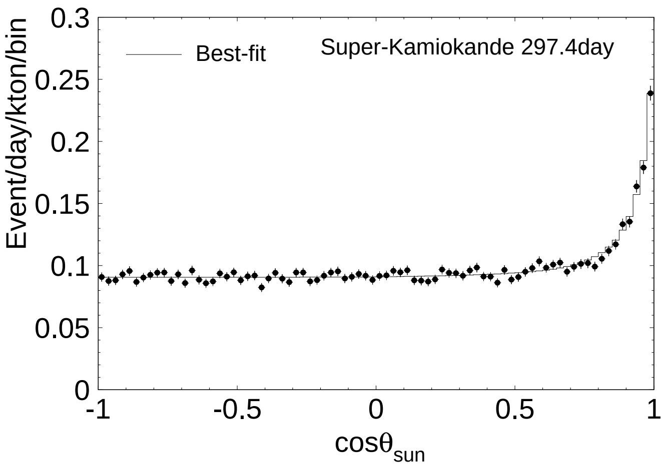
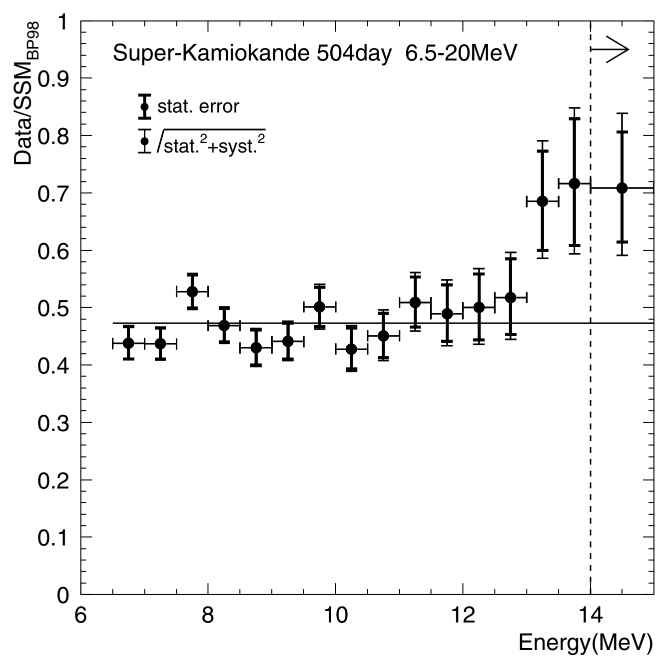
Conclusive Evidence
Nuclear Energy Sustains the Sun

- The SuperK experiment has very high statistics and includes directionality for the detections.

