Stellar Astrophysics I

恒星物理学特論 I

Masaomi Tanaka

田中 雅臣

Masaomi Tanaka (田中 雅臣)

https://www.astr.tohoku.ac.jp/~masaomi.tanaka/

Born in Nagoya (Aichi)
Grew up in Chita peninsula

2001-2009: U. Tokyo
2009: PhD at Univ. of Tokyo
2009-2011: Kavli IPMU
2011-2018: NAOJ
2018-now: Tohoku Univ.

Research topics

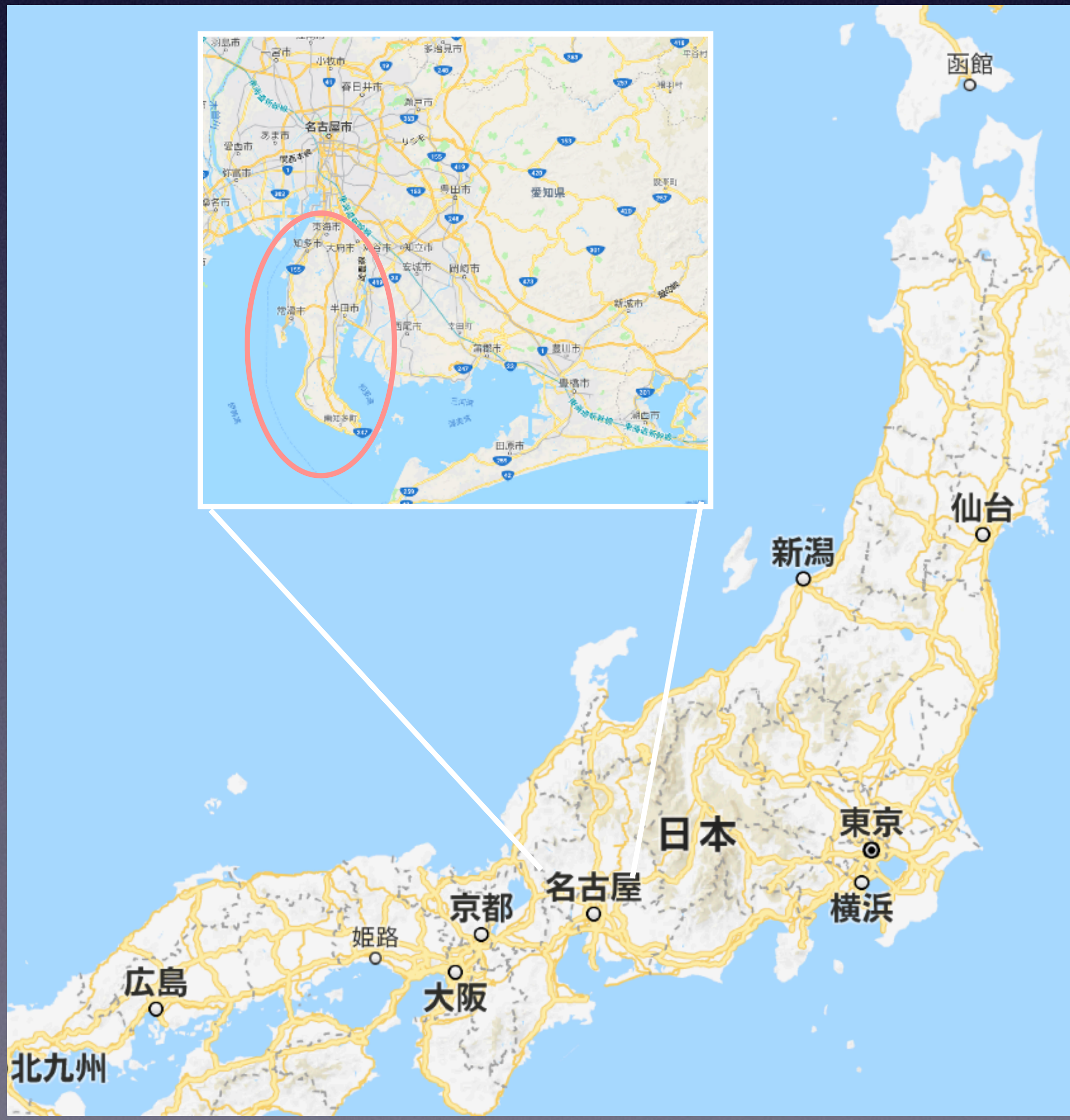
- Time-domain astronomy
- Transients (e.g., supernovae, neutron star mergers)

Observations

- Wide field survey (Subaru, Kiso)
- Spectroscopy and spectro-polarimetry

Theory

- Radiative transfer simulations



Research interests

- Supernovae
- Neutron star merger
  (gravitational wave source)
- Anything variable on the sky

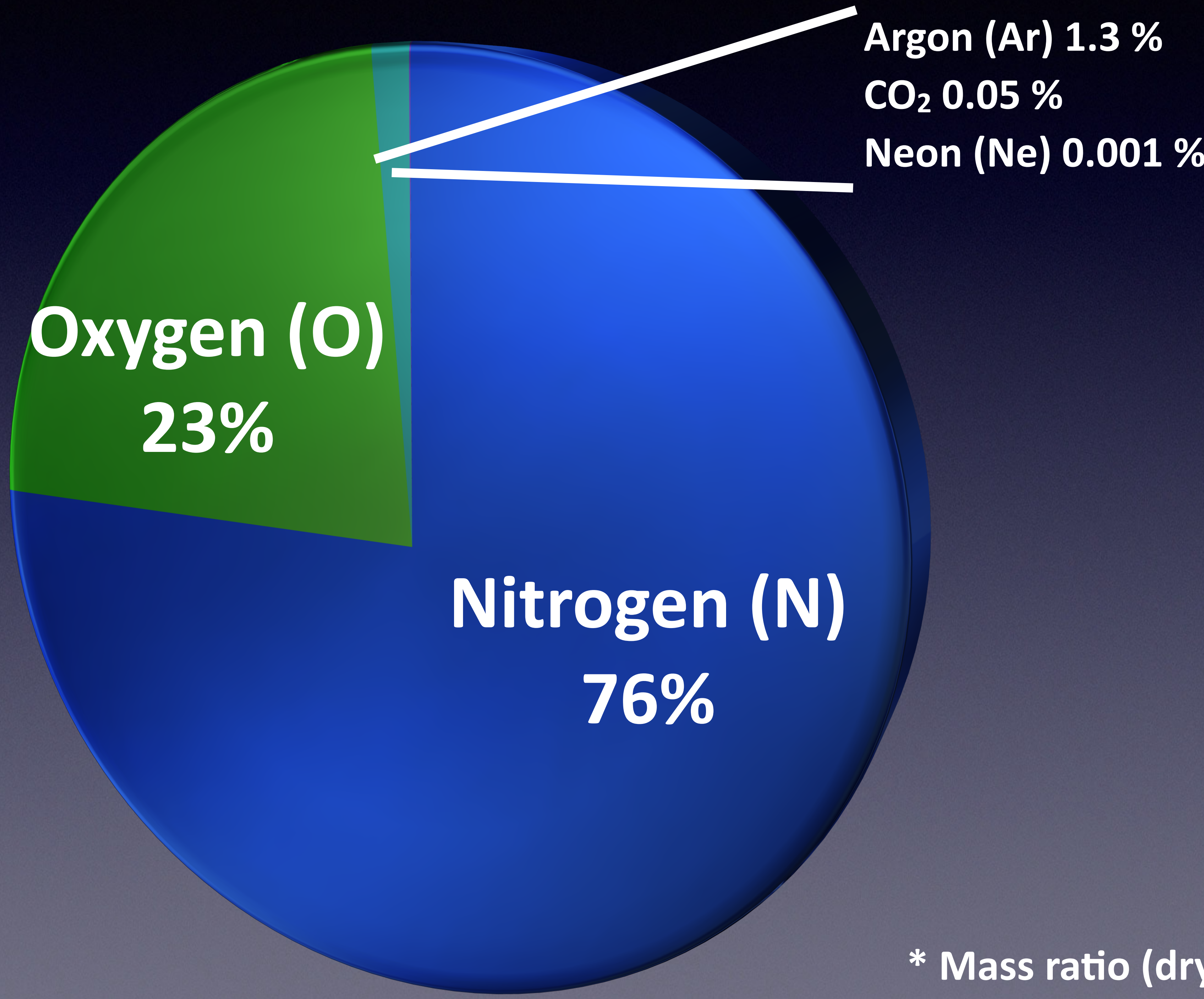
Why do we study transients?

- Extreme physical condition
- End point of stellar evolution
- Origin of the elements
- Many unsolved mystery

"time-domain astronomy"

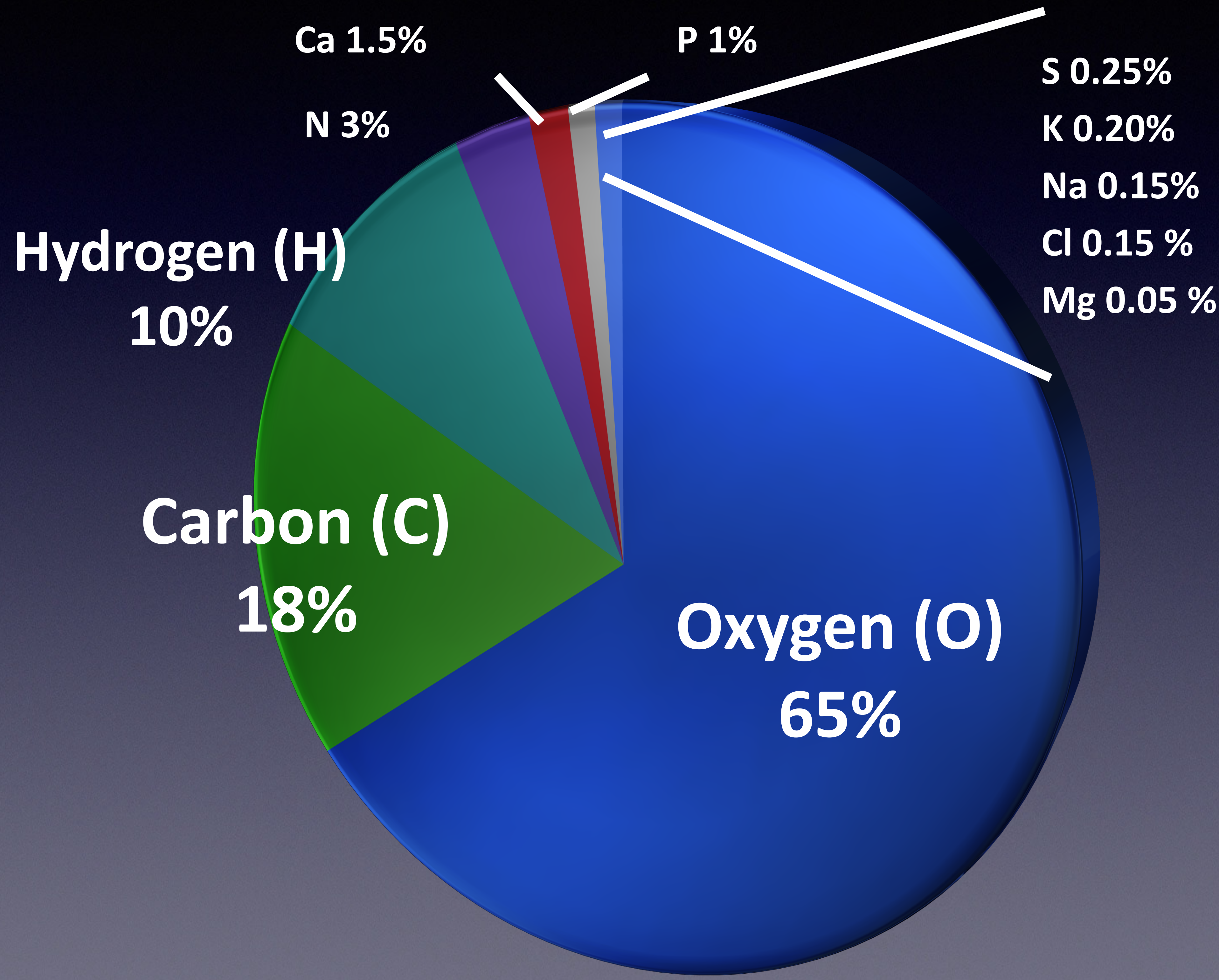
Elements around us

Air

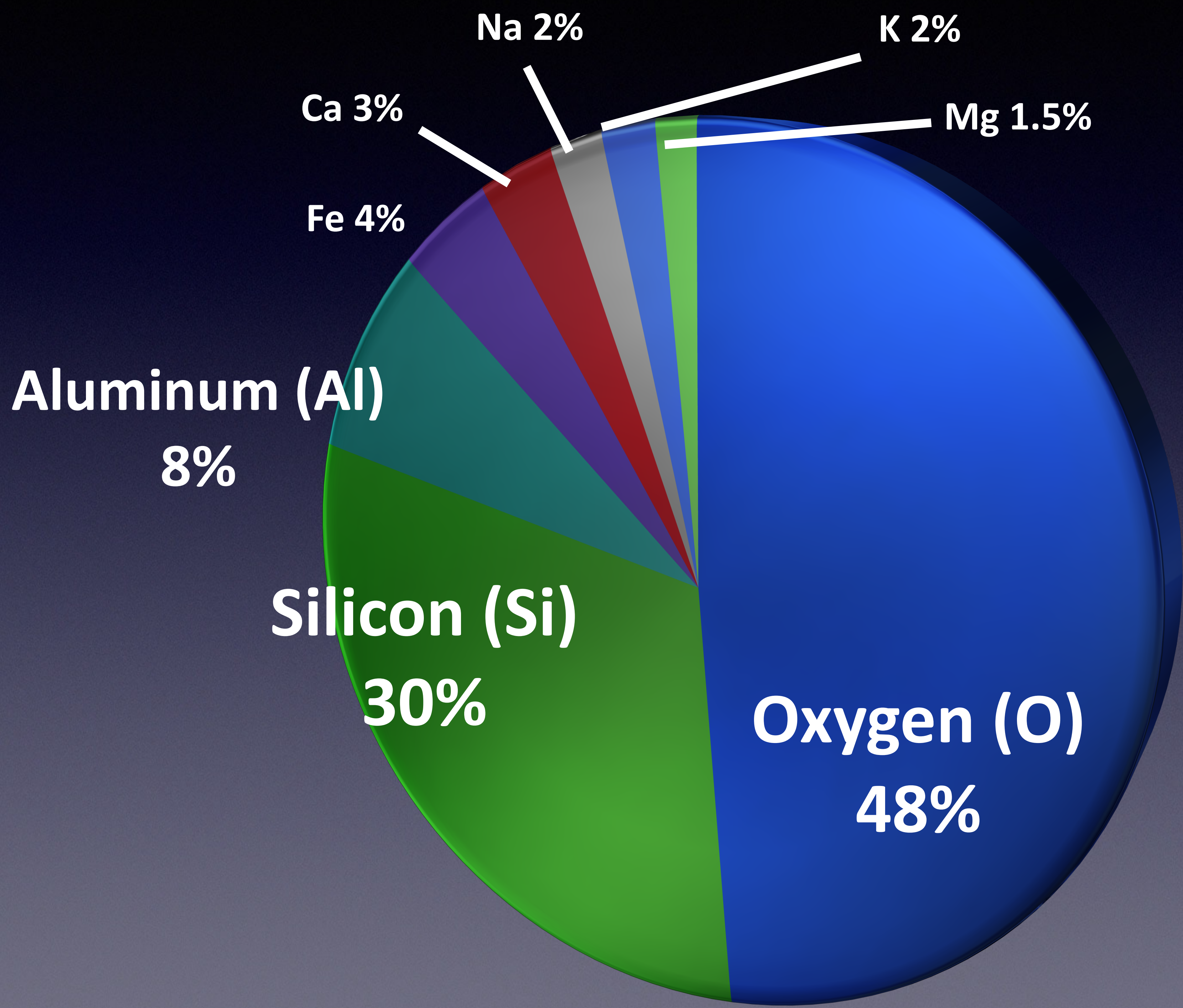


* Mass ratio (dry air)

Our body


Ca 1.5%
P 1%
N 3%
S 0.25%
K 0.20%
Na 0.15%
Cl 0.15 %
Mg 0.05 %
Hydrogen (H)
10%
Carbon (C)
18%
Oxygen (O)
65%

The earth (crust)



