy.
- The positron loses its energy then annihilates with an electron.
- The neutron first thermalizes then is captured by a proton with a mean capture time of ~200ms.



Flux predictions and measurements

	KamLAND [$\times 10^6$ cm^{-2}s^{-1}]	Borexino [$\times 10^6$ cm^{-2}s^{-1}]
S. Enomoto *et al.* (Total)	4.4	5.2
(Crust)	3.2	4.0
(Mantle)	1.2	1.2
F. Mantovani *et al.* (Total)	4.0	4.6
Measured	* $4.3^{+1.2}_{-1.1}$	# $7.1^{+2.9}_{-2.4}$

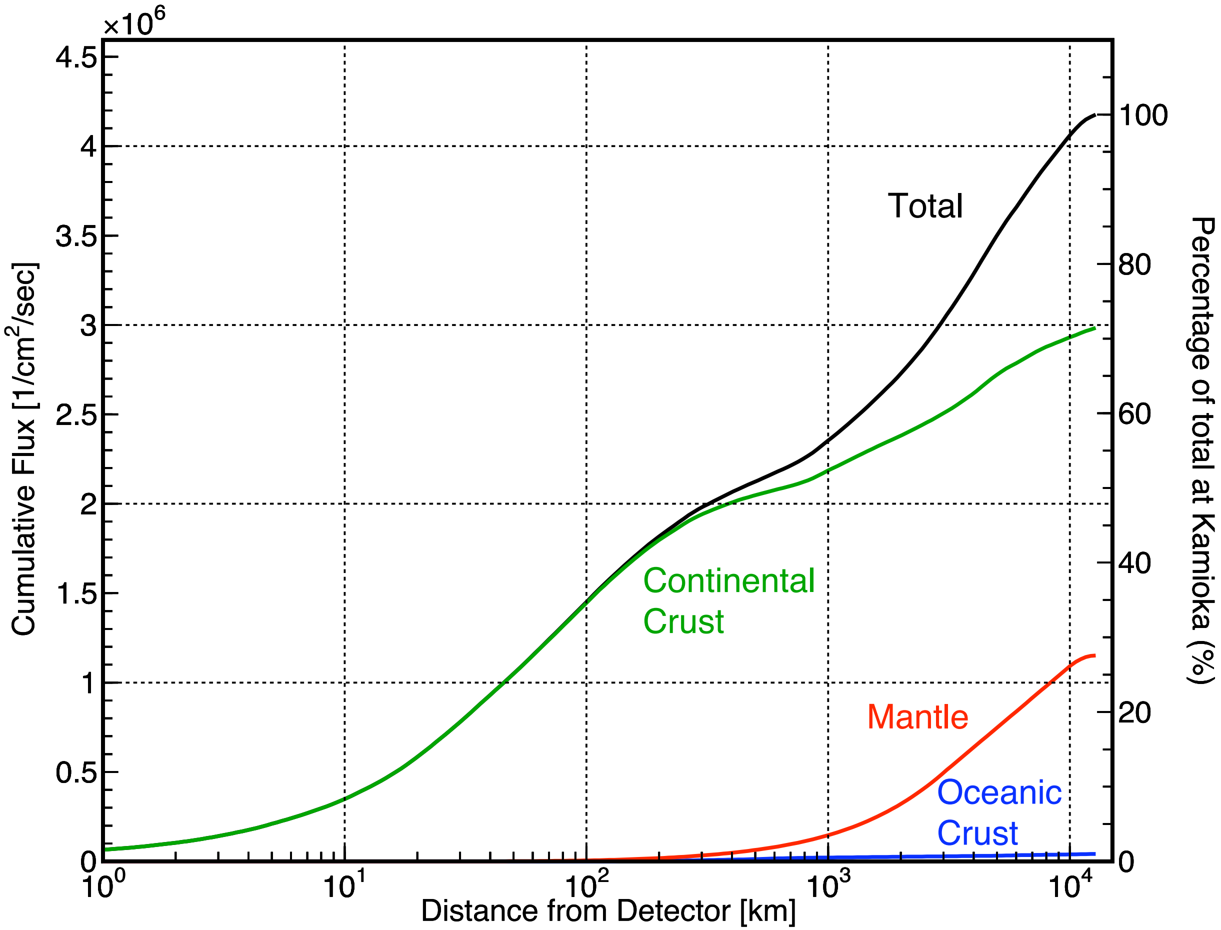
Does not include errors in the model other than scaling the mantle and crust



