Astronomy 150: Killer Skies
Lecture 14, February 20

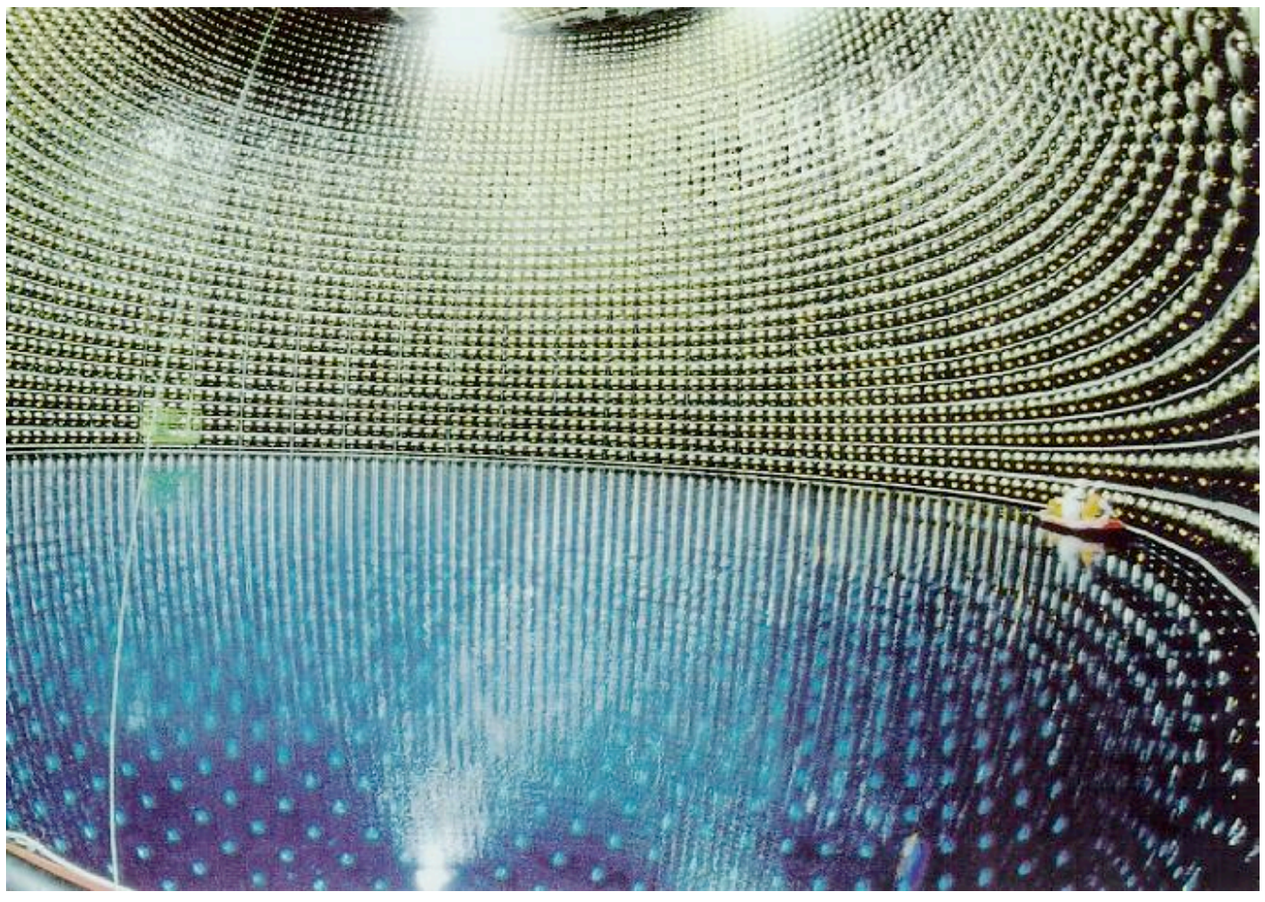
Assignments:

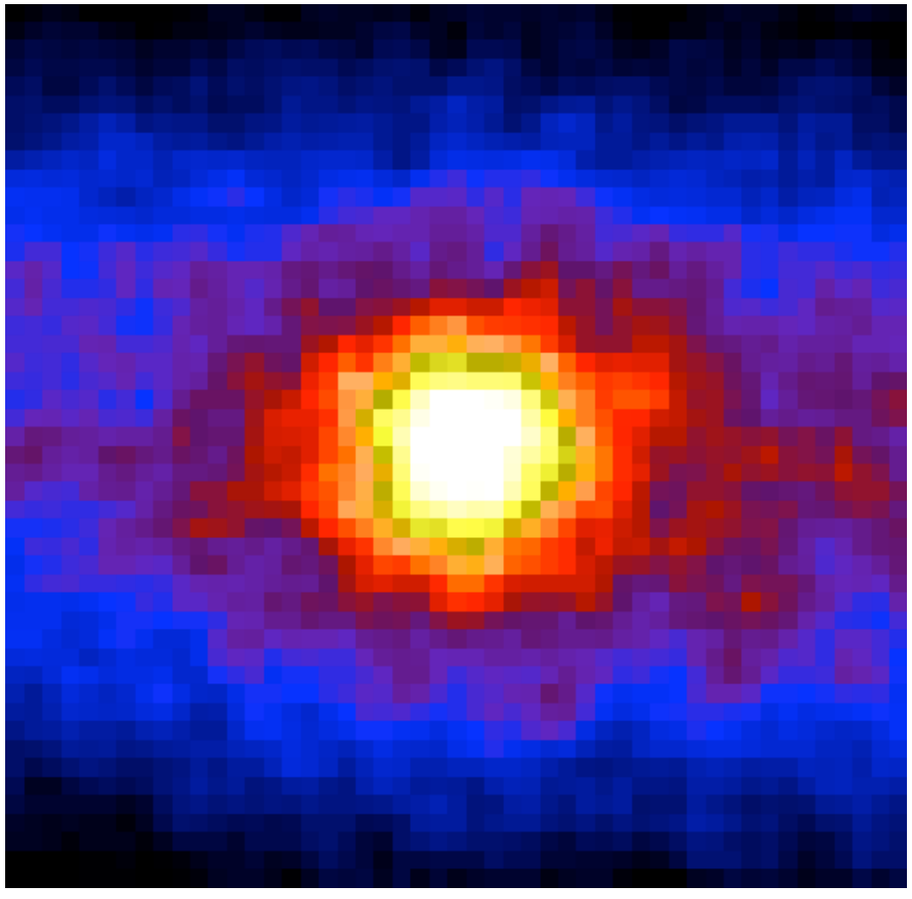
- HW4 posted, due Friday at start of class
- Night Observing begins this week
- Planetarium: report due Feb 24
- Exam being graded, scores posted when available

  sorry for long lines--will try to improve this next time

Last time: the Sun--stability

Today: How does the Sun Shine?





Night Observing

Night Observing begins tonight!

Next two weeks: Mon-Thurs, 7-9pm

3 observing stations:

- Large telescope in observatory dome
- 2 outdoor telescopes
- Night sky constellation tour

Subscribe to Night Observing Status Blog

http://illinois.edu/blog/view/413

Get weather cancellation updates

Assignment details on class website

Report form required!

- download and print out before you go
- Complete report due on or before Mar. 16

The Sun's Energy Output:
Solar Power = "Luminosity"

Power = energy flow rate = energy out per second
= "Wattage"

Sun: 3.85×10^{26} Watts, but how much is that?

A 100W light bulb…

…the Sun could supply 4×10^{24} light bulbs!

U.S. electricity production in 2009: 4.1 trillion kWh…

… Sun = 3×10^{7} times this every second

World's nuclear weapons: 3×10^{4} megatons…

… Sun = 4 million times this every second

Wait…What Exactly is Energy?

Analogy due to Feynman

a child--call him Bart--has 28 blocks

- special blocks--indestructable

every day mother (Marge) finds 28 blocks on floor

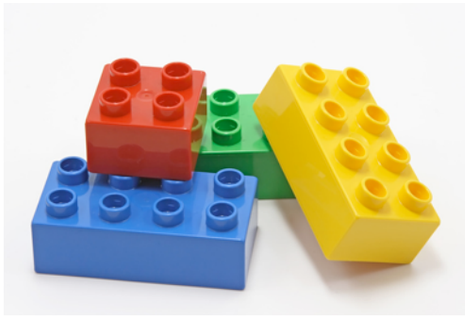
- until one day: 27 visible

but looks out window: one outside

- have to be careful counting blocks

$$28 = \#\,\text{on floor} + \#\,\text{out window} + \text{lumps in carpet}$$

$$+ \text{extra toybox weight} + \cdots$$



Lessons:

blocks are **conserved**

but can take **different apparent forms**

Energy

Energy: abstract but useful concept

- think of as: "ability to make change"

Why useful: energy is conserved

- in a closed system
- total energy = sum of all forms = constant
  - a number that stays the same over time

Energy can take different forms

Examples:

motion of single objects

- if moving: kinetic energy $KE = \frac{1}{2}mv^2$
- if spinning: rotational energy

random motion ("jiggling") of atoms:

- sum of all atom kinetic energies = "thermal energy" of gas = "heat energy"

Energy often linked to forces

- gravity: gravitational energy
- forces between atoms: chemical energy

Consequences of Energy Conservation
The Doomed Stars

the Sun and all stars:

- are constantly releasing energy to the rest of the universe, and
- require fuel, and are unable to "refuel" out of nothing, and
- thus must eventually run of out fuel

Thus:

- all stars – including the Sun – must eventually "burn out"
- = run out of energy = run out of fuel:
- the Sun all stars are doomed to die

the Sun cannot live forever!

But the Sun and other stars are alive today, so…?

- stars alive today were not alive forever
- all stars must be born as well as die
- the Sun and stars have life cycles
- stellar mortality also implies possibility of rebirth!