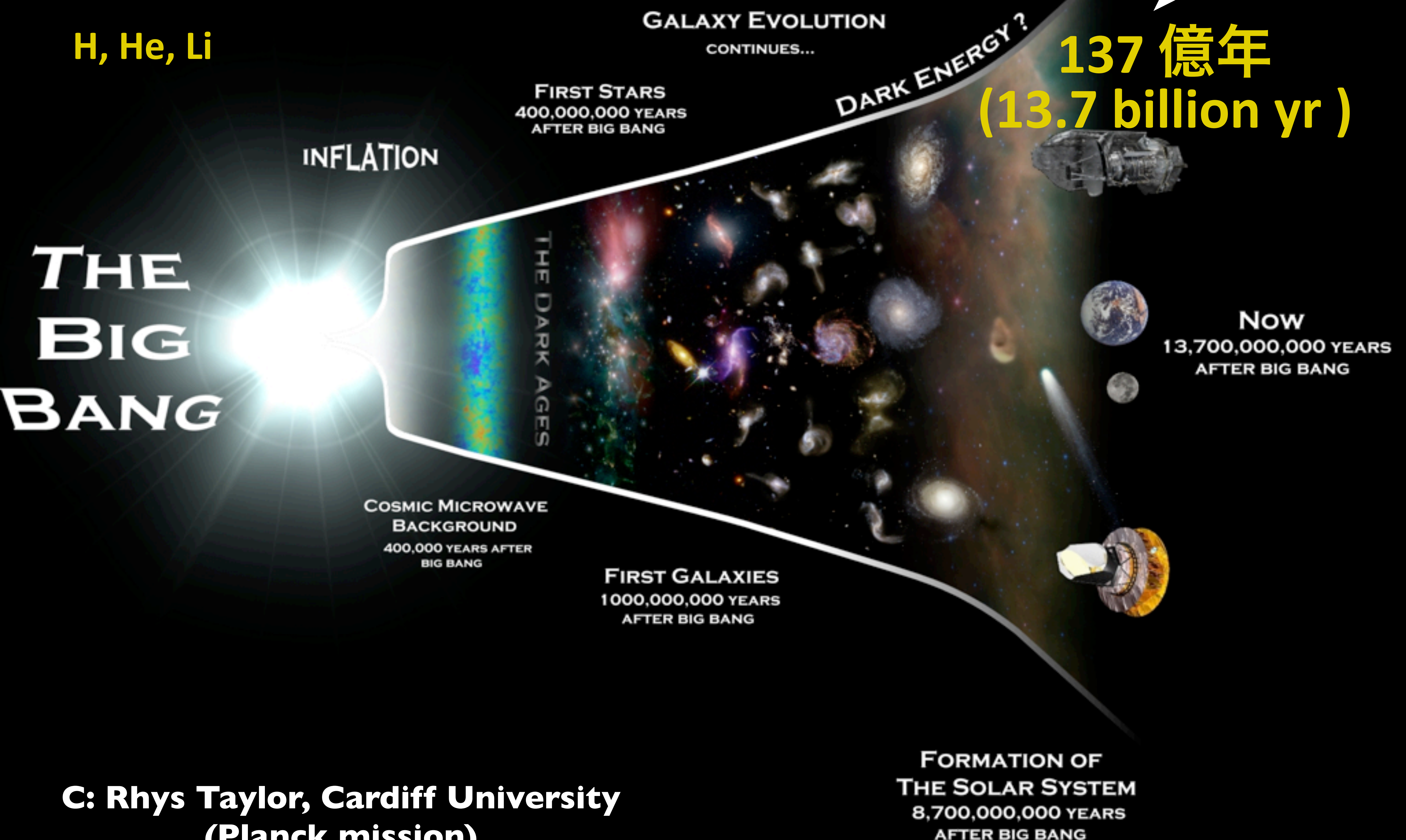
* Mass ratio

The beginning of the Universe

Now

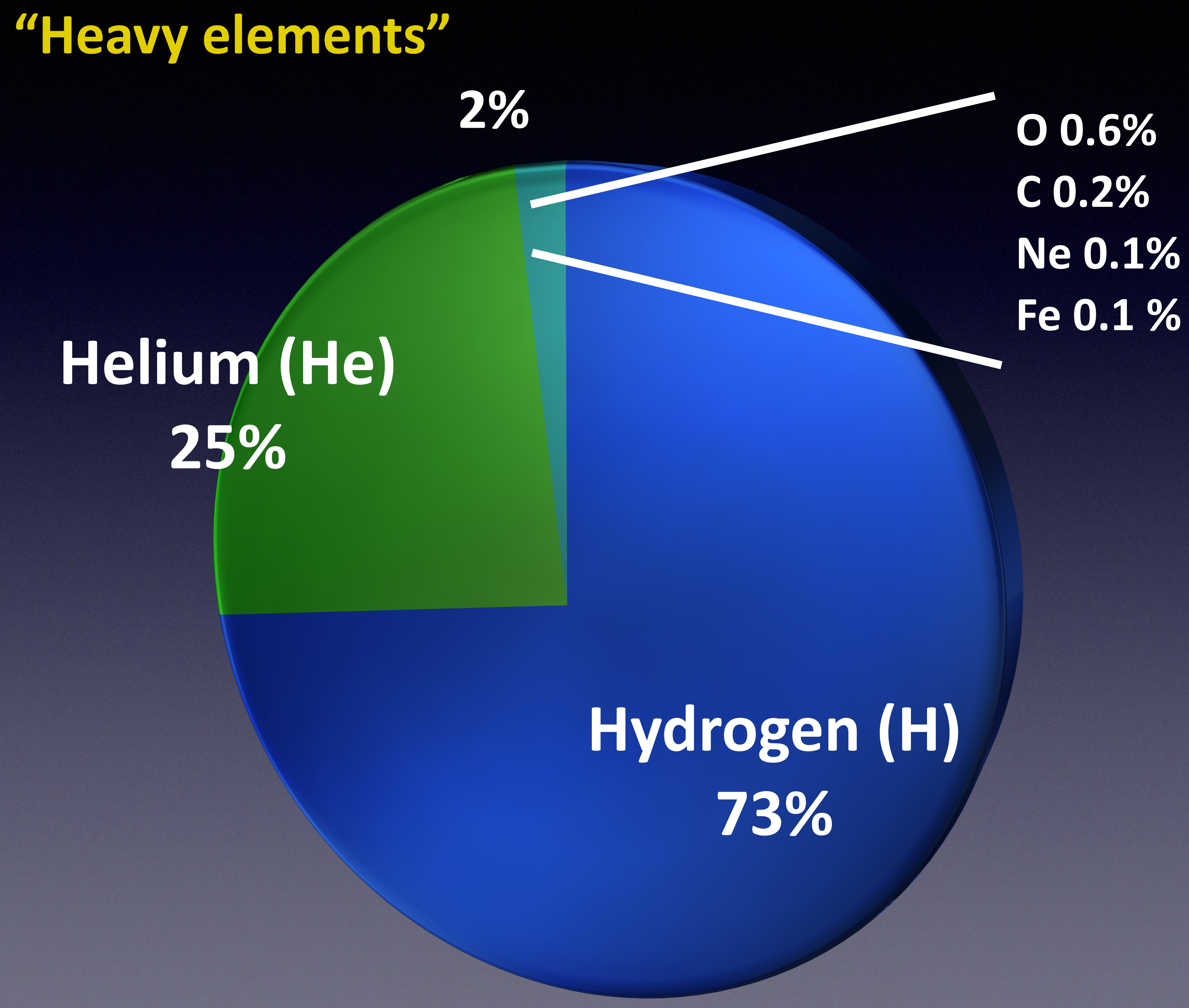
H, He, Li

137 億年
(13.7 billion yr)



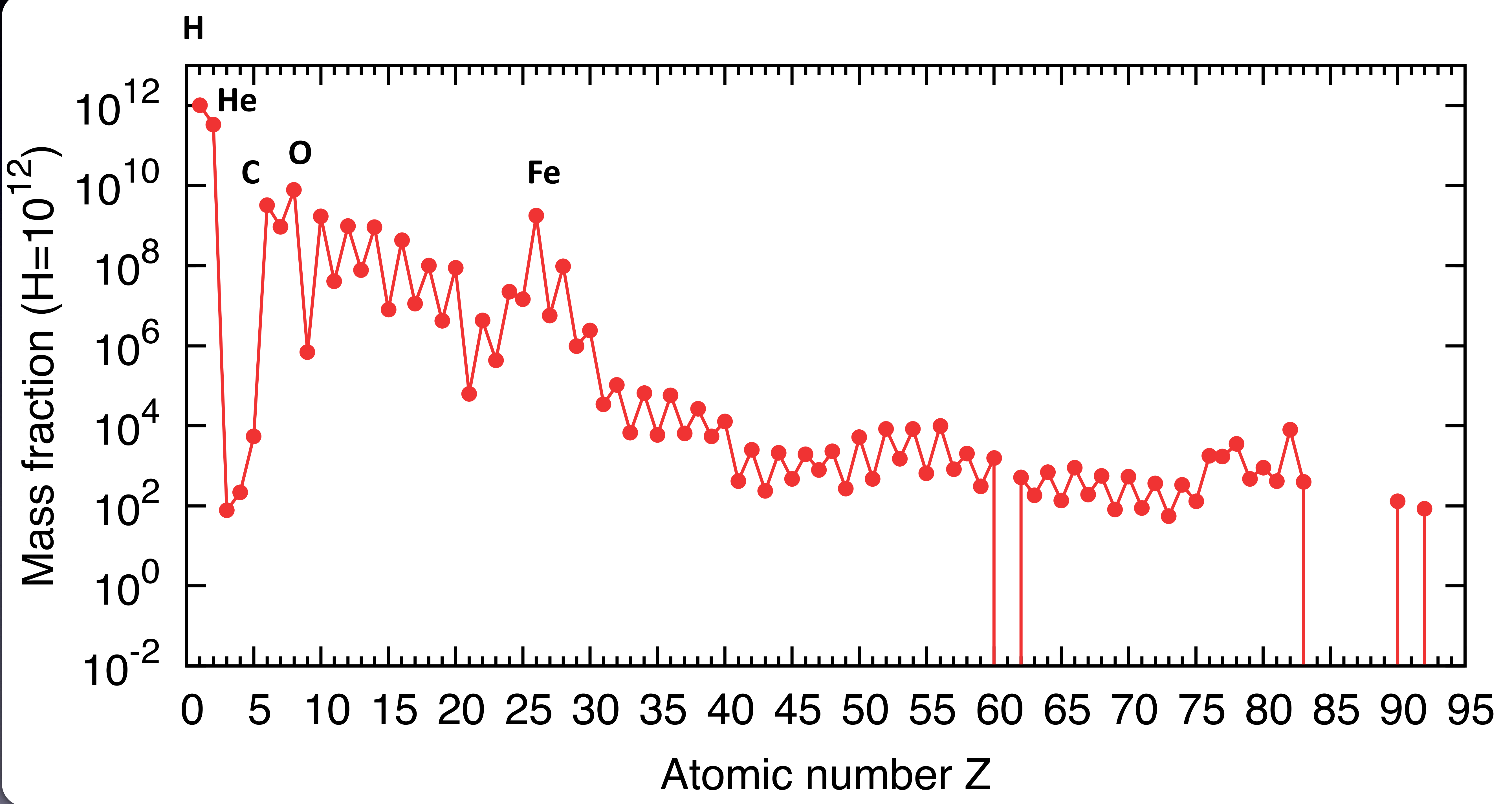
C: Rhys Taylor, Cardiff University
(Planck mission)

Our Universe



*Mass ratio

Element abundances in the Universe



*Mass ratio

Goals of this lecture

- Standard properties of stars
  - Stellar structure and properties
  - Stellar evolution
- Origin of the elements in the Universe
  - Nucleosynthesis in stars and supernovae
  - Explosion mechanism of supernovae
- Topics in time-domain astronomy
  - Radiation from explosive phenomena
  - Multi-messenger astronomy

Minimum required knowledge for galactic astronomy

Course material and schedule

https://www.astr.tohoku.ac.jp/~masaomi.tanaka/tohoku2022

* ~70% blackboard
~30% slides

Contents

- Overview
- Stellar structure and properties
- Stellar evolution
- Supernovae
- Origin of the elements and chemical evolution of the Universe

Credit
成績

- Assignments / レポート課題

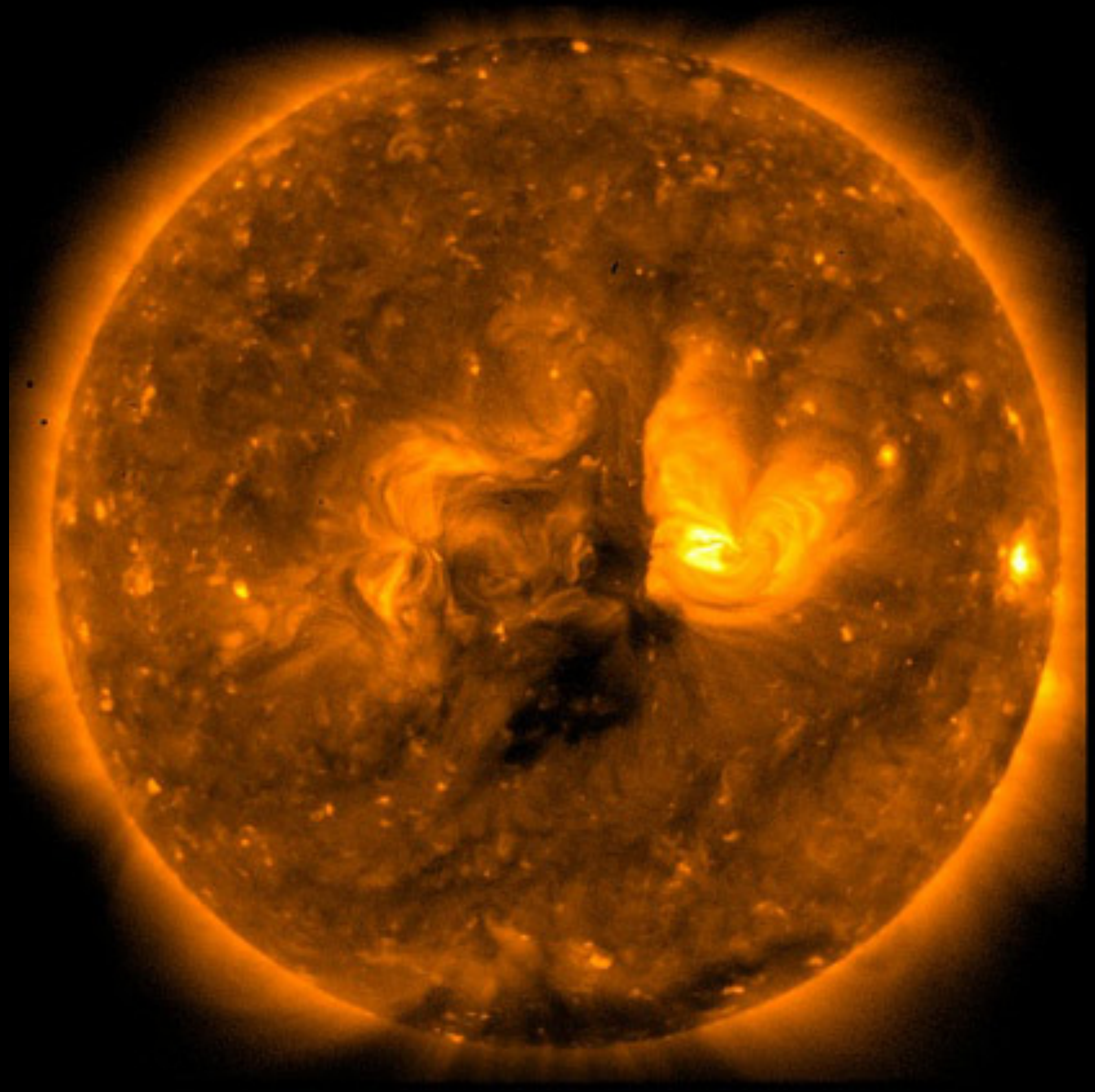
A few rules about this lecture

- **Please try order estimation by yourself**
  - This is essential for astrophysics
- **Please ask questions**
  - Your questions certainly help others' understanding (you can ask questions in Japanese)
- **Please relax and enjoy**
  - You can bring coffee/tea or chocolates/cookies, …

Section 1.
Overview: Life of stars, supernovae, and origin of the elements

1.1 Stellar lives and supernovae

1.2 Origin of the elements



Our sun

Luminosity = 4×10^{33} erg/s

(C) JAXA/ISAS

Japanese energy consumption (1 yr) = 2×10^{19} J = 2×10^{26} erg

Japan 10^7 yr = Sun 1 sec

How is this possible??

