Neutrino experiments

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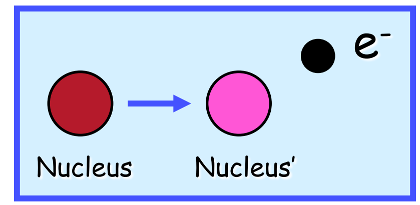
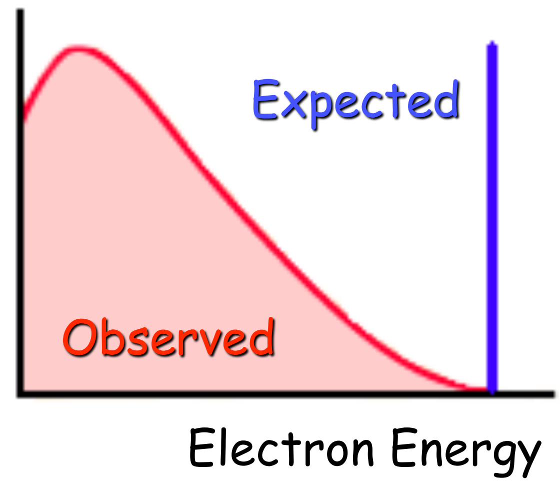
Outline

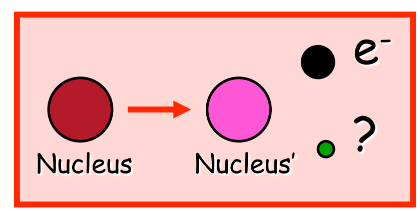
- Introduction
- Neutrino sources
  - Geoneutrinos
  - Solar neutrinos
- Neutrino properties
  - Neutrino mass
  - Neutrinoless double-beta-decay

Pauli’s theory

- In 1930 the theory of β-decay had a nucleus decay into a daughter nucleus and an electron
- Based on conservation of energy and momentum this should have resulted in a mono-energetic electron
- However, the observed electron energy had a continuous energy spectrum
- In 1930 Pauli proposed that a third particle (the neutrino) produced in β-decay could take away some of the energy







Neutrino oscillations

- There are three neutrino "flavors" associated with the charged leptons (e, μ, τ)
- The weak interaction neutrino eigenstates can be expressed as superpositions of definite mass eigenstates

$$\left|\nu_a\right\rangle = \sum_{i=1}^{3} U_{ai} \left|\nu_i\right\rangle$$

- For two neutrino flavors the neutrino survival probability is given by

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

Geoneutrinos

Heat flow from the Earth

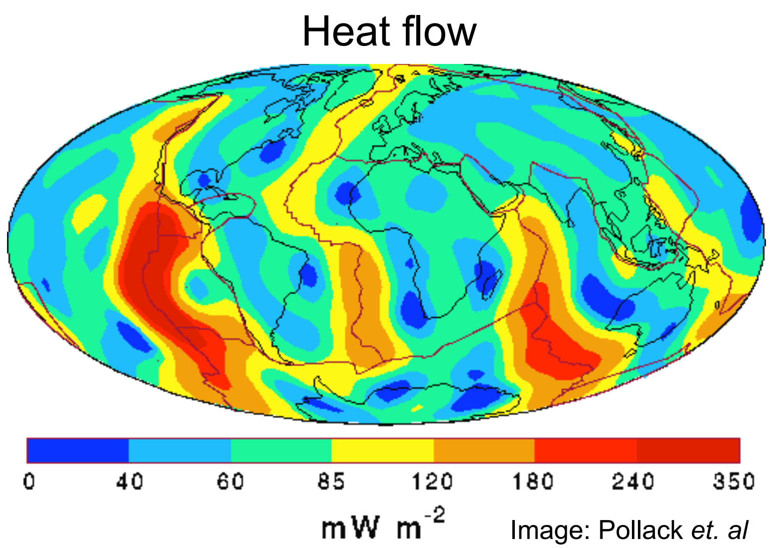
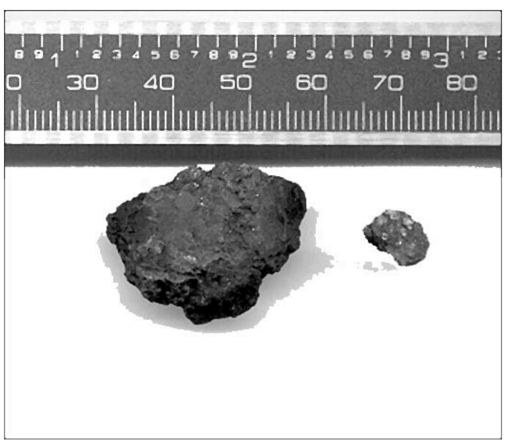


Image: Pollack *et. al*

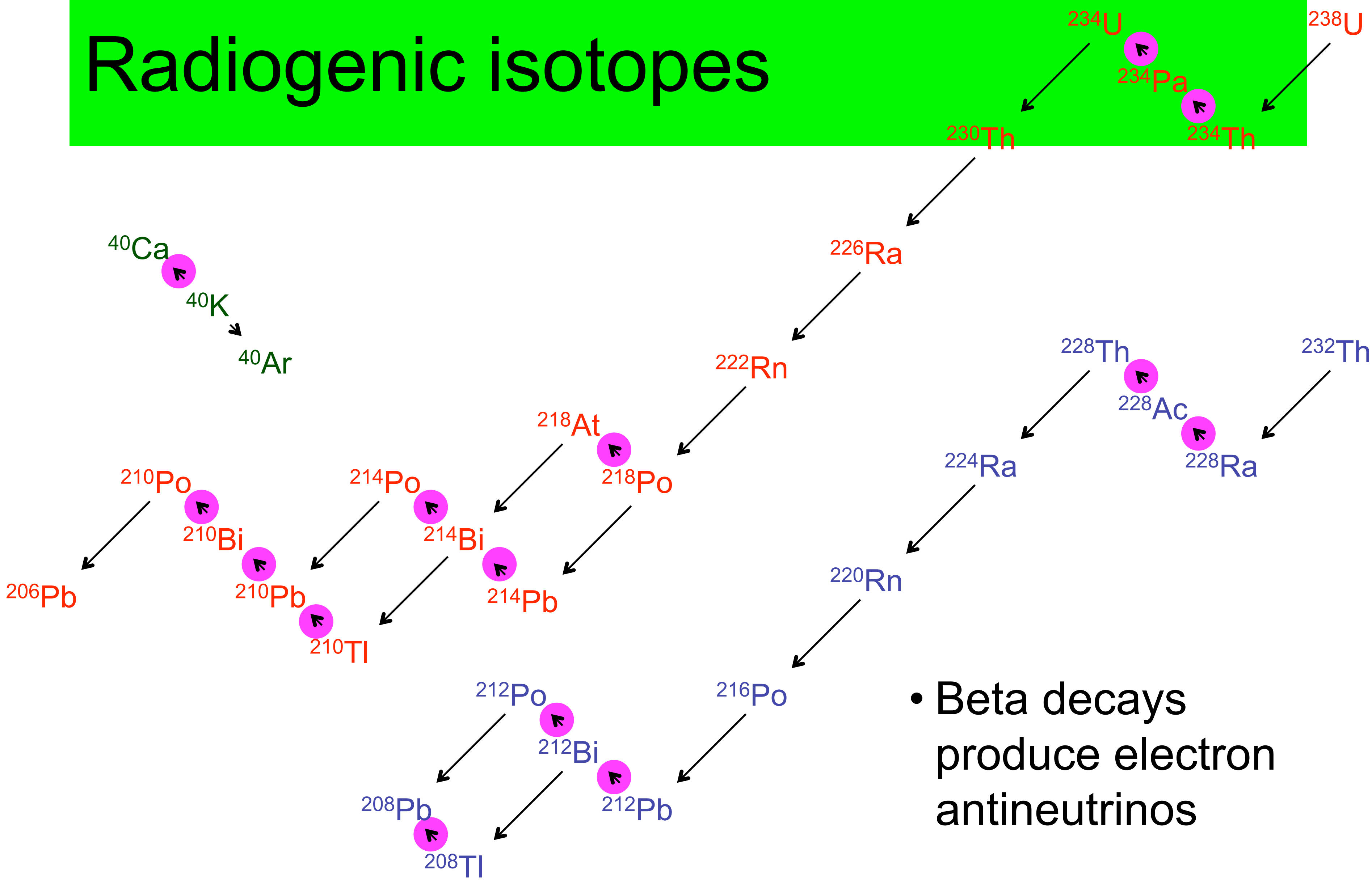


- Conductive heat flow measured from bore-hole temperature gradient and conductivity
- Total heat flow 44.2±1.0TW, or 31±1TW according to more recent evaluation of same data despite the small quoted errors.
- U, Th, and K concentrations in Bulk Silicate Earth (BSE) are estimated to 20ppb, 80ppb, and 240ppm, respectively, based on measurement of chondritic meteorites.
- This results in U, Th, and K heat production of 8TW, 8TW, and 3TW, respectively.

Discrepancy?

- The measured total heat flow is 44 or 31 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.

