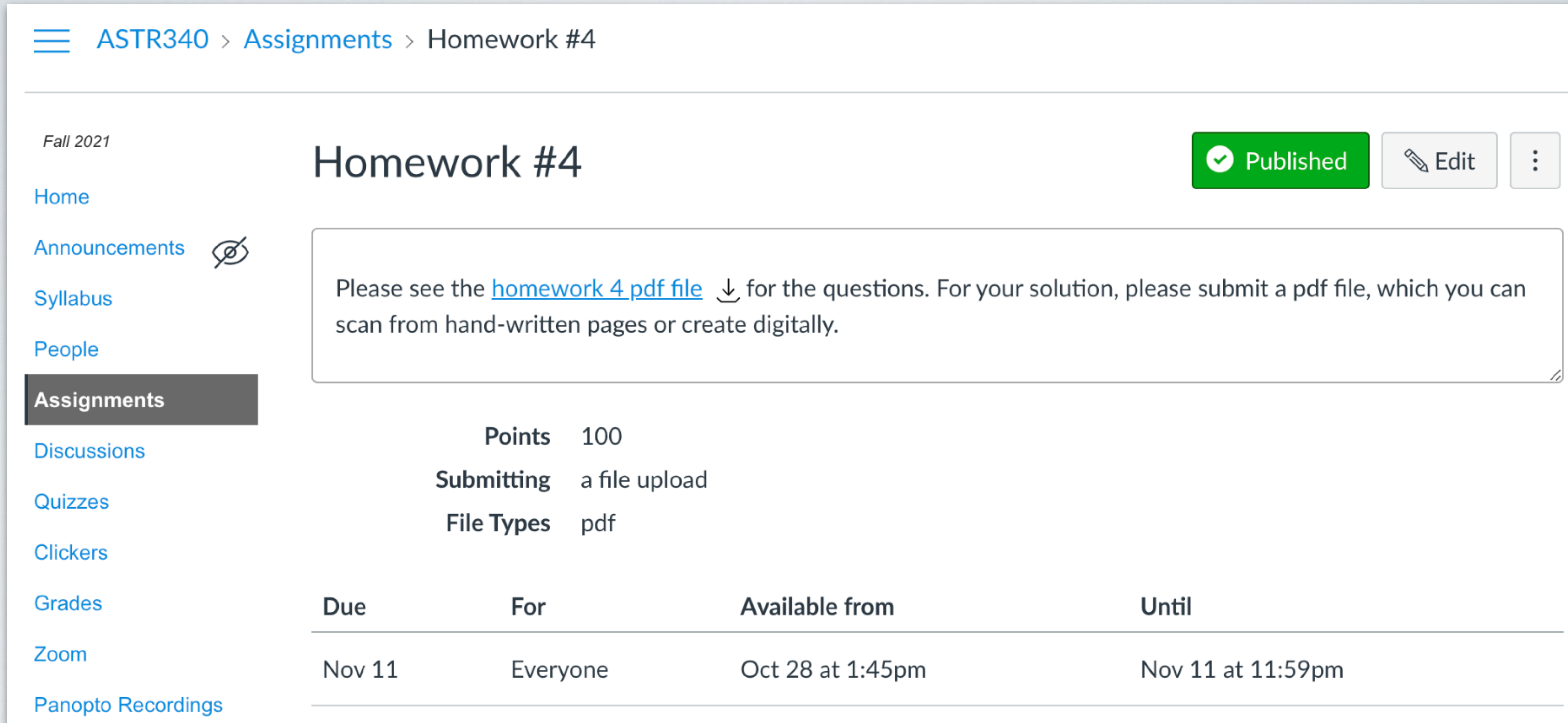
ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 16 • Are we all made of star stuff?

10/28/2021

Homework 4



- Due Thursday 11/11

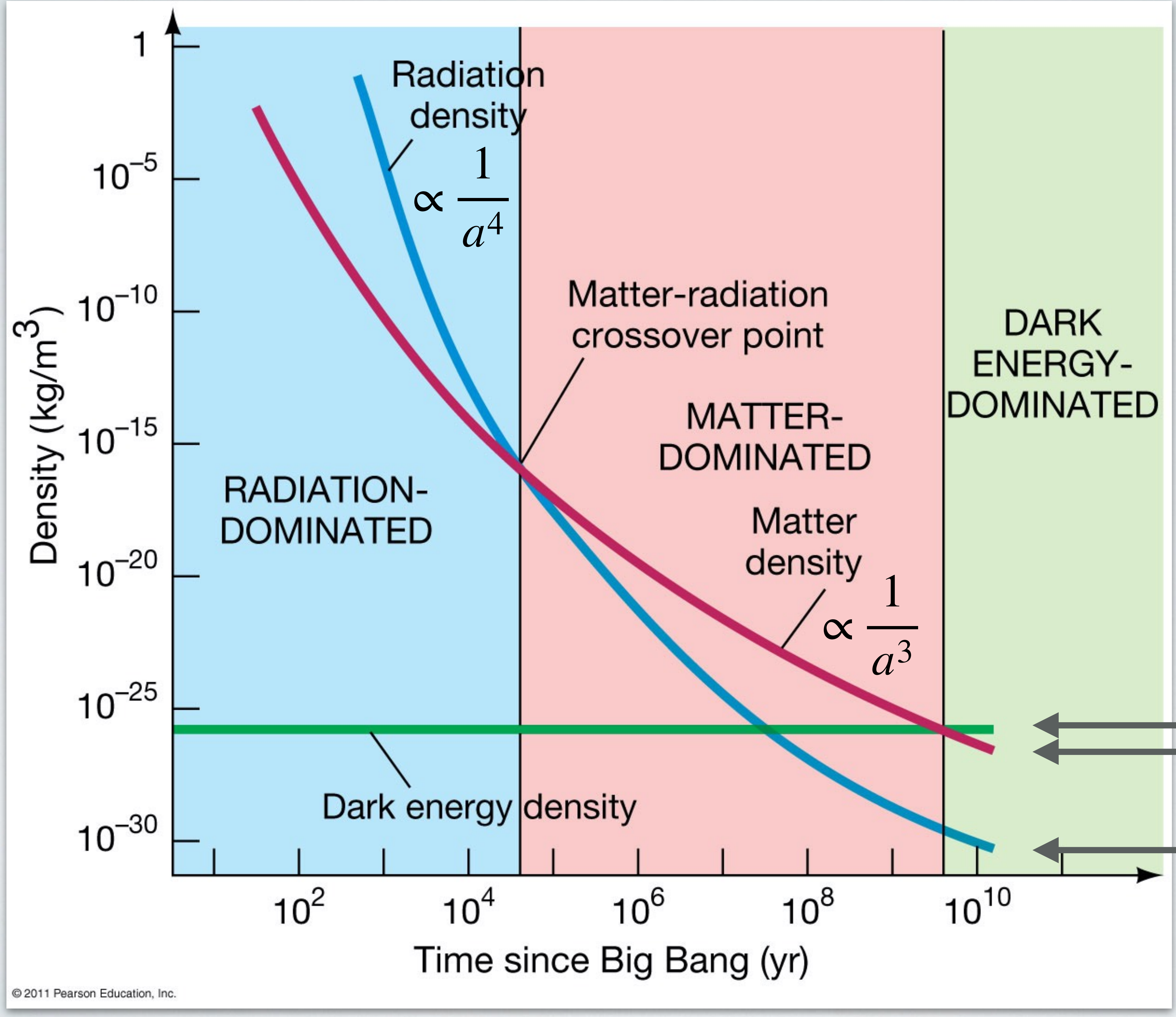
Next week

Time	Monday	Tuesday	Wednesday	Thursday	Friday
11:00-12:00	TA office hours			Offic ours	
12:00-12:30					
12:30-1:45		Lecture		Lecture on zoom!	
1:45–3:00					
3:00-4:00			Offi ours		
4:00-11:59					
11:59			Tue quiz due		Thu quiz due

- No office hours (no homework due)
- Thursday lecture on zoom!

Recap

What dominates the energy density?



Today:

$\approx 70\,\%$

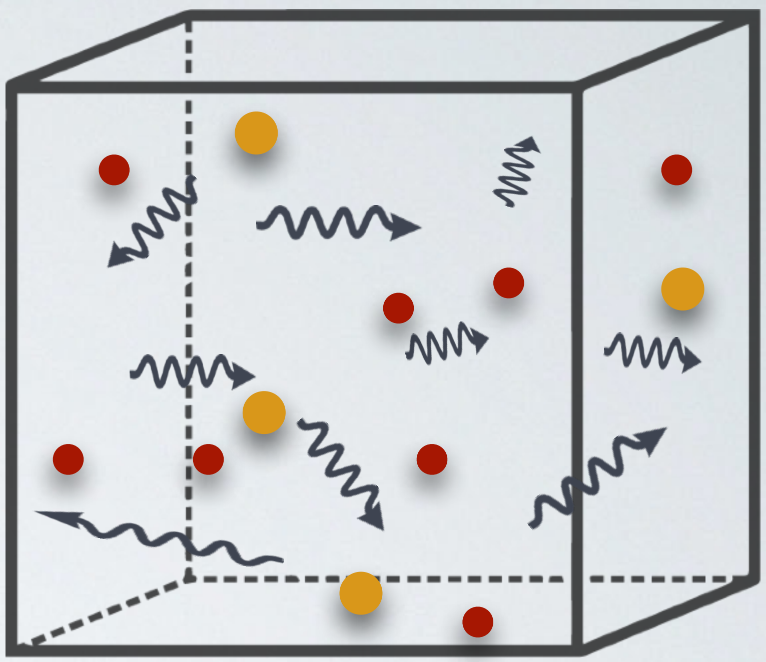
$\approx 30\,\%$

$\approx 0.009\,\%$

University of Oregon / Pearson

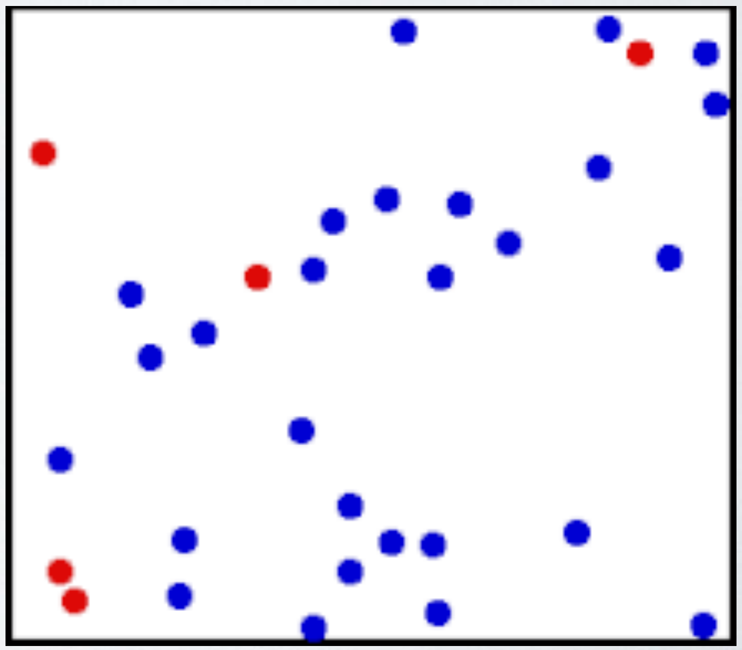
What is temperature?

- In the early Universe, photons and particles were in **thermal equilibrium**
- At a given temperature, each particle or photon has the **same average energy:**



$$\langle E \rangle = \frac{3}{2} k_B T$$

$$k_B = 1.38 \times 10^{-16} \frac{\text{erg}}{K}$$



- k_B is called the **Boltzmann constant**

Participation: Recap #1

TurningPoint:
How does temperature evolve with the scale factor?

Session ID: diemer

30 seconds

Participation: Recap #2

TurningPoint:
What is the temperature of the Universe (the cosmic microwave background photons) today?

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30 seconds

Evolution of temperature

$$E_{\rm phot} \propto \frac{1}{a}$$

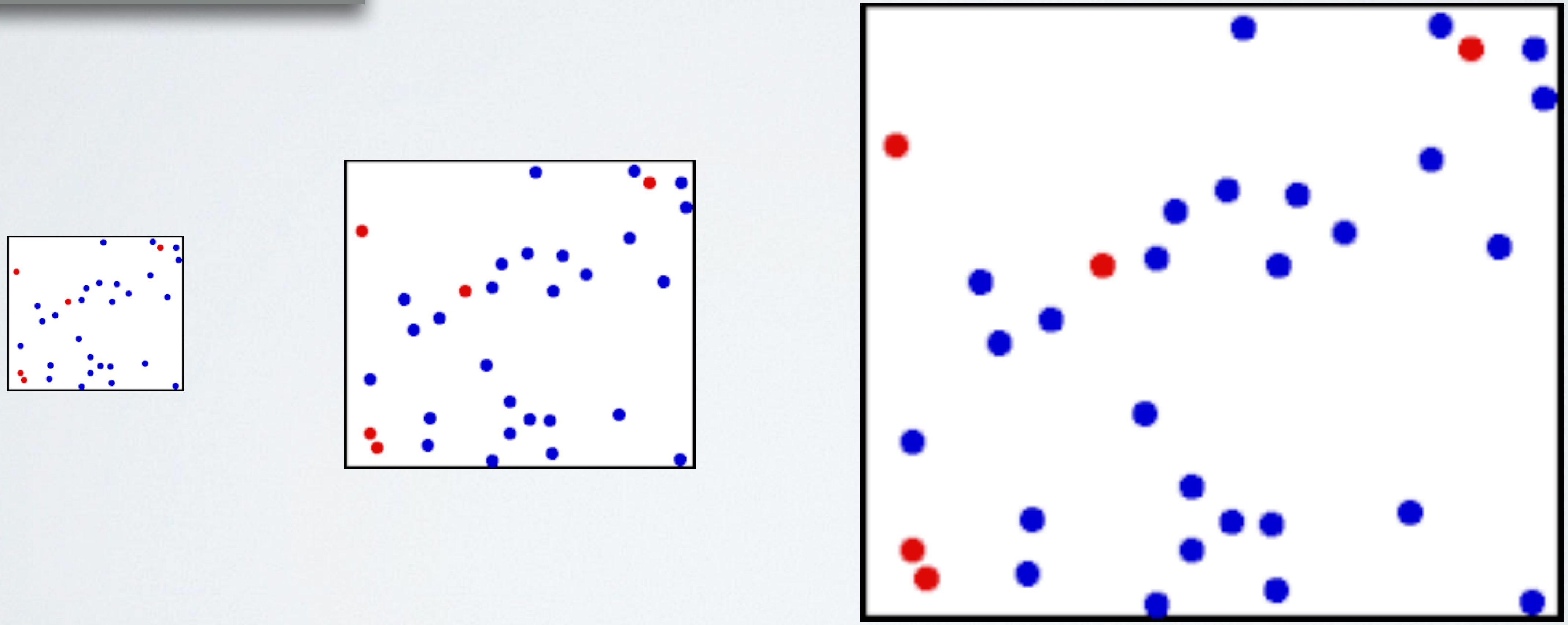
$$\langle E \rangle = \frac{3}{2} k_{\rm B} T$$

$$\Longrightarrow$$

$$T(t) = \frac{T_0}{a}$$

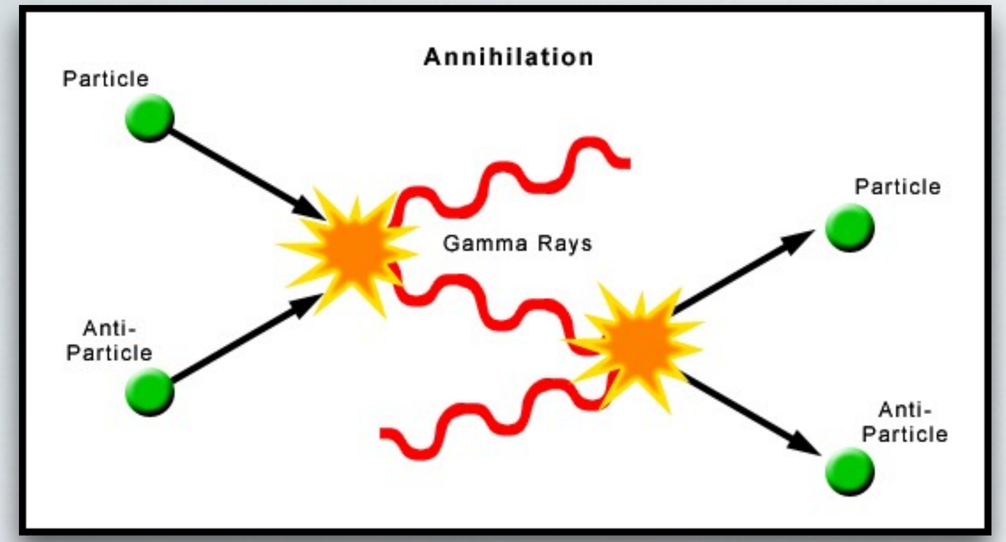
CMB photon temperature today:

$$T_0 = 2.725 \text{ K}$$



Temperature and energy increase towards the Big Bang as 1/a

Matter-light conversion



- If photons have sufficient energy, they can create particle-antiparticle pairs
- Particles annihilate to create photons
- Thus, there is a temperature where photons can, on average, create a certain particle
- For example, protons with $m = 1.7 \times 10^{-24}$ g, $T_{\mathrm{proton}} \approx 10^{13}\mathrm{K}$