Energy source

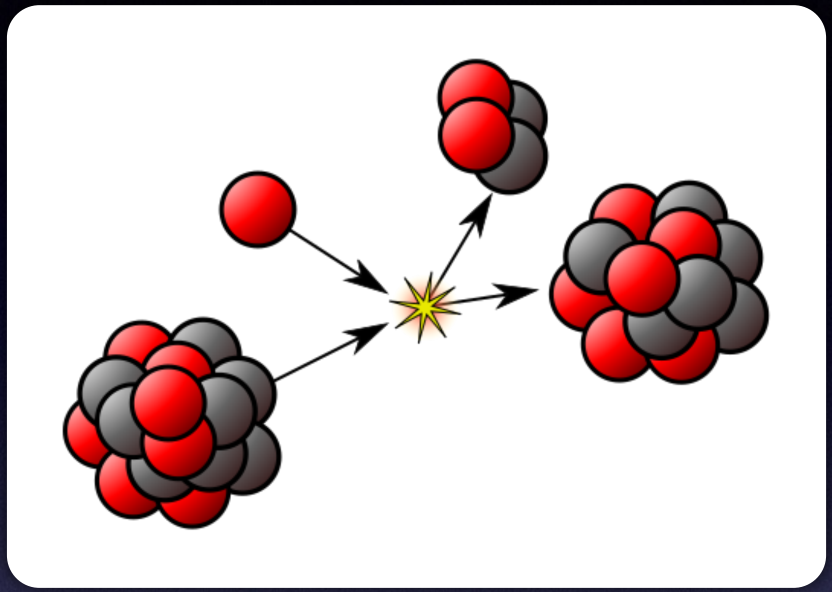
A. Chemical reaction

https://www.britannica.com/science/chemical-reaction

(ex.) $C + O_2 \to CO_2$

Reaction of atoms/molecules
= No change in nucleus

B. Nuclear reaction

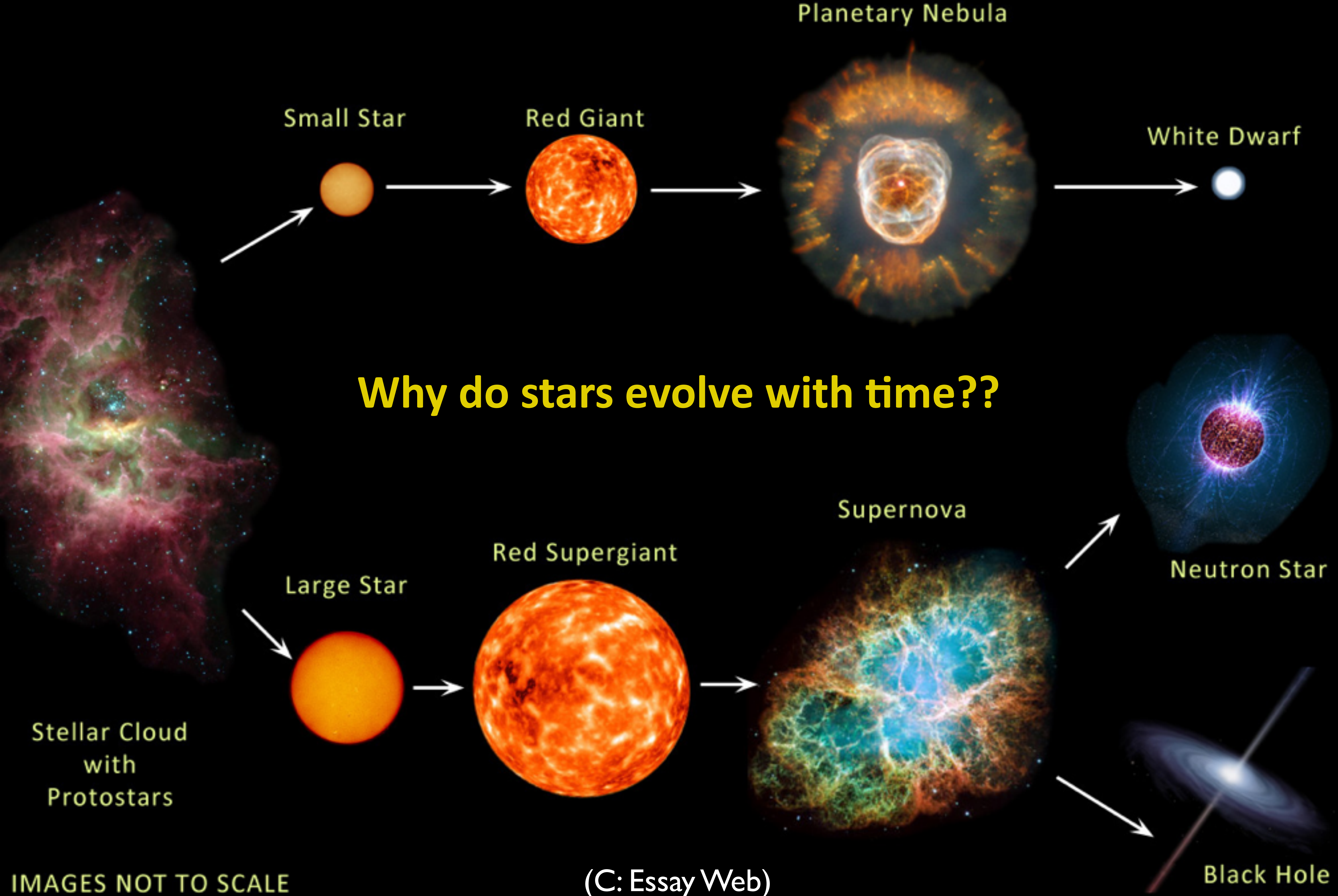


(ex.) H + H + H + H -> He

Change in nucleus
= Production of new elements

Solar luminosity for 10^{10} yr
Really??

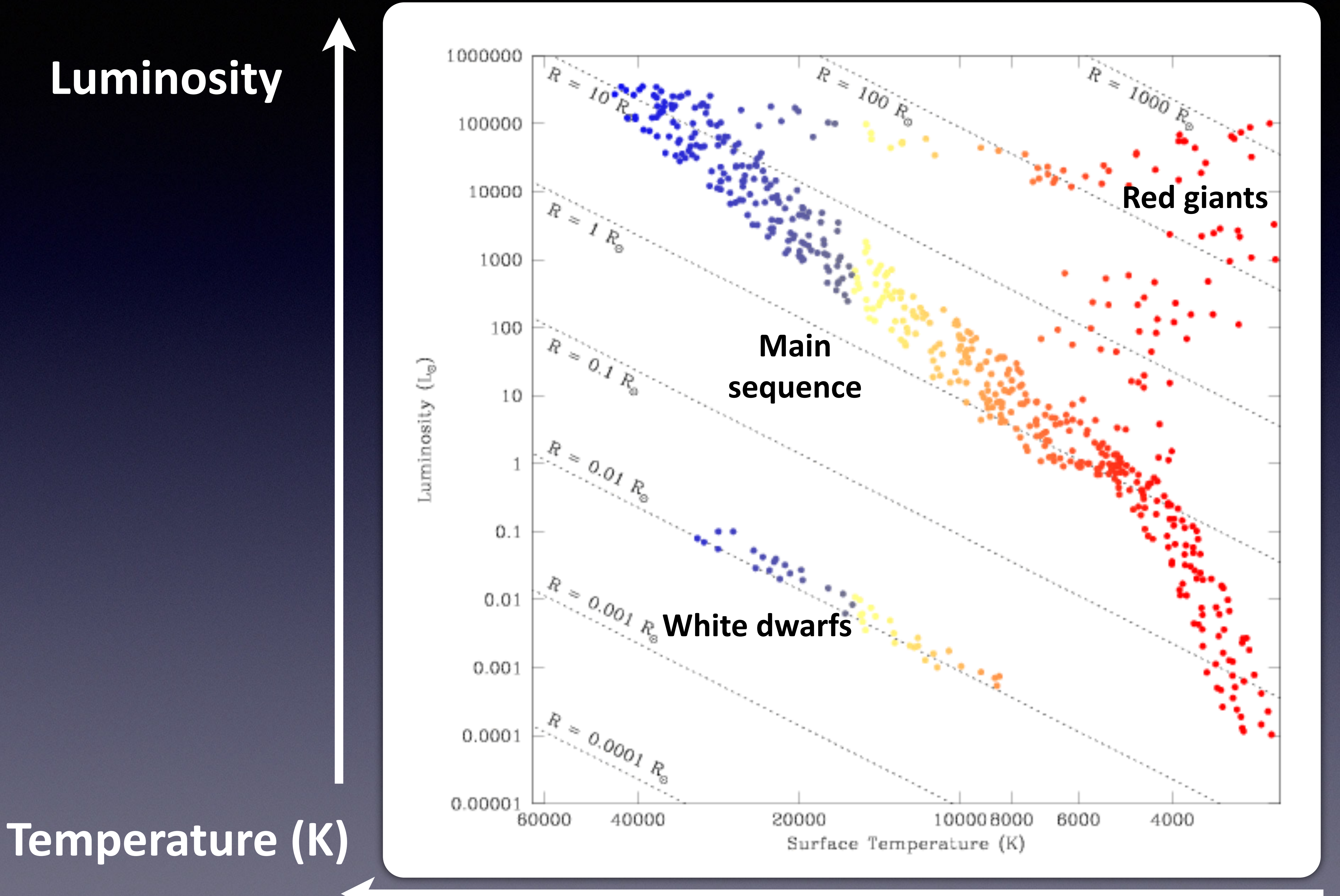
Stellar life



Why do stars evolve with time??

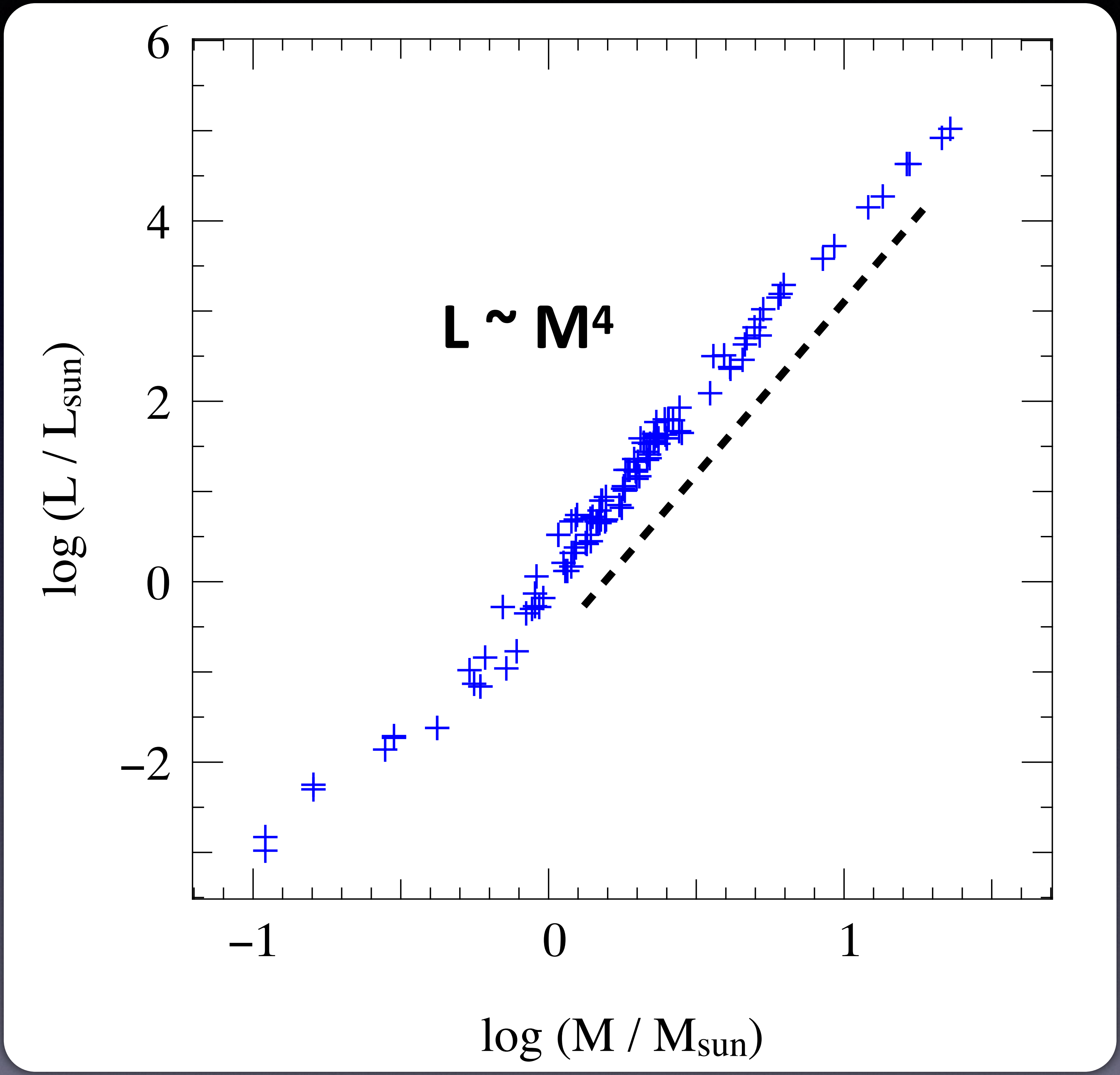
(C: Essay Web)

Hertzsprung-Russel diagram



http://astronomy.nmsu.edu/geas/lectures/lecture23/slide04.html

Mass - luminosity relation of the main sequence stars



Star with M = 10 Msun

=> L ~ 10^4 Lsun

=> Lifetime

~ 1/10^3 of the Sun

~ 10^{10} yr (100億年)/10^3

~ 10^7 yr (1000万年)

More massive stars have shorter lifetime

Why??

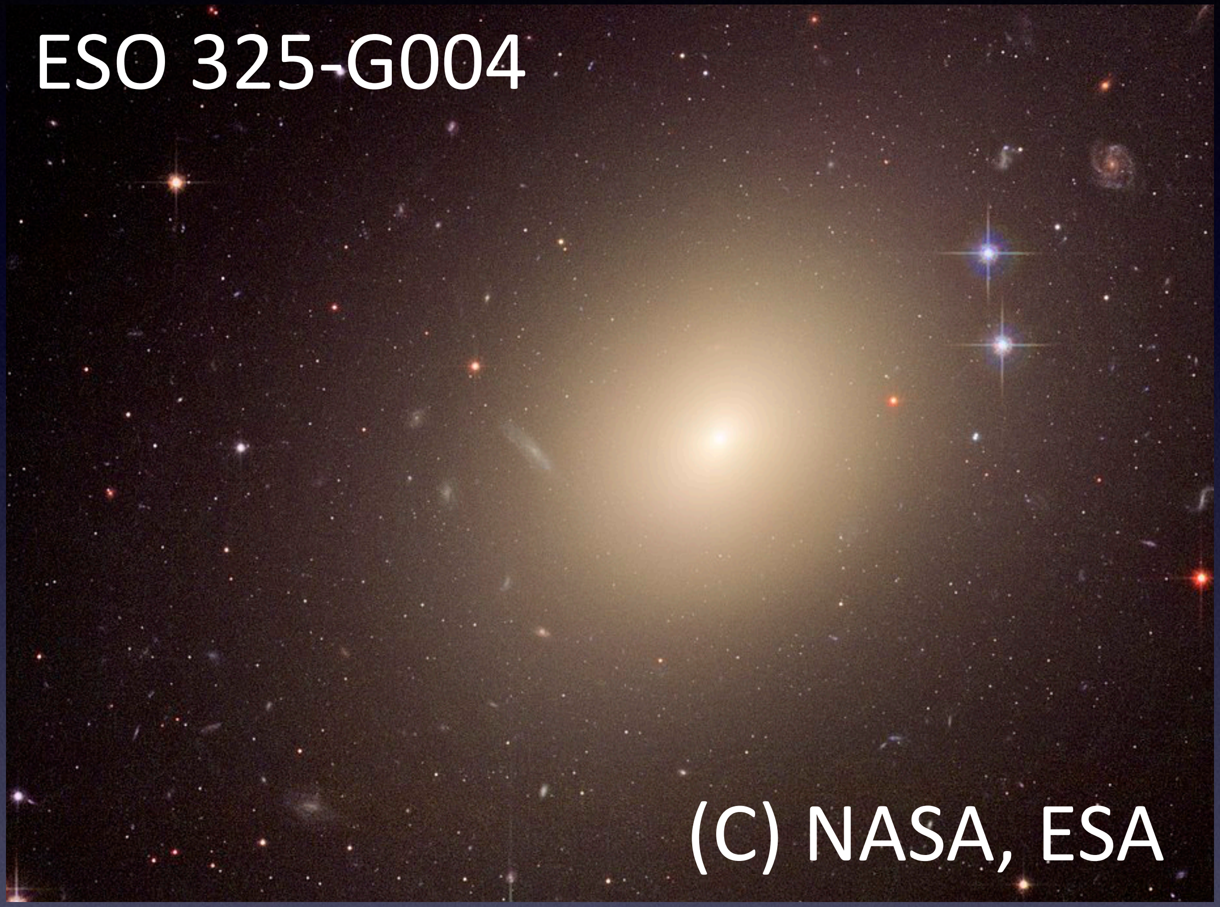
Lecture Note by Pols

Applications to galaxy studies

Spiral galaxy

- Star forming
- More “young" stars
- More massive stars
- Blue (high T radiation)

