Physics of Stars I
恒星物理学特論 I

Masaomi Tanaka
田中 雅臣

Masaomi Tanaka (田中 雅臣)

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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

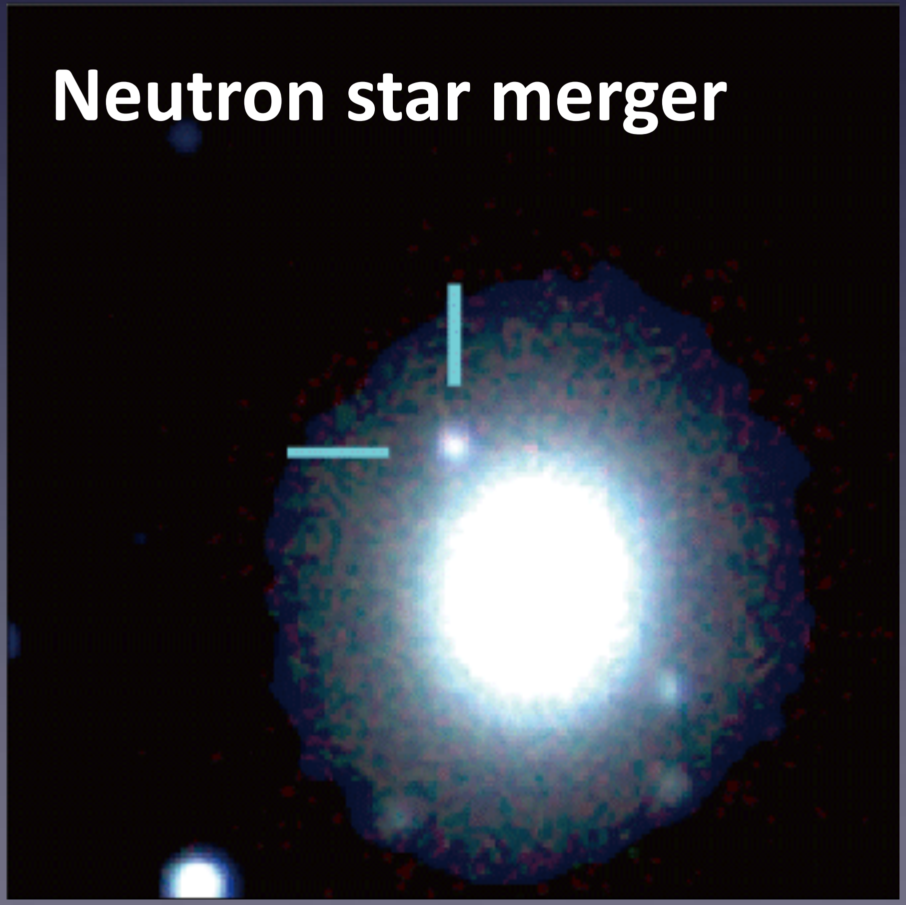
Research interests

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

Why do we study transients?

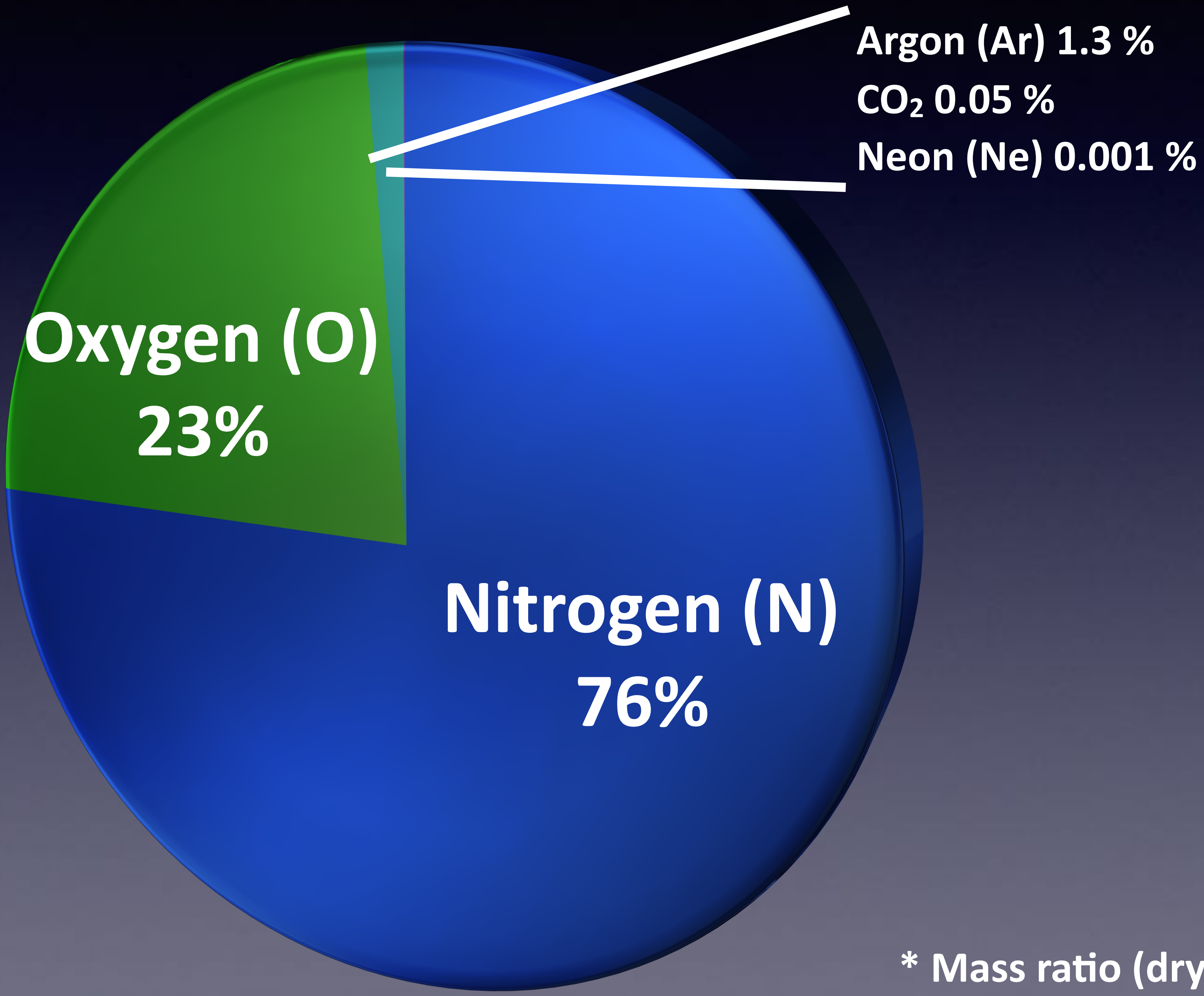
- Extreme physical condition
- End point of stellar evolution
- Origin of the elements
- Many unsolved mystery

"time-domain astronomy"



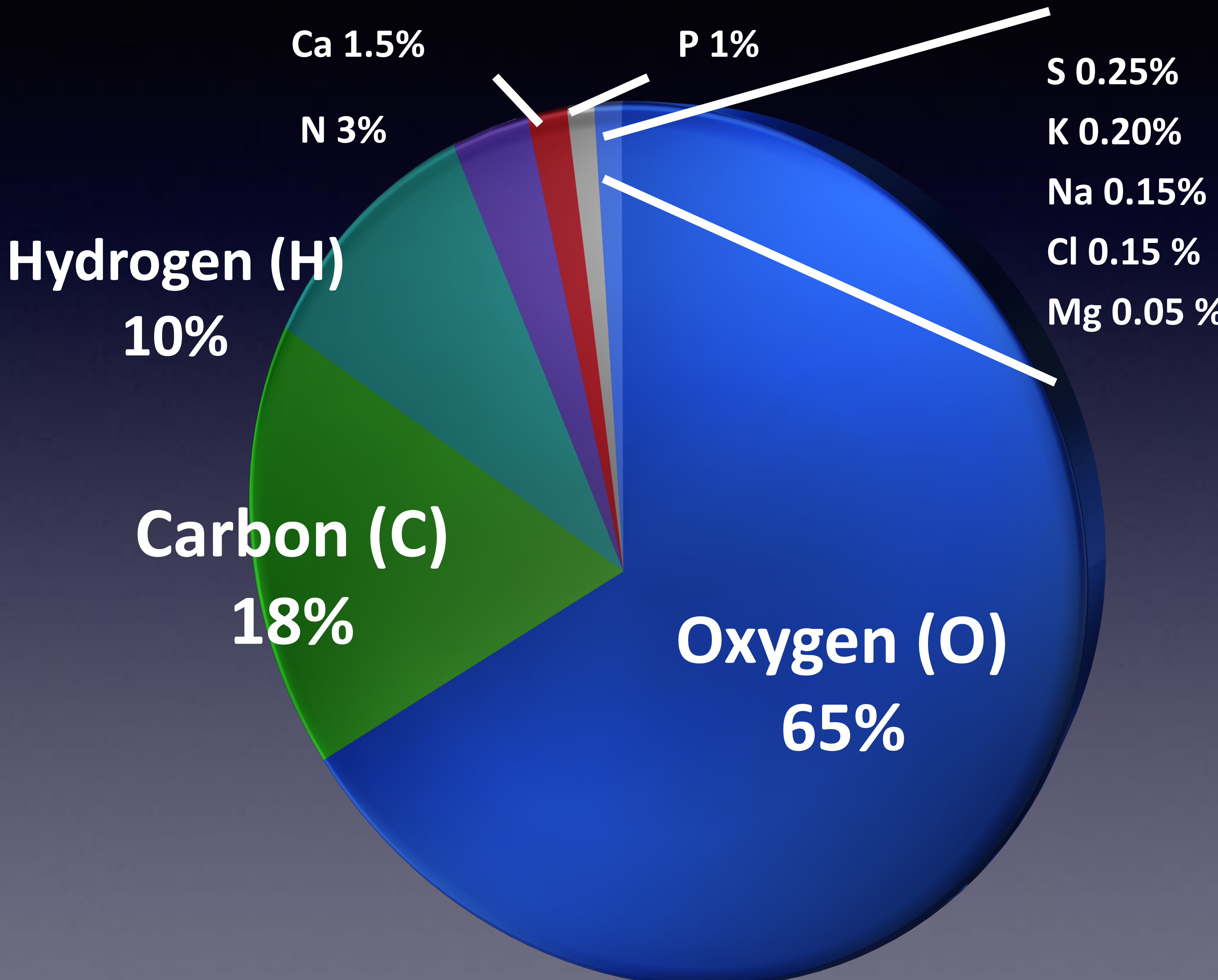
Elements around us

Air



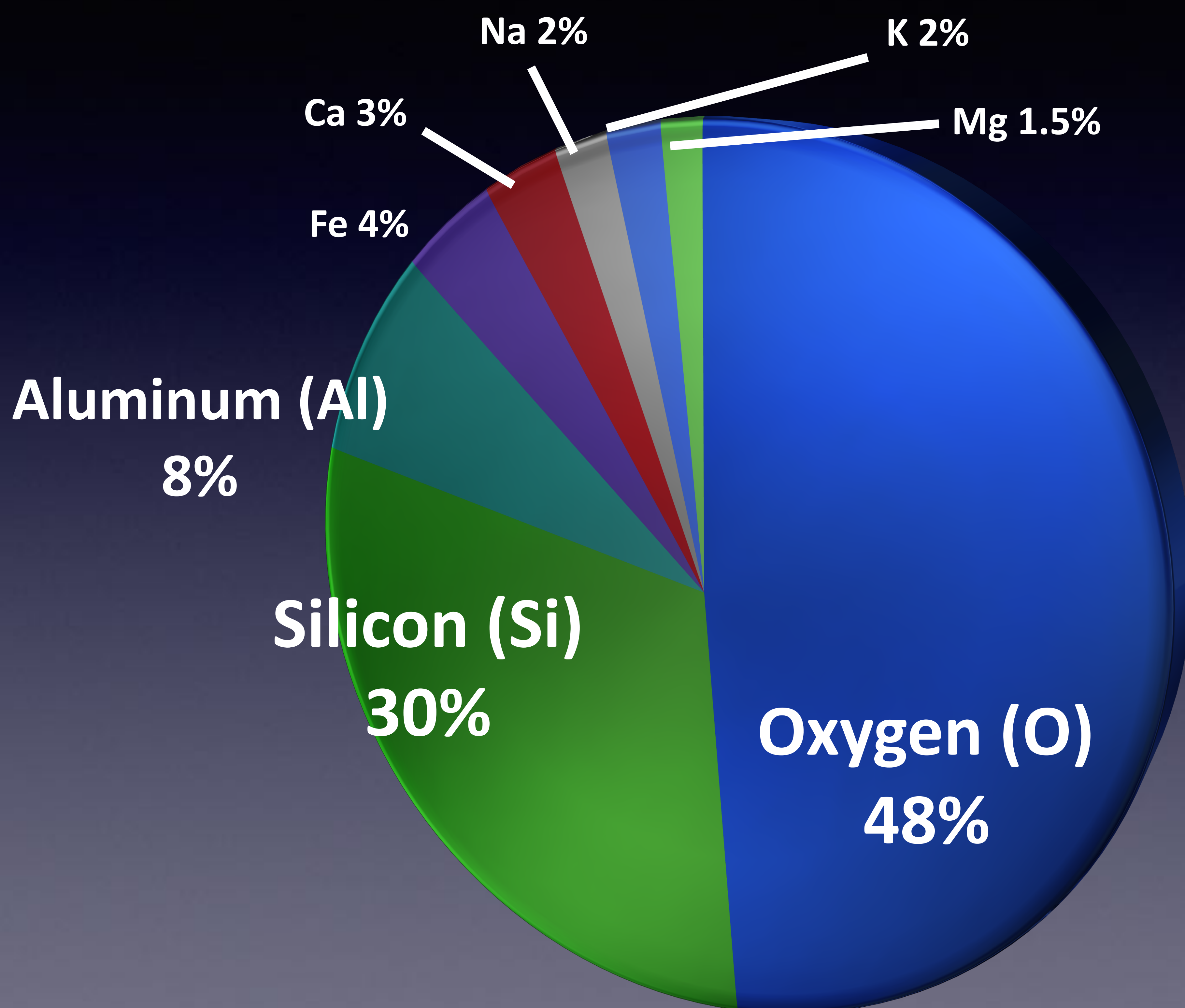
* Mass ratio (dry air)

Our body



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

The earth (crust)