*Presentation by K. Inoue at Neutrino 2010

#Numbers derived from Phys. Lett. B **687** 299, 2009

Where do the neutrinos come from?



S/N crust and mantle

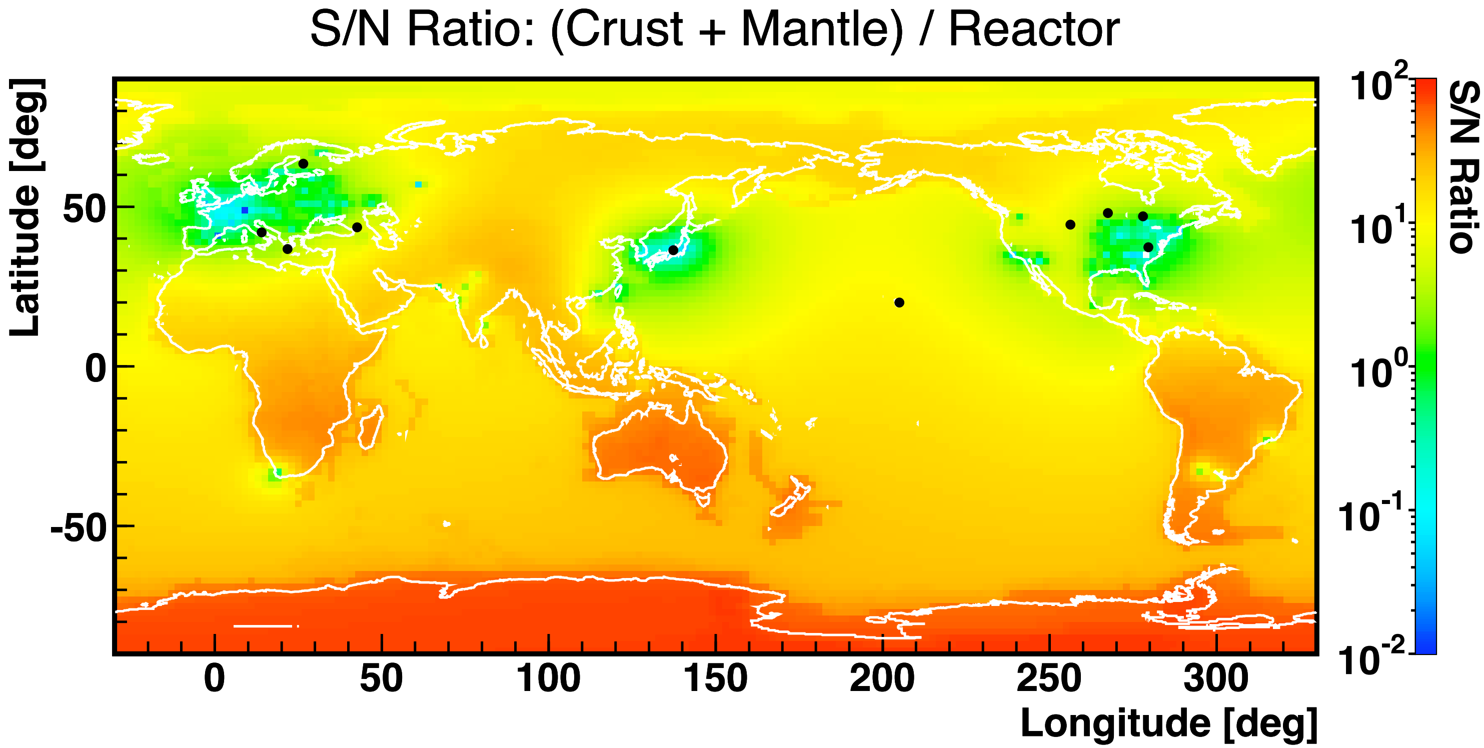


Image: S. Enomoto