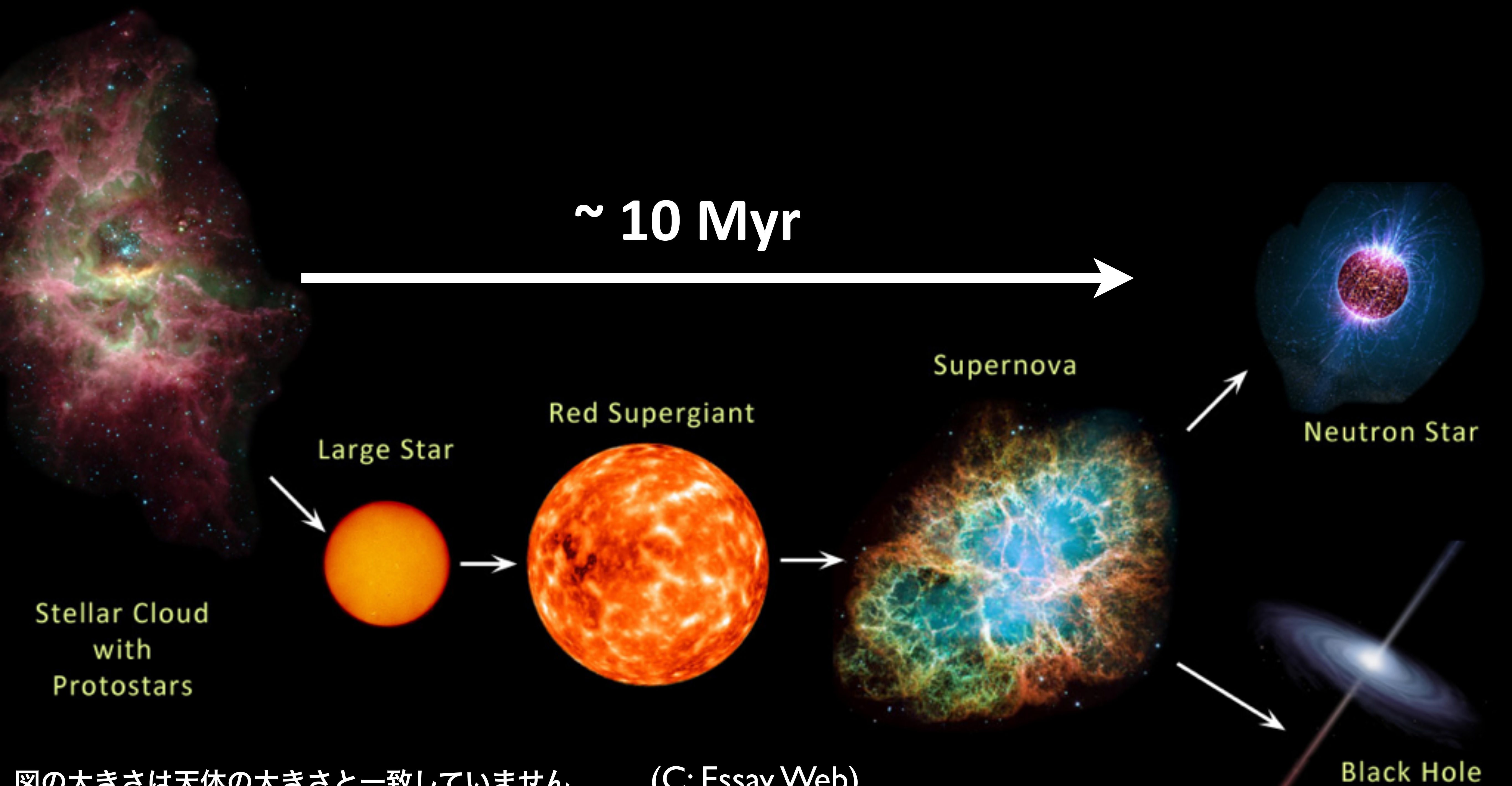
Elliptical galaxy



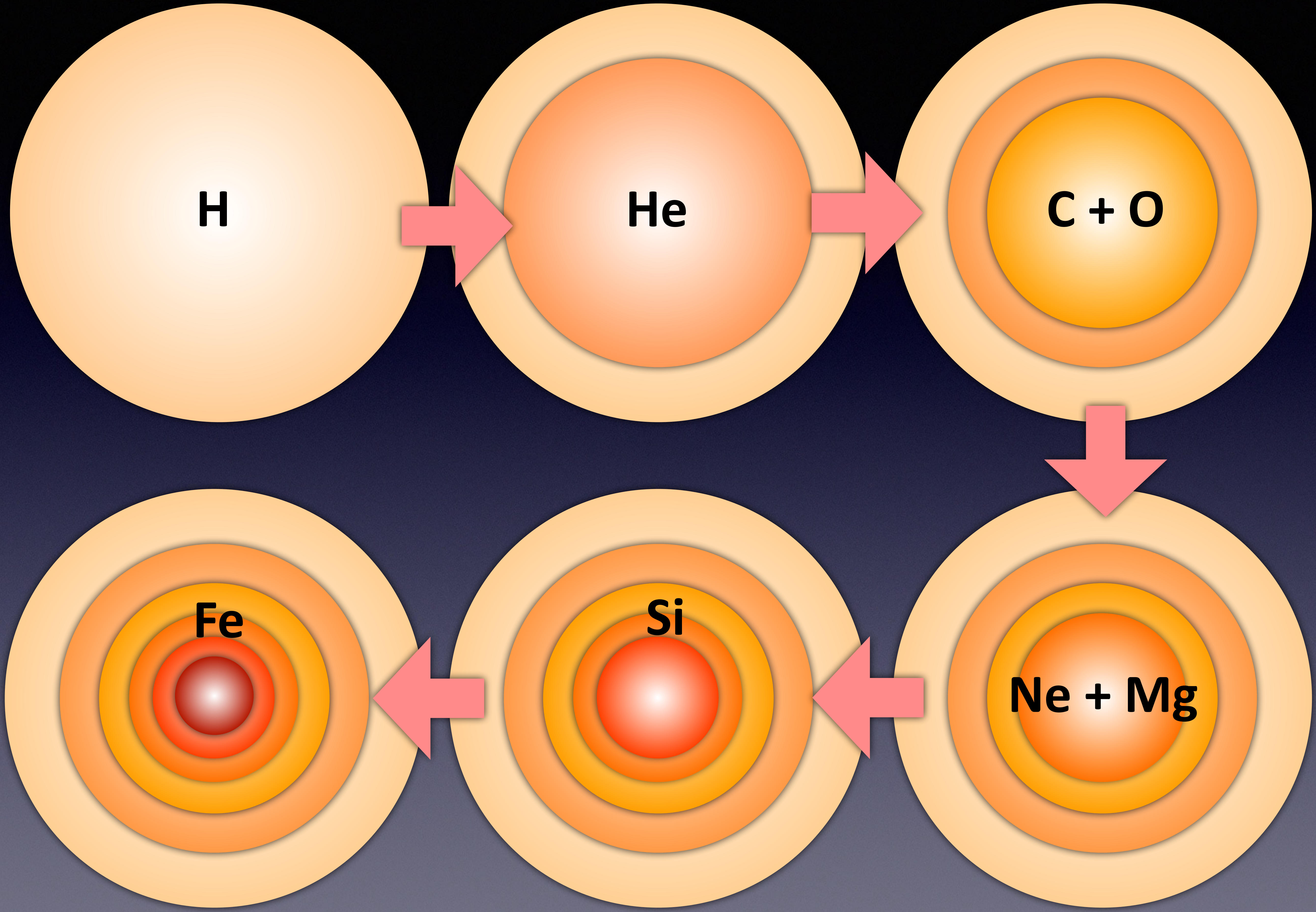
- No star formation
- Old stars
- Less massive stars
- Red (low T radiation)

1. Massive stars

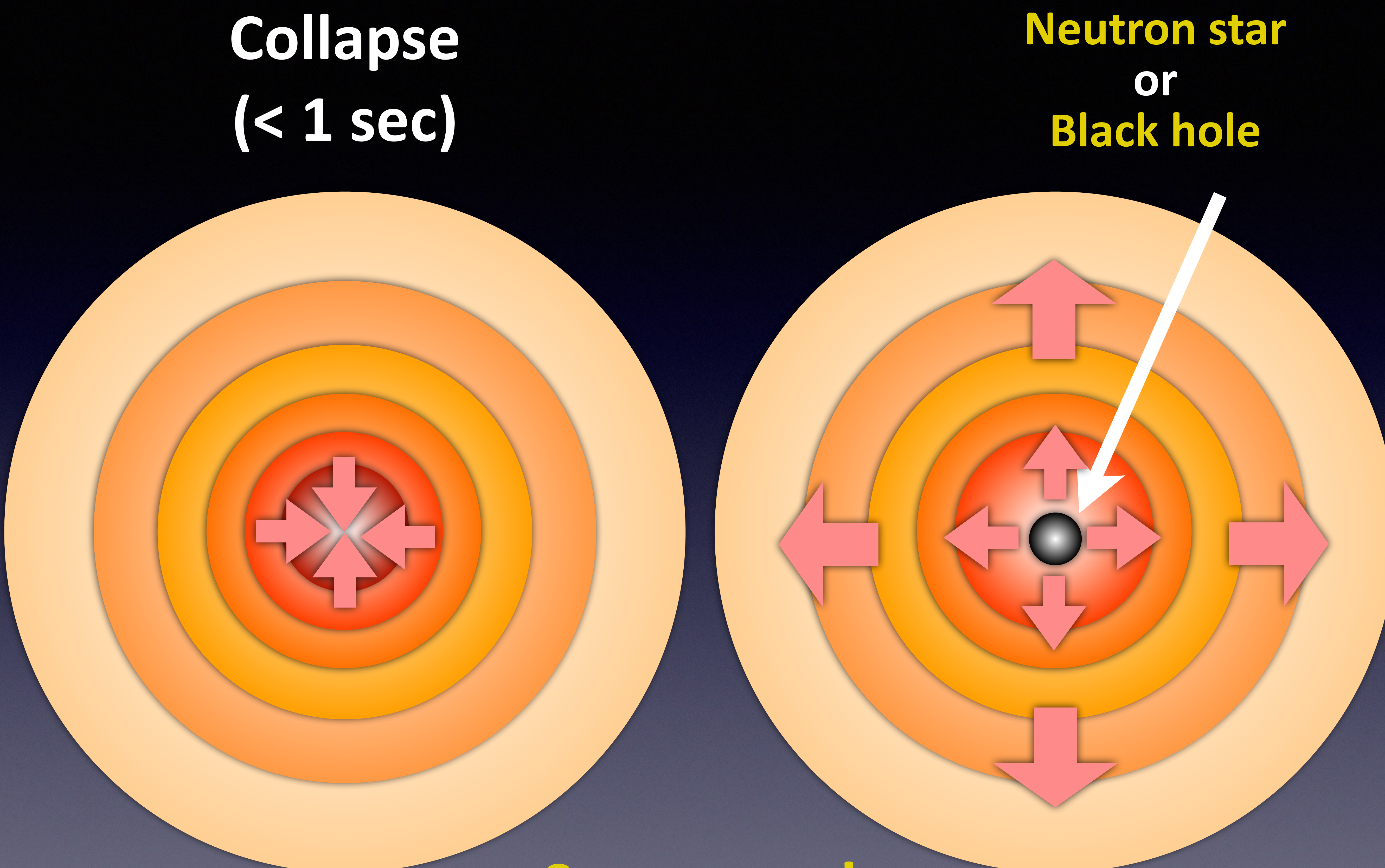
M > 10 Msun



図の大きさは天体の大きさと一致していません　(C: Essay Web)

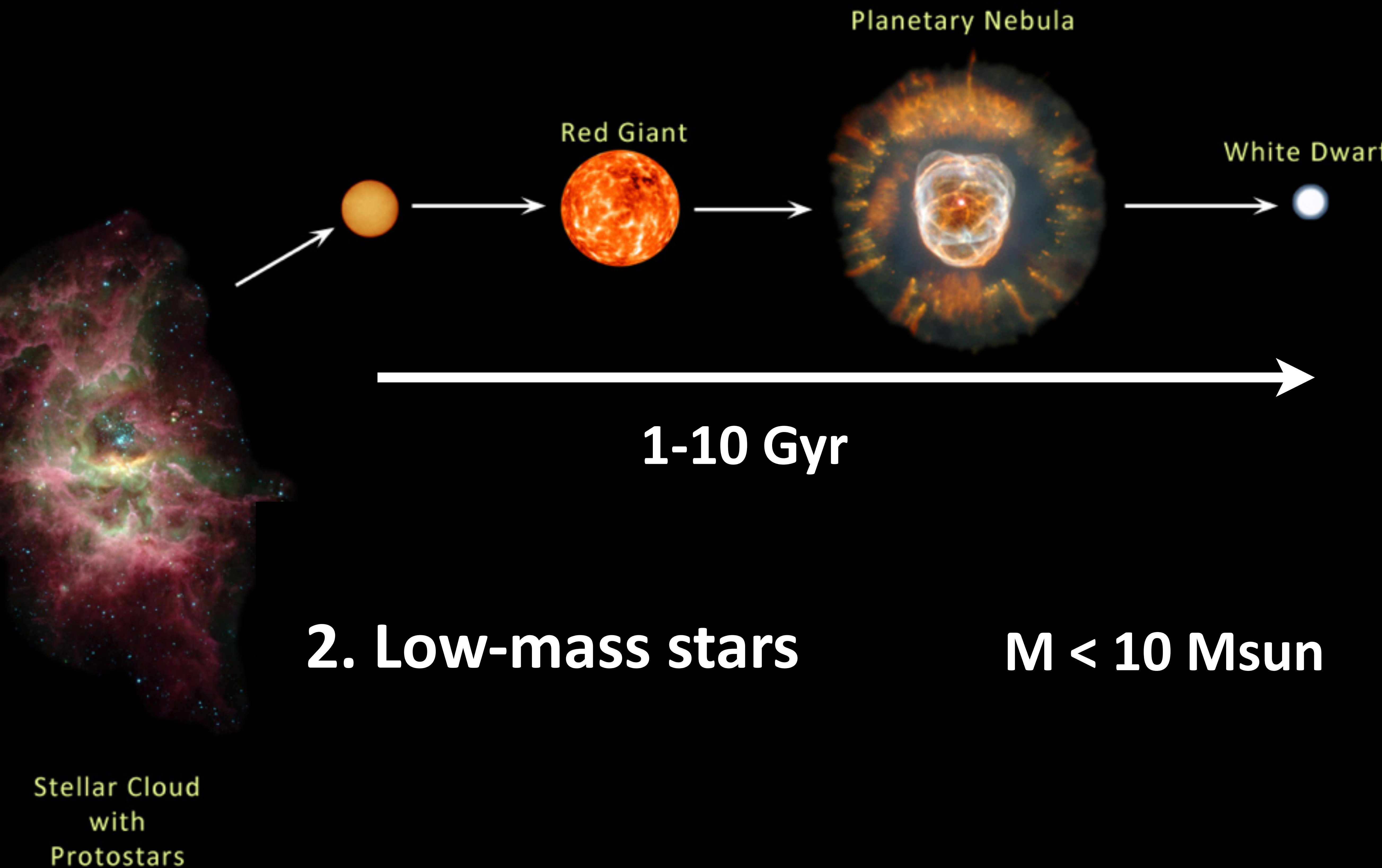


Images are not to scale

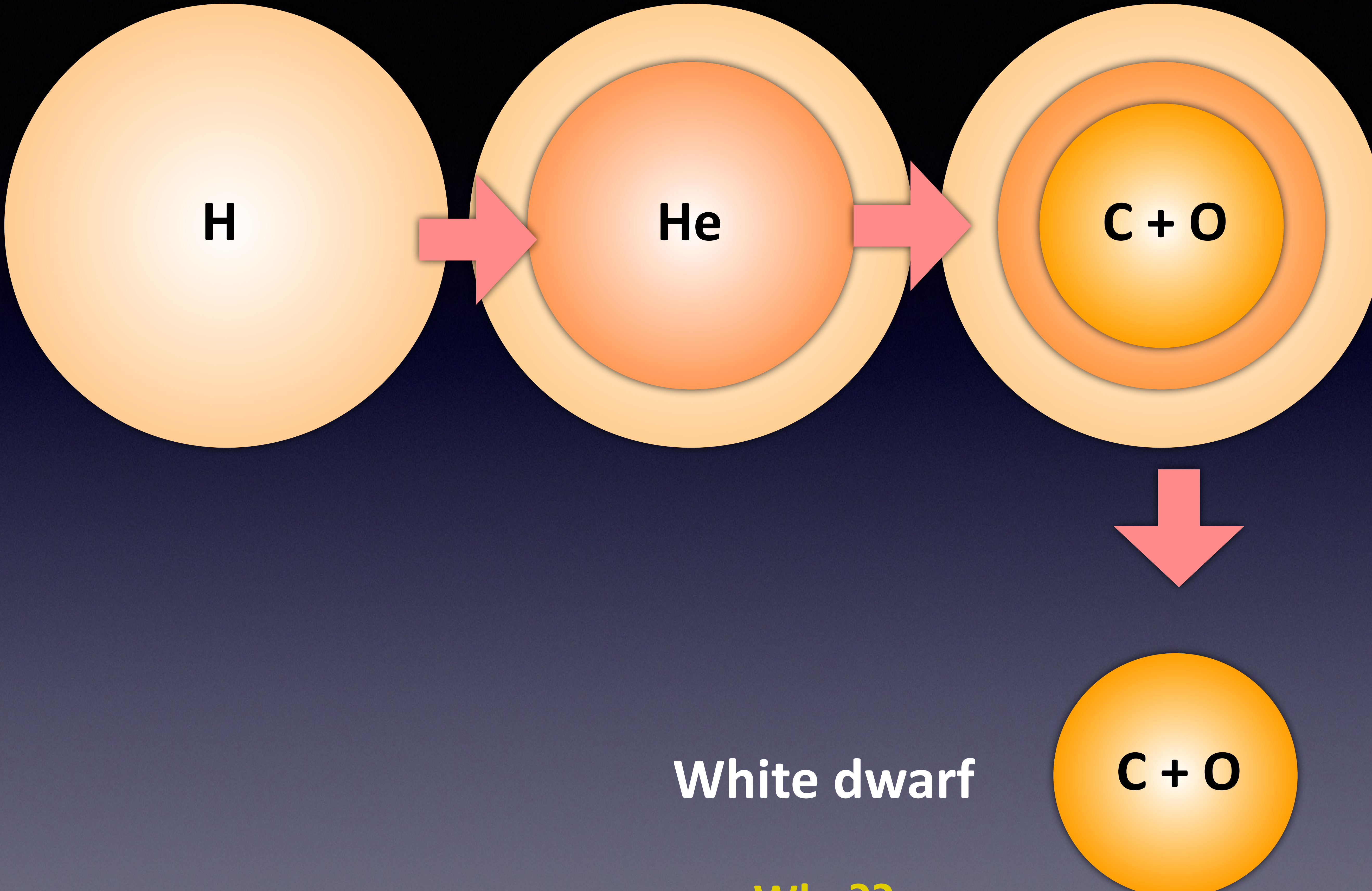


Supernova!