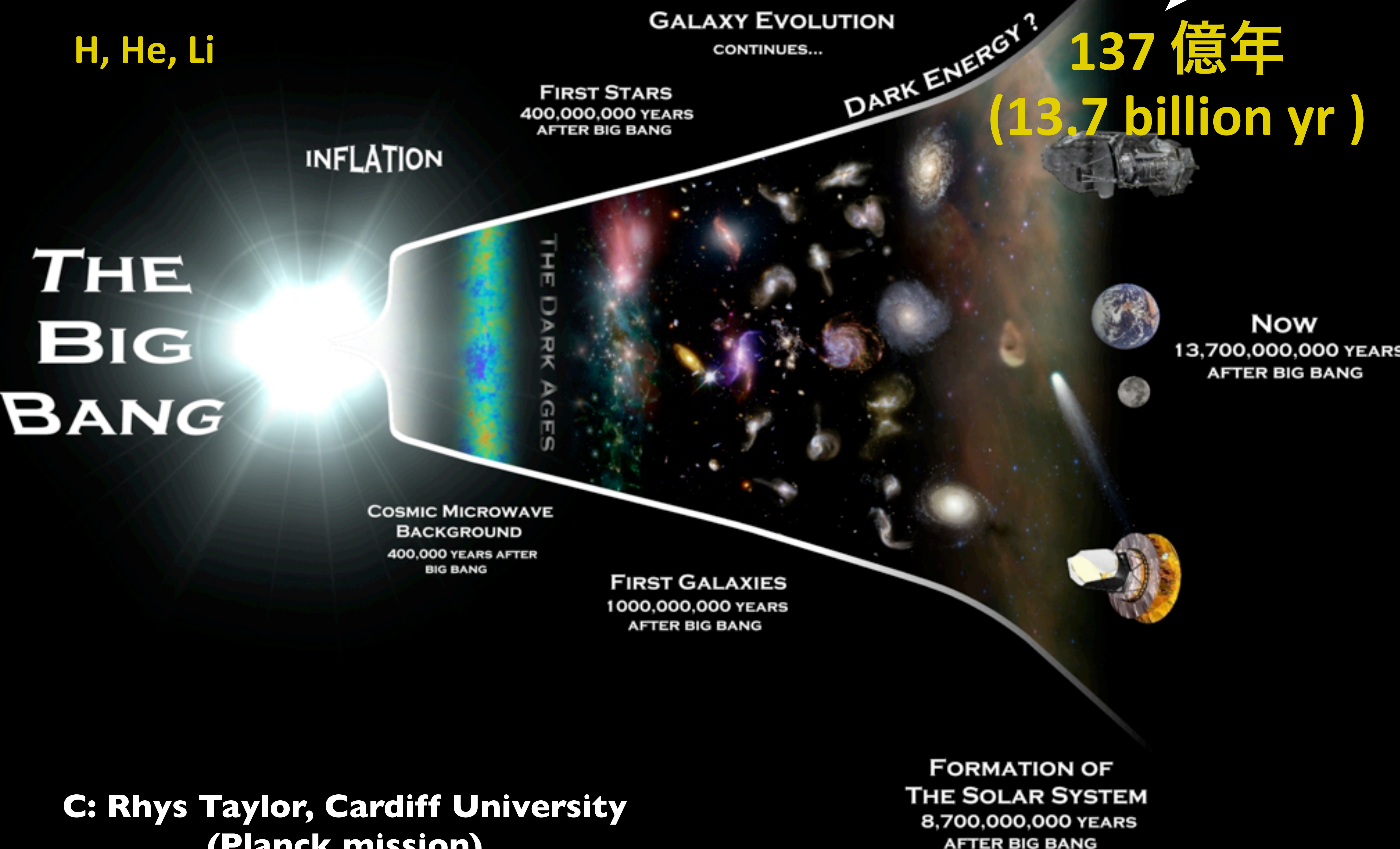
* Mass ratio

The beginning of the Universe

Now

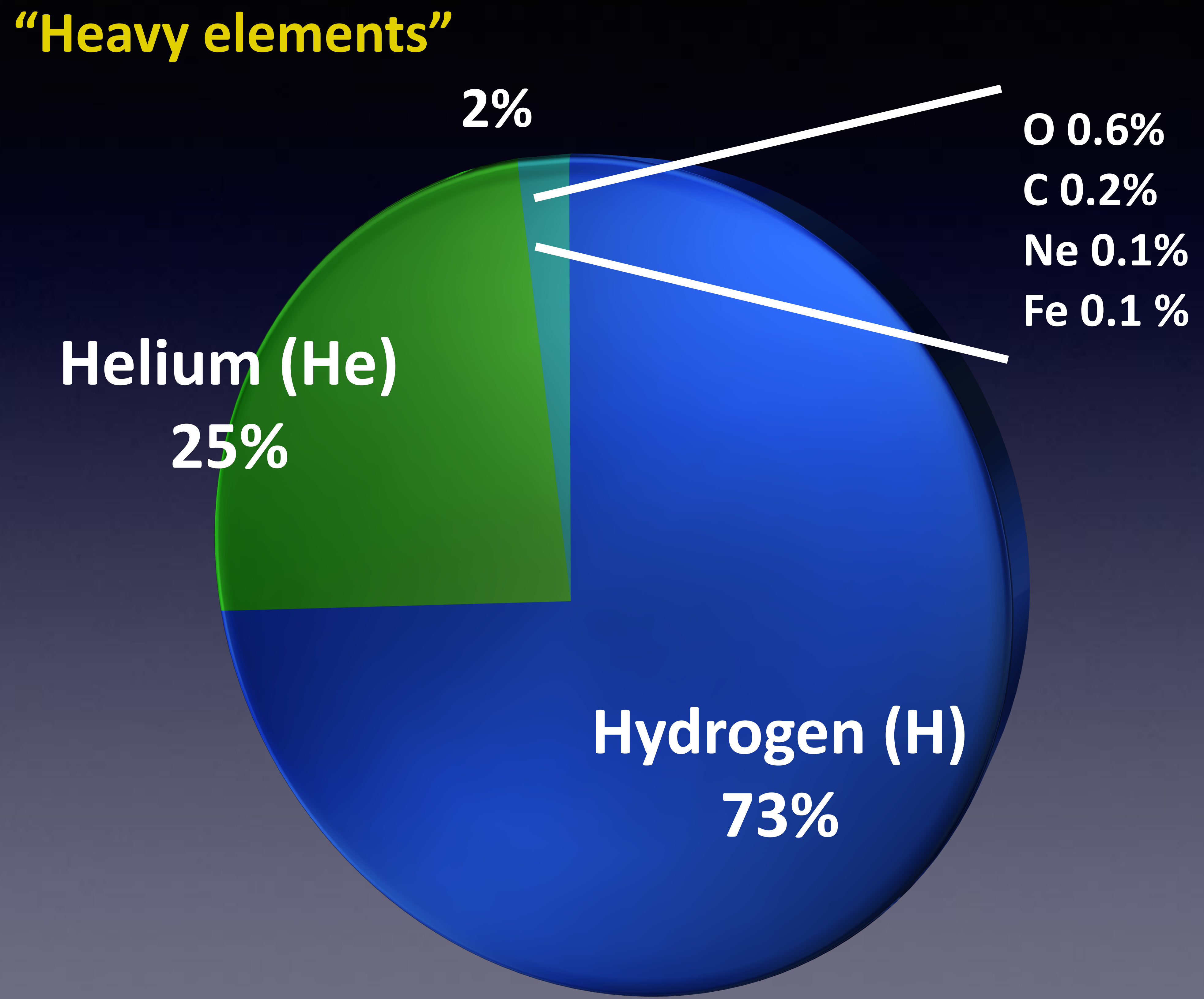
H, He, Li

137 億年 (13.7 billion yr)



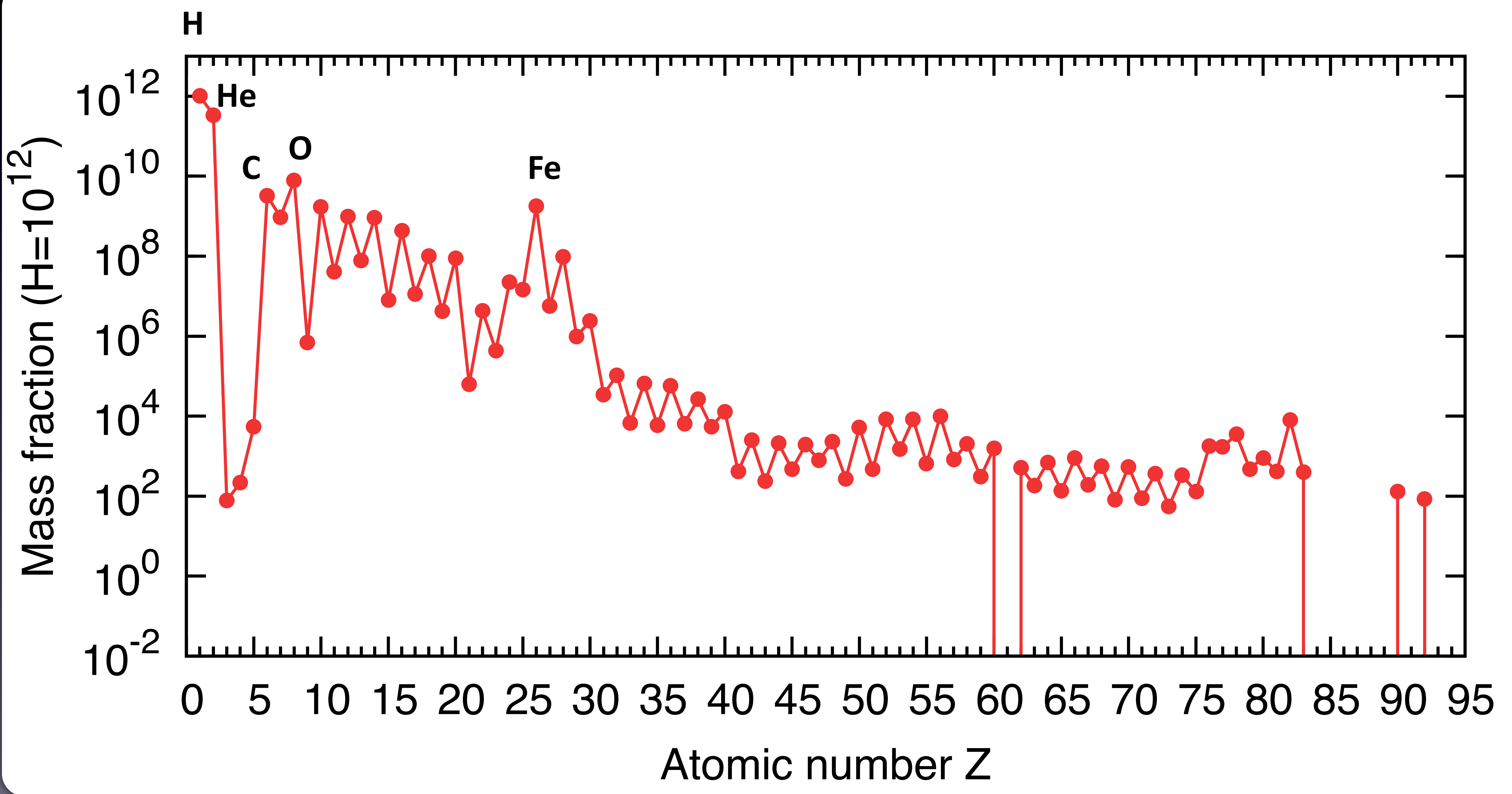
C: Rhys Taylor, Cardiff University (Planck mission)

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/tohoku2020

Contents

* ~70% blackboard
  ~30% slides

- Overview
- Stellar structure and properties
- Stellar evolution
- Thermonuclear supernovae
- Core-collapse supernovae
- Radiation from supernovae
- Time-domain astronomy
- Neutron star merger and multi-messenger astronomy
- 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)
  - You can use "chat" window
- **Please relax and enjoy**
  - You can bring coffee/tea or chocolates/cookies, …

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

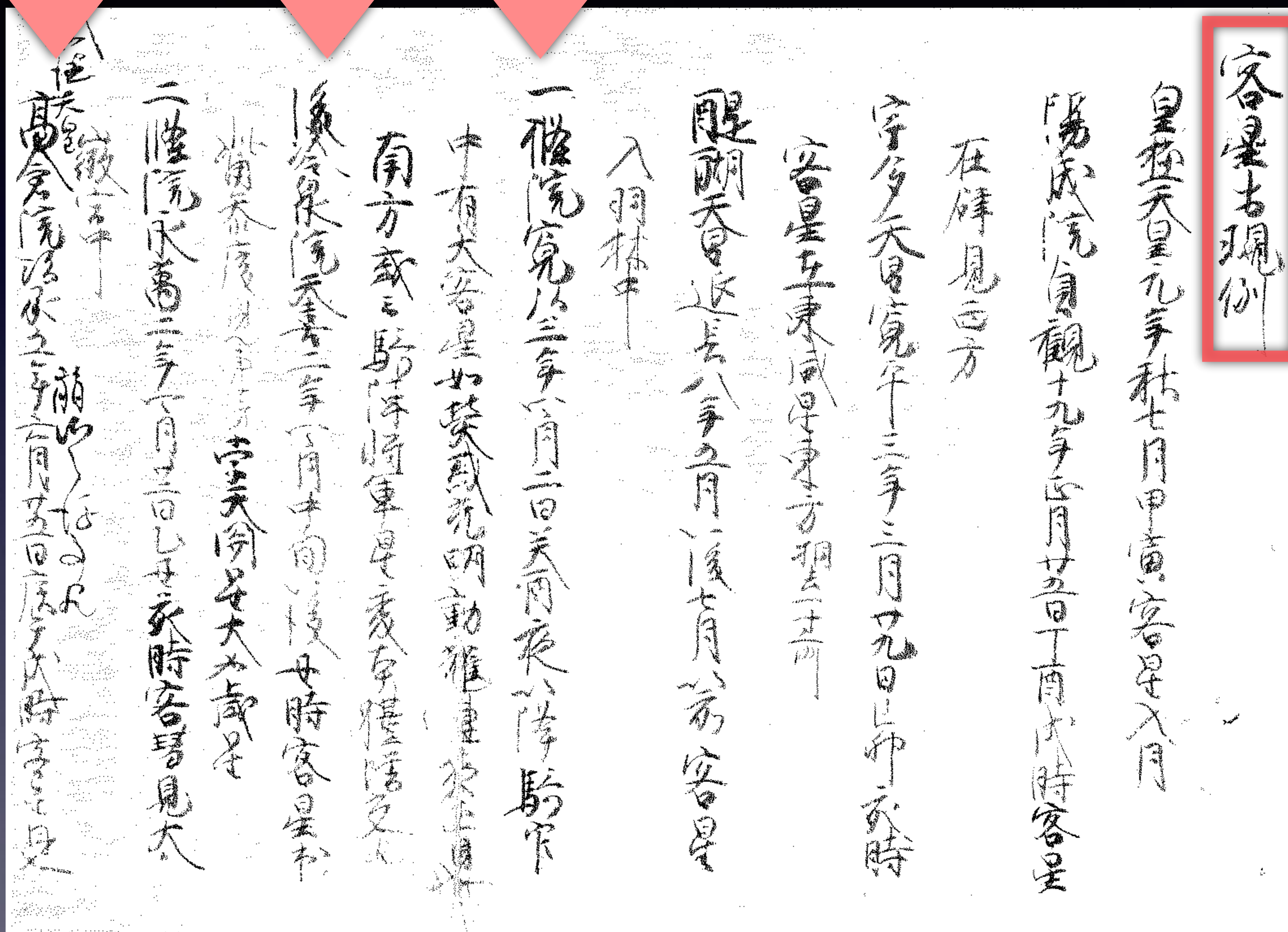
1.1 Stellar lives and supernovae

1.2 Origin of the elements

明月記

Guest stars
客星古現例

1181　1054　1006

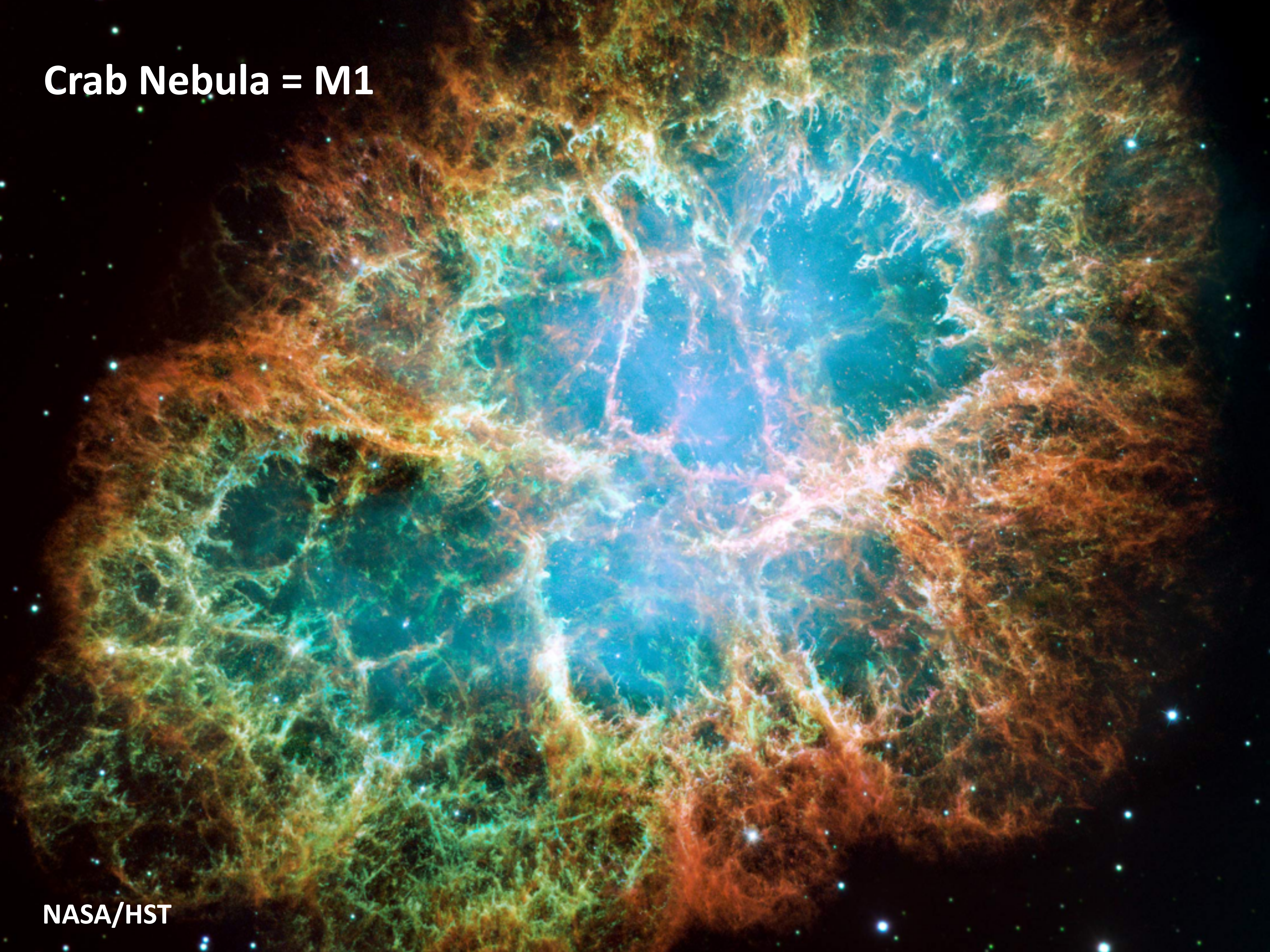

客星古現例
皇極天皇元年秋七月甲寅客星入月
陽成院貞観十九年正月廿五日丁酉戌時客星
在壁見西方
宇多天皇寛平三年三月廿九日己卯戌時
客星在東咸星東方相去一寸許
醍醐天皇延長八年五月以後七月以前客星
入羽林中
一條院寛弘三年四月二日癸酉夜以降騎官
中有大客星如熒惑光明動耀連夜正見南方
或云騎陣将軍星変本体増光歟
後冷泉院天喜二年四月中旬以後丑時客星出
觜参度見東方孛天関星大如歳星
二條院永萬二年五月三日乙丑戌時客星見大
高倉院治承五年六月廿五日庚午戌時客星見

冷泉家時雨亭叢書

フェリス女学院大学蔵
『新三十六歌仙画帖』

A guest star appeared
and it shined as Mars on May 1st in 1006.

