# The Sun – Our Nearest Star

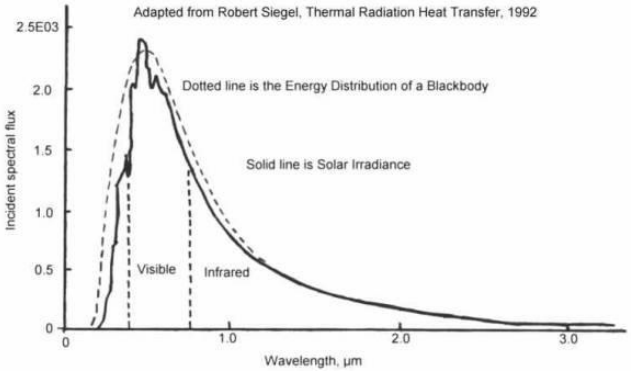
The Sun is an average star in mass, lifetime, and energy output.
We will look at in detail before studying stars in general

Some Properties

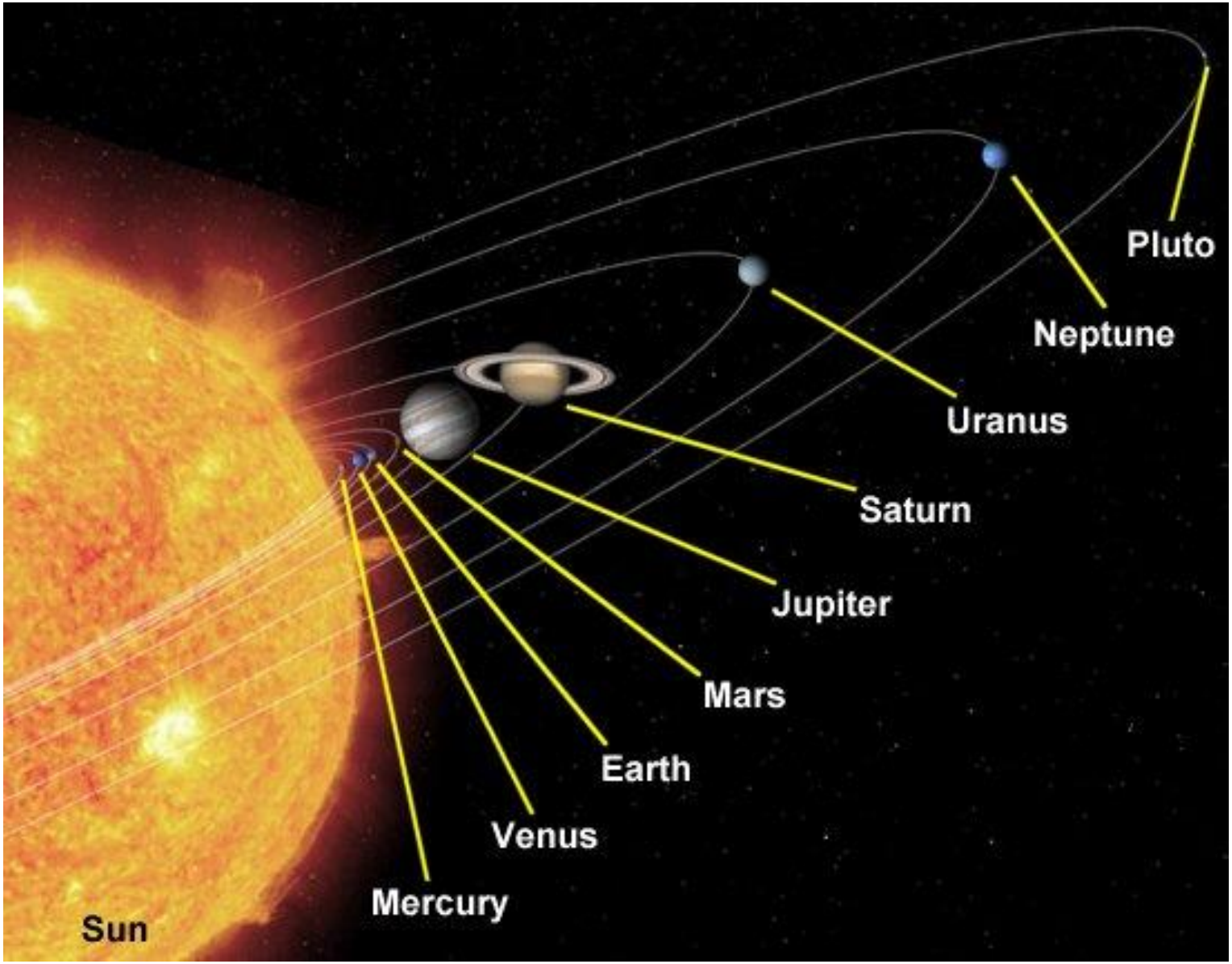
- Diameter - 109 times Earth's
- Volume - about 1,000,000 times Earth's
- Mass - about 300,000 times Earth's 99.8% of Solar System
- Density = Mass/Volume = 1.4 g/cm$^3$