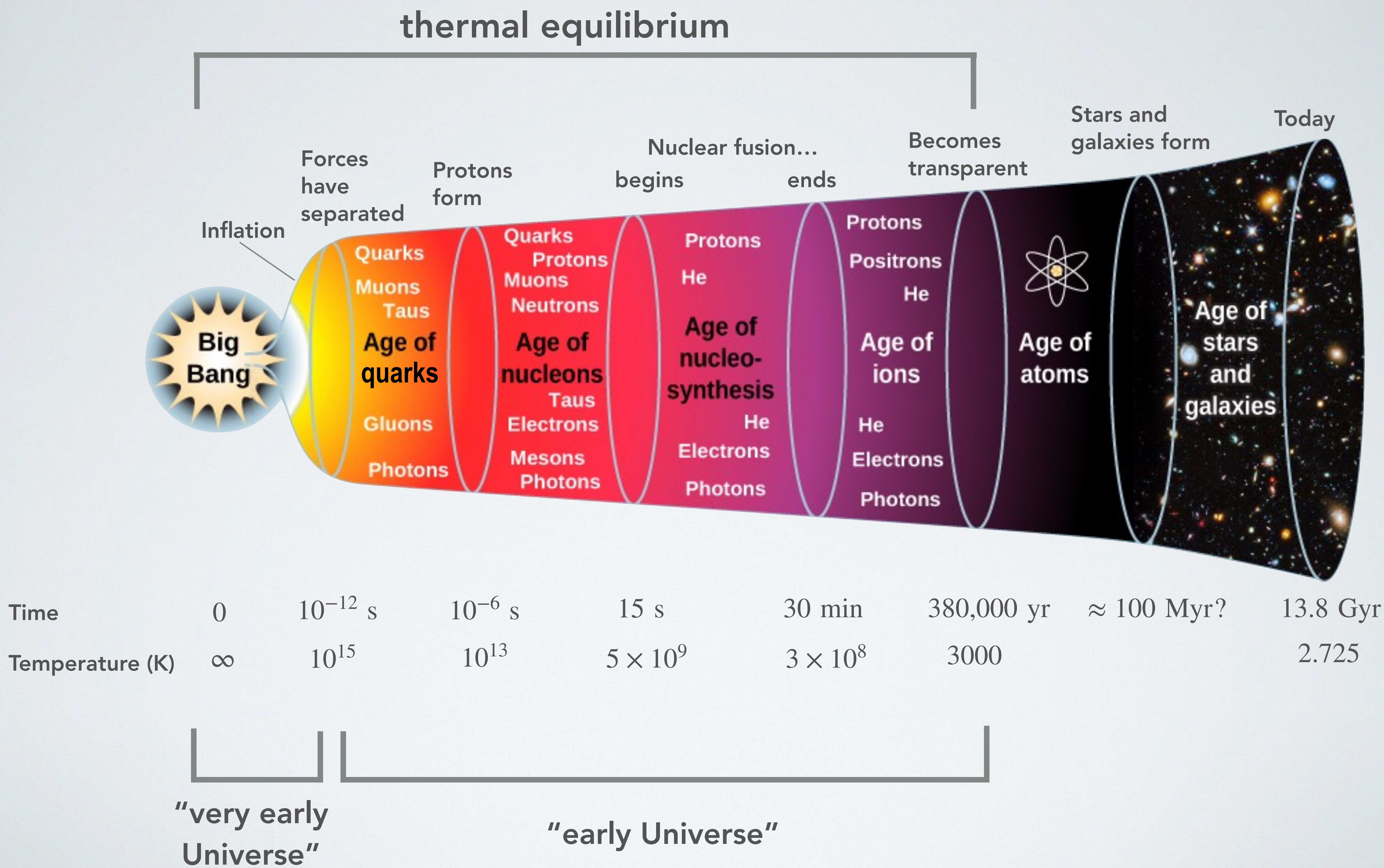
$$E = mc^2$$

$$\langle E \rangle = \frac{3}{2} k_{\mathrm{B}} T$$

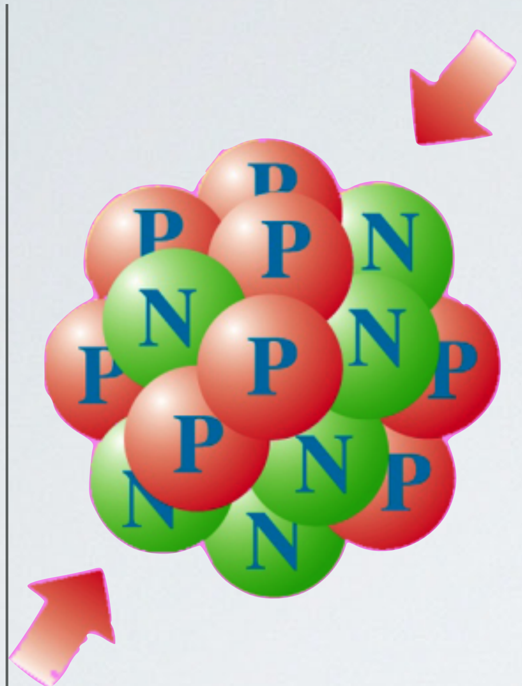
$$\Longrightarrow$$

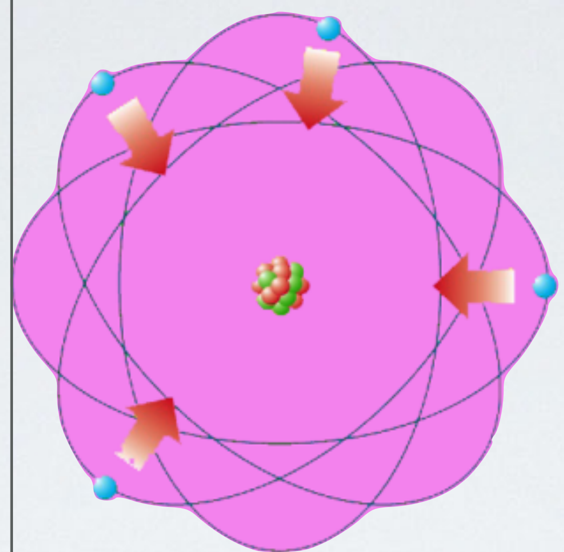
$$T_{\mathrm{thresh}} = \frac{2mc^2}{3k_{\mathrm{B}}}$$

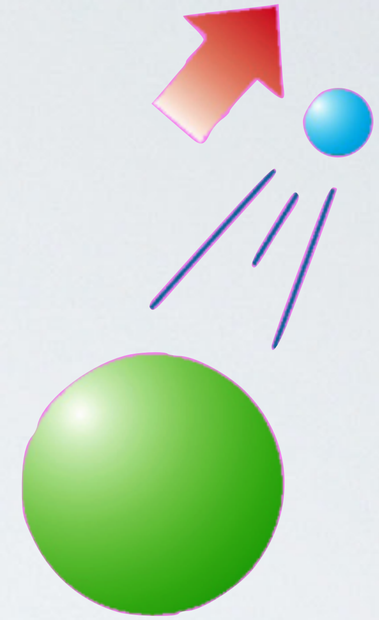
History of the Universe



Fundamental forces

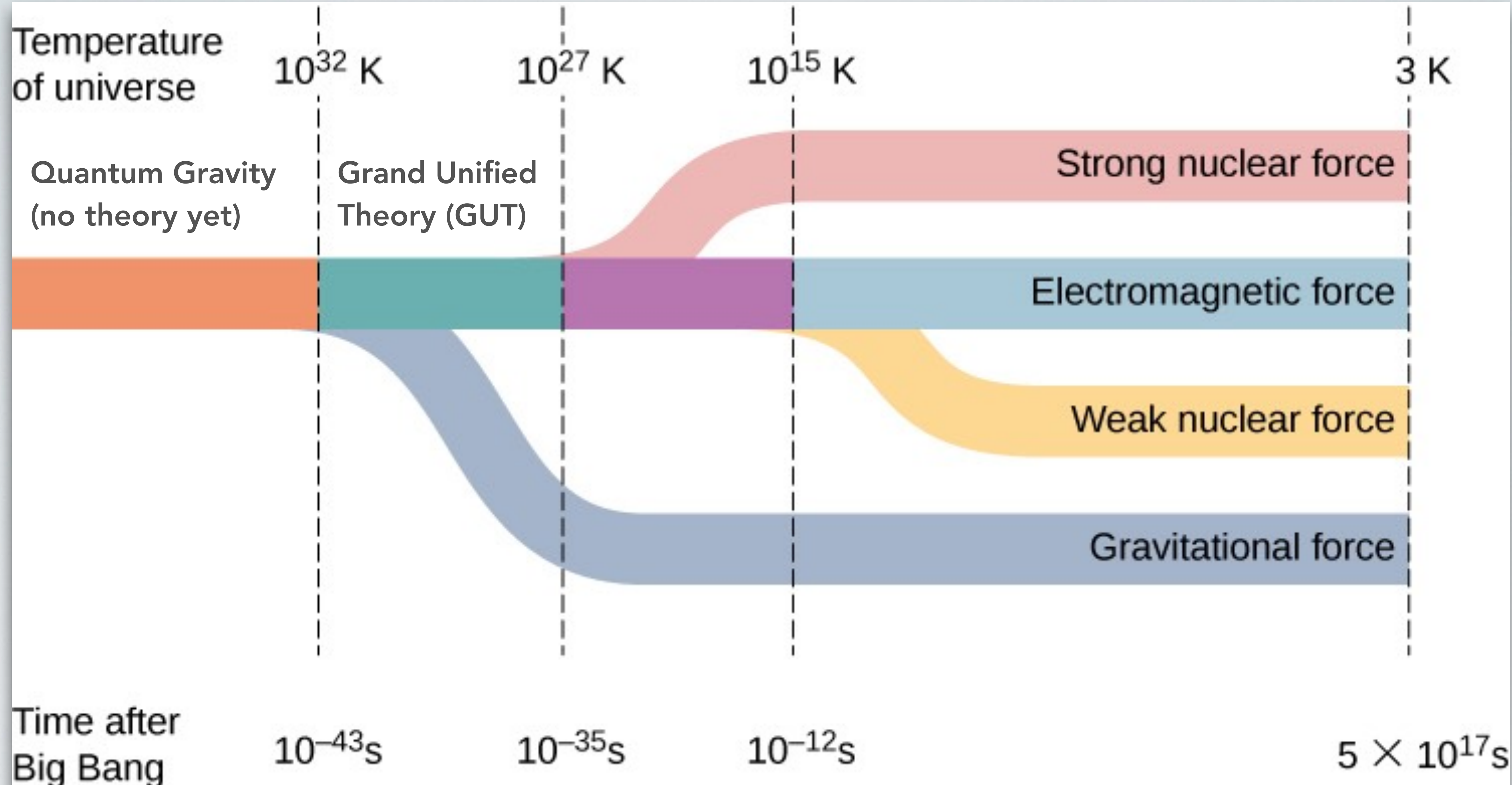






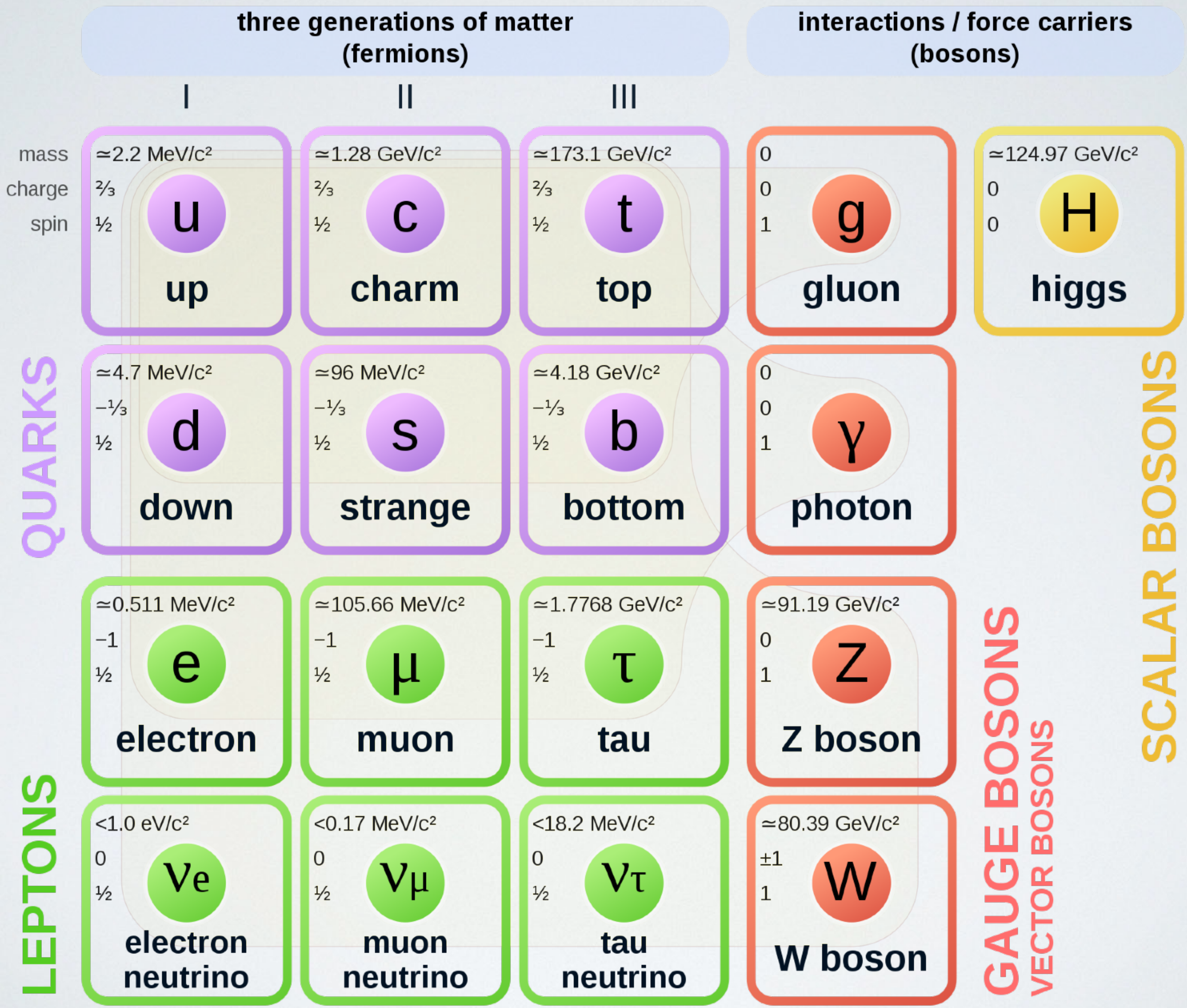
Force	Strong Interaction	Electro-magnetism	Weak Interaction	Gravitation
Strength	1	$\approx 10^{-2}$	$\approx 10^{-6}$	$\approx 10^{-38}$
Mediator particle	gluon	photon	W/Z bosons	graviton?
Examples	• Binds quarks into protons, neutrons etc • Holds nuclei together	• Electric and magnetic fields • Light	• Neutron decay	• Gravity • Graviton has not yet been detected

Four fundamental forces

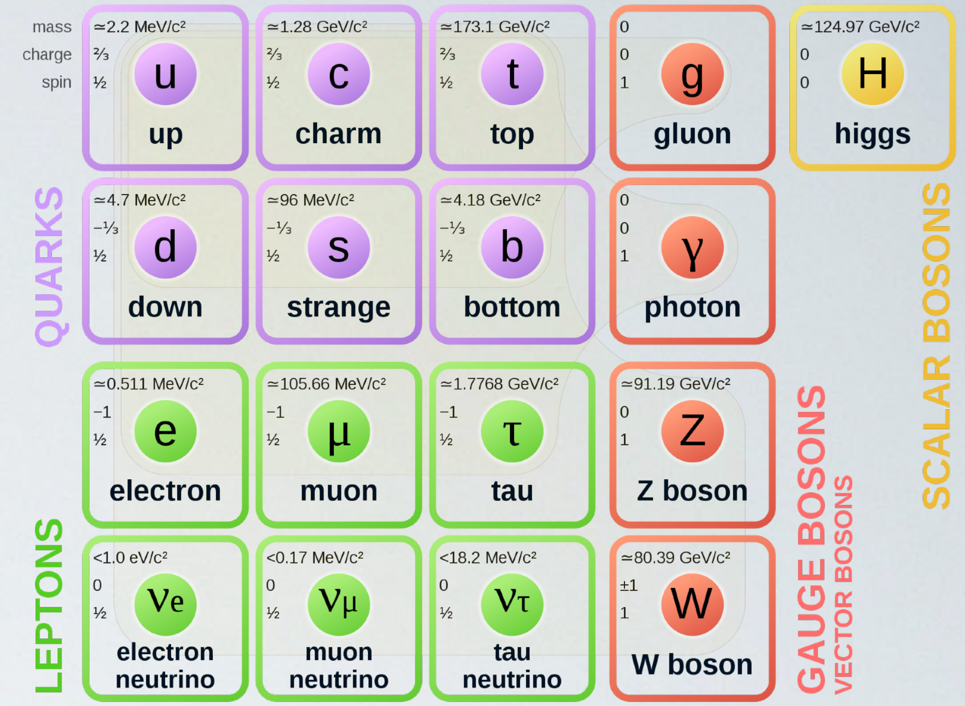


- Not about mass of messenger particle
- Graviton should be massless for $1/r^2$ gravity law (or extremely light)
- Decoupling occurs due to **"phase transitions"**

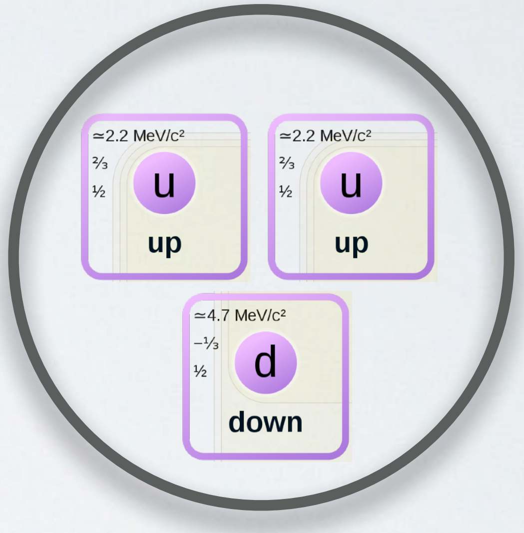
Standard model of elementary particles



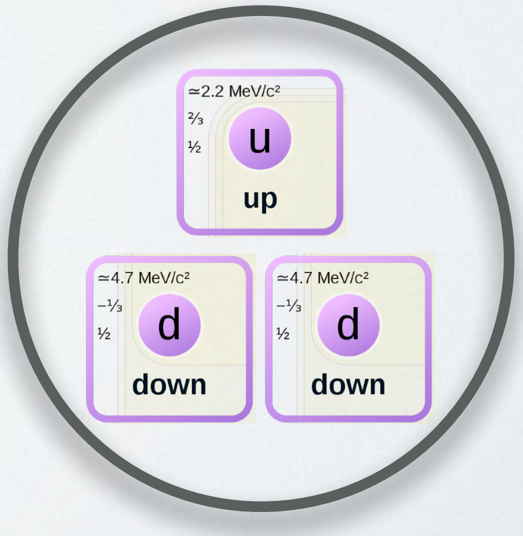
Particles



- Particles created/annihilated in the very early Universe were more than the ordinary types of particles abundant today (protons, neutrons, electrons, photons, neutrinos)
- More exotic particles are observed today only as products of collisions in high-energy accelerators
- Two types of particles: fermions and bosons
  - Primary duty of **fermions** is to make up **matter**
  - Primary duty of **bosons** is to mediate **forces**
- **Fermions** include:
  - Particles made from quarks, called **hadrons**
    - **Baryons** are made of 3 quarks (e.g. proton, neutron)
    - **Mesons** are made of 2 quarks (e.g. pion)
  - Particles not made from quarks, called **leptons**
    - Electrons, muons, tauons
    - Neutrinos
- Hadrons are generally more massive than leptons



proton



neutron

Participation: The question

TurningPoint:
Are we all made from star stuff?