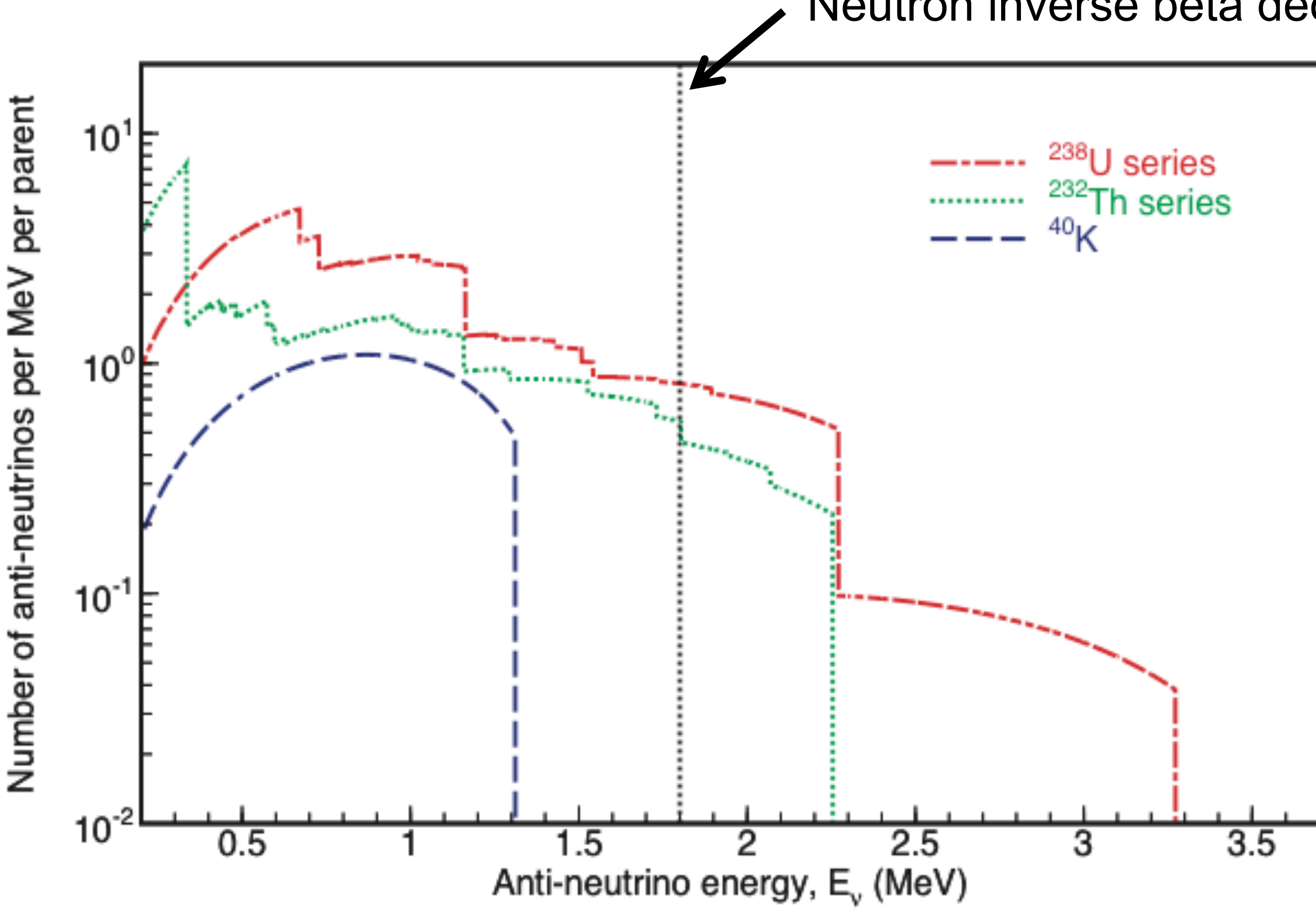
Radiogenic isotopes



- Beta decays produce electron antineutrinos

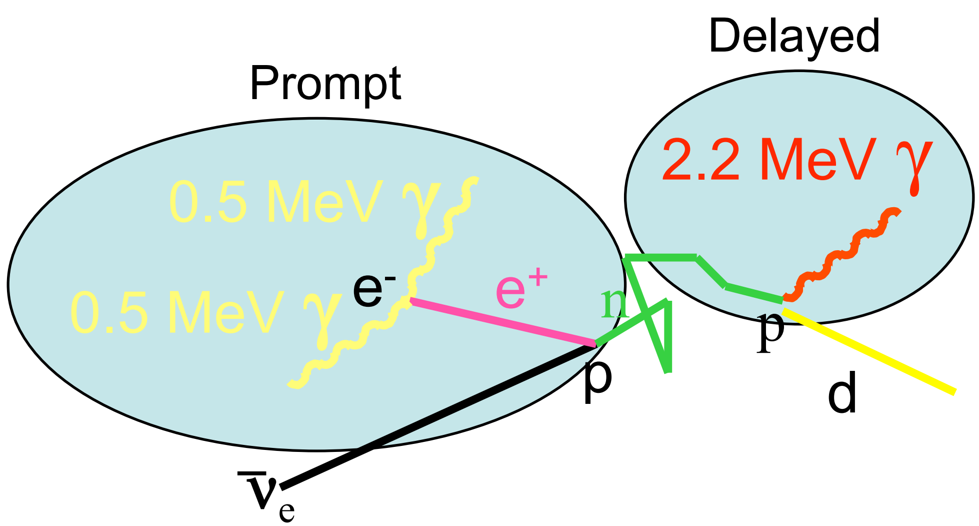
Geoneutrino signal

Neutron inverse beta decay threshold



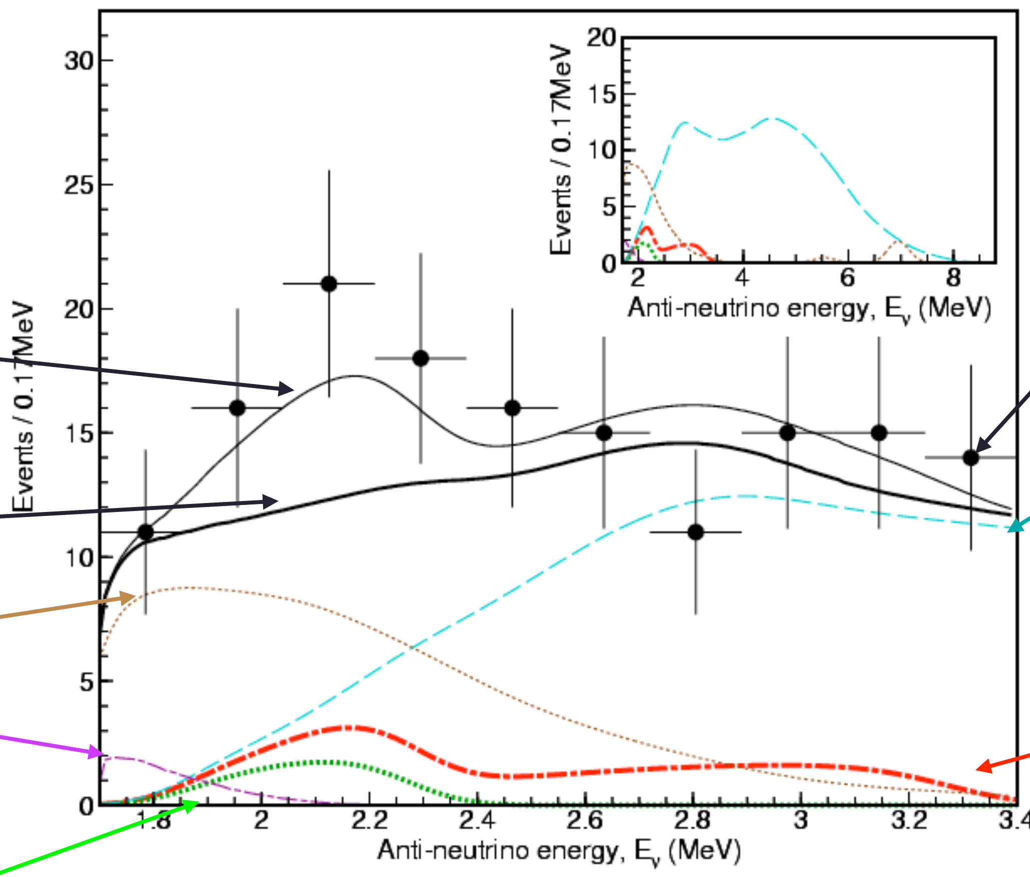
Detecting electron anti-neutrinos

- Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$
- The positron loses its energy then annihilates with an electron
- The neutron first thermalizes then is captured by a proton (or other nucleus)



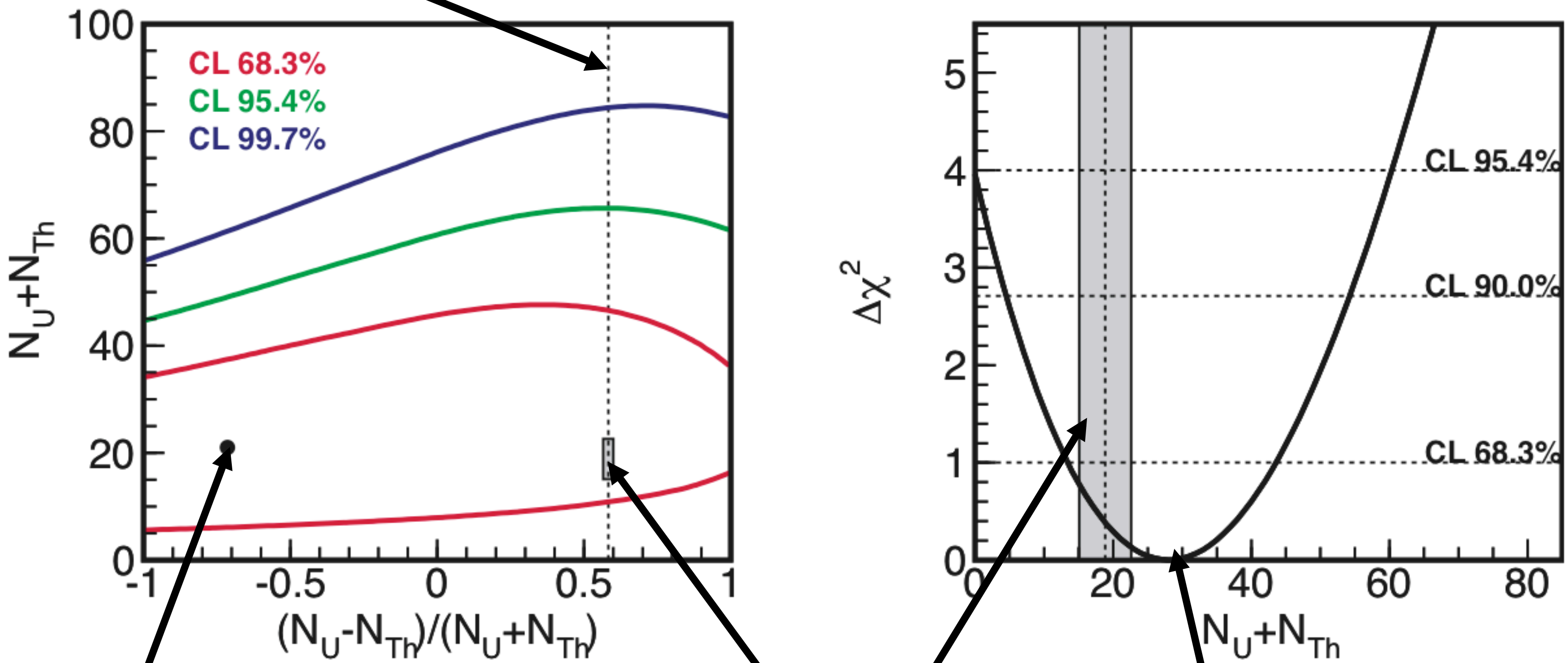
Results from KamLAND

Nature **436**, 499-503 (28 July 2005)



How many geoneutrinos?