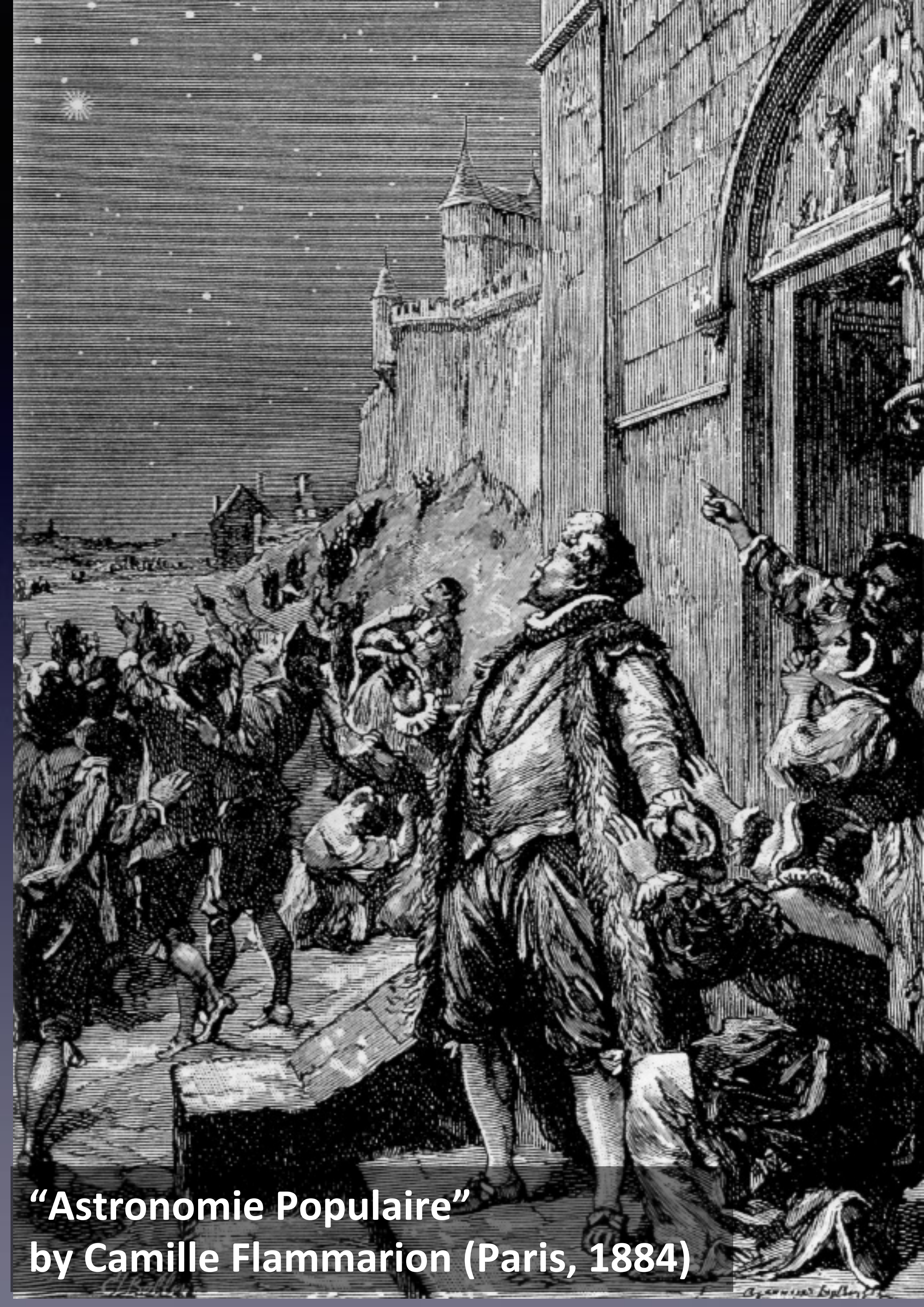
Crab Nebula = M1



NASA/HST

1572
Tycho Brahe
"Stella Nova"

1604
Johannes Kepler

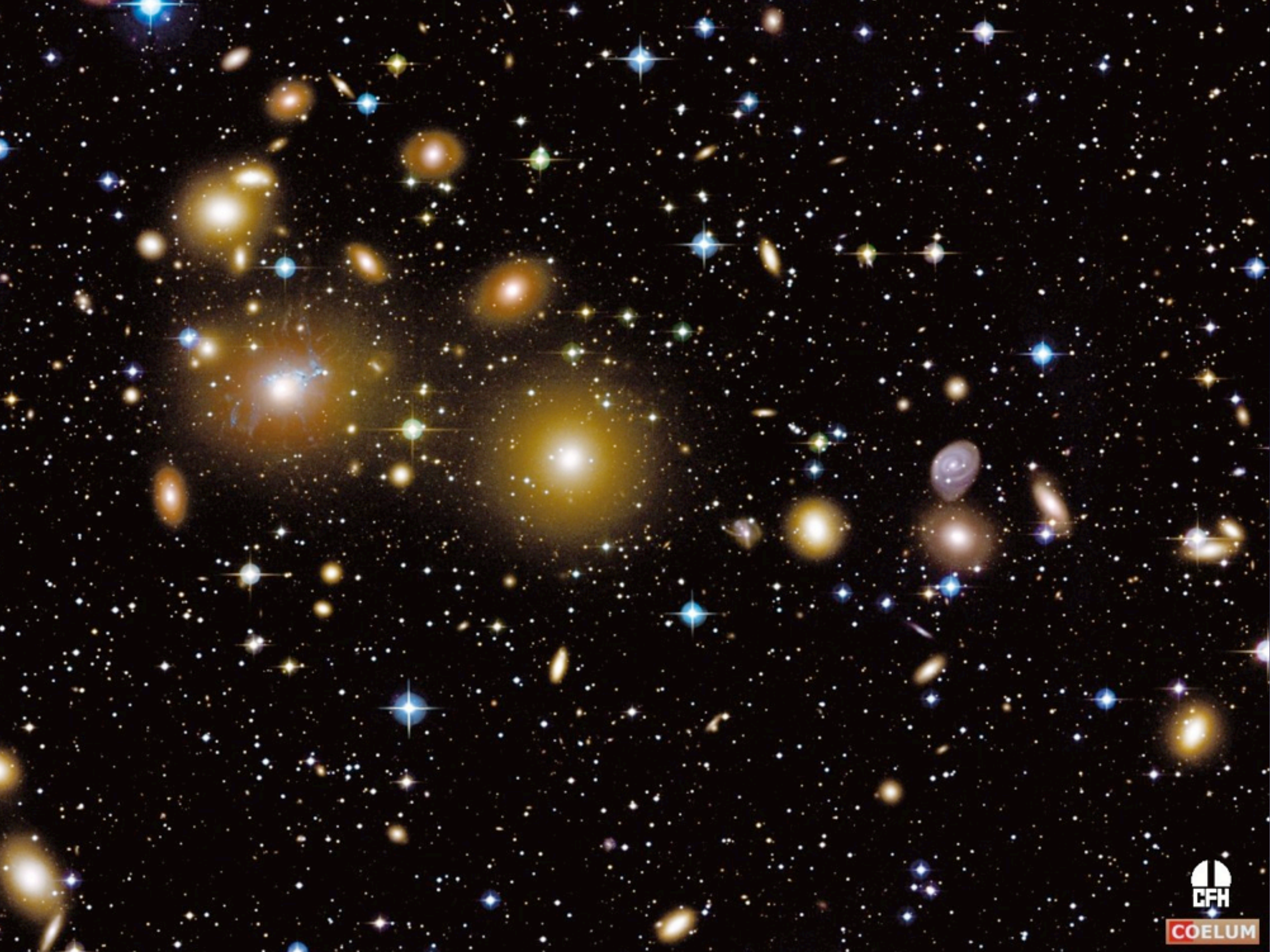


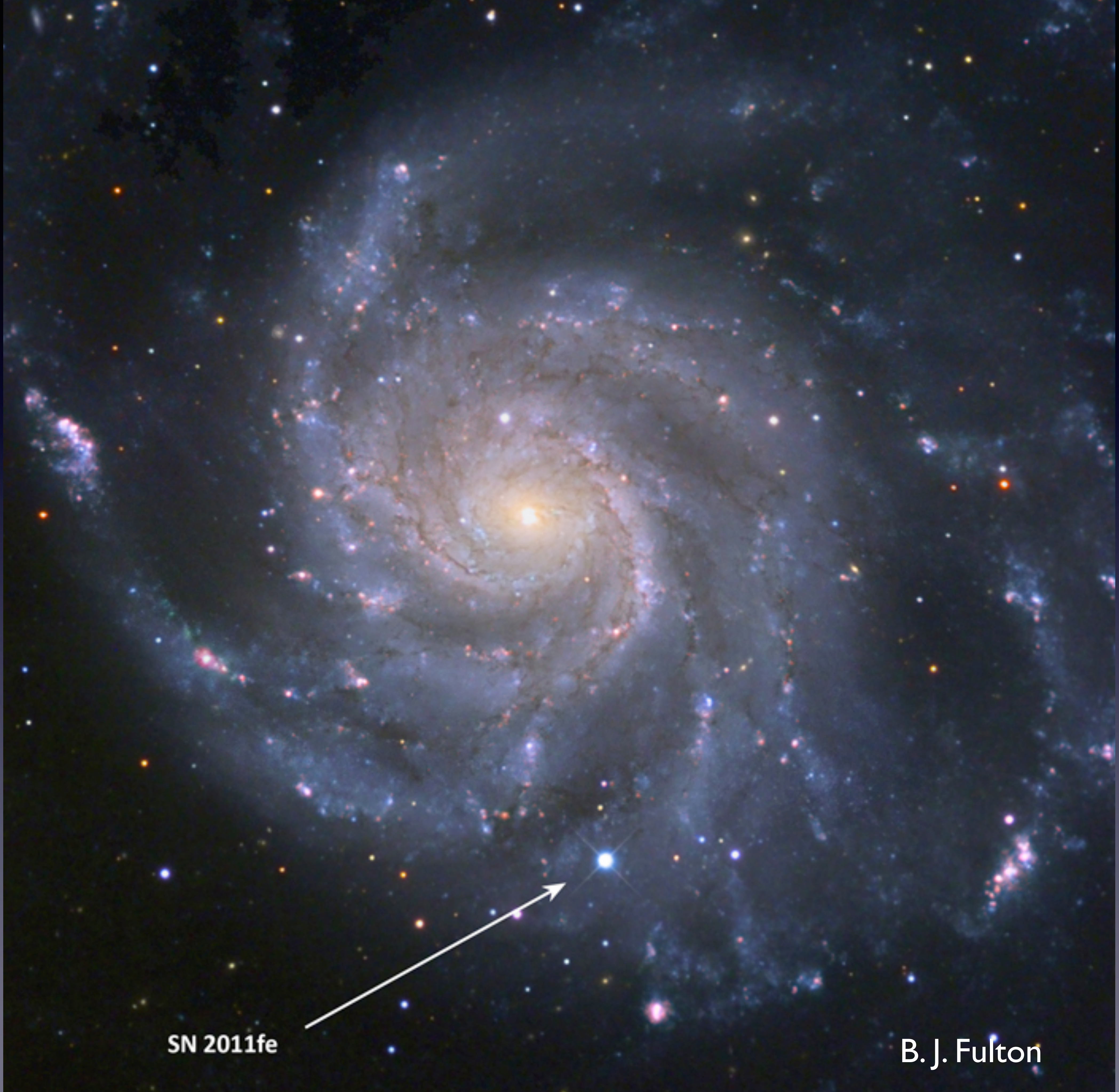
"Astronomie Populaire"
by Camille Flammarion (Paris, 1884)

