Neutrino Physics

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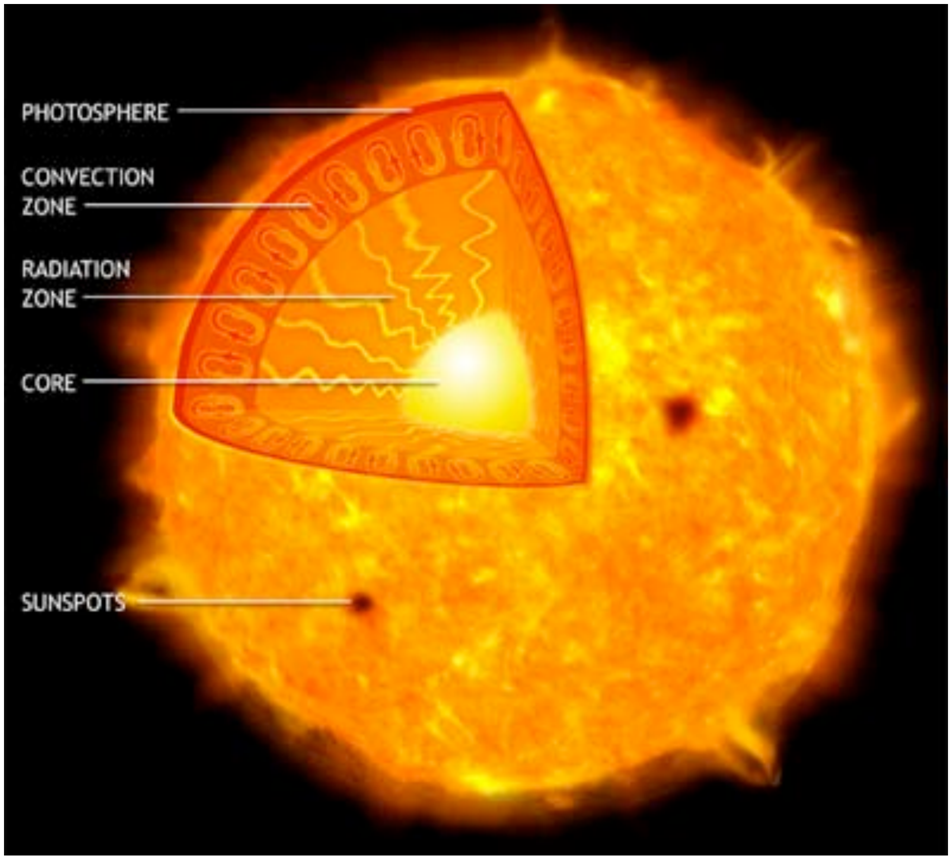
Outline

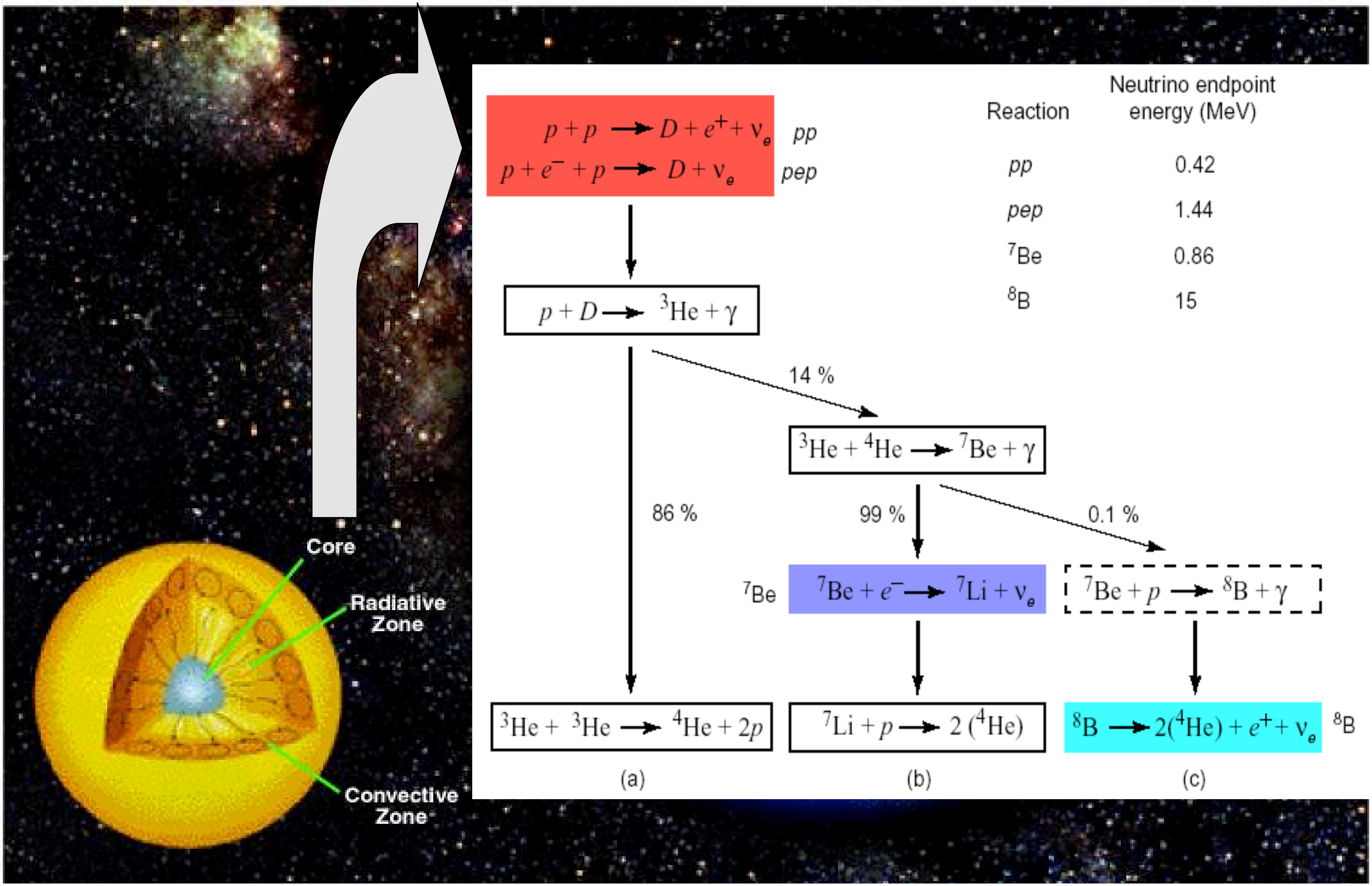
- Solar neutrino
- Studying solar neutrino
  - Experiment using chlorine
  - Experiments using gallium
  - Experiment using water

Here Comes The Sun

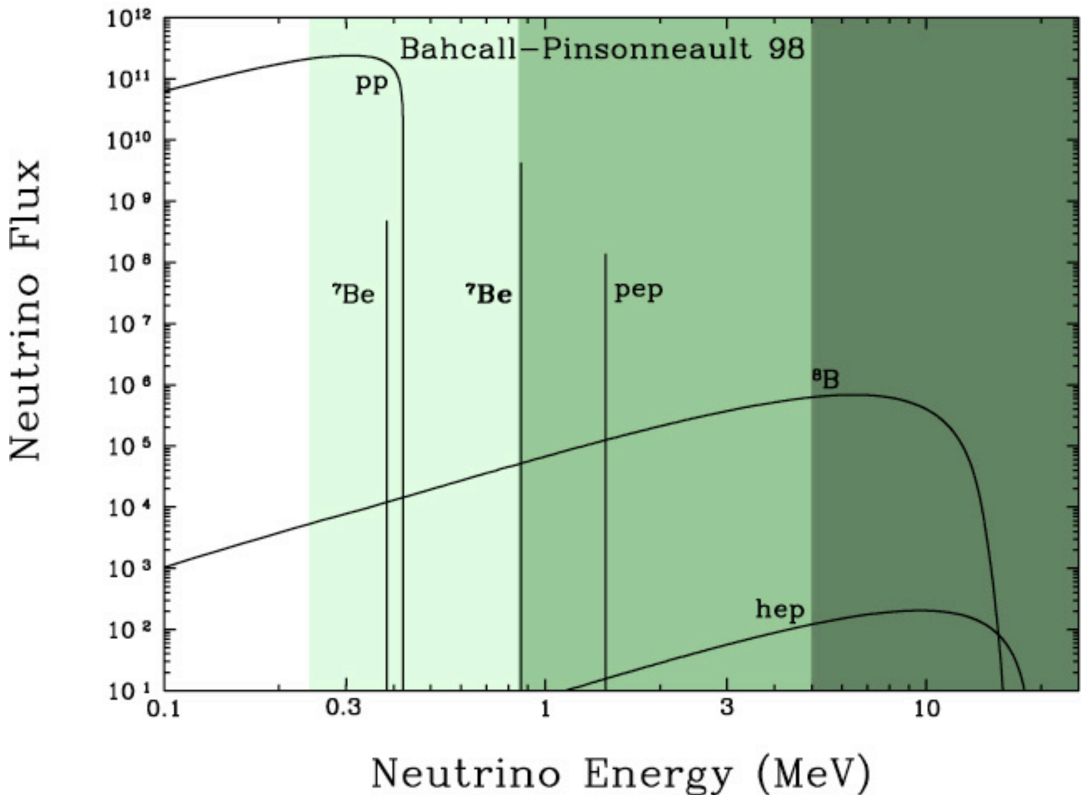


- Gravitational interaction
  - Pulling hydrogen atoms together
- Strong interaction
  - Trigger fusion at the center
- Weak interaction
  - Play a key role in generating energy in the Sun
- Electromagnetic interaction
  - Produce light and heat

The Solar Interior



Solar Neutrinos



The key overall reaction is:

$4p + 2e^- \rightarrow {}^4He + 2\nu_e + 6$ photons, with $Q = 26$ MeV

The intensity of neutrino at Earth is:

$$\Phi_\nu = \frac{2L_{Sun}}{26MeV}\frac{1}{4\pi d^2} = 7\times 10^{10}cm^{-2}s^{-1}$$

$d = 1.5 \times 10^8$ km, distance of Earth from Sun

$L_{sun} = 3.85 \times 10^{26}$ W, solar luminosity

How To Go After The Solar Neutrinos?