Expected ratio from
chondritic meteorites

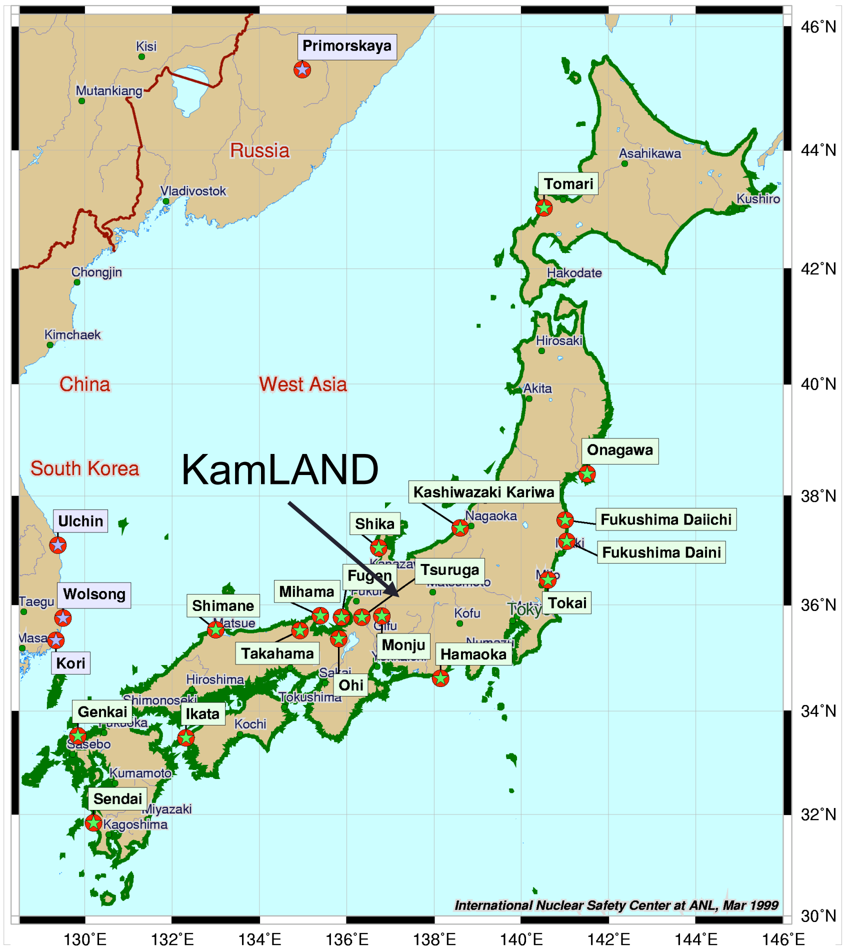


Best fit
3 U geoneutrinos
18 Th geoneutrinos

Expected result
from reference
Earth model

Central value 28

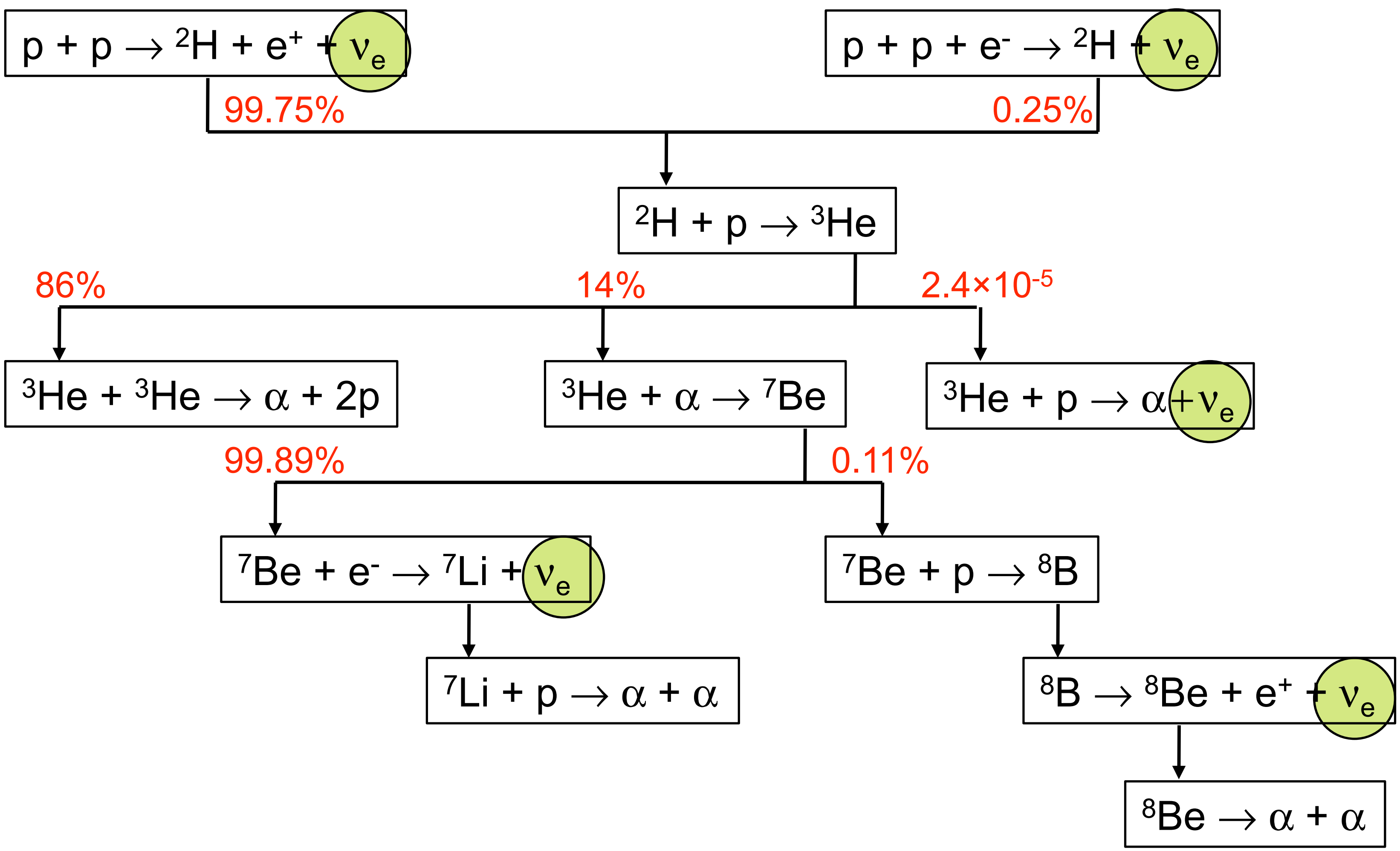
KamLAND and geoneutrinos



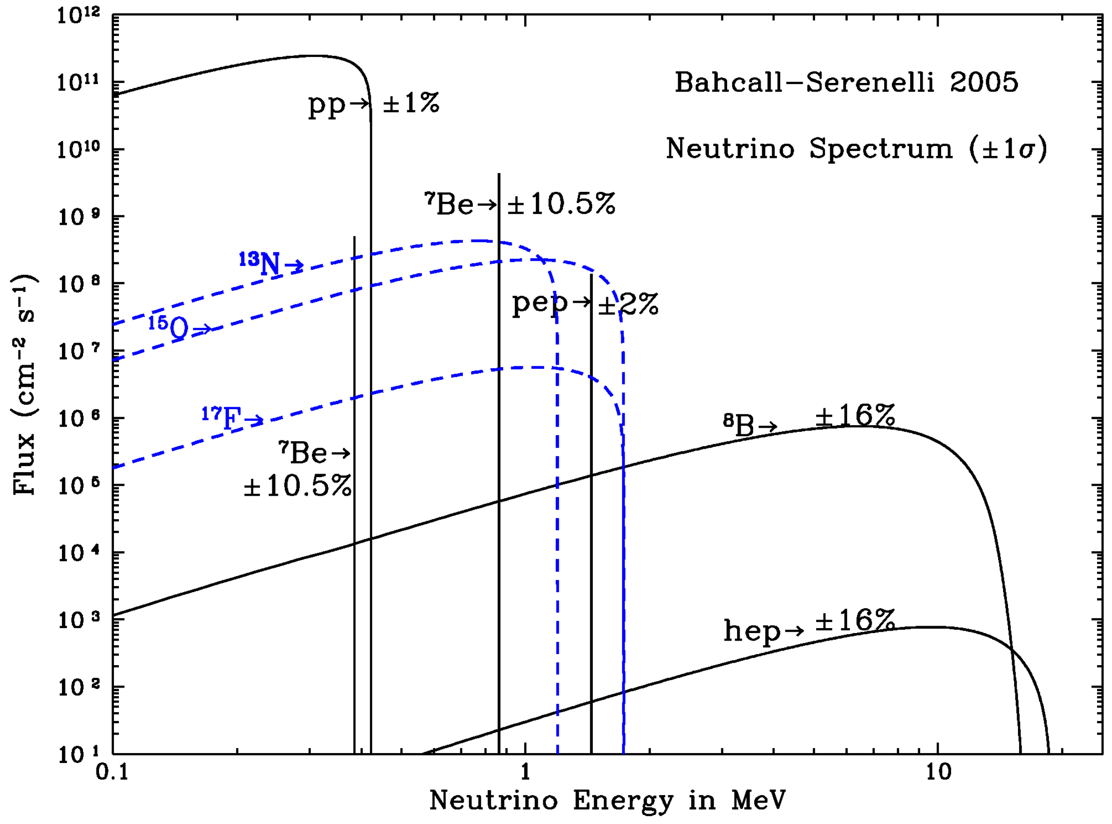
- KamLAND was designed to measure reactor antineutrinos, these are the most significant background and are irreducible.
- Reactor antineutrino signals are identical to geoneutrinos except for the prompt energy spectrum.
- Working on purifying the liquid scintillator, which will reduce the (α,n) background events.
- Preliminary results with 4 times the statstics gives a 35% measurement.