Why?? How is this possible?



図の大きさは天体の大きさと一致していません　(C: Essay Web)

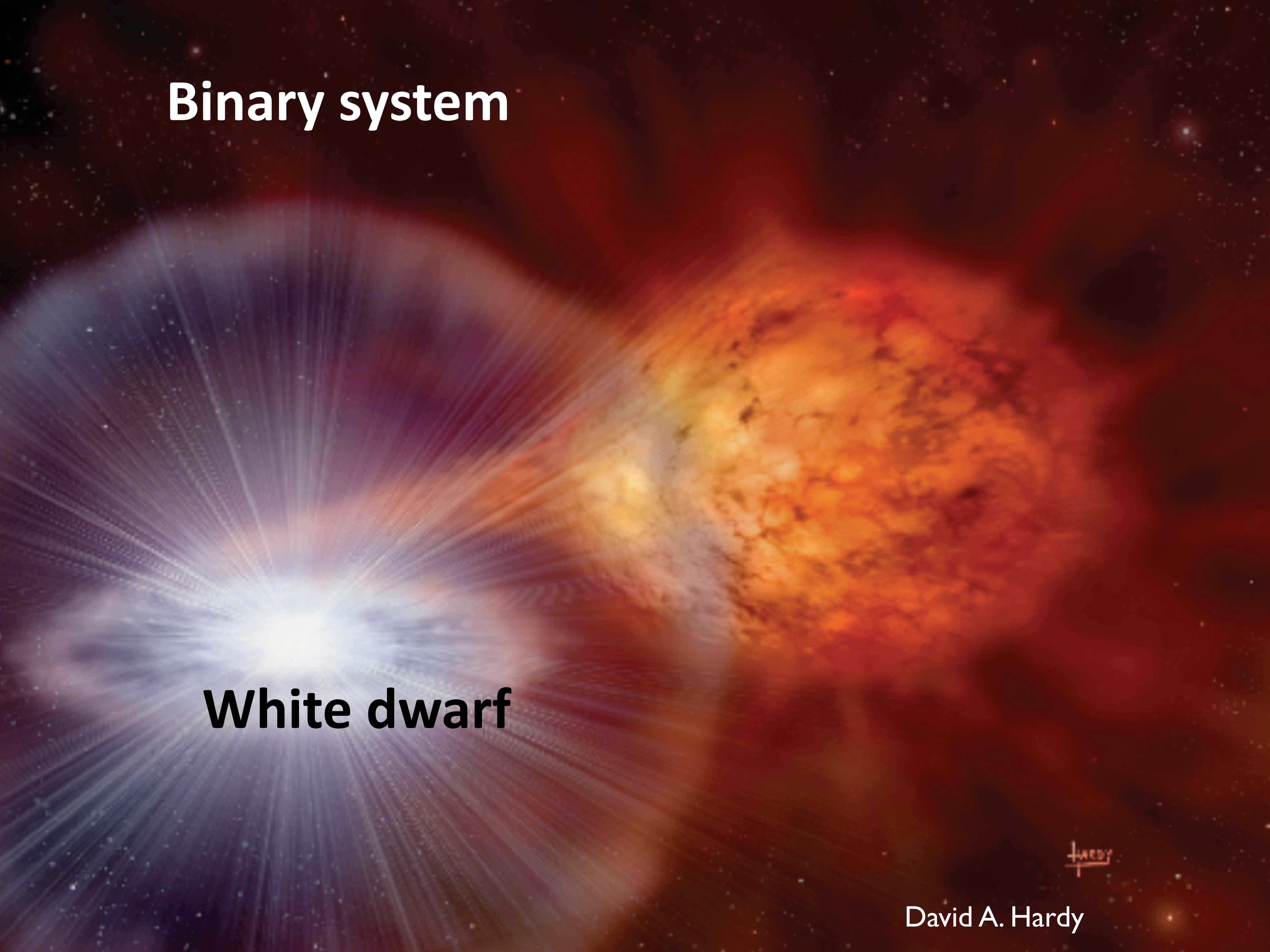


Why??

Low mass stars cannot make Fe?

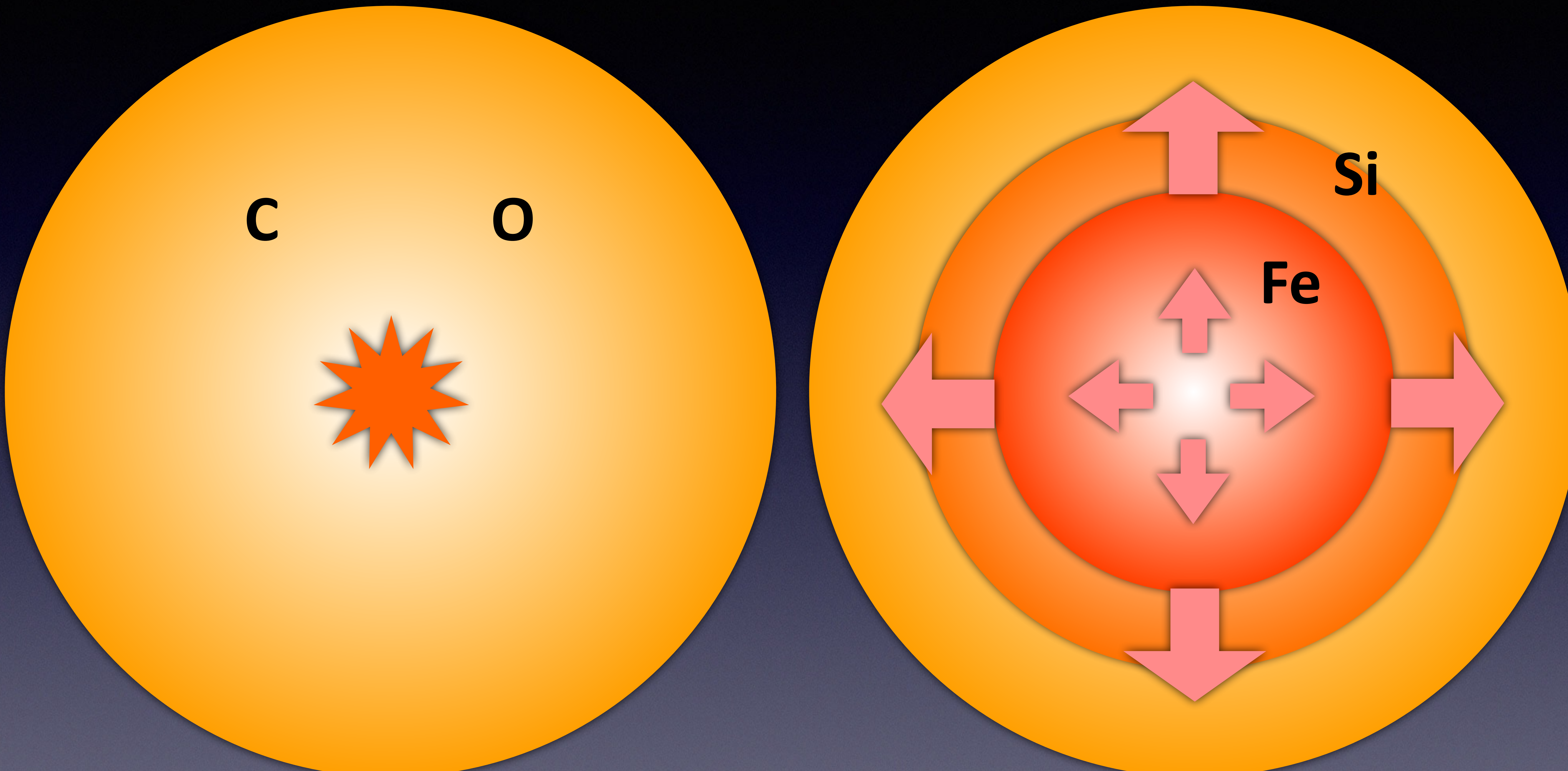
Images are not to scale

Binary system



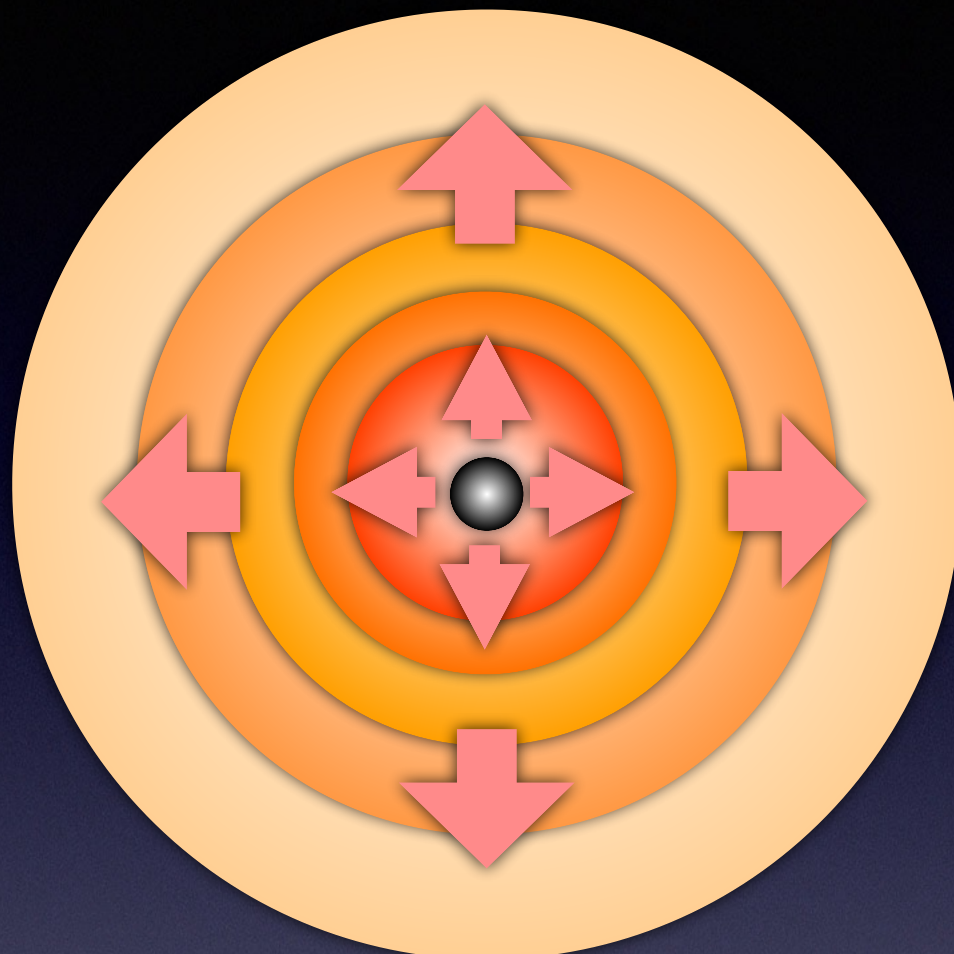
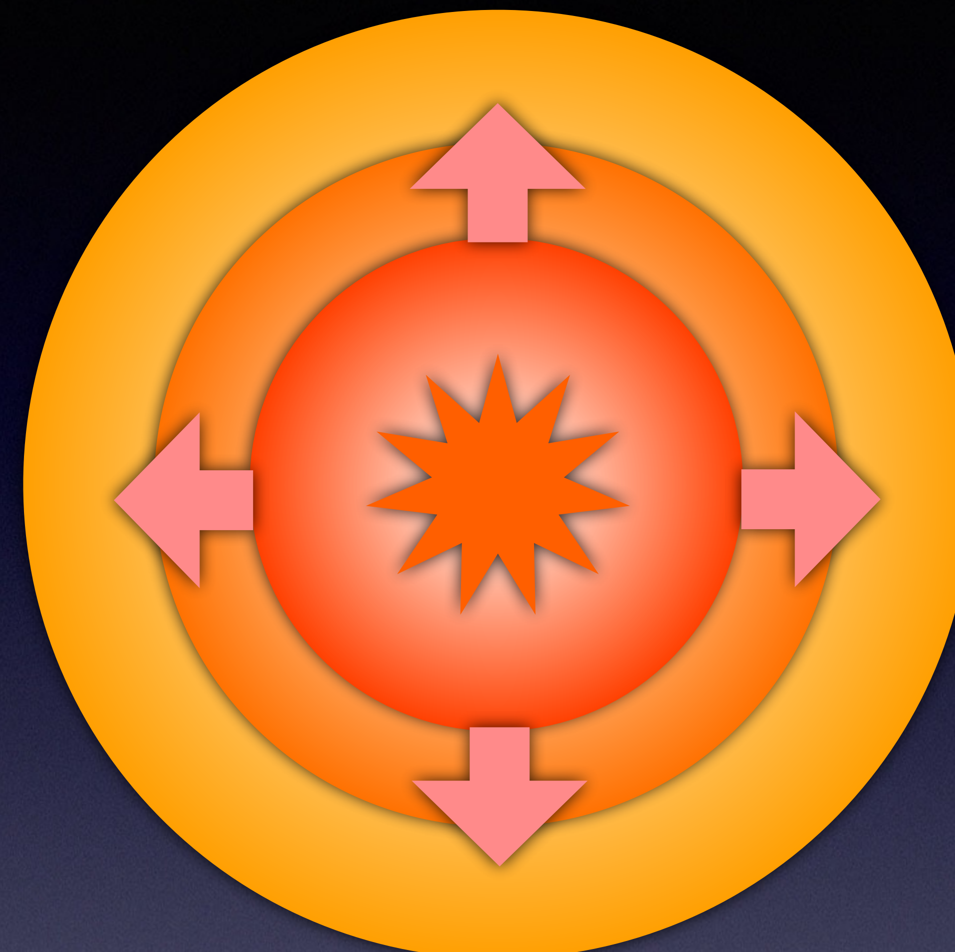
David A. Hardy

Thermonuclear explosion



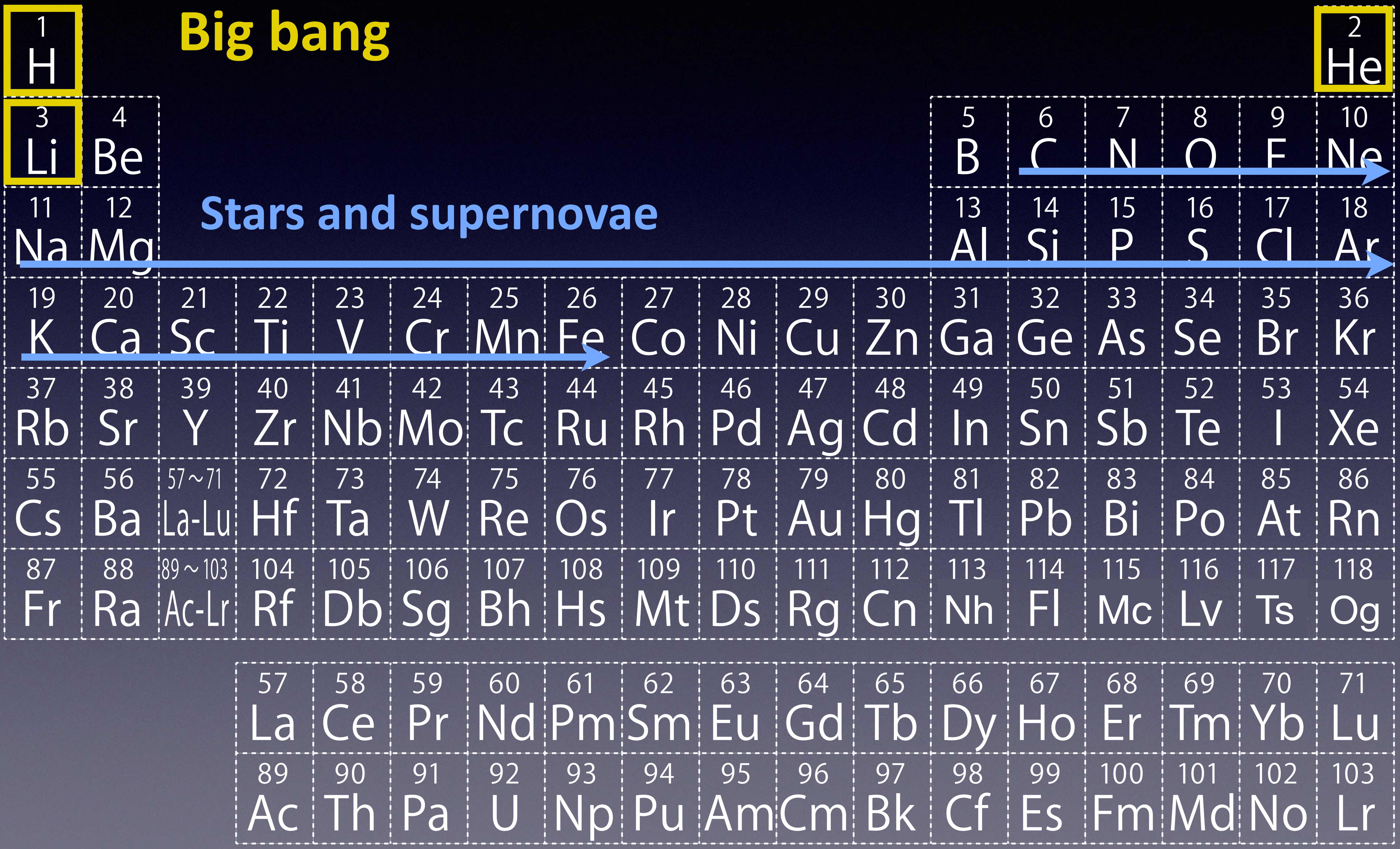
Supernova!

