

Equivalence of mass and energy

Newton

Mass and energy are entirely different things:

- Mass
 - inertial mass
 - gravitational mass
- Energy
 - related to independent properties of the object (how hot it is – “thermal energy”, how fast moving – “kinetic energy” etc)

Einstein

Consequence of special relativity: energy and mass are equivalent

Energy is proportional to the mass, with the scaling factor being speed of light squared:

$$E = mc^2$$

Not at all obvious!



...where is the energy?

Even less obvious when we work out numbers!

$$E = 1 \text{ kg} \times (3 \times 10^8 \text{ ms}^{-1})^2$$

$$= 9 \times 10^{16} \text{ Joules}$$

How big is a Joule?

A power of one Watt is one Joule per second

A power of one Watt is one Joule per second



GE
40 Gal. Medium 6 Year 4500 Watt
Double Element 240 Volt Electric Water
 Model # GE40M06AAG
 ★★★★★ 4/5 69 Reviews
\$214.00

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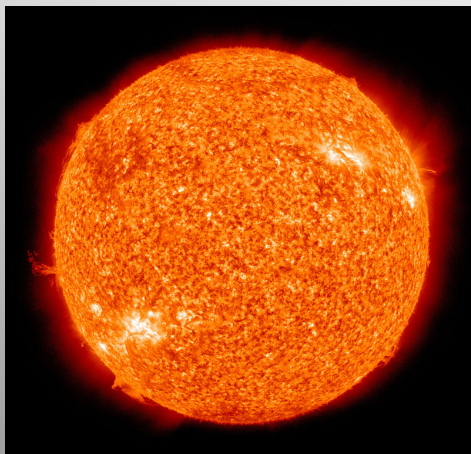
9000 Watts: if run for one hour –
 9000 Joules per second x 3600 seconds
 = 3.24×10^7 Joules

Total US electrical production per day is about
 4×10^{16} Joules

$$E = 1 \text{ kg} \times (3 \times 10^8 \text{ ms}^{-1})^2$$
$$= 9 \times 10^{16} \text{ Joules}$$

this energy is equivalent to ~ 0.5 kg of matter

Consequences

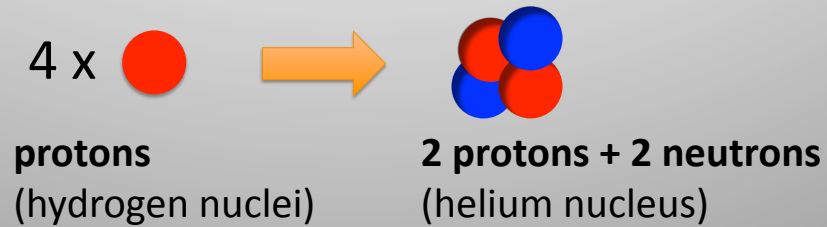


How long would the
Sun last if it was
burning gasoline?

