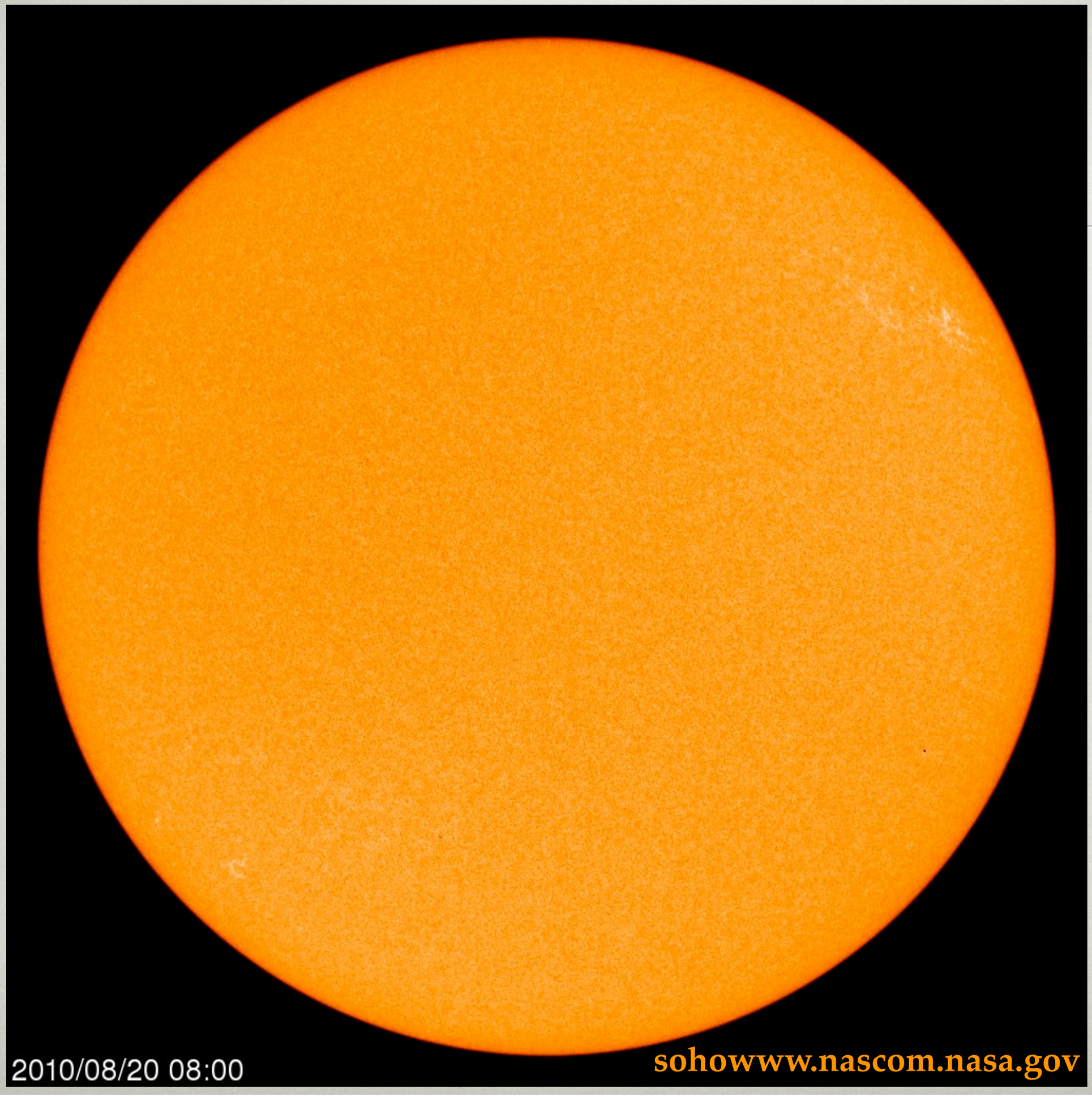
How The Stars Produce All Of Our Energy

Andrew R. Zentner

University of Pittsburgh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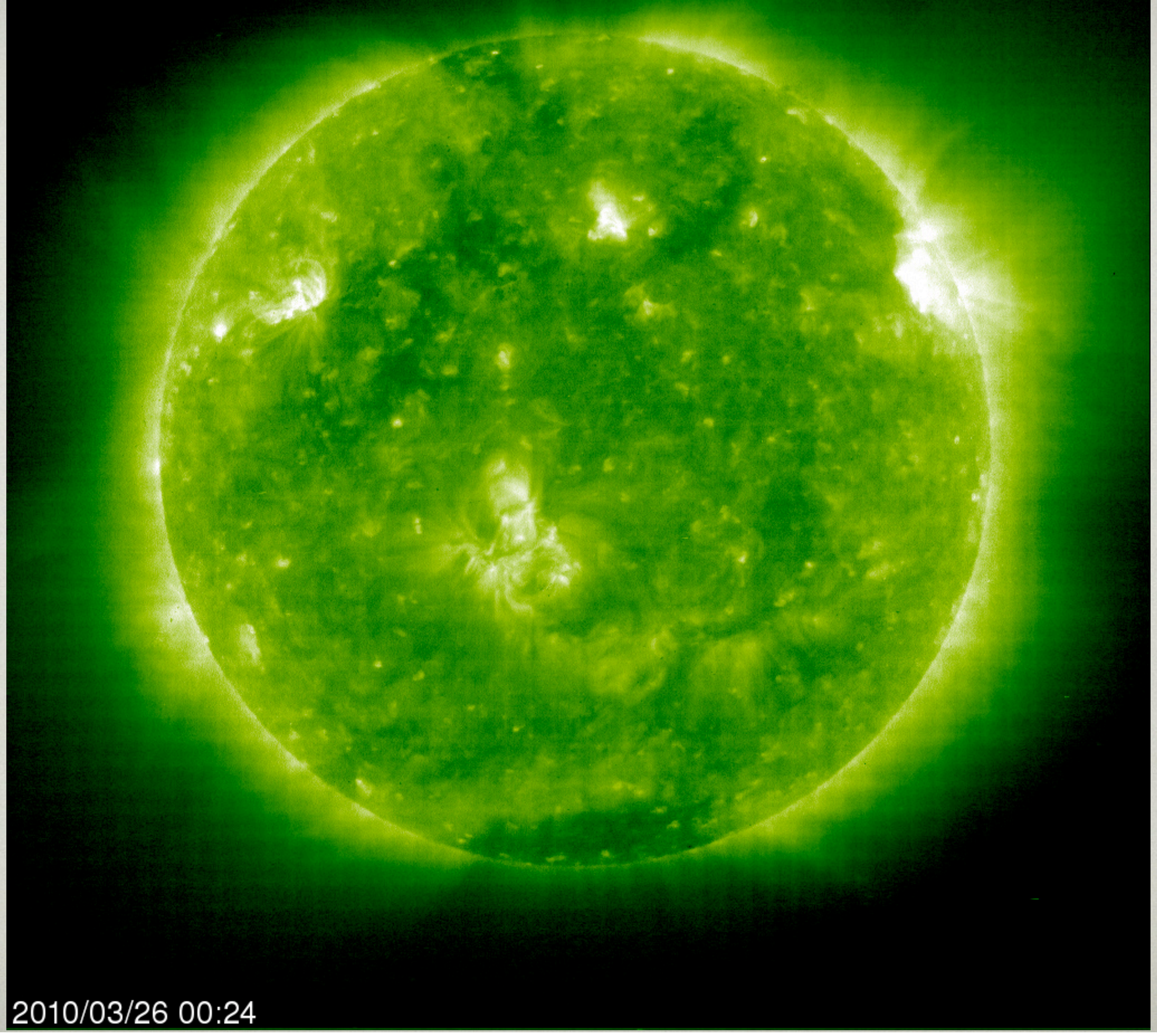
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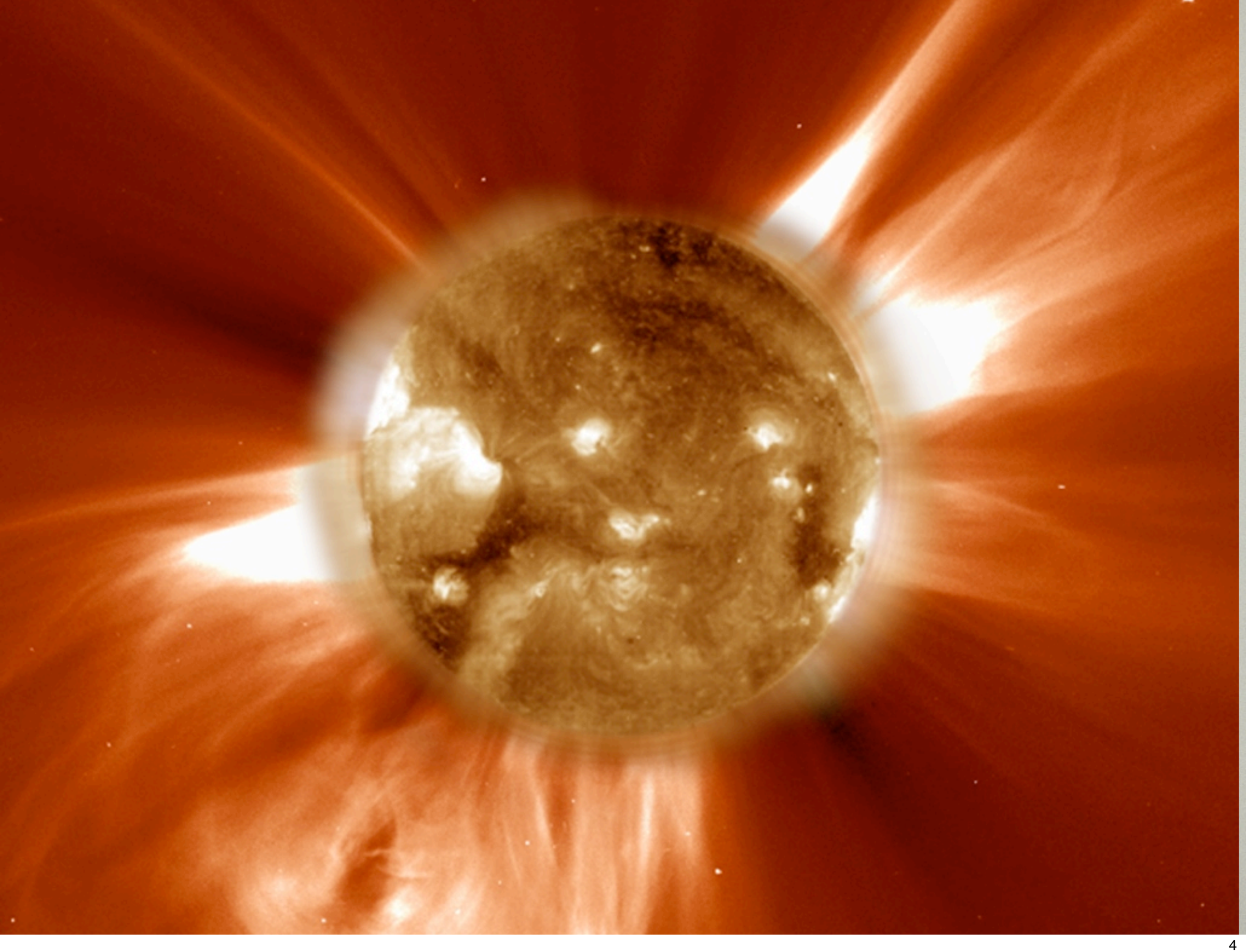


The Sun: Fact Sheet

- One Million times the Volume of the Earth
- 300,000 Times the Mass of the Earth
- 93 Million Miles Away
- About 72% Hydrogen Gas, 27% Helium Gas, and 1% other material (Oxygen, Iron, ...)