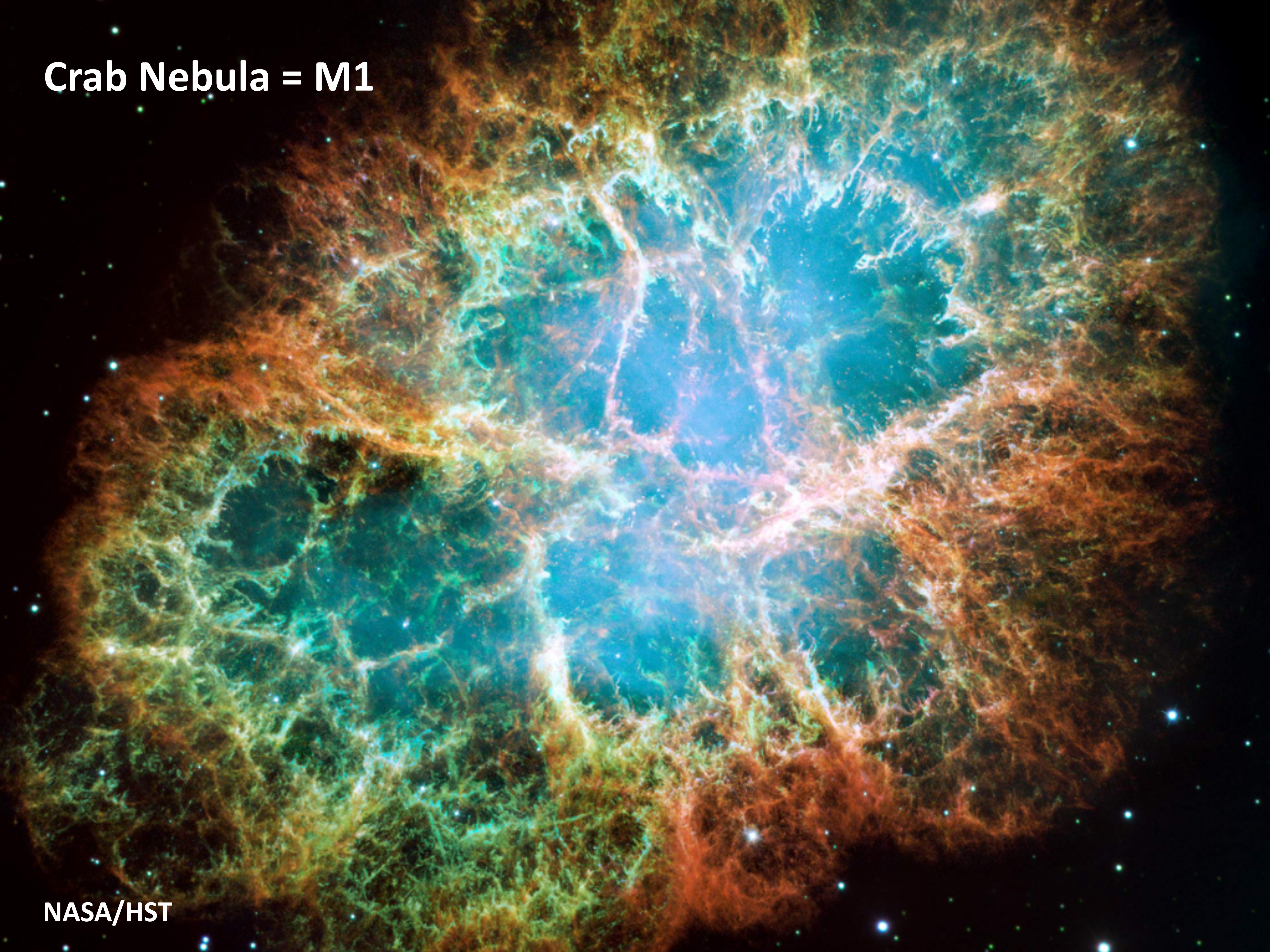
Why?? Normal stars do not explode with nuclear burning!

	Core-collapse SNe	Thermonuclear SNe
		
Progenitor	**Massive stars** Short lifetime	**Low-mass stars (in binary)** Long lifetime
Elements	**O, Mg, Ca, …** (progenitor star)	**Si, Ca, Fe, …** (explosion)

The elements around us are made by stars and SNe

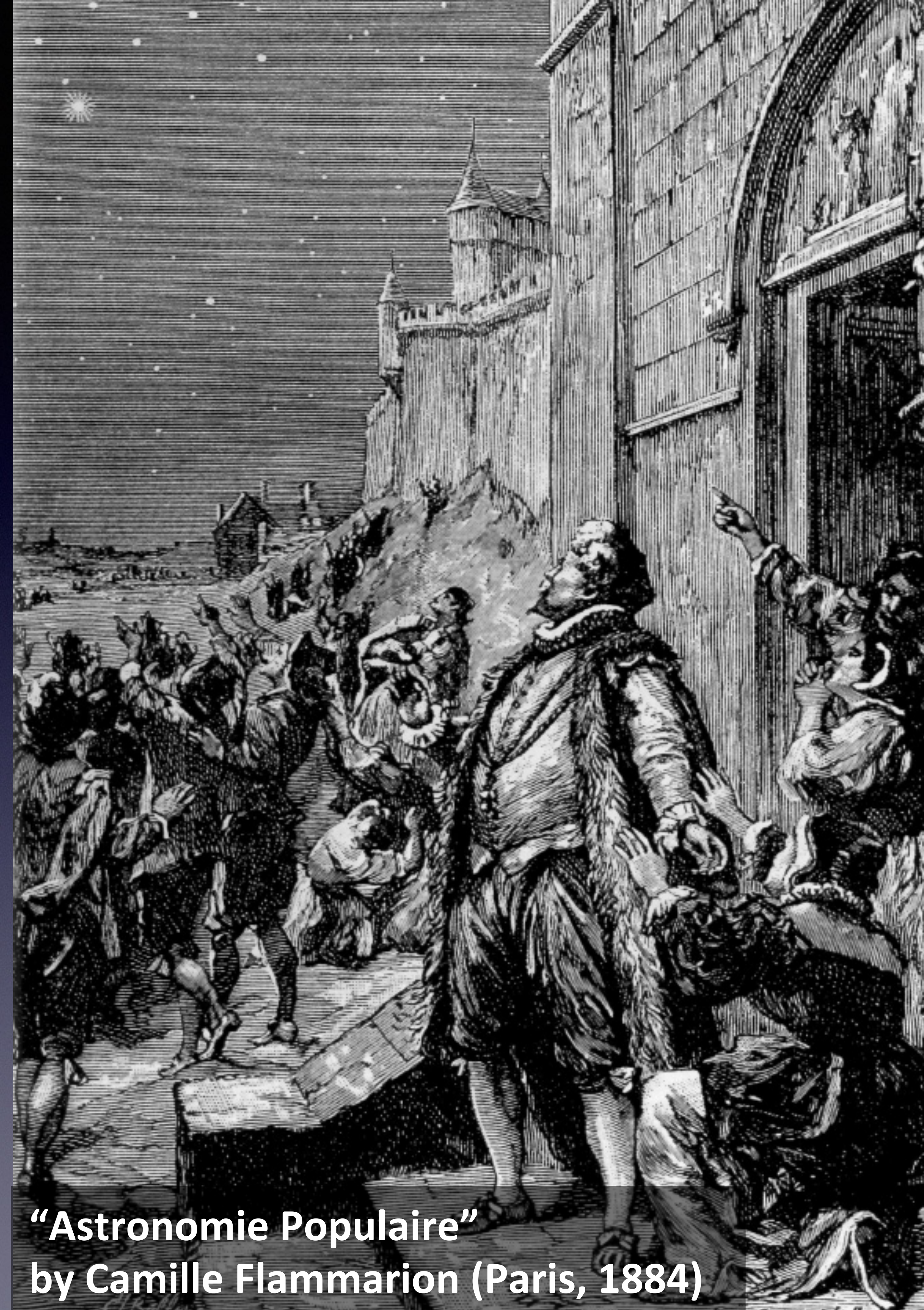
The origin of elements




Crab Nebula = M1
NASA/HST

1572
Tycho Brahe
“Stella Nova”

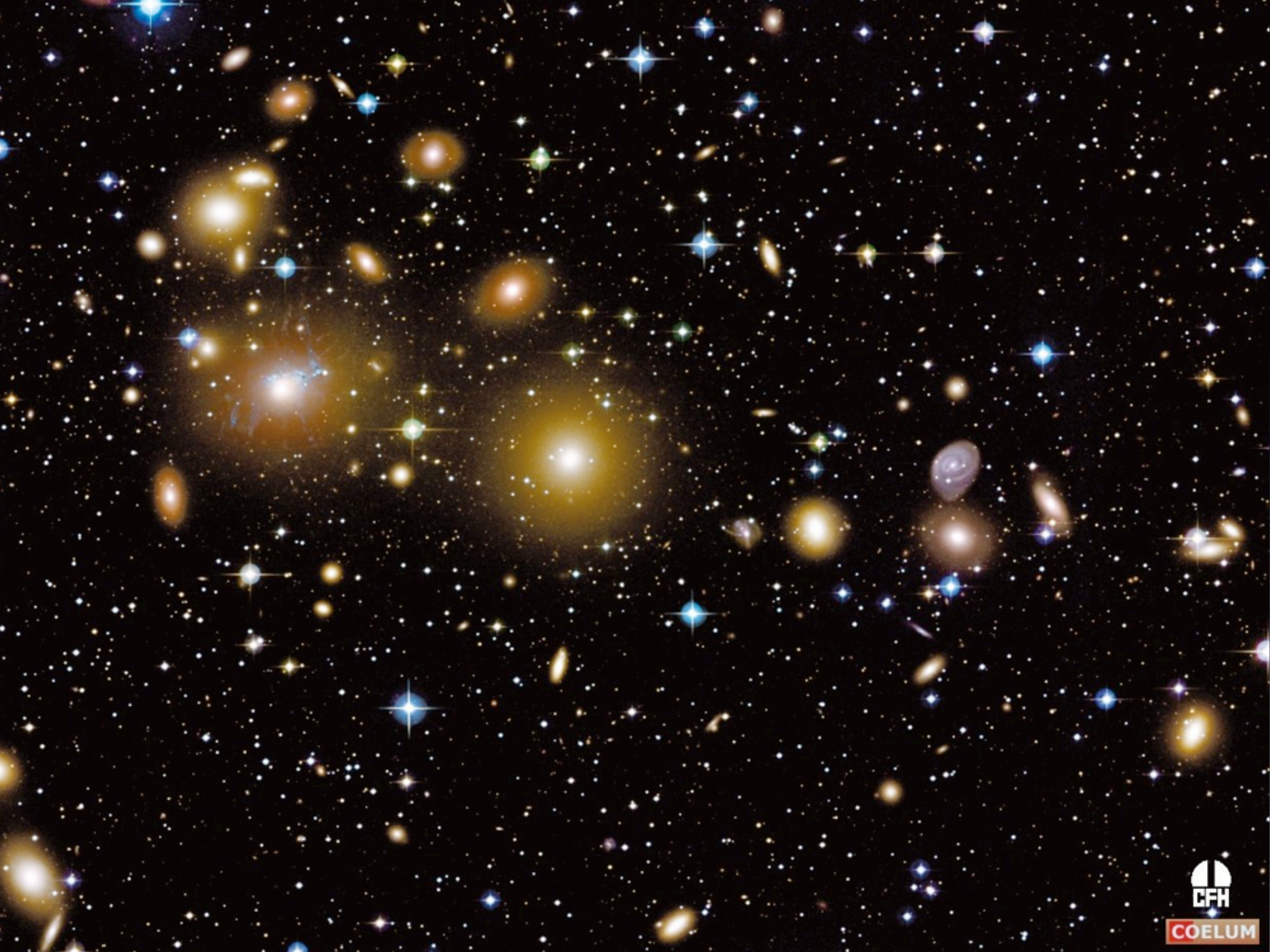
1604
Johannes Kepler

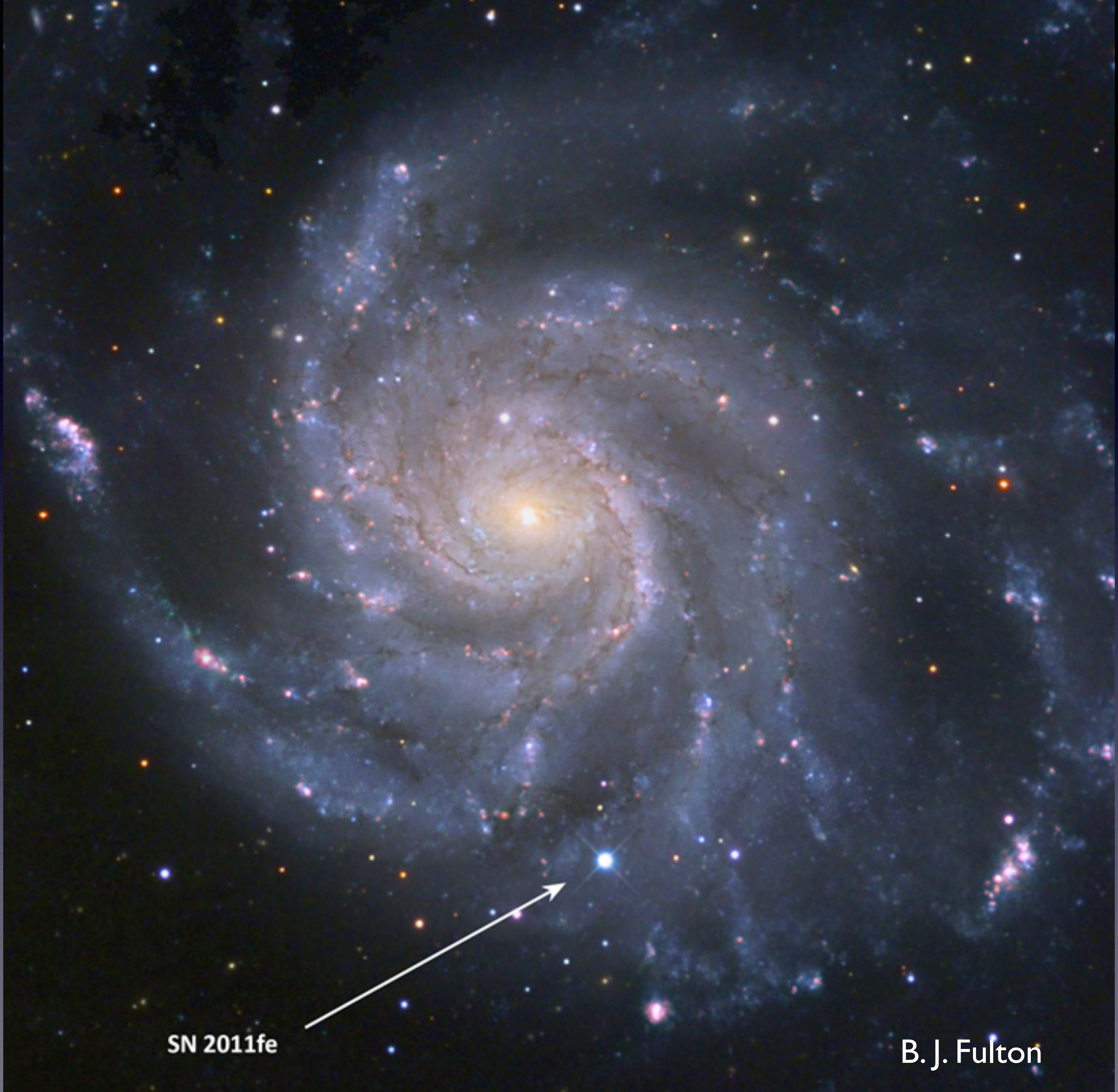

“Astronomie Populaire”
by Camille Flammarion (Paris, 1884)