Session ID: diemer

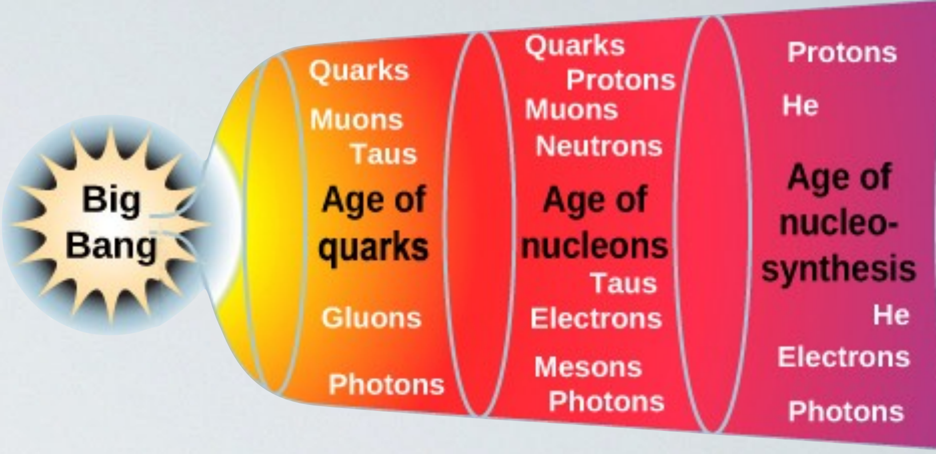
30 seconds

Today

- The (slightly less) early Universe
- Making atoms
- The abundance of elements
- The elements made in stellar explosions

Part 1: The (slightly less) early Universe (cont.)

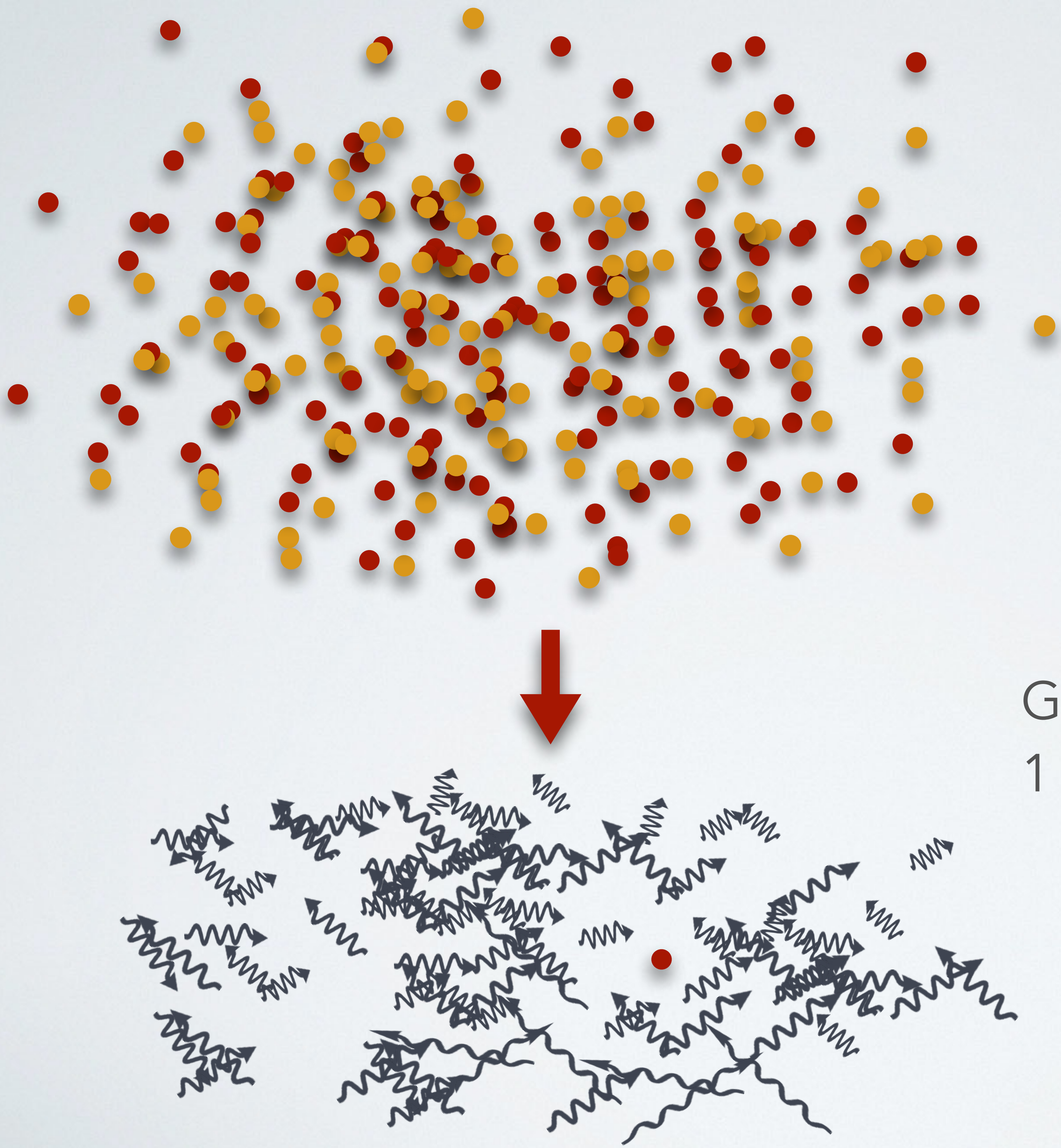
Quark Epoch

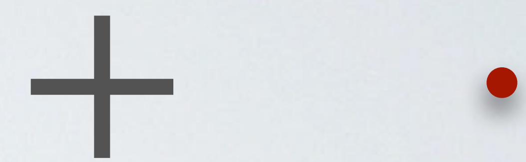


Time	0	10^{-12} s	10^{-6} s	15 s
T(K)	∞	10^{15}	10^{13}	5×10^{9}

- Lasts from 10^{-12} s to 10^{-6} s
- Universe consists of soup of
  - Quarks
  - Gluons
  - W/Z bosons
  - Photons
  - Leptons
  - More exotic particles
- Quark epoch ends when **quarks** pull themselves together into **hadrons** (mesons and baryons)
- **Baryogenesis**
  - Slight asymmetry between particles & antiparticles
  - Get more matter than antimatter by 1 part in a billion
  - This produces all the matter we have today!

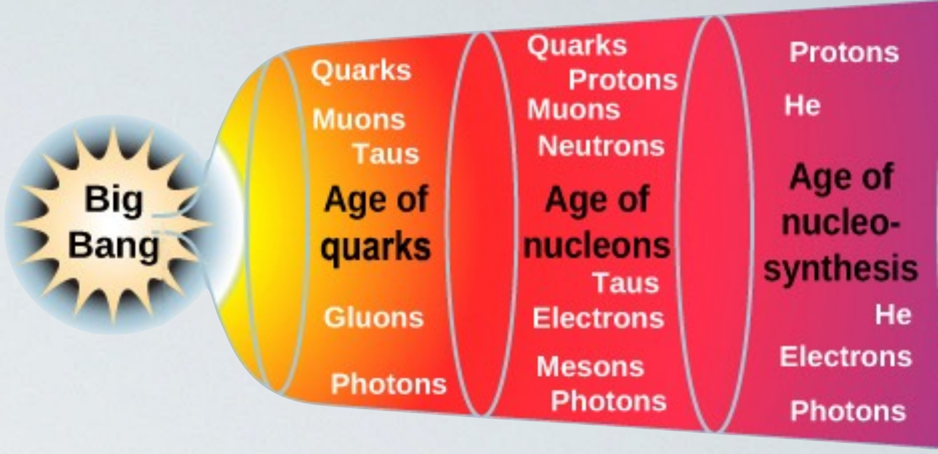
Matter-antimatter asymmetry





Get one particle and about 1 billion photons!

Hadron / Lepton Epochs



Time	0	10^{-12} s	10^{-6} s	15 s
T(K)	∞	10^{15}	10^{13}	5×10^{9}

- Last from t = 10^{-6} s to 15 s
- Universe consists of soup of
  - protons
  - neutrons
  - electons / positrons
  - photons
  - W/Z bosons
  - exotics
- Ongoing production of electron/positron pairs
- Equilibrium between protons and neutrons until about 0.1 s, then protons are favored because slightly lower mass
- Lepton epoch ends when **T falls below electron threshold**, $5{\times}10^{9}$ K, at $t \approx 15\mathrm{s}$
- Most of e^{+} and e^{-} annihilated, leaving just enough e^{-} to balance charge of protons

Part 2: Making atoms

Participation: Atoms #1

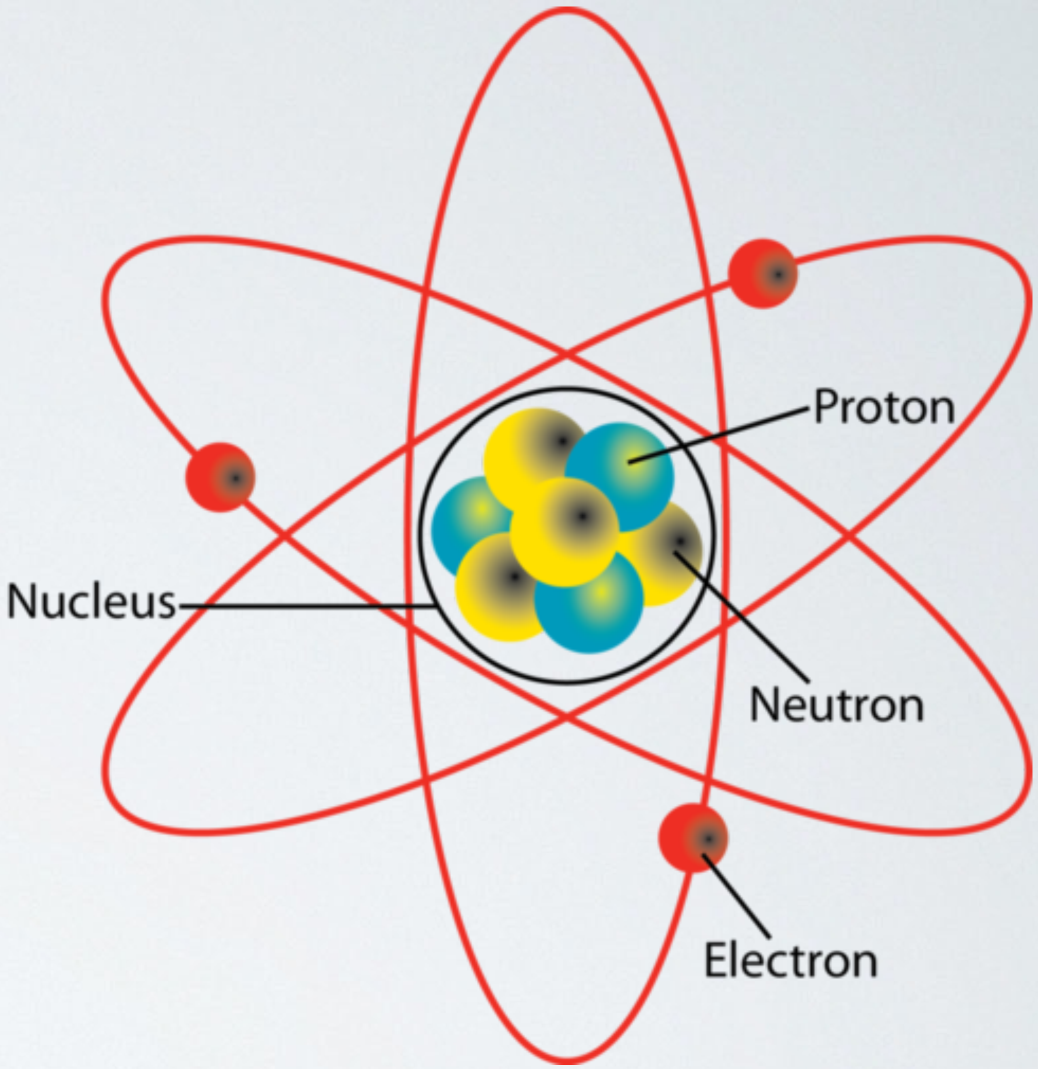
TurningPoint:
What takes up most of the volume inside atoms?

Session ID: diemer

30 seconds

Atoms

- Nucleus is made up of
  - Protons (positively charged)
  - Neutrons (no charge)
- Proton is slightly less massive than neutron (0.1% difference)
- Protons and neutrons bound together by the strong nuclear force (exchange of "gluons")
- Electrons are bound by electromagnetic attraction to the protons



Participation: Atoms #2

TurningPoint:
What determines the element?

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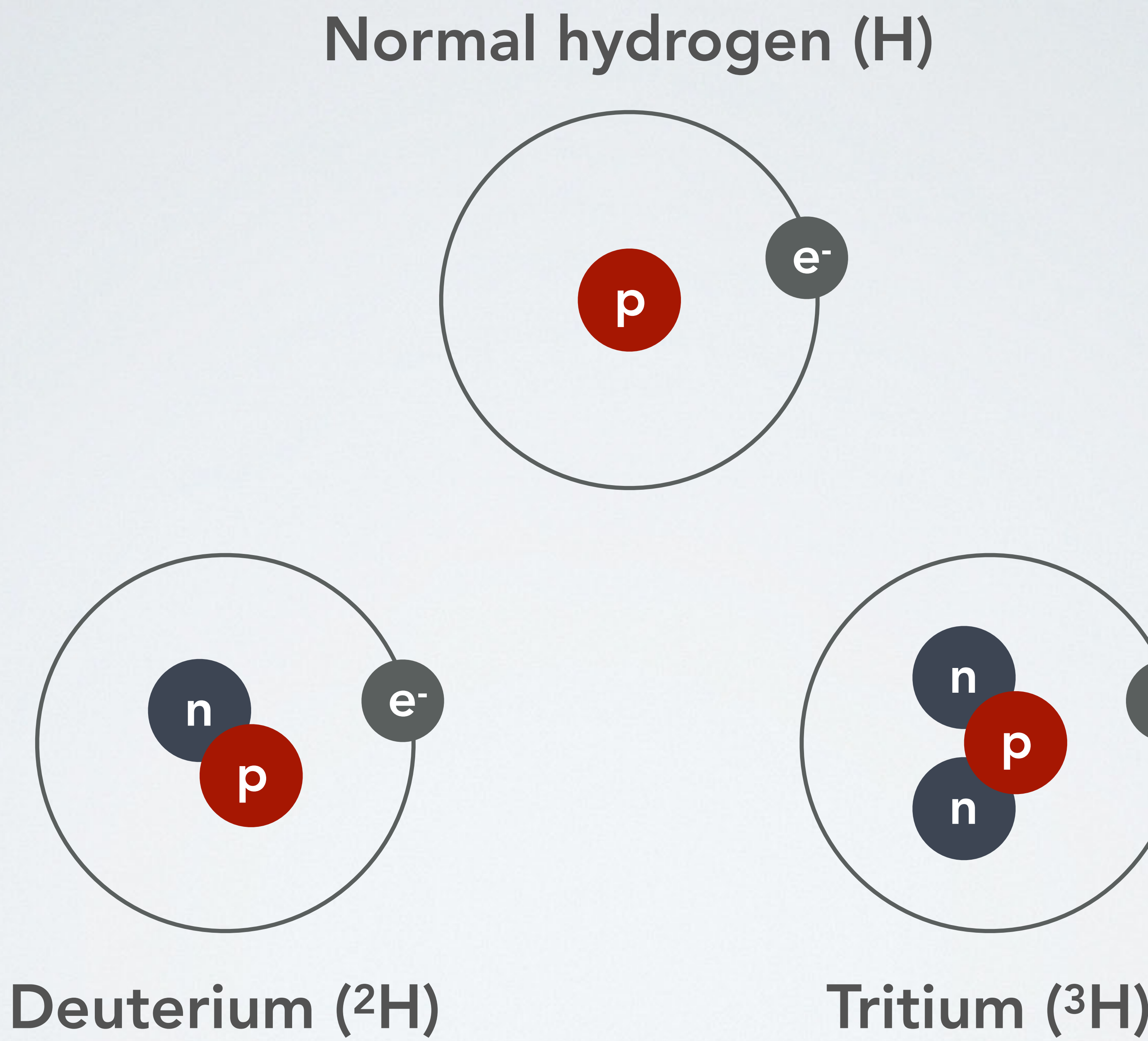
30 seconds

Periodic table

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.008																	2 He Helium 4.002602
3 Li Lithium 6.94	4 Be Beryllium 9.0121831											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998403163	10 Ne Neon 20.1797
11 Na Sodium 22.98976928	12 Mg Magnesium 24.305											13 Al Aluminium 26.9815385	14 Si Silicon 28.085	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955908	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938044	26 Fe Iron 55.845	27 Co Cobalt 58.933194	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921595	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90584	40 Zr Zirconium 91.224	41 Nb Niobium 92.90637	42 Mo Molybdenum 95.95	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
55 Cs Caesium 132.90545196	56 Ba Barium 137.327	57 - 71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.592	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 - 103 Actinoids	104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (269)	107 Bh Bohrium (270)	108 Hs Hassium (269)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (282)	112 Cn Copernicium (285)	113 Nh Nihonium (286)	114 Fl Flerovium (289)	115 Mc Moscovium (289)	116 Lv Livermorium (293)	117 Ts Tennessine (294)	118 Og Oganesson (294)

57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90766	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93033	68 Er Erbium 167.259	69 Tm Thulium 168.93422	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.0377	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (266)

Isotopes of hydrogen



Participation: Atoms #3

TurningPoint:
Why do atoms not spontaneously fuse to make larger atoms?