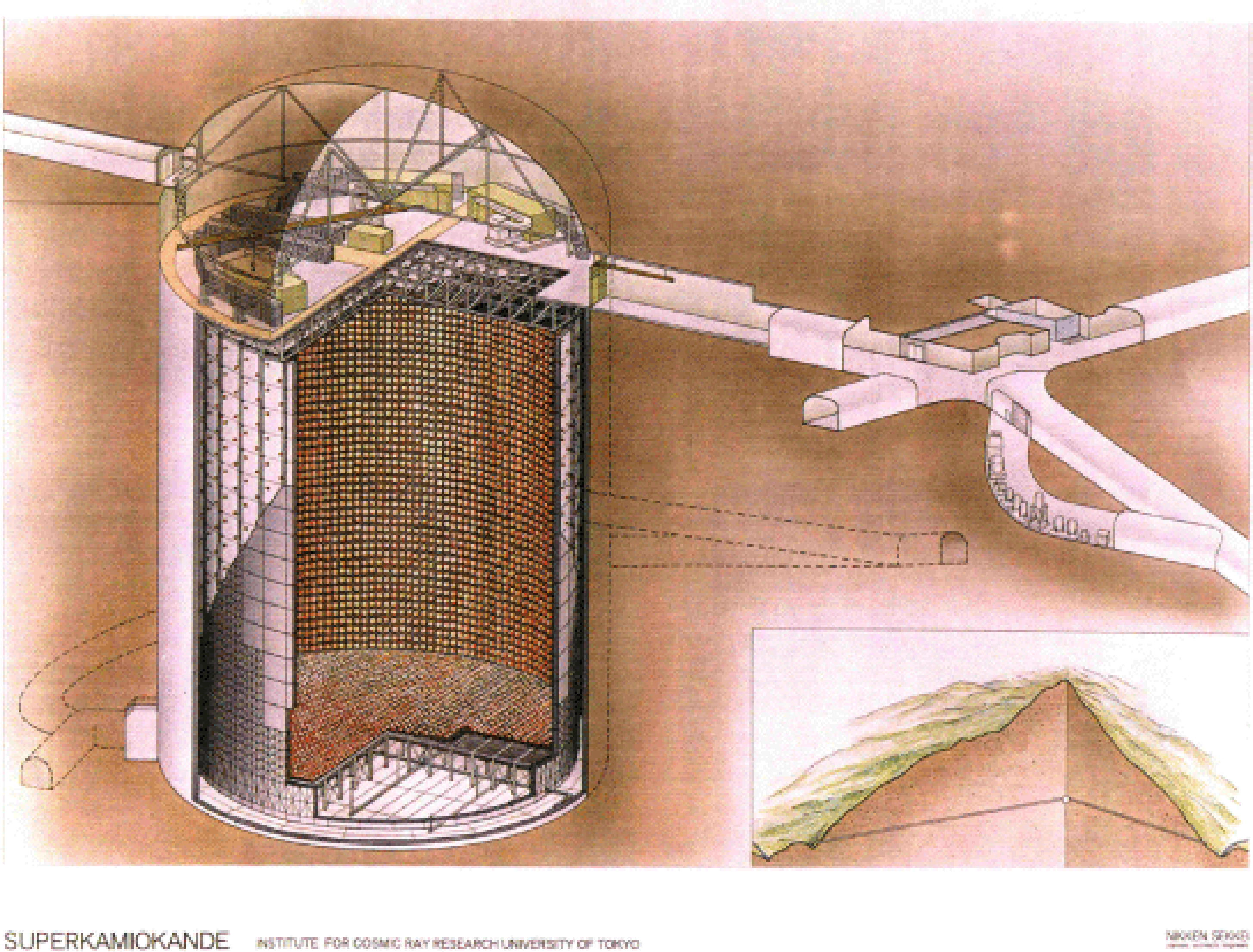
- The energy spectrum of the neutrinos is measured.





The left figure shows the angular distribution of the detected electrons as a function of the deviation angle between the direction away from the sun and the line of travel of the electron. The right figure shows the distribution in energy of the recoil electrons referenced to the predicted energy spectrum.

