The Energy of the Sun

Measures and Theories

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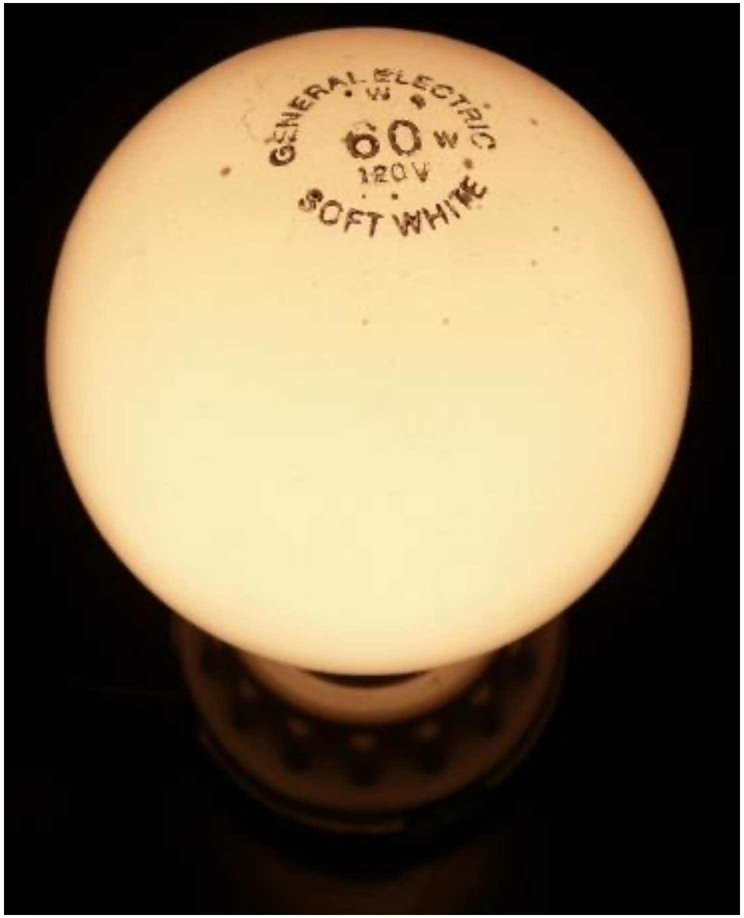
2	Describe the basic properties and composition of each part of the Sun listed above.	
3	Explain and describe granulation and supergranulation.	
4	Explain what is meant by helioseismology and describe how it has yielded information about the Sun's structure.	9, 10
5	Define, explain, and state the approximate values of the solar constant and the Sun's luminosity.	11 – 19
6	Describe mechanisms by which energy is transported from the core of the Sun to its exterior.	
7	Explain the process by which the Sun produces energy – fusion and relate this to the law of conservation of mass and energy and the strong nuclear force.	
8	Describe and explain the steps of the proton-proton chain in terms of reactions involving fundamental and subatomic particles.	
9	Describe efforts to obtain experimental evidence of the fusion process thought to power the Sun including measurements of solar neutrinos.	
10	Compare and contrast the concepts quiet Sun and active Sun.	20 – 23
11	Describe the appearance of sunspots and explain their formation in terms of the Sun's magnetic field.	
12	Define and explain the following concepts: sunspot cycle, solar cycle, solar minimum, and solar maximum.	
13	Describe and explain active regions of the Sun including prominences, and flares, spicules, and coronal mass ejections.	

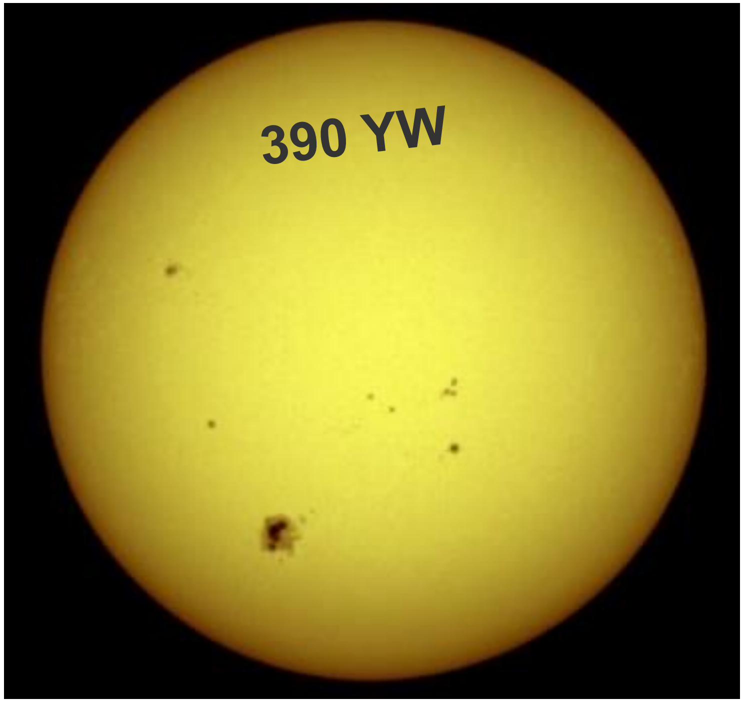
How many Watts is the Sun?

The Sun’s Power

- The Sun radiates electromagnetic energy of many different wavelengths but primarily emits visible light.
- Based on light measured here on Earth, it is known that the total power output of the Sun is 3.9×10^{26} watts.
- This is called the **luminosity** of the Sun.
- This means the Sun emits 3.9×10^{26} joules of energy every second.

How many Watts is the Sun?





The Sun's luminosity = 390 yottawatts!

How Much is Energy is That?

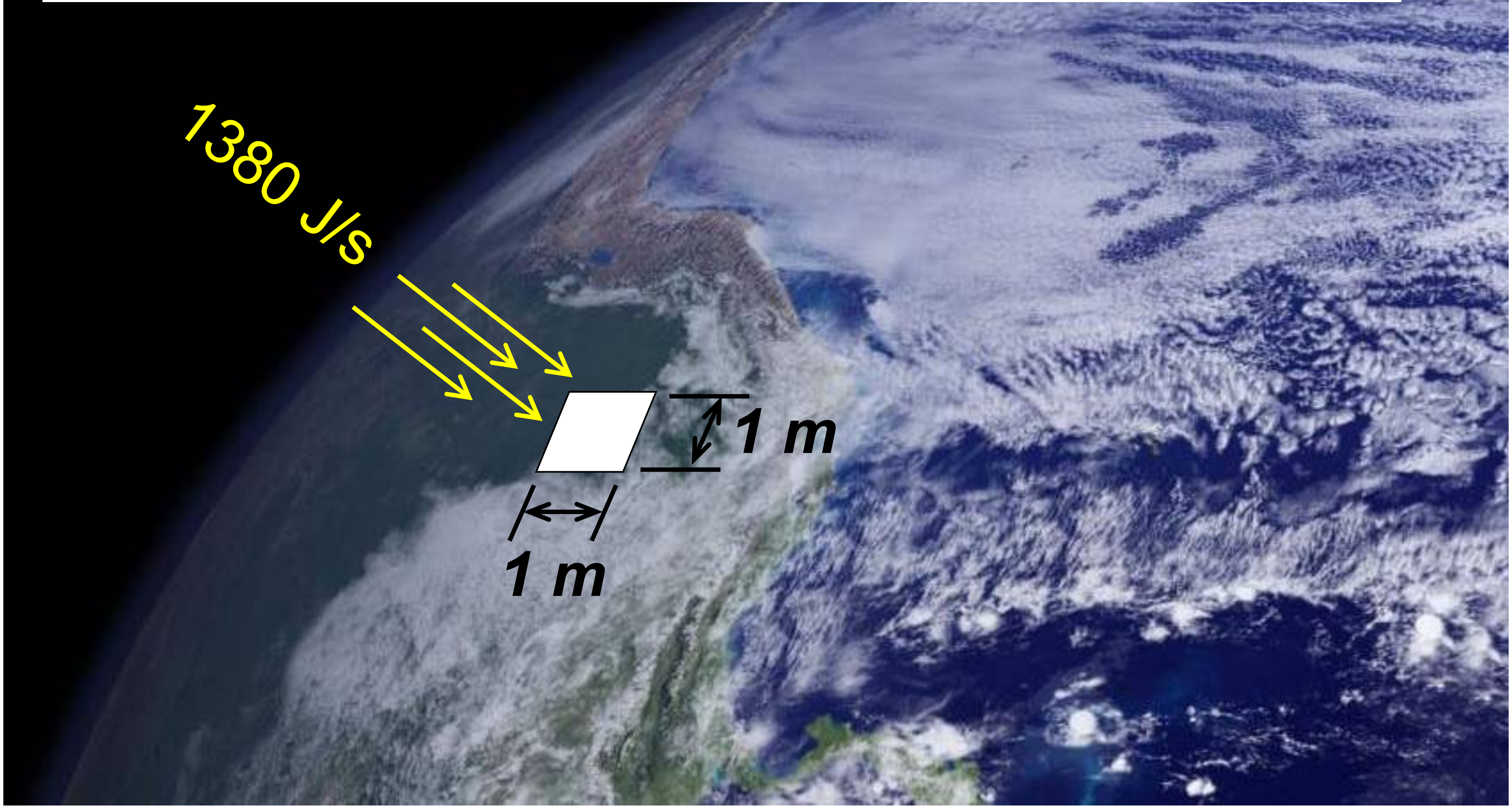
- Compare it to 1 Megaton of TNT, which releases 4.2×10^{15} J of energy.
- It's like 93 billion atomic bombs going off every second!
- Compare it to the total energy used by all the inhabitants of the world: 4×10^{20} J per year.
- The Sun produces enough energy in one second to power mankind's needs for one million years!