Solar neutrinos

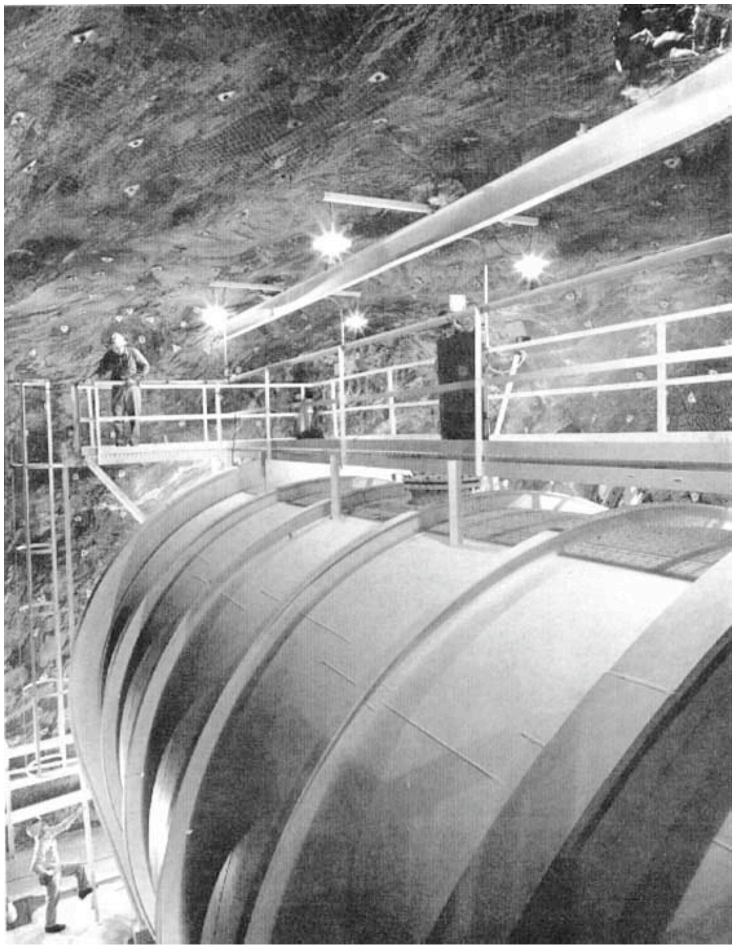
Solar pp chain reactions



Neutrino energy spectrum



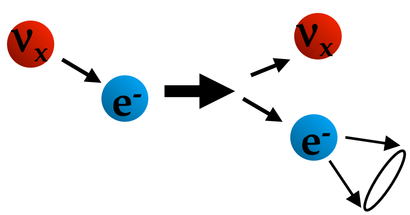
Ray Davis



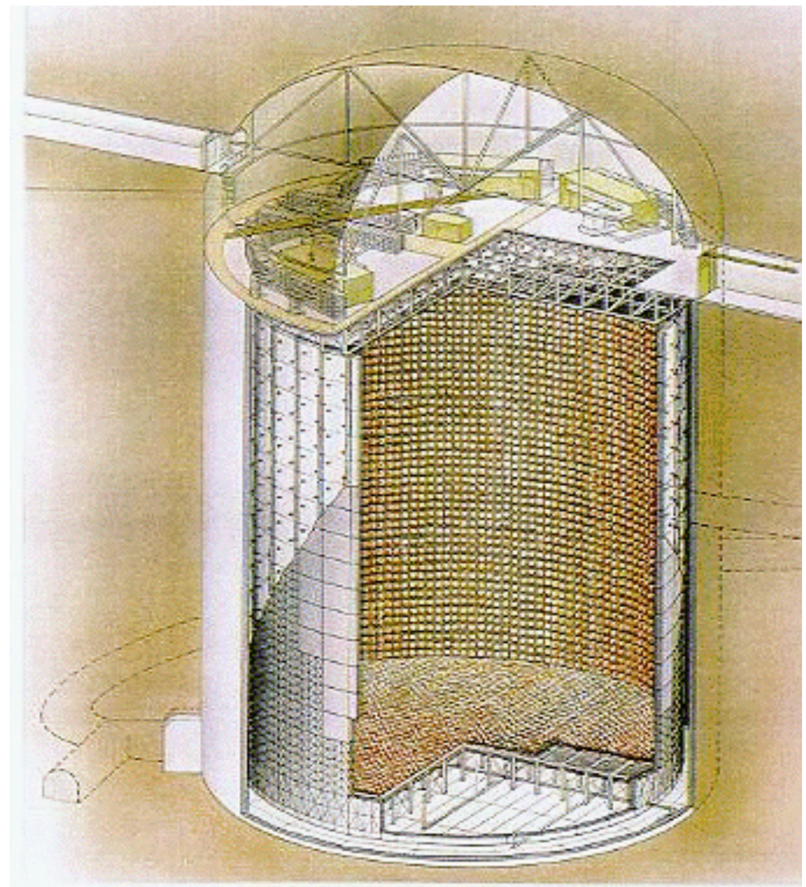
- $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$
- ^{37}Ar is a gas which is removed from detector with He carrier gas
- Outside the active volume the ^{37}Ar is detected via $^{37}Al + e^- \rightarrow {}^{37}Cl + \nu_e$ which has a half-life of 35 days

SuperK detector

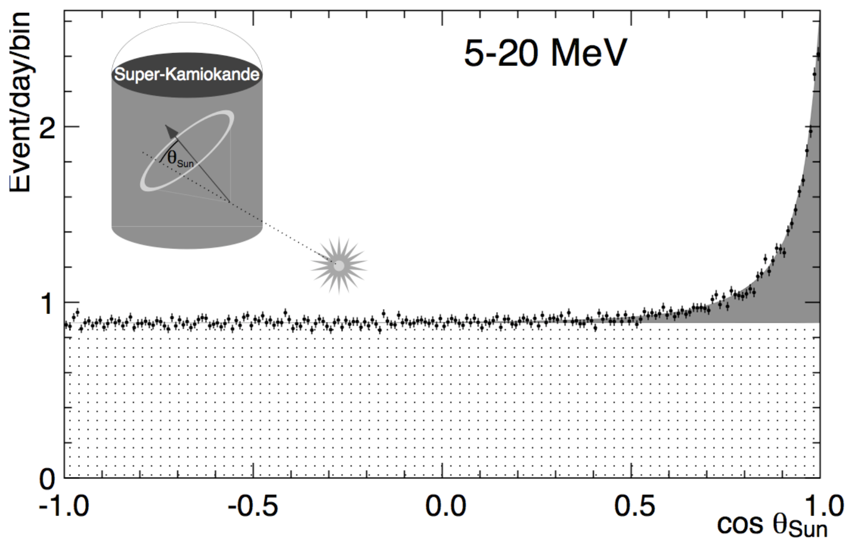
- 50,000 ton ring-imaging water Cherenkov detector
- SuperK detects solar neutrinos from electron elastic scattering

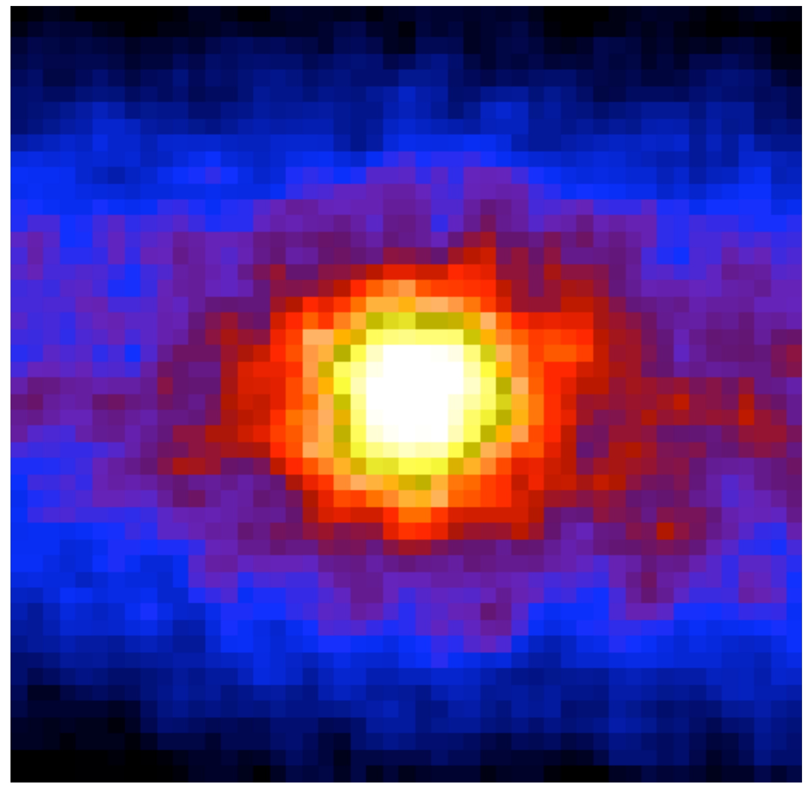


  - $\sigma(\nu_e) \approx 6\ \sigma(\nu_\mu) \approx 6\ \sigma(\nu_\tau)$
  - Strong directionality
- The scattered electron produces a Cherenkov ring