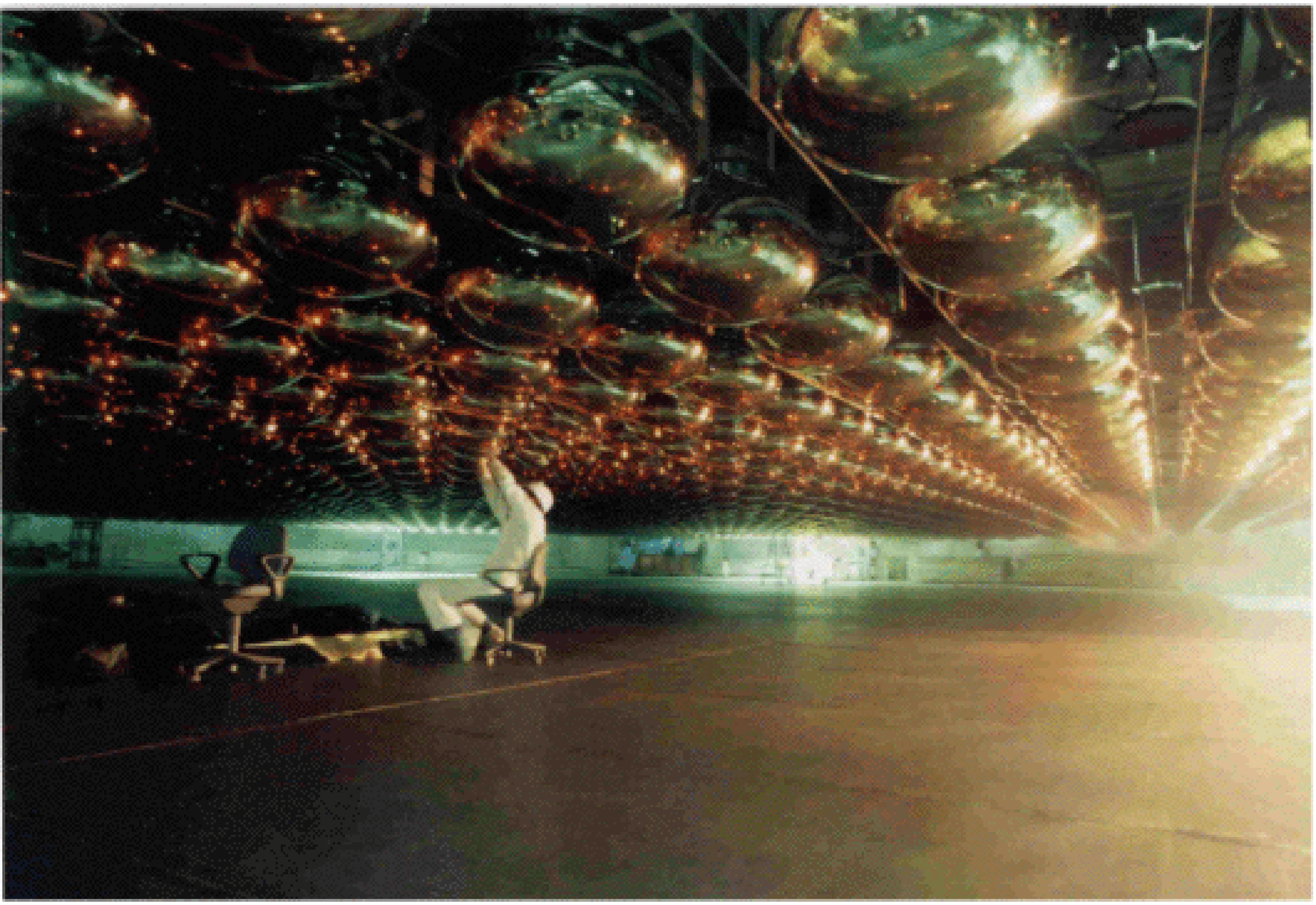
The layout of the neutrino detection system of Super Kamiokanda



The detection of neutrinos must take place deep underground in order to eliminate background radiation from such things as cosmic rays and radioactive decay. This giant tank is filled with ultra pure water and the walls are completely covered with devices called photomultiplier tubes. Each photomultiplier tube can detect extremely weak light pulses and measure the time of the pulse with extremely great time precision. By determining the travel time to all tubes which are triggered by the light pulse, the location of the source of the light can be calculated and the position and direction of travel of the neutrino passing through the tank can be determined.

Note the human sized workstations in the tunnel on the right. Each of the photomultiplier tubes is large compared to a person.