S/N mantle

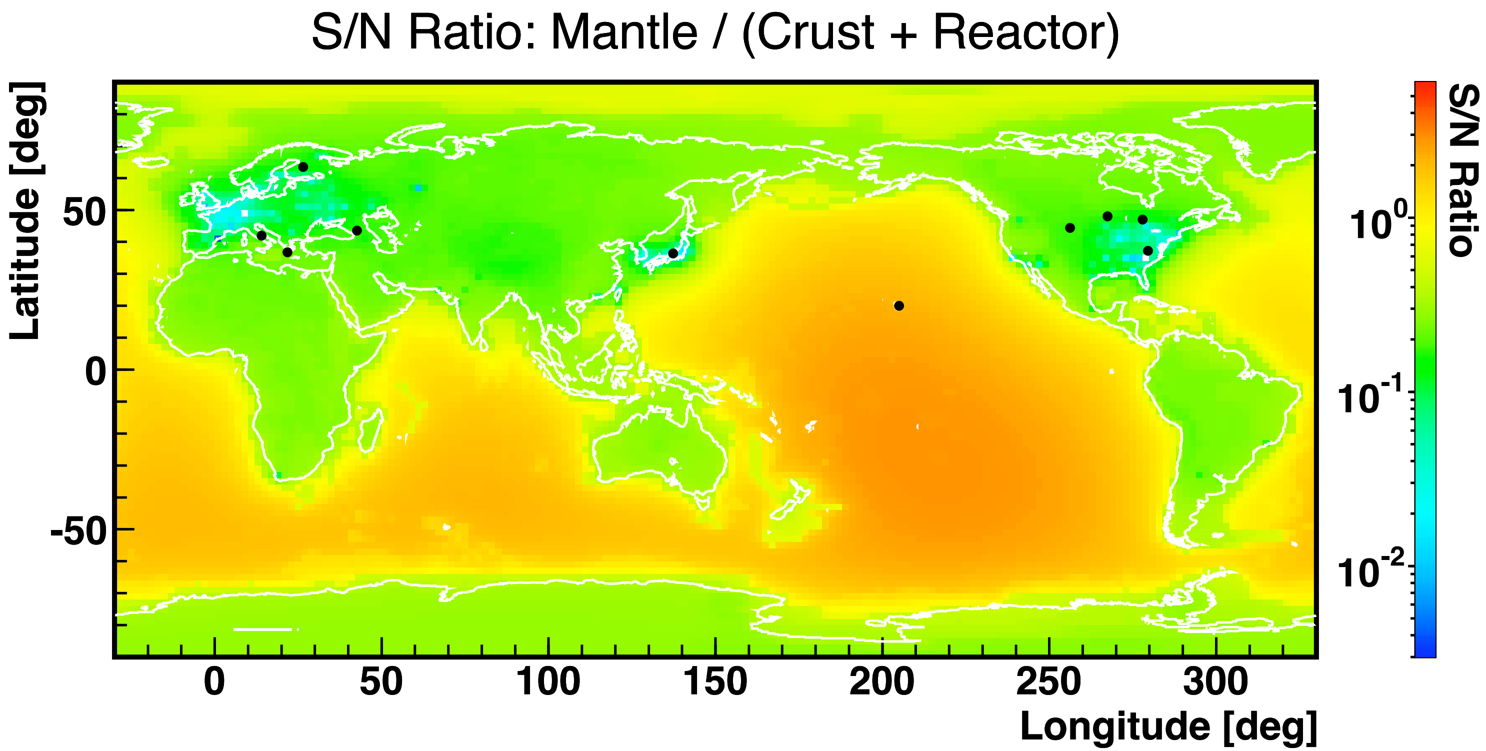
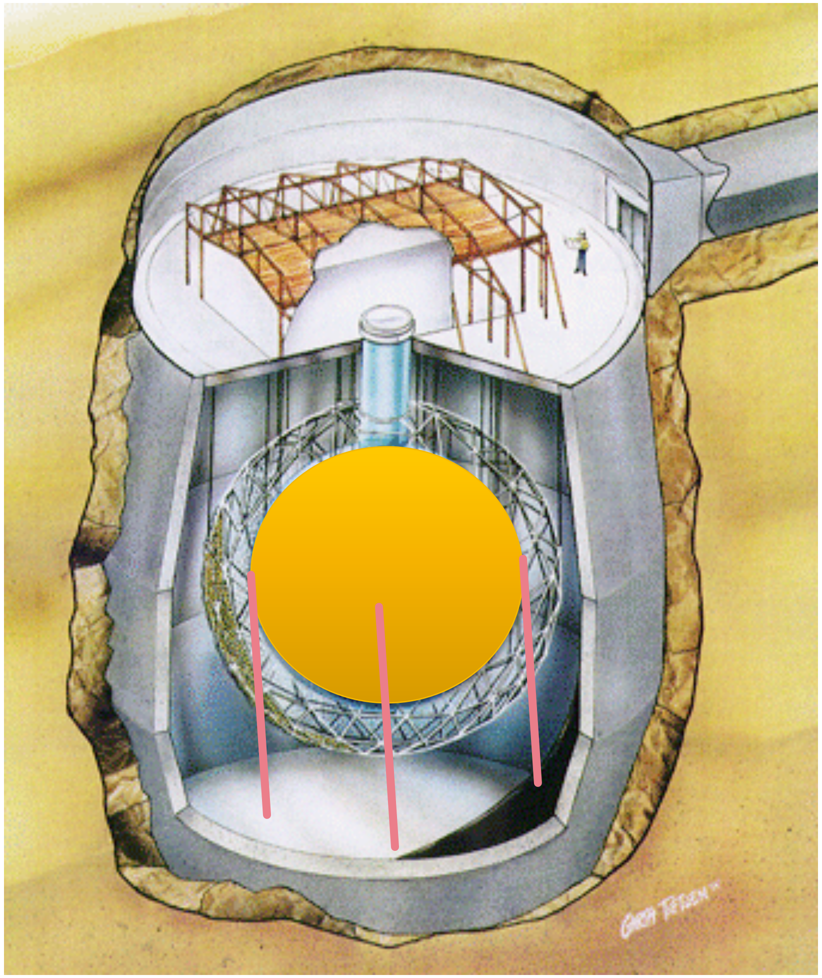