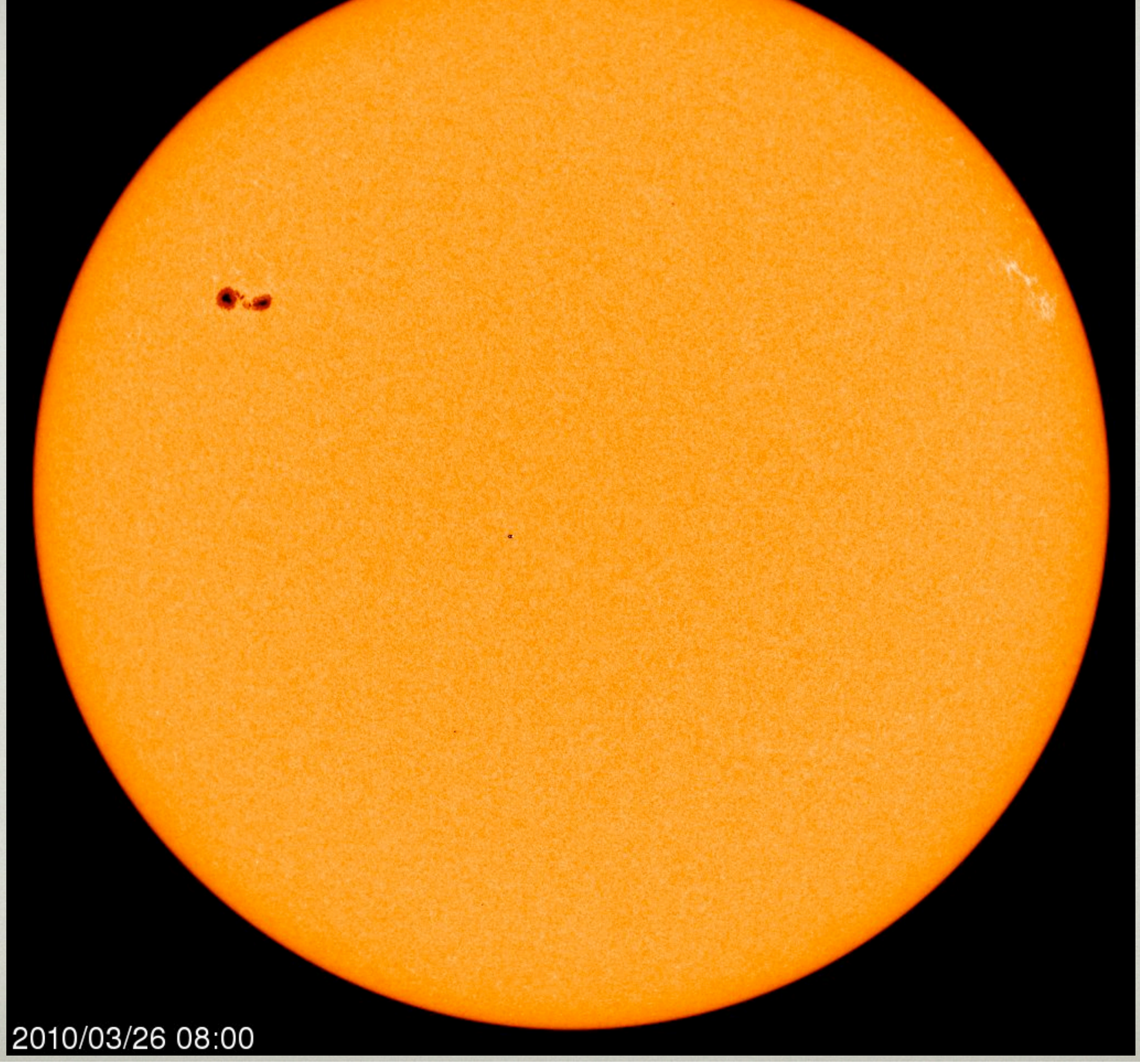
The Sun: Fact Sheet

- Surface Temperature of 10,000 Degrees
- Interior Temperature of 30 Million Degrees
- The Sun radiates 4 Million times the yearly energy consumption of the US Population every second!
- This is more than enough to boil the all of the oceans each second!
- Each person in the US could be sustained if she/he could capture the incoming solar energy on an 8′ x 8′ square (0.02% of the US for everyone!)

The Sun: Fact Sheet

- Your body radiates about 150 W of power, roughly 1/10 of your power usage
- Your body radiates, say, ~W per pound of person
- The Sun radiates about 0.0001 W, per pound of Sun, but its bright because it is really, really, really, really, big

HOW DOES THE SUN MAKE THIS ENERGY?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Energy Production in Stars*

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(Received September 7, 1938)

THE ASTROPHYSICAL JOURNAL, 517:318–327, 1999 May 20

CONTRIBUTION OF HIGH-MASS BLACK HOLES TO MERGERS OF C

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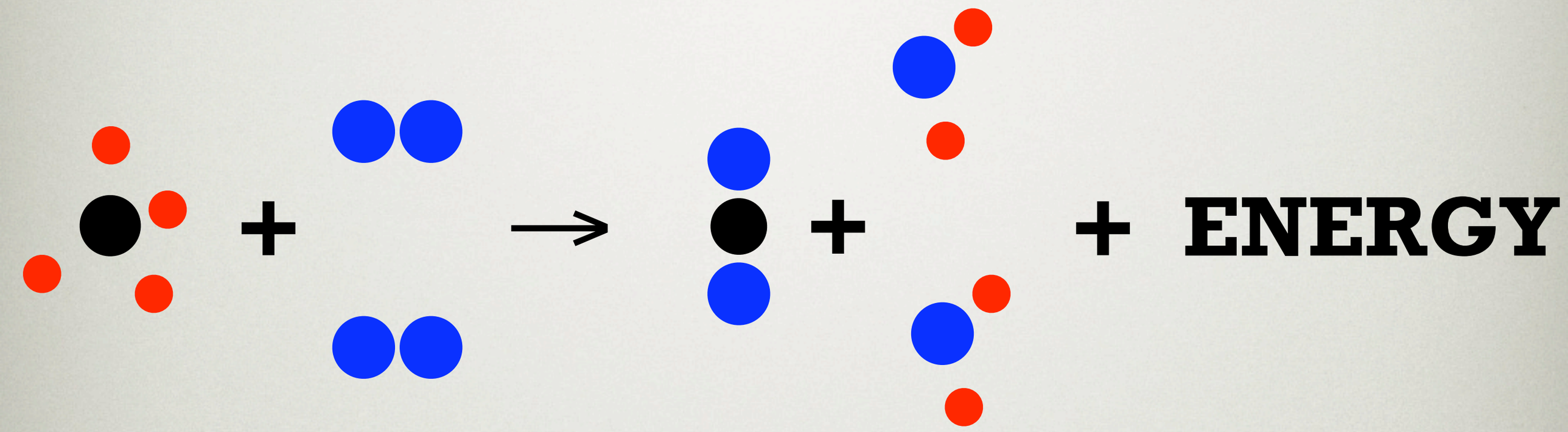
AND

G. E. BROWN
Department of Physics and Astronomy, State University of New York, Stony Brook, New Y

Analogy: Stuff that Falls

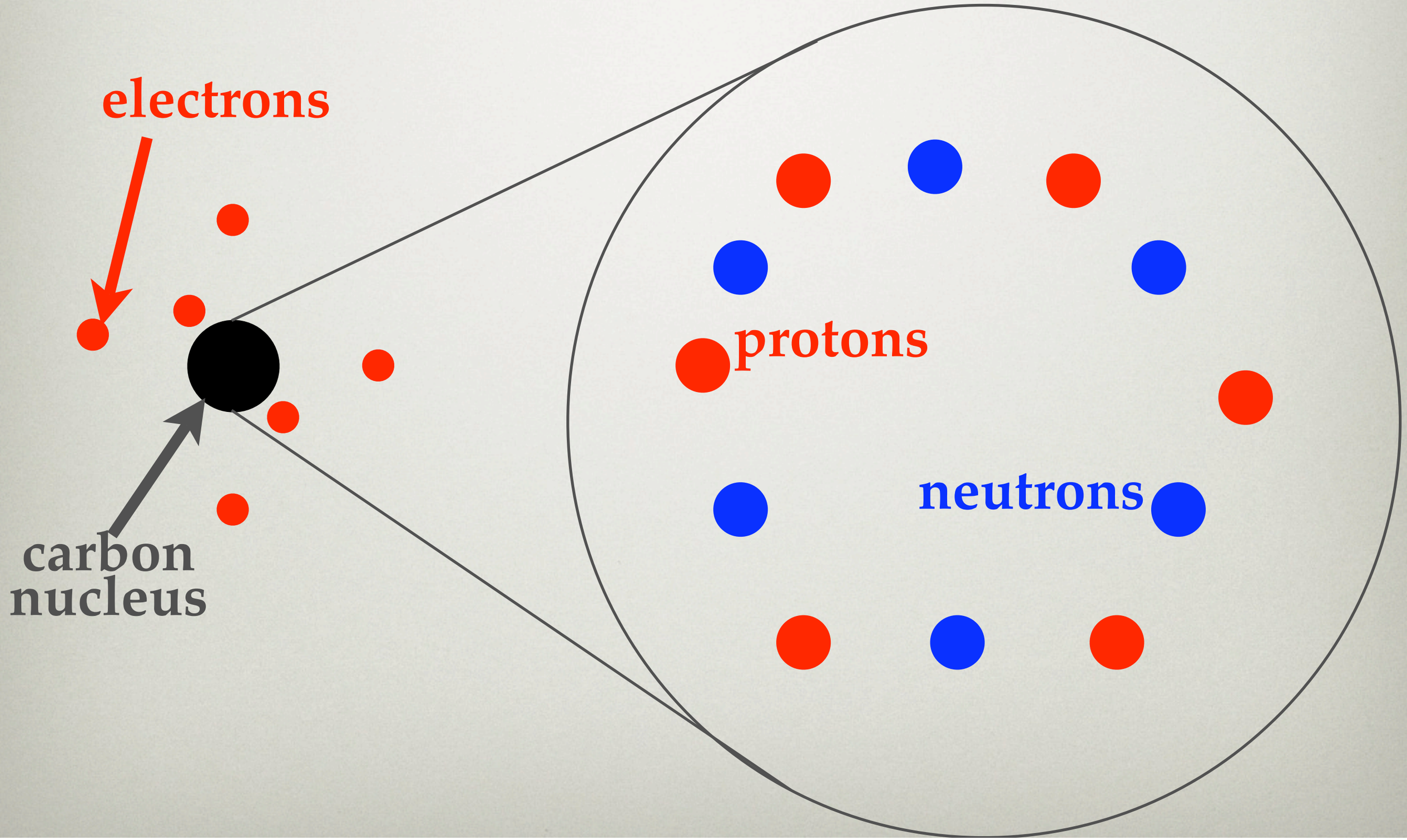
Analogy: Chemical Burning



$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{ENERGY}$$

Natural Gas or Methane — **Oxygen** — **Carbon Dioxide** — **Water** — **Few hours of electricity use per pound**

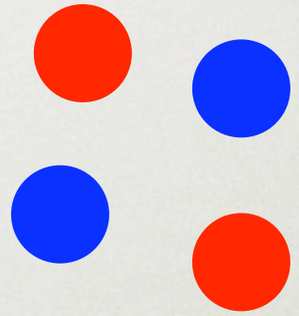
Chemical and Nuclear Reactions



Hydrogen and Helium

- **The Universe is 75% Hydrogen, 24% Helium, and 1% other stuff.**

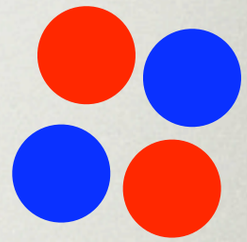
Hydrogen: 1 proton



Helium: 2 protons, 2 neutrons, very strongly held together

The "Strong" Nuclear Force

- Our Helium nucleus is held together by a new force, the Strong Nuclear Force
- The Strong force can overcome electricity & magnetism, but only over a short range (one millionth of one billionth of an inch!)
- Nuclear fusion is the act of getting nuclei close enough such that the strong force takes over, and nuclei "fall" together according to the nuclear force



Stars Form By Squeezing

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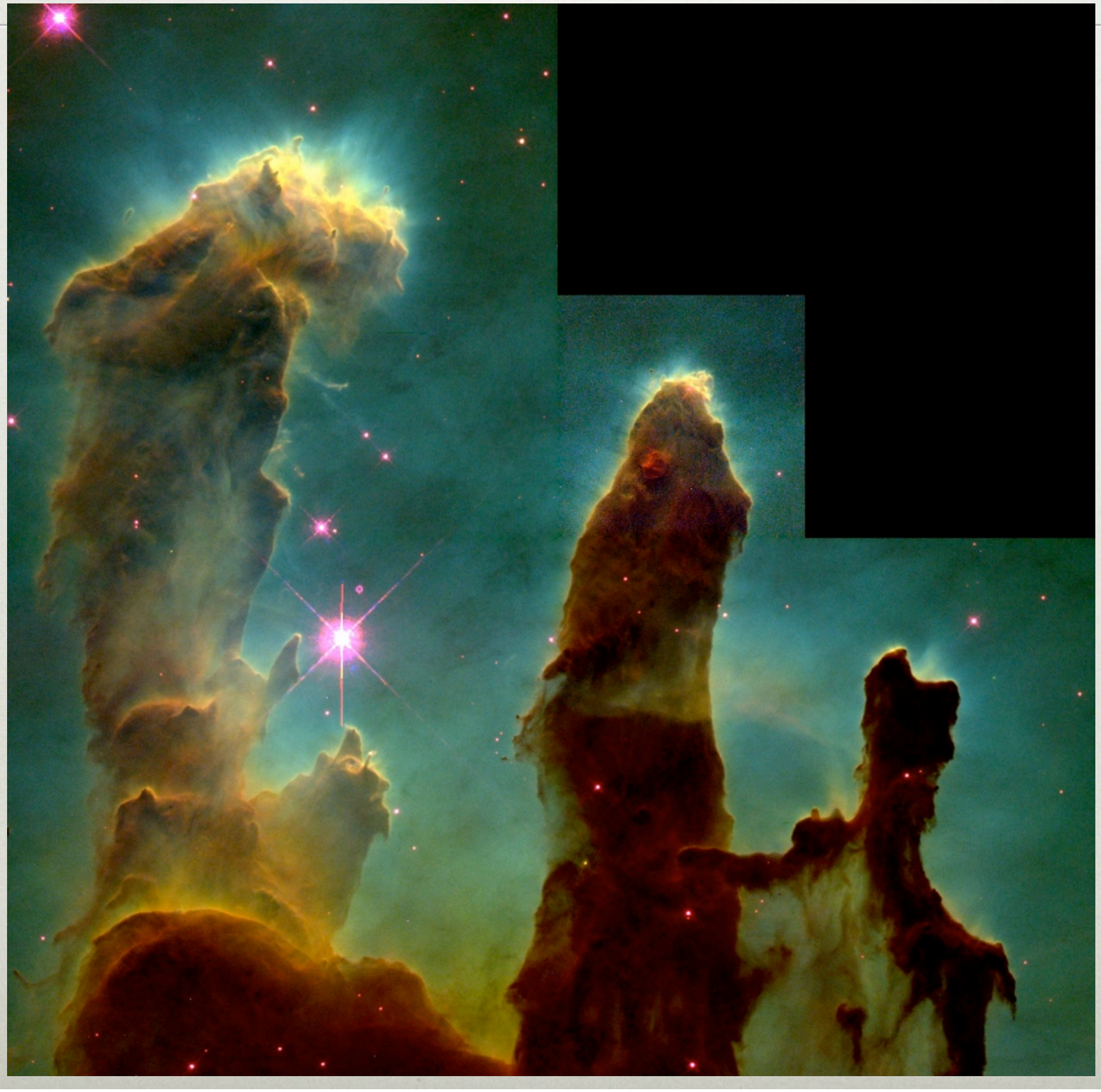