- First choose the reaction:

$$\nu_e + e^- \to \nu_e + e^-$$

$$\sigma(\nu_e e \to \nu_e e) \approx 9.5 \times 10^{-45} \left(\frac{E_\nu}{1MeV} \right) \; cm^2$$

$$\nu_e + n \to e^- + p$$

$$\sigma(\nu_e n \to e^- + p) = 9.3 \times 10^{-44} \left(\frac{E_\nu}{1MeV} \right)^2 \left(1 + \frac{Q}{E_\nu} \right) \sqrt{1 + 2\frac{Q}{E_\nu} + \frac{Q^2 - m_e^2}{E_\nu^2}} \; cm^2$$

Thus, it is better to use ν_e-n collision.

- But it is hard to get tons of free neutrons. Need to use neutrons in nuclei:

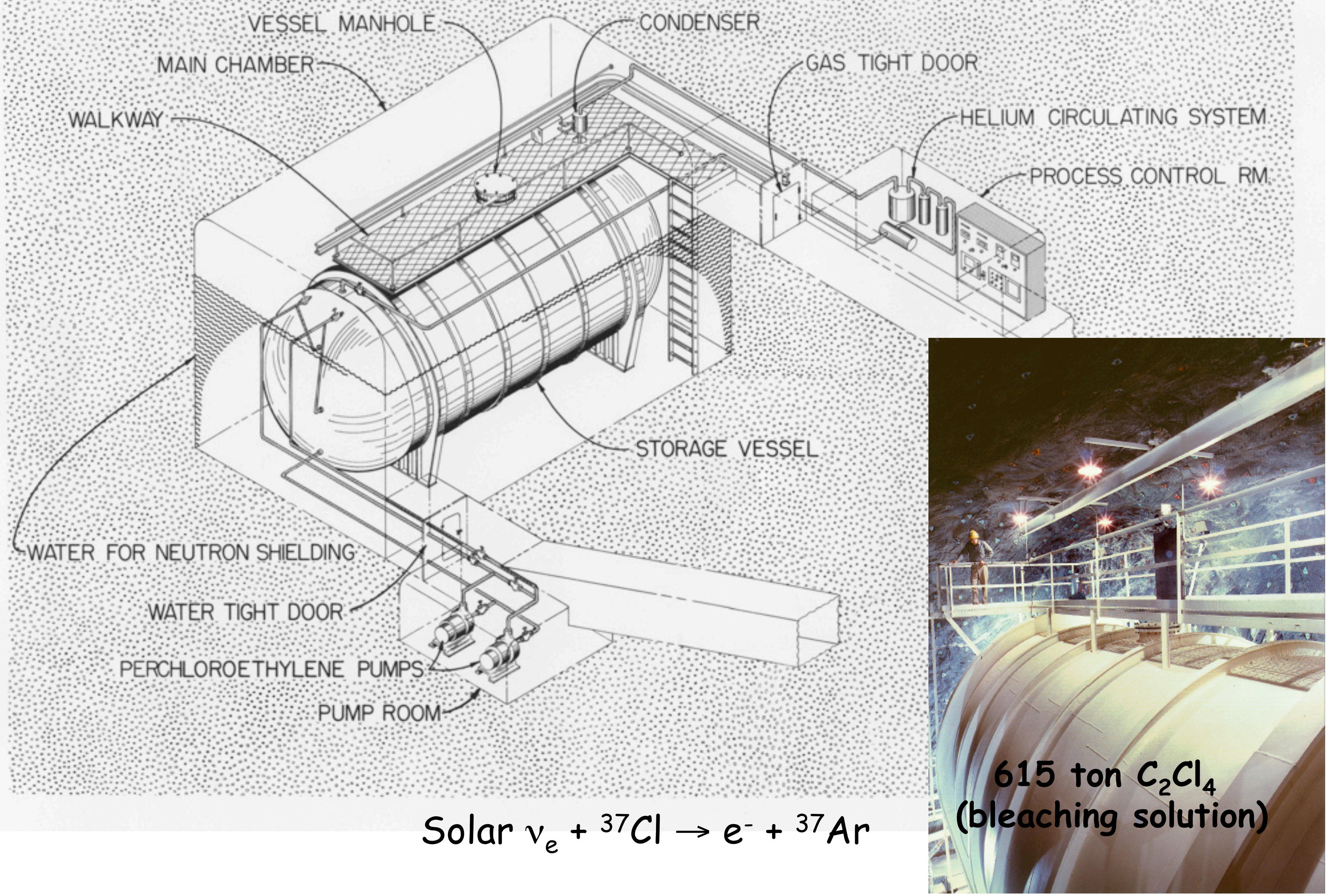
$$\nu_e + {}^{37}Cl \to e^- + {}^{37}Ar, \qquad E_\nu > 0.814 \text{ MeV}$$

Natural chlorine has 24.23% stable ^{37}Cl.

$$^{37}Ar + e^- \text{(K-shell)} \to {}^{37}Cl + \nu_e\,, \qquad \tau_{1/2} = 34 \text{ days}$$

Then count the number of ^{37}Ar decays by observing the 3-5 Auger e^-s emitted with a total energy of 2.823 keV by ^{37}Cl.