Solar Energy

The Sun is not a cup of coffee!

- what's the difference?
- coffee cools if left on table
- Sun does not cool off

The Sun shines by generating its own heat (energy)

- Which eventually leaks into space as sunlight
- So: Sun's heat has to constantly be replentished

the Sun must have an energy source!

- What is it?
- Knowing this is crucial to understand future of Sun

How does the Sun Shine?

The Sun shines by its own power

- hot ⇨ glows = emits light

but what keeps the Sun hot?

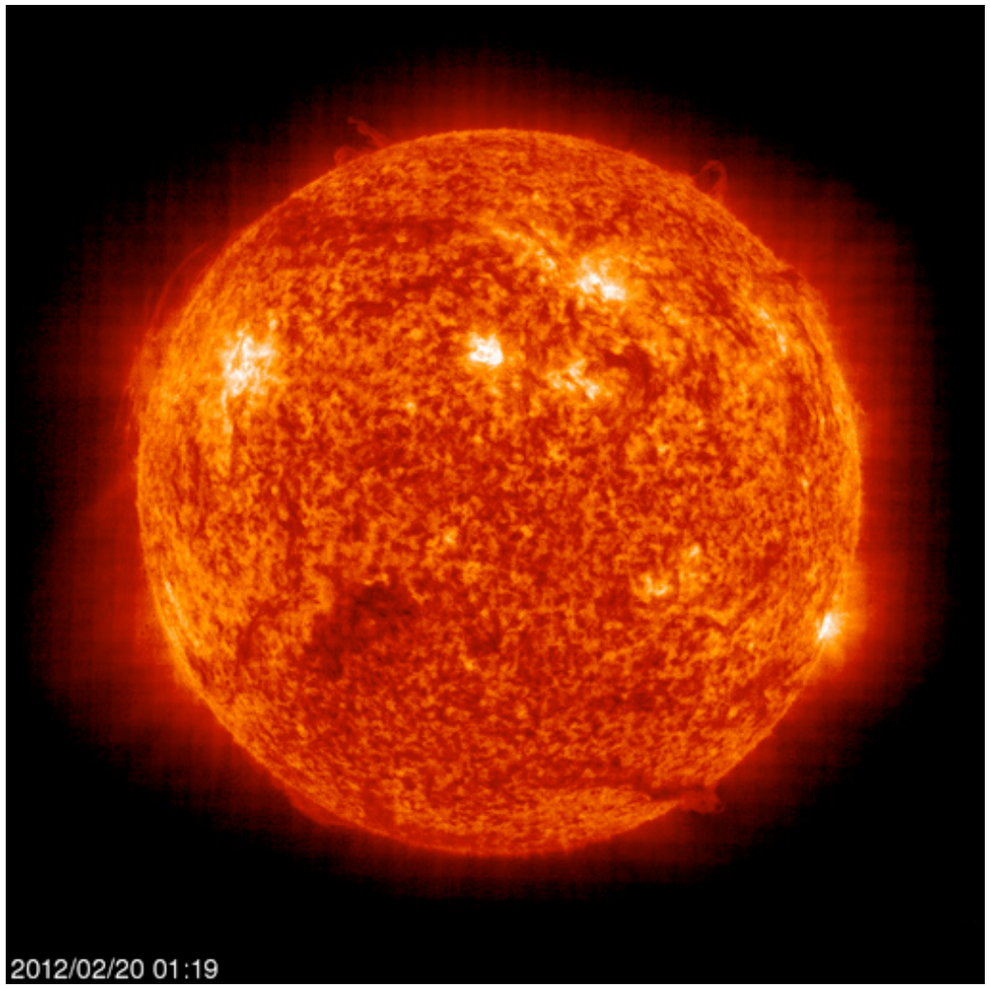
- What energy source is transformed into thermal energy, light energy?

Discuss in groups

Find at least two plausible answers

even if know right one

Click A when done



How to Test?

"Flashlight test"

- each energy source represents some amount of "fuel" = "battery charge"
- see how long Sun can stay lit up for each fuel source
- but know needed "lit time":
  at least 4.6 billion years = age of solar system

Gravity:

- Seems like a good idea
- A contracting Sun does release gravitational energy
- But only enough for 20 million years

Chemical:

- If the Sun was made from TNT, something that burns very well, then it would last for only 20,000 years

Rotational:

- if Sun's spin slowed down, and somehow harness e the energy, would only last for about 100 years!

Need something more powerful!

The Nuclear Option

the only workable solar power source:

- nuclear energy

The Sun is a vast nuclear reactor

in its hot core, hydrogen is converted to helium

by nuclear reactions

nuclear "burn time" about 10 billion years

Q: why is this good news?

Note how we concluded this:

- needed quantitative info (numbers: "burn times")
- to answer qualitative question "What powers the Sun"

example of the power and necessity of number crunching

Fusion in the Sun

Fusion is a kind of nuclear reaction

Nuclear reactions

- one kind of nucleus transformed into another
- but nucleus defines element type:
- in nuclear reactions: atoms changed from one element to another!
- alchemy!