The Sun is a **Gas Cloud** of mostly **Hydrogen** and Helium

- Surface Temperature = 5,800 degrees K
- Core Temperature = 15,000,000 degrees K
- Age about 5 billion years



# Sun's volume ~1,000,000X larger then Earth and ~1,000X larger then Jupiter



# Energy Production in the Sun

Sun produces

2 calories/cm$^2$/minute at Earth's surface

$10^{11}$ cal/minute entire Earth's surface

$10^{27}$ calories/minute entire Sun's surface

Energy produced in the Sun flows out as light (and other EM energy).

Equivalent energy units:

4 times $10^{26}$ Watts

same as

100 billion 1 Megaton Hydrogen bombs every second (though also hard to understand that) → LOTS of energy being produced

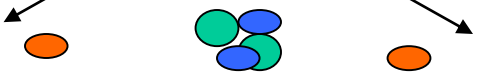
# Source of Sun's Energy

- Measured in 1800s but big mystery before 1940
- Chemical Reactions  NO, not even close
- Gravitational energy: can produce 100 million years at the Sun's output. Geology shows Earth is billions of years old. We will see gravity is the "spark" that starts the nuclear reactions
- Need nuclear reactions to power Sun. Uses $E=mc^2$
- Explained in 1939:Hans Bethe (1906-2005): Cornell University, Nobel prize for explaining nuclear reactions in Sun. Character in movie Fat Man and Little Boy about WWII atomic bomb (and I met in 1980 when I gave a talk at Cornell). As his mother was Jewish he lost his position in Germany in 1933, moved to England, and then the US where he accepted a faculty position at Cornell in 1935

# Atom = nucleus + electrons

He atom

size=$10^{-10}$ m



He nucleus size = $10^{-15}$ m

Proton

neutron

electron

## Some common atoms

Isotopes of Hydrogen

| | #e | #p | #n |
|---|---|---|---|
| Hydrogen | 1 | 1 | 0 |
| Deuterium | 1 | 1 | 1 |
| Tritium | 1 | 1 | 2 |
| Helium-4 | 2 | 2 | 2 |
| Carbon-12 | 6 | 6 | 6 |
| Carbon-14 | 6 | 6 | 8 |

# Atom = nucleus + electrons

Mass of atom is the sum of the mass of the protons, neutrons, and electrons minus the binding energy holding the neutrons and protons together in the nucleus

$$m(^1H) = 1.008u$$
$$m(electron) = 0.0005u$$
$$m(n) = 1.009u$$
$$m(^2H) = 2.014u$$
$$m(^3He) = 3.016u$$
$$m(^4He) = 4.0026u$$
$$m(^8Be) = 8.0055u$$
$$m(^{12}C) = 12.00000u$$

Isotopes of Hydrogen

u=atomic mass unit

Some common atoms

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|---|---|---|---|
| Hydrogen | 1 | 1 | 0 |
| Deuterium | 1 | 1 | 1 |
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# Strong Nuclear Force

- Holds protons and neutrons together in nucleus
- Strongest force. 20 times stronger than electric force
- Short range – about the size of proton
- Attractive. affects particles like protons and neutrons. Electrons do not “feel” this force

# More on strong force

As strong force is attractive:

2p + 2n "prefer" being bound together in Helium

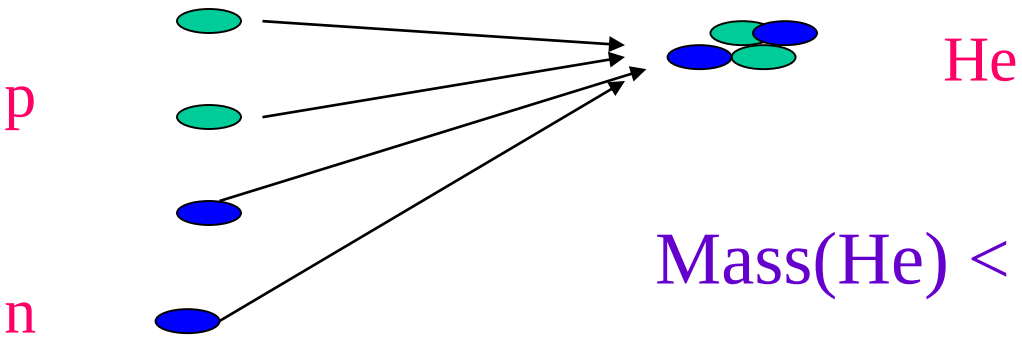
"preference" → mass of He is smaller than adding up the masses of 2 protons and +2 neutrons. Mass difference → energy released if the reaction happens

What nuclei are stable depends on interplay between attractive strong force and repulsive (between protons) electric force. Some nuclei are stable (H-1 H-2 C-12) and some are not (H-3 C-14) (half lives of 12.3 years and 5730 years)

# Mass converts to Heat Energy

Combining 2 protons + 2 neutrons into Helium converts Mass into Energy/Heat → Source of Sun's energy

$$m(^1H) = 1.008u$$
$$m(n) = 1.009u$$
$$m(^2H) = 2.014u$$
$$m(^4He) = 4.0026u$$




Mass(He) < Mass(2p)+Mass(2n)

4.0026 < 2.016 + 2.018 = 4.034

$$E = MC^2$$

Energy difference=binding energy holding n + p together

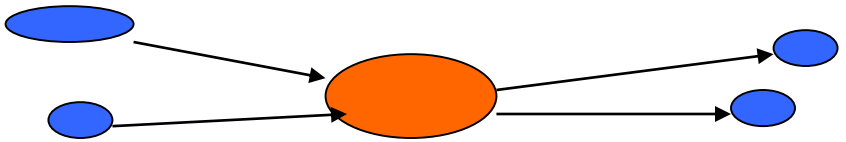
# Nuclear Reactions

- Nuclear reactions provide the source of the Sun's energy
- Strong nuclear force binds protons and neutrons together. Combining 2 protons and 2 neutrons into Helium converts a few percent of the initial particles mass into energy (heat). Called FUSION.
- For heavier nuclei, the repulsive electromagnetic force between the protons causes them to be less stable

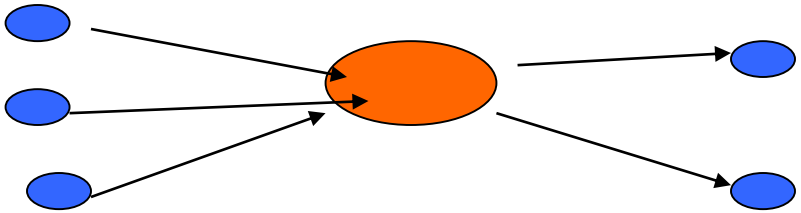
  Iron is the most stable (largest binding energy per nuclei)
- If heavy nuclei (Uranium) are broken up into light nuclei, energy is released. Called FISSION. Not "astronomy" and used for nuclear reactors or weapons.