Solar Neutrino Experiment in Homestake Mine



Solar $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$

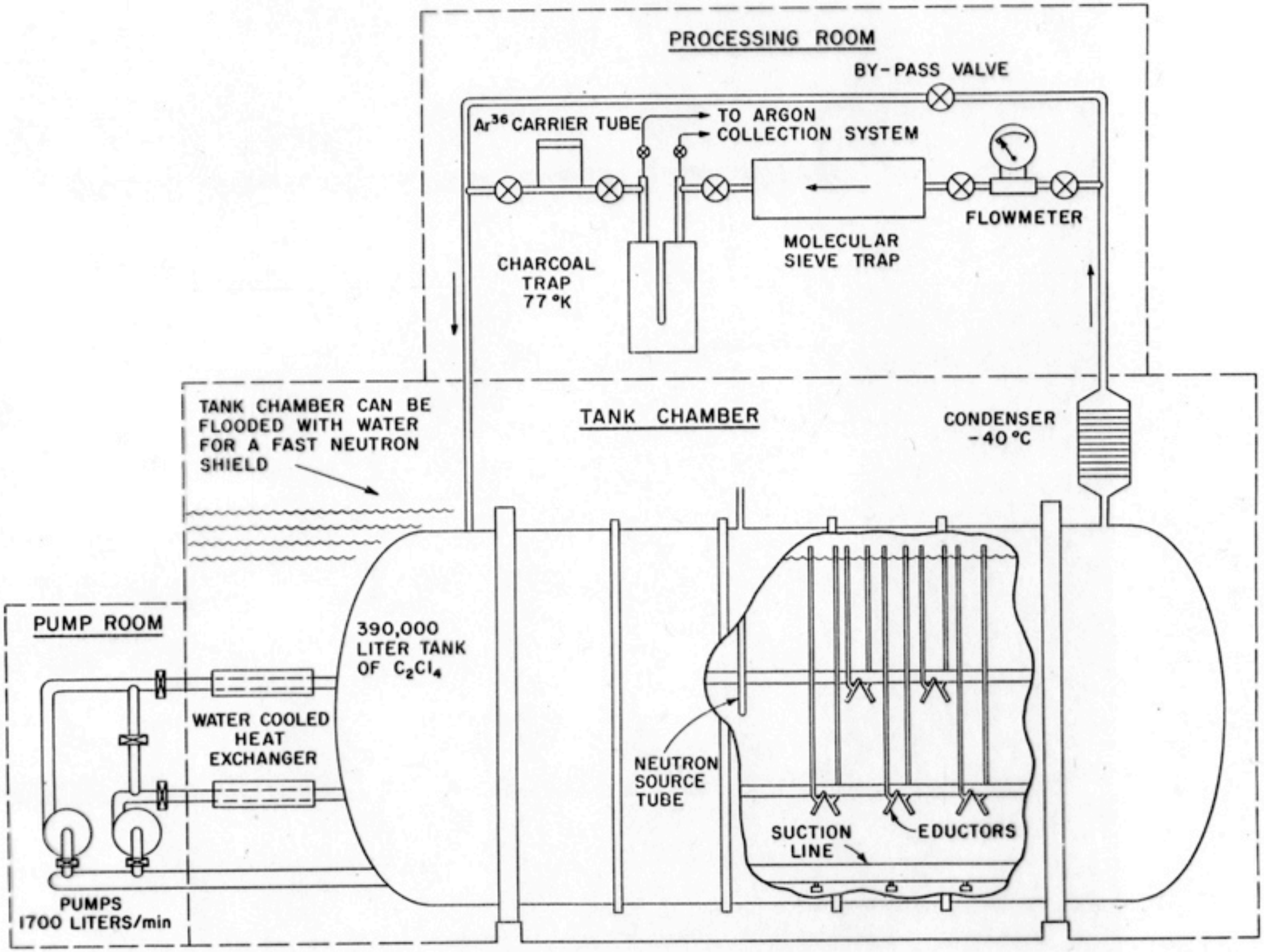
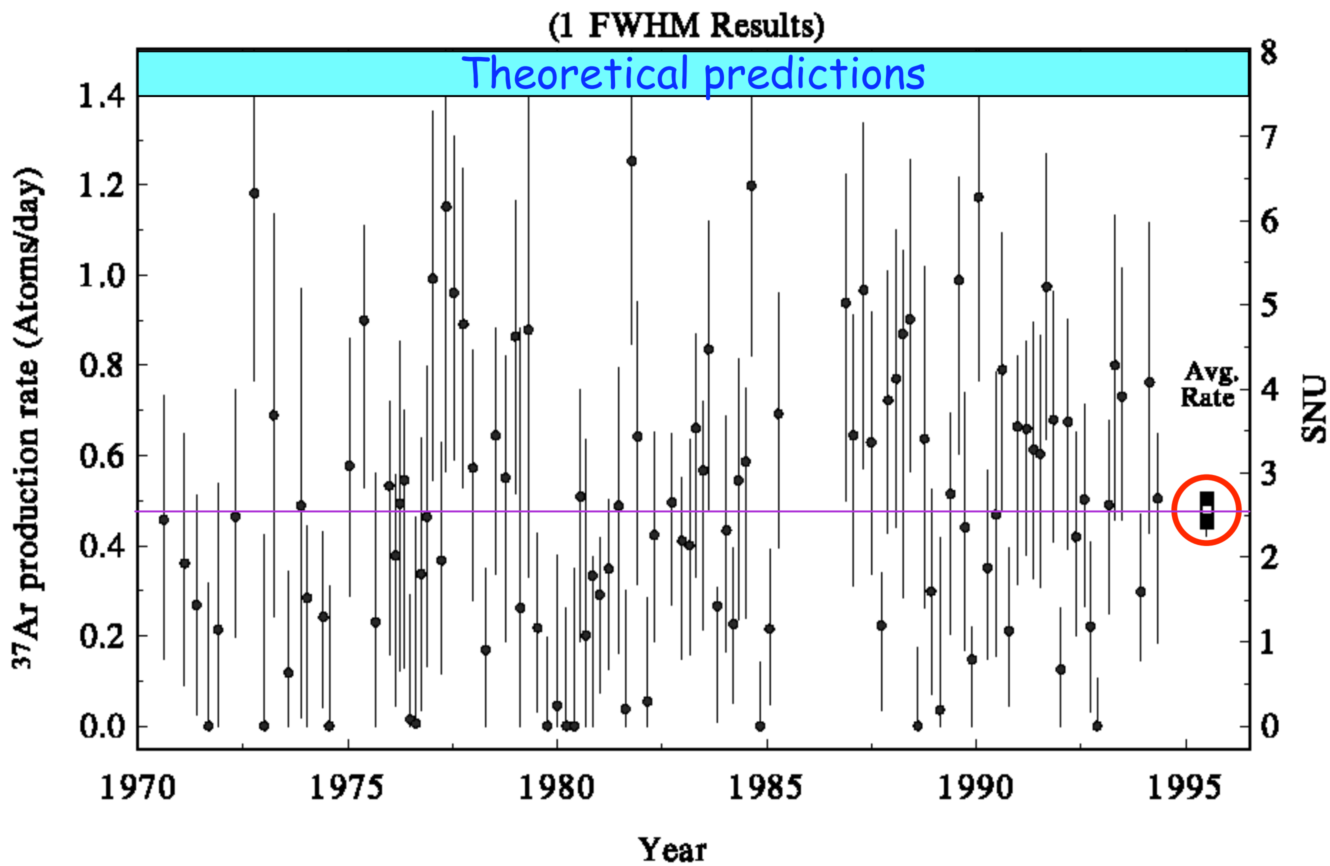


Figure 2.3. Schematic drawing of the argon recovery system. The pump-eductor system forces helium gas through the tetrachloroethylene liquid and provides the helium gas flow through the argon collection system.

Something Funny Is Going On In The Sun



1 SNU = 1 interaction/10^{36} target atoms/sec

Based on 108 extracted ^{37}Ar atoms, obtained a result:

2.56±0.16(stat)±0.16(sys) SNU

Repeat The Experiment

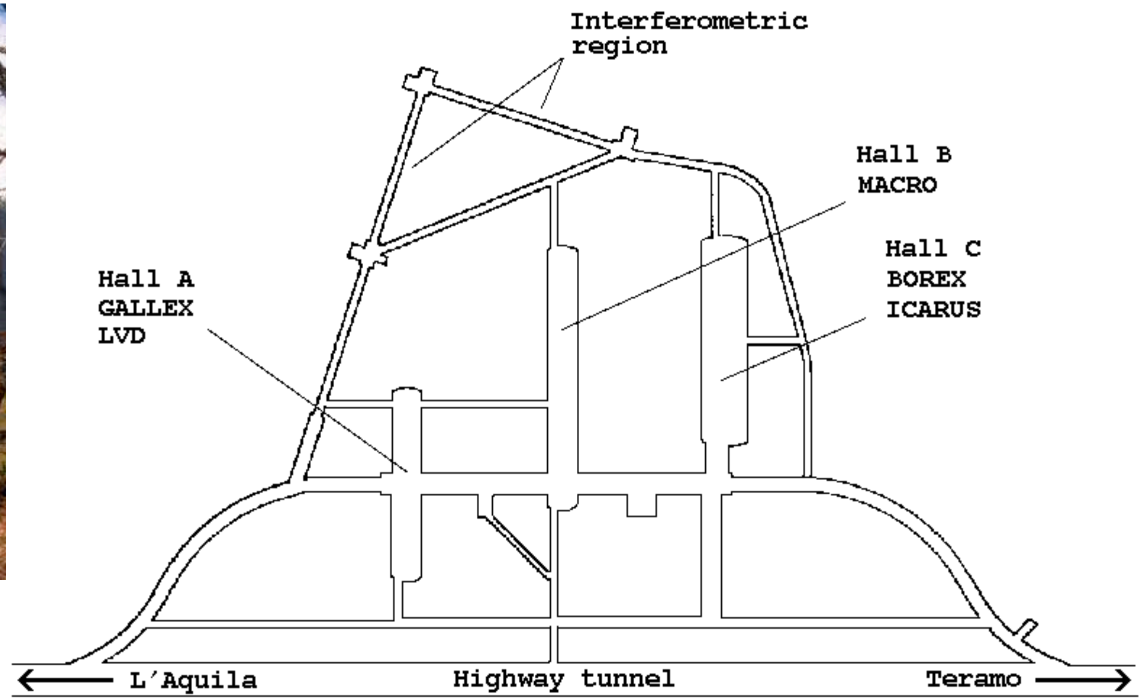
- Use a different reaction that is sensitive to the solar neutrinos from the pp reaction:

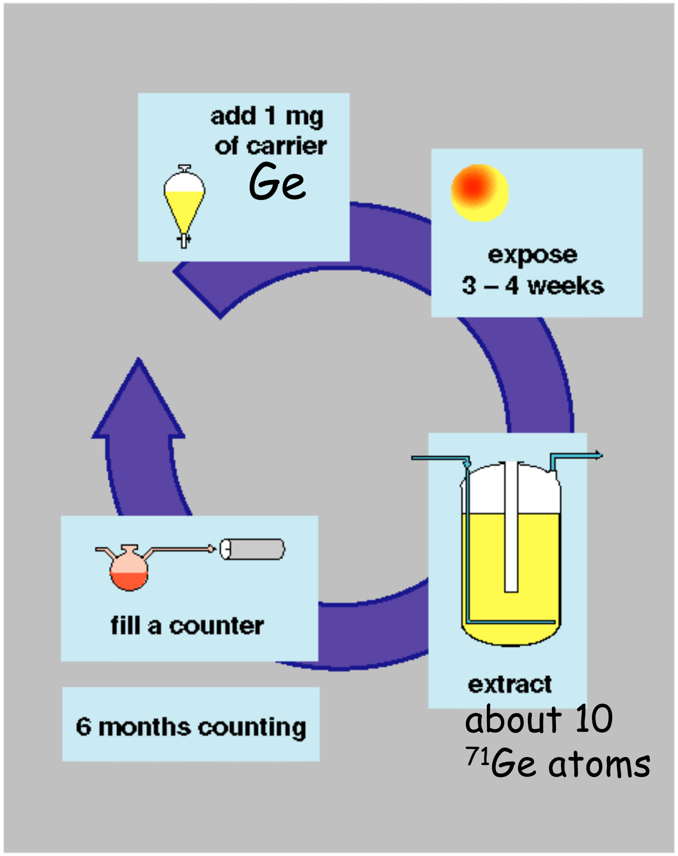
$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge \qquad E_\nu > 0.233\ \text{MeV}$$

then count $\quad {}^{71}Ge + e^- \rightarrow {}^{71}Ga + \nu_e \qquad \tau_{1/2} = 11.43\ \text{days}$

- Three experiments adopted this approach: Gallex and GNO in Italy and SAGE in Russia.