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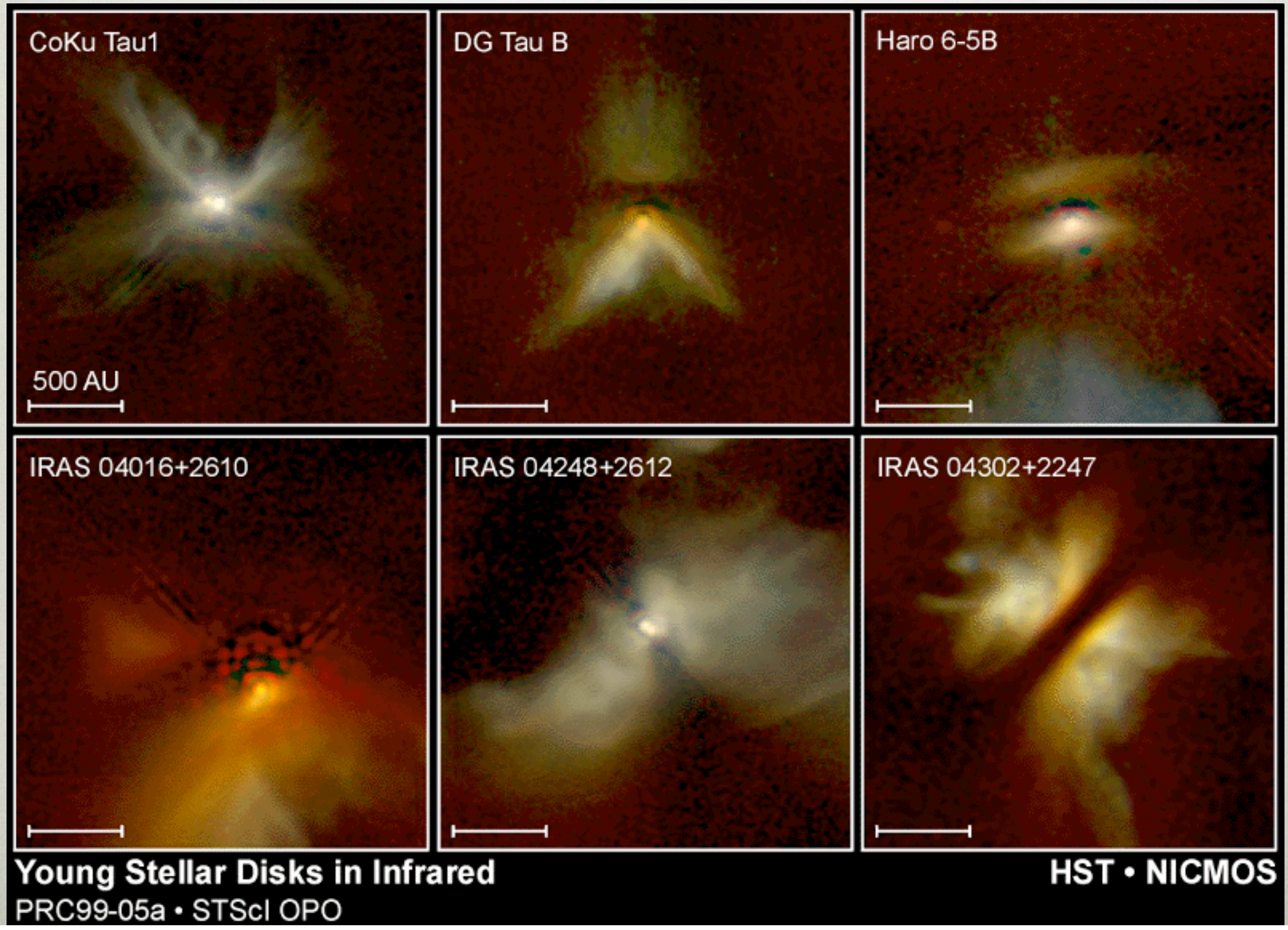

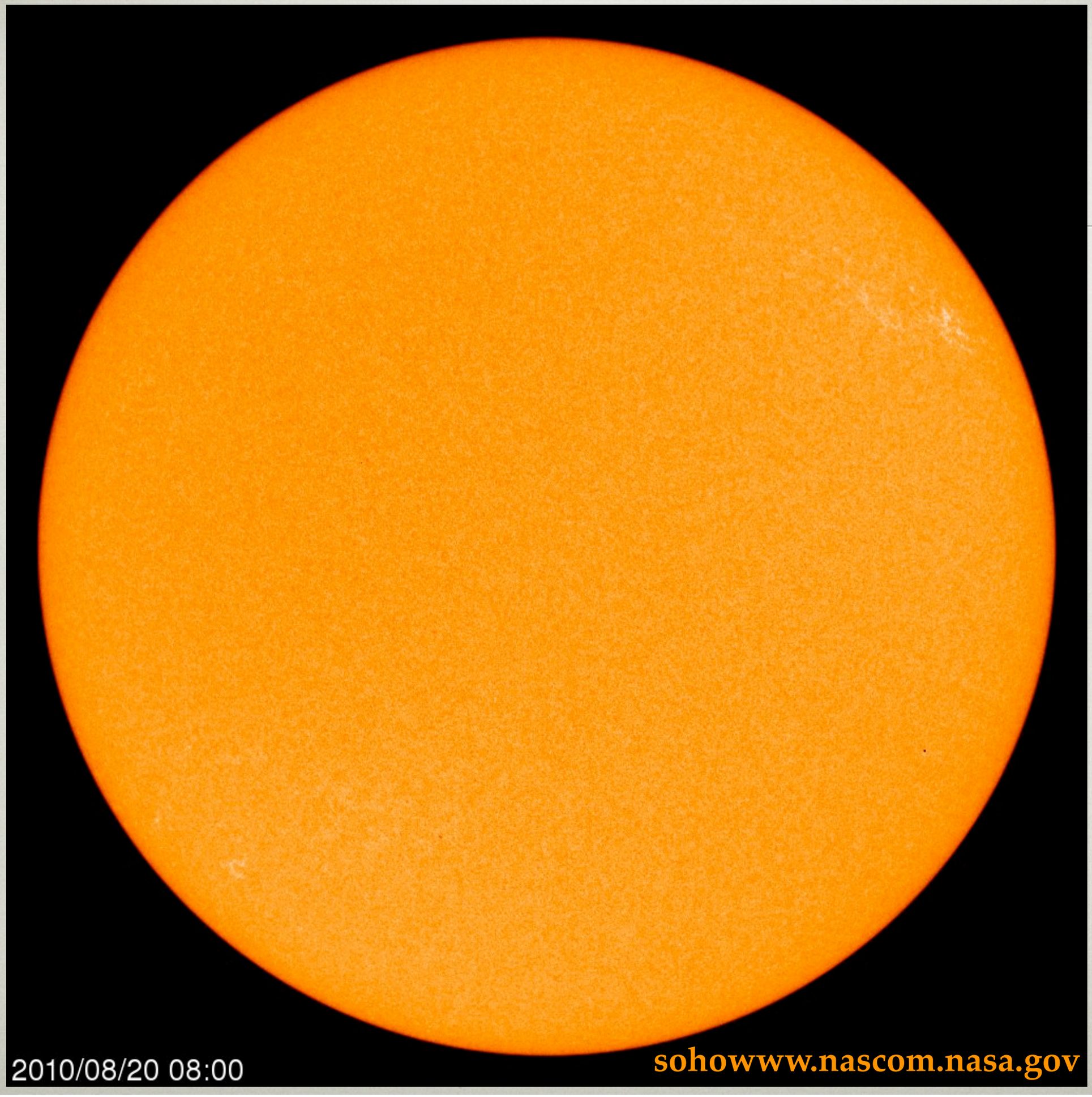
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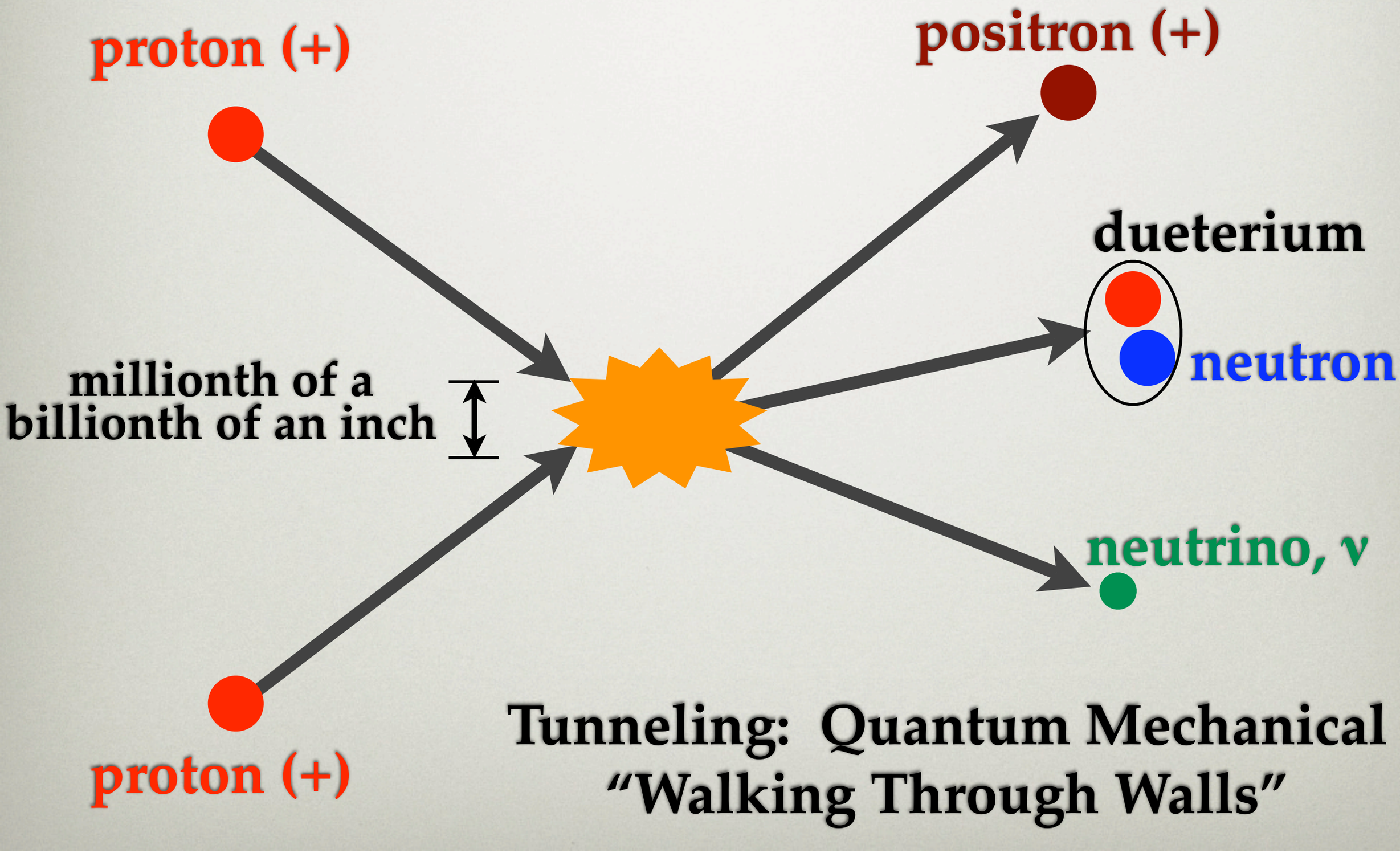
Nuclear Fusion



Tunneling: Quantum Mechanical "Walking Through Walls"

THE OBSERVATORY,

A MONTHLY REVIEW OF ASTRONOMY.

VOL. XLIII. OCTOBER, 1920. No. 557.

The Internal Constitution of the Stars *.

LAST year at Bournemouth we listened to a proposal from the President of the Association to bore a hole in the crust of the Earth and discover the conditions deep down below the surface. This proposal may remind us that the most secret places of Nature are, perhaps, not 10 to the n-th miles above our heads, but 10 miles below our feet. In the last five years the outward march of astronomical discovery has been rapid, and the most remote worlds are now scarcely safe from its inquisition. By the work of H. Shapley the globular clusters, which are found to be at distances scarcely dreamt of hitherto, have been explored, and our knowledge of them is in some respects more complete than that of the local aggregation of stars which includes the Sun. Distance lends not enchantment but precision to the view. Moreover, theoretical researches of Einstein and Weyl make it probable that the space which remains beyond is not illimitable; not merely the material universe, but space itself, is perhaps finite; and the explorer must one day stay his conquering march for lack of fresh realms to invade. But to-day let us turn our thoughts inwards to that other region of mystery—a region cut off by more substantial barriers, for, contrary to many anticipations, even the discovery of the fourth dimension has not enabled us to get at the inside of a body. Science has material and non-material appliances to bore into the interior, and I have chosen to devote this address to what may be described as analytical boring devices—*absit omen*!