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

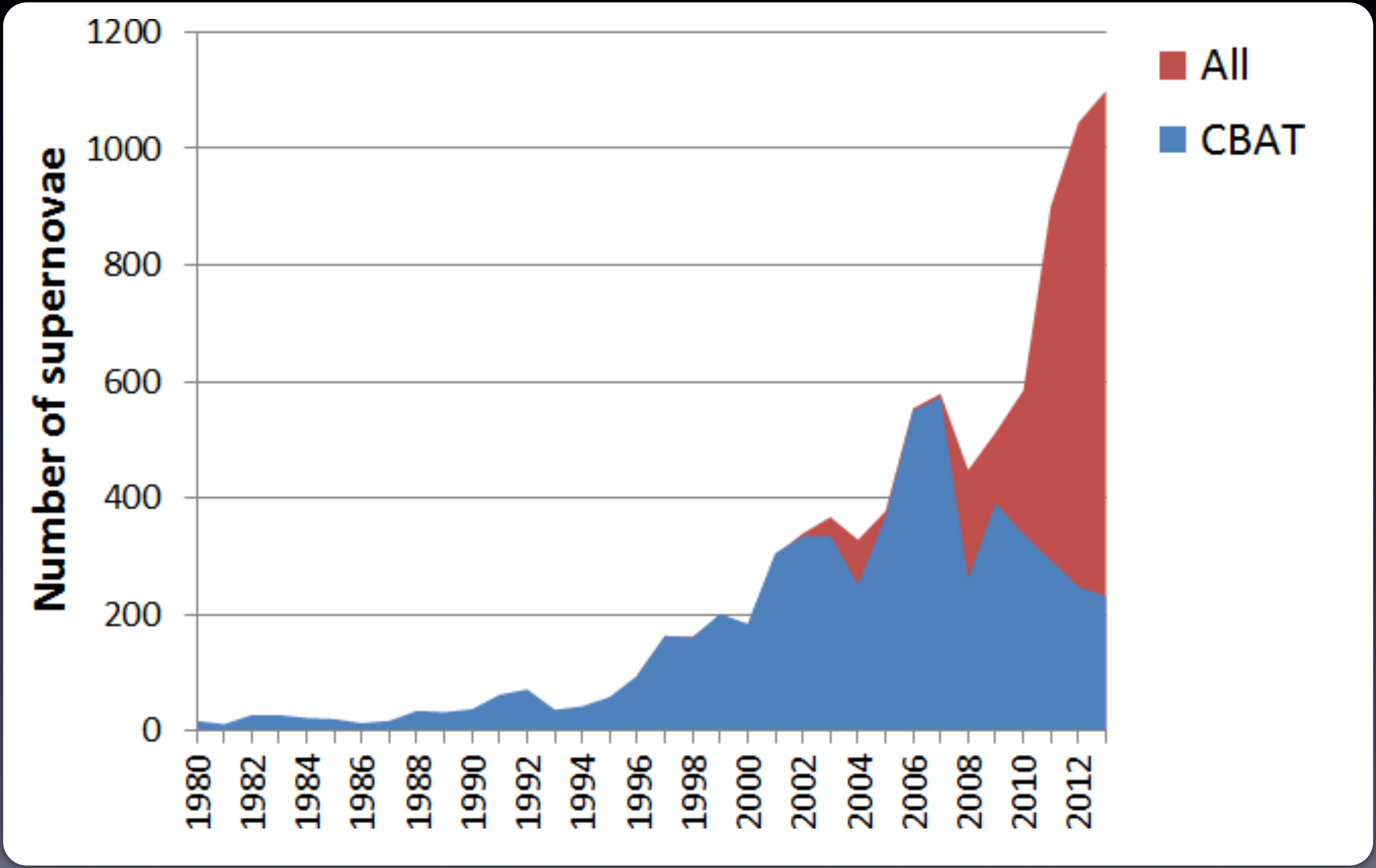

CFH
COELUM


SN 2011fe
B. J. Fulton


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

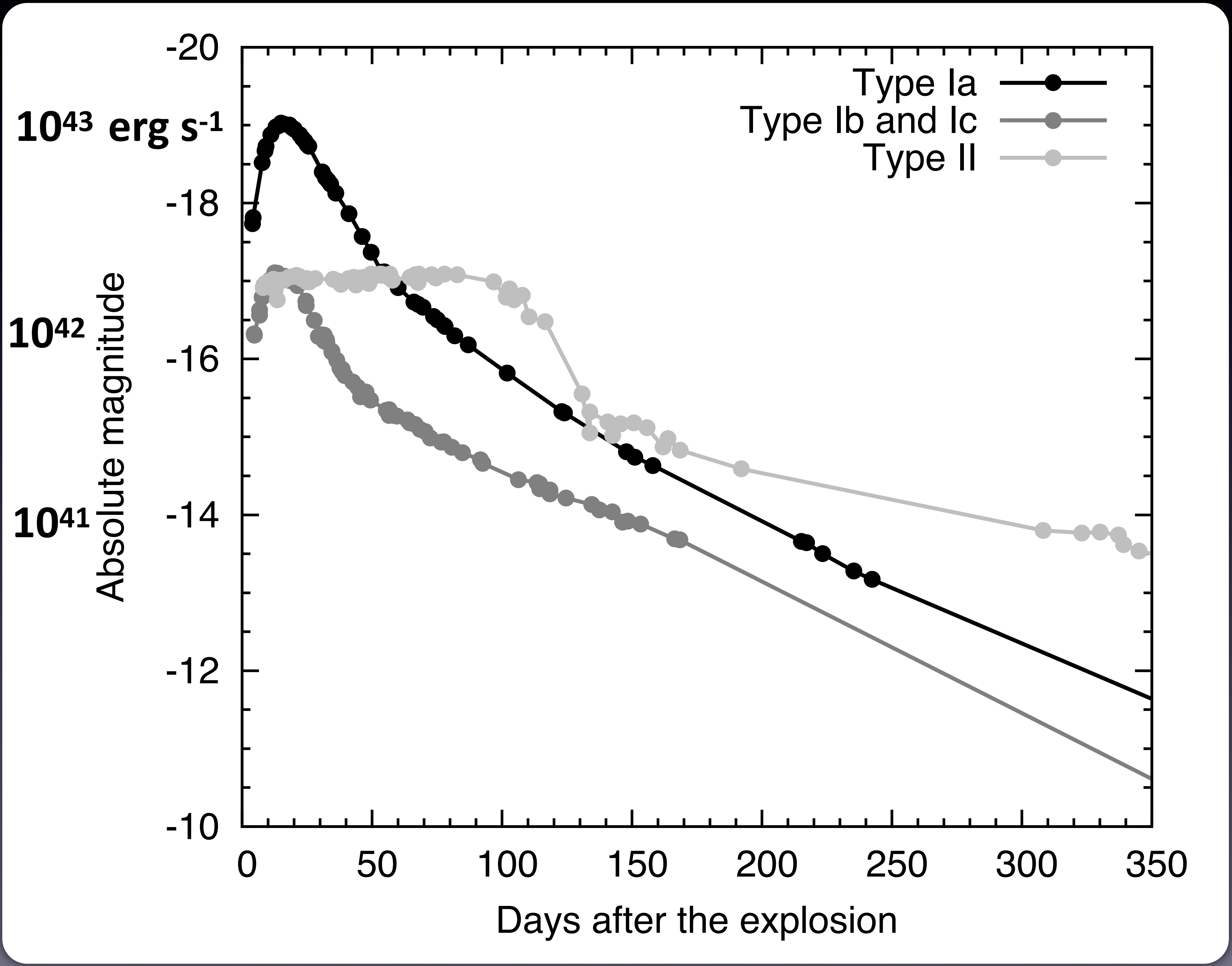

SDSS

History of SN discovery

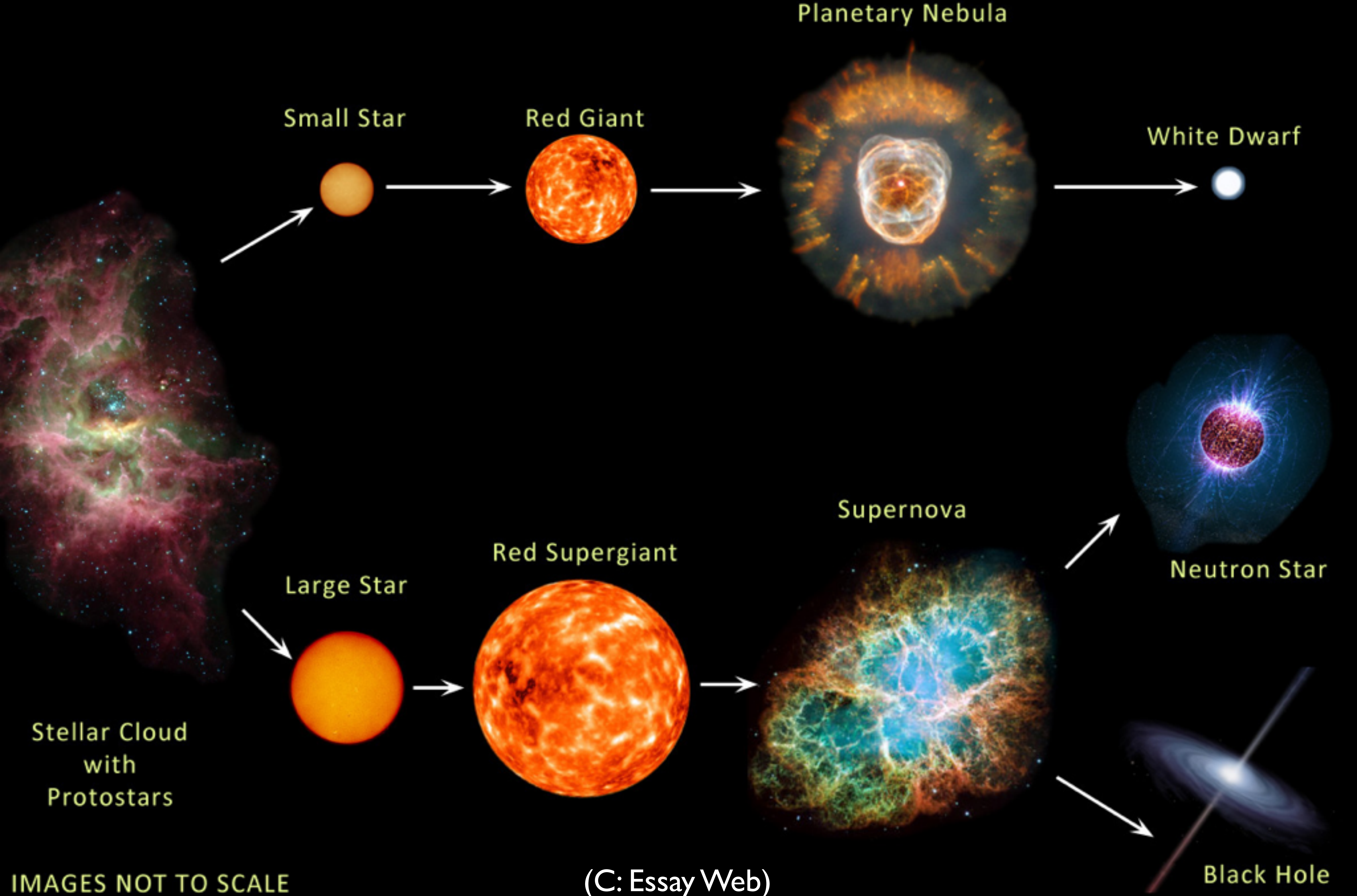


http://proftimobrien.com/2014/02/supernova-2014j-in-m82/

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



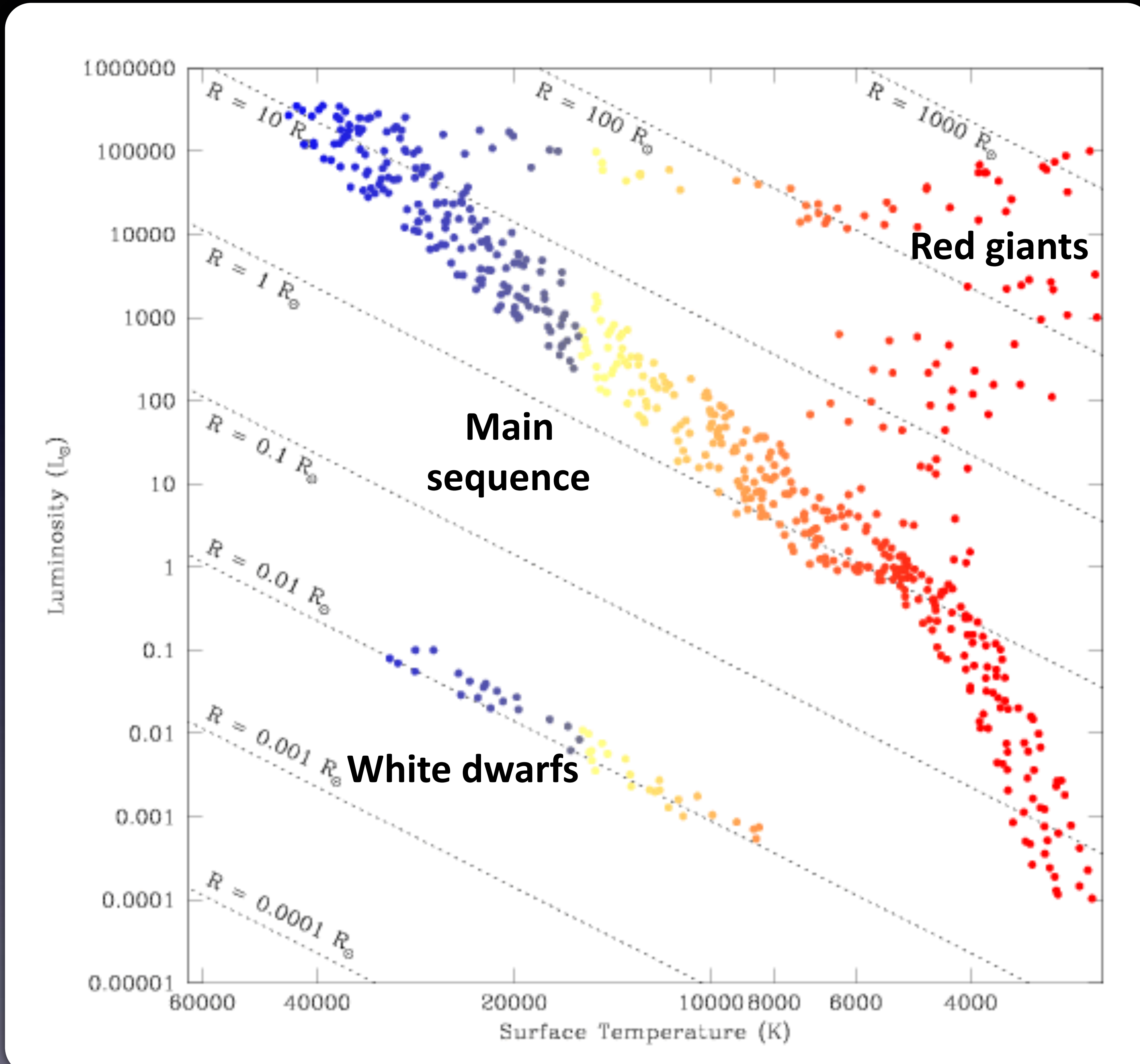
Stellar life



(C: Essay Web)

Hertzsprung-Russel diagram

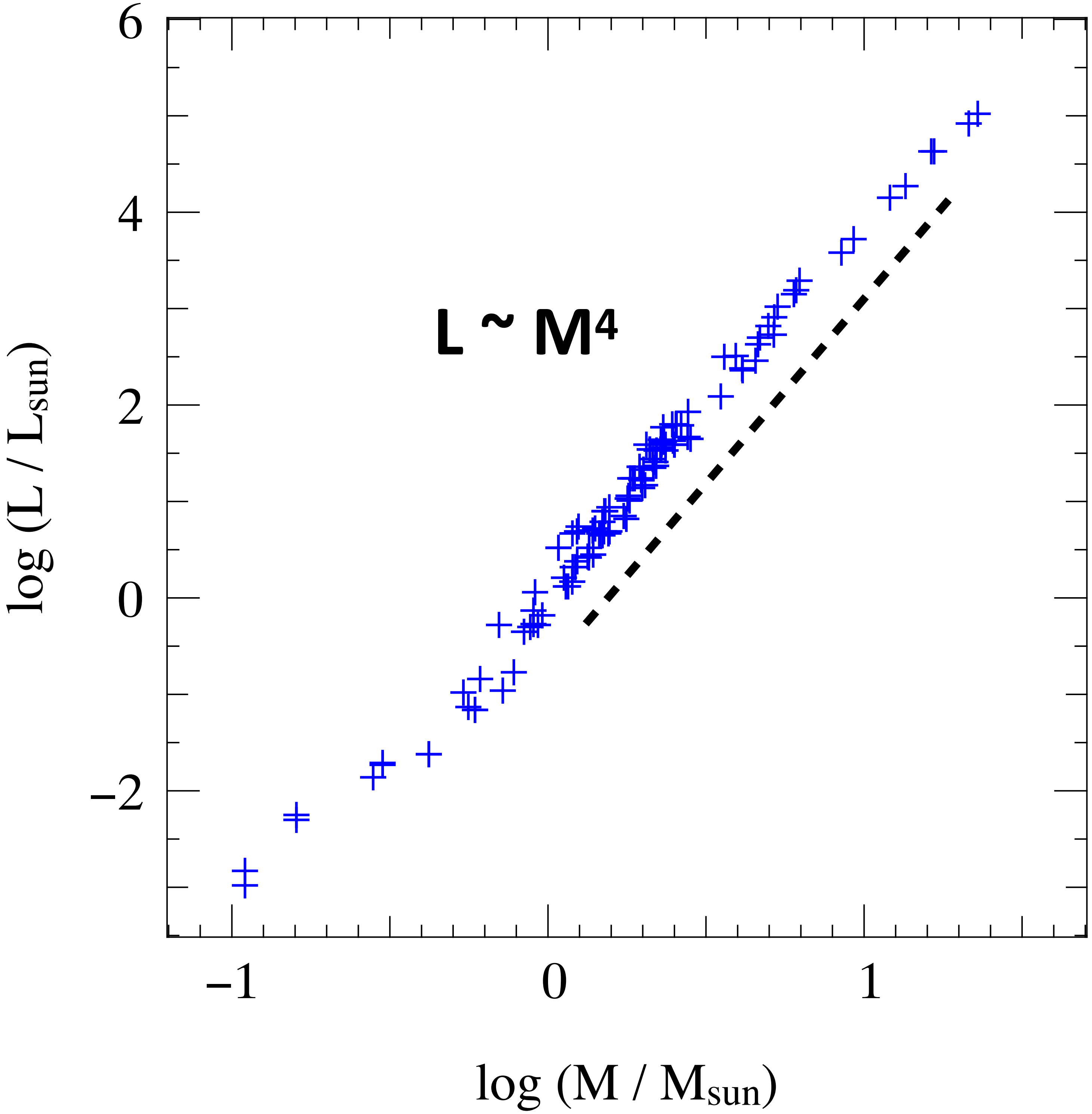
Luminosity



Temperature (K)