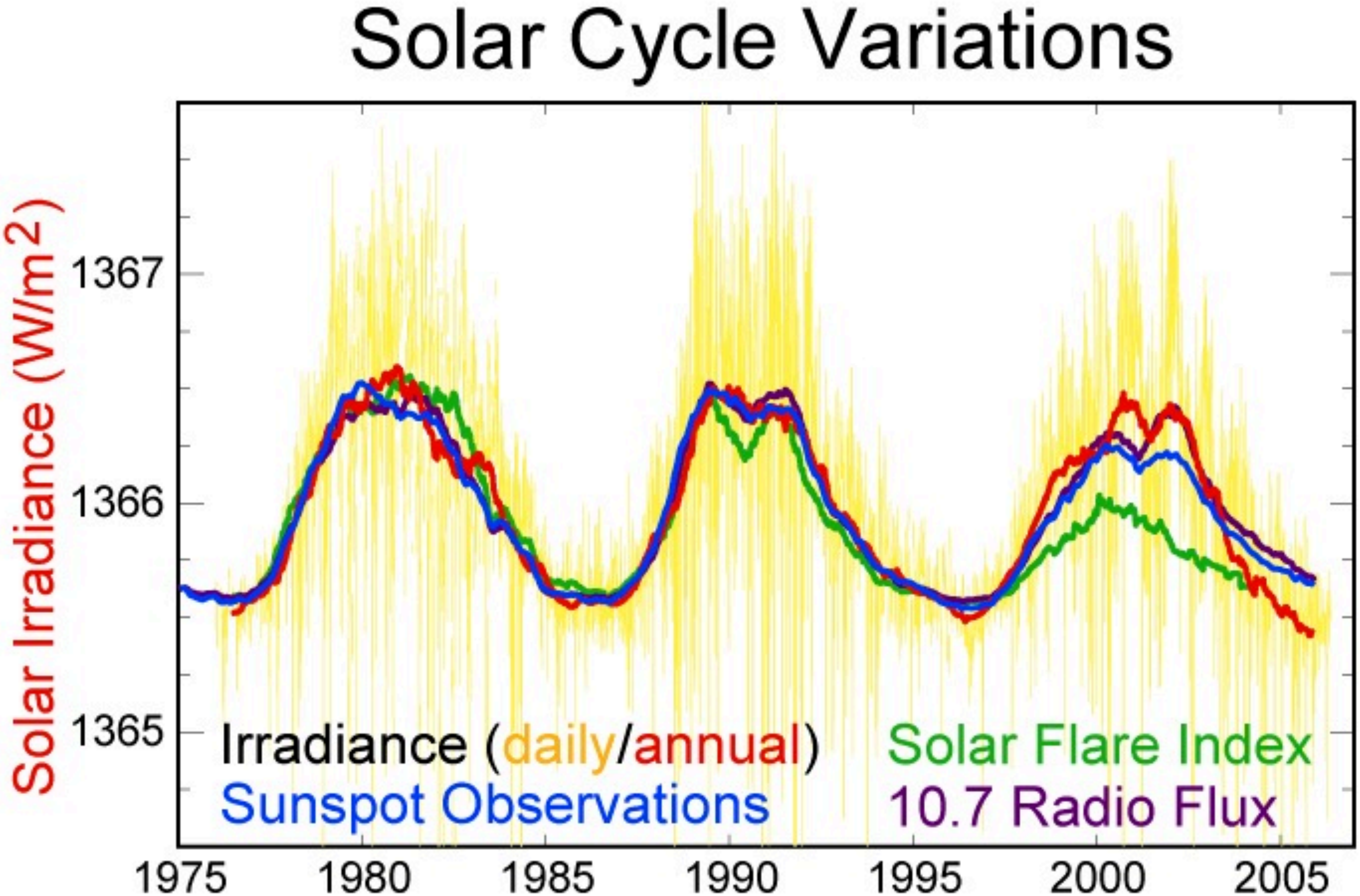
How do we know?

- The Sun's light has an intensity of 1380 watts per square meter as it reaches the Earth. This is called the "solar constant".
- This means that every square meter of a surface gets hit by 1380 watts of sunlight.
- Based on the distance to the Sun this value can be used to determine the wattage of the Sun…


Sunlight falls upon Earth …

…but only 1380 joules of energy per second falls upon a single square meter. This is called the **solar constant** (or irradiance).





Solar Cycle Variations
Solar Irradiance (W/m2)
1367
1366
1365
1975
1980
1985
1990
1995
2000
2005
Irradiance (daily/annual)
Sunspot Observations
Solar Flare Index
10.7 Radio Flux

Using a solar panel with area one square meter how much time would it take to “collect” energy equivalent to that in one gallon of gasoline (120 MJ)?

$$rate = \frac{amount}{time}$$

$$time = \frac{amount}{rate} = \frac{120 \times 10^6 \text{J}}{1380 \frac{\text{J}}{\text{s}}}$$

t = 86957 s = 24 hours

Suppose the same energy is to be collected in one hour – how big should the solar panel be?

24 times bigger in terms of area,
for example a rectangle 4 m by 6 m

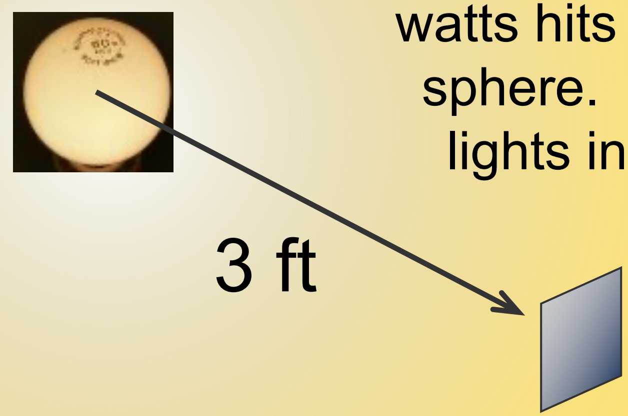
Understanding irradiance or flux…

$$Flux = \frac{Luminosity}{surface\ area}$$

In this example imagine being 3 feet away from a 60 watt light bulb – how intense is the light's energy at that distance. The total energy at that distance is spread out evenly over a sphere of radius 3 feet so that 0.53 watts hits each square meter of the sphere. This is a measure of the lights intensity at that distance.

$$F = \frac{L}{4\pi r^2}$$

60 W



$$F = \frac{60}{4\pi 3^2}$$

$$F = \frac{60\ \text{W}}{113\ \text{ft}^2}$$

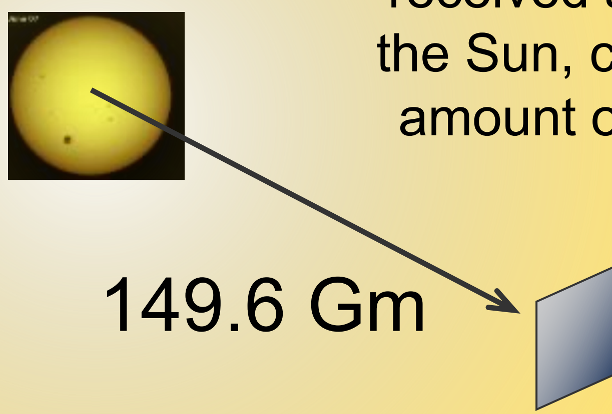
? W/ft^2

0.53 W/ft^2

Finding the Wattage of the Sun

To find the luminosity of the Sun is to find its total power output in watts. This is similar to the example with the light bulb, but now work the problem in reverse. The intensity of sunlight received at Earth, 1 AU distant from the Sun, can be used to find the total amount of light emitted by the Sun.

? W



149.6 Gm

1380 W/m^2

$$F = \frac{L}{4\pi r^2}$$

$$L = F(4\pi r^2)$$

$$L = 1380\frac{W}{m^2}(4\pi(149.6\times10^9 m)^2)$$

$$L = 3.9\times10^{26}\text{ W} = 390\text{ YW}$$

How Can the Sun Do It?!

- The Sun is thought to have been giving off energy at about the same rate for billions of years.
- The only known source of energy that could possibly account for the Sun's output is **nuclear fusion**.
- For example, if the Sun were a huge ball of pure gasoline it would represent "only" 4.1×10^{37} J – how long could it burn?
- Only 3300 years!

Why Fusion?

- In nuclear reactions such as fusion, the amount of energy released can be determined by Einstein's equation:
  $E = mc^2$
- A reduction in mass results in a release of energy. If this is happening in the Sun, then its mass is decreasing as it emits energy!
- Find the time for the Sun's mass to decrease by one Earth mass...
- 44 million years!

Why Fusion?

- Find the mass converted to energy in 3300 years of Solar output...
- 1/100 th the mass of the Moon!
- At this rate the Sun can continue to “burn” for billions of years!
- It is thought that the Sun will continue to shine at about the same brightness for another 5 billion years!

What *is* Fusion?

- A fusion reaction is one in which "lighter" nuclei fuse or join with one another to form "heavier" nuclei.
- If the mass of the products is less than the mass of the reactants then energy is released as given by $E = mc^2$. This is Einstein's famous equation stating that energy equals mass times the speed of light squared.

What *is* Fusion?

- Every nucleus contains positive charge and so repel one another due to the like charges. However if the nuclear particles get close enough to one another there is a different force called the strong nuclear force that can hold the particles together (in spite of their mutual electrical repulsion).
- Only if particles are moving very fast can the nuclei get close enough for the strong force to overcome the electric force. Therefore fusion can only occur at very high temperatures and densities such as found in the core of the Sun.

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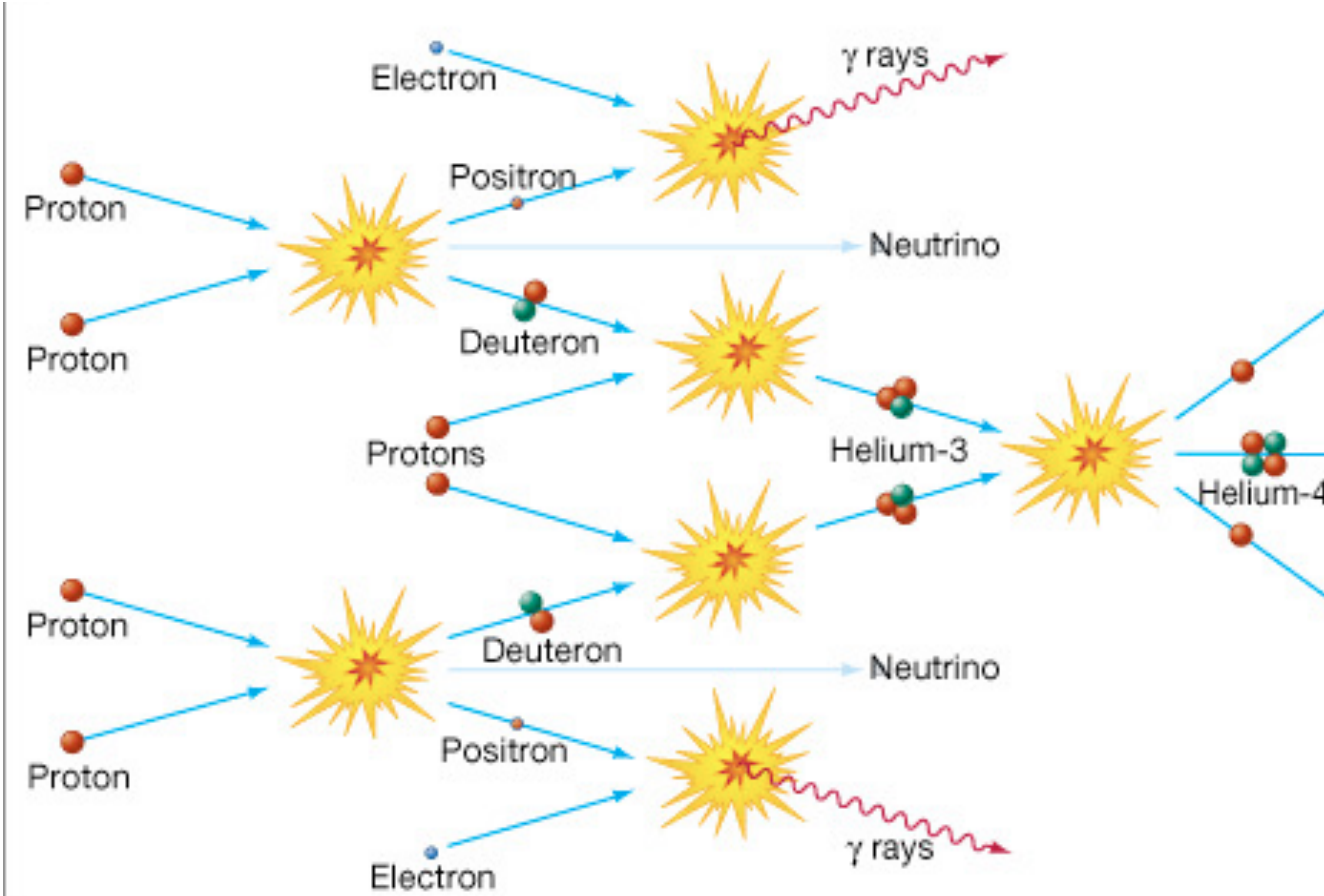
The Proton-Proton Chain