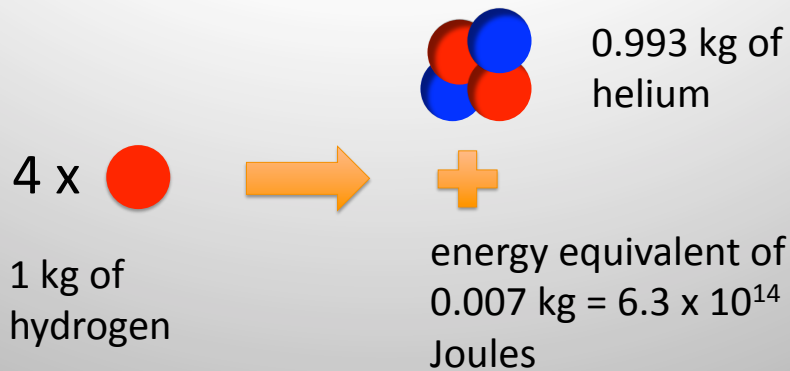
About 10,000 years

Efficiency of nuclear reactions

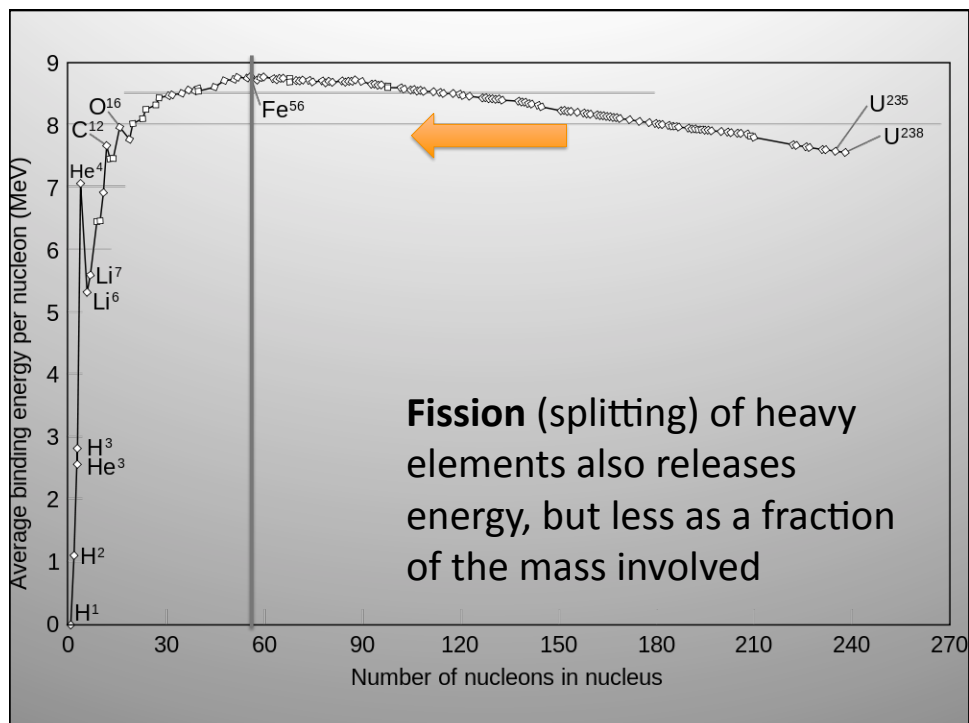
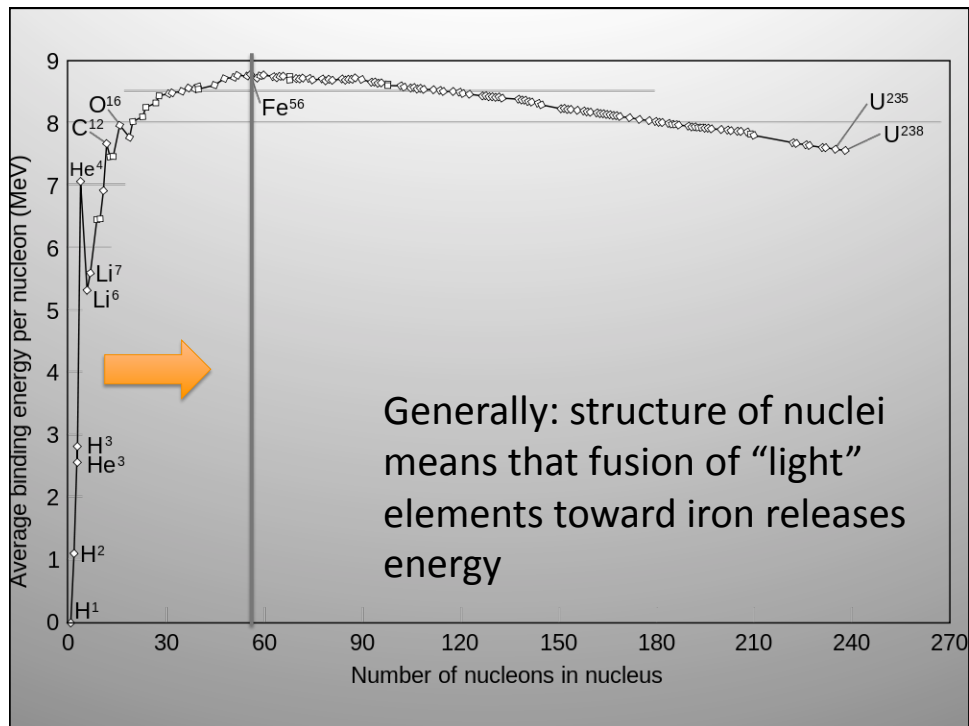
In the Sun, nuclear fusion



Mass of a helium nucleus is 0.7% *less* than the mass of 4 protons: reaction releases energy



Enormous energy: 600 millions tonnes of hydrogen fusing per second to helium suffice for the Sun's luminosity



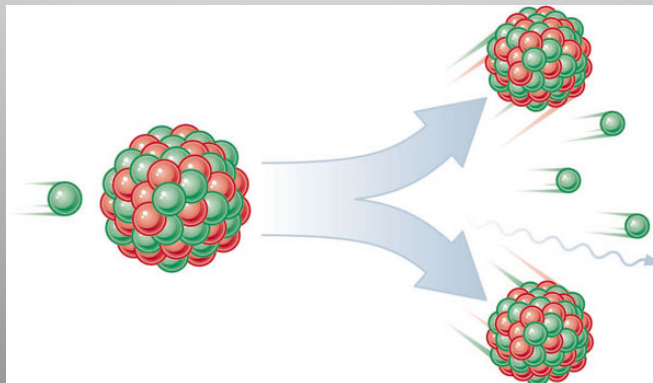
Fusion reactions are hard...