# Nuclear Reactions Primer

- No free neutrons exist (lifetime is 15 minutes)
- repulsive electric force between protons. → high temperatures (at least 5 million degrees K) to get protons close to each other → then strong force binds them together
- usually 2 body reactions as much more probable



2 to 2

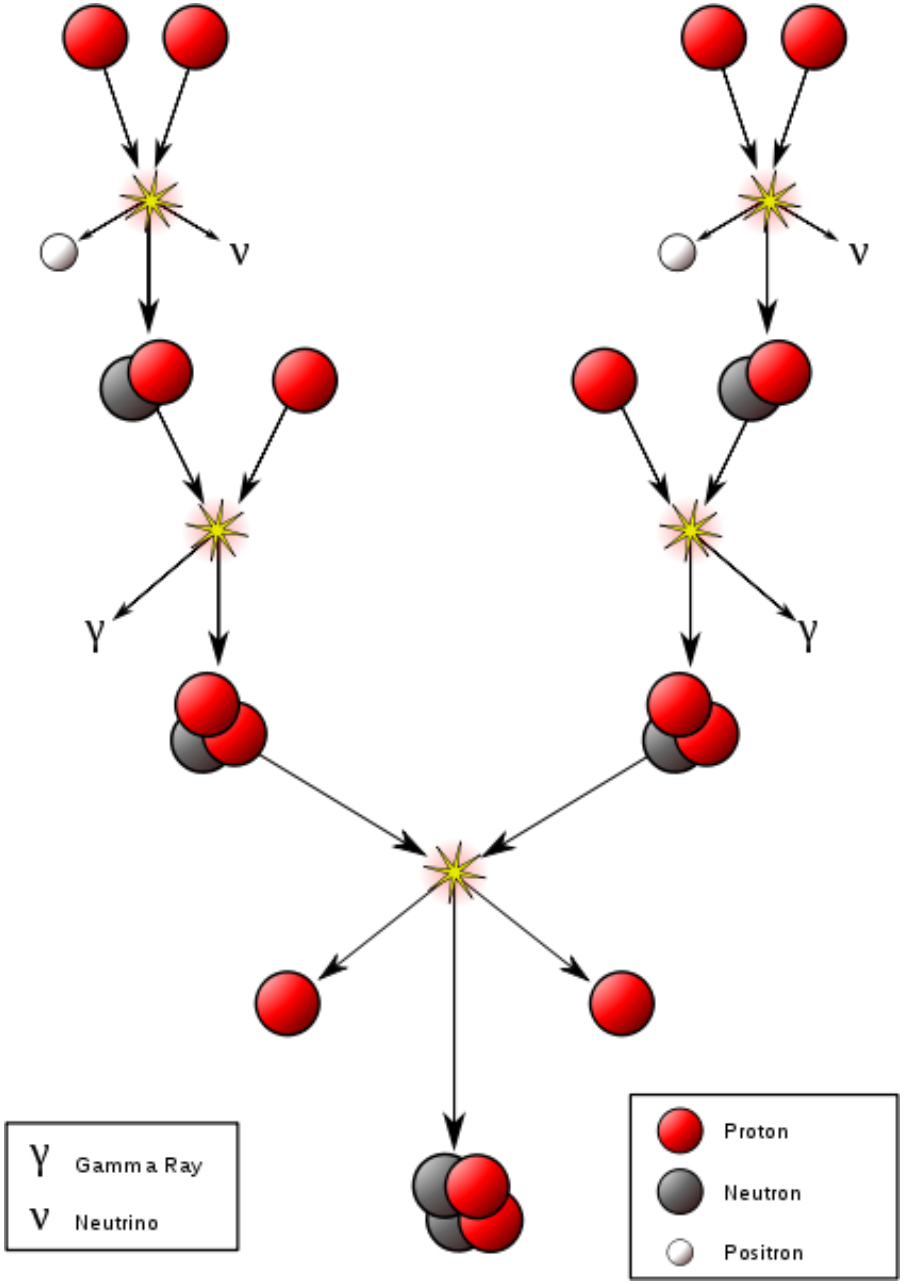


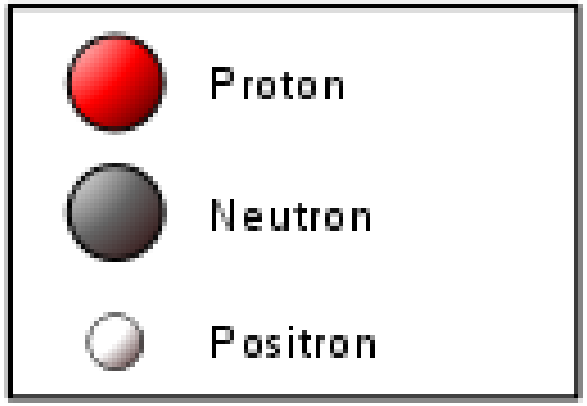
3 to 2

# The Neutron

- The neutron is just like the proton but without an electric charge
- The neutron has a mass slightly larger then the proton. No one understands why "accident of Nature"
- A free neutron radioactively decays to a proton (plus electron and antineutrino) with a lifetime of about 15 minutes
  → no free neutrons in Sun and so have to "make" by changing protons into neutrons. This slows up the fusion reactions in the Sun allowing it to live for about 10 billion years
- Stable neutrons exist in nuclei like Helium, Carbon, etc

# Proton-proton cycle 3 steps




# Proton-proton cycle Reaction 1

$$m(^1H) = 1.008u$$
$$m(n) = 1.009u$$
$$m(^2H) = 2.014u$$

$p + p \rightarrow (pn) + e^+ + \nu_e$

- Slowest reaction as have to "make" the neutron
- (pn) = Deuterium nucleus (heavy hydrogen)
- $e^+$ = positron. antiparticle of electron (electrons and positrons can annihilate each other). Mass of positron = mass of electron and is 1/2000 mass of proton. For this class assume their masses are 0 and mass of Hydrogen = mass proton
- $\nu_e$ is neutrino. Basically an electron without any charge. Only feels weak nuclear force
- Reactions releases energy since Mass(D+electron+neutrino) is less than Mass(p+p) $2.014 + 0 + 0 = 2.014 < 2.016$

# Weak Nuclear Force

- Affects all particles (except photon)
- Weaker than electromagnetic force but much stronger than gravity
- Short range - size of proton
- Causes changes in particle type. Many radioactive decays are “weak” and can occur slowly

proton ⟷ neutron

electron ⟷ neutrino

particle ⟷ antiparticle

# Neutrinos - little neutral ones (Italian joke)

- Postulated to exist in 1930s (partially by Enrico Fermi), discovered in 1950s. Three types. Neutrinos (ν) have:

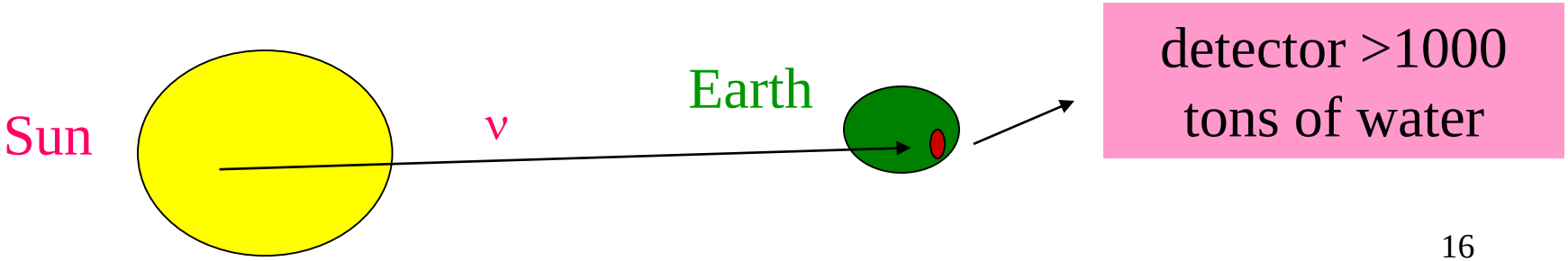
  almost 0 mass

  no electric charge

  unaffected by strong nuclear force

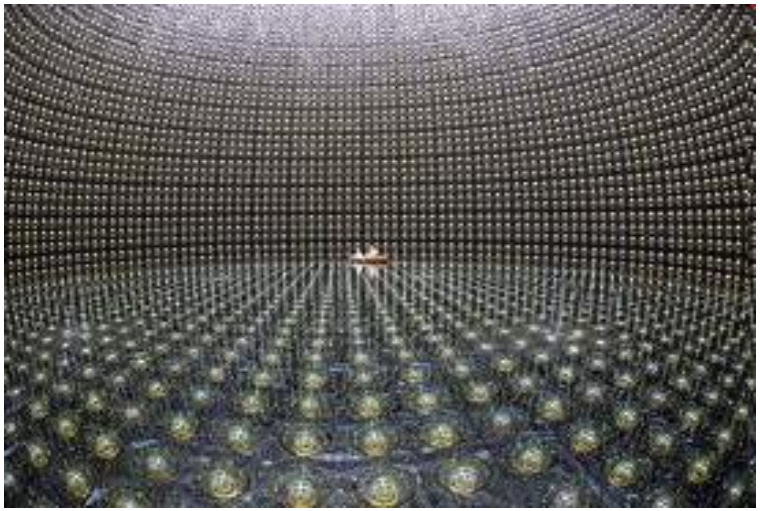
and so only interact through the weak nuclear force

- only $1/10^{10}$ produced in the Sun's interior interact when going through the Sun's outer layers → so can be used to study Sun's interior

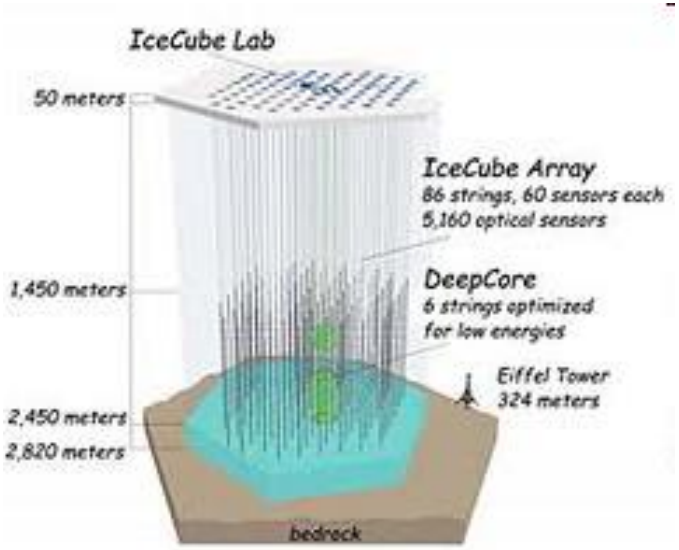


# Neutrino Astronomy

- Neutrino observatories can observe neutrinos coming from the Sun, from supernovas, and maybe from black holes
- most are large water containers deep underground – Japan, Canada, US, Russia, Italy, India (movie 2012. Link on class web page)
- some instrument Antarctica ice or Mediterranean water



Note physicists in boat working on the detectors which surround the water tank




Make 3000 m holes in ice with hot water and then place strings of detectors in holes

# p-p cycle Reaction 2

(pn) + p → (ppn) + γ

Deuterium nucleus (pn) absorbs a proton, becomes Helium-3 (ppn).
Helium in excited state, emits a photon (γ) → ground state.

# p-p cycle Reaction 3

(ppn) + (ppn) → (ppnn) + p + p

Two He-3 nuclei collide. rearrange particles

very stable He-4 nuclei formed

2 extra protons left over.

Both happen relatively quickly as mostly just strong force
and do not have to "make" any new particles

# p-p cycle total

- p+p+p+p+p+p → (ppnn) + ν + ν + Energy

or 6 protons are used to form 1 Helium nucleus plus 2 neutrinos plus Energy (in the form of the 2 positrons and 2 protons and 2 photons)

- Sun is converting Hydrogen into Helium
- Sun is converting part of its Mass into Energy.
- In 10 billion years about 1% of Sun's mass is so converted (and then Hydrogen fusion burning stops)
- fusion rate depends on temperature and density of the very inner region of the Sun, which is called the core → larger temperatures will cause rate to happen faster; see in larger stars

# Summary

- The STRONG NUCLEAR force can cause energy to be released if protons and neutrons are combined
- High temperatures, provided by the GRAVITATIONAL force, are needed to overcome the ELECTROMAGNETIC repulsive force between the protons
- Neutrons must be made from protons by the WEAK NUCLEAR force.
- All 4 forces are necessary for the Sun to produce energy

# Extra slides