- The primary nuclear reaction in the Sun is thought to be the “proton-proton chain”.
- This is a fusion reaction in which hydrogen atoms fuse to form helium atoms.
- It consists of several intermediate reactions involving mainly protons.

The Proton-Proton Chain



The Proton-Proton Chain

1. $^{1}H + ^{1}H \rightarrow ^{2}H + e^{+} + \nu + \text{energy}$

2. $^{2}H + ^{1}H \rightarrow ^{3}He + \text{energy}$

3. $^{3}He + ^{3}He \rightarrow ^{4}He + ^{1}H + ^{1}H + \text{energy}$

4. $e^{+} + e^{-} \rightarrow \text{energy}$

↓

numbers for use with worksheet…

Notation – Nuclear/Particle Reactions

$^{A}_{Z}X$

X = chemical symbol

Z = atomic number (number of protons)

A = mass number (number of nucleons)

note: Z is often omitted

"Nucleons" are any particles in the nucleus – protons and neutrons.

<u>Isotopes – same element, different masses</u>

$^{12}_{6}C$ A carbon atom with 12 nucleons: 6 protons and 6 neutrons

^{14}C A carbon atom with 14 nucleons: 6 protons and 8 neutrons

Proton-Proton Chain – the Players:

^{1}H – an ordinary hydrogen nucleus (a proton)

^{2}H – a deuteron – an isotope of hydrogen (1 proton and 1 neutron)

^{3}He – an isotope of helium (2 protons 1 neutron)

^{4}He – ordinary helium (2 protons 2 neutrons)

Proton-Proton Chain – the Players:

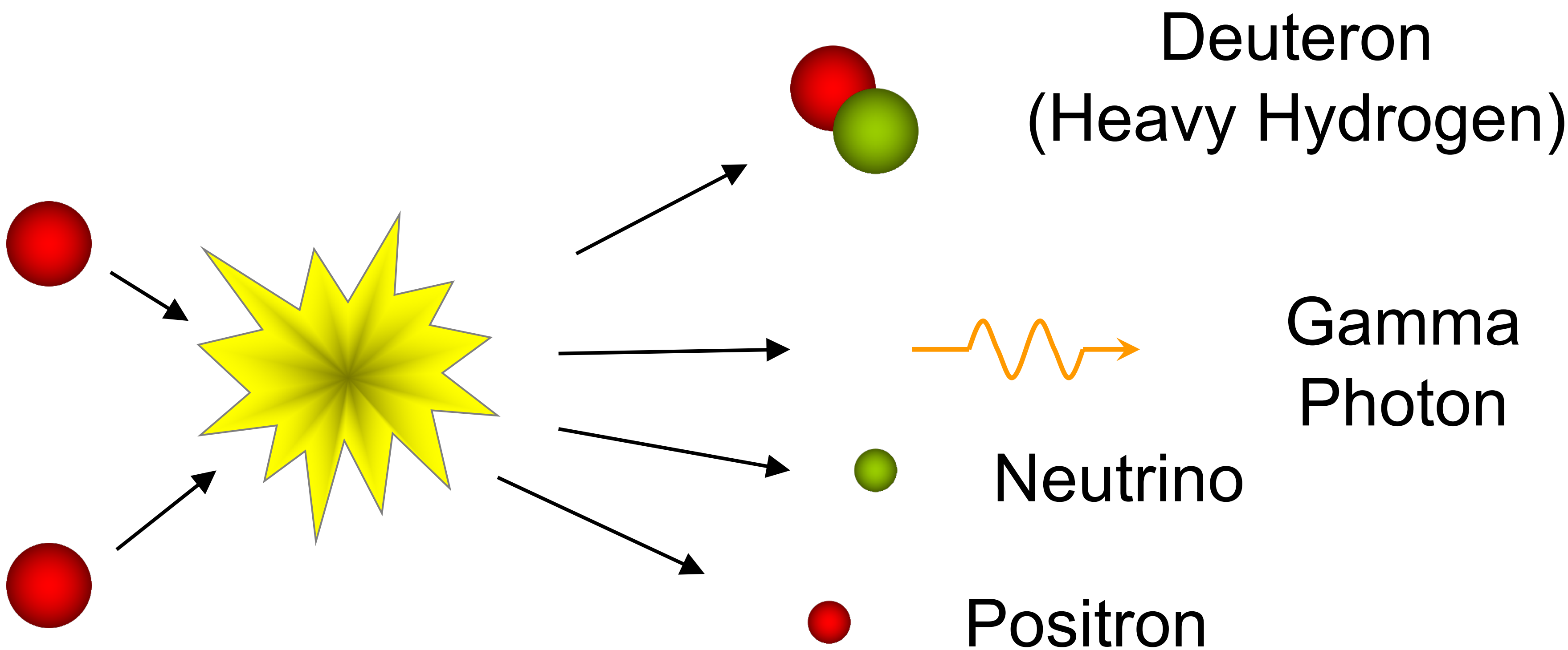
e^- – an electron

e^+ – a positron
(identical to electron, but positively charged)

ν – a neutrino
(a tiny tiny tiny tiny tiny tiny tiny particle
with zero charge)