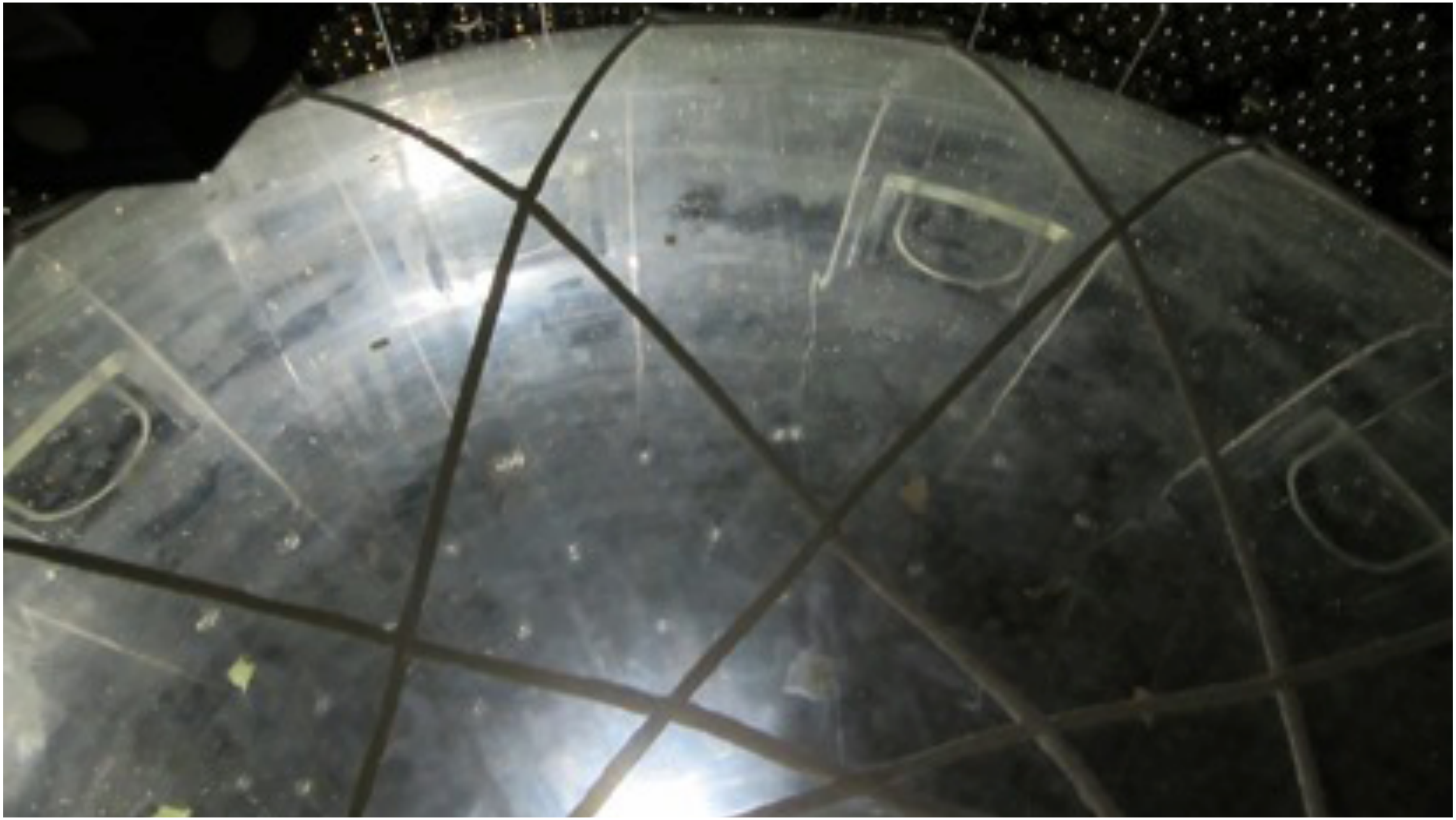
Image: S. Enomoto

SNO+

SNO→SNO+

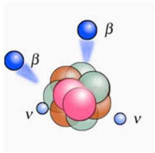
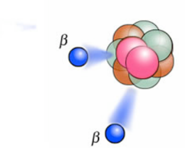
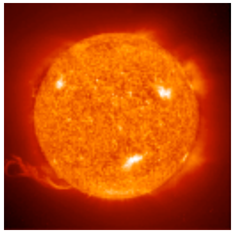
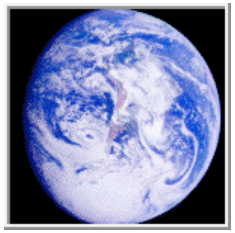