SuperK solar neutrino results





SNO

1000 tonnes D_2O

12 m diameter acrylic vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

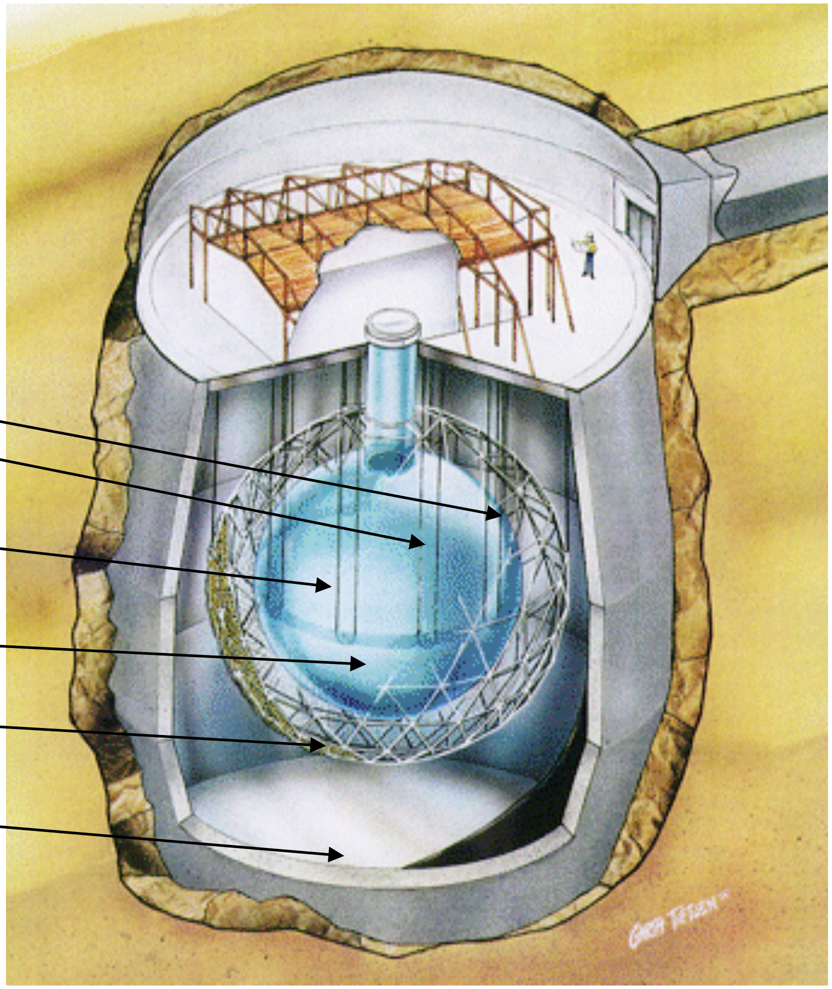
1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

Urylon liner radon seal

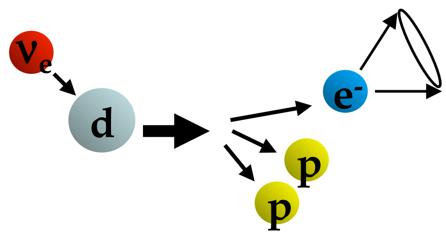
depth: 2092 m (~6010 m.w.e.)

~70 muons/day

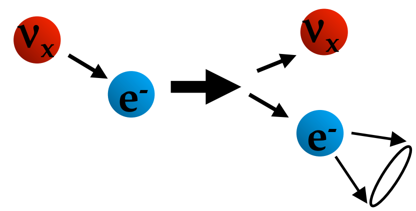


SNO neutrino detection

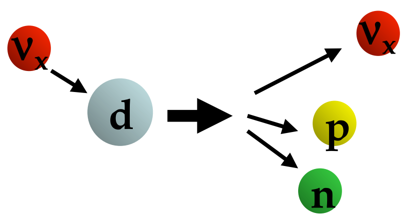
CC $\nu_e + d \rightarrow p + p + e^-$



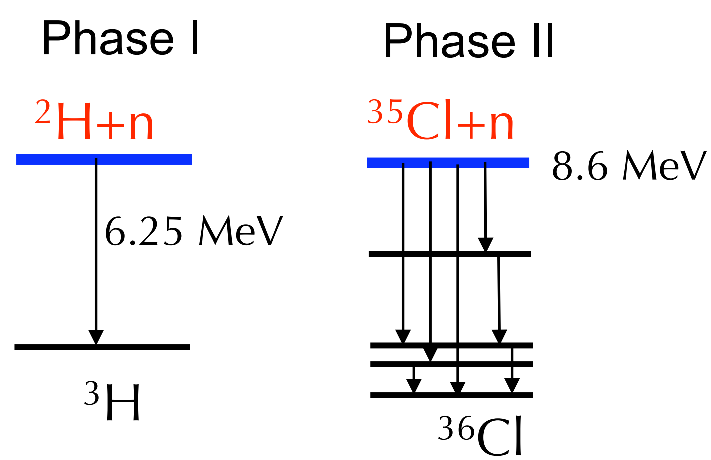
ES $\nu_x + e^- \rightarrow \nu_x + e^-$



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

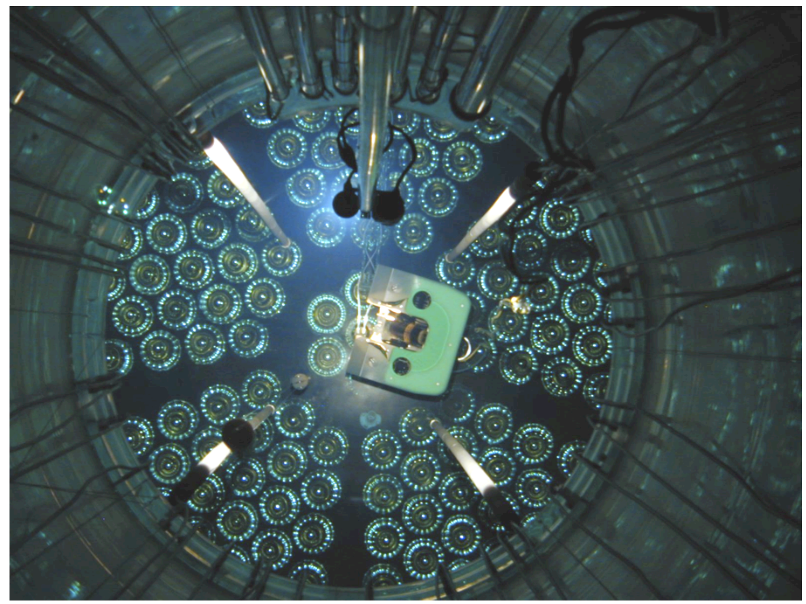


There were three phases of SNO. Each detected the neutrons produced in NC reactions a different way

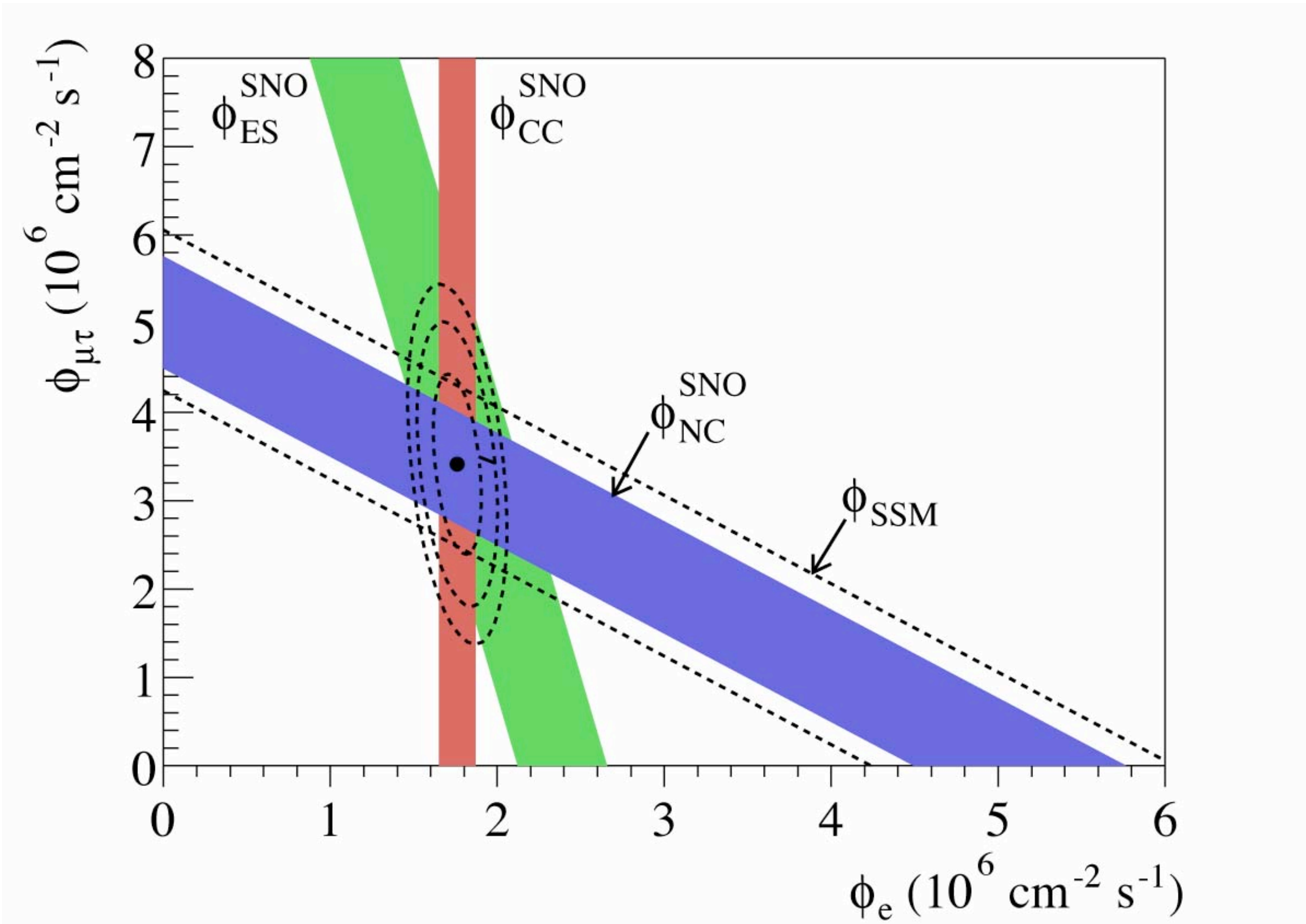


SNO phase III

- Added array of 40 ^{3}He proportional counters neutral-current detectors (NCDs).
- NC signal observed in NCD array via $n + {}^3He \rightarrow {}^3H + p$