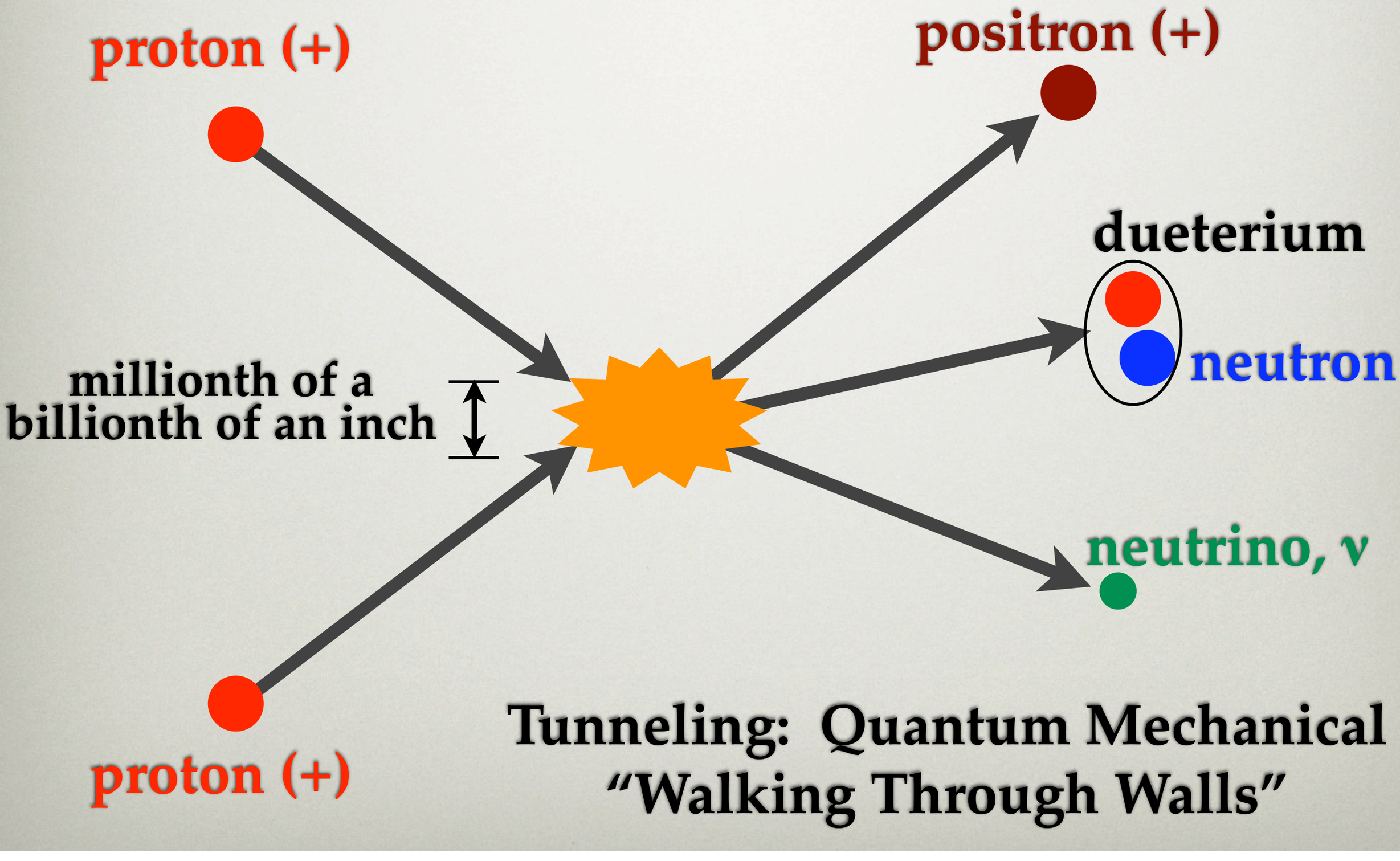
The analytical appliance is delicate at present, and, I fear, would make little headway against the solid crust of the Earth. Instead of letting it blunt itself against the rocks, let us look round for something easier to penetrate. The Sun? Well, perhaps. Many have struggled to penetrate the mystery of the interior of the

* Presidential Address of Professor Eddington to Section A of the British Association at Cardiff, 1920 August 24.

The helium which we handle must have been put together at some time and some place. We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place.

Sir Arthur Eddington, 1920
The Internal Constitution of the Stars

Nuclear Fusion



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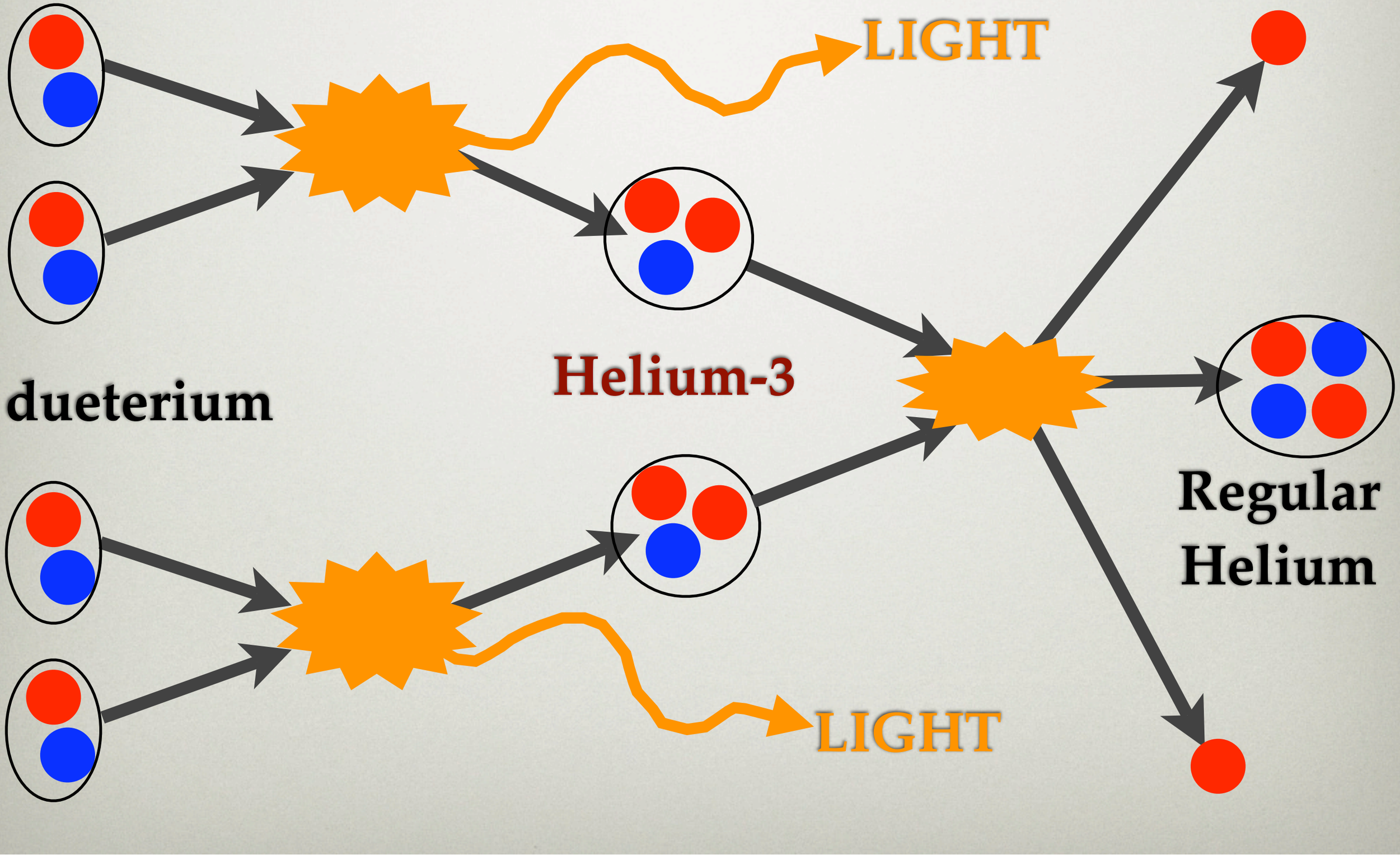
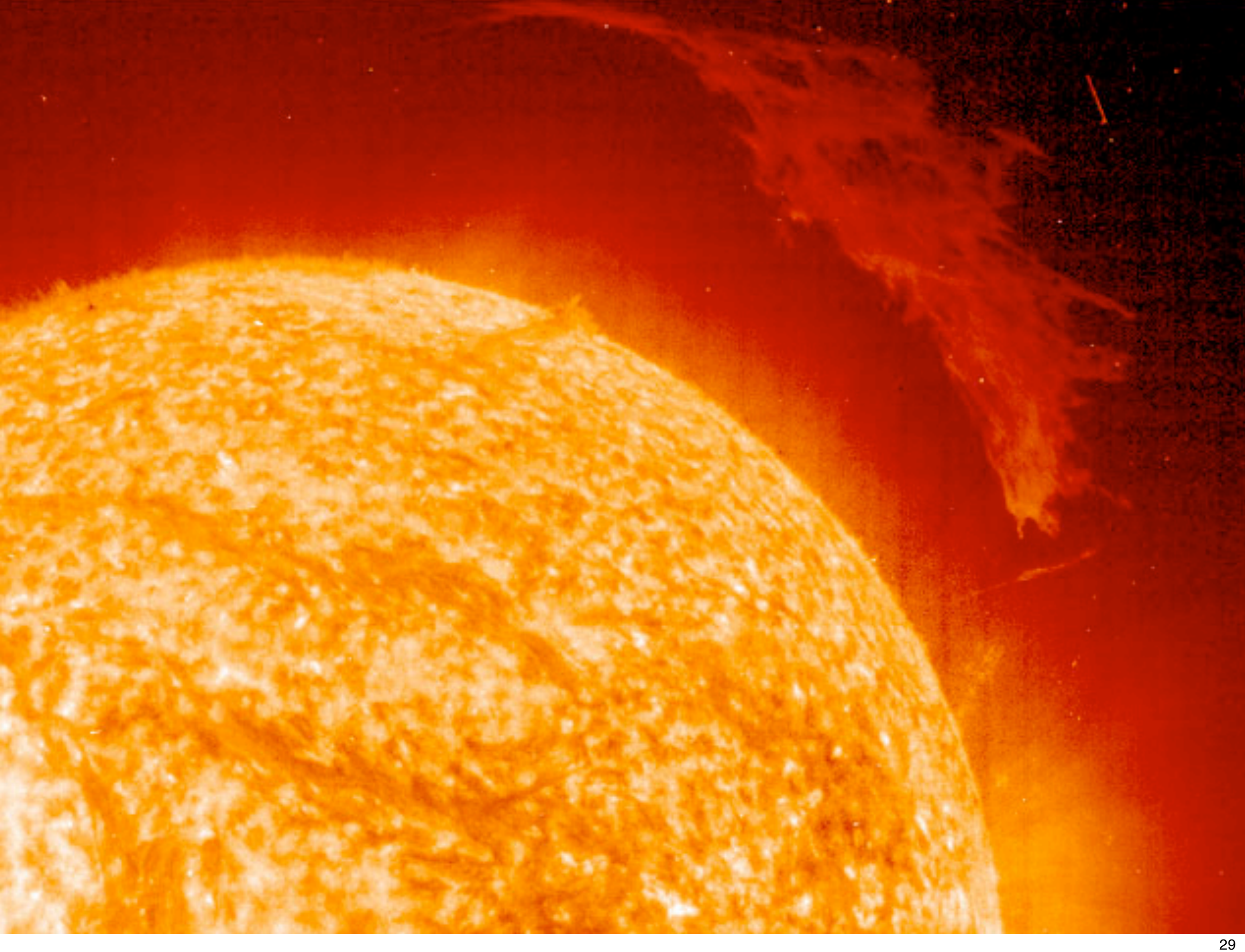


Energy Transport

- Almost all of the energy produced by the Sun, is produced within 10% of the Solar radius
- The sun is very thick with gas, so this energy leaks out, it takes 100,000 years for the energy produced, to find its way to the surface 400,000 miles away
- It takes only 8 minutes to go from the surface of the sun, to us, another 93,000,000 miles away!

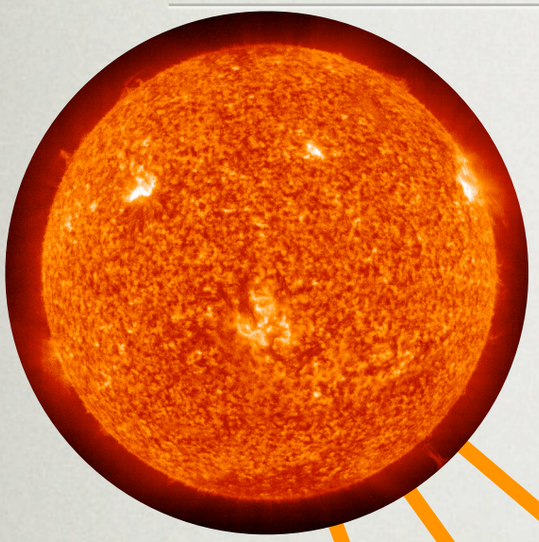
Seeing Neutrinos

- In Visible Light, we only see the Sun's surface...
- We have detected neutrinos from the inner 0.1% of the Sun, where fusion is furious!