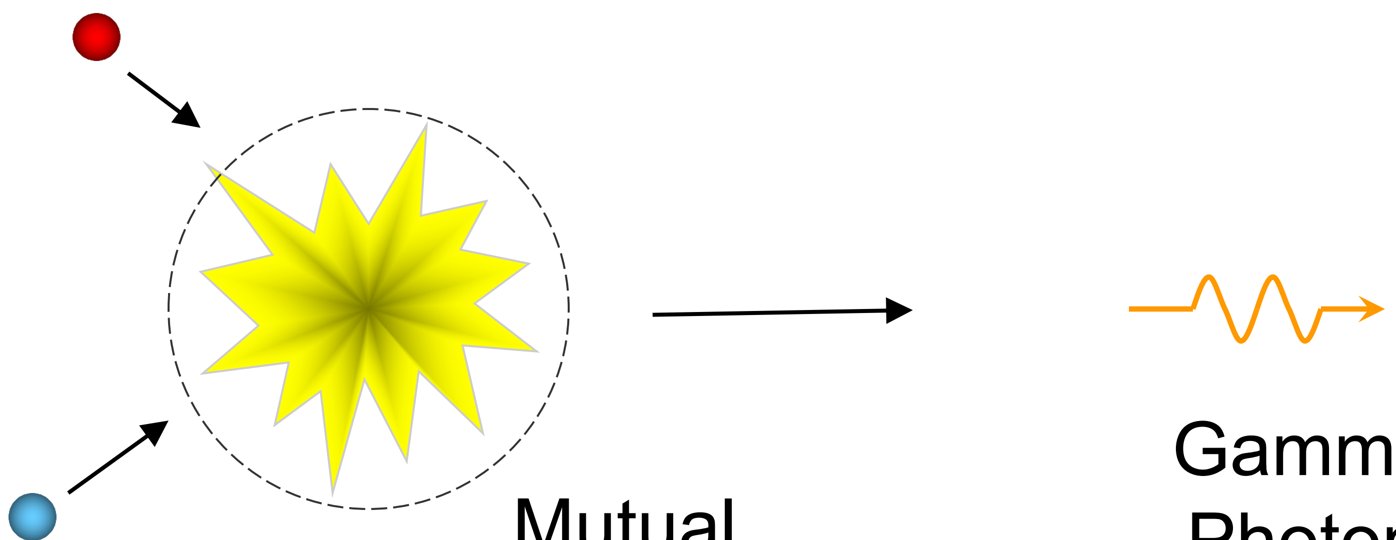
The Proton-Proton Chain

$$^{1}H + ^{1}H \rightarrow ^{2}H + e^{+} + \nu + energy$$



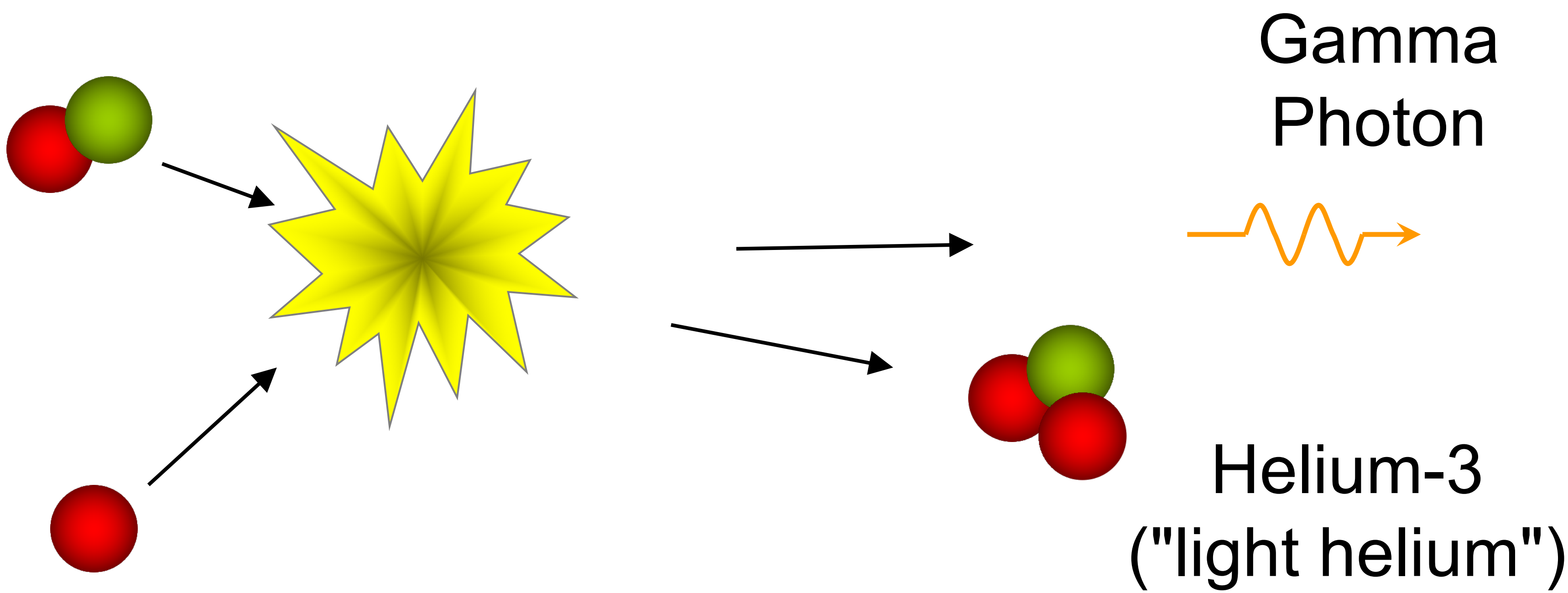
The Proton-Proton Chain

$e^+ + e^- \rightarrow$ energy



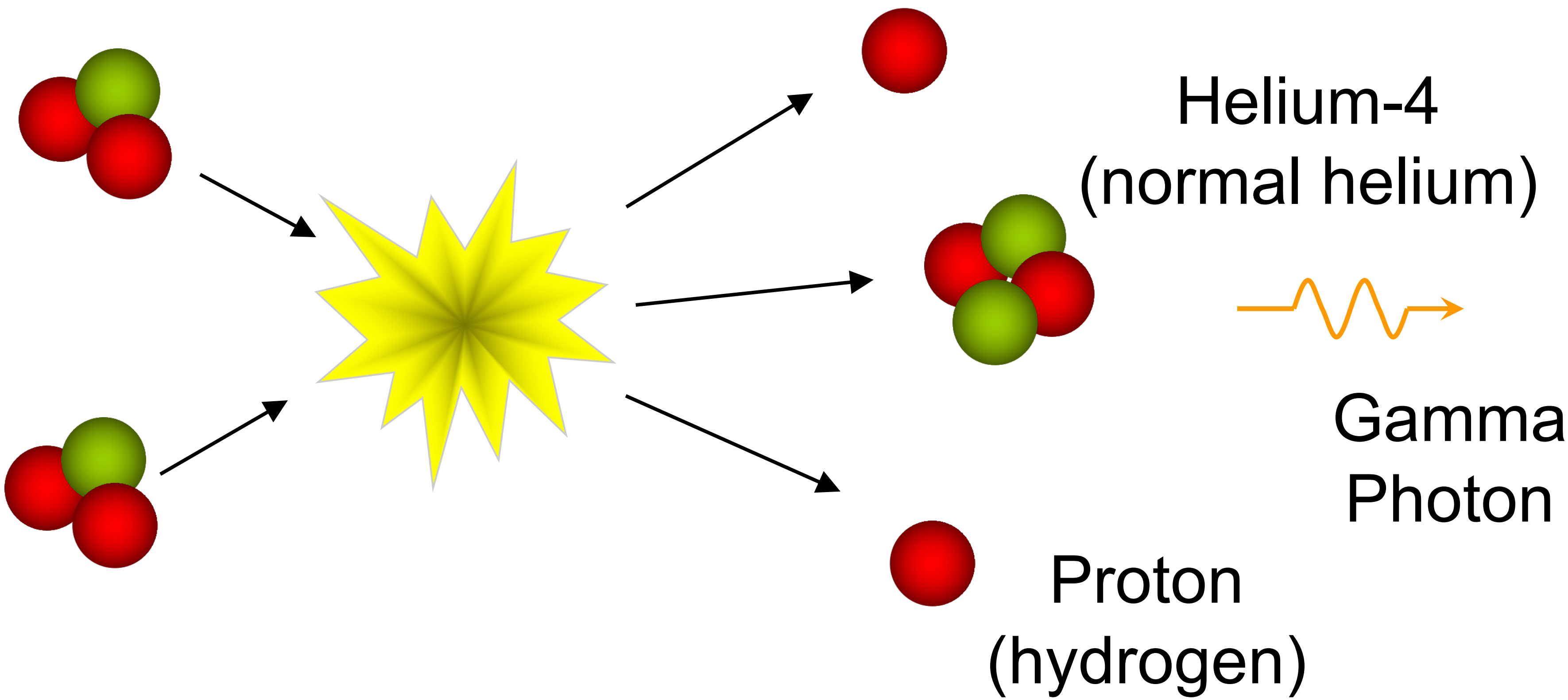
The Proton-Proton Chain

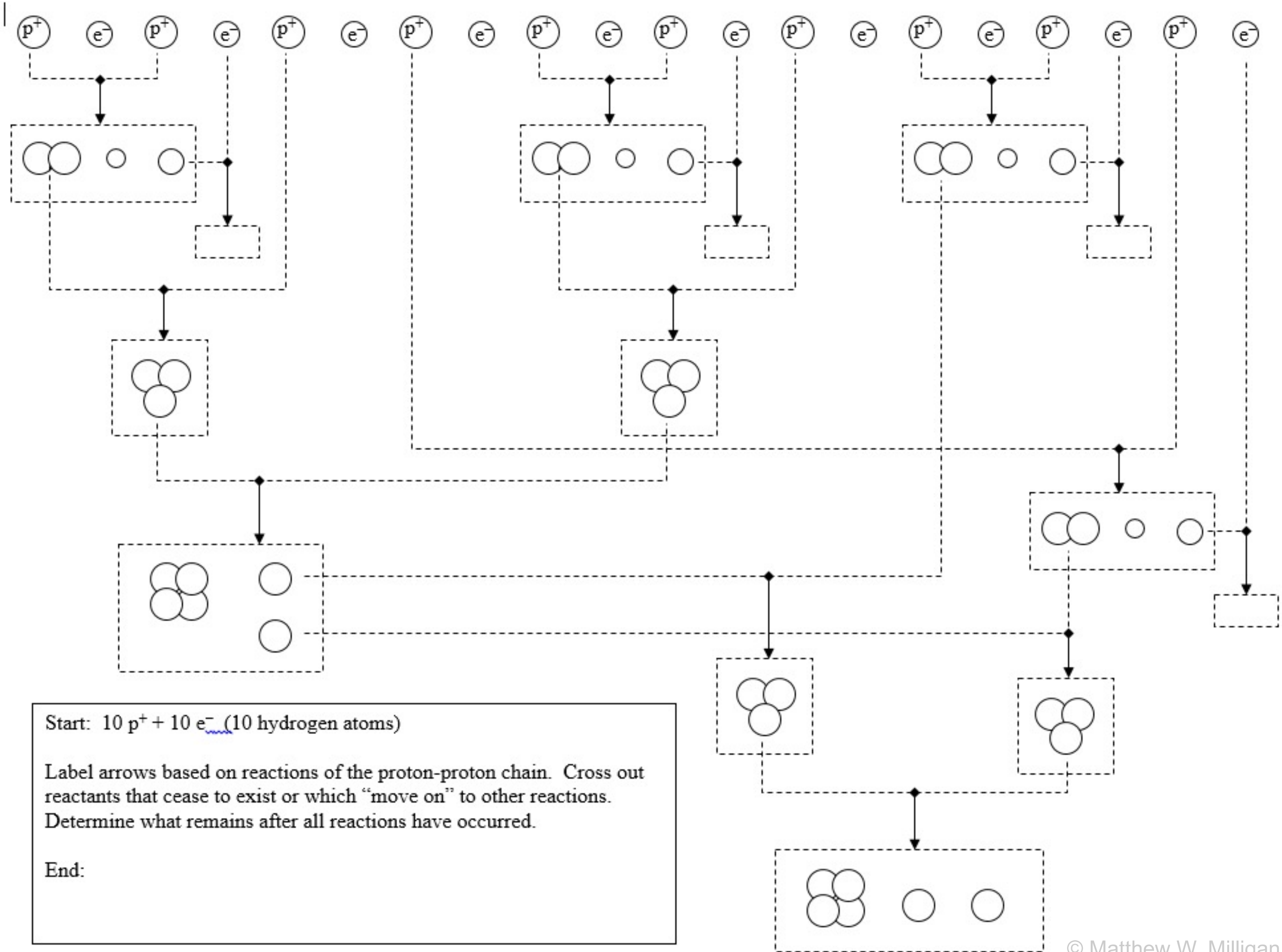
$^{2}H + ^{1}H \rightarrow ^{3}He + \text{energy}$



The Proton-Proton Chain

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + {}^{1}H + {}^{1}H + \text{energy}$$





Start: 10 p^{+} + 10 e^{-} (10 hydrogen atoms)