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

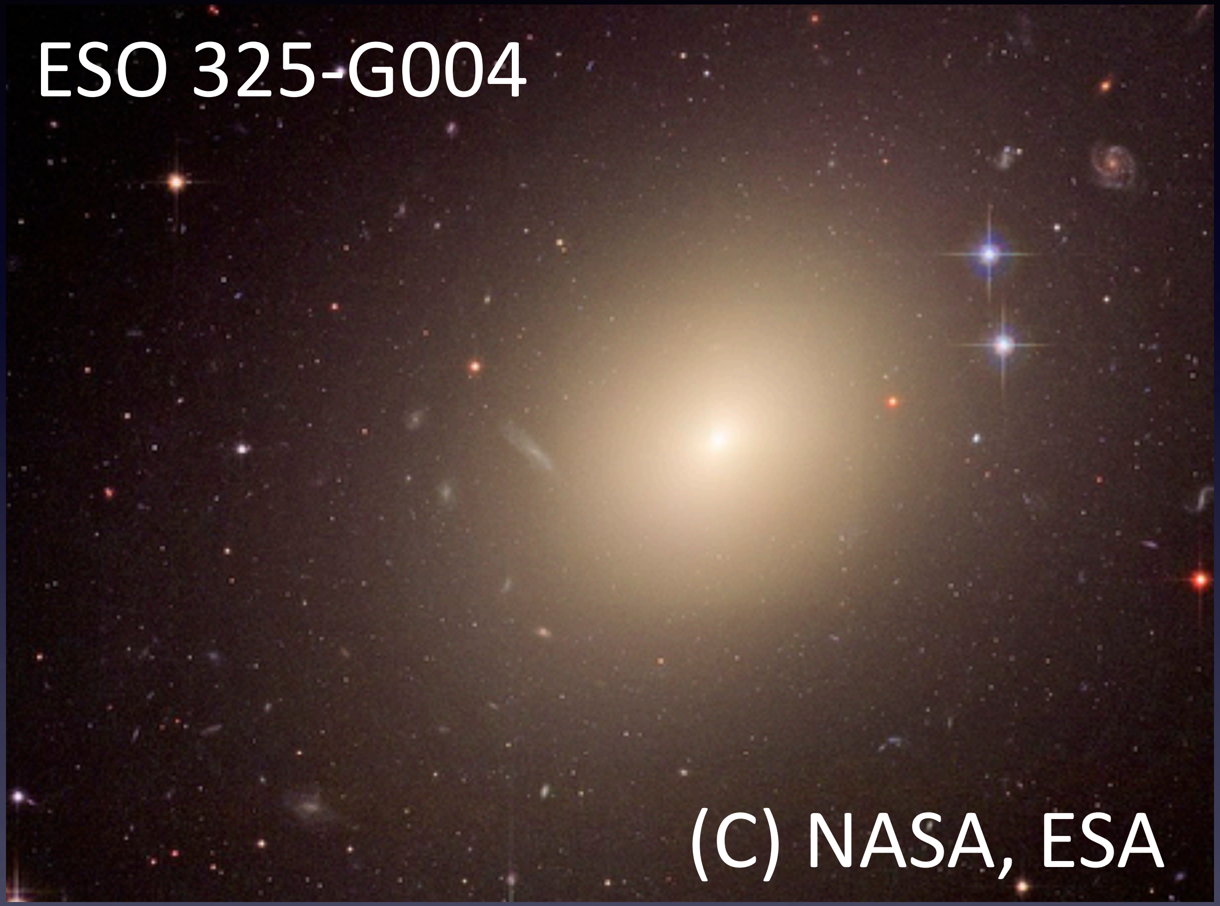
Lecture Note by Pols

Applications to galaxy studies

Spiral galaxy

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

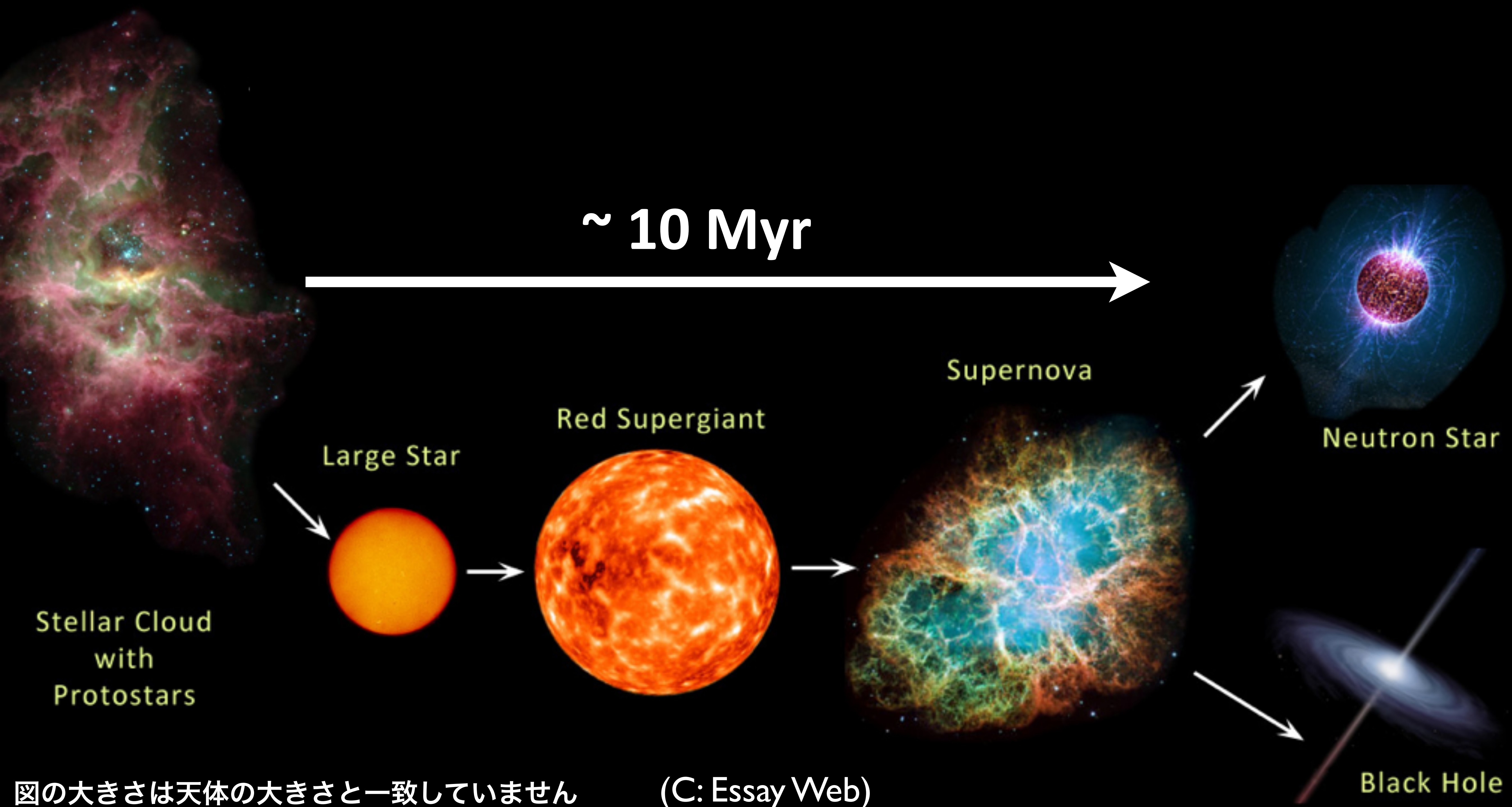
Elliptical galaxy



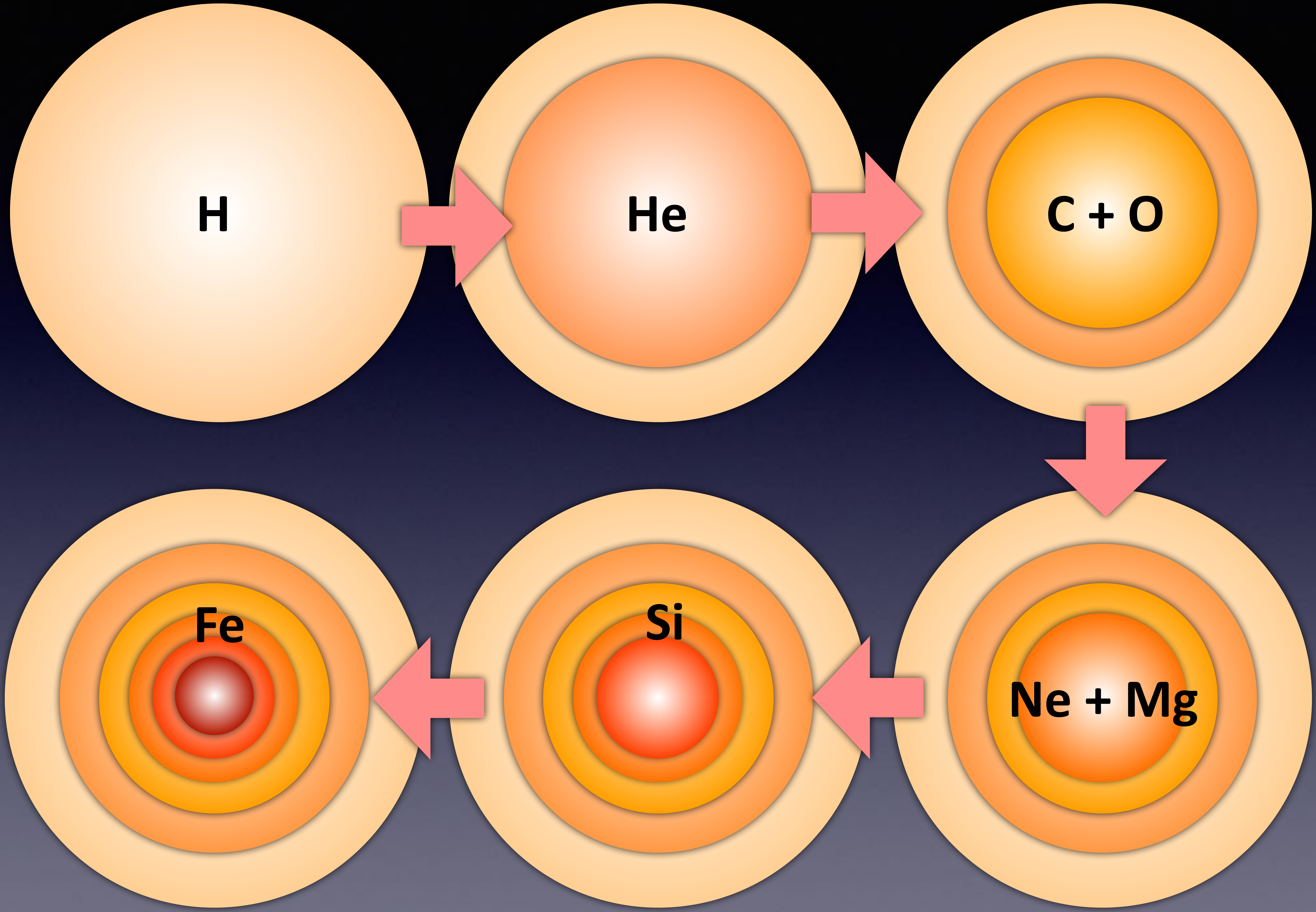
- No star formation
- Old stars
- Less massive stars
- Red (low T radiation)