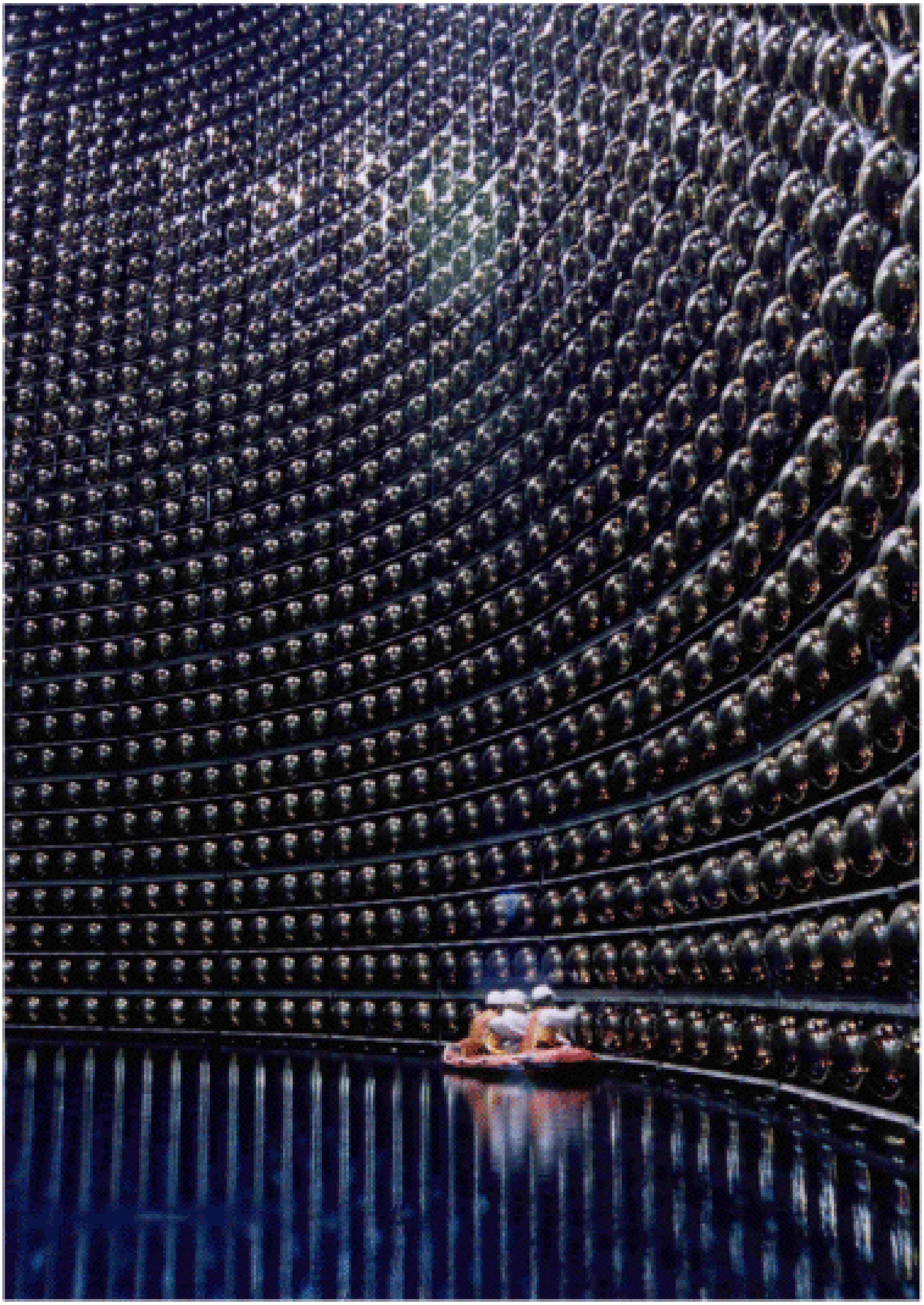
Installing Photomultiplier Tubes at SuperKamiokanda



This is the inside of the water tank for the SuperKamiokanda system which detects neutrinos as they pass through the water. At this stage of the instrument, the tank was empty and the electronics to drive the photomultiplier tubes could be reached.

The system uses the fact that neutrinos can pass through the Earth to reach the tank. A very small fraction of the neutrinos from the sun and other cosmic sources collides with an electron in the water and gives it a large fraction of the neutrino energy. These ejected electrons are moving faster than the speed of light in water and produce light as a shock wave which resembles the sonic boom from a supersonic aircraft. The photomultiplier tubes detect this light boom and thus the effect of the passing neutrinos.