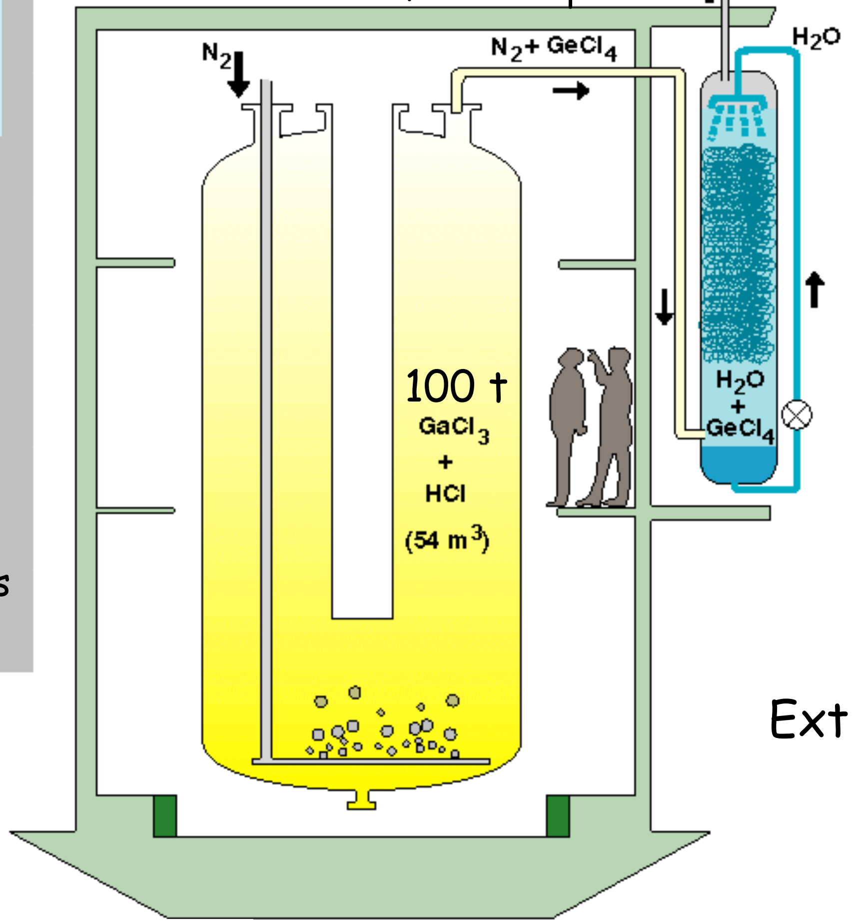
Gran Sasso underground facility



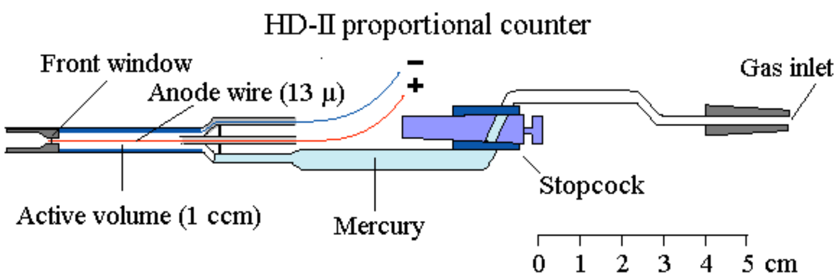


Gallex And GNO

Purge with 1900 m^3 of N_2 for
20 hrs at the end of each exposure

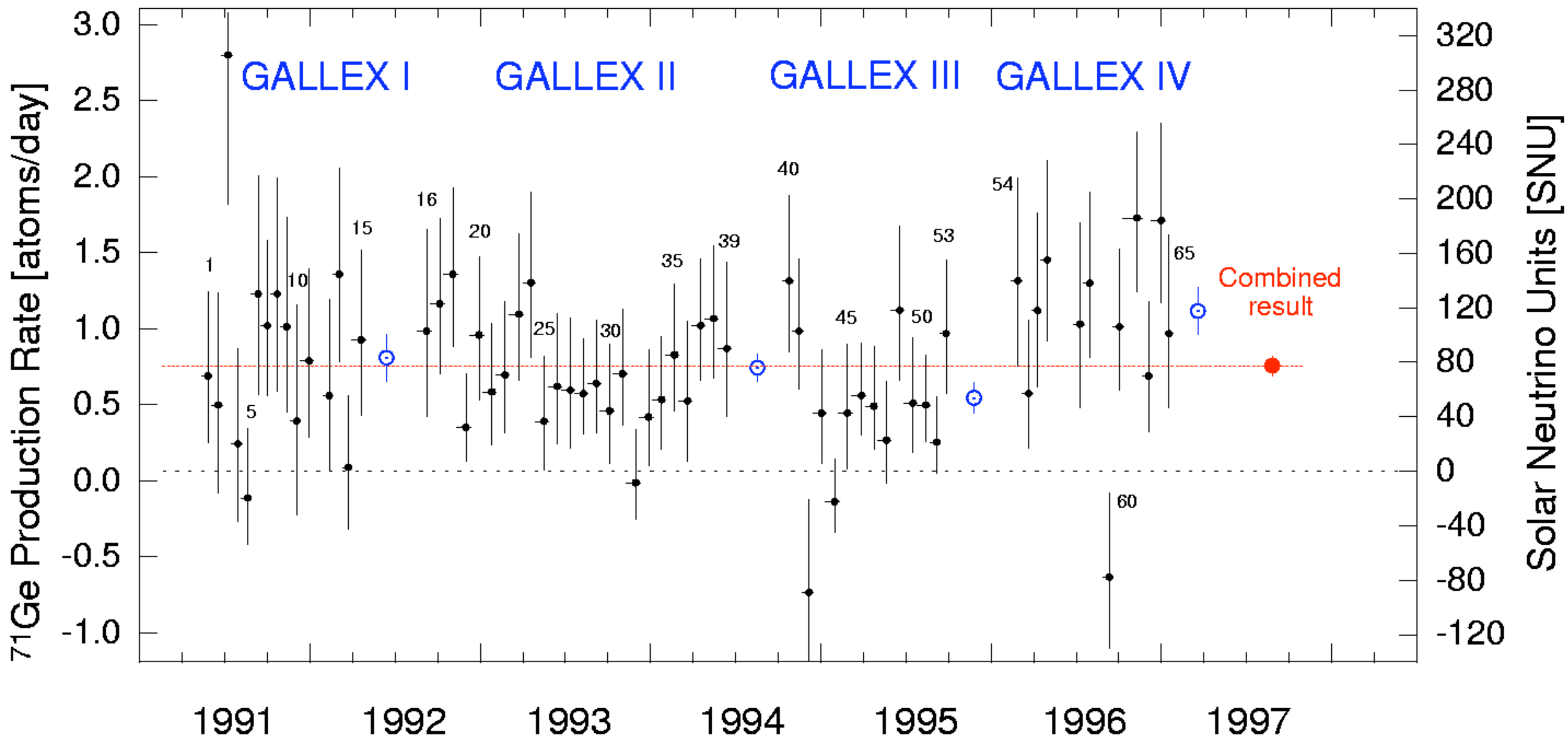


- $GeCl_4$ is dissolved in water
- Convert it to GeH_4 (gas) with $NaBH_4$
- Mix with Xe before counting ^{71}Ge.