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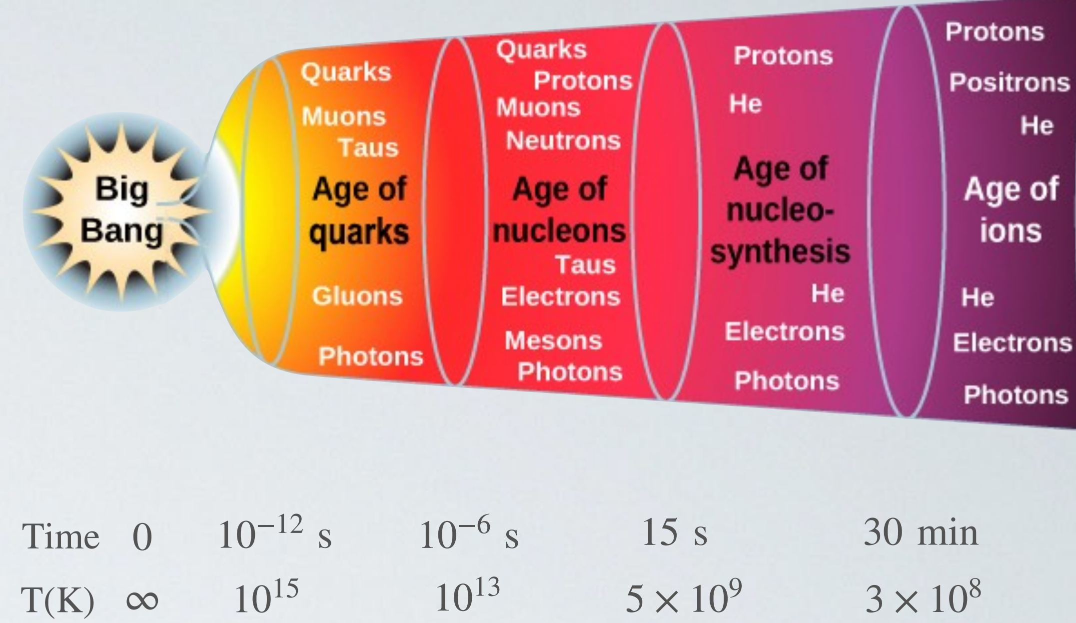
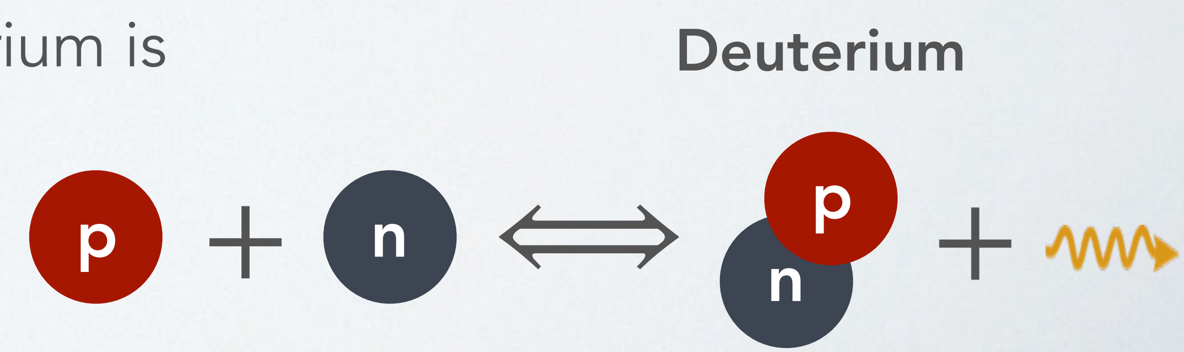
30 seconds

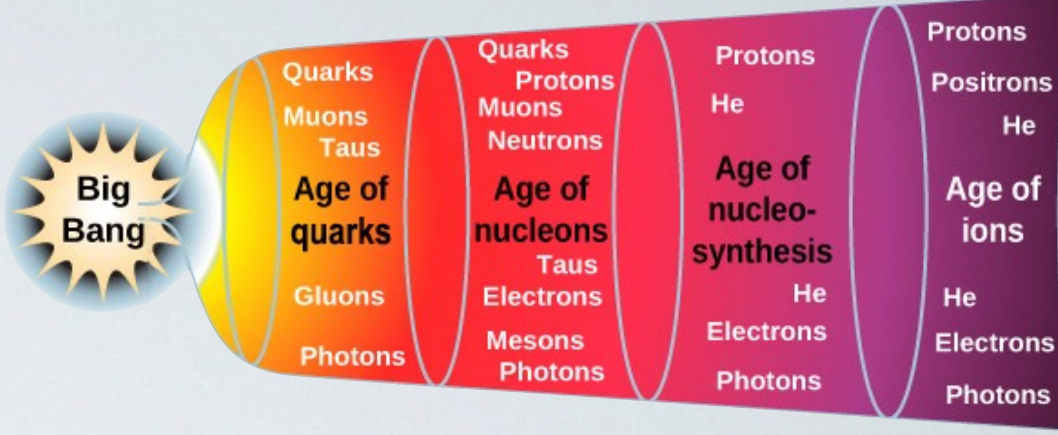
Nucleosynthesis



- Nucleosynthesis: the **production of different elements via nuclear reactions**
- Need very high temperature and density to **overcome electrostatic repulsion of protons**
- Explaining nucleosynthesis was part of the motivation for Gamow et al. to propose hot Big Bang
- At t = 15s, $e^{\pm}$ stopped being created and destroyed
- Heavier nuclei are built up from lighter nuclei (or free protons / neutrons) by fusion
- Nuclei do not have electrons yet! Too hot
- The lightest thinkable nucleus is **Deuterium** (p + n)
- Before 180s (3 minutes), $T > 10^9$ K and Deuterium is formed but also destroyed:

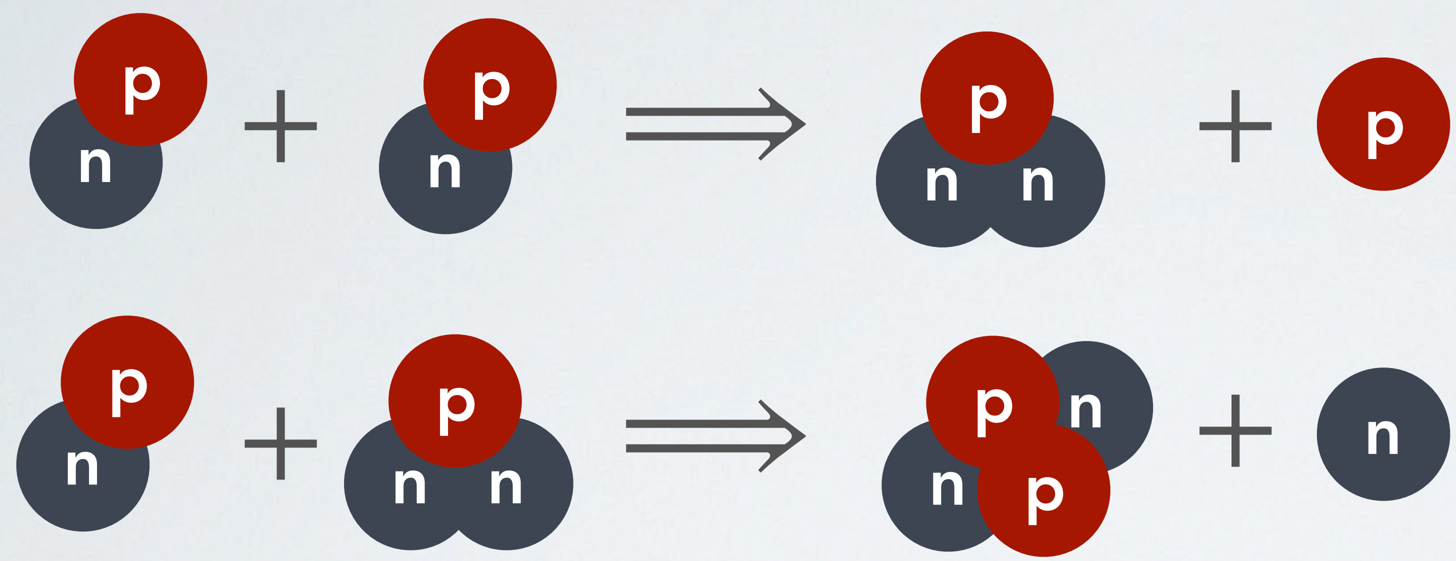


Nucleosynthesis



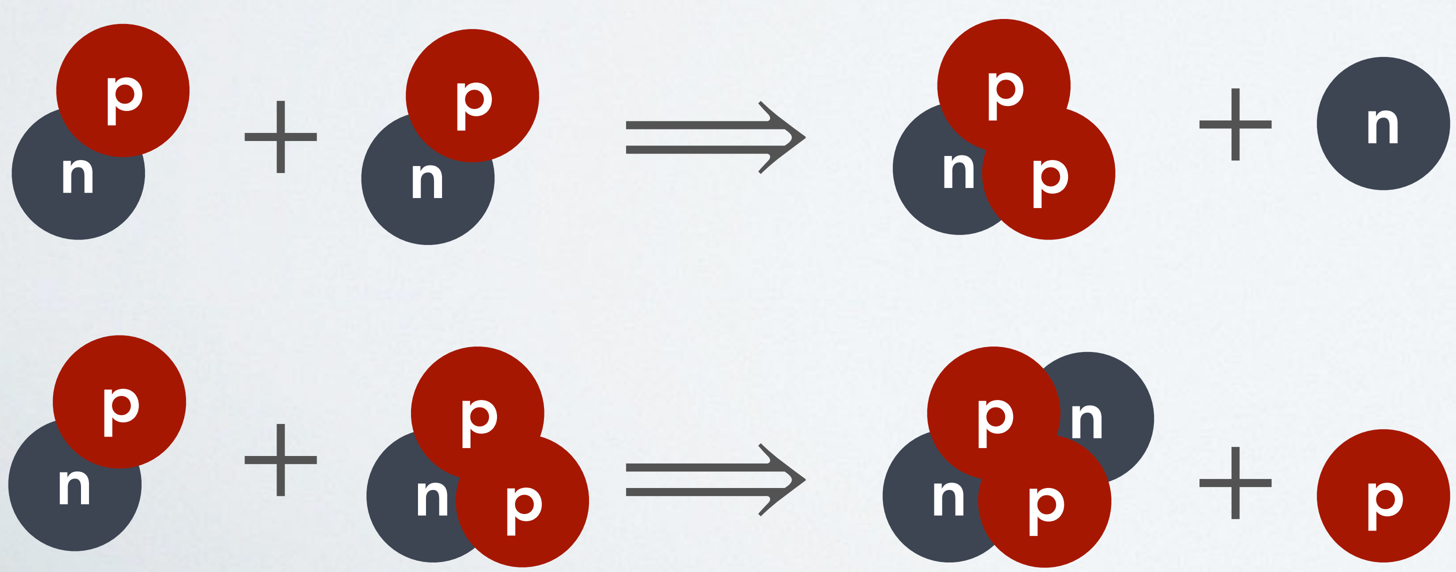
Time	0	10^{-12} s	10^{-6} s	15 s	30 min
T(K)	∞	10^{15}	10^{13}	5×10^{9}	3×10^{8}

After 180s, Deuterium becomes stable and we get more interesting reactions:



^{4}He

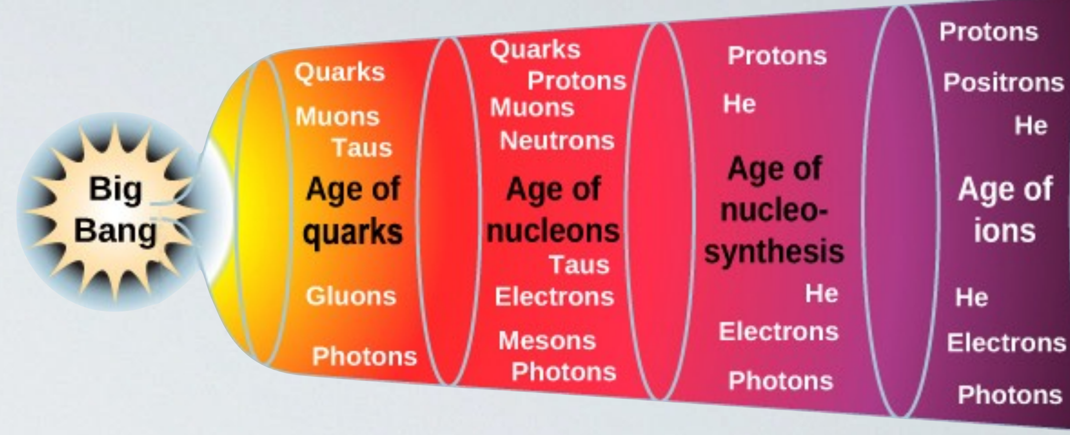
alternatively:



^{3}He

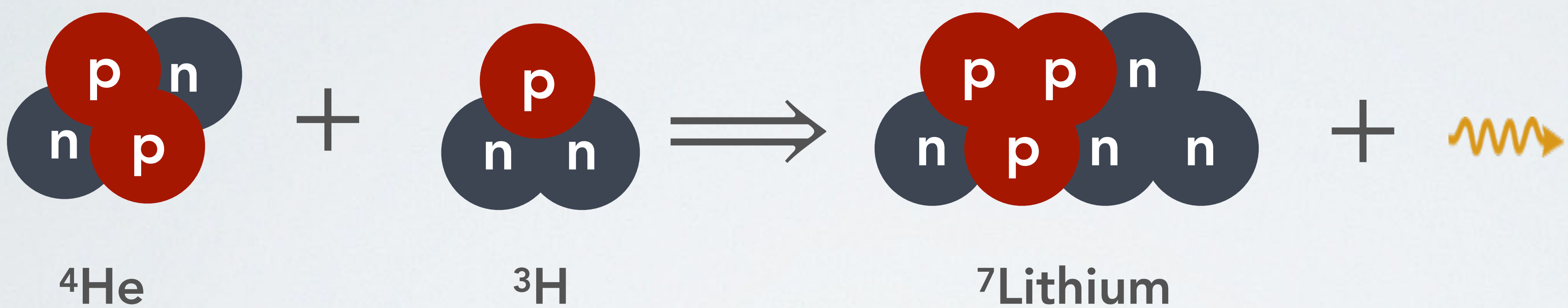
^{4}He

Nucleosynthesis



Time	0	10^{-12} s	10^{-6} s	15 s	30 min
T(K)	∞	10^{15}	10^{13}	5×10^{9}	3×10^{8}

From Helium and Deuterium, we can make Lithium:

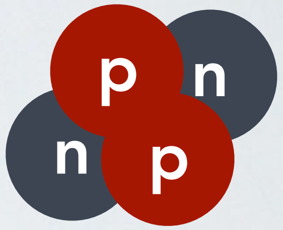


- Reactions **do not proceed beyond Lithium** because the easiest-to-make isotopes of the following elements (Beryllium and Boron) are not stable
- Nucleosynthesis was essentially **completed by t = 30 min**, with free neutron abundance down to less than 0.0001%