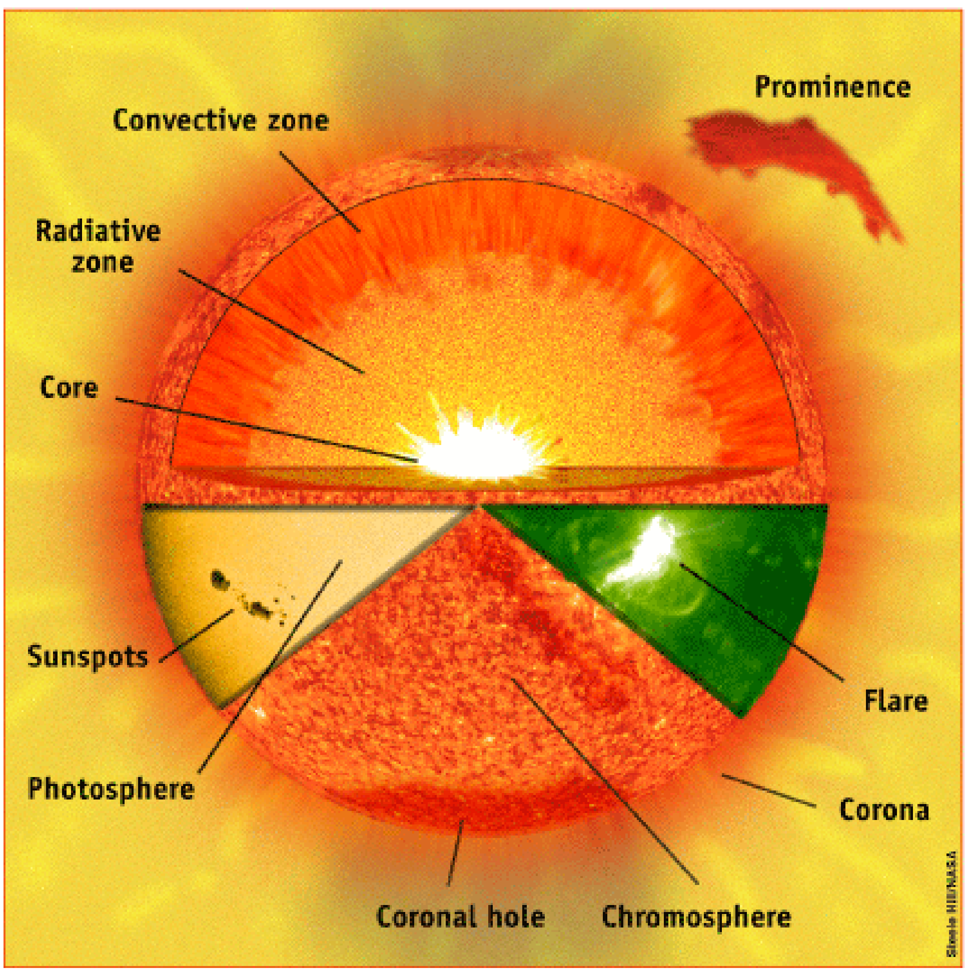
Finalizing the installation of the photomultiplier tubes



As the giant tank is filled with the ultra pure water, it is necessary to give each photomultiplier tube one last check. The electrical connections must be secure and isolated from the water to prevent the ruining of the tubes. After the tank is filled, when a tube fails, it is just left in place since it is well below the top of the tank and there is no way to pull it out to put in a new one without draining and refilling the tank.

The parts of a main sequence star – the Sun

A main sequence star like the sun includes several layers. The outer layer known as the photosphere is marked by magnetic features known as sunspots. These can produce instabilities in the magnetic configuration capable of generating high energy particles. The next layer down is known as the convection zone and matter here is in a constant state of overturning as energy is transported from the deep interior by means of large scale motions like a boiling pot of water. The energy is generated in the region near the solar center and migrates to the solar surface by means of electromagnetic radiation.



Stellar energy and stellar evolution

Changes in the structure of stars are what we call stellar evolution. The flow of energy and the fact that it causes changes in the elemental makeup of the star is responsible for stellar evolution. The pull of gravity drags parts of the star deeper and deeper into an energy hole until the star either reaches a situation where it is supported by quantum pressure and can quietly cool off or it becomes unstable and undergoes a catastrophic change. The energy flow and elemental transformations involve the following factors:

- All stars are bound together by gravity. This means they are always in a gravitational hole — the only question is: "How deep is the hole?"

- The star's heat content and the depth of the star within the gravitational hole are competing factors — the greater is the heat content, the shallower within the gravitational hole will be the star.

- The total energy of the star (neglecting the potential nuclear energy) is the sum of the heat energy and the gravitational energy (which is negative). Since the star is in a gravitational hole, the sum must be negative otherwise the star would evaporate into the interstellar spaces.

- For a main sequence type star where quantum pressure is not important, the gravitational binding energy (the negative of the gravitational energy) is twice the heat energy content of the star.