Extraction of $GeCl_4$

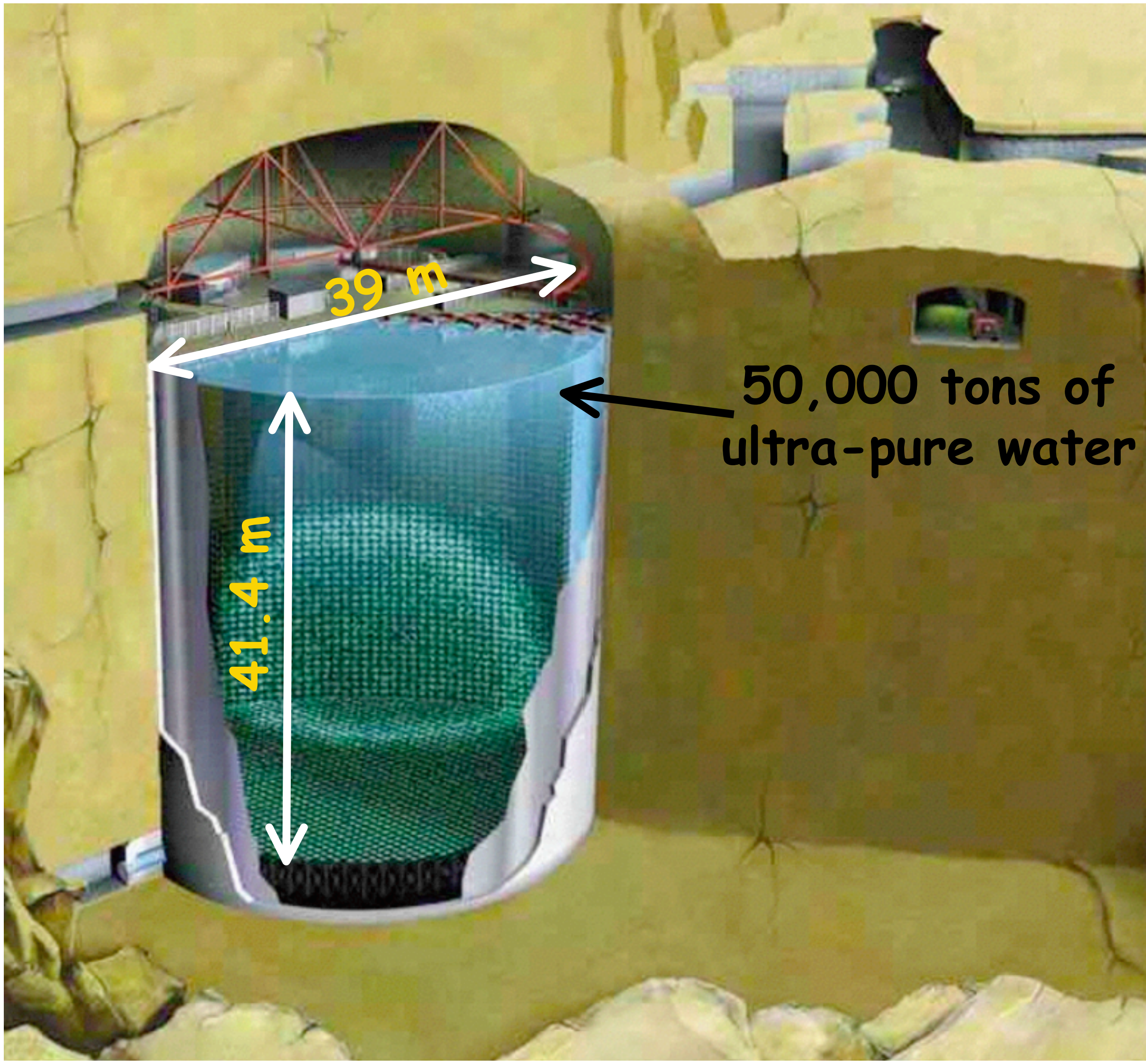
Some Solar Neutrinos Are Still Missing

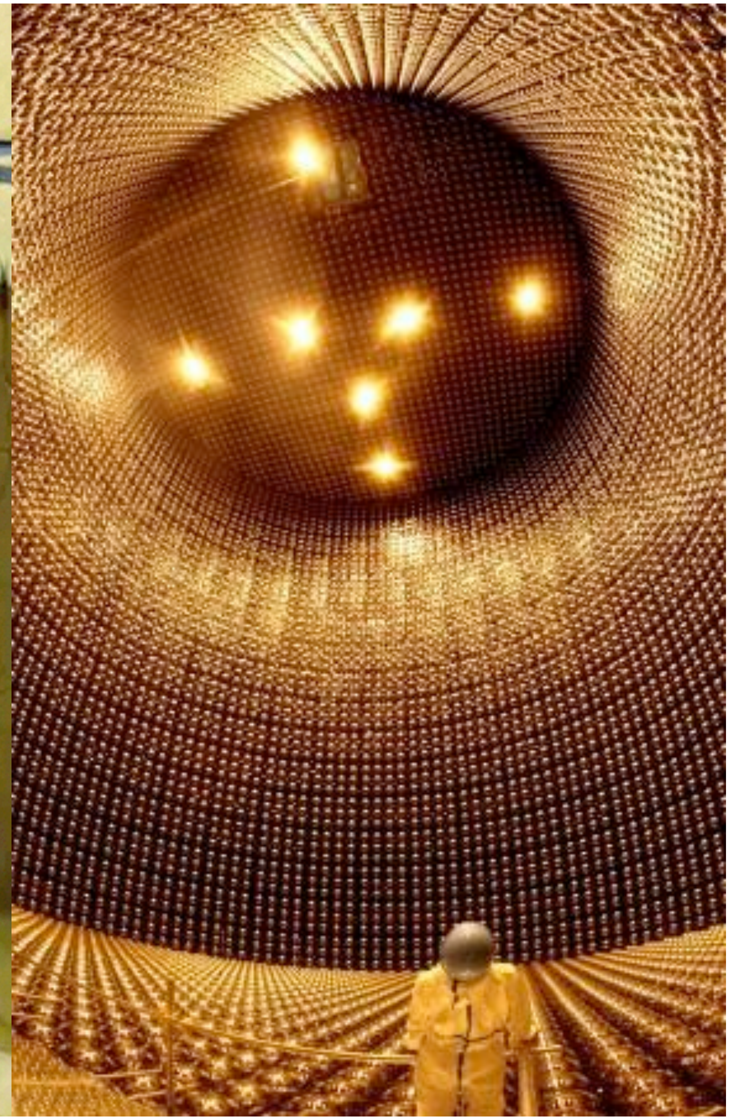


GALLEX:	77.5 +/- 6.2 (stat.) +4.3 -4.7 (sys.) SNU	
GNO:	65.2 +/- 6.4 (stat.) +/- 3.0 (sys.) SNU	
GNO+GALLEX:	70.8 +/- 4.5 (stat.) +/- 3.8 (sys.) SNU	
Prediction:	132 SNU	

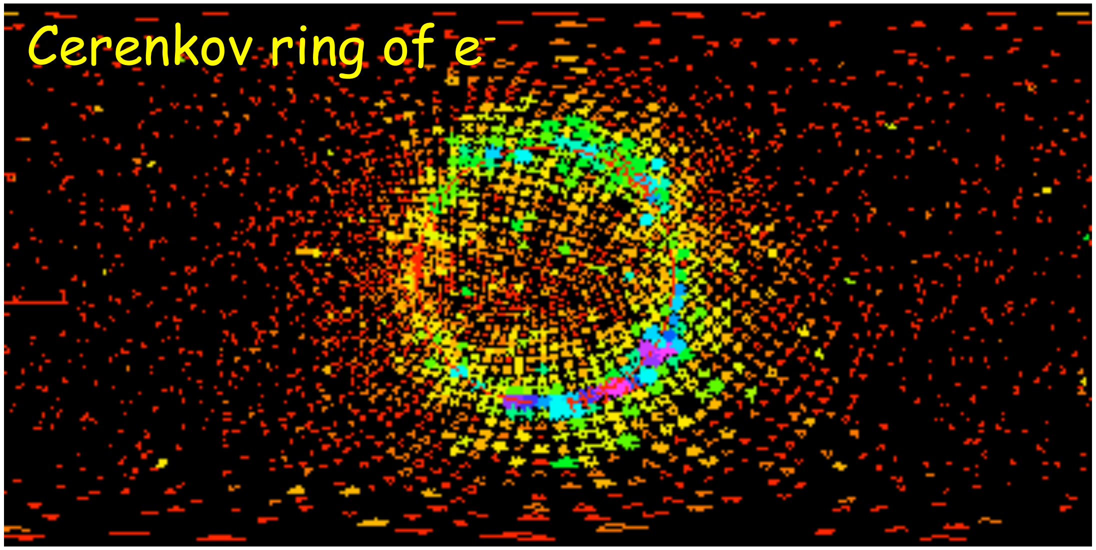
Studying Solar Neutrino With Water

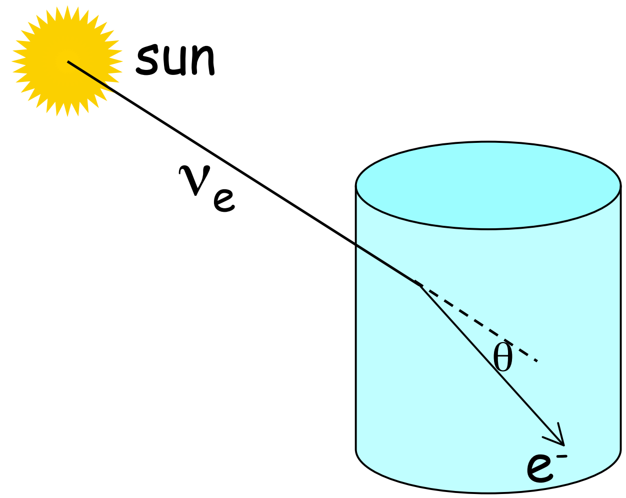
- Utilize water Cerenkov detector: Kamiokande, and Super-Kamiokande in Japan
- Employ $\nu + e^- \rightarrow \nu + e^-$