Part 3: The abundance of elements

Abundances: Hydrogen vs. Helium

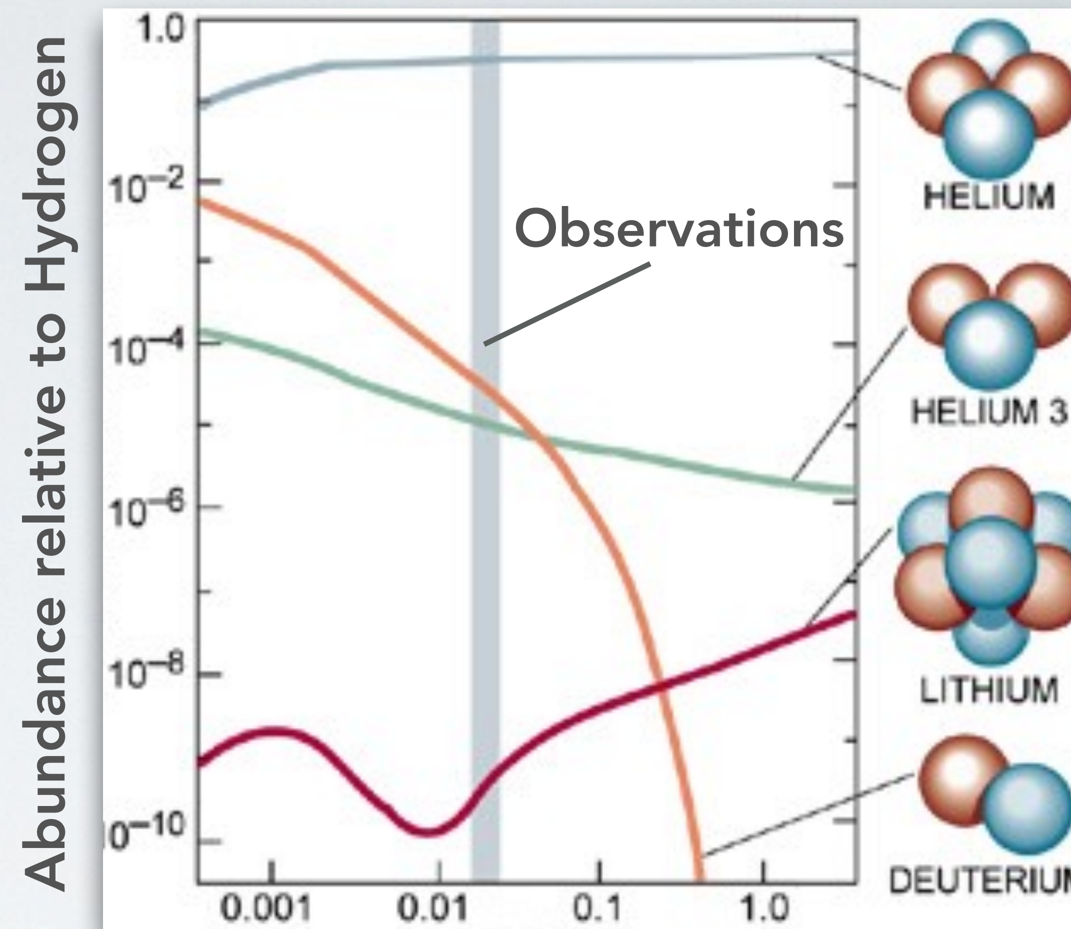
- Ratio of hydrogen and helium is determined by number of protons and neutrons
- If equal number of protons and neutrons, almost everything would turn to ^{4}He (2p + 2n)
- But most of the matter in the Universe is hydrogen; why?
- Protons are more common than neutrons because:
  - **Protons are slightly lighter** and thus favored energetically, so they were more abundant to begin with (86% vs. 14%)
  - **Free neutrons decay** quickly, with a half-life of 10.5 minutes. Thus, by the time nucleosynthesis starts (180s), many neutrons have already decayed
- Result: about **76% hydrogen, 24% helium (by mass)**



$$n \Longrightarrow p + e^- + \bar{\nu}$$

Baryon Density

- In astromomy, **"baryons" means "normal matter"** (i.e., standard model particles that we know and understand)
- Abundances are determined by evolving **density** (how often particles hit each other) and **temperature** (how hard they hit), and **neutron decay**
- Can be worked out by computer; depends on **baryon density relative to critical density**
- We can use the spectra of stars and nebulae to measure abundances of elements (corrected for reactions inside stars)
- By **measuring the abundance** of H, D, ^{3}He, ^{4}He, and ^{7}Li, we can test the consistency of the Big Bang model - are relative abundances all consistent?



$\Omega_{b,0}h^2$

$$h = \frac{H_0}{100\mathrm{km/s/Mpc}} \approx 0.7$$

$$\Omega_{b,0} \equiv \frac{\rho_{b,0}}{\rho_{c,0}}$$

$$\rho_c(t) = \frac{3H^2(t)}{8\pi G}$$

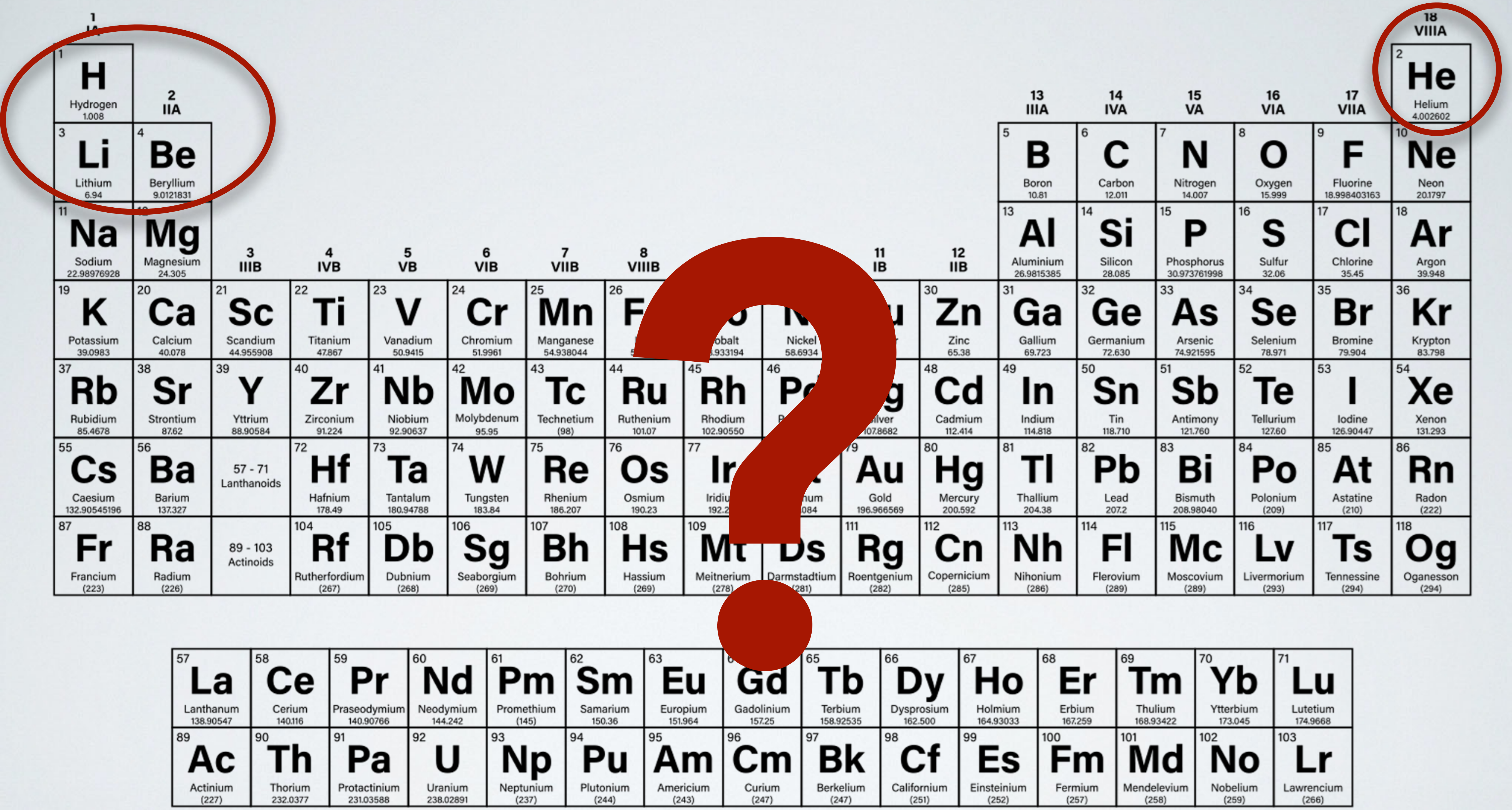
$$\Omega_{b,0}h^2 \approx 0.019 \implies$$

$$\Omega_{b,0} \approx 0.05$$

Baryons are only 5% of the critical density!

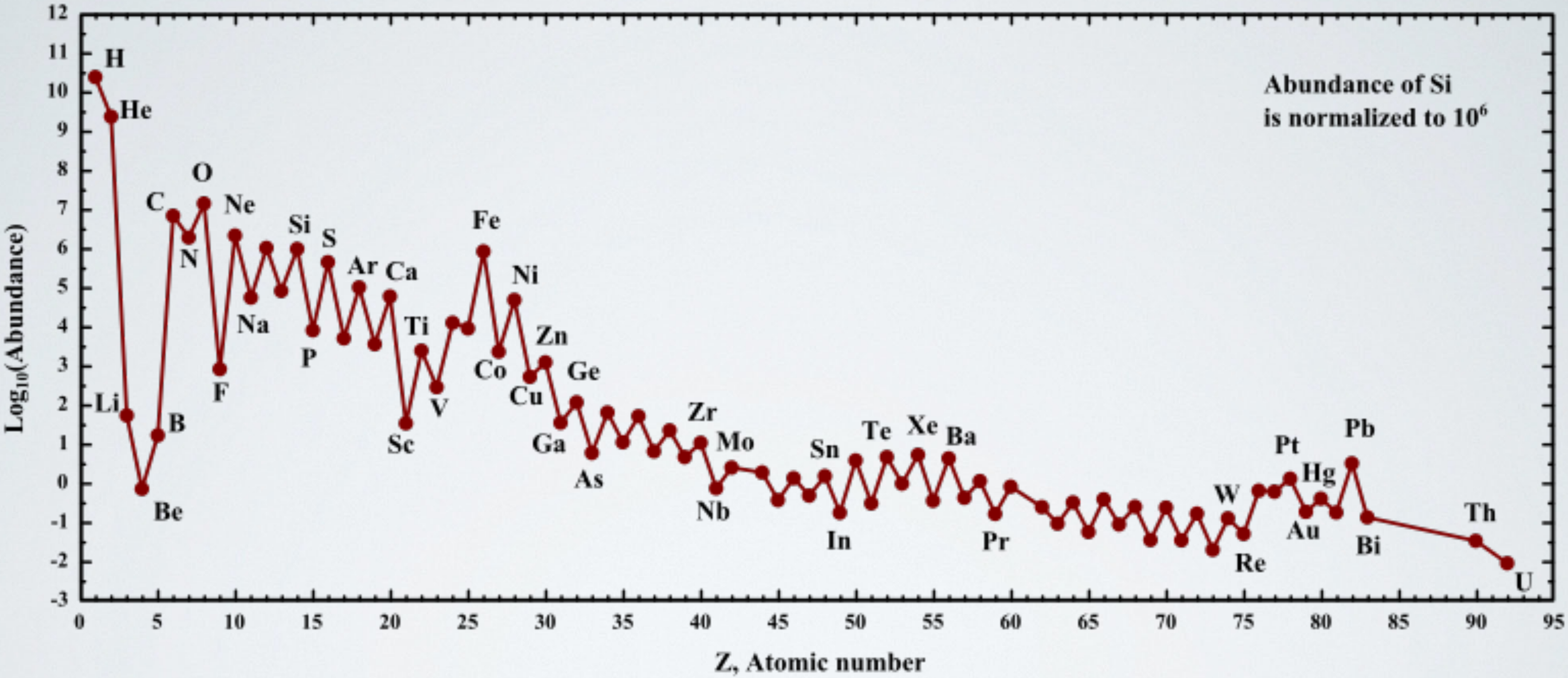
Plot by Martin White

Where are the other elements made?

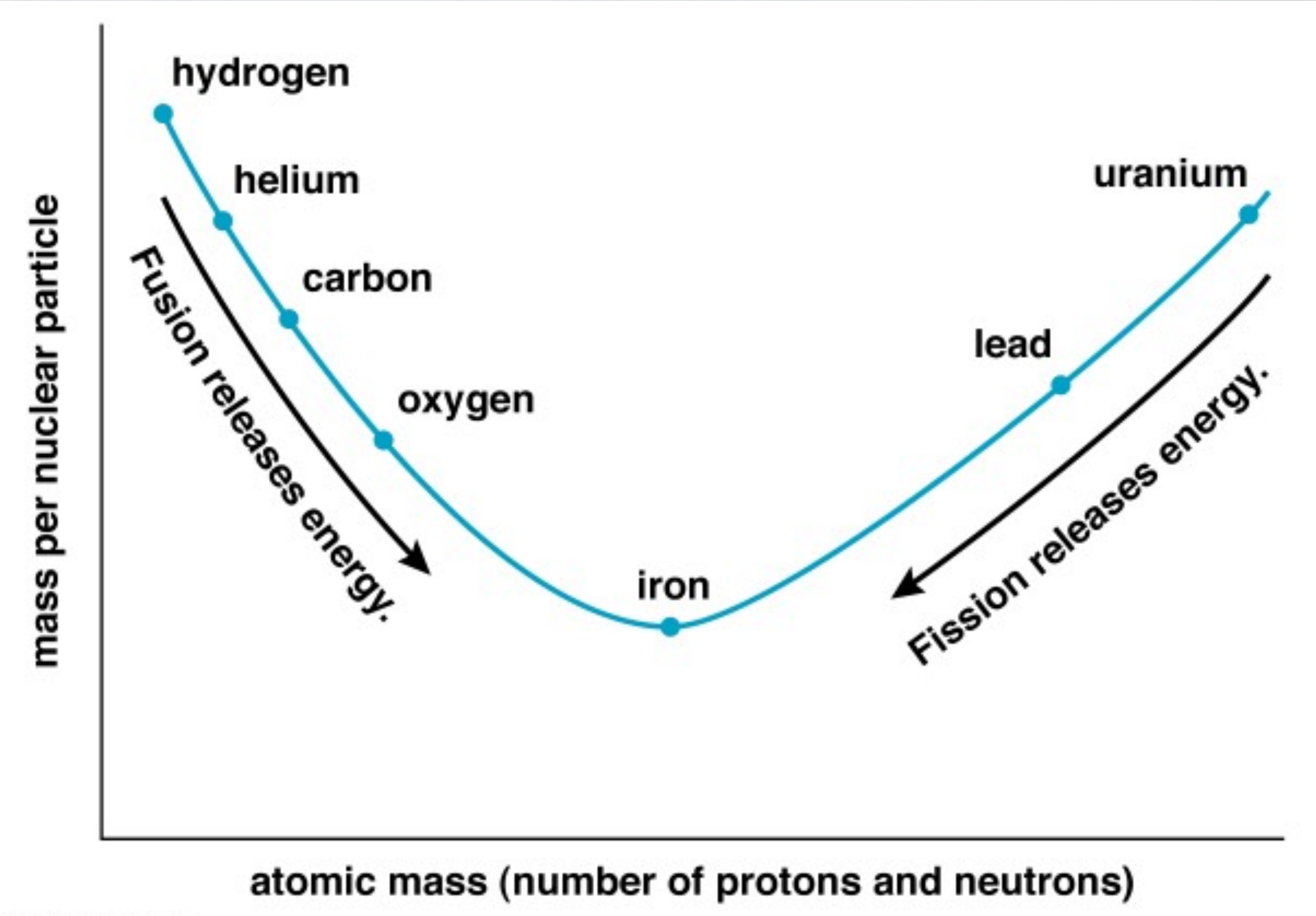


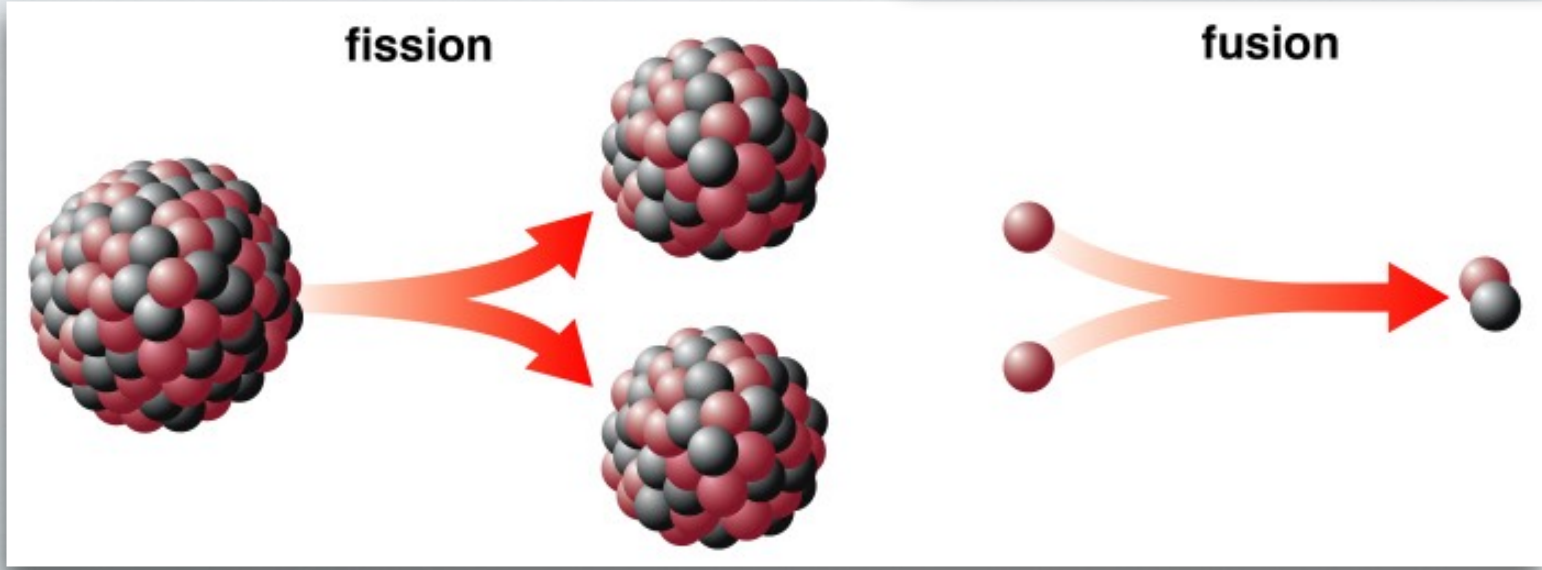
Part 4: The elements made in stars (and explosions)