Historical supernovae

Name	Location	Year	Magnitude
SN 185	Galactic	185	-8?
SN 1006	Galactic	1006	-9?
Crab	Galactic	1054	-4?
SN 1181	Galactic	1181	0
Tycho	Galactic	1572	-4
Kepler	Galactic	1604	-3
SN 1987A	LMC	1987	3

~ 1 supernova every 100-200 years

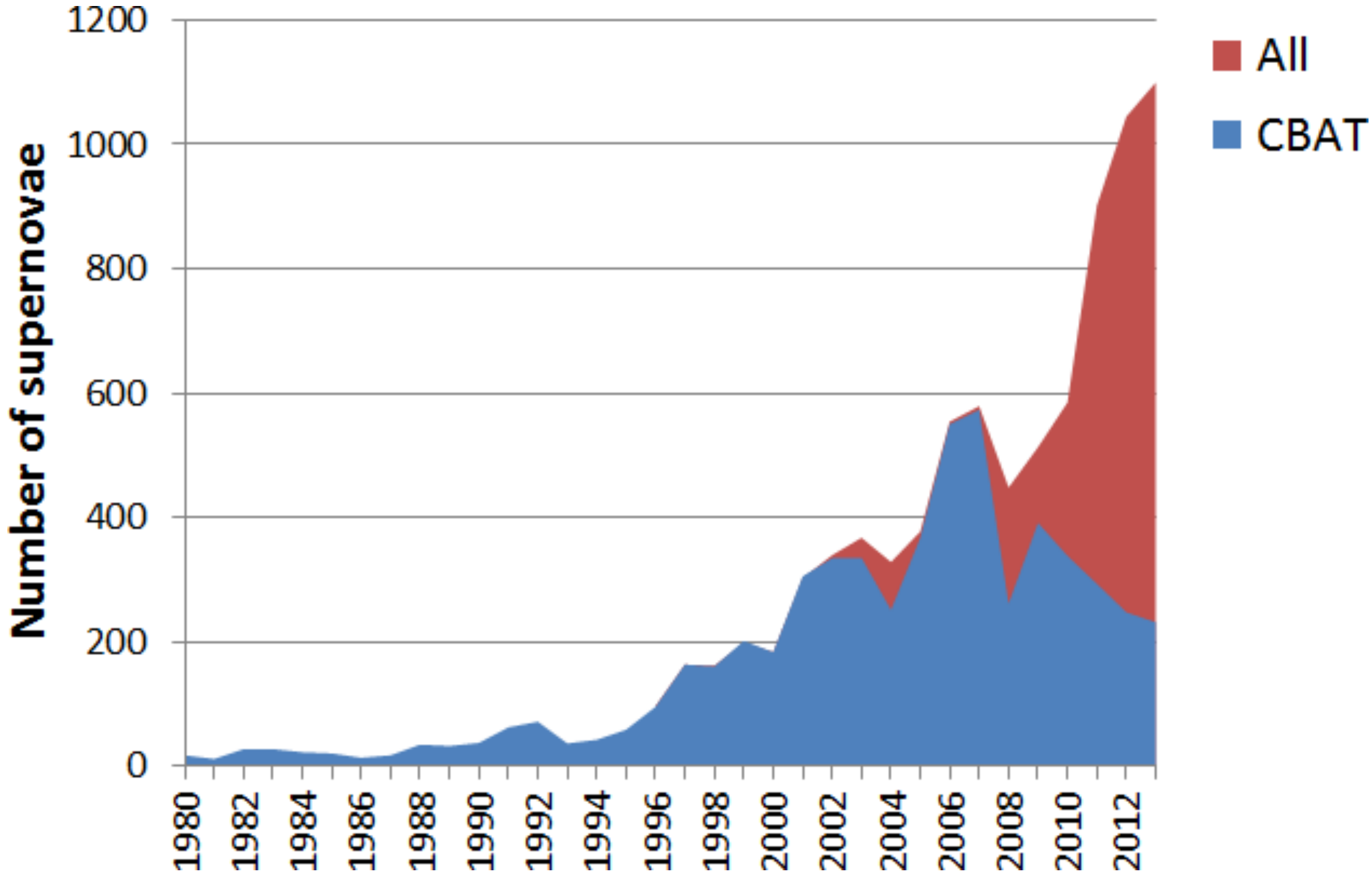

CFH
COELUM


SN 2011fe
B. J. Fulton


SN 2011dh
© Copyright 2011 Donald P. Waid
Margate, Florida

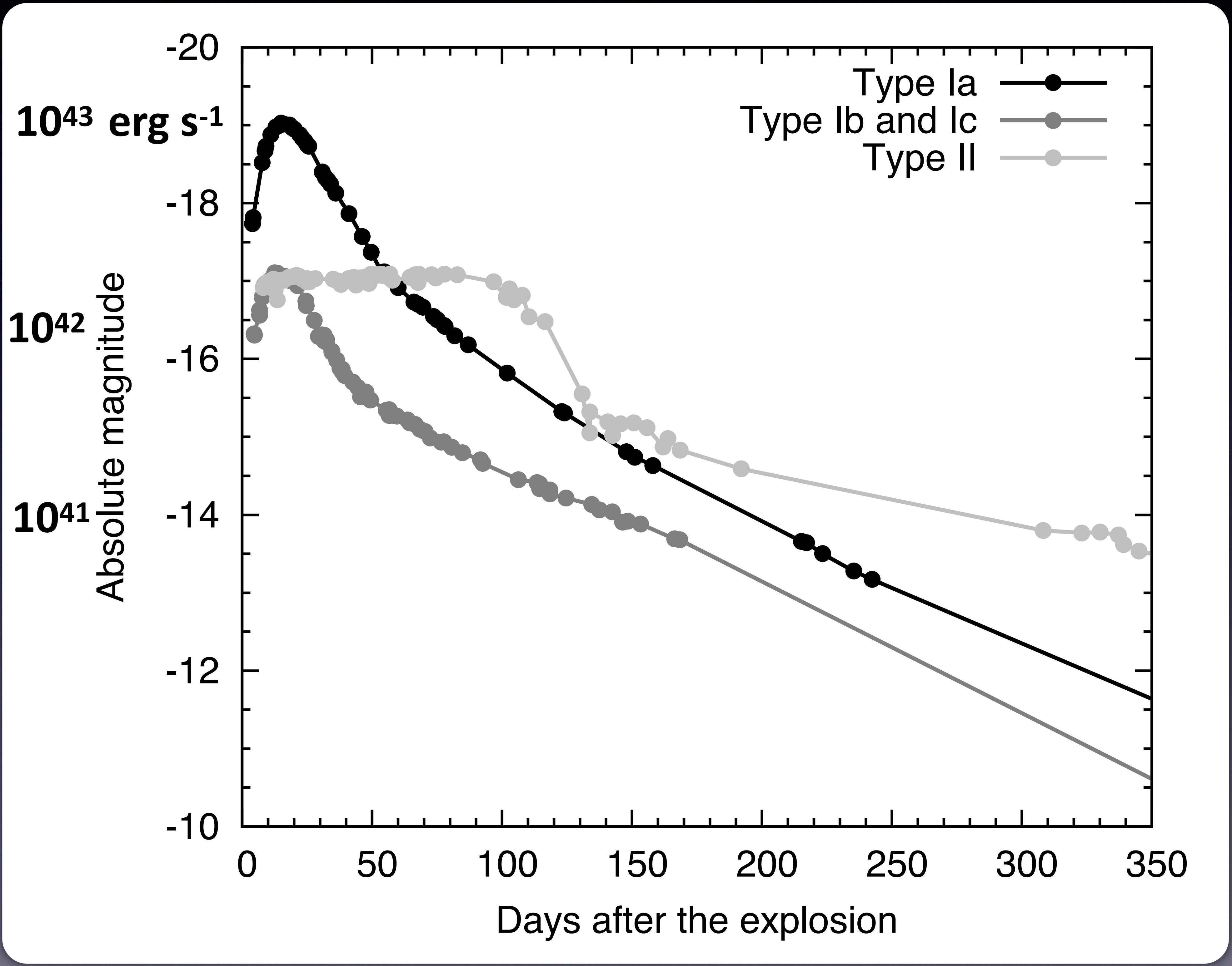

SDSS

History of SN discovery



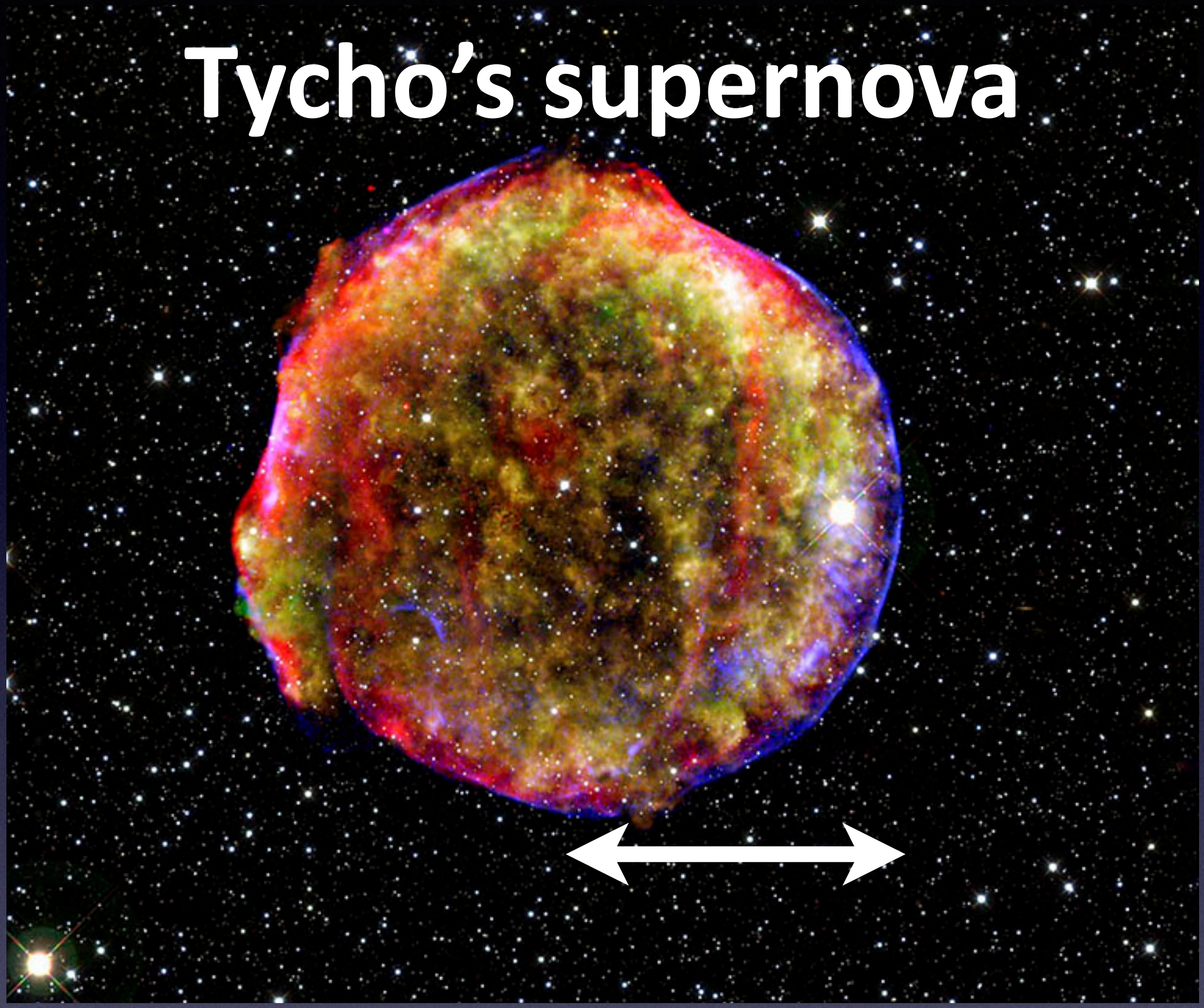
http://proftimobrien.com/2014/02/supernova-2014j-in-m82/

Light curve of supernovae
(brightness as a function of time)



Why so luminous??

Let's feel SN explosion



R ~ 10^{19} cm （10 light year ~3 pc）

Observed by Tycho Brahe in 1572
(Type Ia)

Q. What is the average Velocity of SN?

Velocity = Distance/time

Distance: 10^{19} cm

Time: ~400 years

Velocity = 10^{19} / ($400 \times 3 \times 10^{7}$)

~ 10^{9} cm/s ~ 10,000 km/s

10 light year = 10 year with light speed
SN takes 400 year to expand
Velocity = c/40= (300,000 km/s) / 40

~10,000 km/s !


10,000 km

Q. How large is the kinetic energy?

$$E = \frac{1}{2}Mv^2$$

Msun = 2×10^{33} g

Ekin = 1/2 x Mass x $(\text{Velocity})^2$

= 1/2 x (2×10^{33} g) x (10^9 cm/s)^2

~ 10^{51} erg

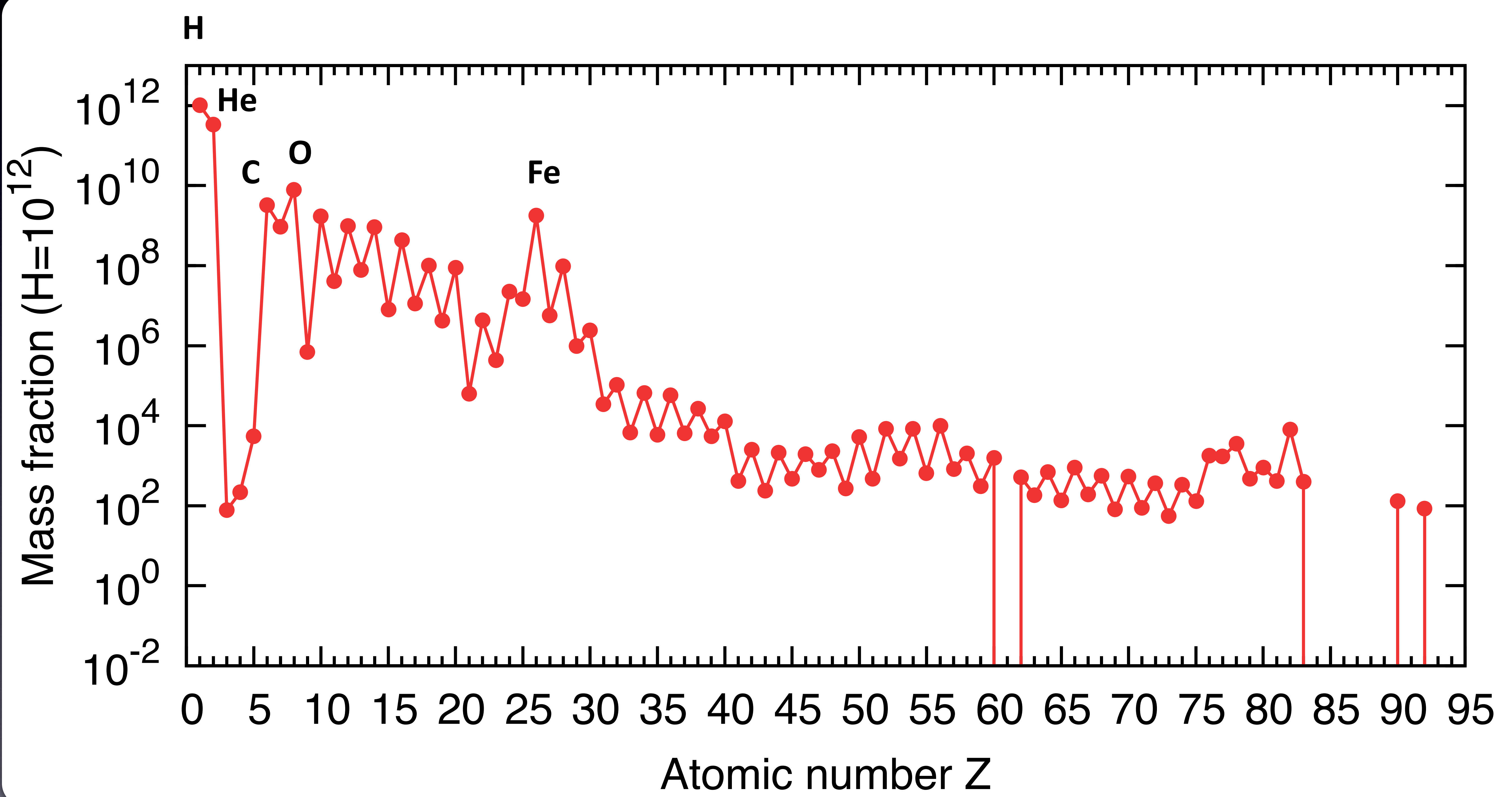
Where does this huge energy come from?