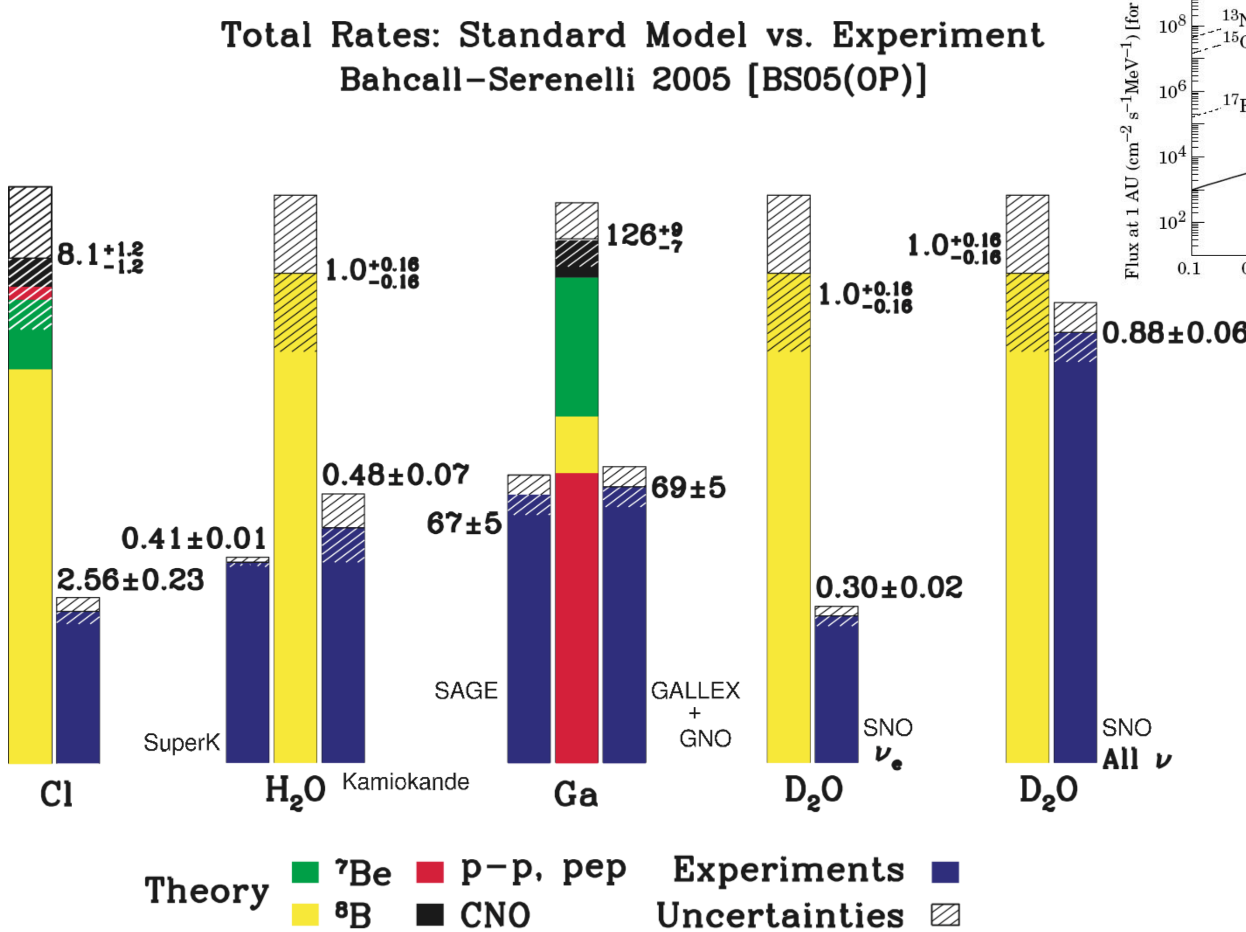


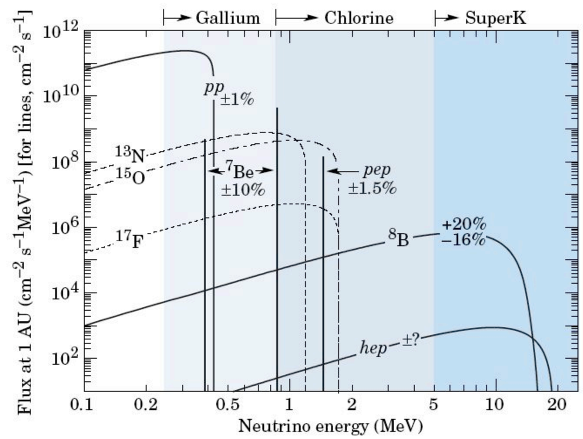
SNO results



$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})
ϕ_e (10^6 cm^{-2} s^{-1})
ϕ_{ES}^{SNO}
ϕ_{CC}^{SNO}
ϕ_{NC}^{SNO}
ϕ_{SSM}
0
1
2
3
4
5
6
7
8

Solar neutrino measurements



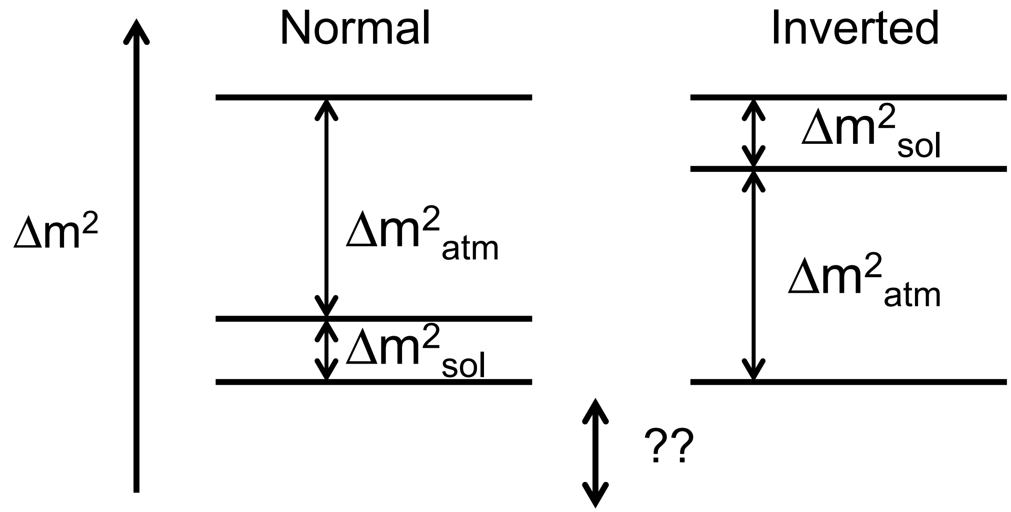


Neutrino mass

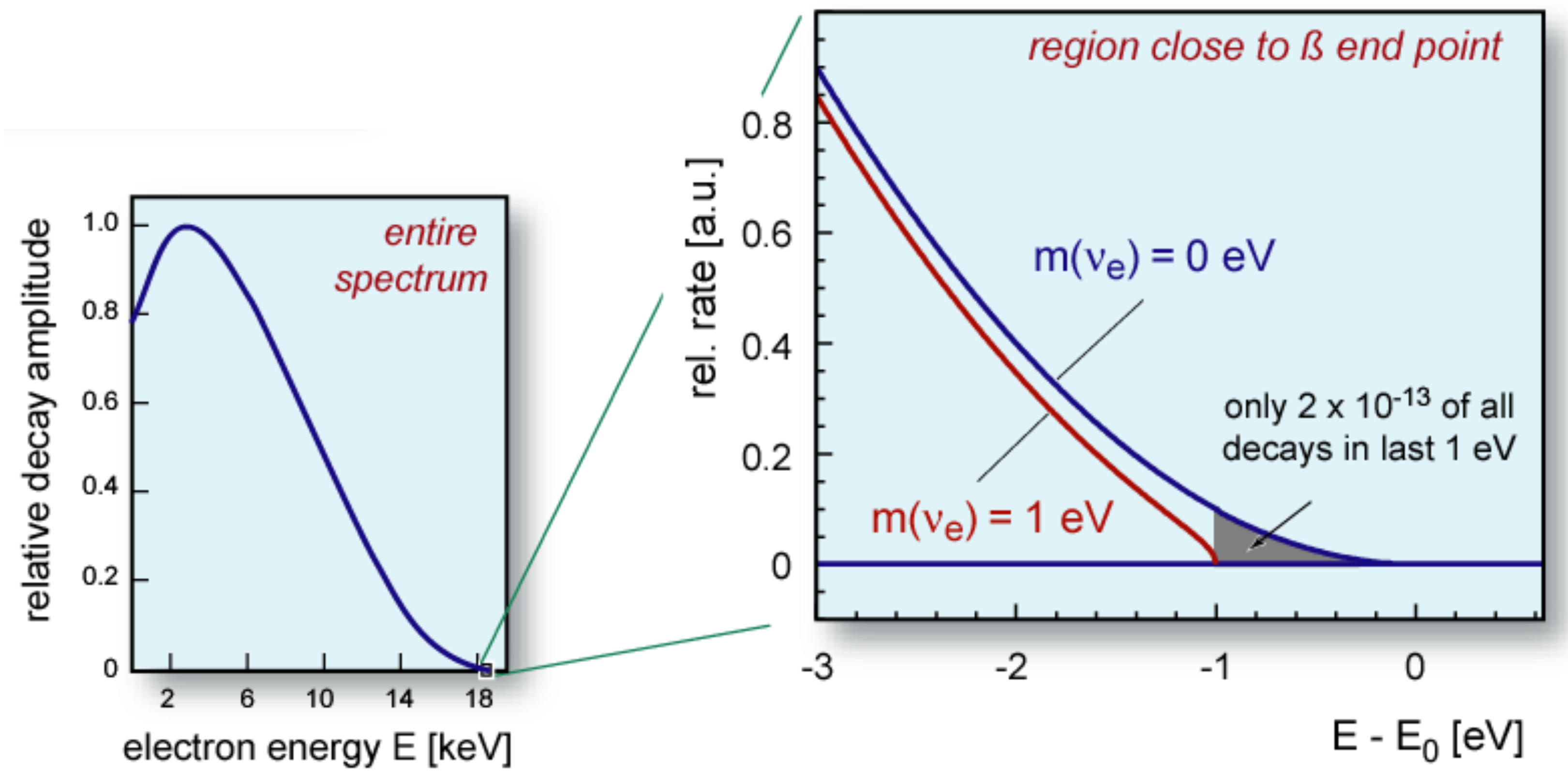
Neutrino oscillations

- Neutrino oscillation experiments
  - give us the difference in the masses squared (Δm^2_{atm}, Δm^2_{sol})
  - do not give us the absolute mass