Abundance of elements in the Sun



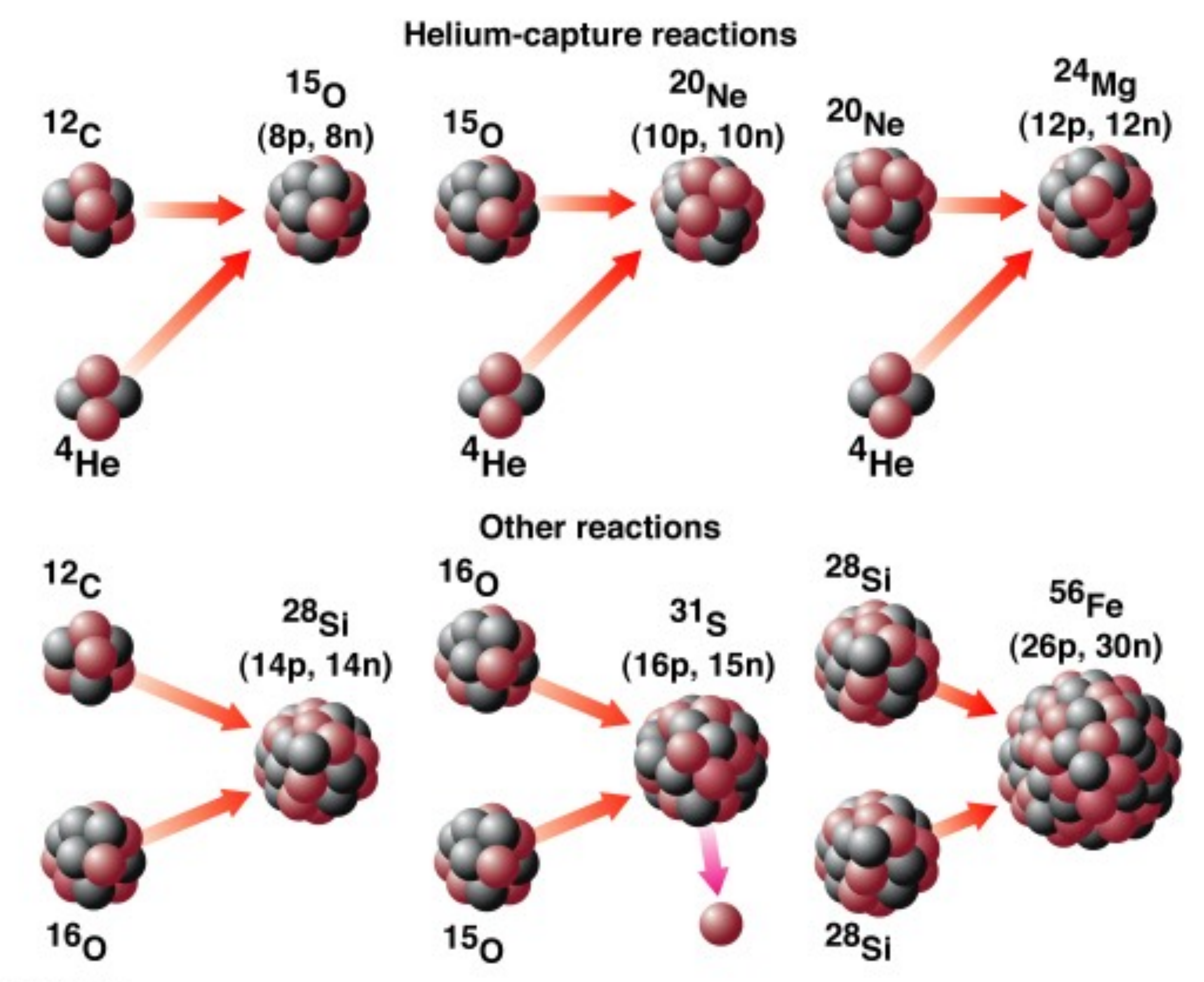
Stellar nucleosynthesis





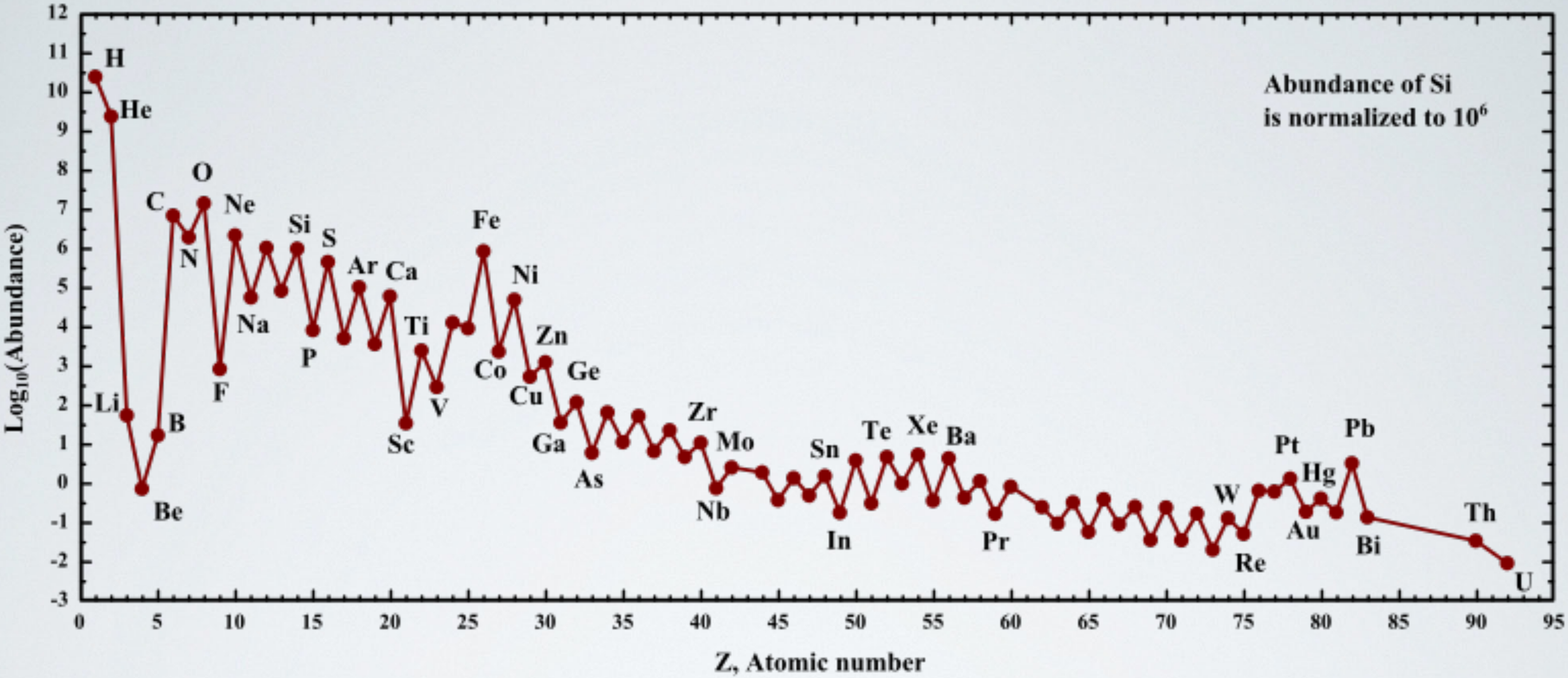
Addison Wesley

Stellar nucleosynthesis

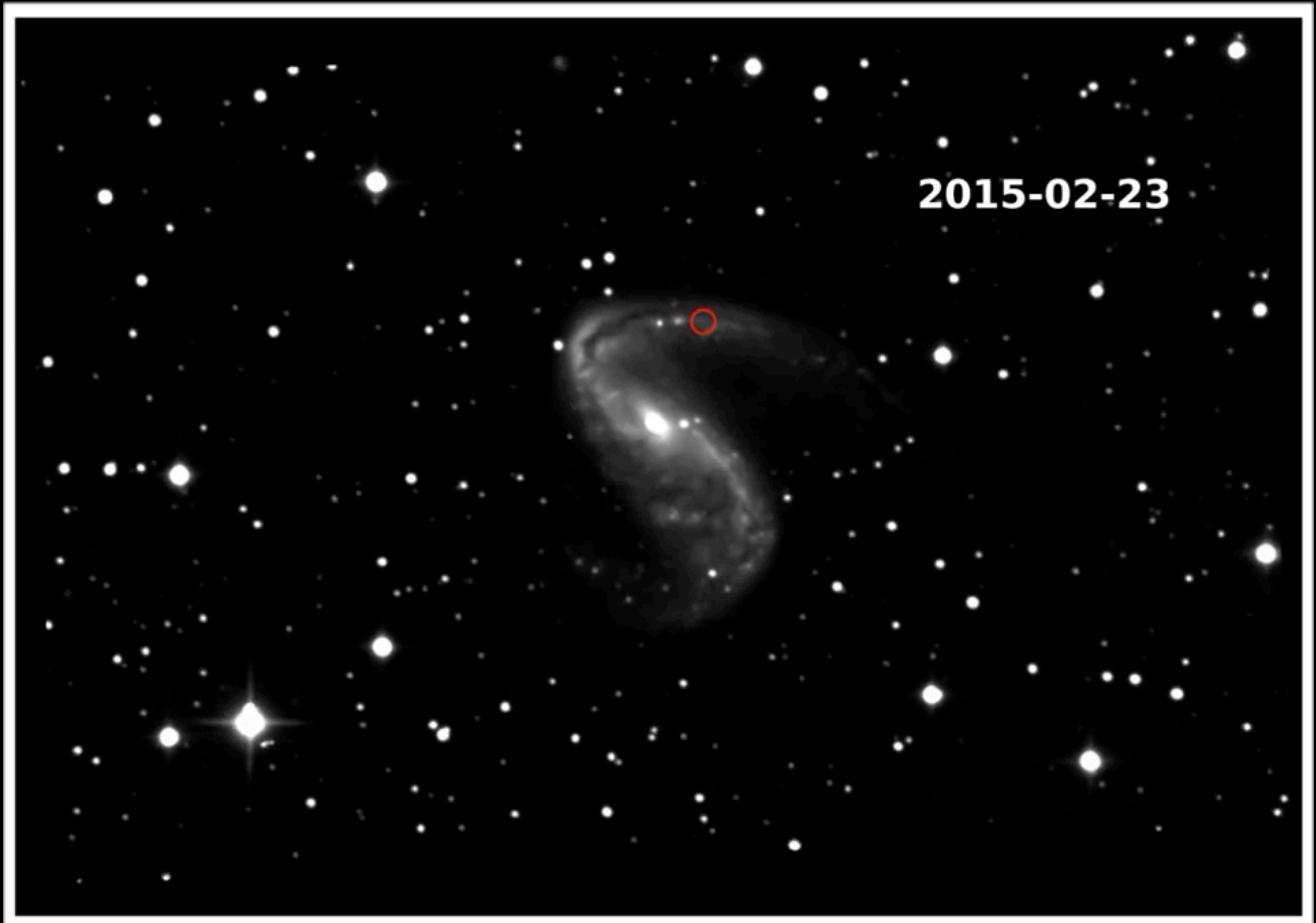


Addison Wesley

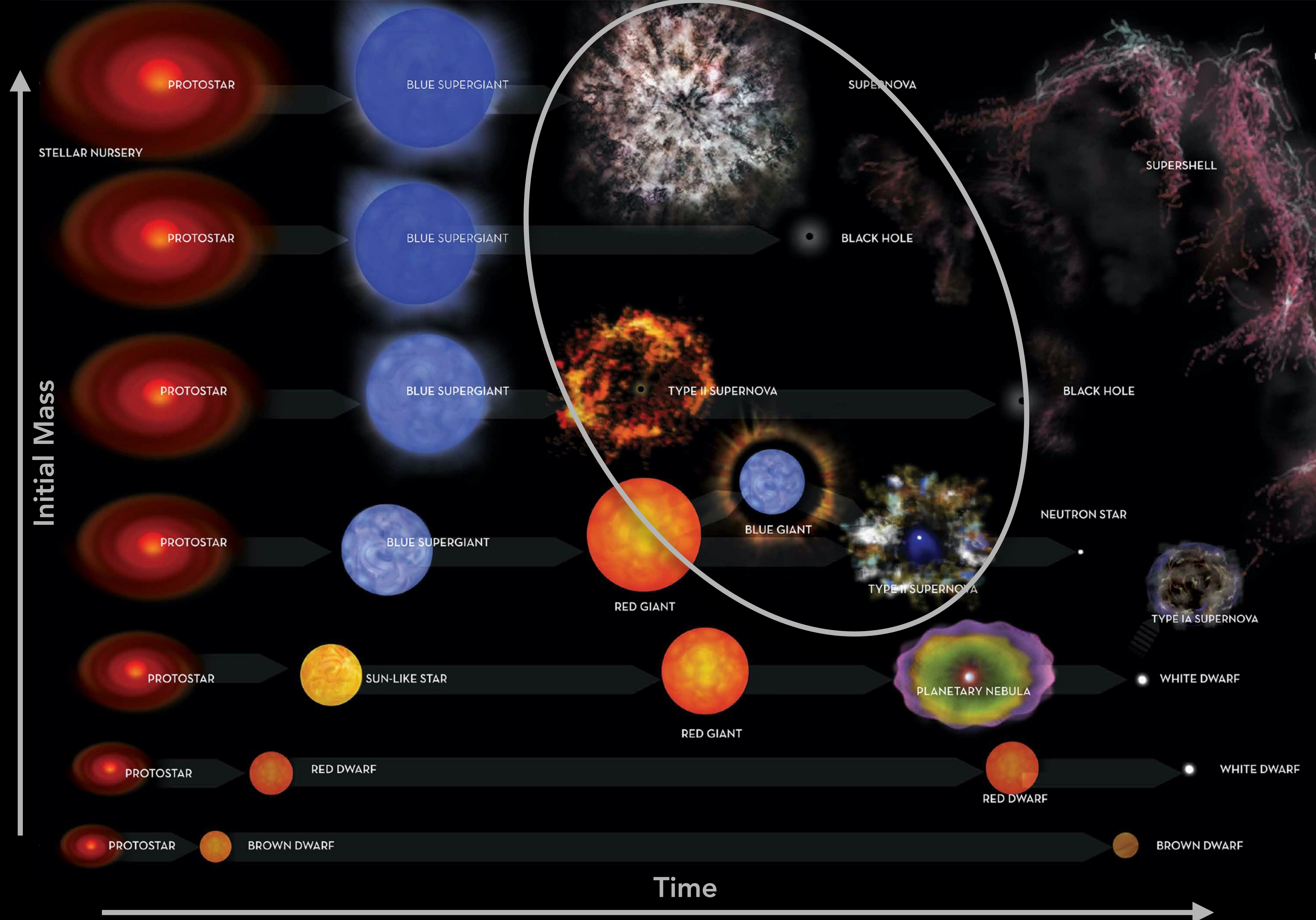
Abundance of elements in the Sun



- Most of these elements are **not made in the Sun**
- How are heaviest elements produced even though they need energy input?
- Supernovae provide an extreme environment where this is possible