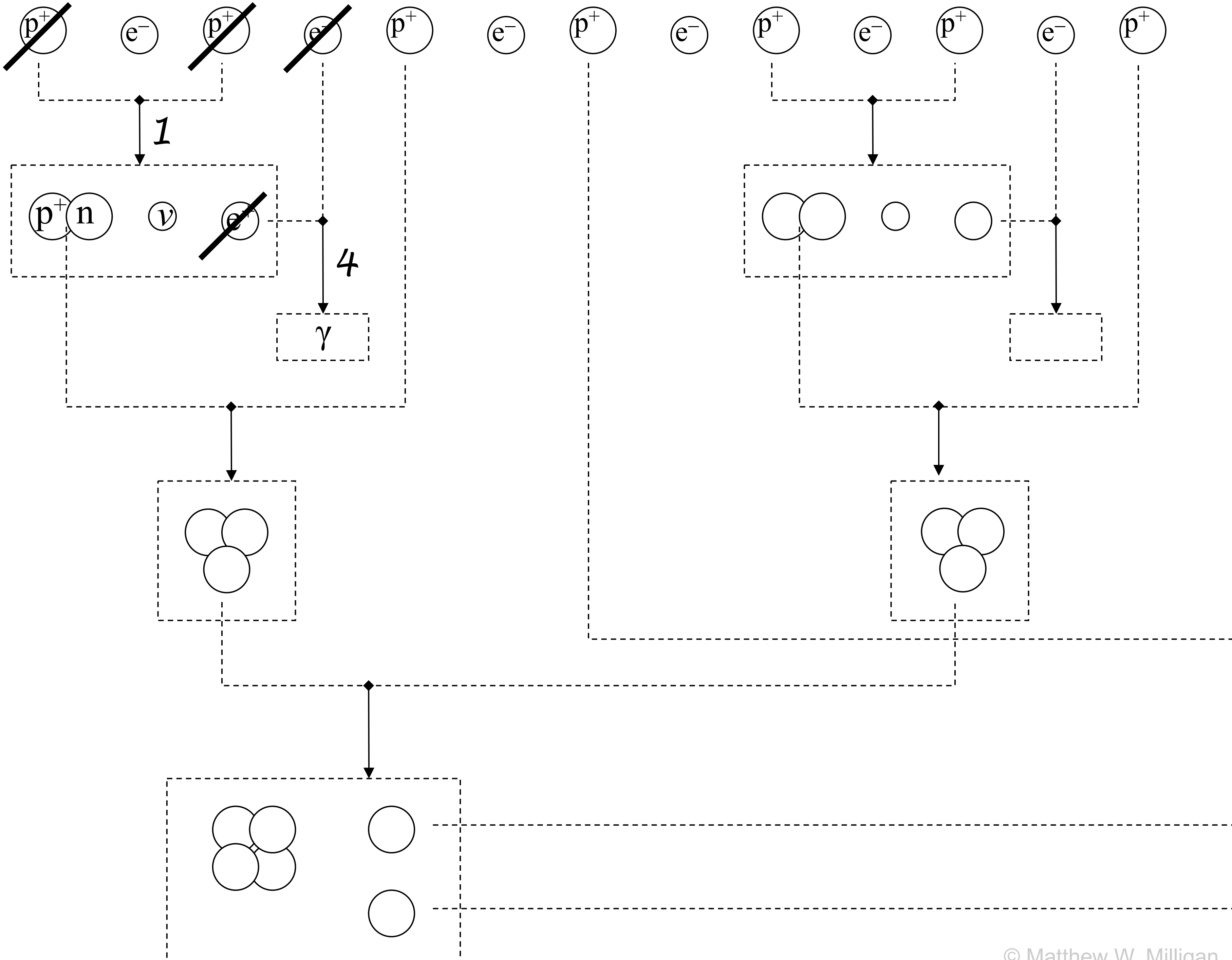
Label arrows based on reactions of the proton-proton chain. Cross out reactants that cease to exist or which "move on" to other reactions. Determine what remains after all reactions have occurred.

End:

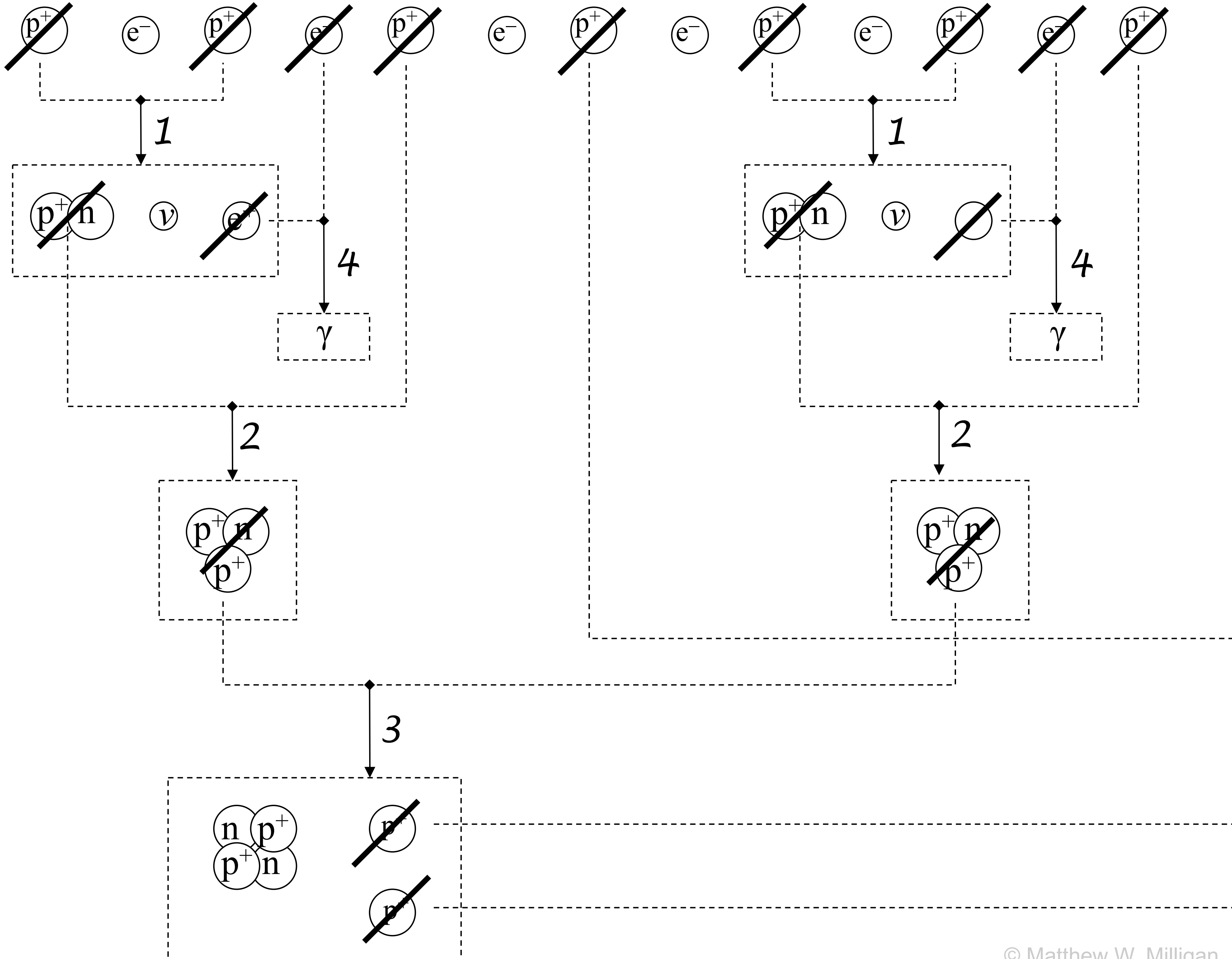
Start: $10\ p^+ + 10\ e^-$ (10 hydrogen atoms)

Label arrows based on reactions of the proton-proton chain. Cross out reactants that cease to exist or which "move on" to other reactions. Determine what remains after all reactions have occurred.

End:



p+
e−
p+
e+
p+
e−
p+
e−
p+
e−
p+
e−
p+
1
p+
n
ν
e+
4
γ



p+
e−
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p+
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1
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p+
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4
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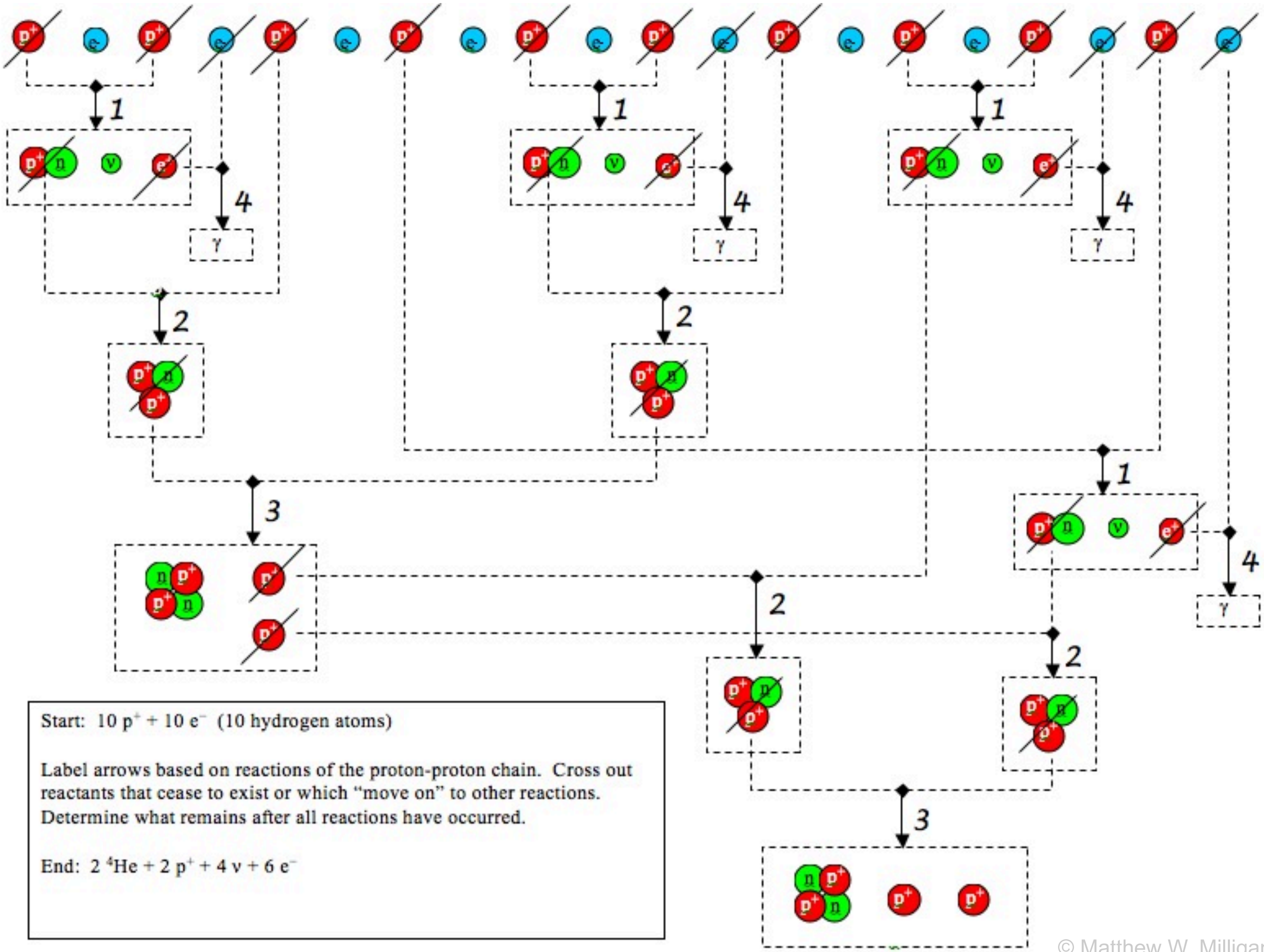


Start: 10 p^+ + 10 e^- (10 hydrogen atoms)

Label arrows based on reactions of the proton-proton chain. Cross out reactants that cease to exist or which "move on" to other reactions. Determine what remains after all reactions have occurred.