1. Massive stars

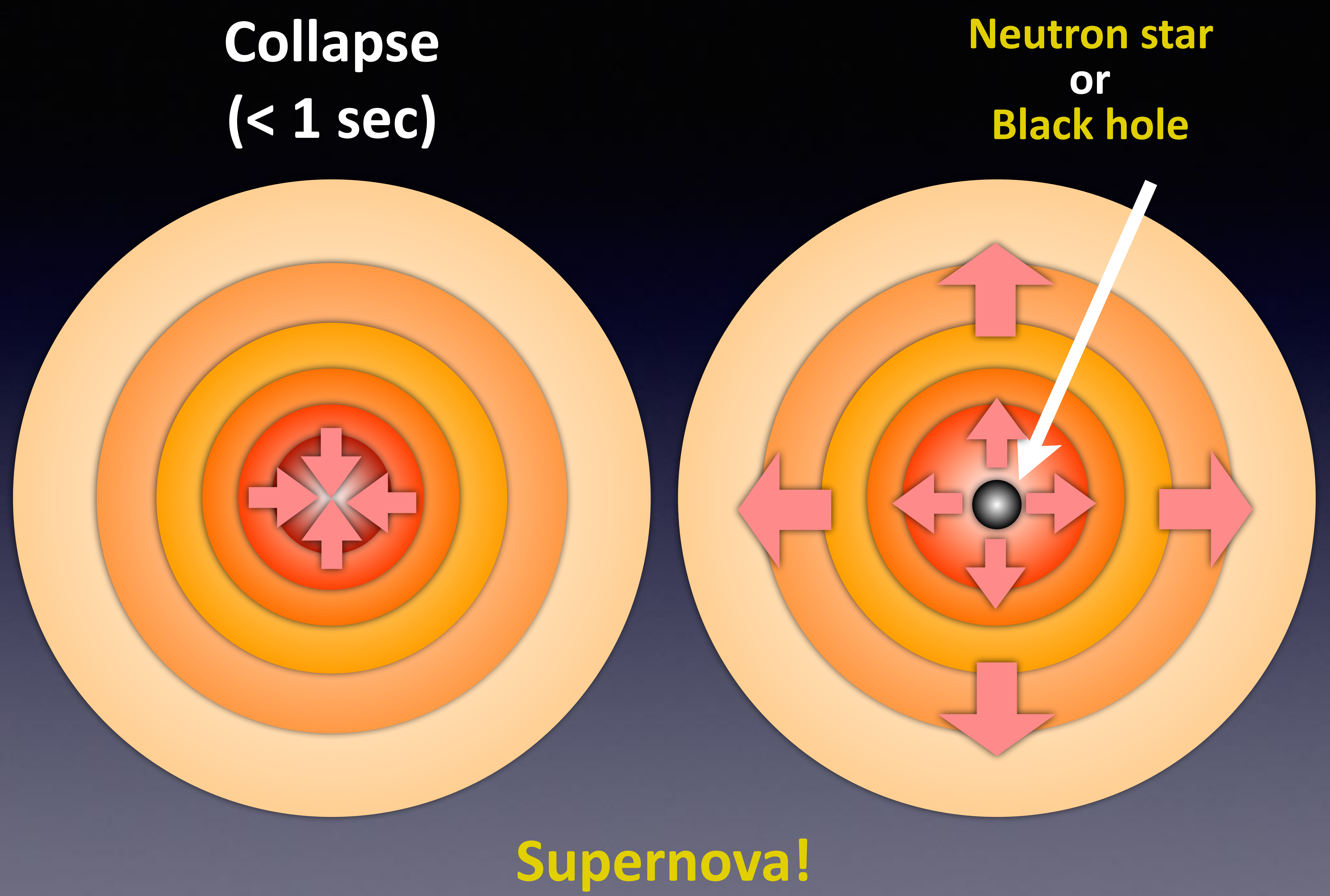
M > 10 Msun

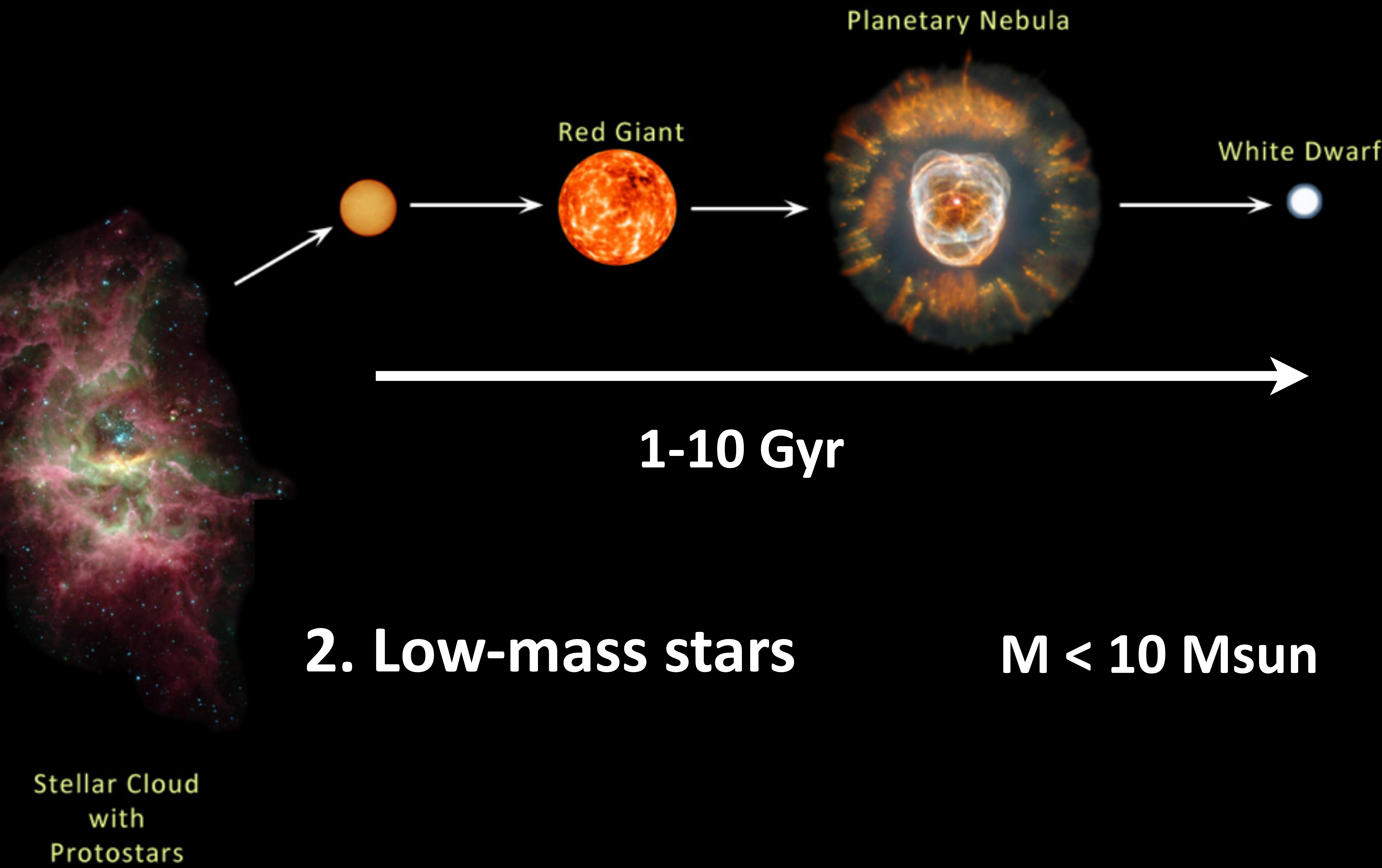


図の大きさは天体の大きさと一致していません　　(C: Essay Web)



Images are not to scale

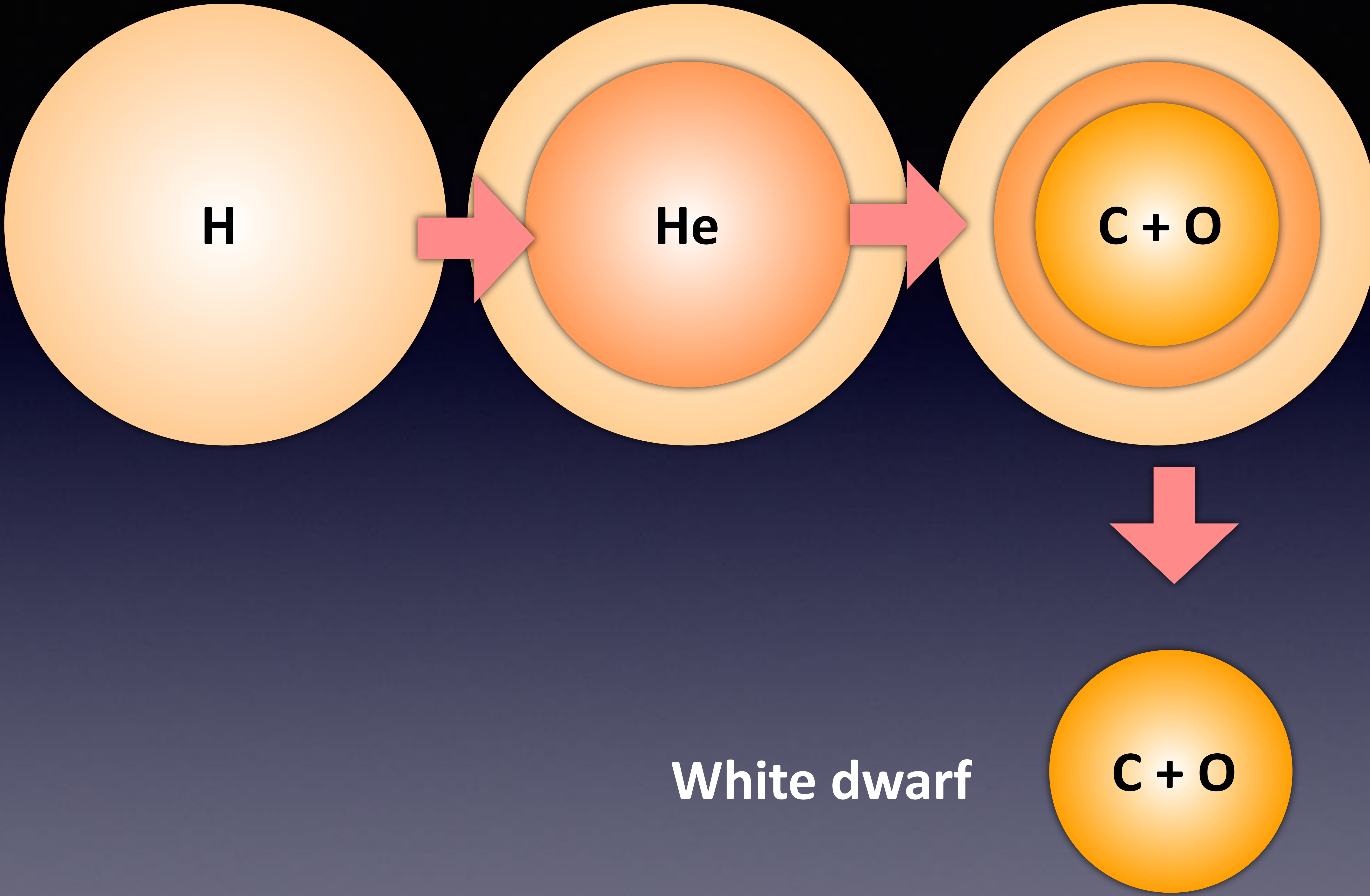

Collapse
(< 1 sec)
Neutron star
or
Black hole
Supernova!



2. Low-mass 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)



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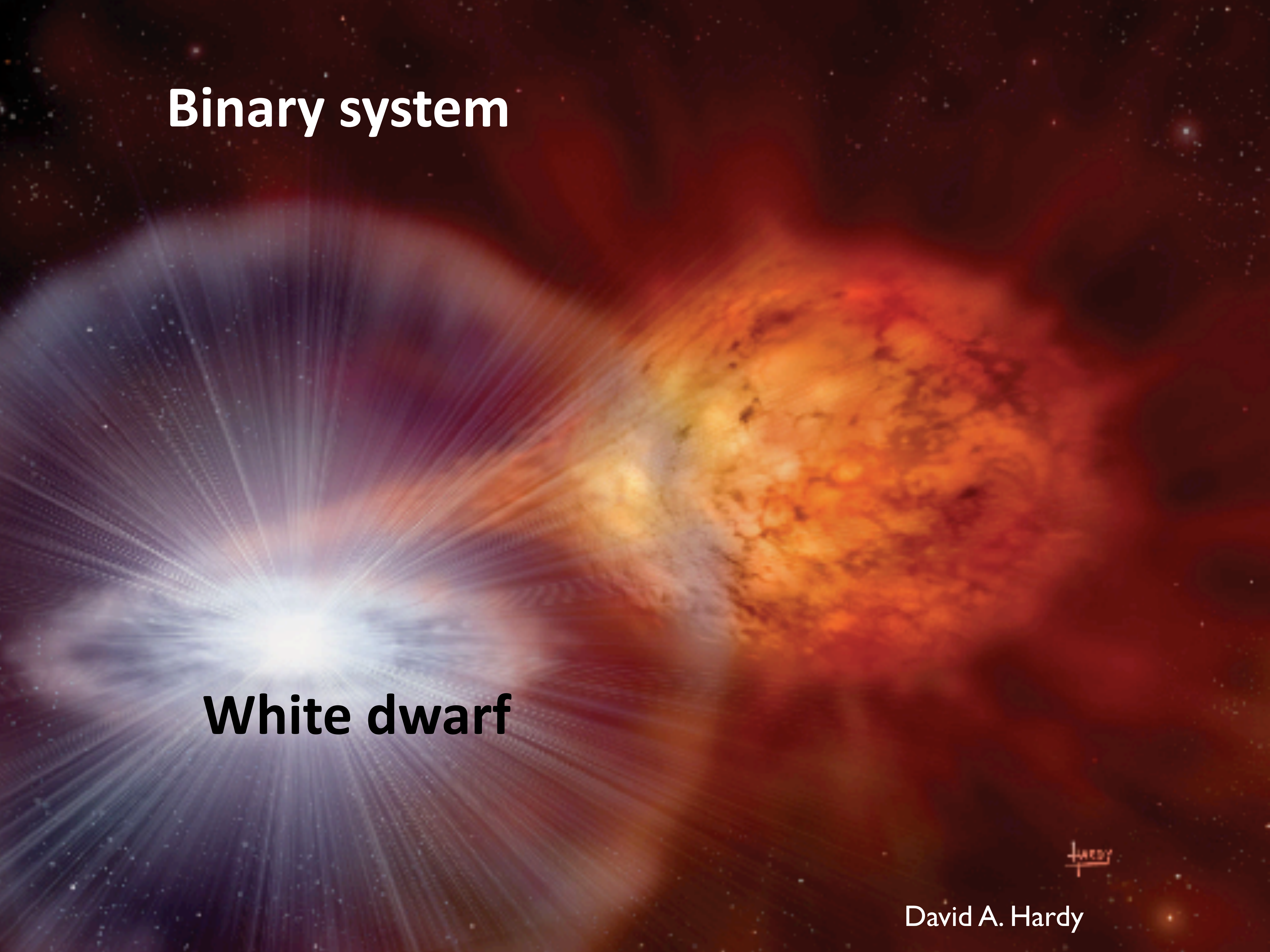
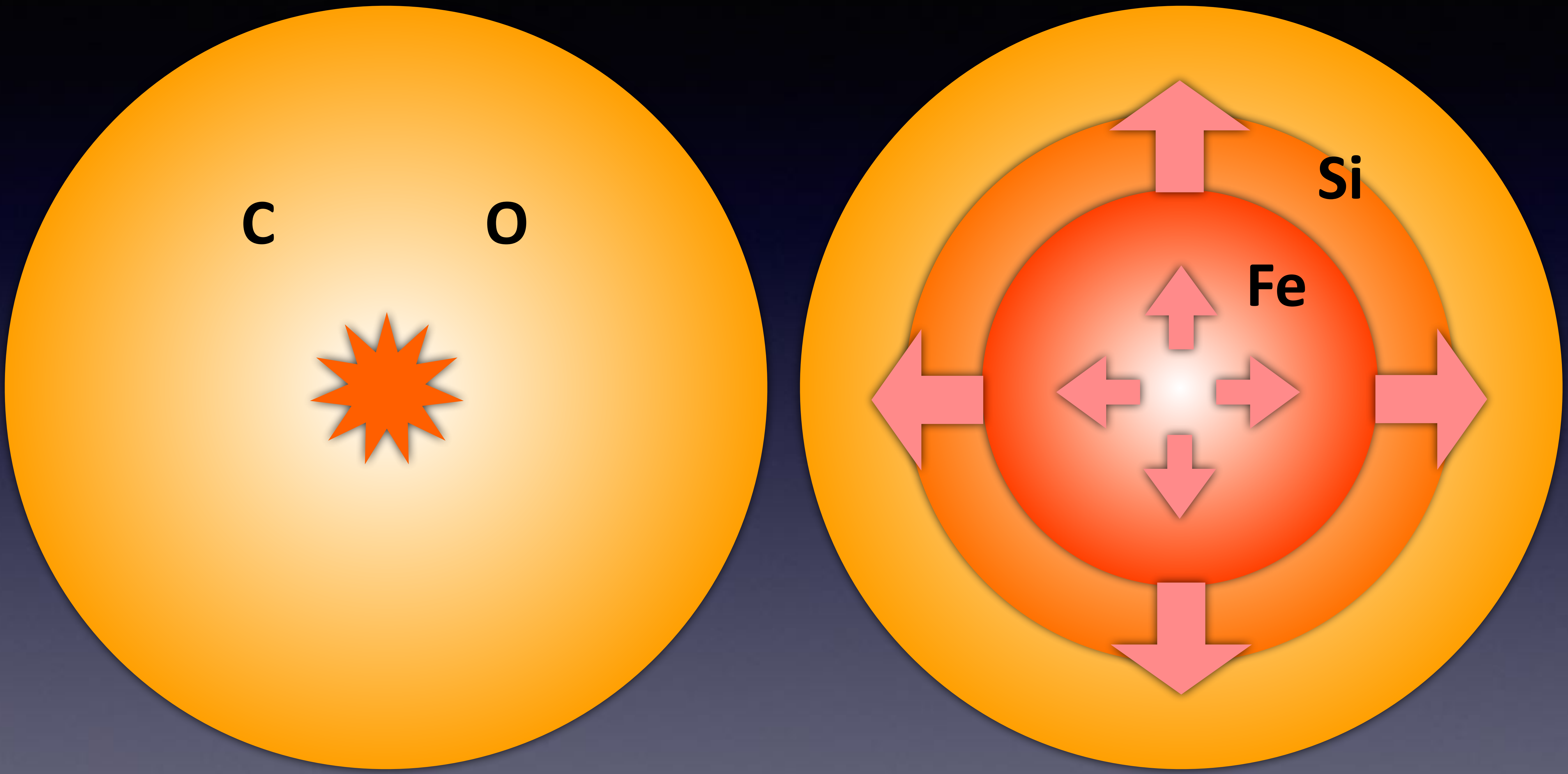
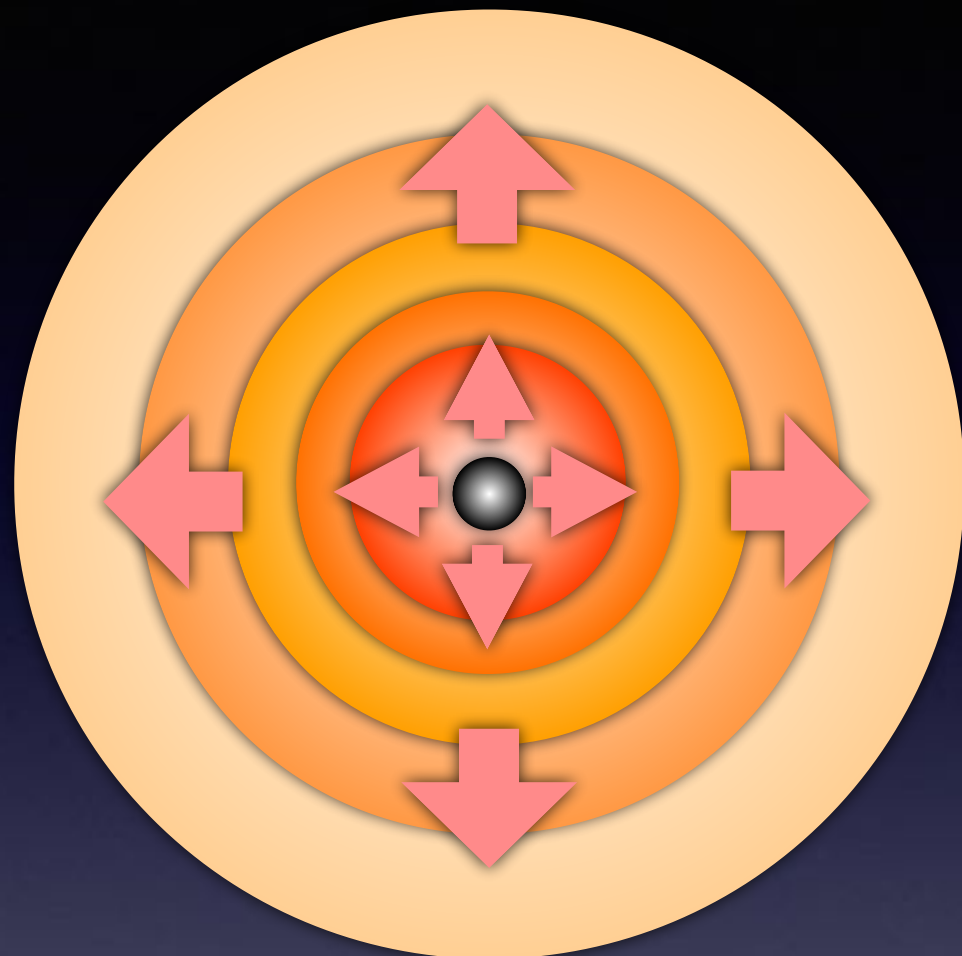