Hold down net



Science goals

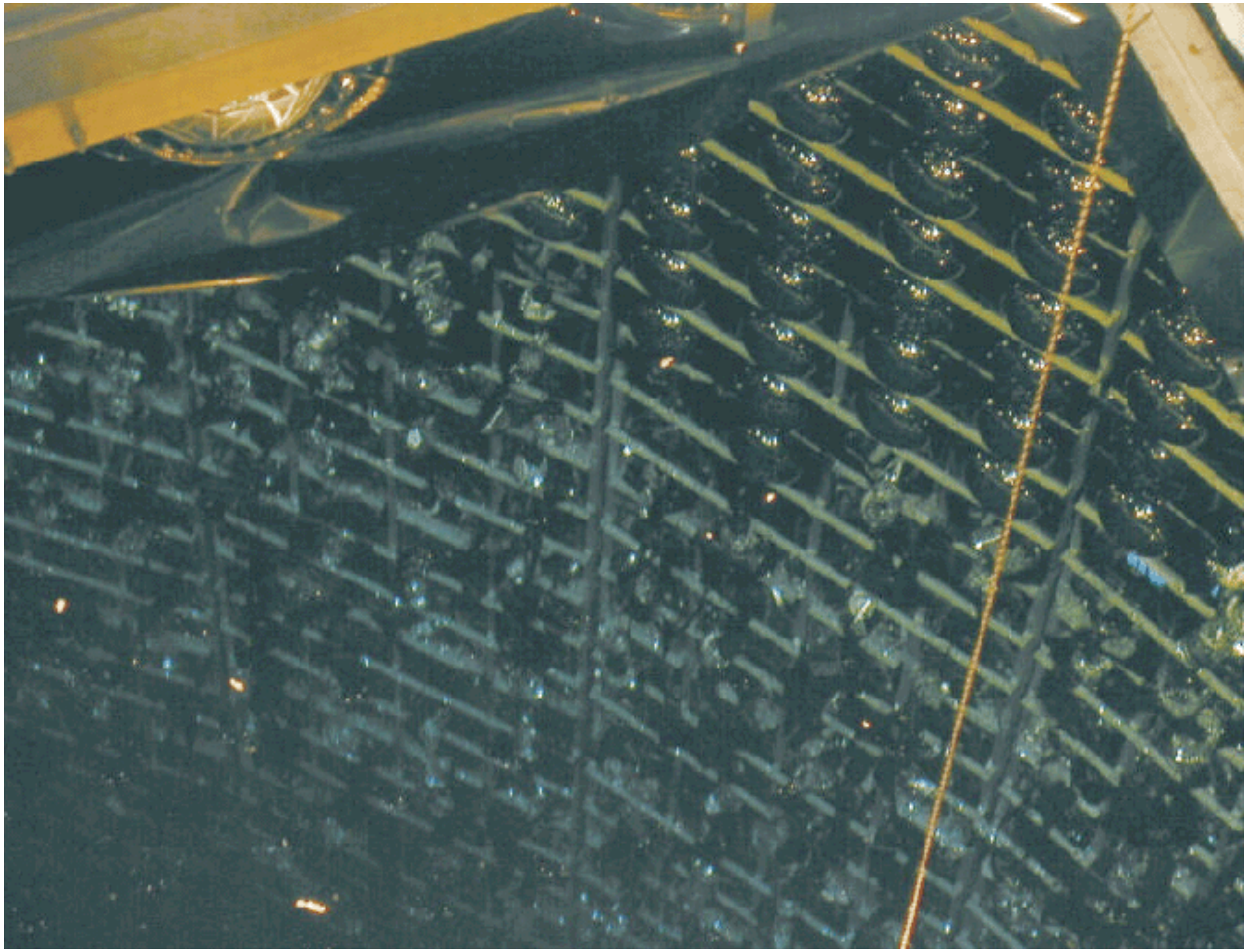
- Search for neutrinoless double-beta-decay.
- Neutrino physics:
  - Solar neutrinos
  - Geo antineutrinos
  - Reactor antineutrinos
  - Supernova neutrinos


Pretending to be miners

Very clean miners

Boating in Super-K, not likely again



Questions?