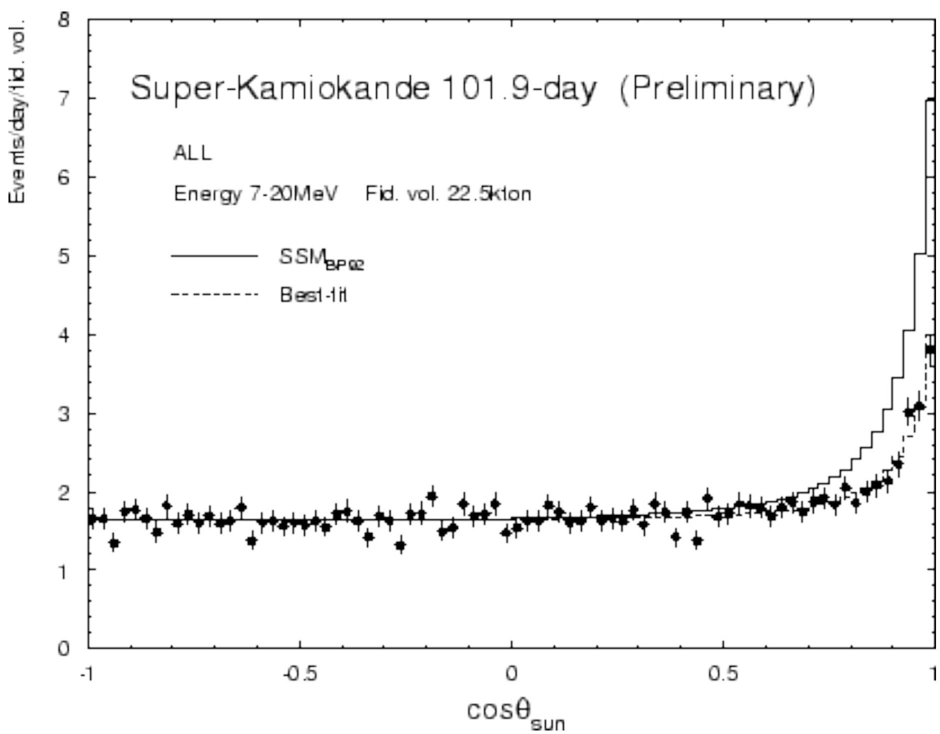


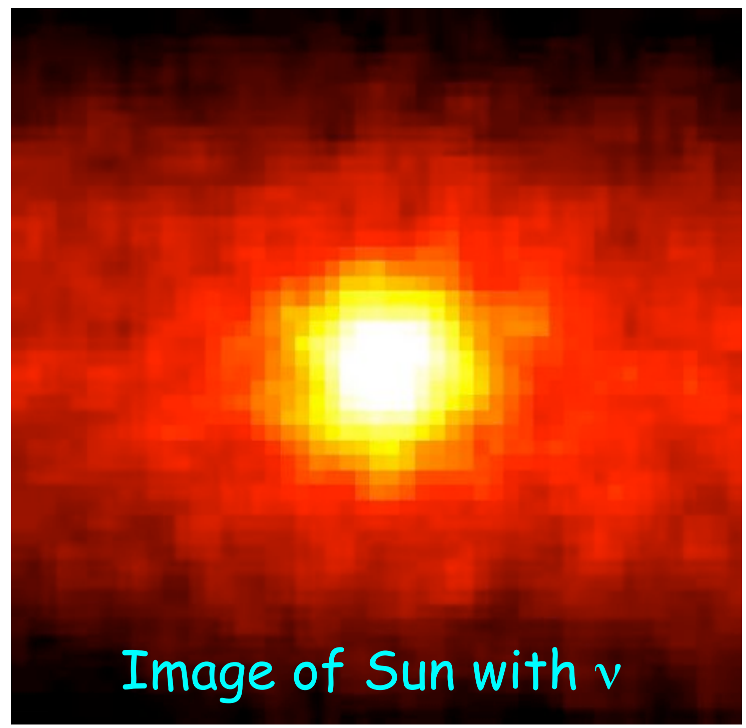


What Are Measured?