Nuclear Fusion of 5
ounces of Hydrogen

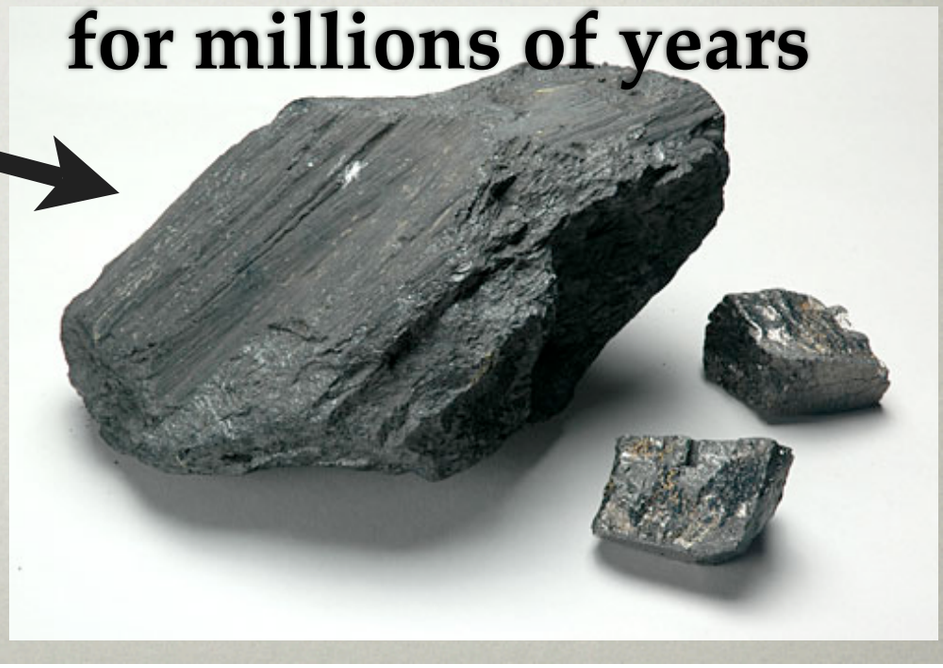
Energy Use



oil: decay, heat, compress for millions of years

photosynthesis

coal: decay, heat, compress for millions of years



Can We Capture the Sun's Energy?

- With Plants?

- Unfortunately, only 1/7 of the Sun's energy makes it to the ground
- Plants only capture about 0.05% of that (USDoE)
- So ... supporting US Energy on corn requires 3 times the area of the US! Transportation needs alone require 1 entire US filled with corn!

Can We Capture the Sun's Energy?

- With Solar Power Plants?

Can We Capture the Sun's Energy?

- With Solar Power Plants?
- The best such systems are more than 10% efficient...
- So, crunching the numbers indicates that we could cover only 3% of the US that way, and get all of our energy!

Nuclear? Geothermal?

- Nuclear power comes from Uranium *fission*
- Geothermal heat comes from radioactivity deep below the Earth's surface
- The raw materials for these processes (Uranium, Thorium, Potassium, ...) are produced by earlier generations of stars

The end of the Sun

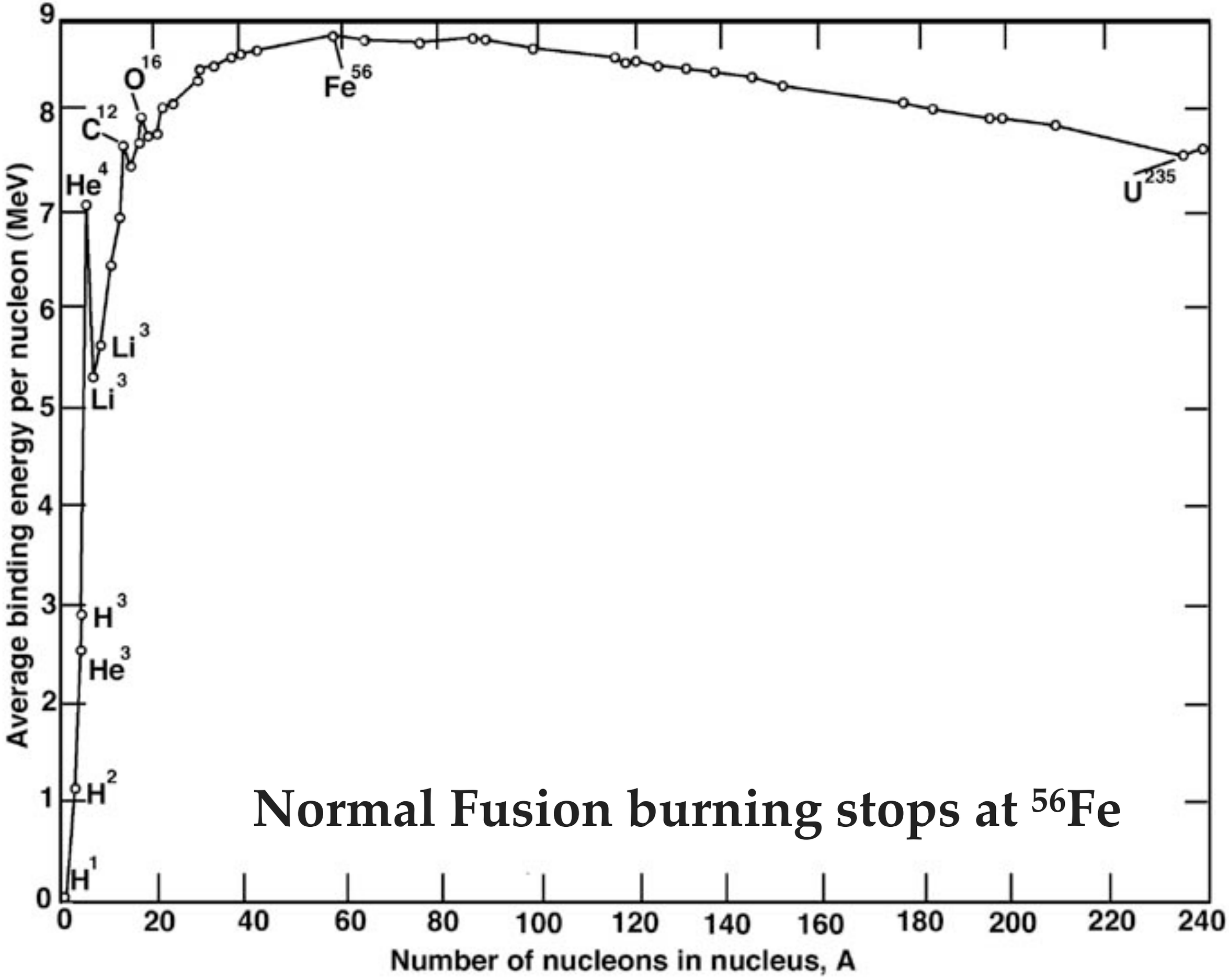
- When the Sun runs out of Hydrogen to burn in its core, it will stop producing its own energy and eventually, become a "white dwarf"

- The Sun has been around for about 5 billion years, this "death" will occur in about 5 billion years.


The Helix Nebula — NGC 7293
HUBBLESITE.org

Making Heavy Elements

- More massive stars can exert more gravitational squeezing on their interiors, and cause continued fusion
- Helium can combine to form Carbon, then Neon, then Magnesium, then Silicon, then Sulfur, ...
- A star more massive than ~5 solar masses will "burn" its interior all the way to Iron
- Burning produces by adding one Helium to the previous nucleus in the chain



Normal Fusion burning stops at ^{56}Fe

hydrogen 1 H 1.0079																	helium 2 He 4.0026
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potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]			

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hydrogen 1 H 1.0079																	helium 2 He .0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122											boron 5 B 10.81	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	agnesium 12 Mg 24.305											aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
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STOP