Fusion

- reactions where two nuclei combine to make a new, more massive nucleus
- "light" nuclei combine to make "heavy" nuclei

Fusion in Sun

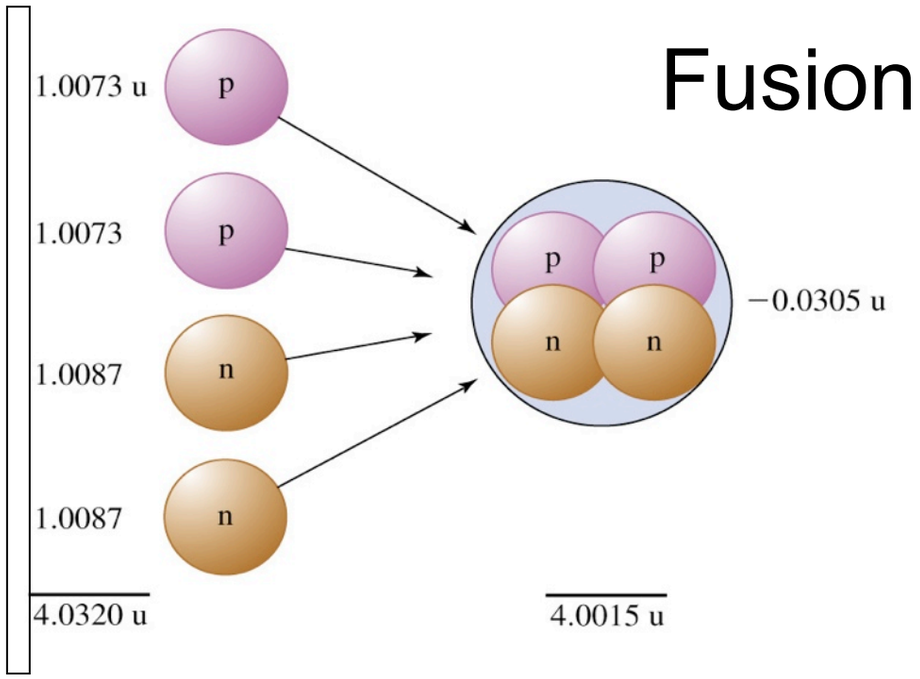
- a series ("chain") of reactions changes $\text{hydrogen} \longrightarrow \text{helium}$
- specifically: $4p \longrightarrow {}^4\text{He}$