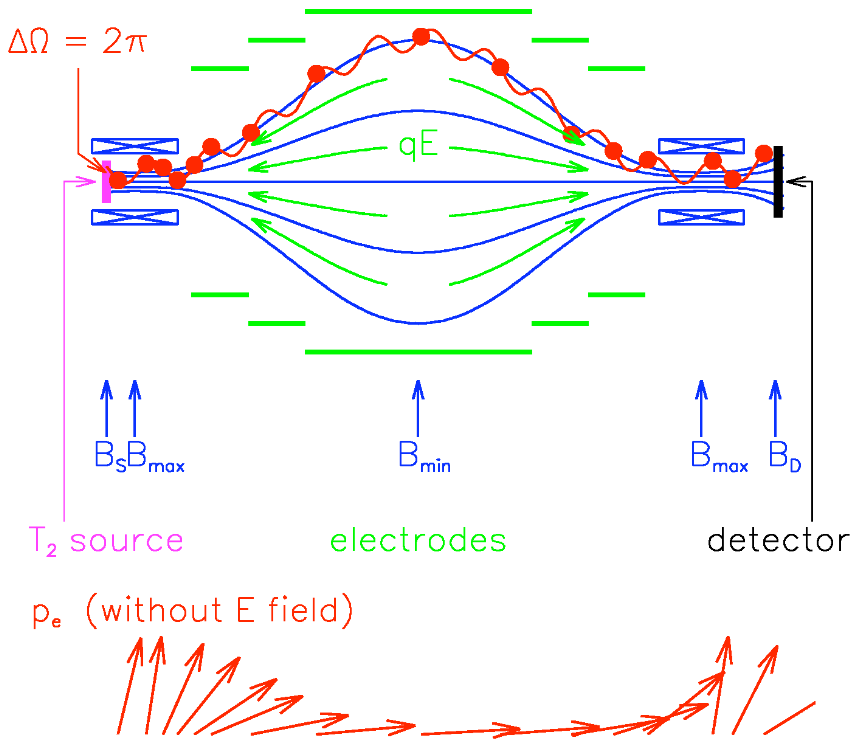
$$P_{\nu_e \to \nu_e}\left(E_{\nu_e}, L\right) \approx 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4 E_{\nu_e}}\right)$$