End: 2 ^4He + 2 p^+ + 4 ν + 6 e^-

Start: 10 p^+ + 10 e^- (10 ^1H)

Reaction 1 occurs 4 times

Reaction 2 occurs 4 times

Reaction 3 occurs 2 times

Reaction 4 occurs 4 times

End: $2\ ^4He + 2\ p^+ + 4\ \nu + 6\ e^-$

or

$2\ ^4He + 2\ ^1H + 4\ \nu + 6\ e^-$

The Proton-Proton Chain

Net result:

$4(^1H) \rightarrow {}^4He + 2\nu + \text{energy}$

Hydrogen converts to Helium and energy and neutrinos are produced.

The Proton-Proton Chain

- To produce 0.9929 kg of helium requires 1.0000 kg of hydrogen to undergo this process.
- The "missing" mass of 0.0071 kg is "converted" to energy by $E = mc^2$
- For every kilogram of hydrogen used there is a release of 6.4×10^{14} J of energy.
- This is equivalent to the energy in six million gallons of gasoline!

The Neutrino Problem

- Neutrinos generated in the core of the Sun during the proton-proton chain fly out into space in all directions.
- Detection of these particles is evidence of the reactions occurring in the Sun.
- For years neutrino detectors recorded only about one third the neutrinos expected.

Fun Fact: The flow of neutrinos from the Sun that reaches the Earth has an intensity of about 64 billion per cm^2 per second!

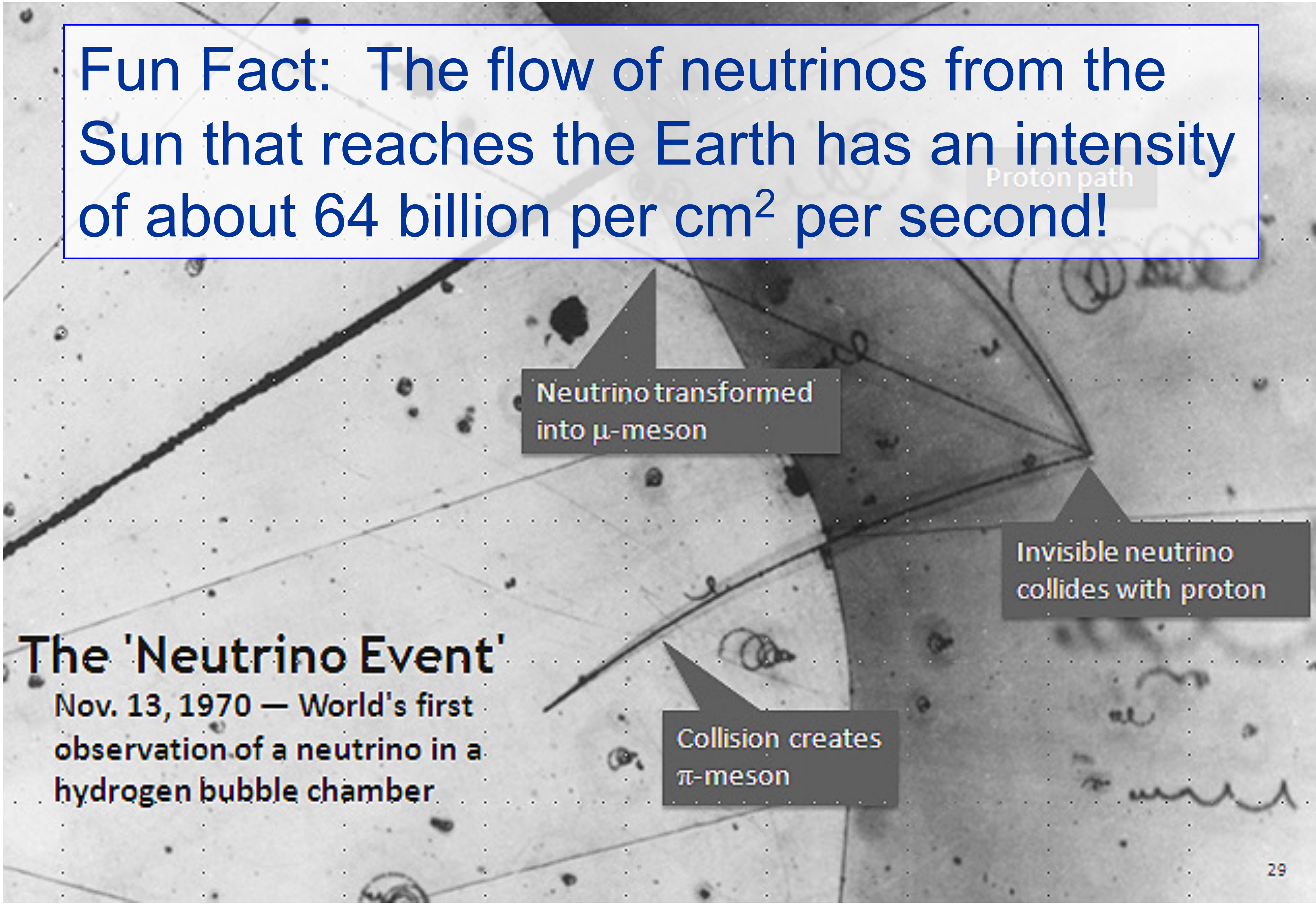
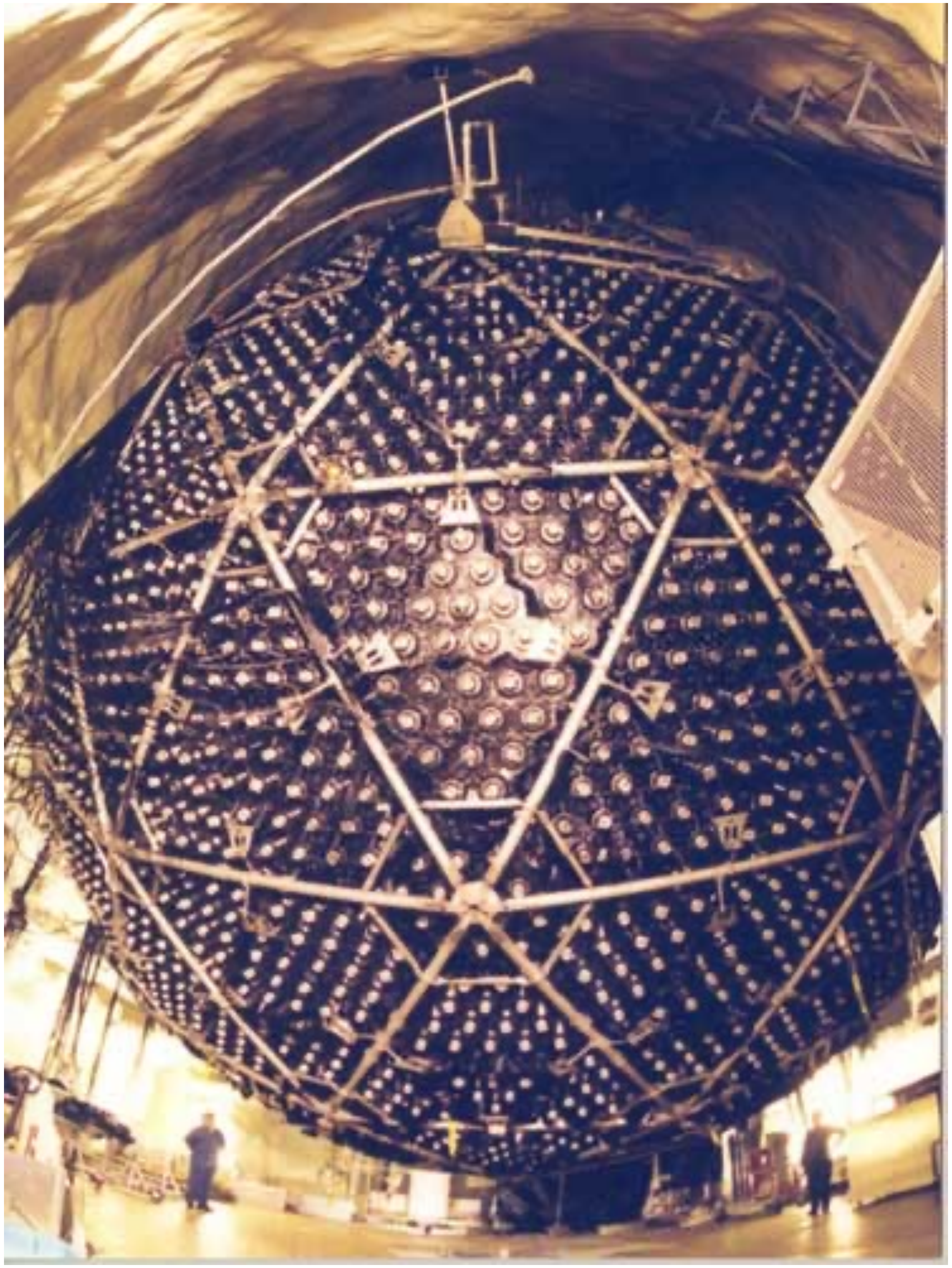


image: Argonne National Laboratory

The Neutrino Problem – Solved!

- It has been determined that neutrinos have a very small but nonzero mass.
- This "allows" for neutrinos to "oscillate" among three types – electron neutrinos, muon neutrinos, and tau neutrinos.
- Early detection methods could only measure electron neutrinos.
- The electron neutrinos produced in the Sun oscillate into other types while traveling to Earth.