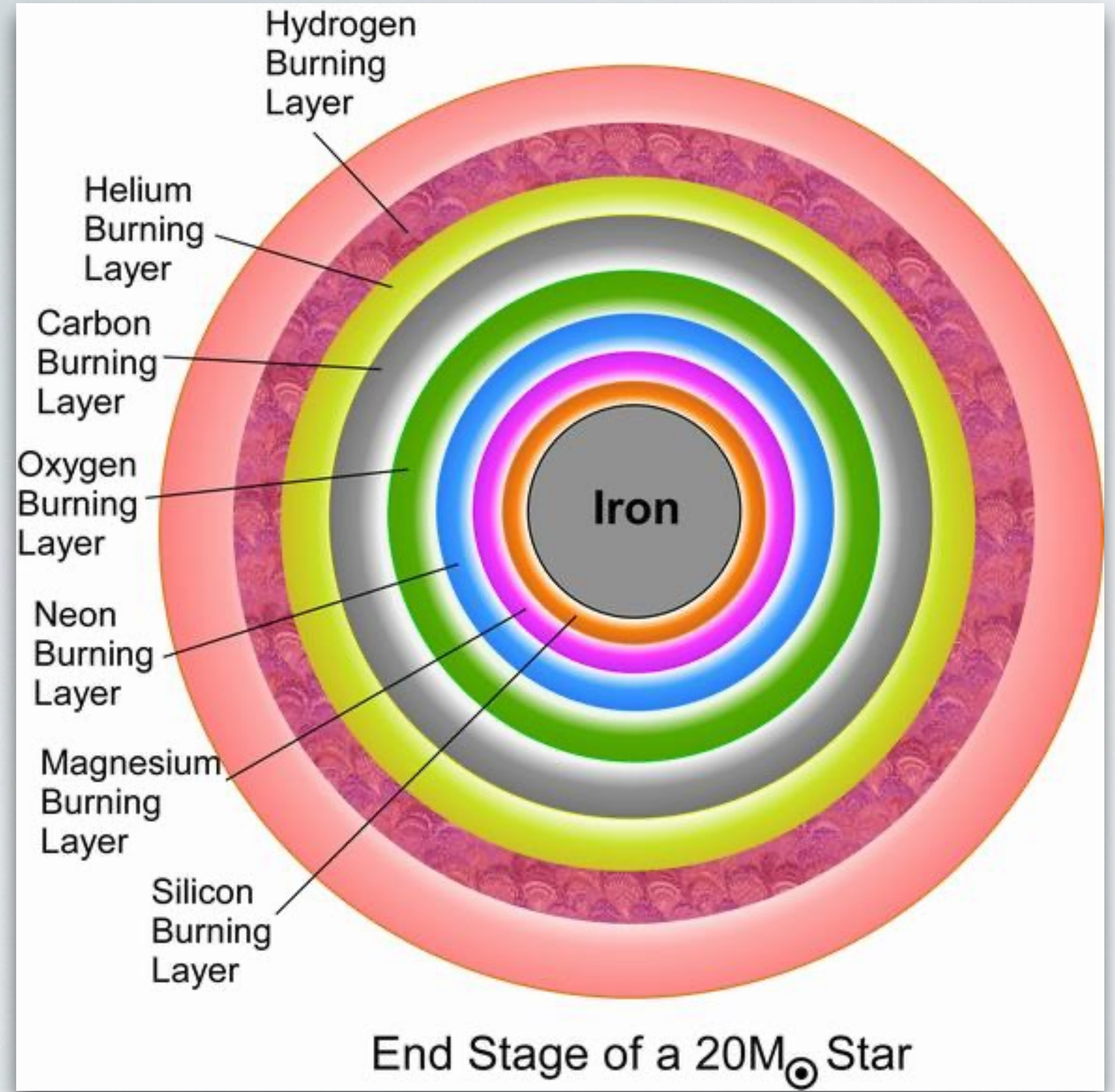
NASA / Astronomy picture of the day



Summary of stellar evolution

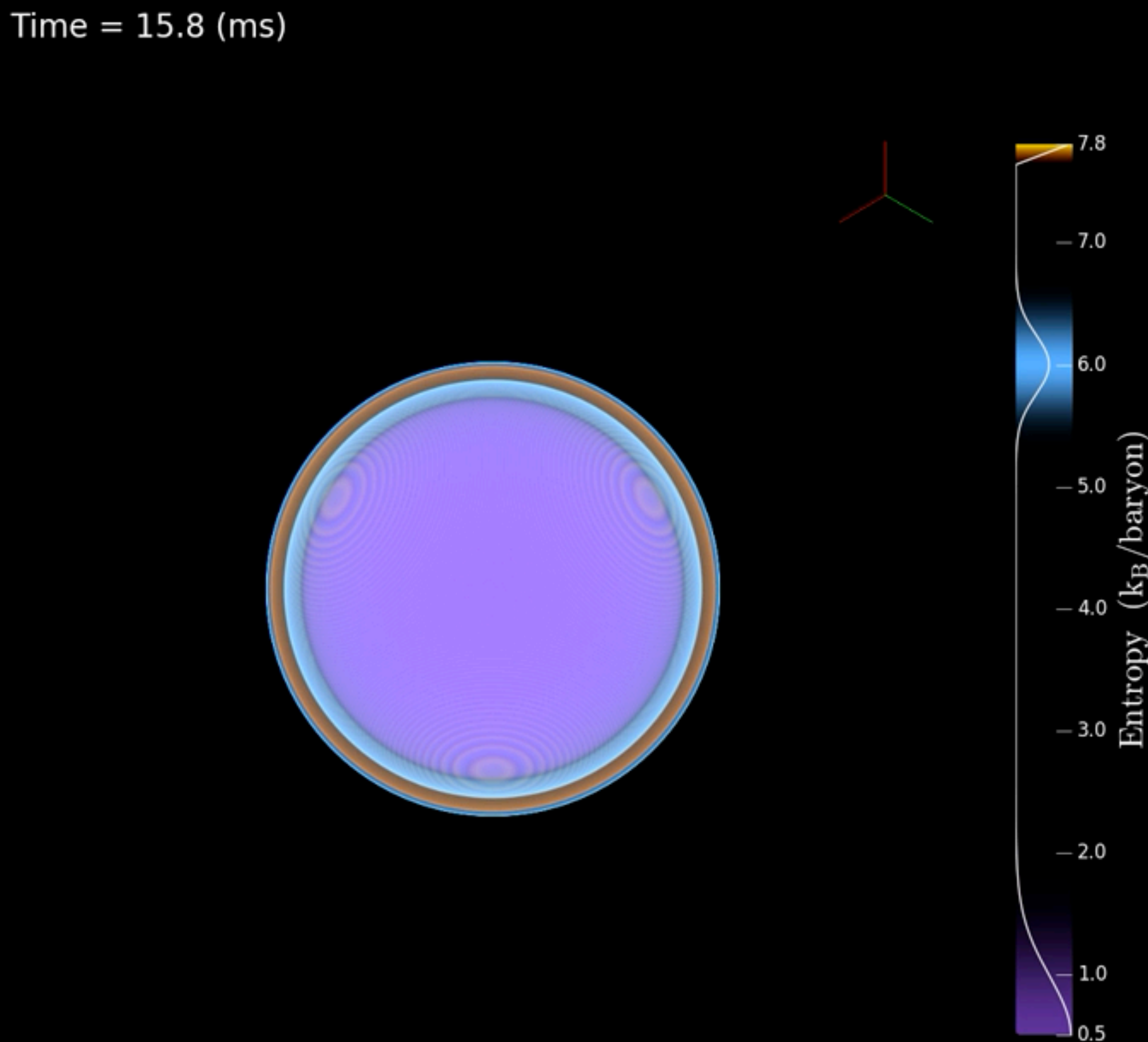
NASA

Core-collapse supernovae



- Massive stars nuclear-burn through all available elements
- There is less and less energy to be gained, so they burn faster and faster
- Finally, iron cannot be burned and the star suddenly runs out of fuel
- Iron core implodes and causes shockwave that triggers "core collapse supernova" explosion

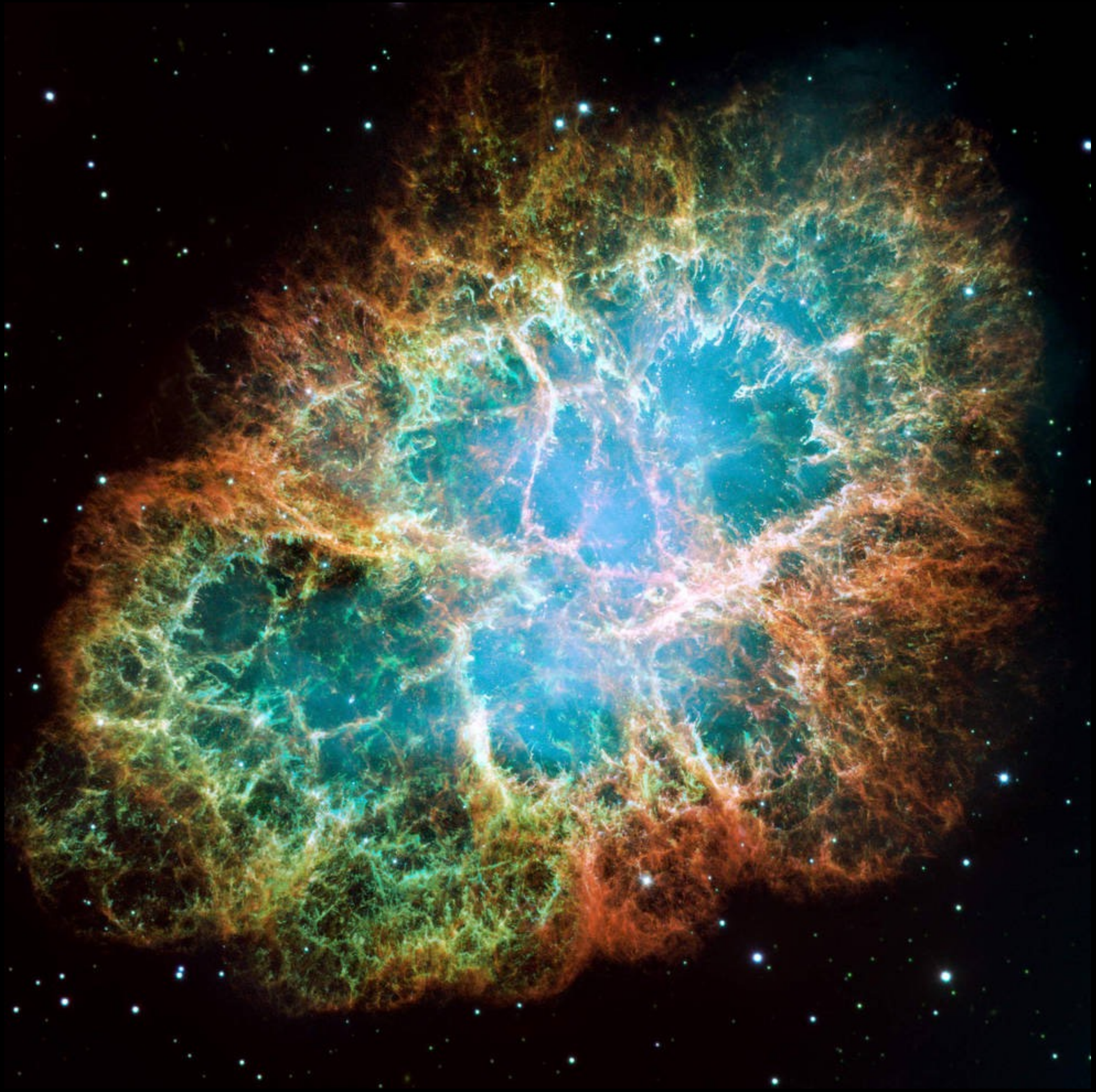
NASA Ames, STScI/G. Bacon



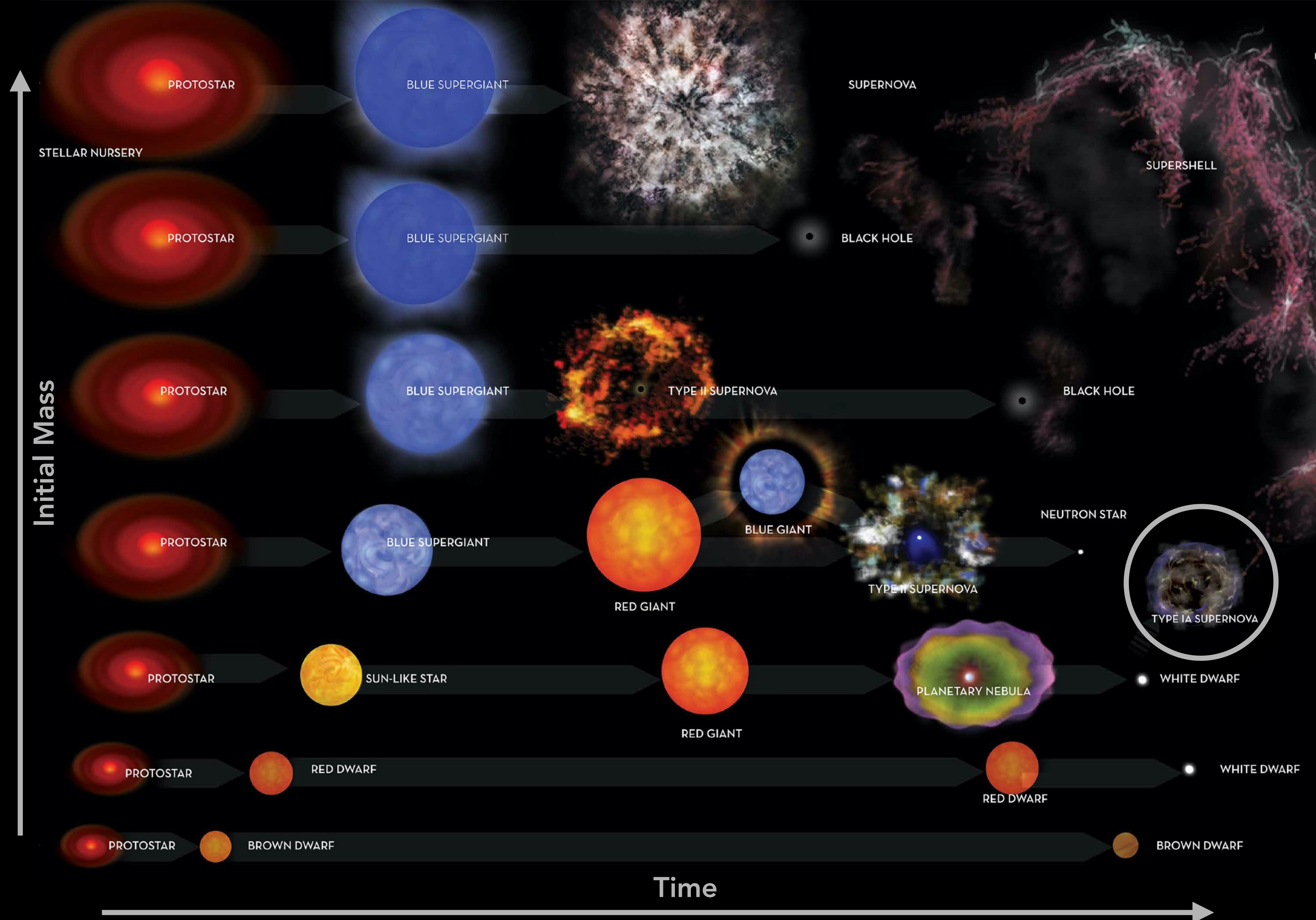
Sean M. Couch and Kuo-Chuan Pan, Michigan State University

ESA

Crab Nebula (M01)



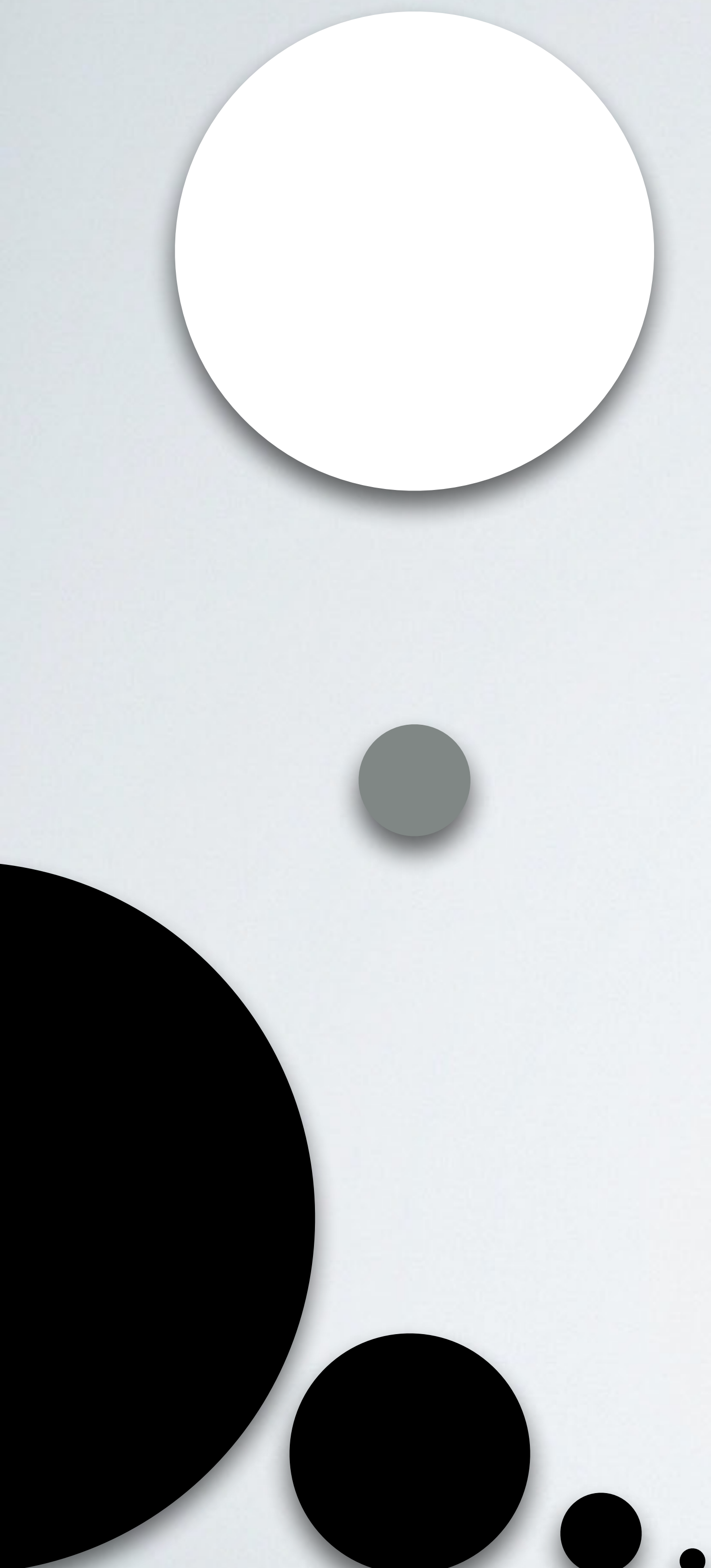
NASA/HST



Summary of stellar evolution

NASA

Compact objects

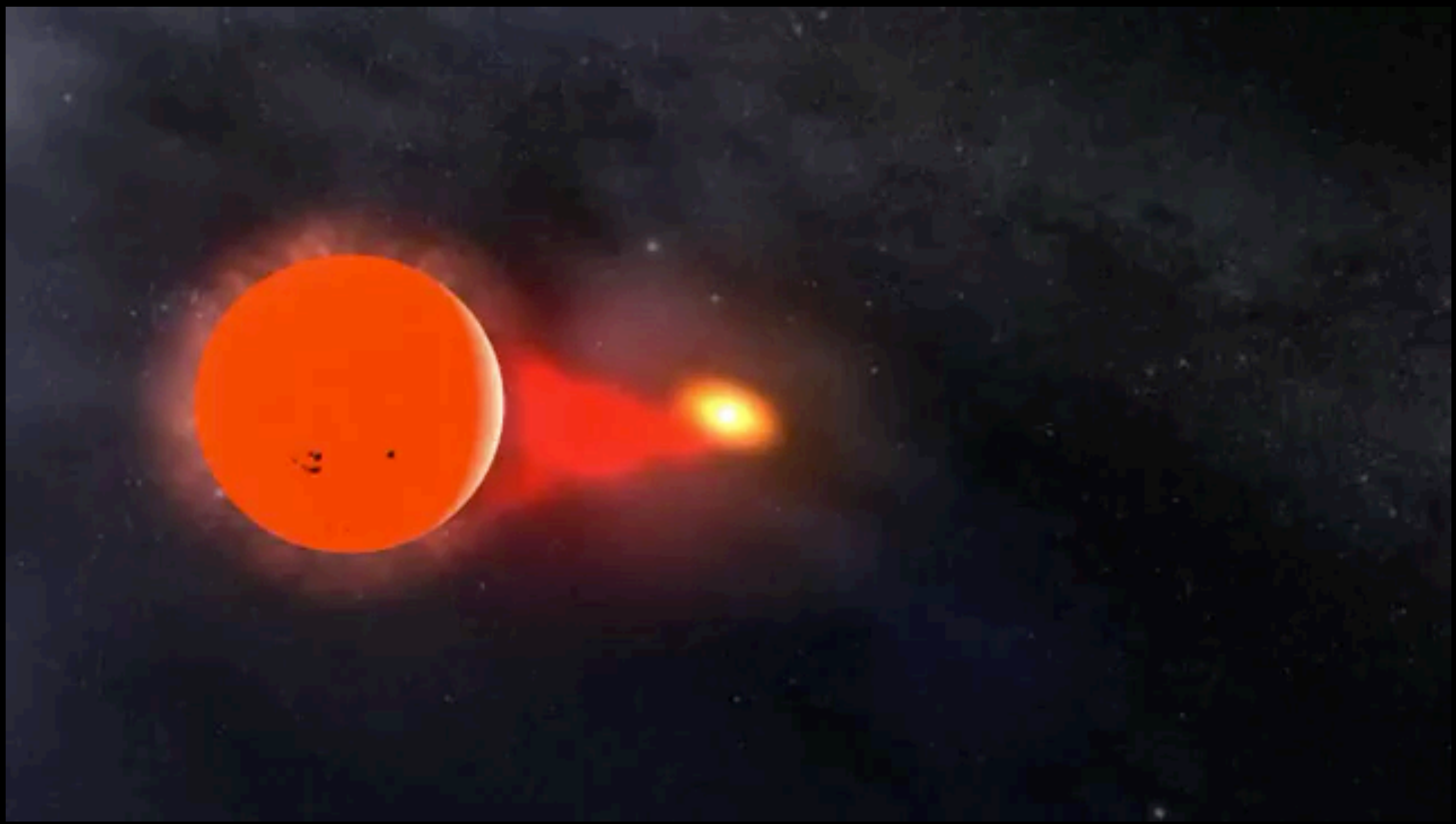


- **White dwarf**
  - Made of C / O / Ne / Mg nuclei + electrons
  - Mass about 0.15 - 1.4 $M_\odot$
  - Radius about 7000 km (one Earth radius)
  - Average density about 10^6 g/cm^3