  where "helium-4" ${}^4\text{He} = \boxed{2p, 2n}$

Fusion vs. Fission

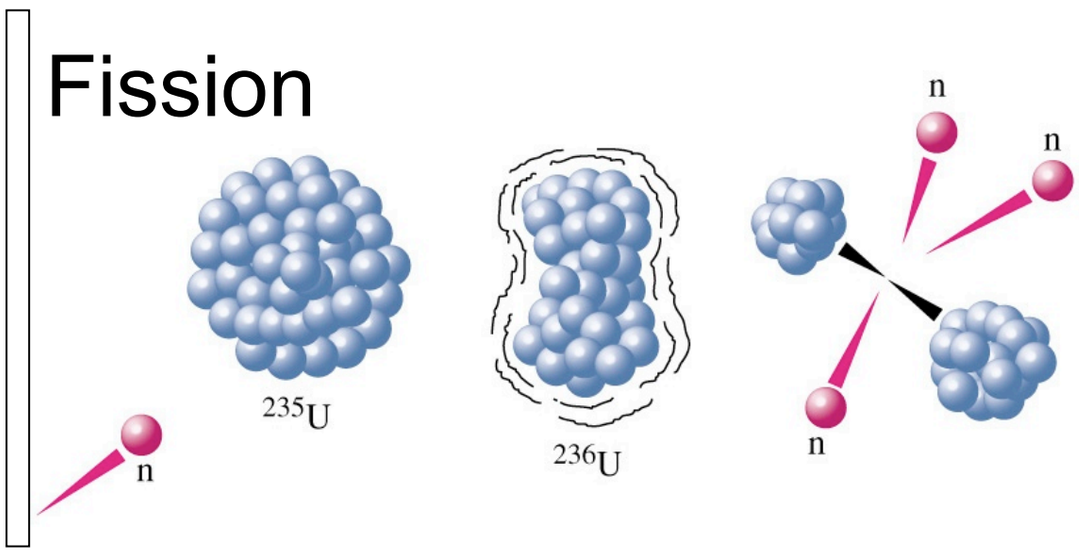
Light nuclei: fusion

- Fuse together light atoms to make heavier ones
- Happens in the Sun
- H-Bomb

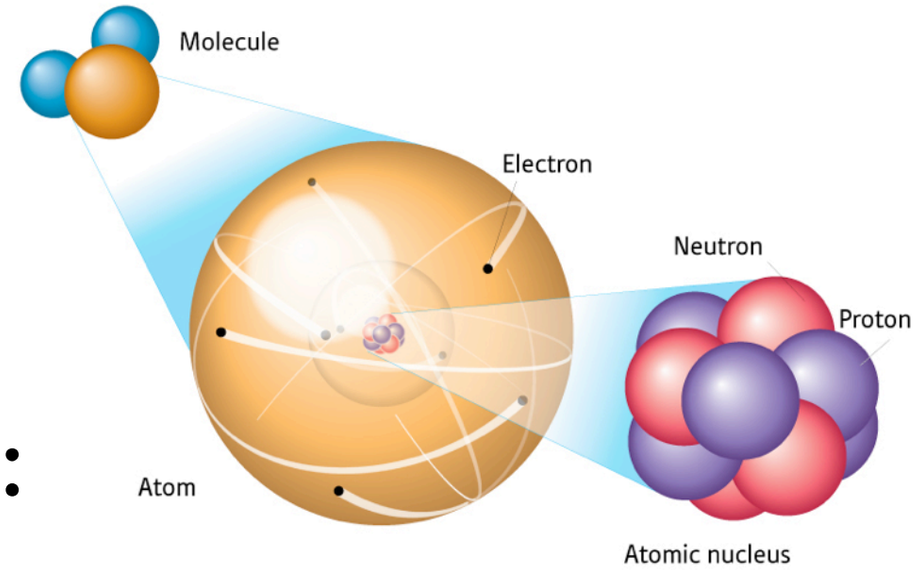


Heavy nuclei: fission

- Break apart heavier atoms into lighter ones
- Used in power plants
- A-Bomb



Why don't nuclei fly apart?



Atomic nuclei:

- very small
- contain protons: electric charge +1

but two positive charges feel force:

- electrical repulsion
- another inverse square force: strongest when protons close

in nucleus: protons very close

- electrical repulsion huge!

If this were the whole story, nuclei should explode! Atoms could not exist!

Q: Why don't nuclei explode?

Discuss, and Click A when you have an answer

Why don't nuclei fly apart?

Nuclei are stable:

- not flying apart
- not accelerating: a = 0
- so no net force: F = 0

But electrical repulsion exists and is huge!

- must be an attractive force to balance

what about gravity?

- Good guess! $F_{\rm grav}(pp) = G\frac{m_p^2}{d^2}$
- good news protons close -- makes gravity stronger
- bad news protons have tiny mass

Run the numbers:

- compare gravity/electric forces between protons

$$\frac{F_{\rm grav}}{F_{\rm electric}} = 10^{-36} = 0.000000000000000000000000000000000001$$

Conclusions:

- gravity feeble in nucleus
- need another force to hold nuclei together!
- new force better be very strong!

The Fantastic 4 Fundamental Forces

All known forces in the Universe trace back to one or more of just four:

Gravity

- acts between all masses
- attractive
- inverse square law $F \propto \frac{1}{\text{distance}^2}$

Electromagnetic

- acts between charges
- attractive between unlike charges, repulsive between like charges
- also inverse square law