Binary system
White dwarf
David A. Hardy

Thermonuclear explosion

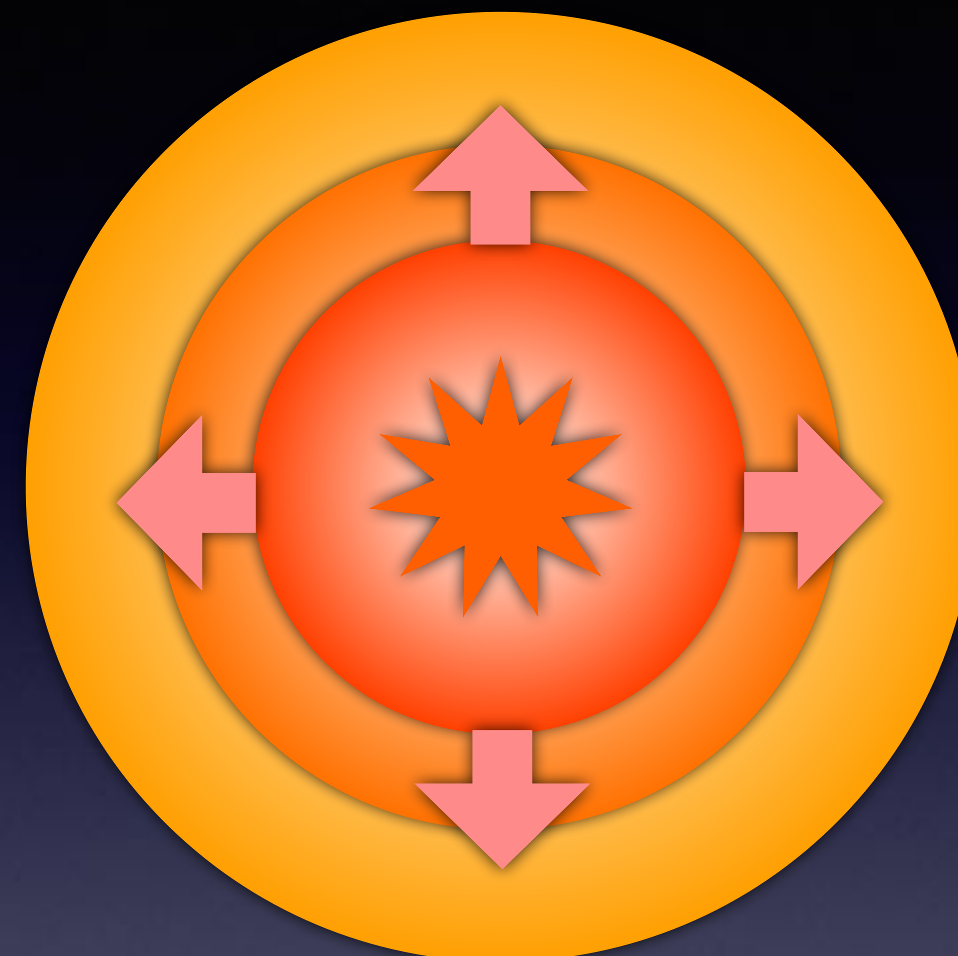


Supernova!

Core-collapse SNe



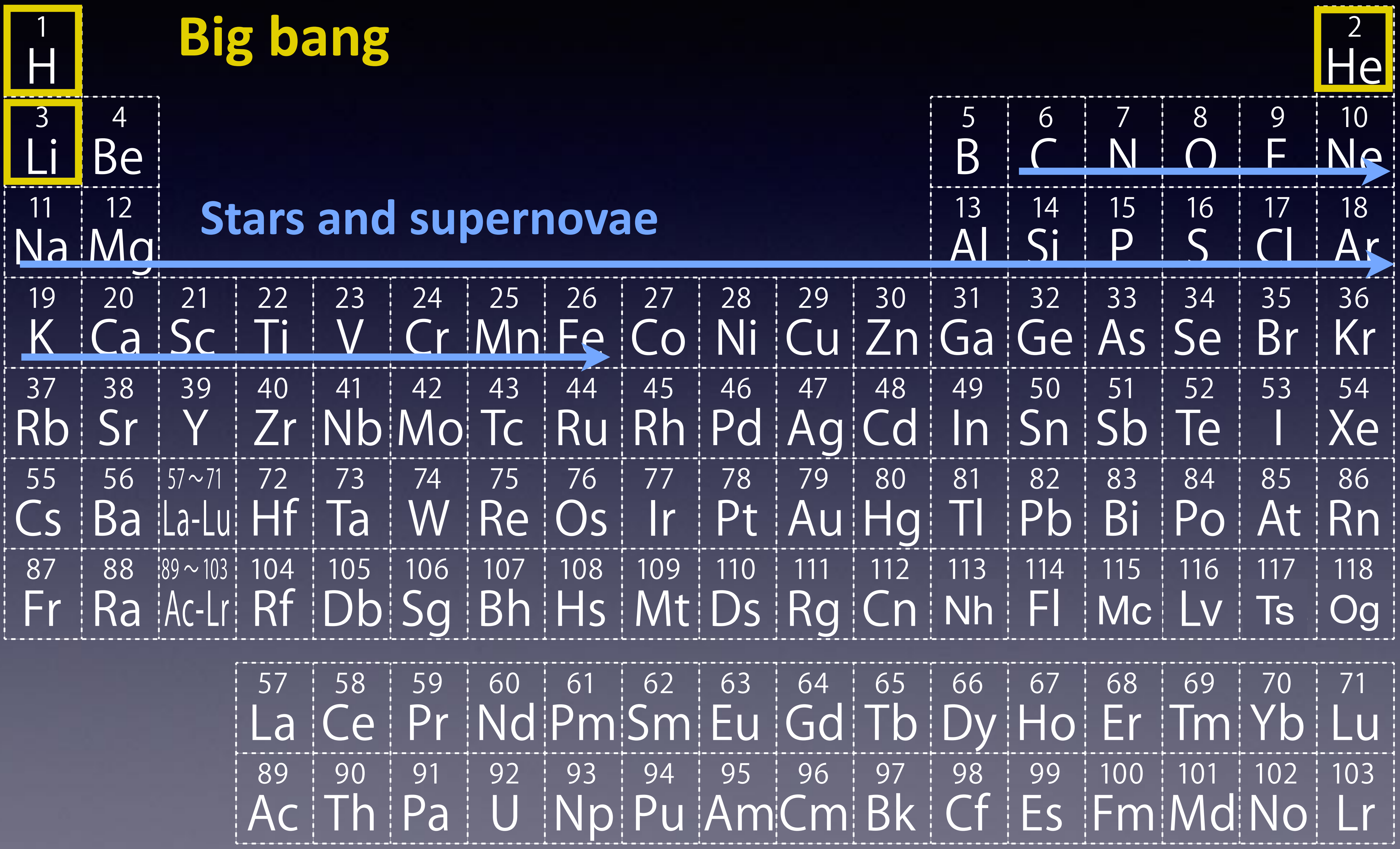
Thermonuclear SNe



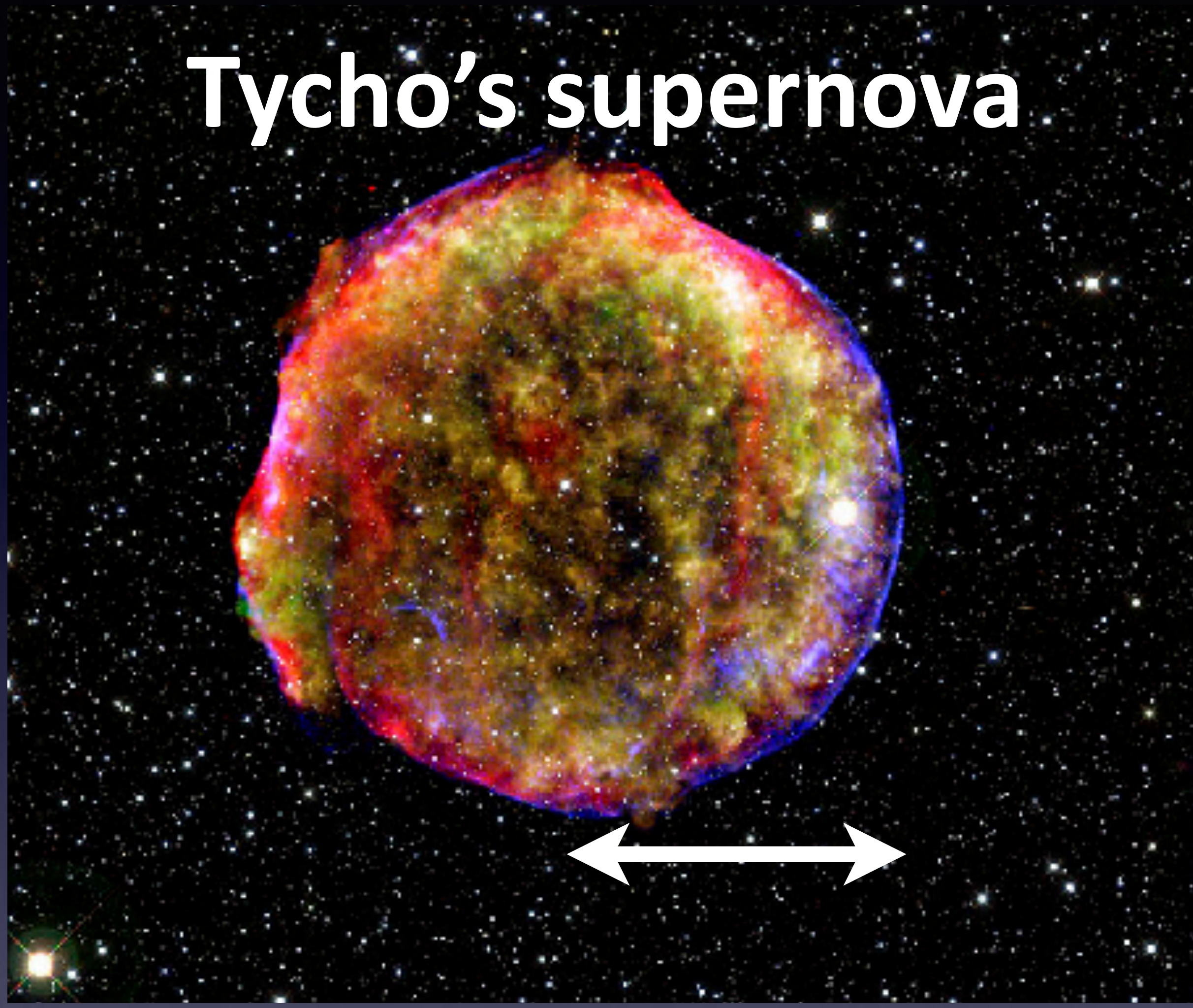
	Core-collapse SNe	Thermonuclear SNe
Progenitor	**Massive stars** Short lifetime	**Low-mass stars (in binary)** Long lifetime
Elements	**O, Mg, Ca, …** (progenitor star)	**Si, Ca, Fe, …** (explosion)

The elements around us are made by stars and SNe

The origin of elements



Let’s feel SN explosion



Q. What is the average Velocity of SN?

R ~ 10^{19} cm （10 light year ~3 pc）

Observed by Tycho Brahe in 1572
(Type Ia)

Velocity = Distance/time

Distance: 10^{19} cm

Time: ~400 years

Velocity = 10^{19} / (400 x 3 x 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 x 10^{33} g) x (10^9 cm/s$)^2$