Sudbury Neutrino Observatory



Cherenkov Radiation

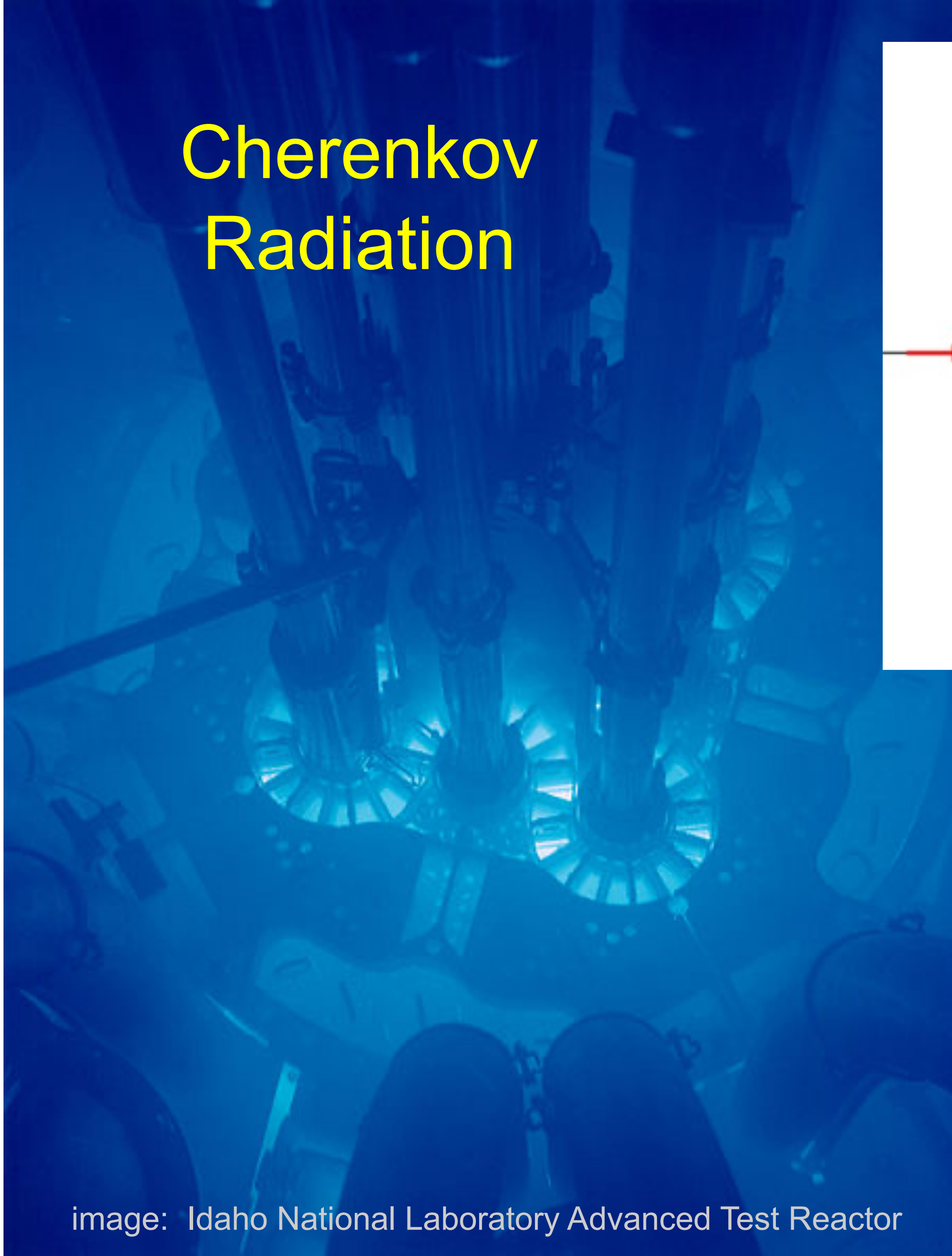


image: Idaho National Laboratory Advanced Test Reactor

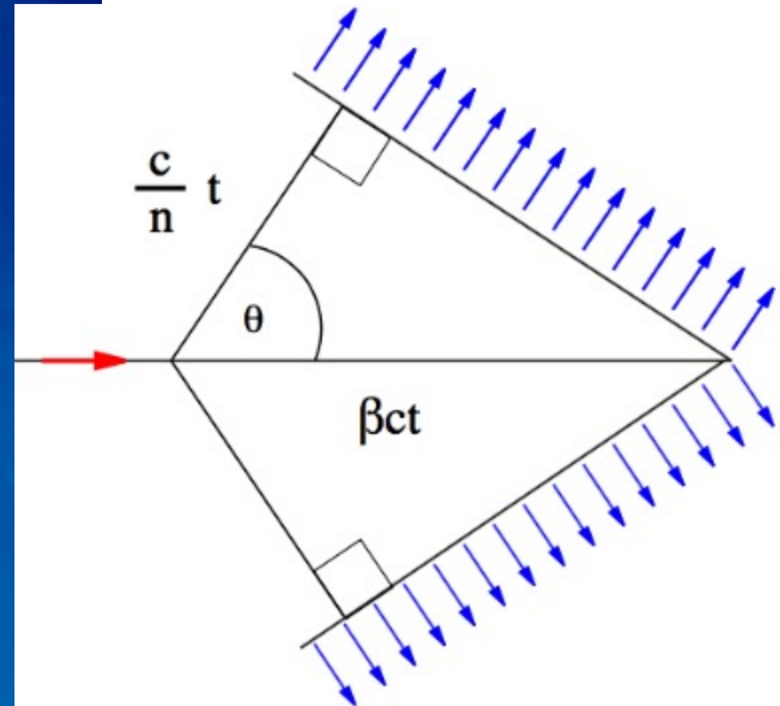
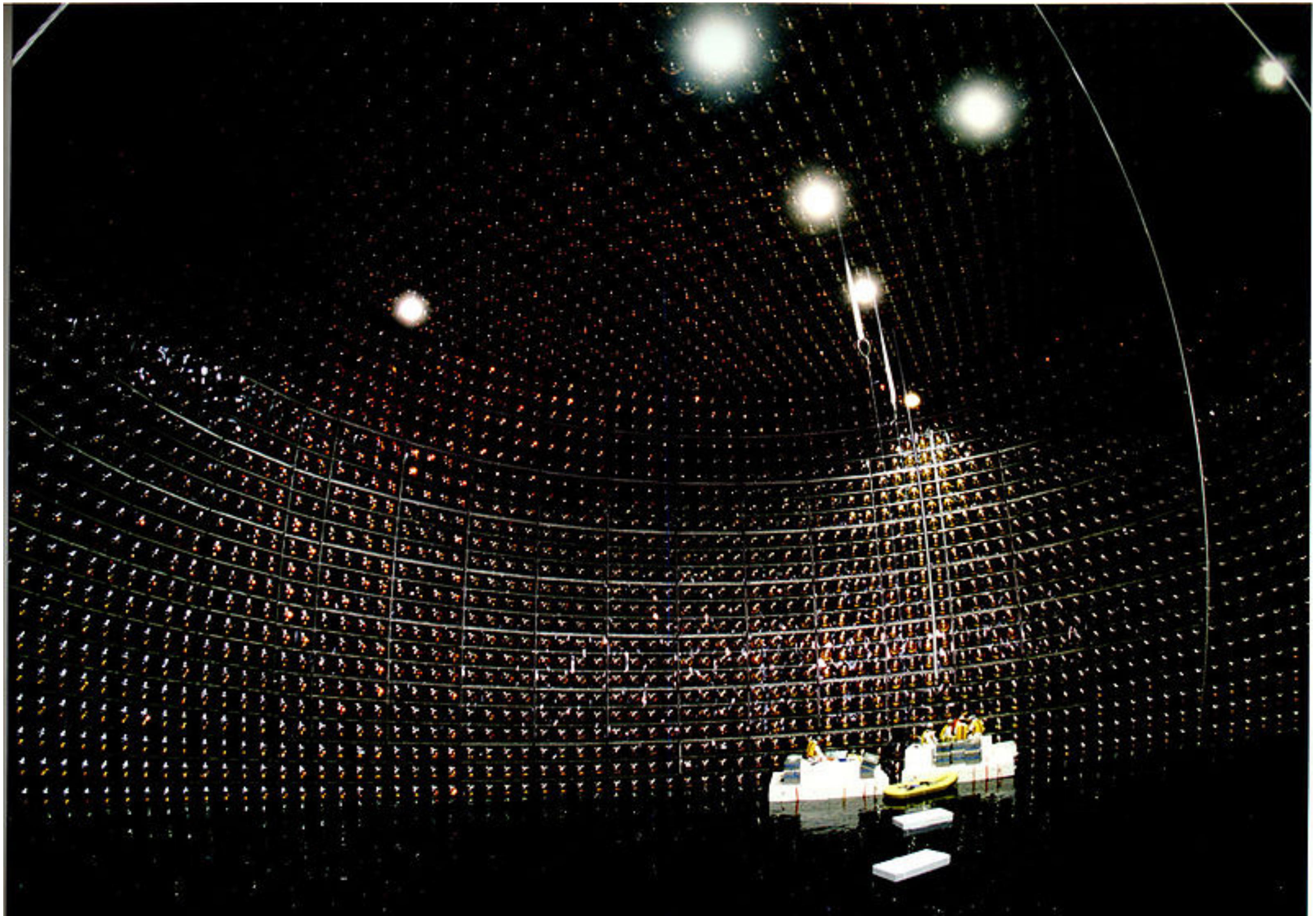
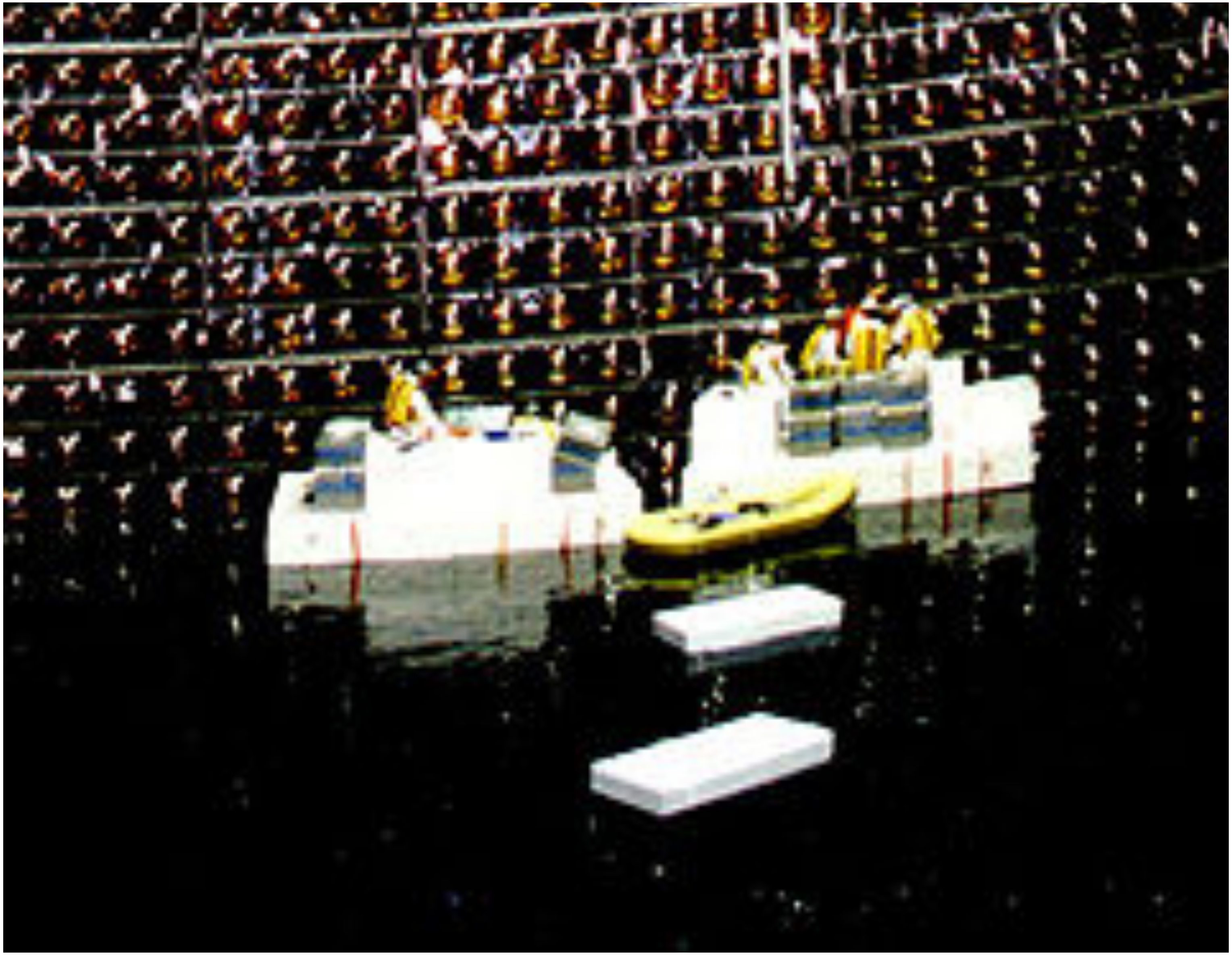