Strong Nuclear

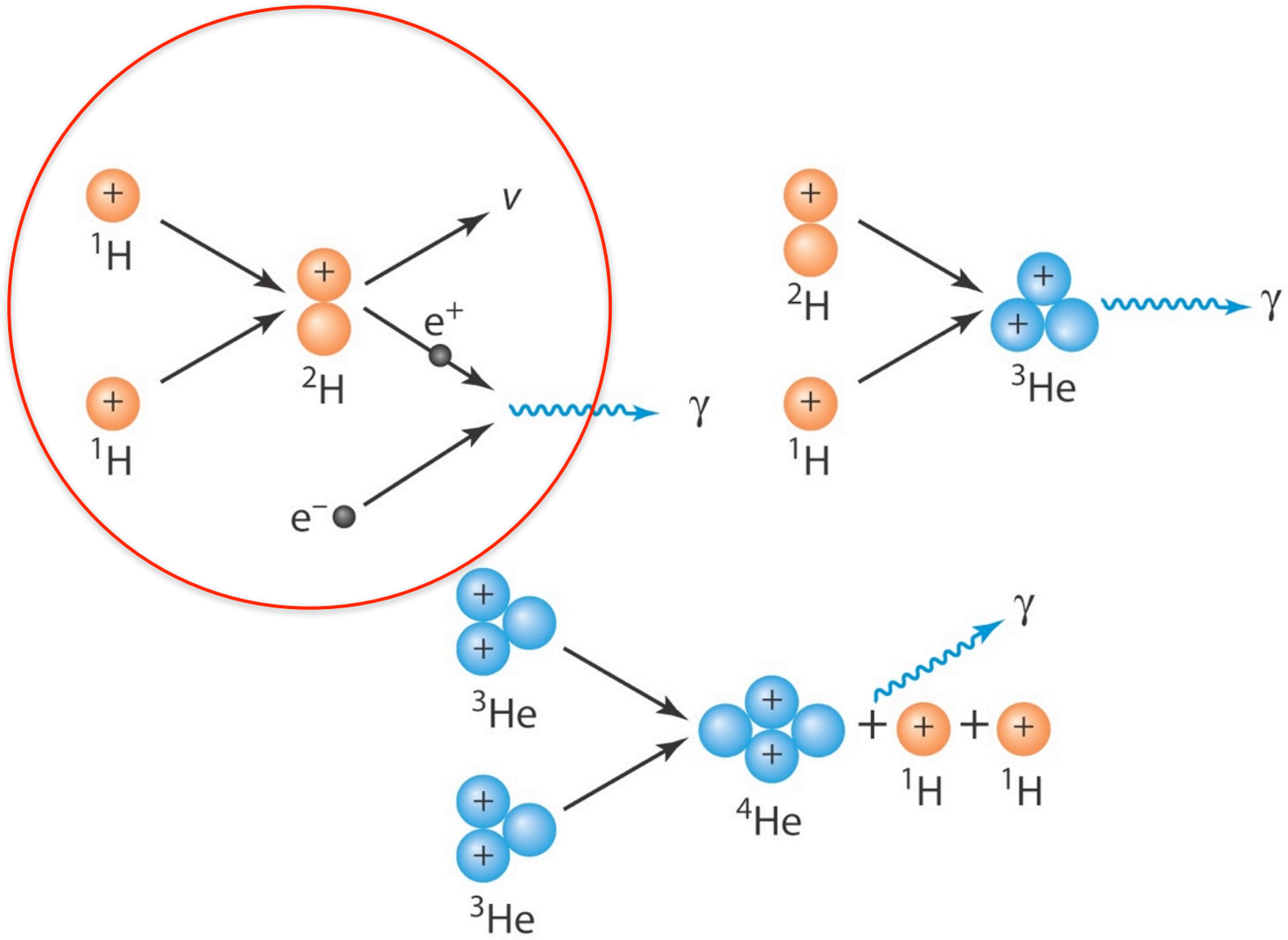
- The strongest of the 4 forces
- Acts between protons and neutrons
  - ultimately, between quarks
  - does not act on electrons
- Attractive: this force holds an atom's nucleus together, overcoming electrical repulsion between the protons.
- Not an inverse square law– very short range.

Weak Nuclear

Nuclear Fusion in the Sun's Interior

Proton-Proton Chain

- 4 hydrogen atoms fuse to make 1 helium atom
- Nuclear energy released each time a new ^{4}He is made
- Requires very high density and temperature (at least 7 million K!)



The Proton-Proton (p-p) Chain

http://www.youtube.com/watch?v=Czbh_sdqX84

Nuclear Reactions in the Sun

Chain: 4 protons ⟹ helium

First step in chain (2 protons combine):

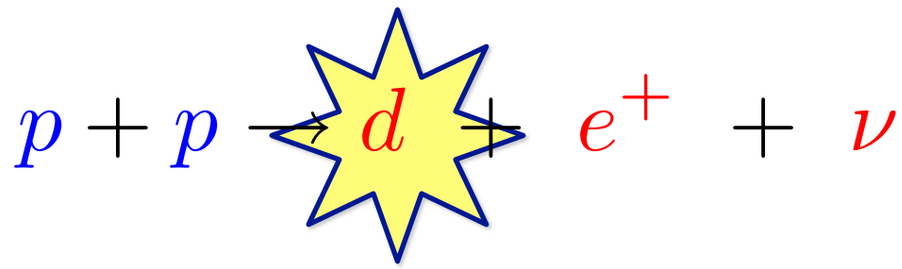
$$p + p \rightarrow d + e^{+} + \nu$$

Start with 2 particles (protons)

End up with 4 particles (two of which are glued together)

each of products is very interesting in its own right....

Nuclear Reactions in the Sun



deuterium $d = pn$

1 proton + 1 neutron bound together into nucleus of element…

Hydrogen, but has neutron, so 2 times mass of normal H

- "Heavy Hydrogen"
- Simplest composite nucleus

Discovery of D in lab: Nobel Prize

about 0.01% of all H on earth is D

✓ including in your body:

you contain about 10 kilos (20 lbs) of H, and about 2 grams of D

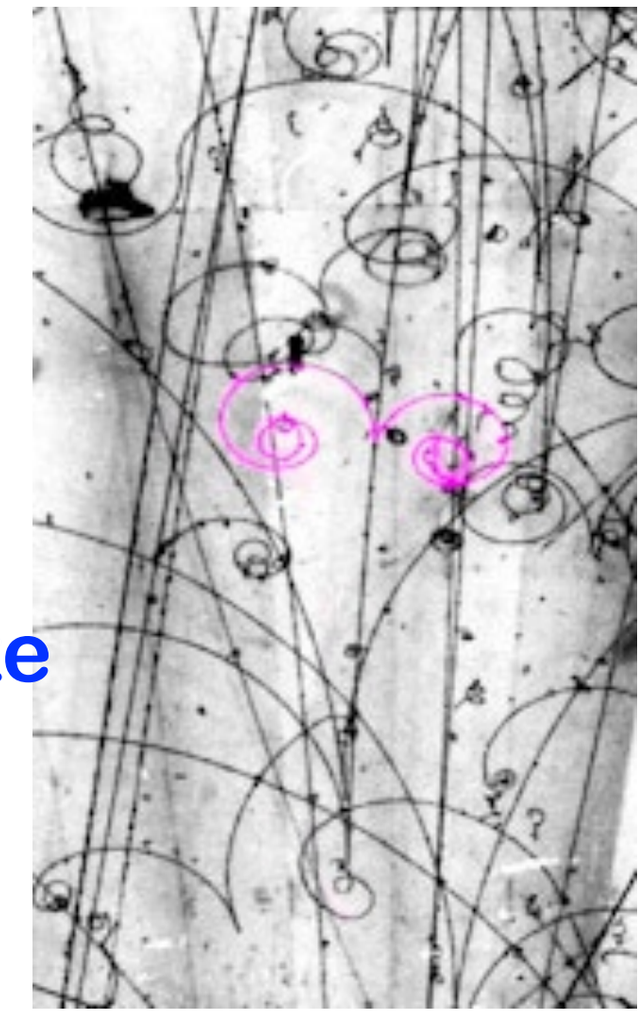
✓ Water (normally H_2O) with D is D_2O : "heavy water"

Nuclear Reactions in the Sun

$$p + p \rightarrow d + e^{+} + \nu$$

positron e^{+}

- Exactly the same as electron but charge **+1**
- **Antimatter**
- Combines with normal **e⁻**
  - Both are gone, release of energy
  - **Annihilation**



Discovery of positron in lab: Nobel Prize

Because of this reaction

- **The Sun contains a small amount of antimatter!**

Nuclear Reactions in the Sun

$$p + p \longrightarrow d + e^{+} + \nu$$

neutrino ν (greek letter "nu")

- Particle produced in nuclear reactions only
- Tiny mass: $m(\nu) < 10^{-6} m(e)$!
- Moves at nearly the speed of light
- very weakly interacting: ghostly!
- only created in nuclear reactions
  - in fact: only feel Weak Nuclear Force
  - created in reactions transforming protons to neutrons or vice versa

Discovery of neutrino in lab: Nobel Prize

10 billion from Sun go through your hand every sec

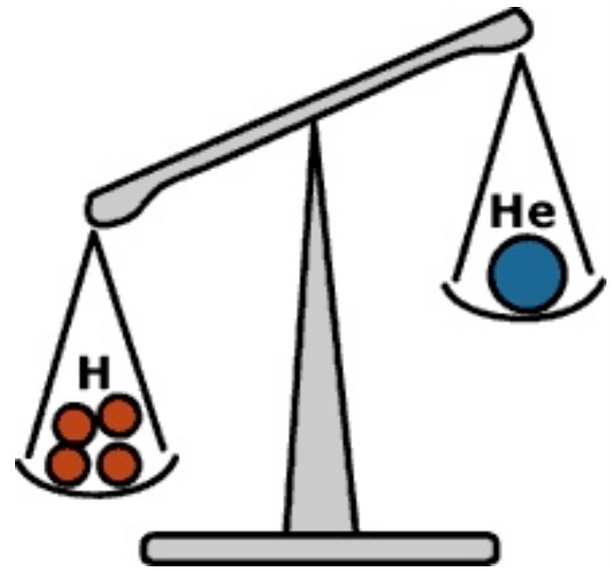
- Reach out!
- Go through your body, Earth, but almost never interact

Why does fusion release energy?

Fusion: $4p \rightarrow {}^4\mathrm{He} = \boxed{2p, 2n}$

Fact: $m(4p) \; > \; m({}^4\mathrm{He})$

mass of whole < sum of masses of parts!

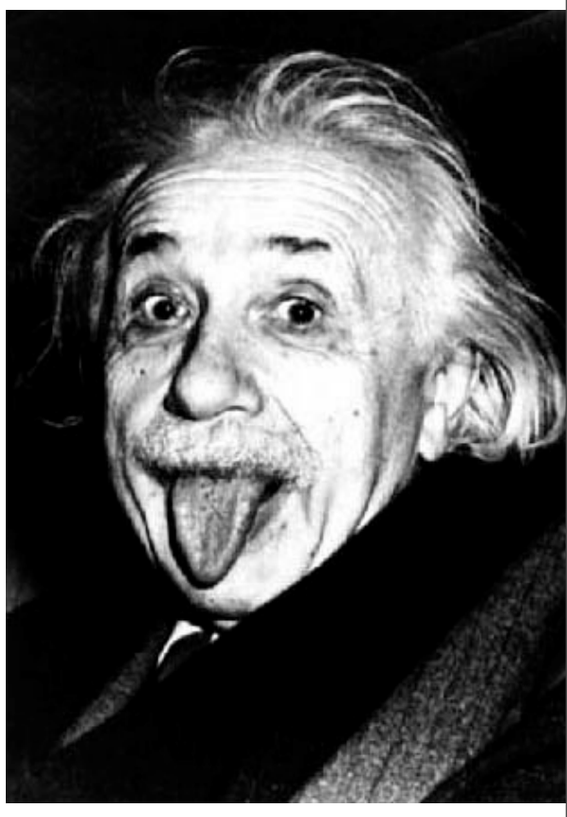


Einstein says $E = mc^2$

Mass is a form of energy!