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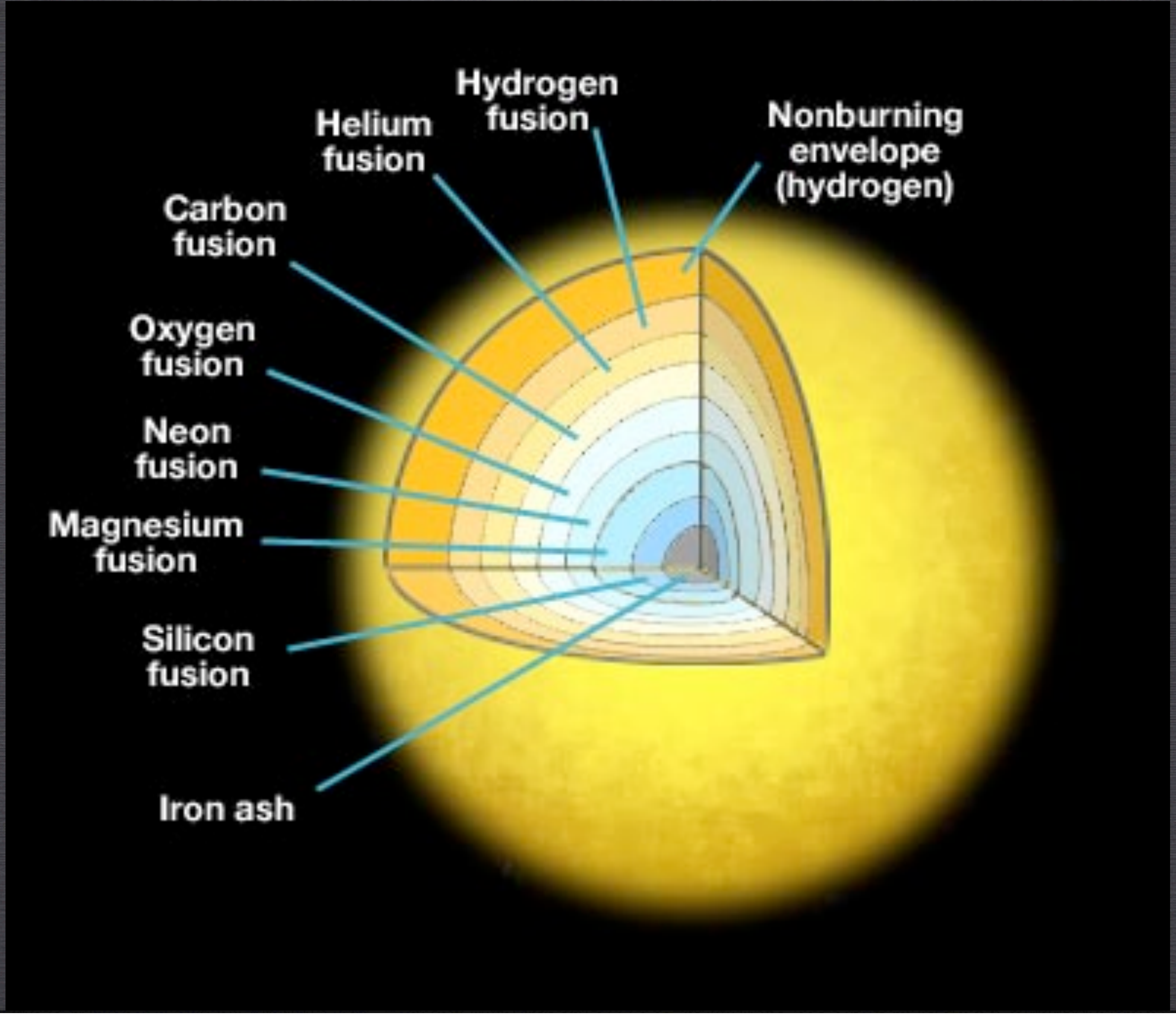
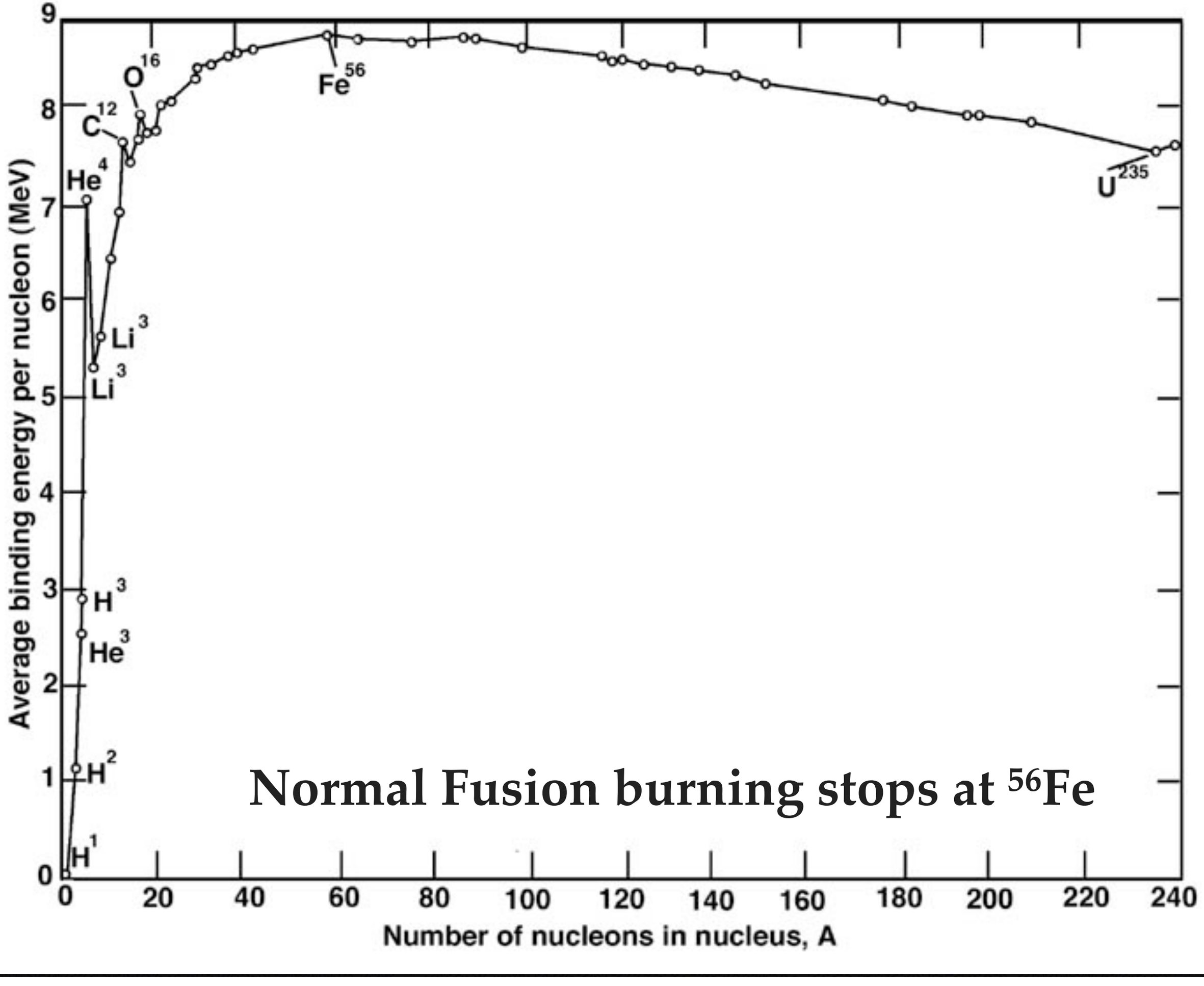
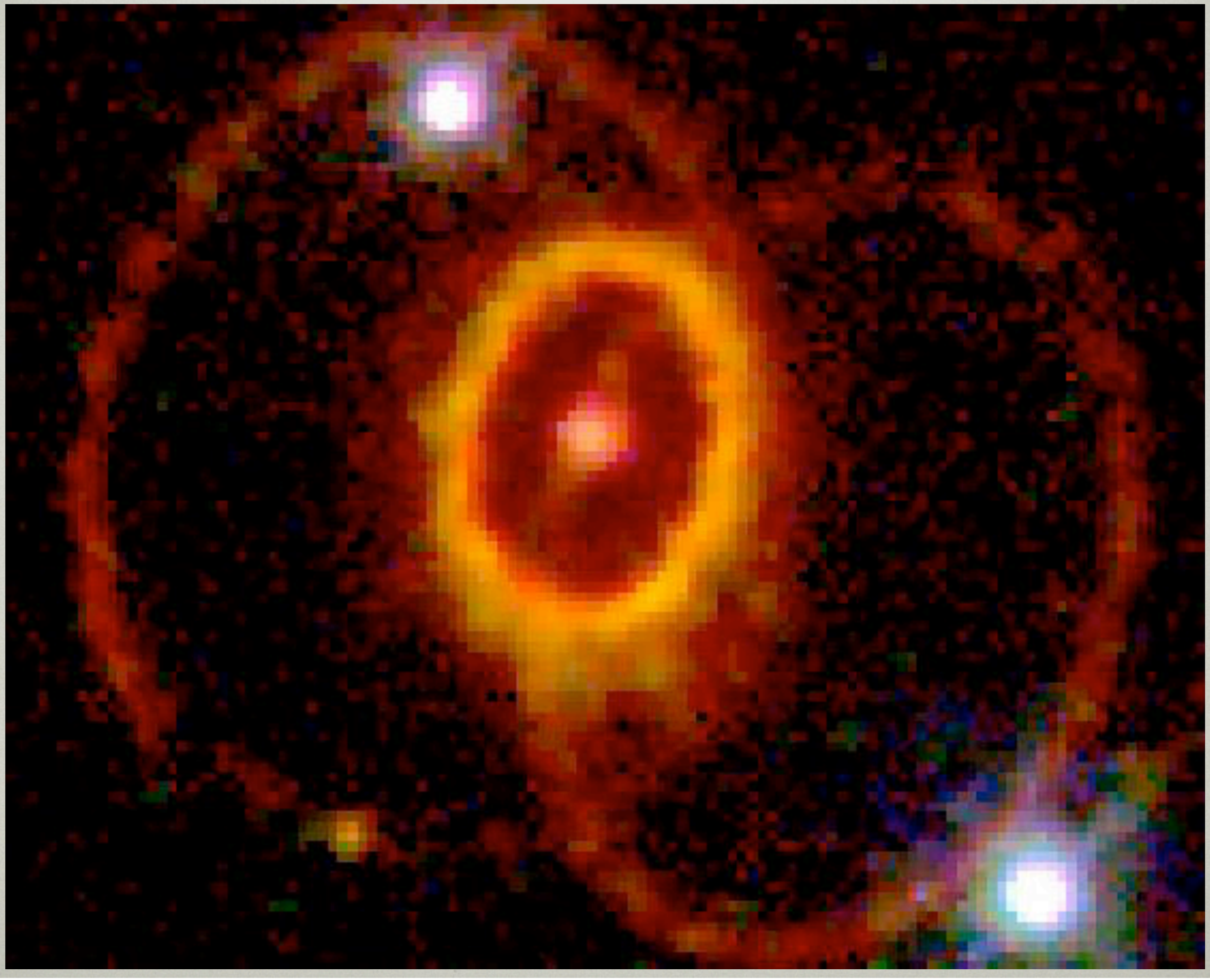
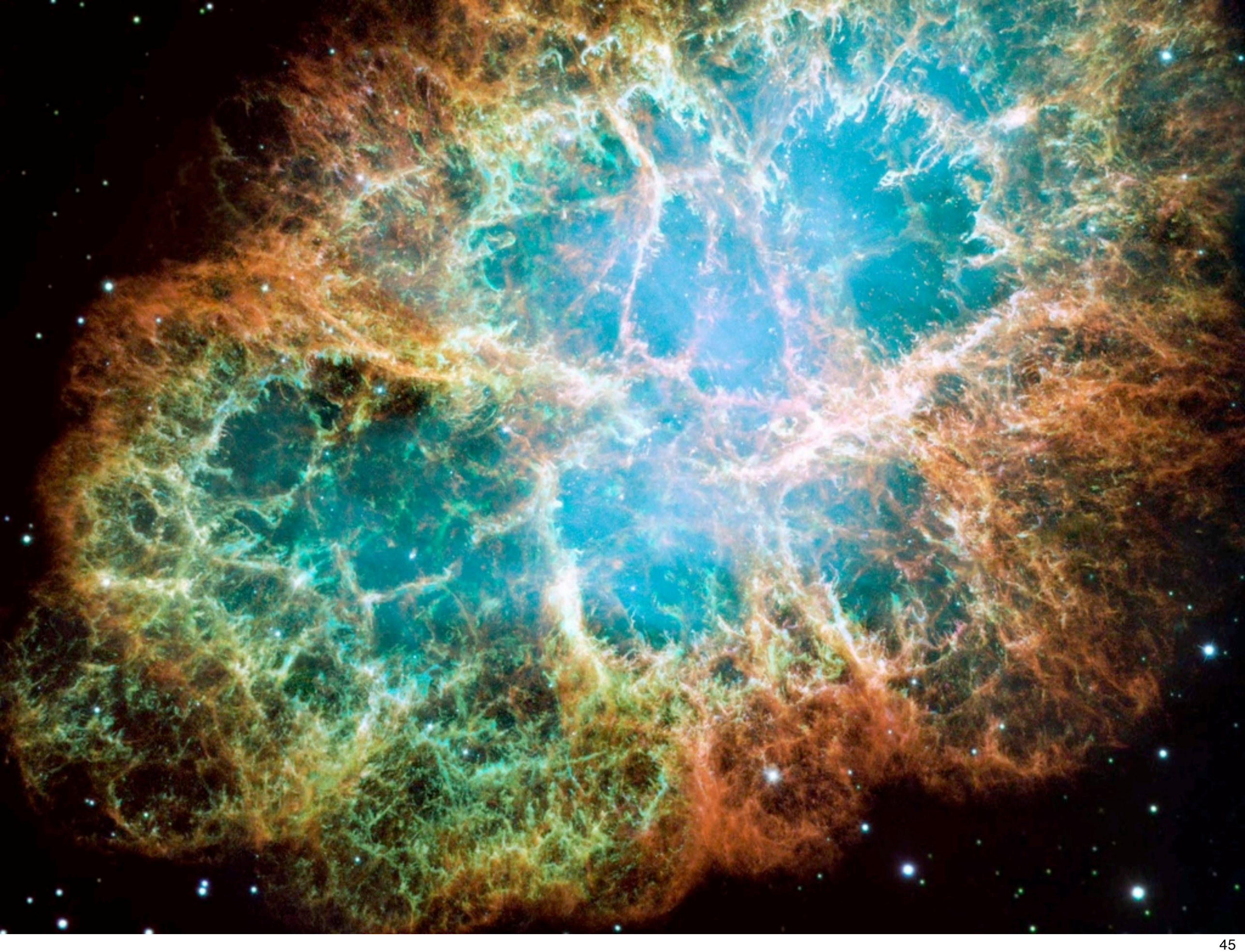
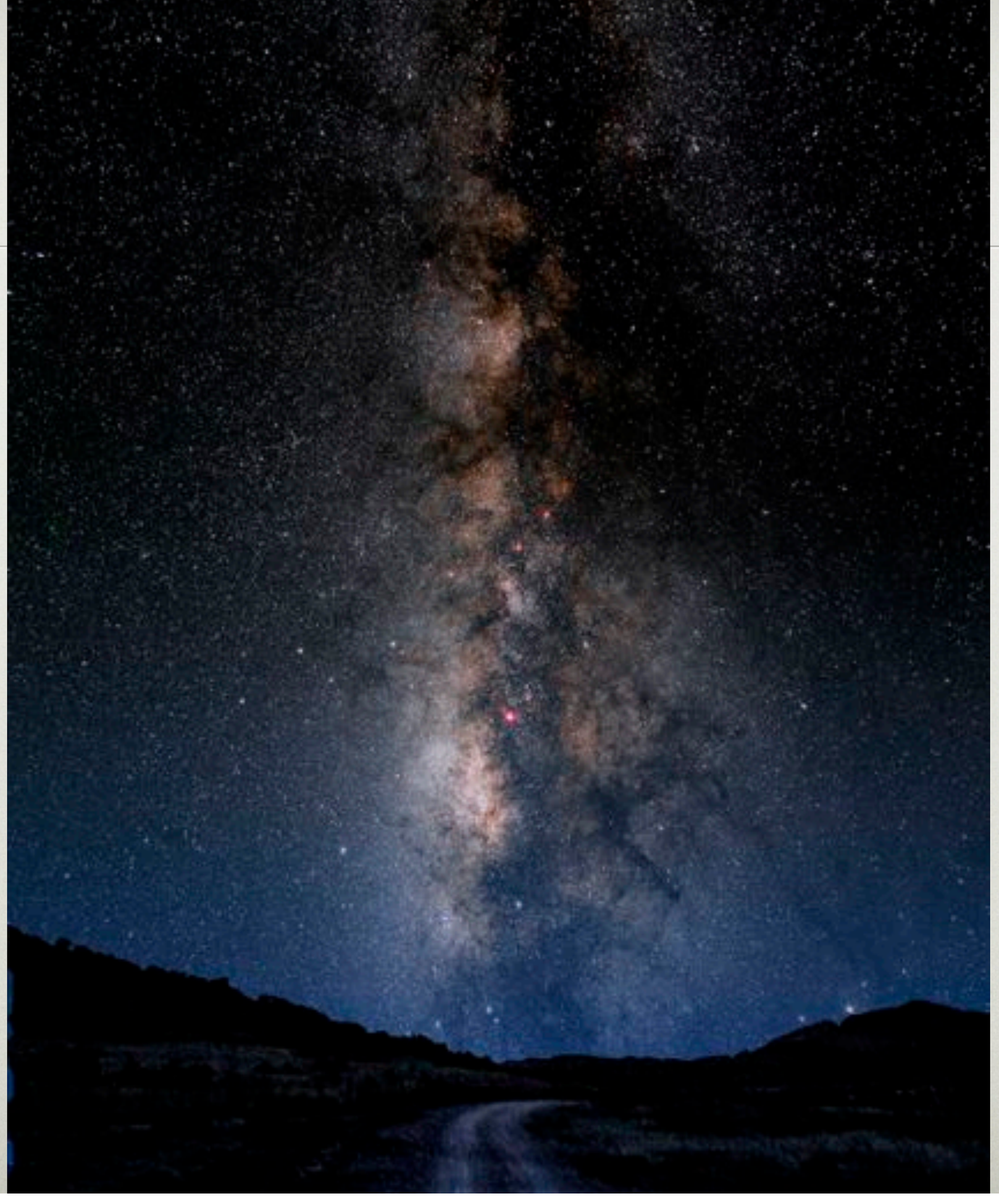

Hydrogen fusion
Helium fusion
Nonburning envelope (hydrogen)
Carbon fusion
Oxygen fusion
Neon fusion
Magnesium fusion
Silicon fusion
Iron ash