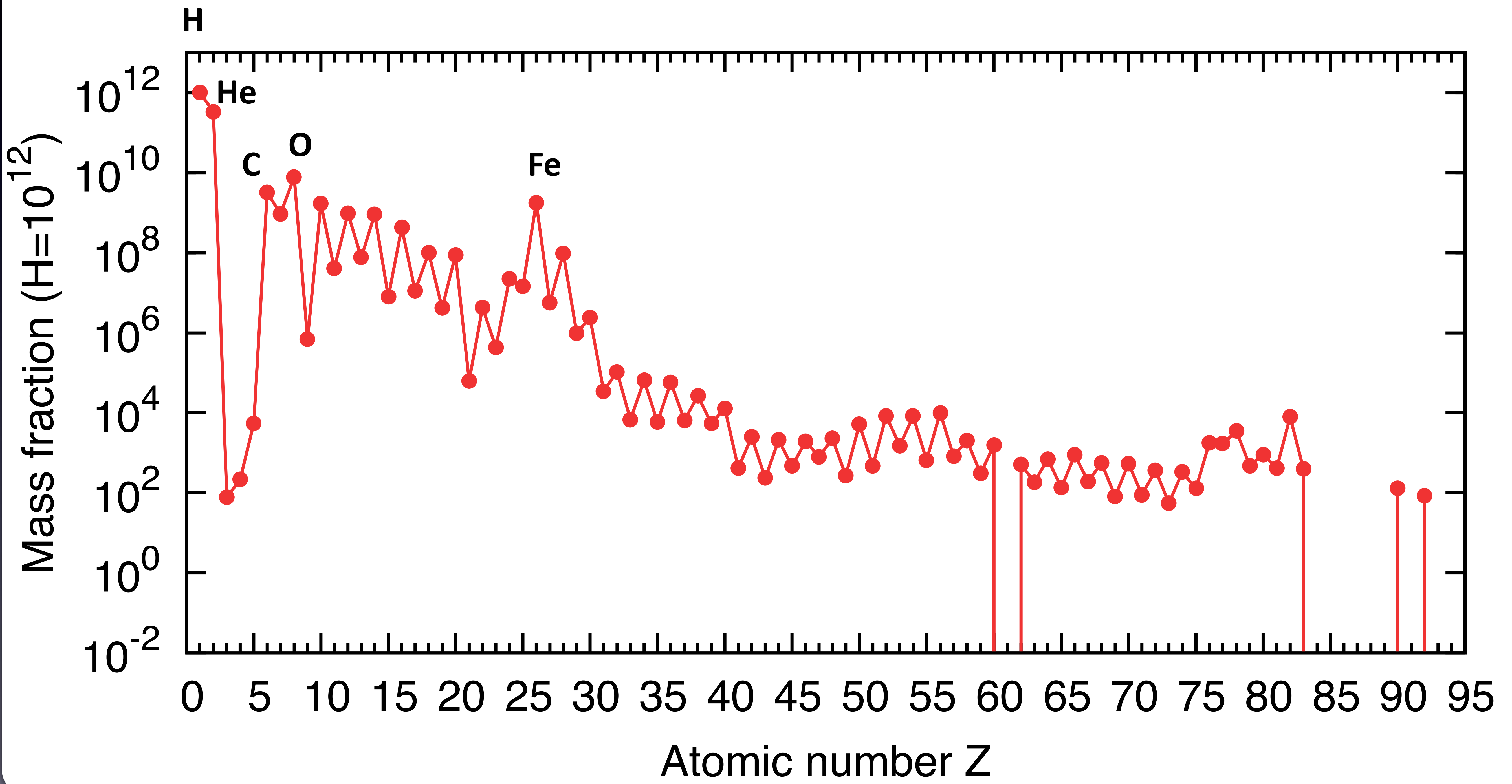
~ 10^{51} erg

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

1.1 Stellar lives and supernovae

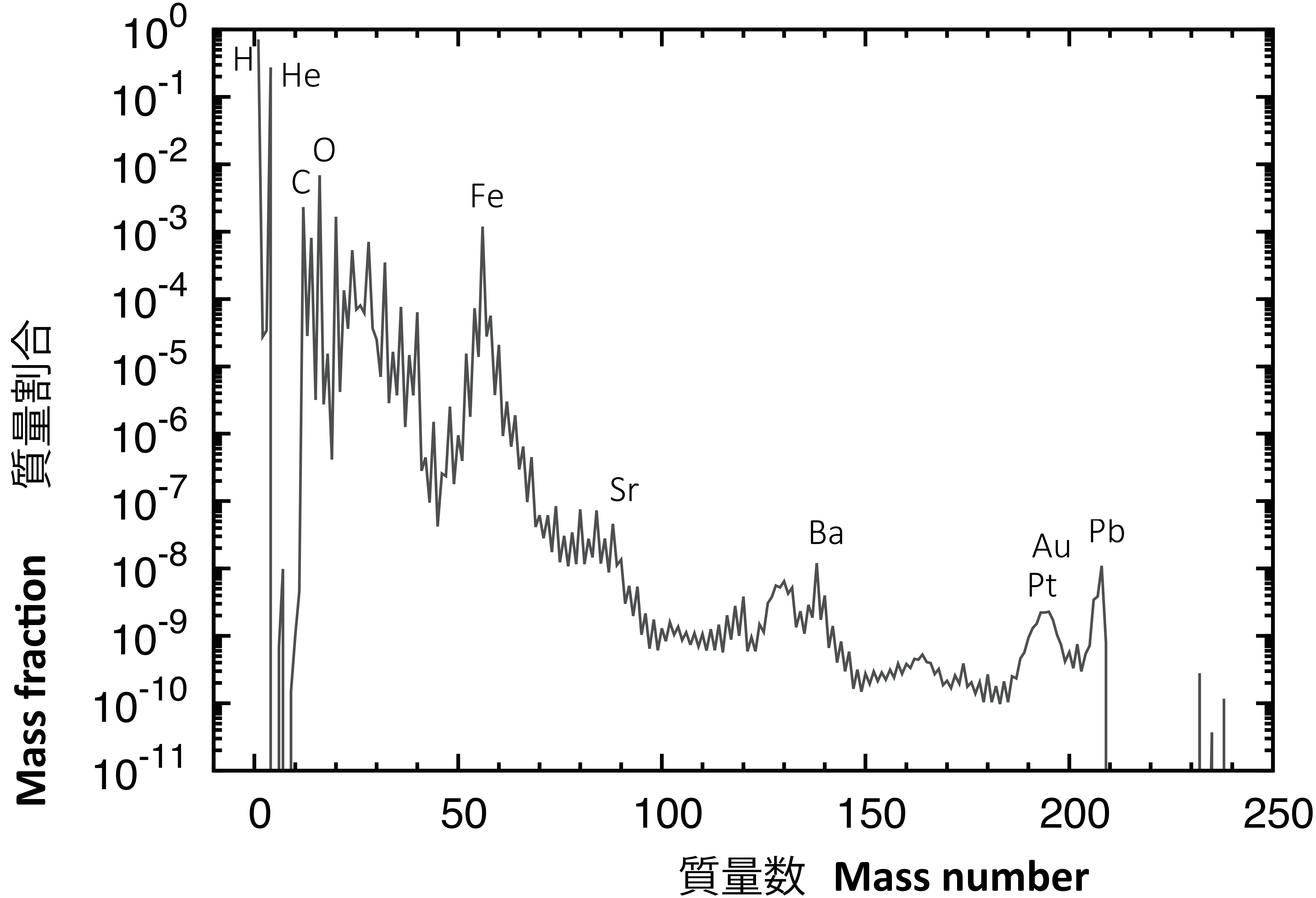
1.2 Origin of the elements

Cosmic abundances (atomic number)



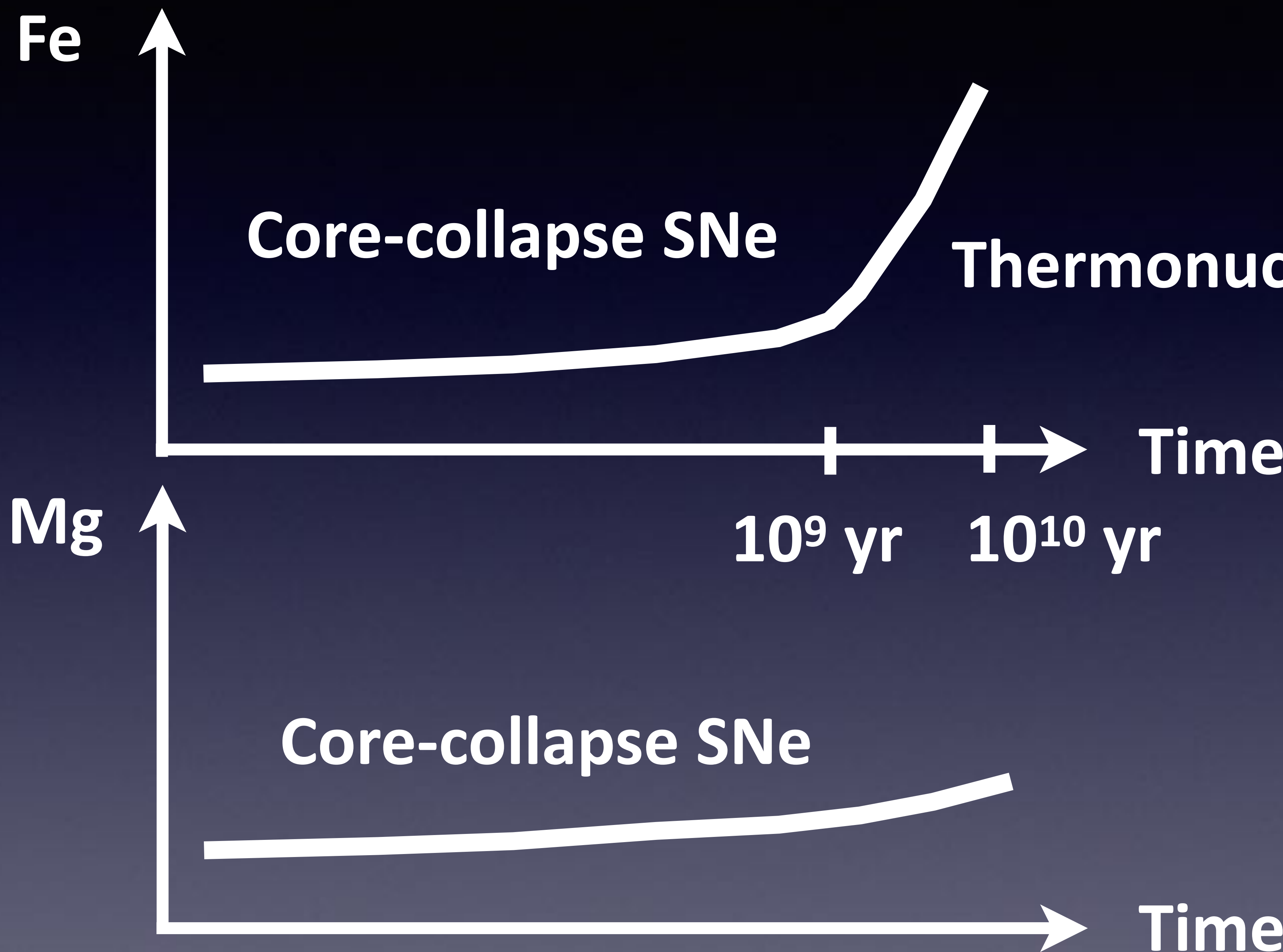
*Mass ratio

Cosmic abundance (mass number)



Our understanding about the nucleosynthesis is correct??

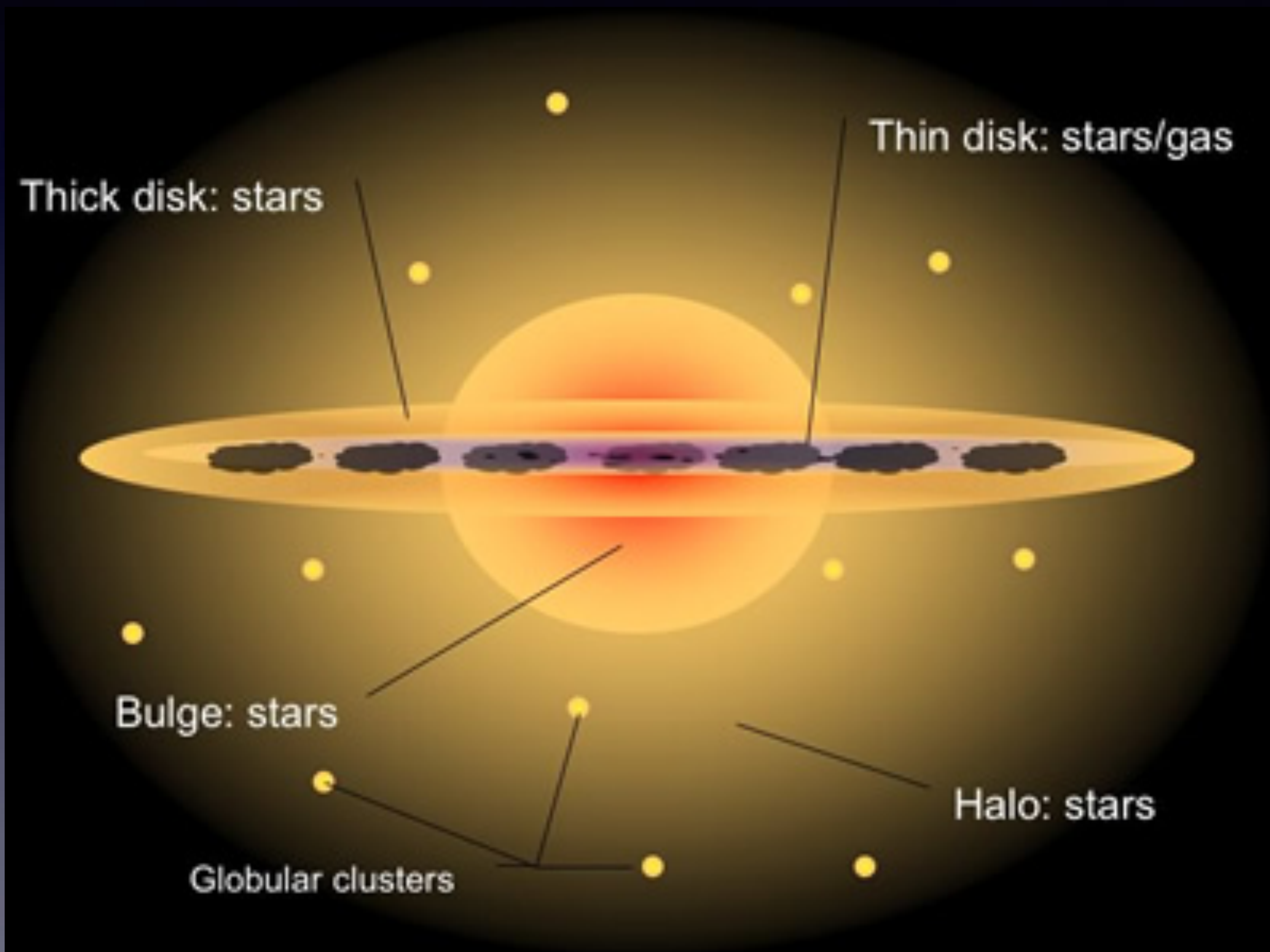
Chemical evolution of the Universe



Stars formed recently should have low Mg/Fe ratios

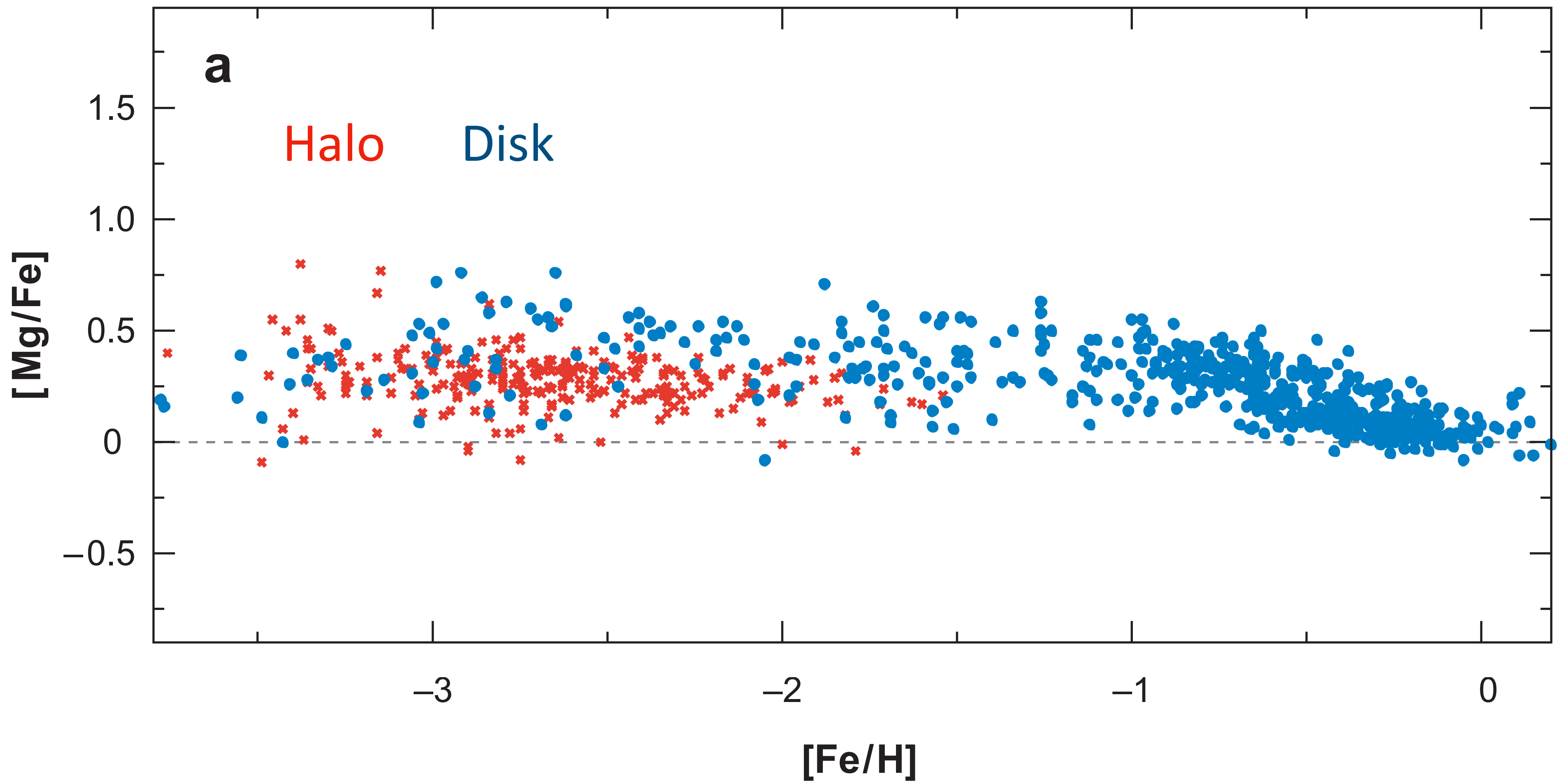
Our Galaxy

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**

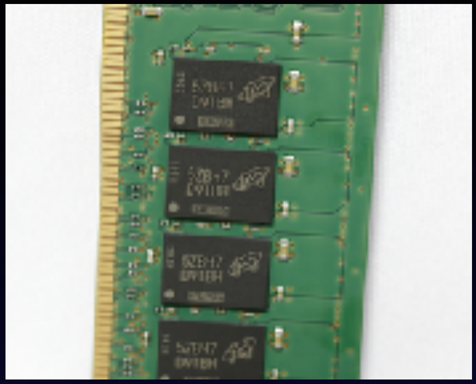
Let's **understand** these questions with the word of physics

Knowing ≒ Understanding

- Why do some stars explode?
- Why don't normal star explode?
- Why do stars show $L \sim M^4$?
- Why do stars evolve?
- Why does the destiny of stars depend on the mass?
- 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!!

- $L \sim M^4$

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