- **Neutron star**
  - Made of neutrons
  - Mass about 1.1 to 2.1 $M_\odot$
  - Radius about 10 - 20 km
  - Average density about 10^{14} g/cm^3

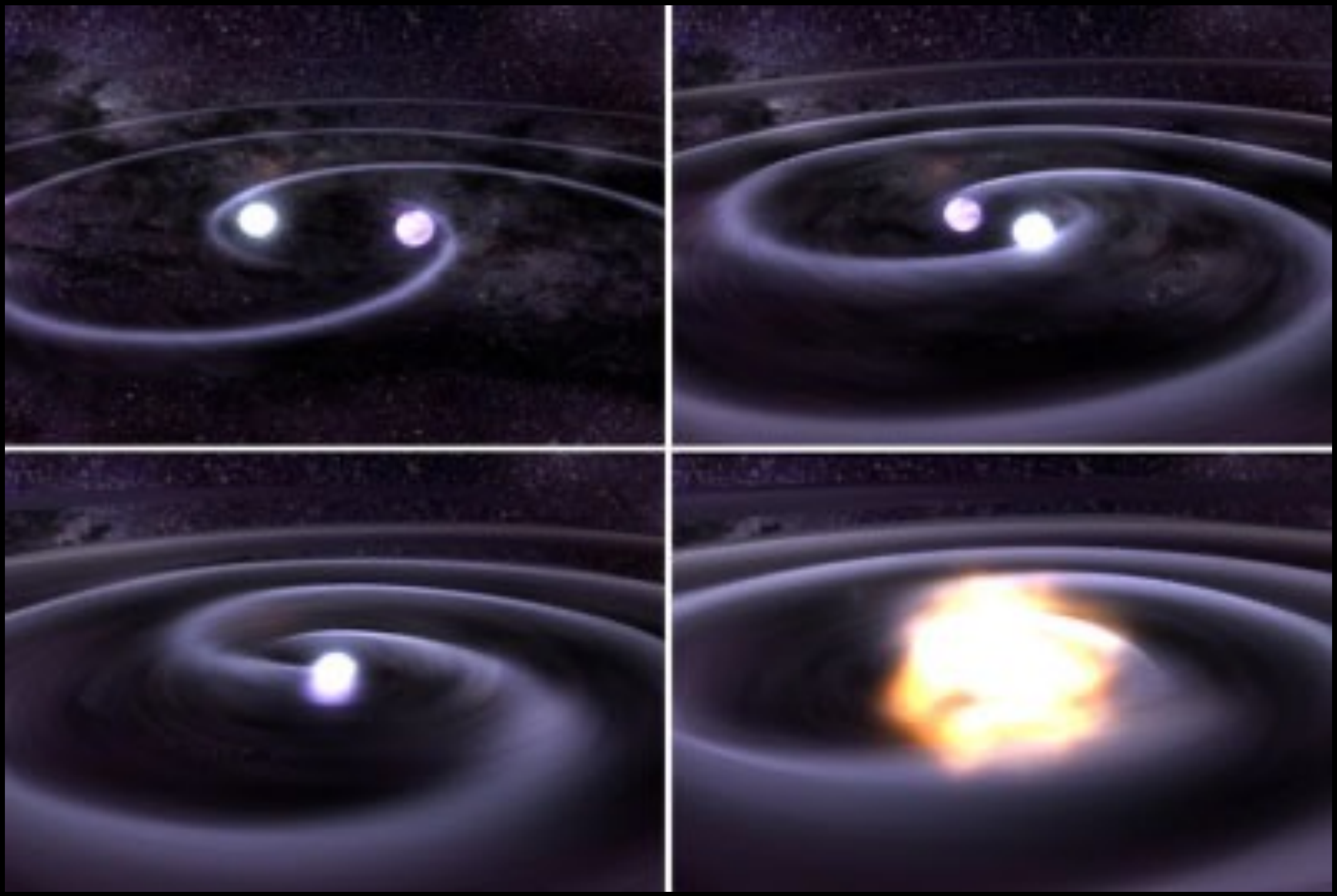
- **Black hole**
  - More on them later…

Supernova from White Dwarf + Red Giant

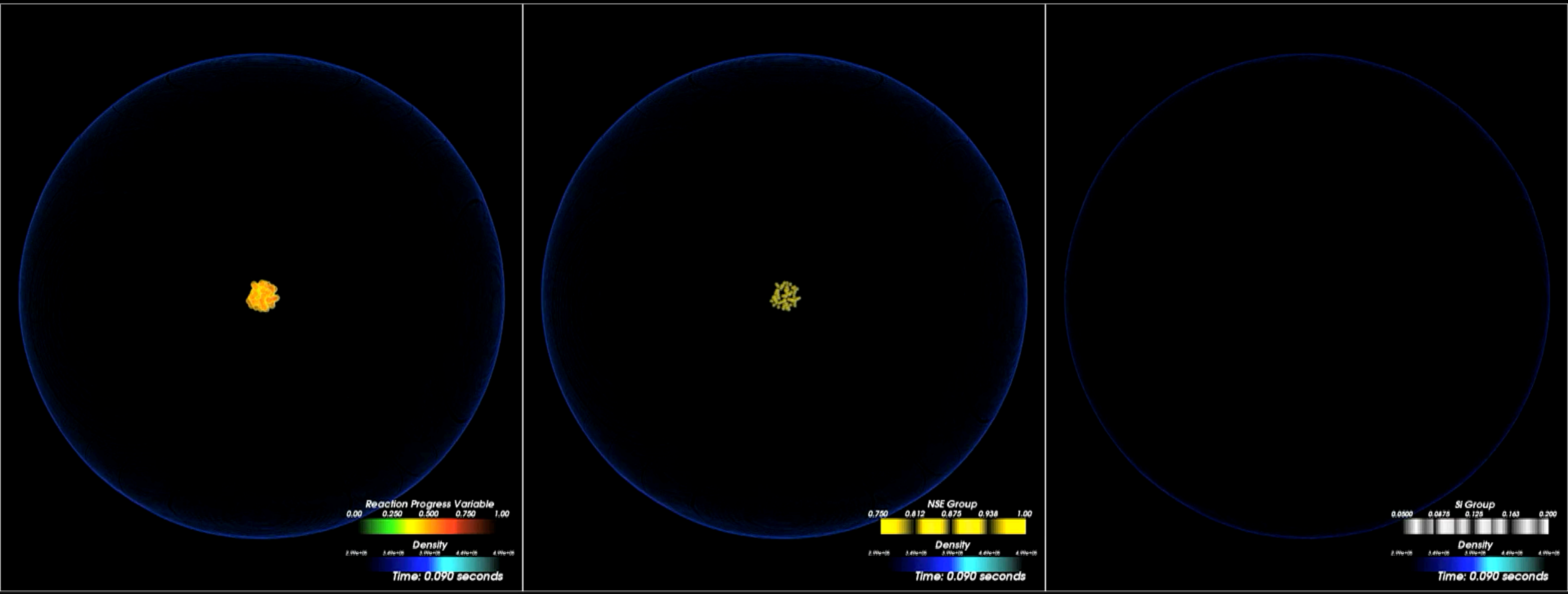


NASA/Goddard

Supernova from two White Dwarfs



NASA Goddard / Dana Berry

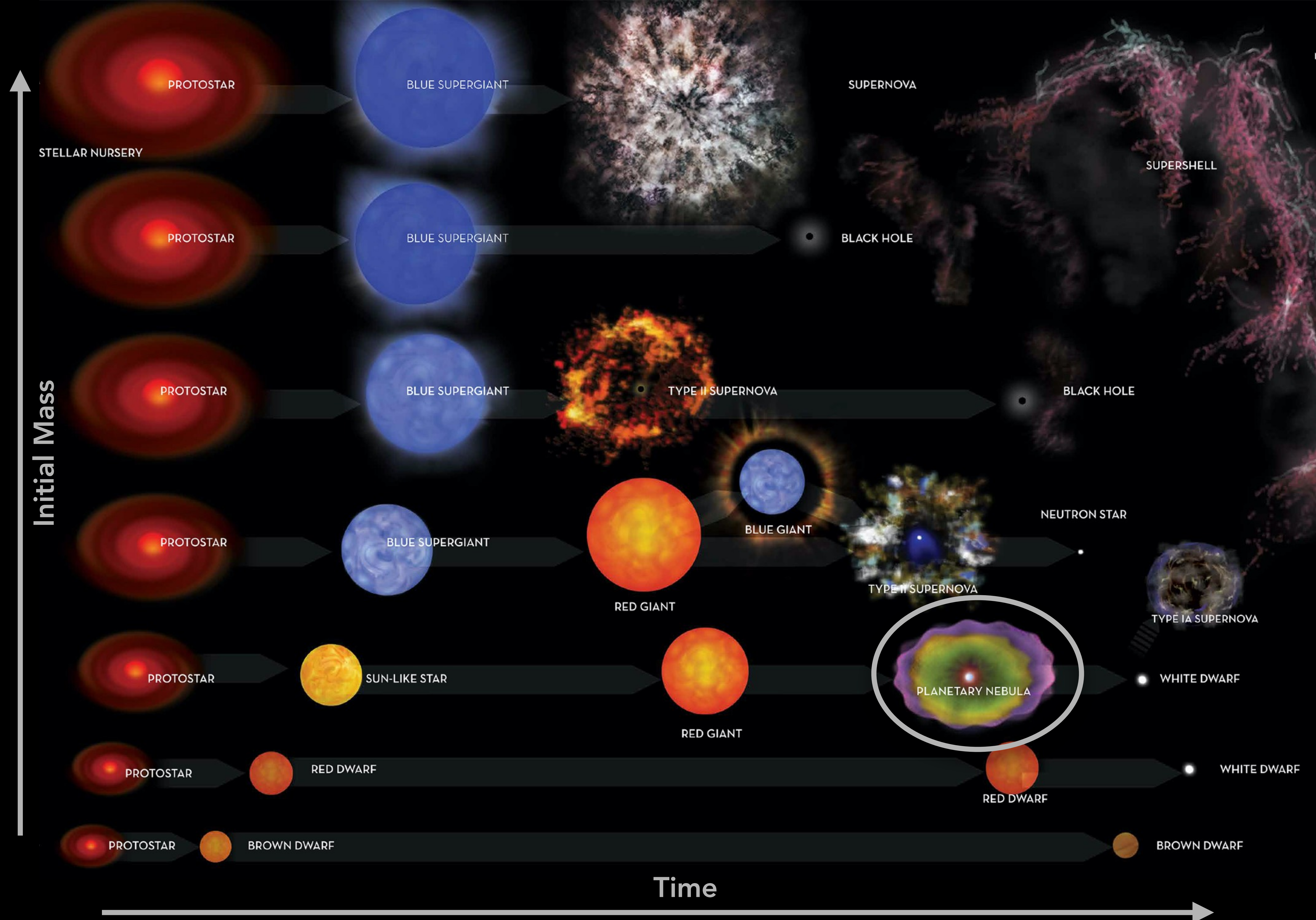


Nuclear burning progress

Iron produced
(and similar elements)

Silicon produced
(and similar elements)

Flash Center / University of Chicago



Summary of stellar evolution

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Neutron star merger

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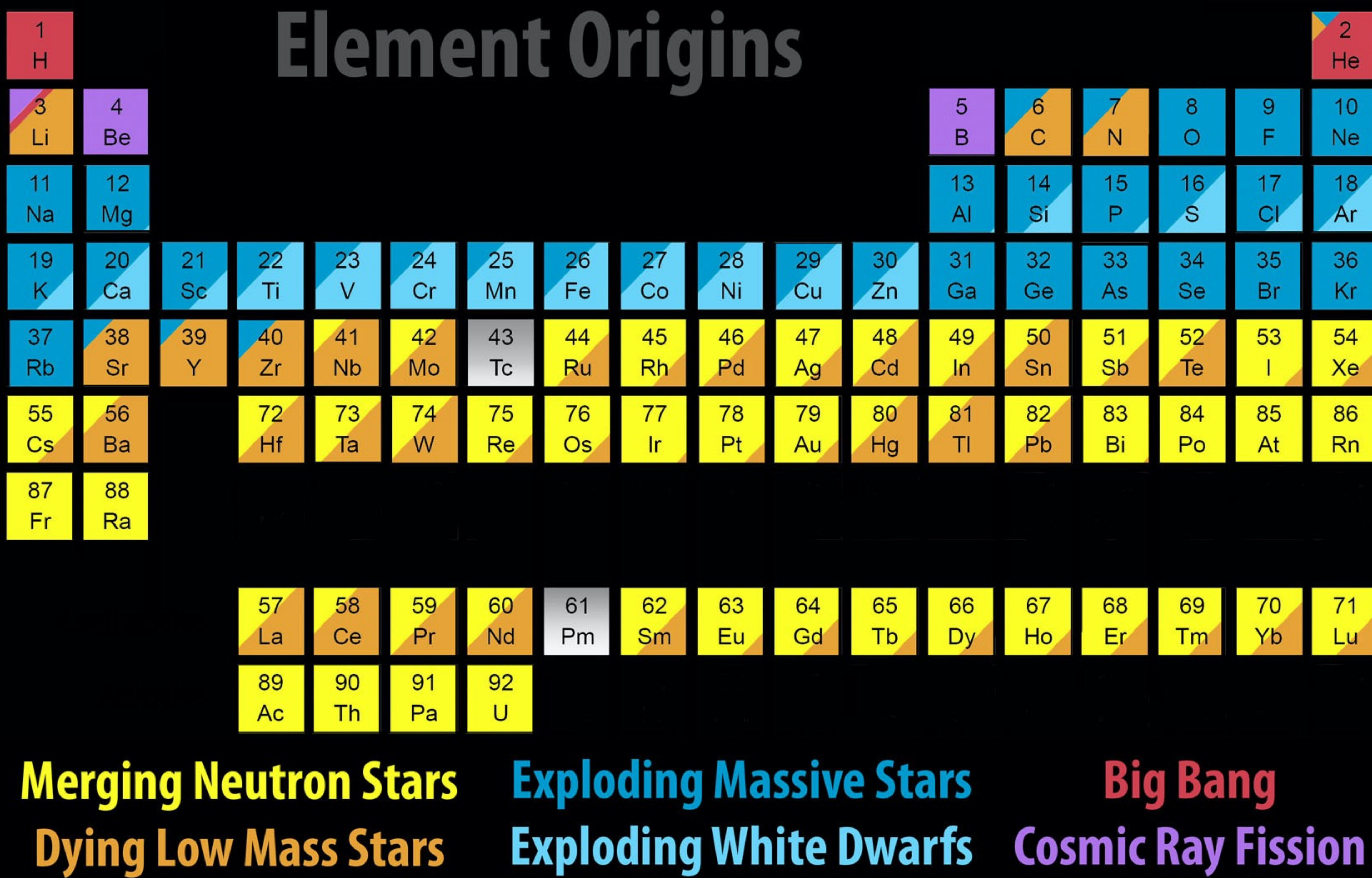

Image: Jennifer Johnson

Are we all made from star stuff?

Pretty much!

Take-aways

- In the first ~30 minutes after the Big Bang, the Universe cooled enough to form **hydrogen, helium, and lithium**, but no heavier elements

- From the abundances of these elements, we can tell that **baryons** (normal matter) make up for only **5% of the critical density** (as opposed to ~30% for all matter)

- All **heavier elements are made by stars**, either during their late burning stages or in supernova explosions

Next time…

We'll talk about:

- The cosmic microwave background

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework #4 (due 11/11)

Reading:

- H&H Chapter 14