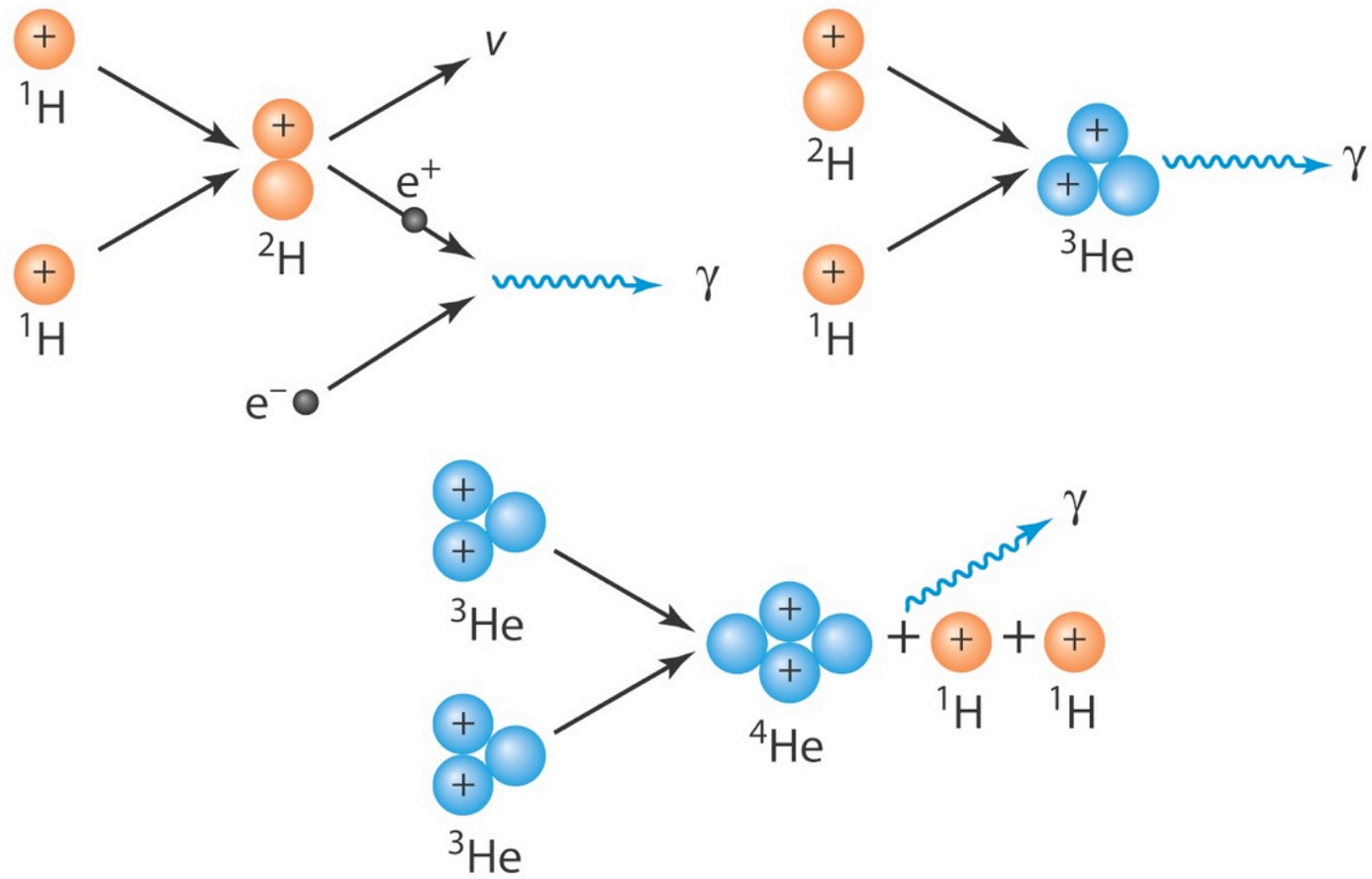
Each ^{4}He liberates energy:

$$E_{\mathrm{fusion}} = m_{\mathrm{lost}} c^2 = 4m(p)\, c^2 - m({}^4\mathrm{He})\, c^2 > 0 \quad !$$



Nuclear Fusion in the Sun's Interior

- Proton-proton in stars like the Sun
  - Hydrogen fused to make helium
  - 0.7% of mass converted to energy



The Proton-Proton Cycle