Section 1.
Overview: Life of stars, supernovae, and origin of the elements

1.1 Stellar lives and supernovae

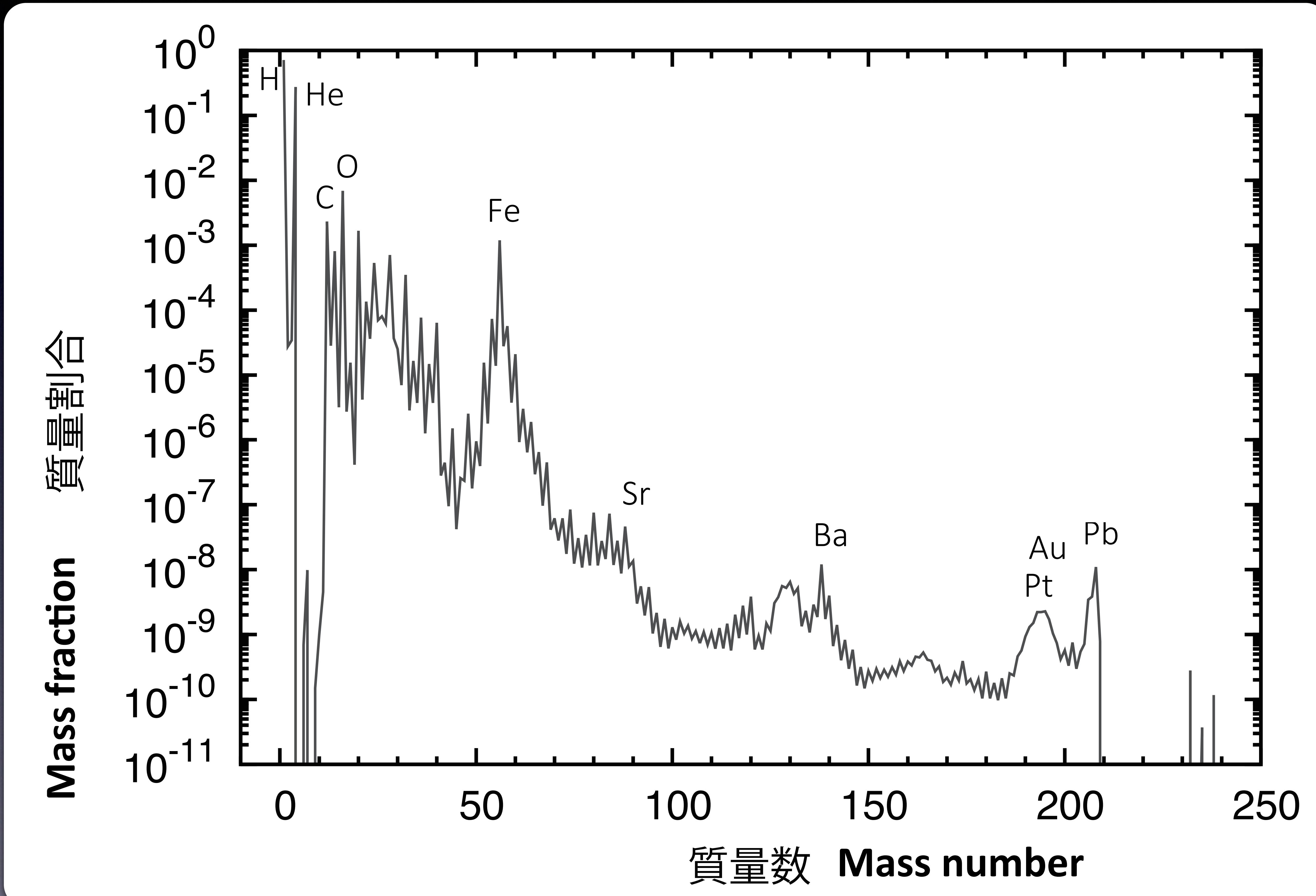
1.2 Origin of the elements

Cosmic abundances (atomic number)



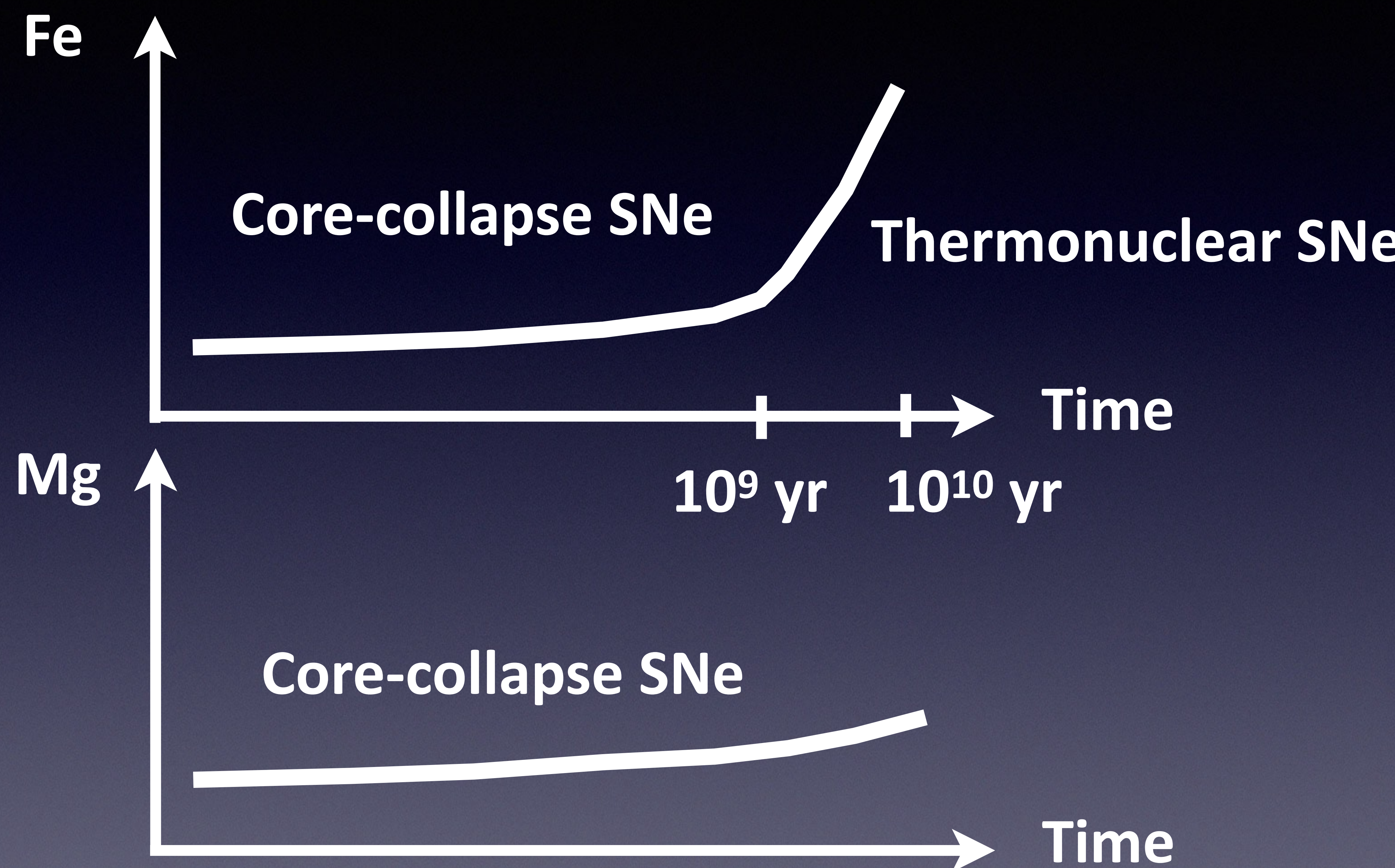
*Mass ratio

Cosmic abundance (mass number)



Our understanding about the nucleosynthesis is correct??

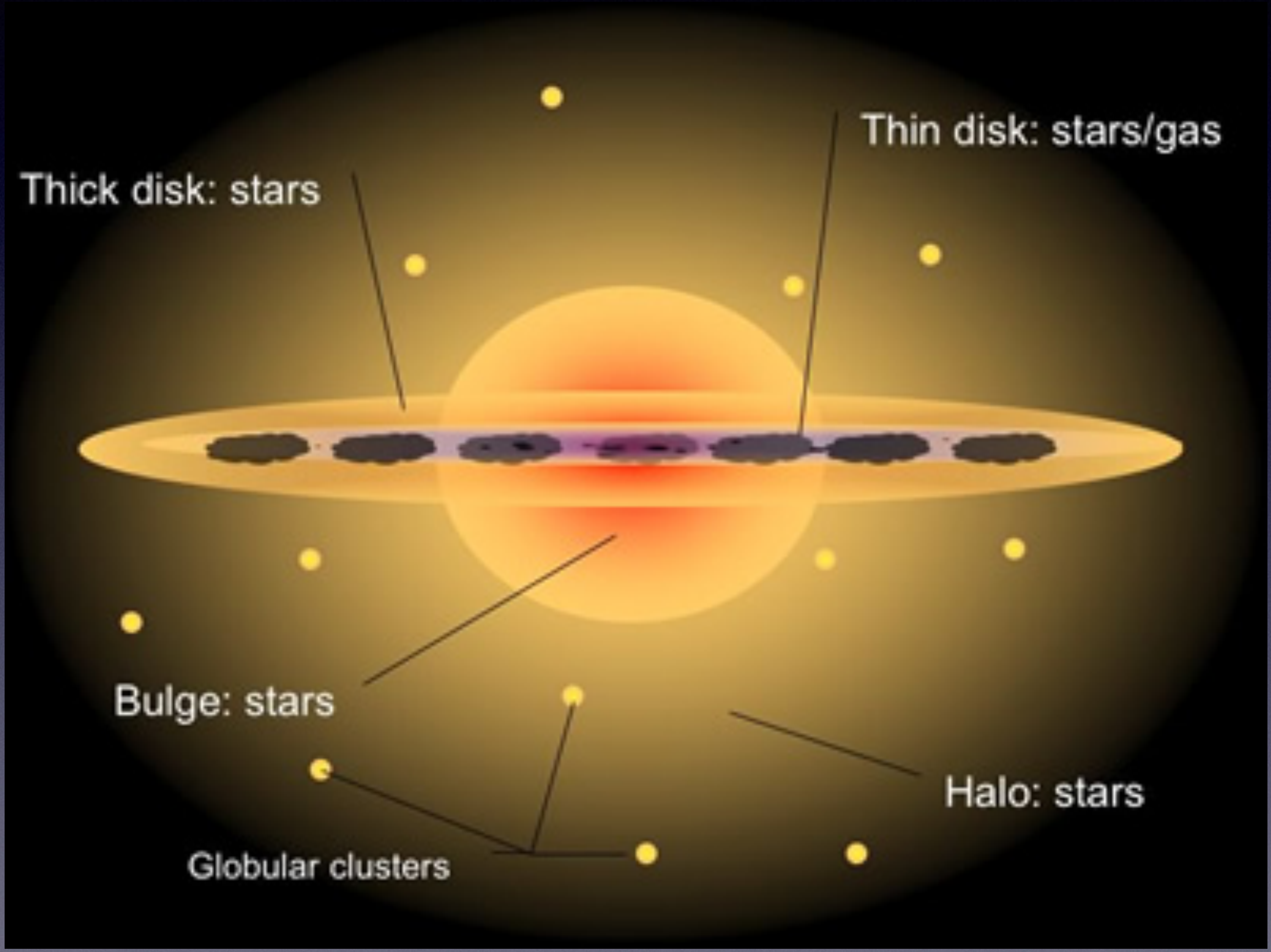
Chemical evolution of the Universe



Stars formed recently should have low Mg/Fe ratios

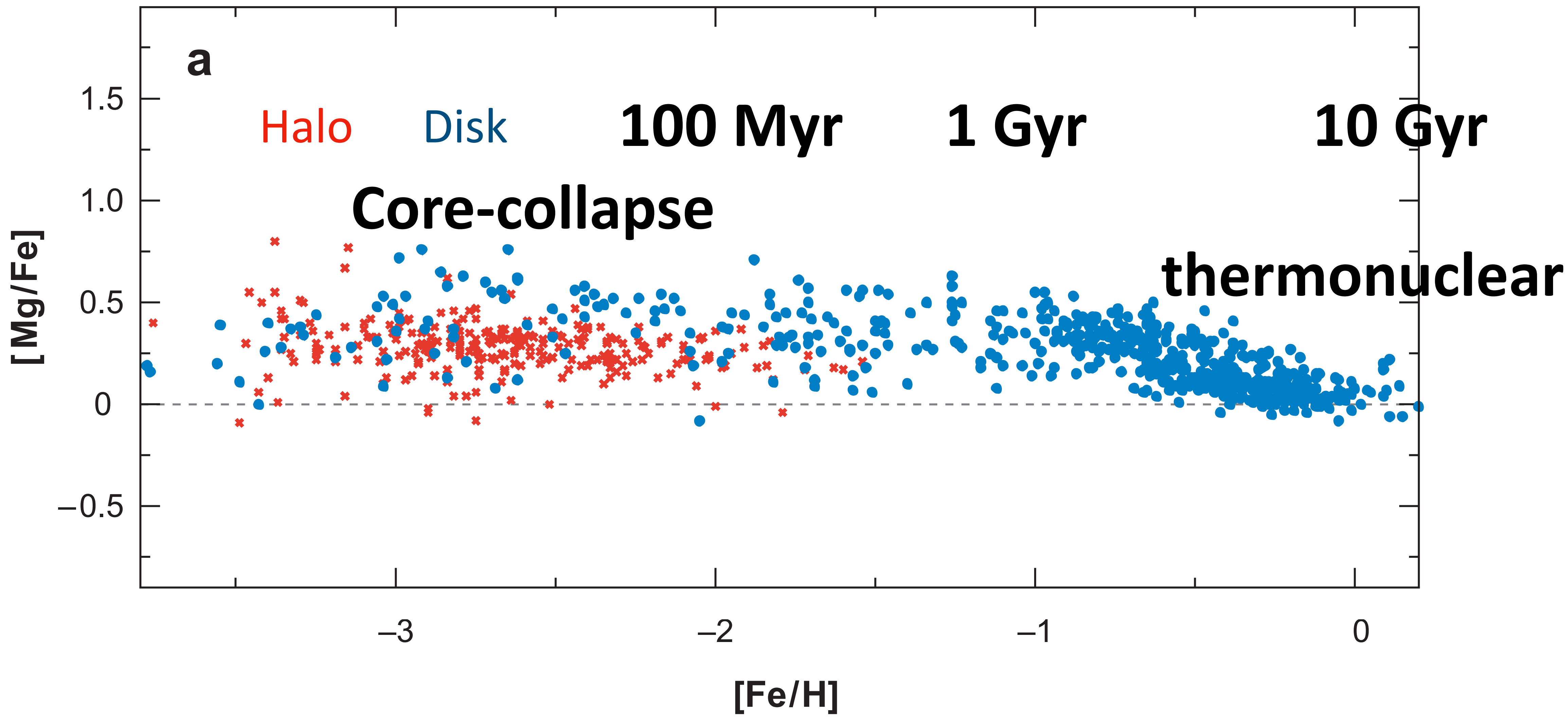
Our Galaxy

Stars keep information about nucleosynthesis in the past "Galactic archeology"



http://astronomy.swin.edu.au/cms/astro/cosmos/T/Thick+Disk

Abundance ratio in Galactic stars (Mg/Fe)



Sneden+08

Time

Longer delay time for Type Ia SNe

Summary

- **Stars synthesize heavy elements**
- **Stars evolve with time**
- **Core-collapse supernovae**
  - Origin of the elements such as Oxygen and Magnesium
- **Thermonuclear supernovae**
  - Origin of Fe-peak elements
- **Supernova explosions**
  - V ~ 10,000 km/s
  - Ekin ~10^{51} erg (10^{44} J) => Feedback to galaxy formation
- **Stellar nucleosynthesis is imprinted in Galactic stars**

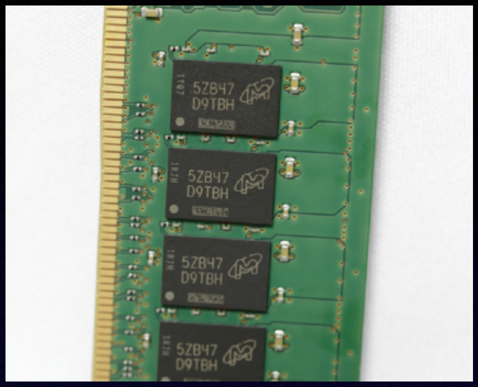
Let's **understand** these questions with the words of physics

Knowing ≒ Understanding

- Why are stars so luminous?
- Why do stars show $L \sim M^4$?
- Why do stars evolve?
- Why does the destiny of stars depend on the mass?
- Why do some stars explode?
- Why don't normal star explode?
- Why does stellar core collapses?
- Why is the energy of supernova so huge?
- ...

3 steps of learning

Short-term memory



1. Know
   Have information

<= Google is much better than we are!!

- L ~ M⁴

Long-term memory

2. Connect with other knowledge
   Integrate knowledge, put it in some contexts
   - Massive stars have shorter lifetime
   - Physics behind it (radiation energy/diffusion time)

3. Use the knowledge
   Apply to other cases
   - Use galaxy color as indicator of star formation
   - radiation energy/diffusion time => L vs M of other systems

=> understand

"make it stick - The Science of Successful Learning" Brown et al. 2016

Thermodynamics

Electromagnetism

Classical mechanics

Statistical mechanics

Astrophysics

Hydrodynamics

Quantum mechanics

Relativity

Nuclear physics