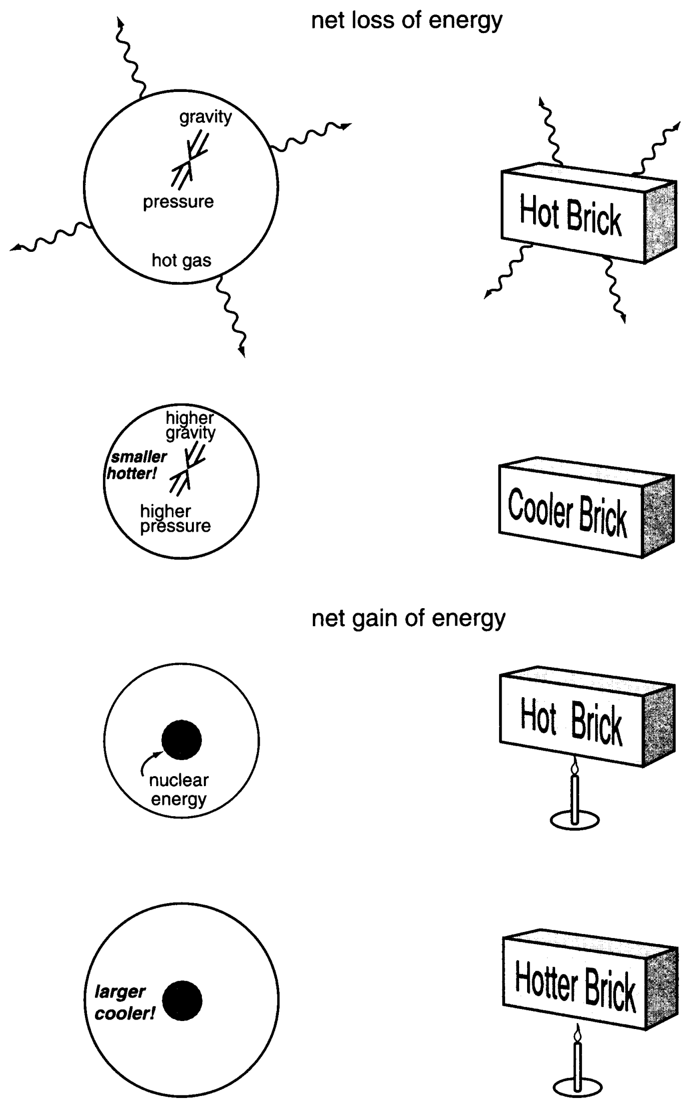
- For these stars we get the result:

$$\boxed{\text{Total Energy}} = \boxed{\text{Gravitational Energy}} + \boxed{\text{Heat Energy}}$$

$$\boxed{\text{Total Energy}} = -2 \times \boxed{\text{Heat Energy}} + \boxed{\text{Heat Energy}} = -\boxed{\text{Heat Energy}}$$

Comparing a star to a brick

The result described on the previous slide leads to some rather strange differences between a star and ordinary matter. When you heat something like a brick, it gets hotter. The process of heating a brick corresponds to increasing the brick's total energy. When we do the equivalent thing to a star which has the properties required on the previous slide, we find it climbs a ways out of its gravitational hole and gets cooler:



These sketches illustrate the differing behavior of the brick and the star when energy is added.

Stability of stars and their evolution

Because of the peculiar result that stars cool off when energy is added, they are stable. The production of energy from the nuclear transformation of hydrogen into helium depends on temperature. When the temperature goes up, the reaction speeds up and energy is produced more quickly.

Let us compare a hydrogen burning brick and a main sequence star:

Brick	Main Sequence Star
Energy added	Energy added
Temperature Rises	Temperature Falls
Hydrogen burning speeds up	Hydrogen burning slows down
More energy added	Less energy added
Temperature Rises More	Star settles back as before
Brick explodes	Star stays on main sequence

This stabilization does not work for stars supported by quantum pressure.

- When a star runs out of hydrogen, it can contract and heat up.
- A sequence of nuclear fuels can burn and supply energy to the star:

1. Hydrogen $\longrightarrow$ helium
2. Helium $\longrightarrow$ carbon and oxygen
3. Carbon and oxygen $\longrightarrow$ magnesium, silicon, sulfur, iron and many other elements

The centers of stars undergo a series of steps of nuclear fuel burning, nuclear fuel exhaustion, contraction, heating and new fuel ignition.

- Here is a puzzle: Where do red giants come from?