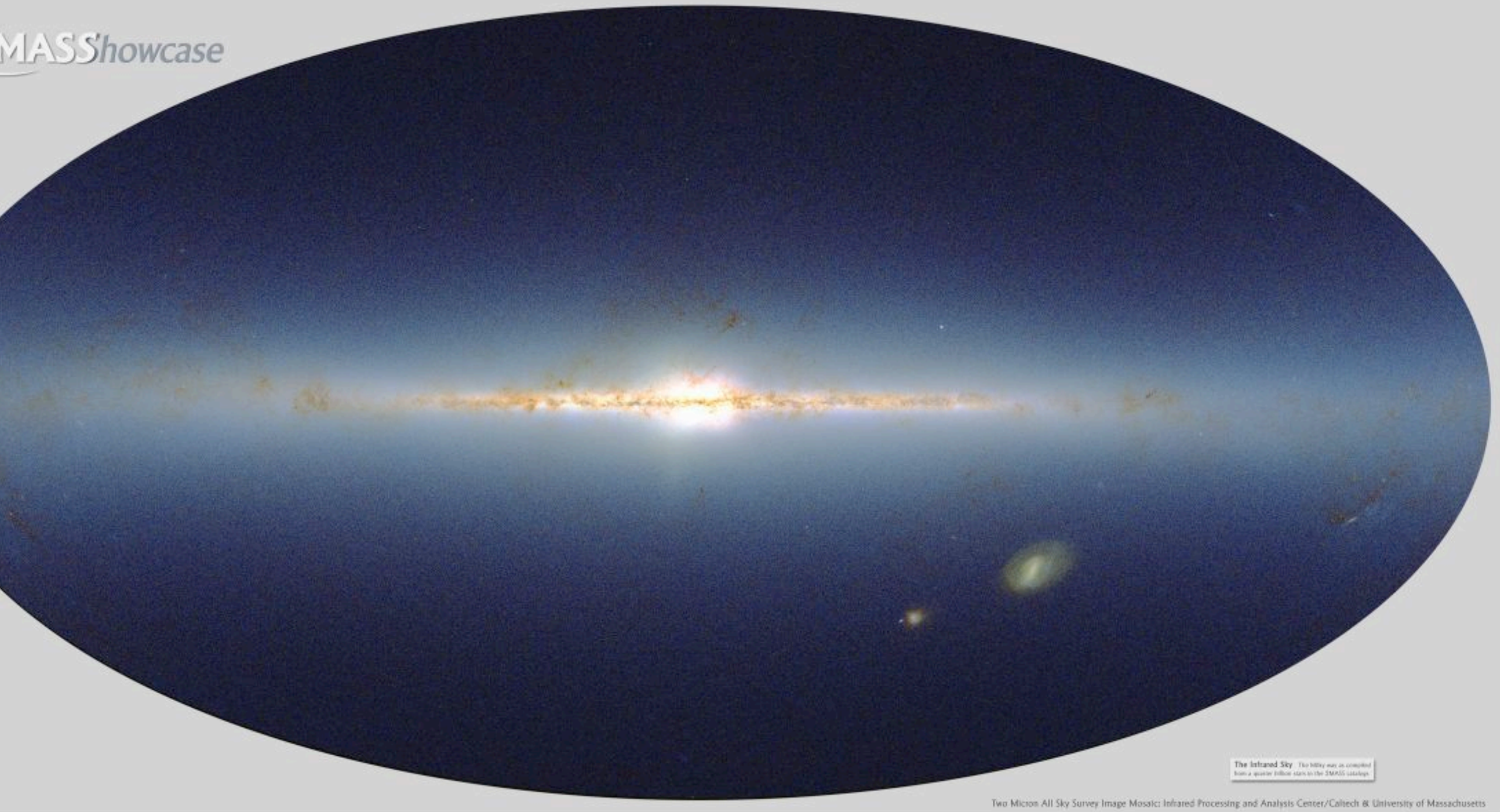


Normal Fusion burning stops at ^{56}Fe

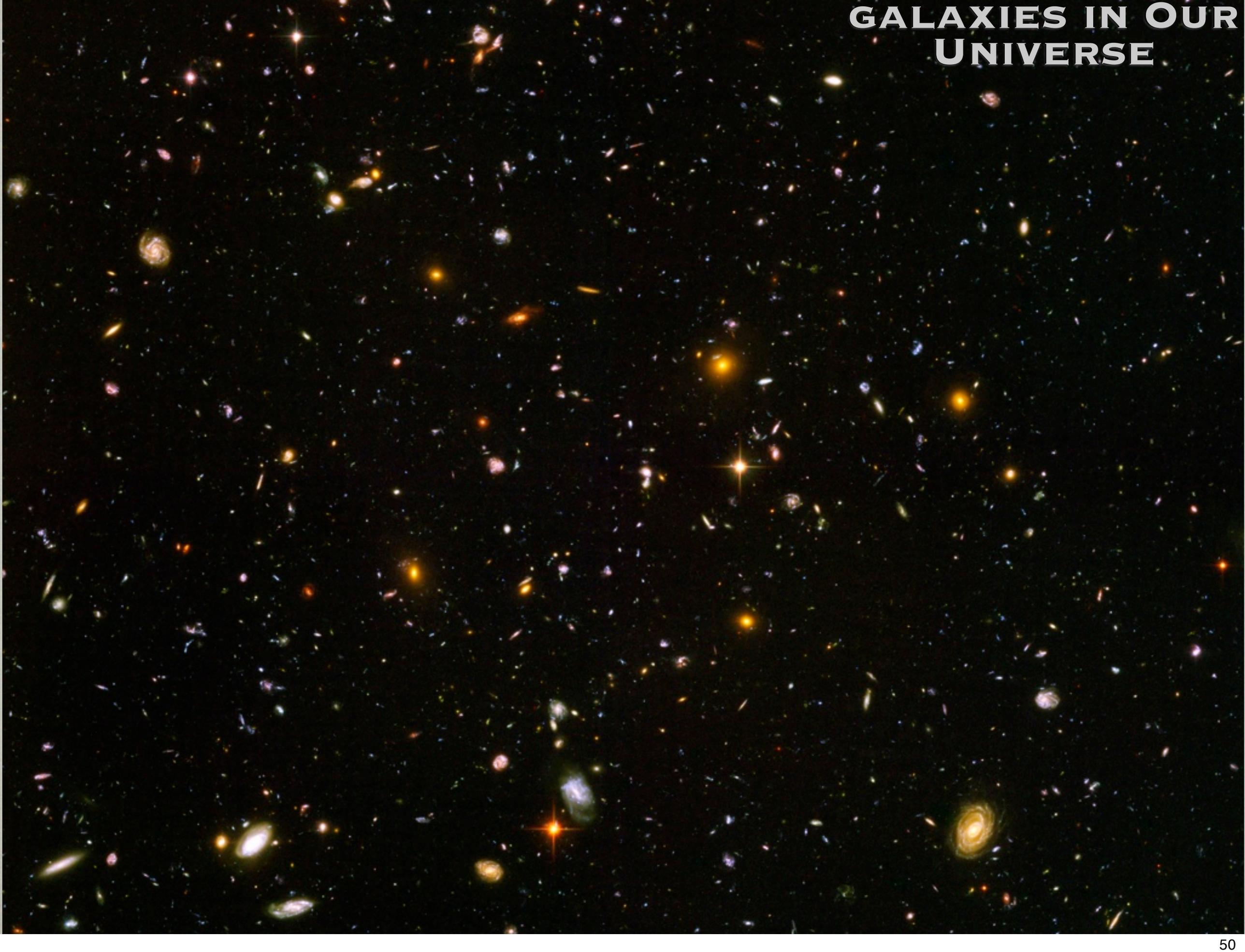


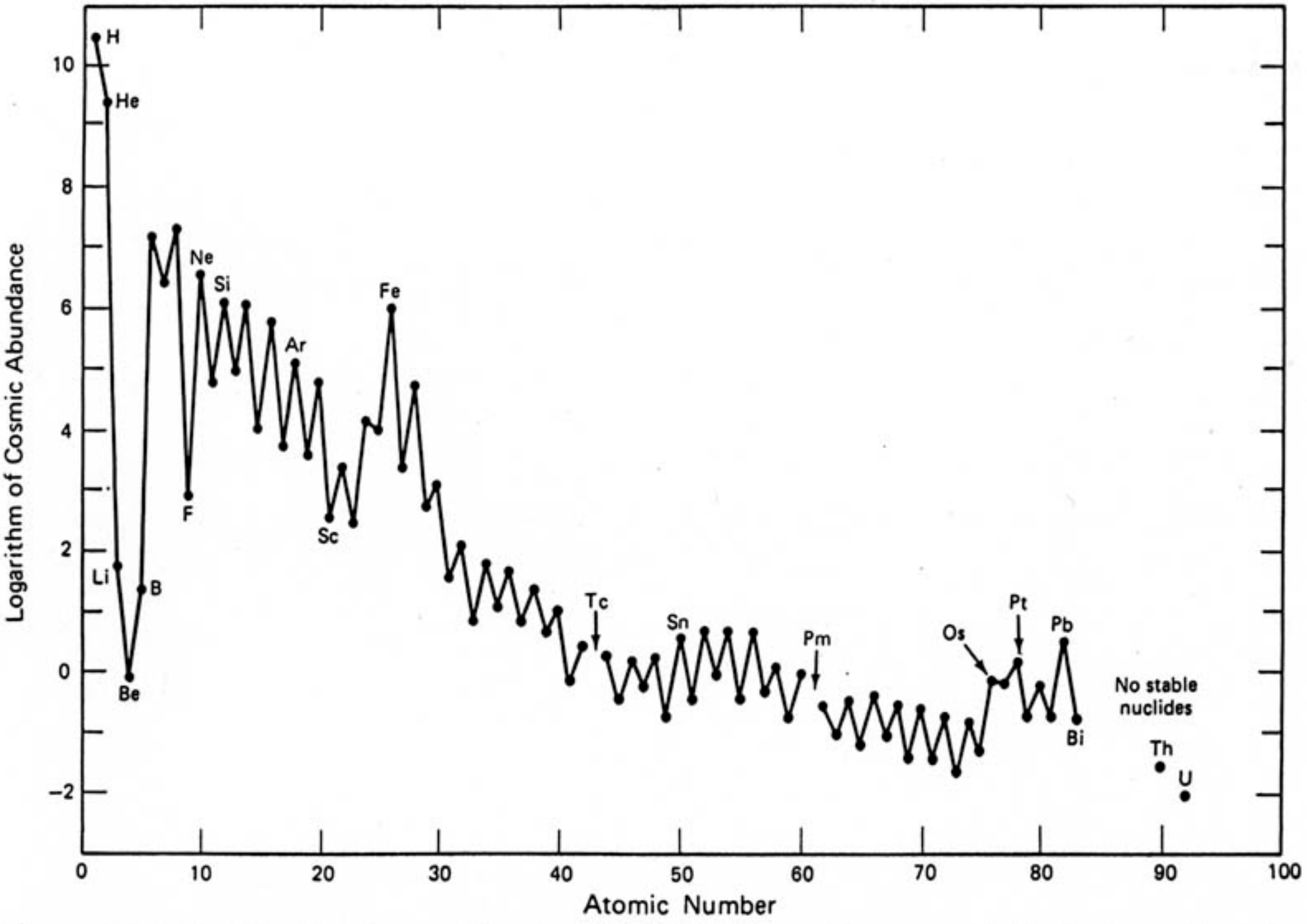




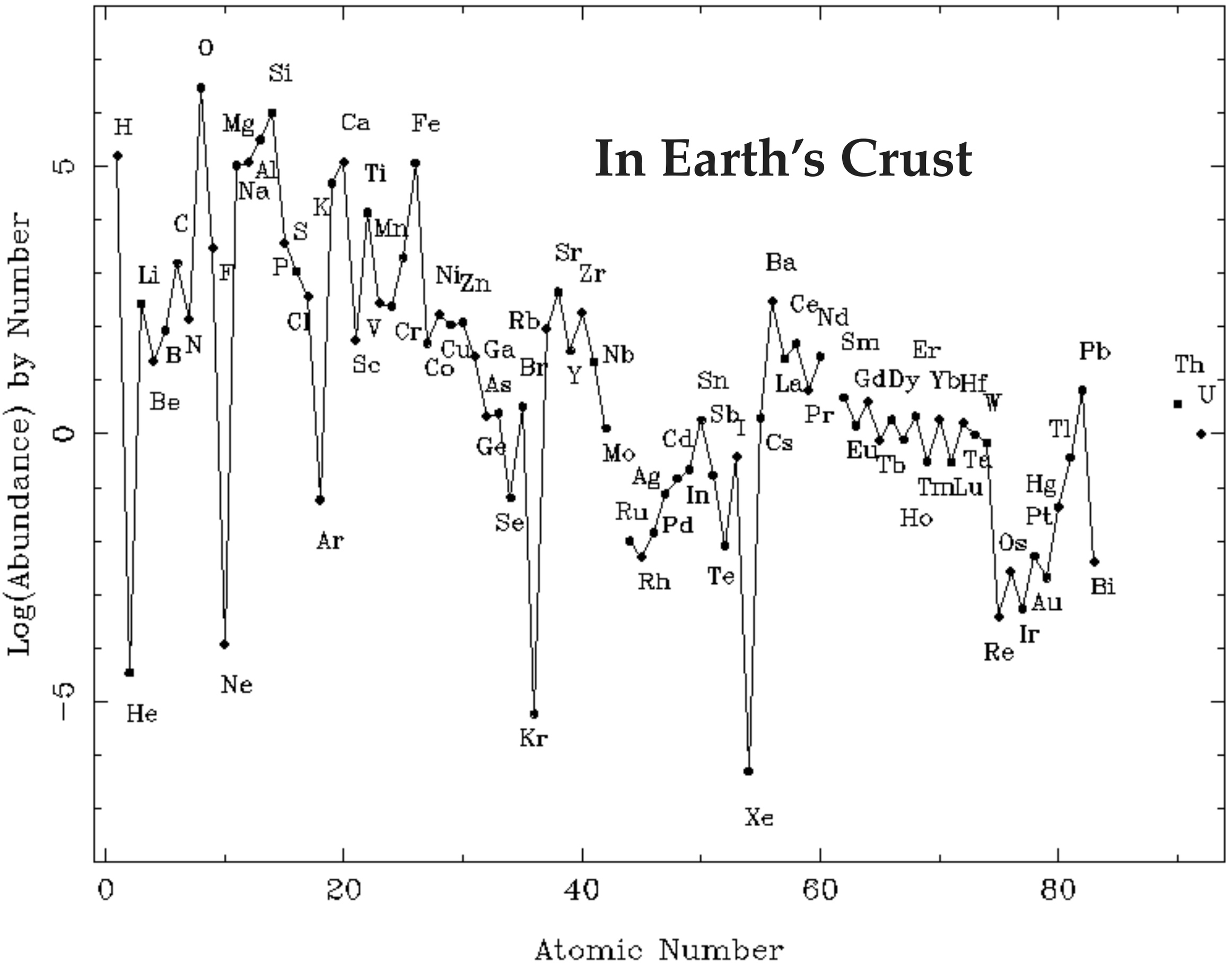

MASShowcase
The Infrared Sky The Milky way as compiled from a quarter billion stars in the 2MASS catalogs.
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