Requires very high temperatures (15 million degrees in the Sun) to force protons to collide and fuse

Fission reactions:

- can occur spontaneously for some heavy elements (e.g. uranium)
- can release neutrons that trigger additional fission reactions



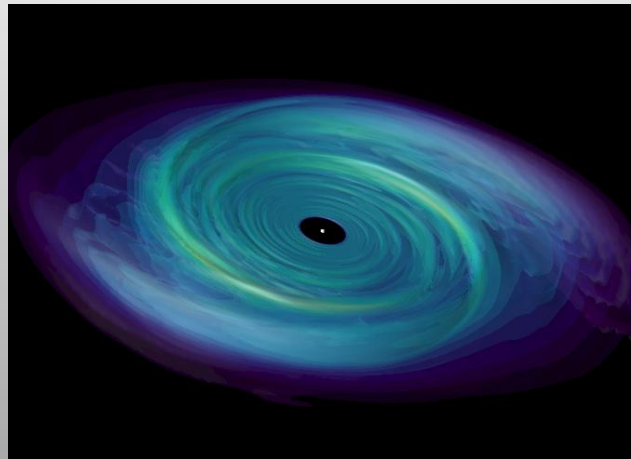
Oklo natural nuclear reactor



Active ~1.7 billion years ago in Gabon

...important test that constants of Nature have actually been constant over a long time!

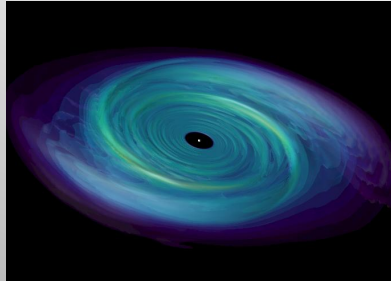
Efficiency of accretion



Michael Owen, John Blondin

Gas spiraling toward a black hole also releases energy as it falls deeper into the gravitational field

Efficiency of accretion



Characterize as fraction of the mass falling in: **about 10%** (depending on spin of black hole)

1 kg of gas at large distance from hole



increases mass of hole by 0.9 kg



release energy equivalent of 0.1 kg

Efficiencies

Nuclear fusion: 0.7% (hydrogen to helium)

Black hole accretion: ~10% (no fusion involved)

About 10-20 times more efficient: why black holes are important in *astronomy*

Annihilation

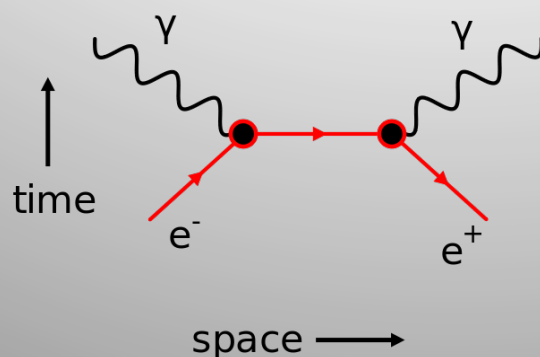
Paul Dirac predicted that the electron should have an **anti-particle**



Later discovered: the **positron** (same mass, opposite electric charge)

Other examples of anti-matter: proton / anti-proton, hydrogen / anti-hydrogen (hard to make!)

Annihilation

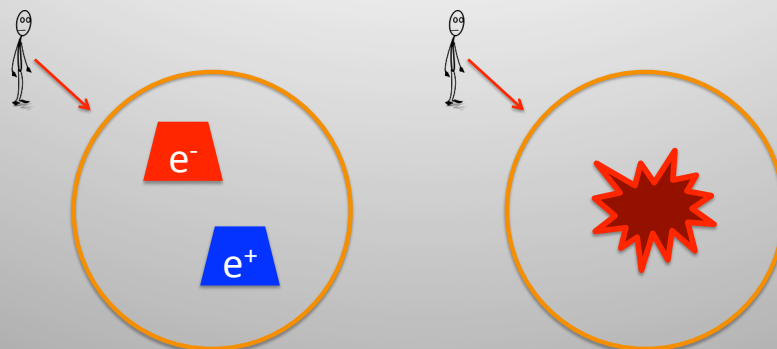


photons (energy equal to rest mass of electron + positron, **plus** any kinetic energy)

matter: particle and anti-particle

Only process allowing 100% efficient conversion of mass into its equivalent energy

What about gravity?



Gravitational effect doesn't care if it's matter or energy: just the same thing