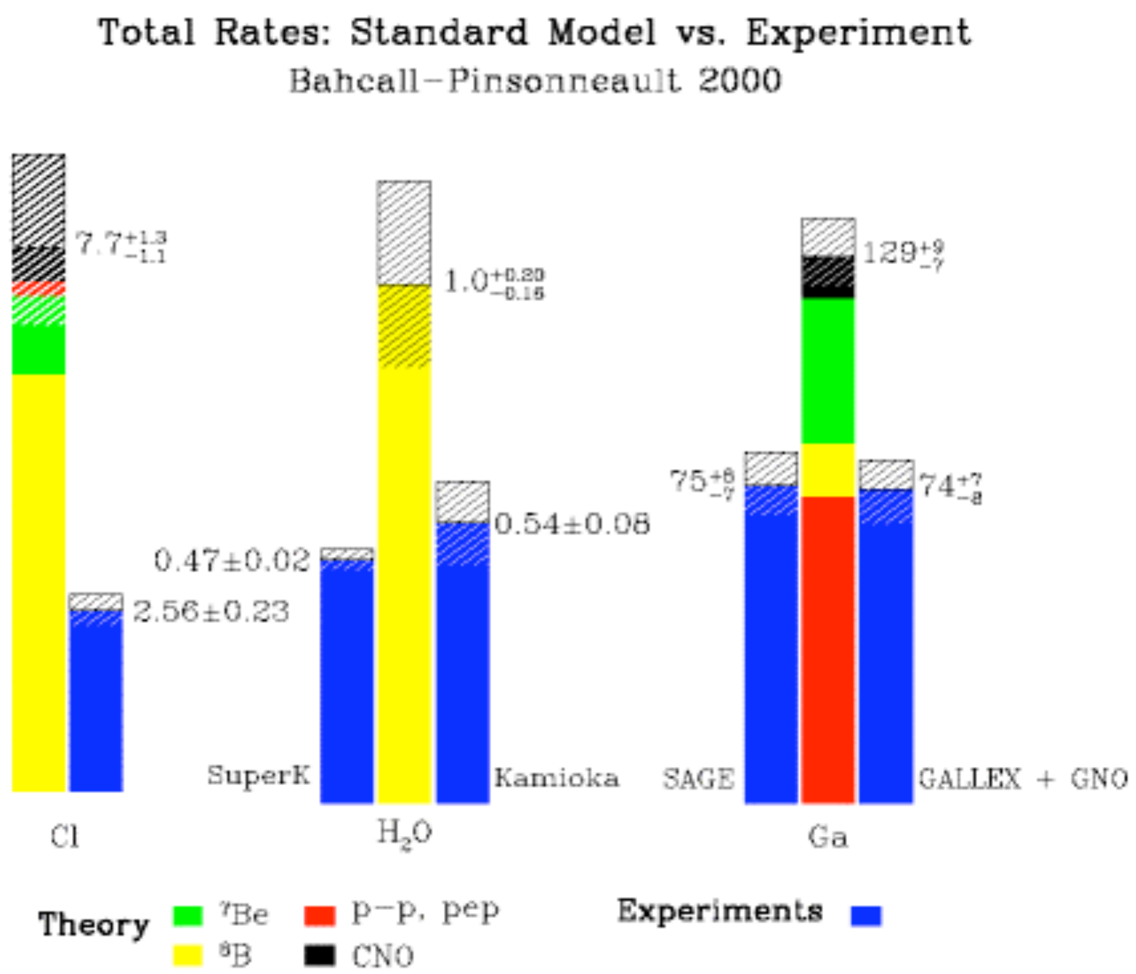




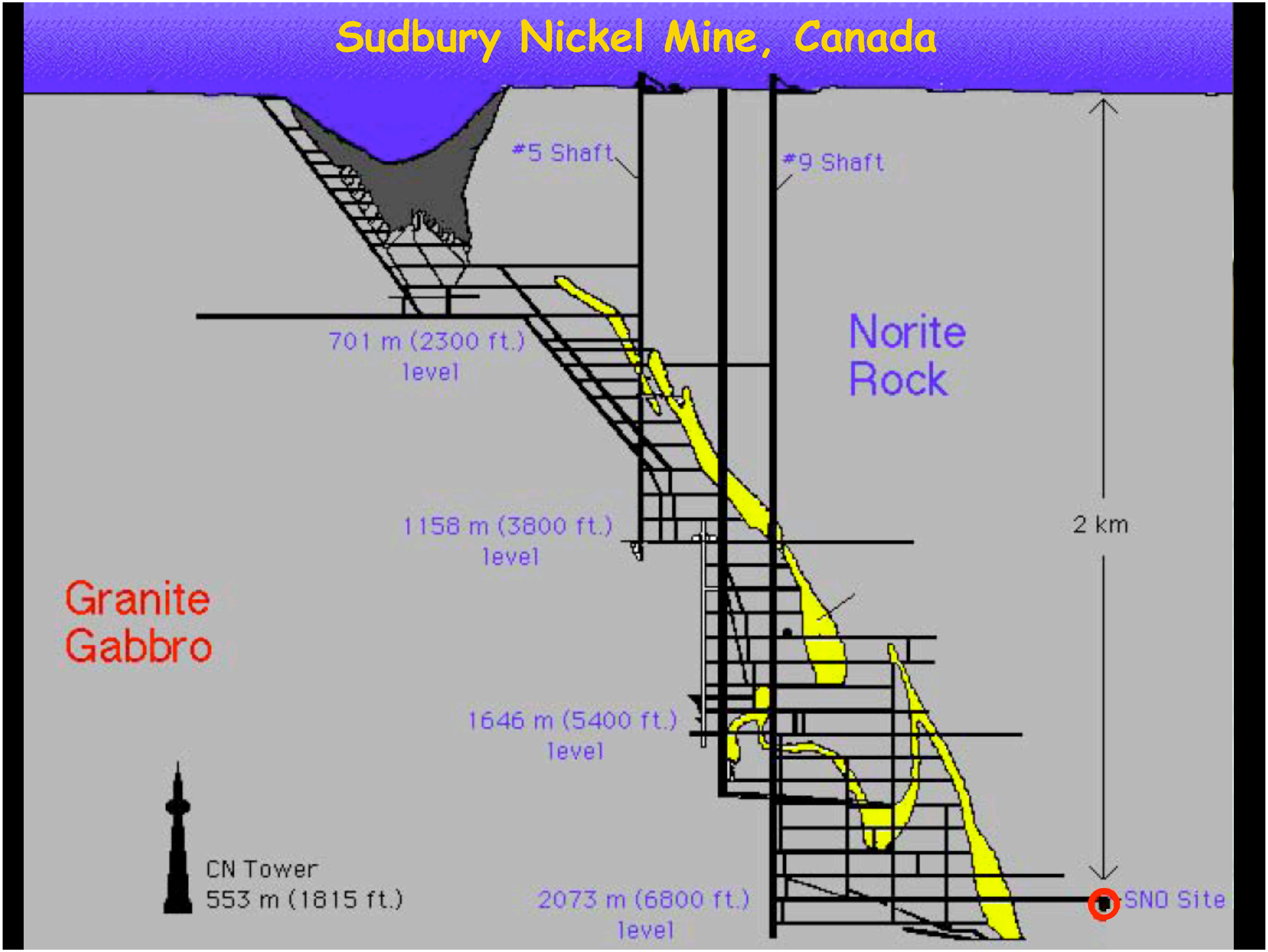




Summary

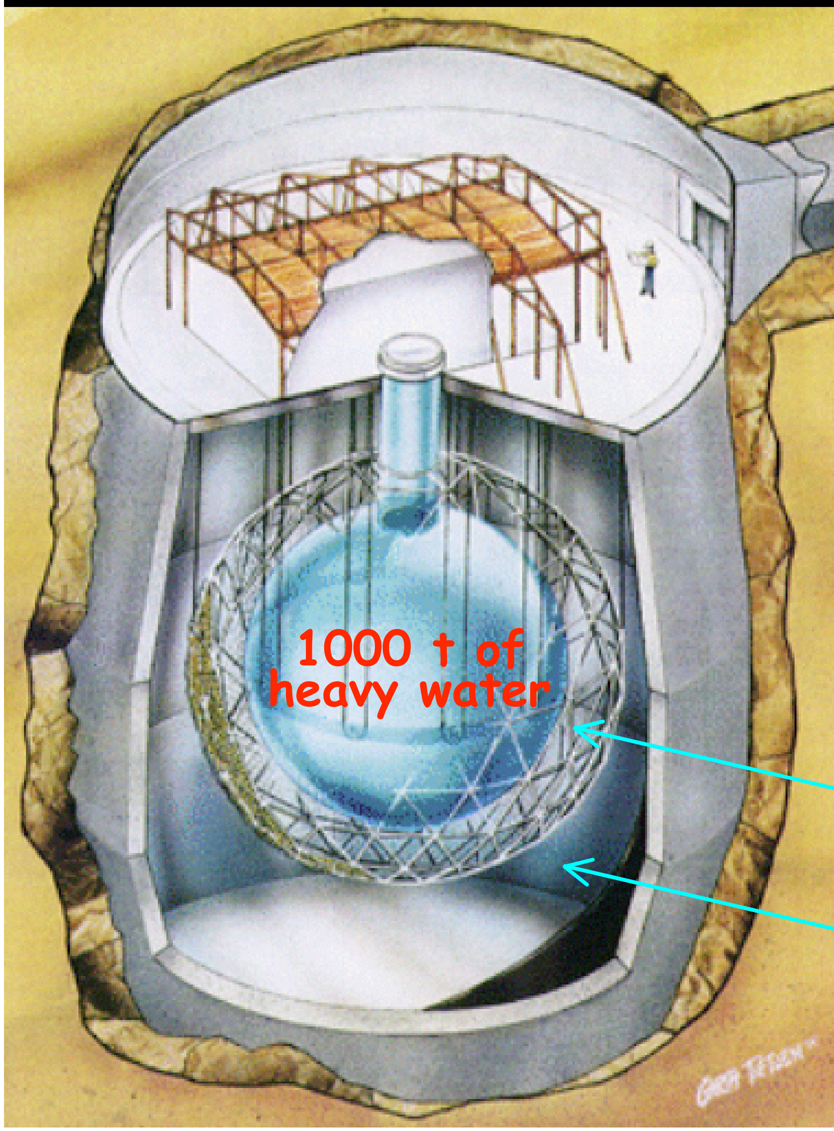


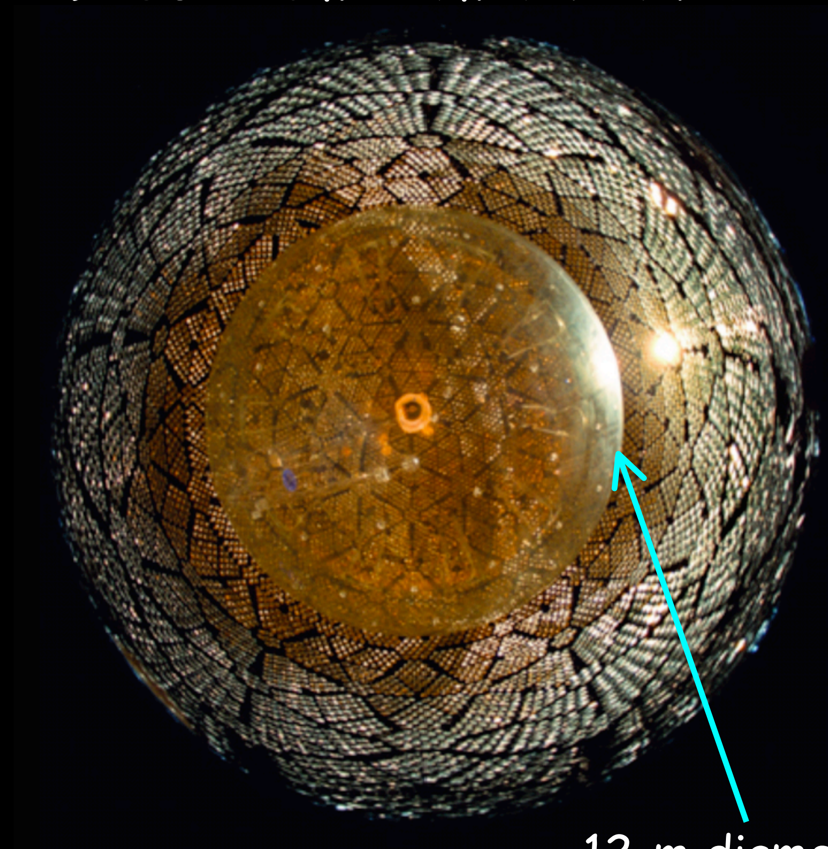
- Some ν_es from the Sun are not accounted for !!


Sudbury Nickel Mine, Canada
#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
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

Sudbury Neutrino Observatory

9456 20cm-diameter PMTs



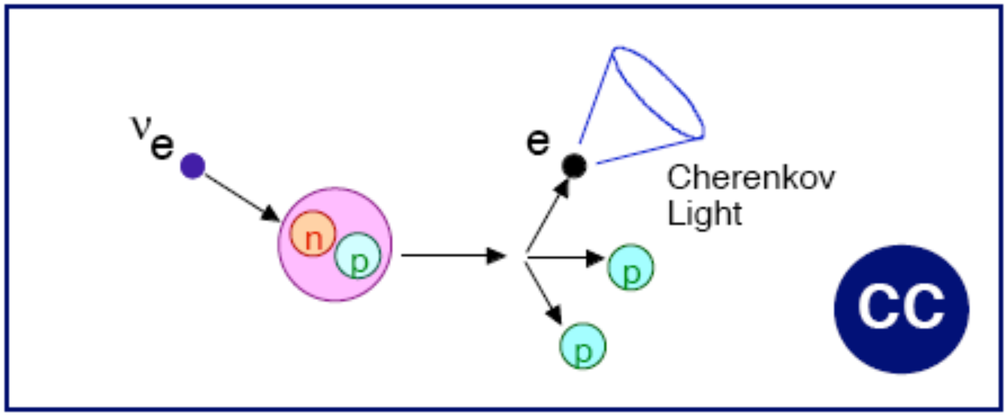


12-m diameter
acrylic sphere

1700 t of water
in inner shield

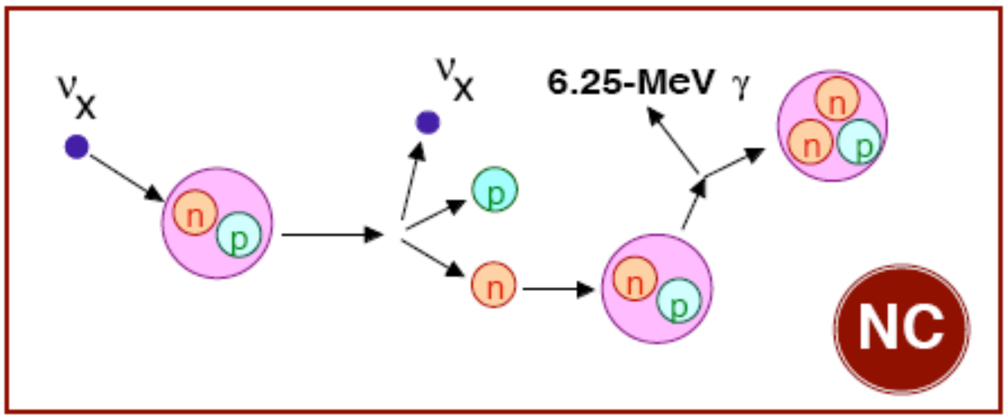
5300 t of water
in outer shield

Why Use Heavy Water?



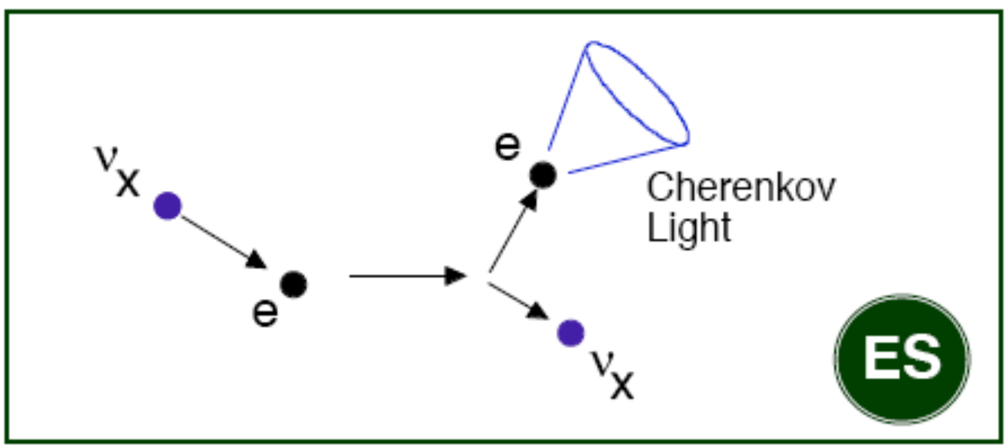
$\nu_e + d \rightarrow p + p + e^-$

- Measure the energy spectrum of ν_e
- Direction of e^- not strongly correlated with that of ν_e



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

- Measure the total flux of ν from ^8B
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$



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

- Measure the total flux of ^8B ν: $\Phi = \Phi(\nu_e)+0.16\Phi(\nu_\mu)+0.16\Phi(\nu_\tau)$
- Strongly directional, e^- tends to follow ν

What The Measure Can Tell us?