galaxies in Our Universe



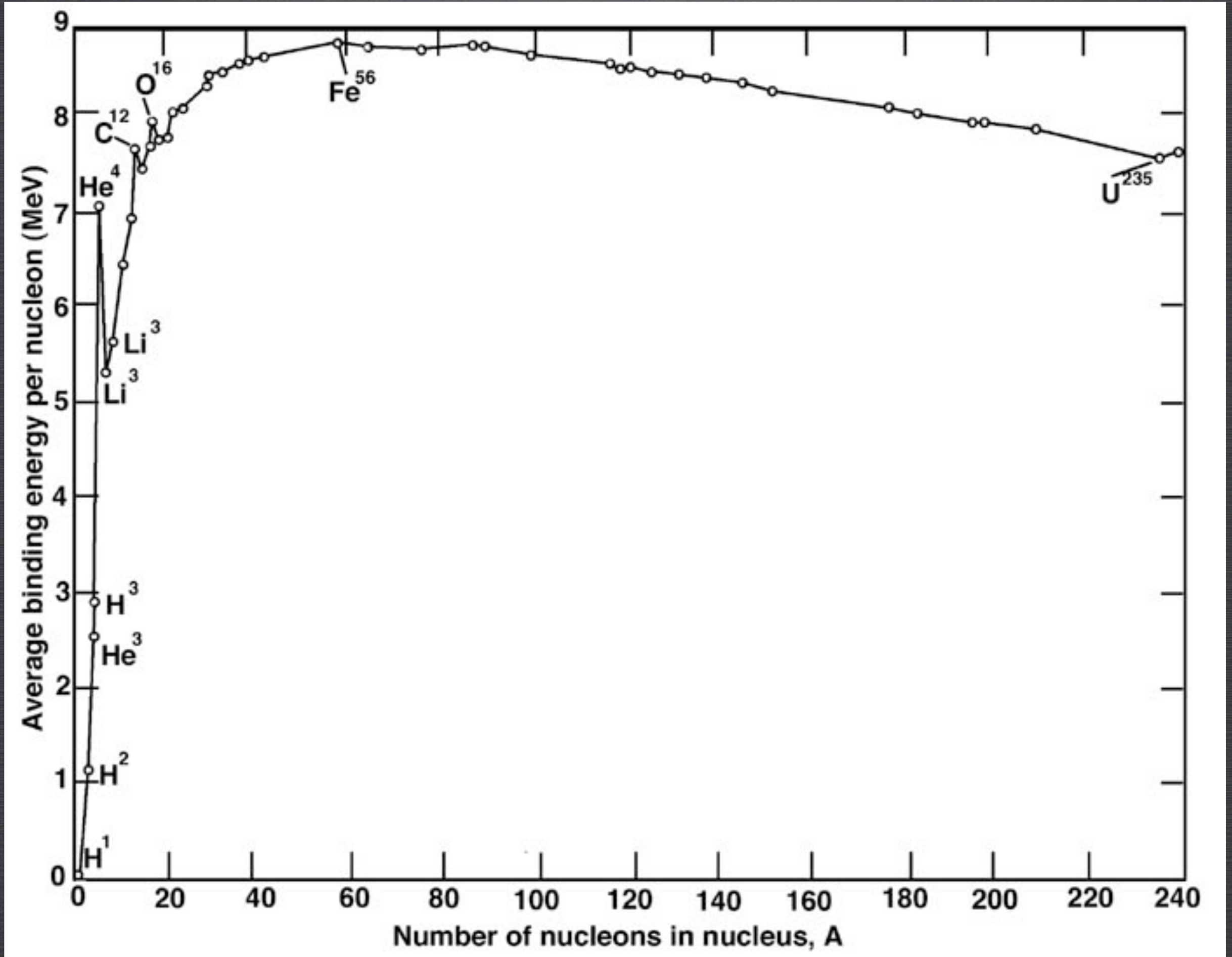

Logarithm of Cosmic Abundance
10
8
6
4
2
0
−2
H
He
Li
Be
B
F
Ne
Si
Ar
Sc
Fe
Tc
Sn
Pm
Os
Pt
Pb
Bi
No stable nuclides
Th
U
0
10
20
30
40
50
60
70
80
90
100
Atomic Number

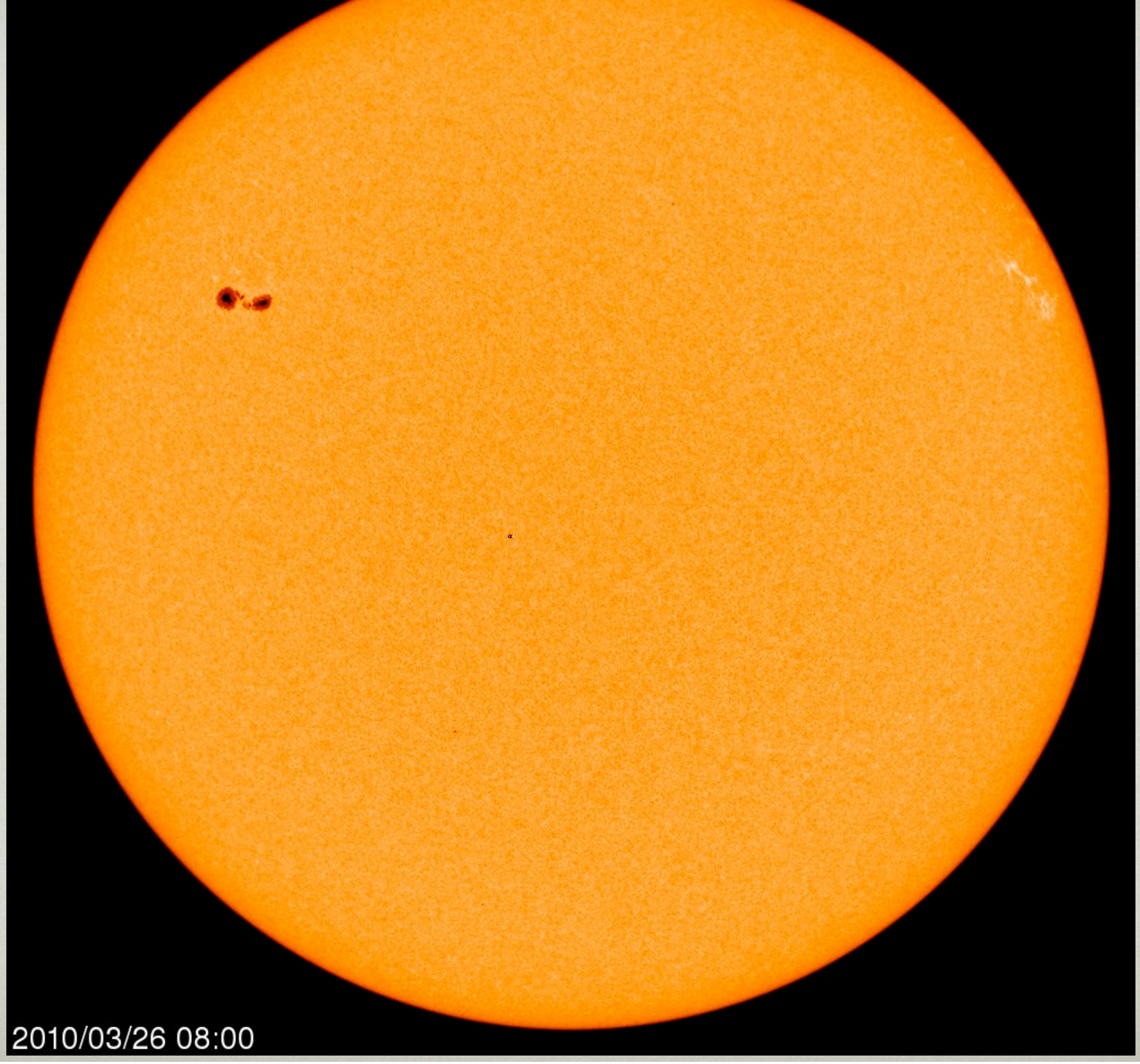
In Earth's Crust



Nuclear? Geothermal?

- These are energy sources from stars other than the Sun!
- Nuclear fission energy can sustain all of our needs for ~100 years, utilizing only 0.01% of US land area!
- Unfortunately, US energy needs are about as much as all upward flux of geothermal energy!

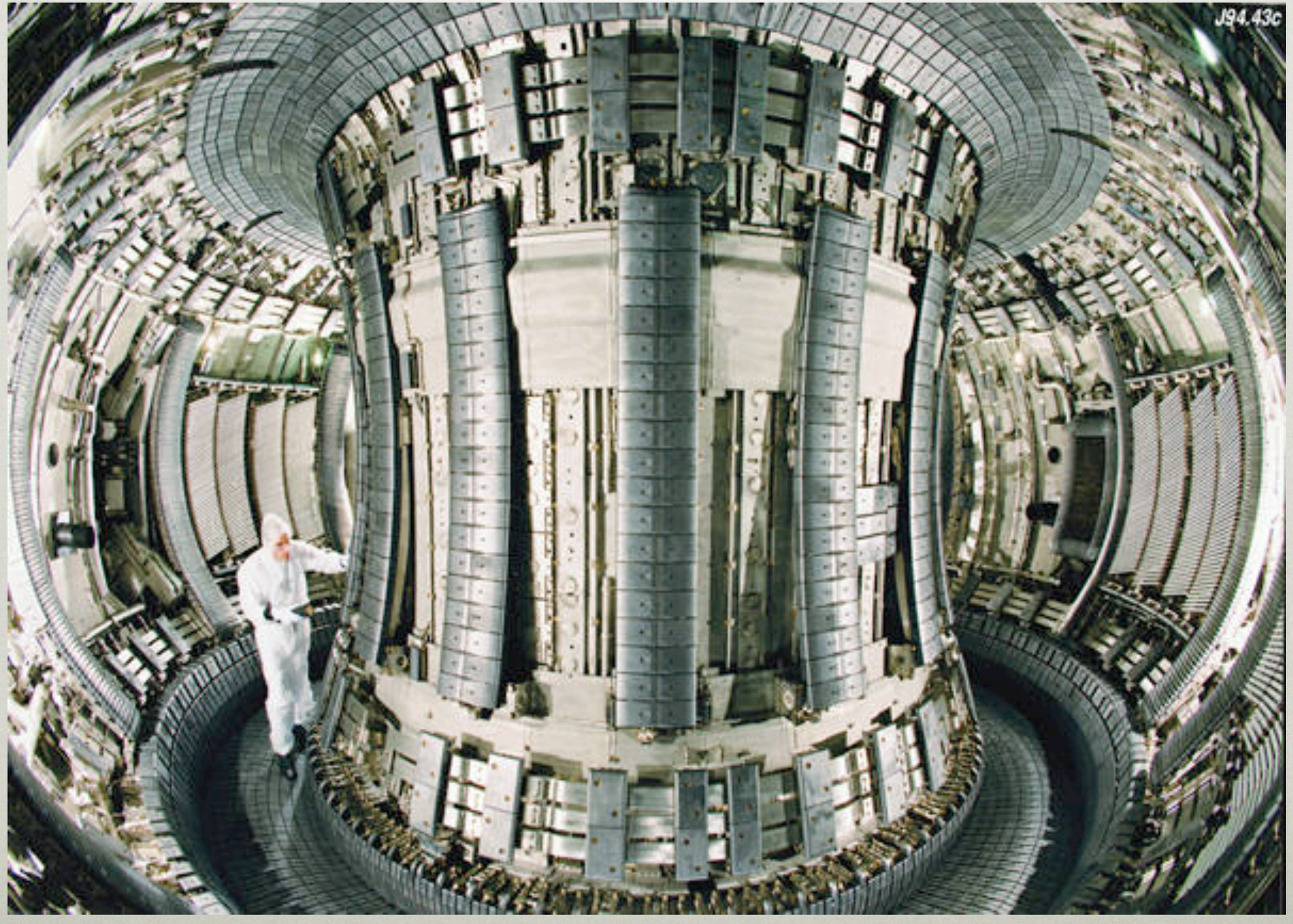

Average binding energy per nucleon (MeV)
Number of nucleons in nucleus, A
0
1
2
3
4
5
6
7
8
9
0
20
40
60
80
100
120
140
160
180
200
220
240
H1
H2
H3
He3
He4
Li3
Li3
C12
O16
Fe56
U235


2010/03/26 08:00

Fusion on Earth?

- Can we recreate the fusion reaction on Earth to produce energy?
- This would be the first time we would be able to utilize an energy source not packaged for us by a star!
- An amount of water equal to 1/3 the annual drinking water used in Mt. Lebanon, could supply all US energy needs in this way.

Recreating the Sun?



Conclusions

- **Stars are powered by squeezing Hydrogen and letting quantum mechanics work its magic**
- **Stars provide all of the materials (other than Hydrogen and Helium) that we use for energy or anything else**
- **Nuclear fusion could end our exploitation of the stars for energy**