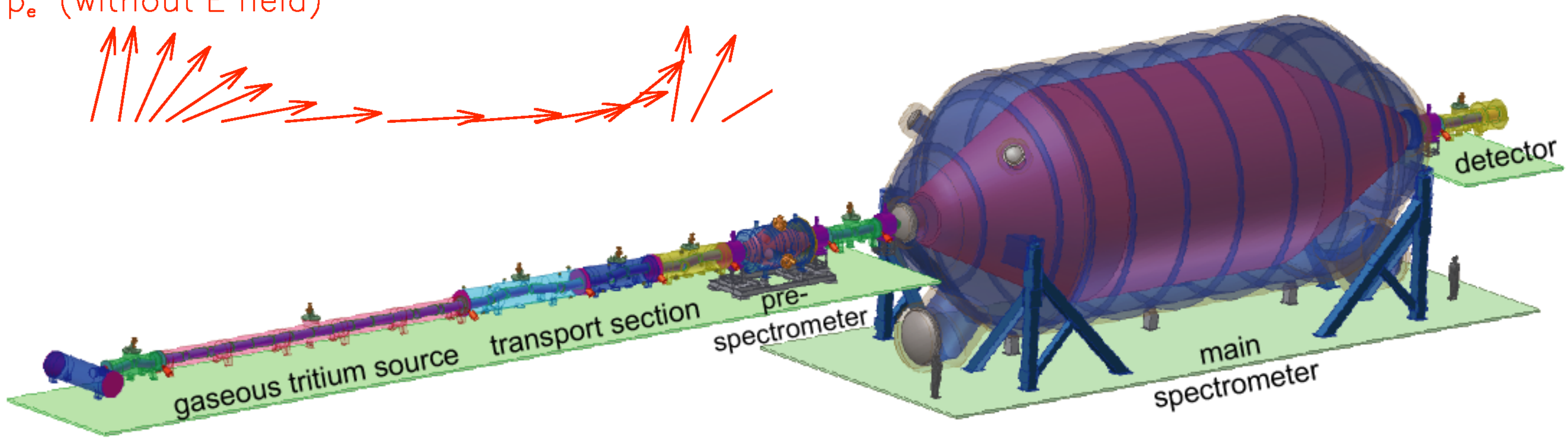


β-decay energy spectrum



Measuring electron energy



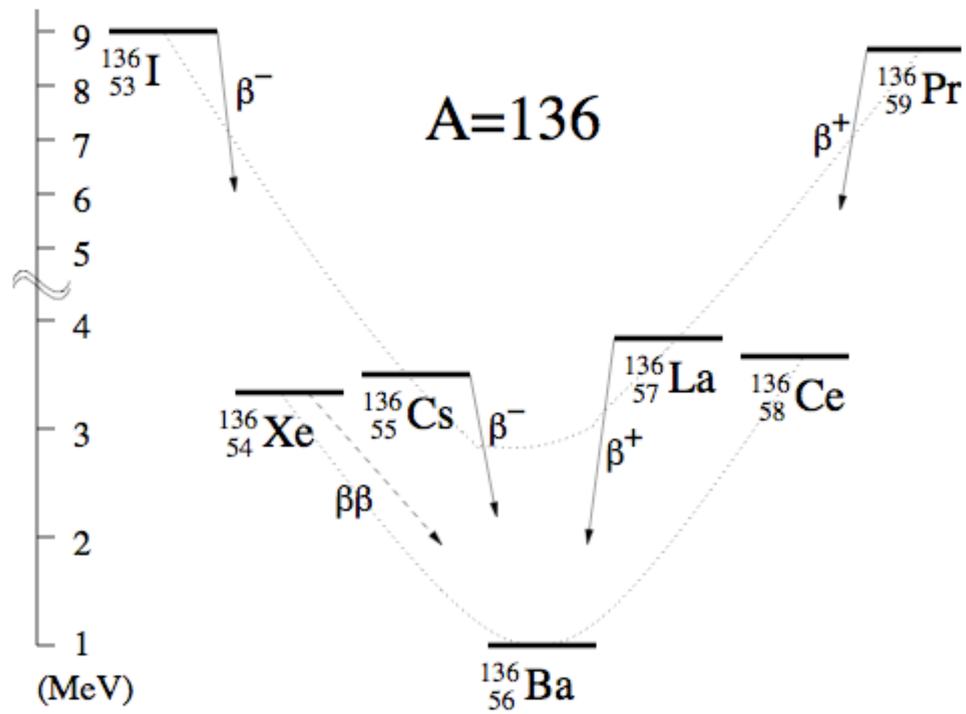


KATRIN

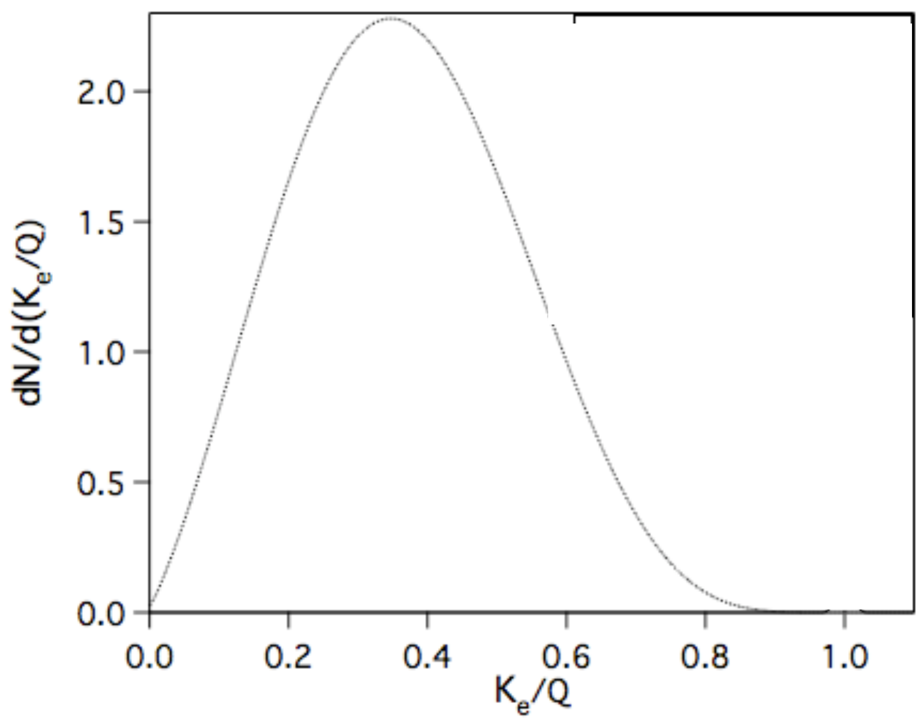
Tour of Europe

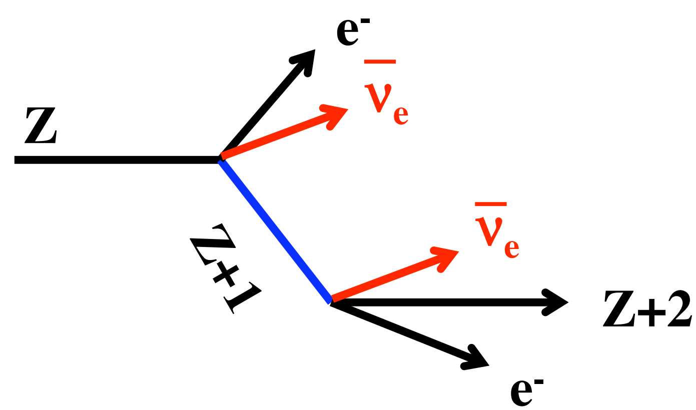
Neutrinoless double-beta-decay

Occurs when β-decay is not possible



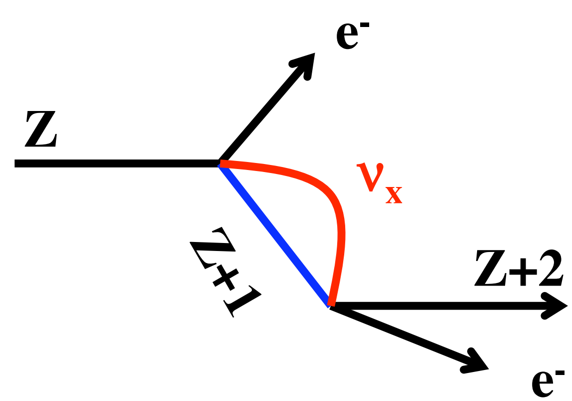
Double beta decay





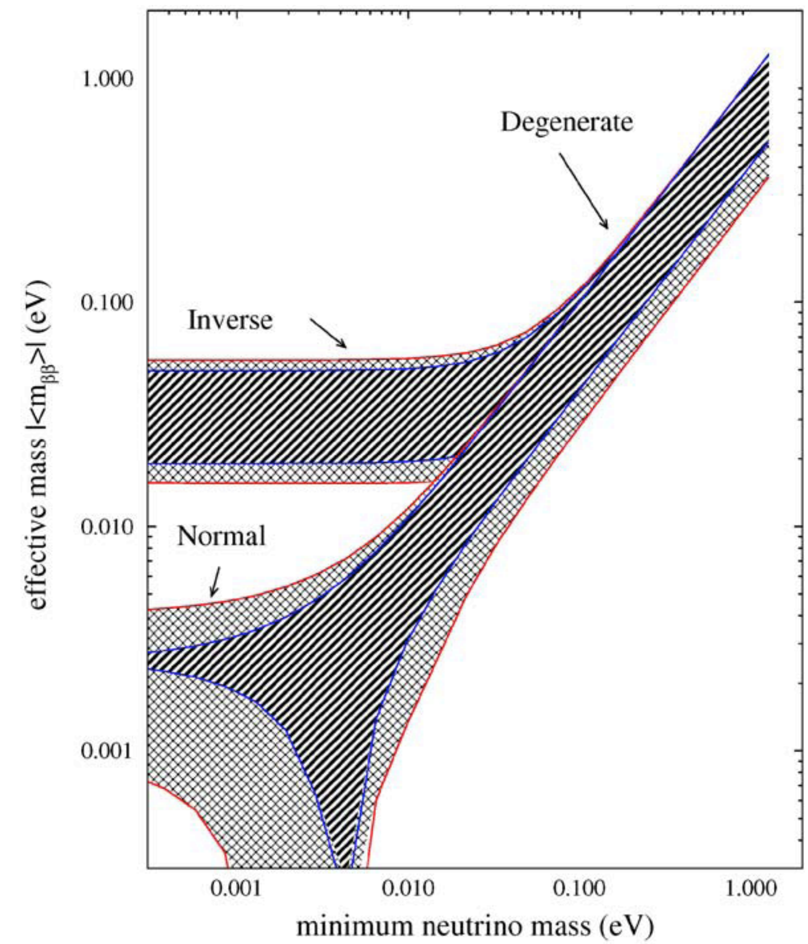
Neutrinoless double beta decay

- Requires massive majorana neutrino $\Delta L=2$



$$\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_\nu^2$$

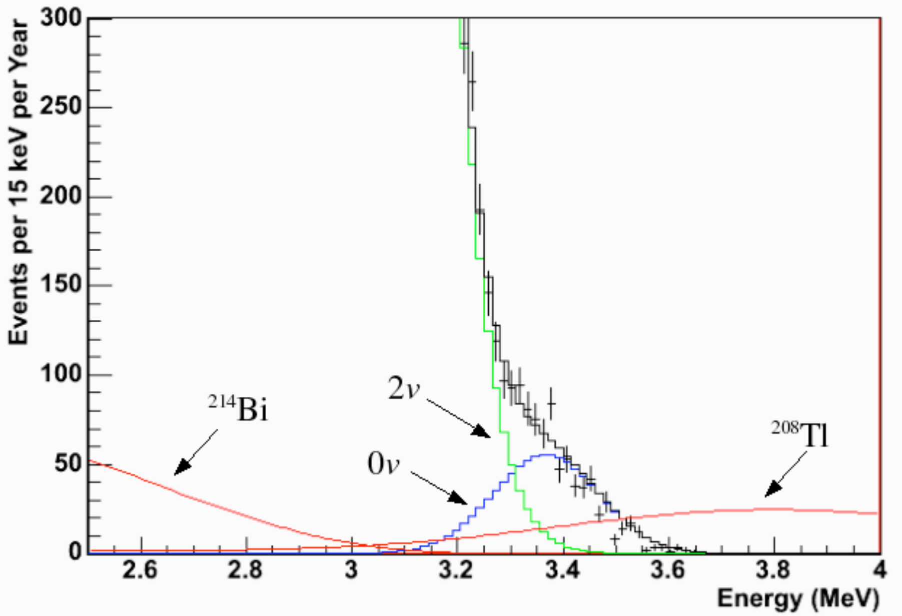
Allowed neutrino mass



SNO+

Test $<m_\nu> = 150$ meV

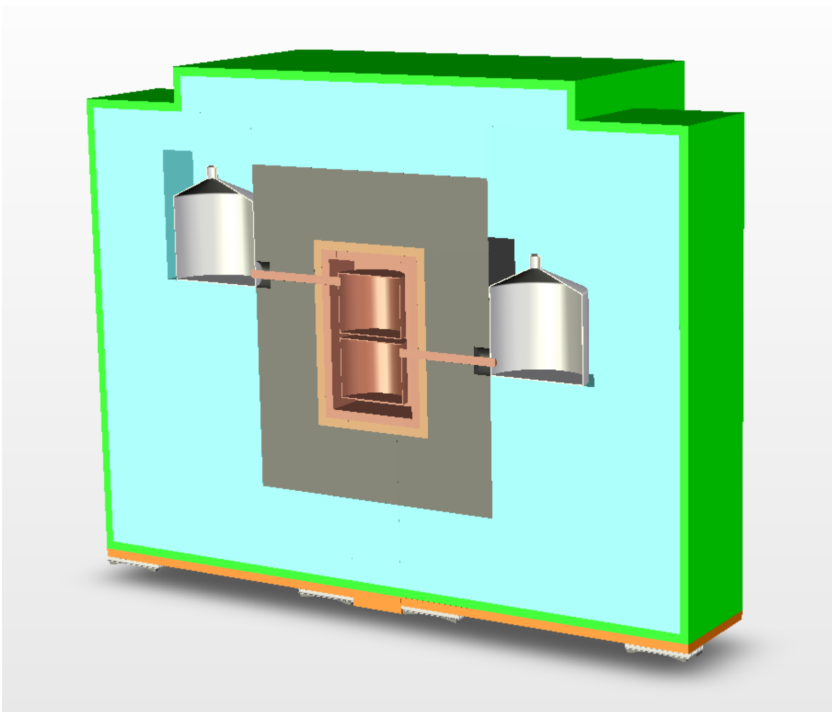
Klapdor-Kleingrothaus et al.,
Phys. Lett. B **586,** 198, (2004)



simulation: one year of data

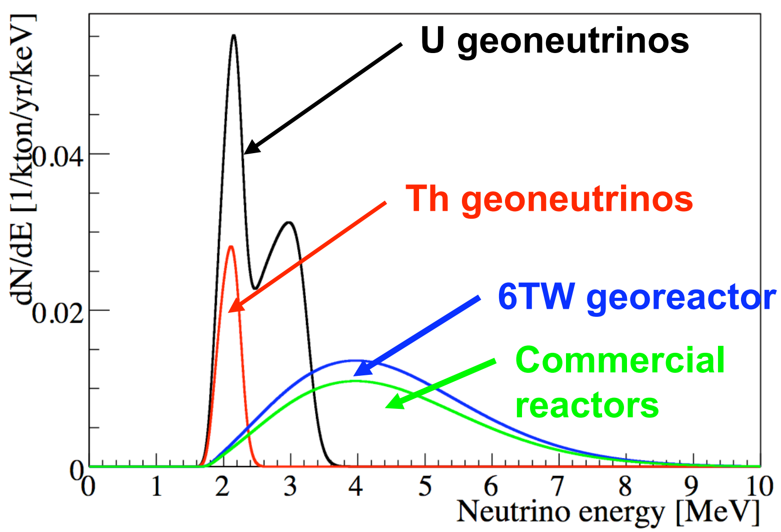
- Replace D_2O in SNO with liquid scintillator (like KamLAND)
- Add ^{150}Nd to liquid scintillator.
- Advantages
  - Large mass
  - Low backgrounds
- Disadvantage
  - Poor energy resolution

MAJORANA



- Use Ge crystals to look for neutrinoless double-beta-decay in ^{76}Ge
- Ge crystals have excellent energy resolution
- However, small volume makes it harder to control backgrounds

Homestake geoneutrino detector



- Homestake was recently chosen as the preferred site for a national underground laboratory in the US.
- Background from power plants is ~7% that in KamLAND
- Sensitive to georeactor power down to ~1TW.