image: Arpad Horvath



Super-Kamiokande



Super-Kamiokande

Other Nuclear Reactions

- Although the Proton-Proton Chain is thought to be by far the most *common* reaction, there are other nuclear reactions that occur in the Sun.
- These include the Carbon Cycle (or CNO Cycle) and the Triple Alpha Process.

Carbon Cycle

$^{12}C + ^{1}H \rightarrow ^{13}N$ + energy

$^{13}N \rightarrow ^{13}C + e^{+} + \nu$

$^{13}C + ^{1}H \rightarrow ^{14}N$ + energy

$^{14}N + ^{1}H \rightarrow ^{15}O$ + energy

$^{15}O \rightarrow ^{15}N + e^{+} + \nu$

$^{15}N + ^{1}H \rightarrow ^{12}C + ^{4}He$ + energy

Carbon Cycle

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$

$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$

$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He + \gamma$$

Proton-Proton Chain

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu + \gamma$$

$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$$

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H + \gamma$$

$$e^{+} + e^{-} \rightarrow \gamma$$

Net result:

$$4({}^{1}H) \rightarrow {}^{4}He + 2\nu + \text{energy}$$

What are some similarities? differences?

What happens to positrons in the Carbon Cycle?

What is the *net* result of the Carbon Cycle?

Carbon Cycle

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$$
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu$$
$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$
$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu$$
$$^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He + \gamma$$

Net result:

$$4({}^{1}H) \rightarrow {}^{4}He + 2\nu + \text{energy}$$

Proton-Proton Chain

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu + \gamma$$
$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$$
$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H + \gamma$$
$$e^{+} + e^{-} \rightarrow \gamma$$

Net result:

$$4({}^{1}H) \rightarrow {}^{4}He + 2\nu + \text{energy}$$

Triple Alpha Process

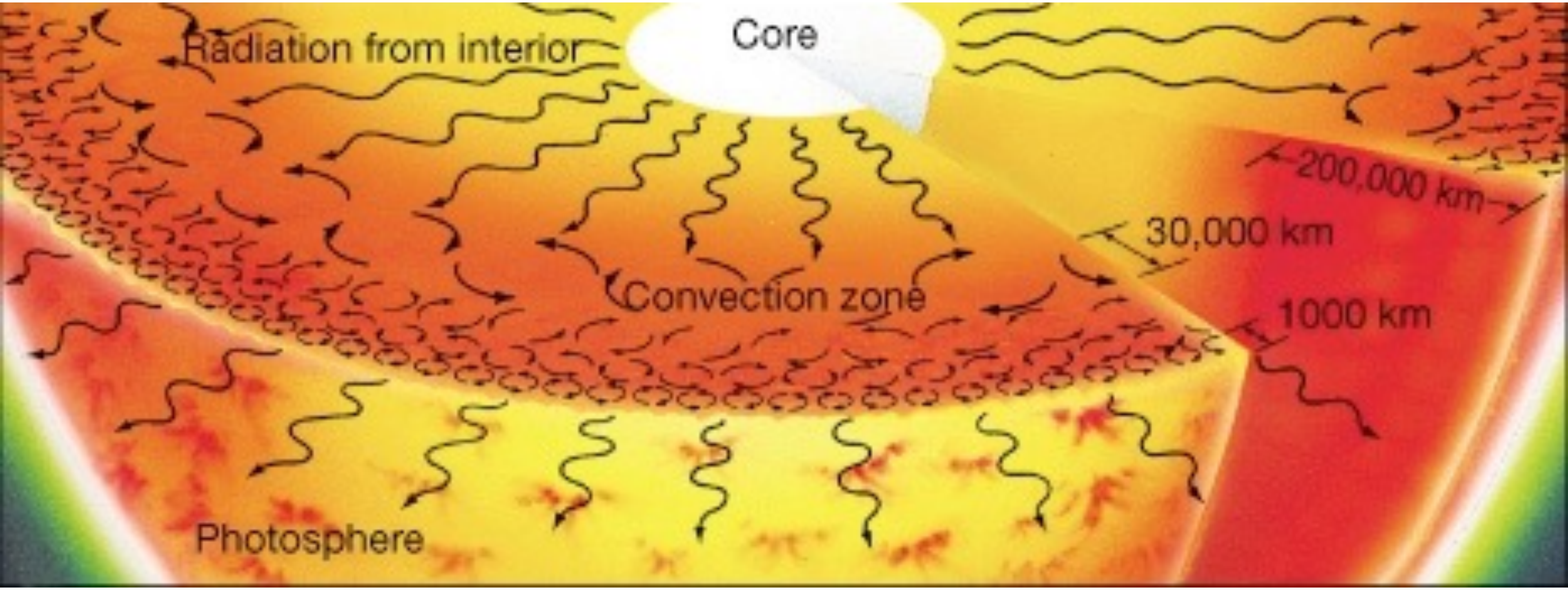
$^{4}He + {}^{4}He \rightarrow {}^{8}Be + \text{energy}$

$^{8}Be + {}^{4}He \rightarrow {}^{12}C + \text{energy}$

Reactions in Other Suns

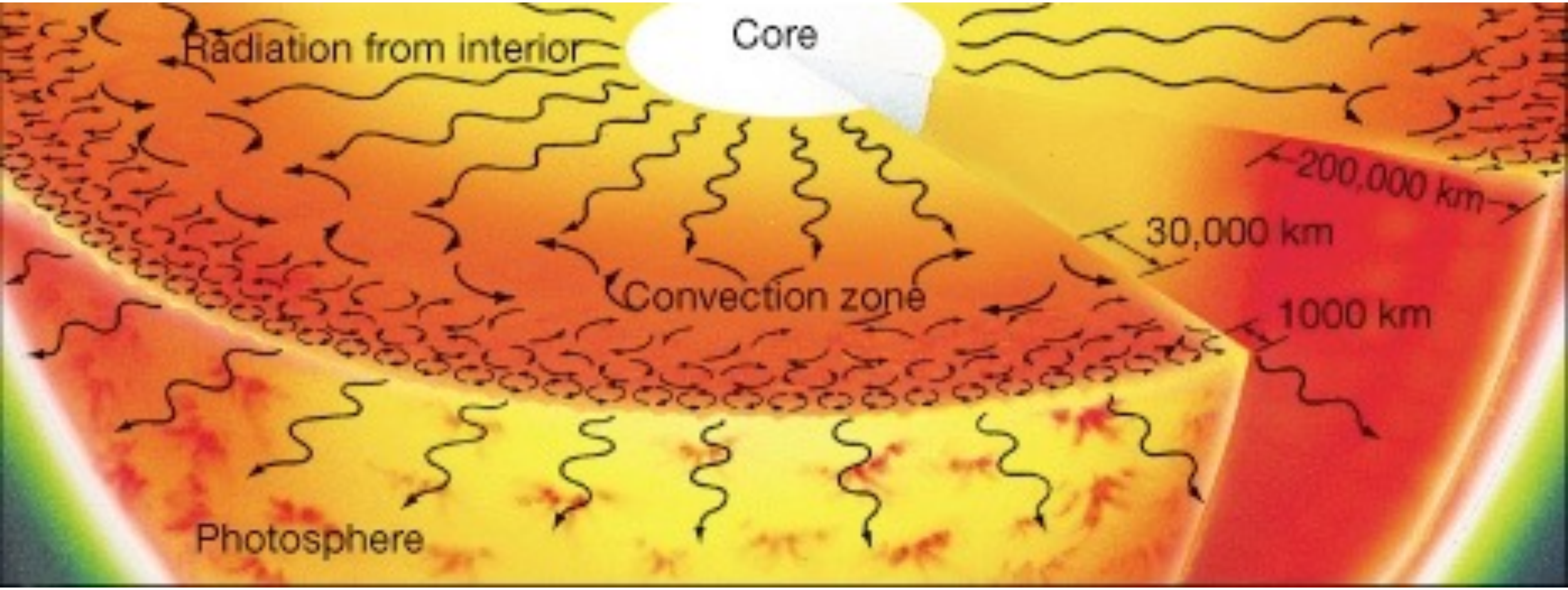
- Stars that have masses greater than eight times that of the Sun have pressures and temperatures great enough for "Helium Capture" to occur.
- In a Helium Capture reaction a nucleus such as ^{12}C fuses with a ^{4}He to produce ^{16}O and release energy.
- In a similar fashion Helium Capture can convert oxygen to neon, neon to magnesium, magnesium to silicon, and silicon to iron!

Energy Transport



- It takes about 200,000 years for energy to travel from core to photosphere
- In the radiation zone photons scatter randomly among densely packed particles.

Energy Transport



- At base of convection zone the density is low enough that particles absorb energy and retain heat – setting up convection cells.
- At the thin layer of the photosphere density is so low that photons can escape into space.