- Count the number of events for each type of reaction:

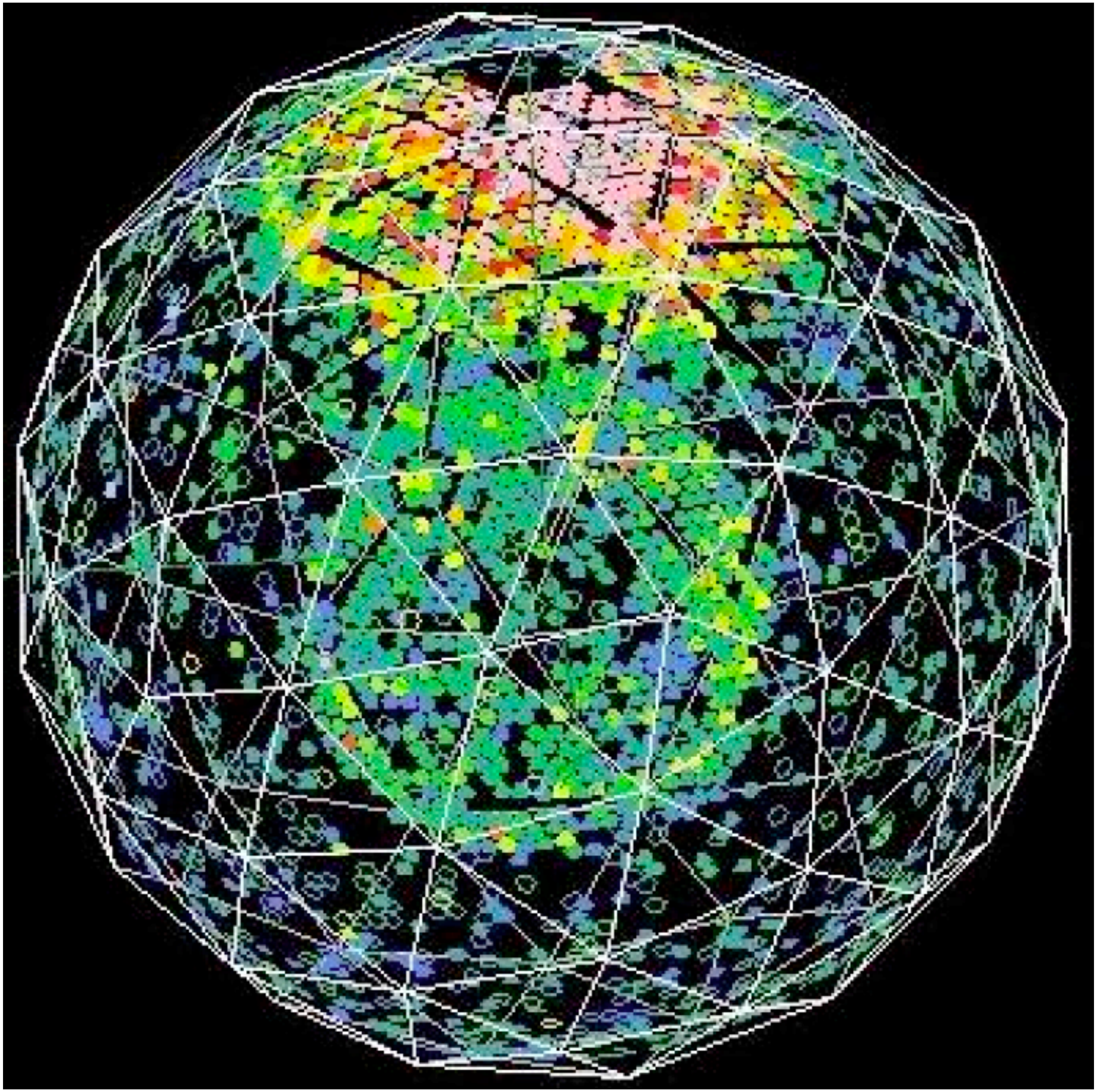
N_{cc}, N_{NC}, N_{ES}

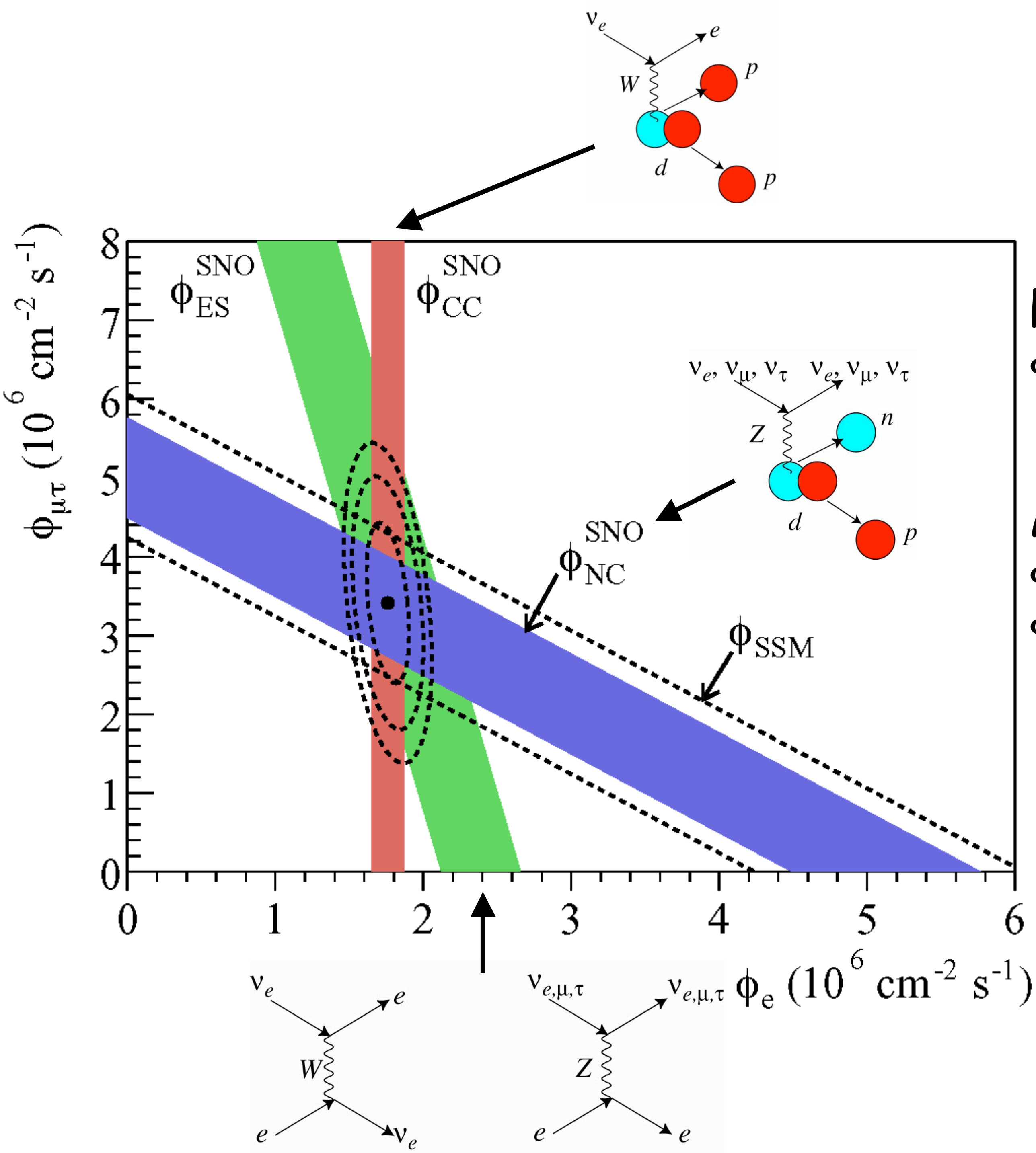
- Then determine the following ratios:

$$\frac{N_{CC}}{N_{NC}} = \left(\frac{\sigma_{CC}}{\sigma_{NC}}\right) \frac{\Phi(\nu_e)}{\Phi(\nu_e) + \left[\Phi(\nu_\mu) + \Phi(\nu_\tau)\right]}$$

$$\frac{N_{CC}}{N_{ES}} = \left(\frac{\sigma_{CC}}{\sigma_{NC}}\right) \frac{\Phi(\nu_e)}{\Phi(\nu_e) + 0.156\left[\Phi(\nu_\mu) + \Phi(\nu_\tau)\right]}$$

Hence, one can find out whether there are other kinds of neutrino arriving on Earth from the Sun.





Prediction:

$\Phi(\nu_e) \approx 5 \times 10^6\ cm^{-2}s^{-1}$

Measured:

$\Phi(\nu_e) \approx 1.8 \times 10^6\ cm^{-2}s^{-1}$

$\Phi(\nu_{\mu\tau}) \approx 3.4 \times 10^6\ cm^{-2}s^{-1}$

Conclusions

- Some ν_e neutrinos are transformed into ν_μ and ν_τ on their way out from the center of the Sun to Earth.

- It appears that our understanding of the Sun is good.