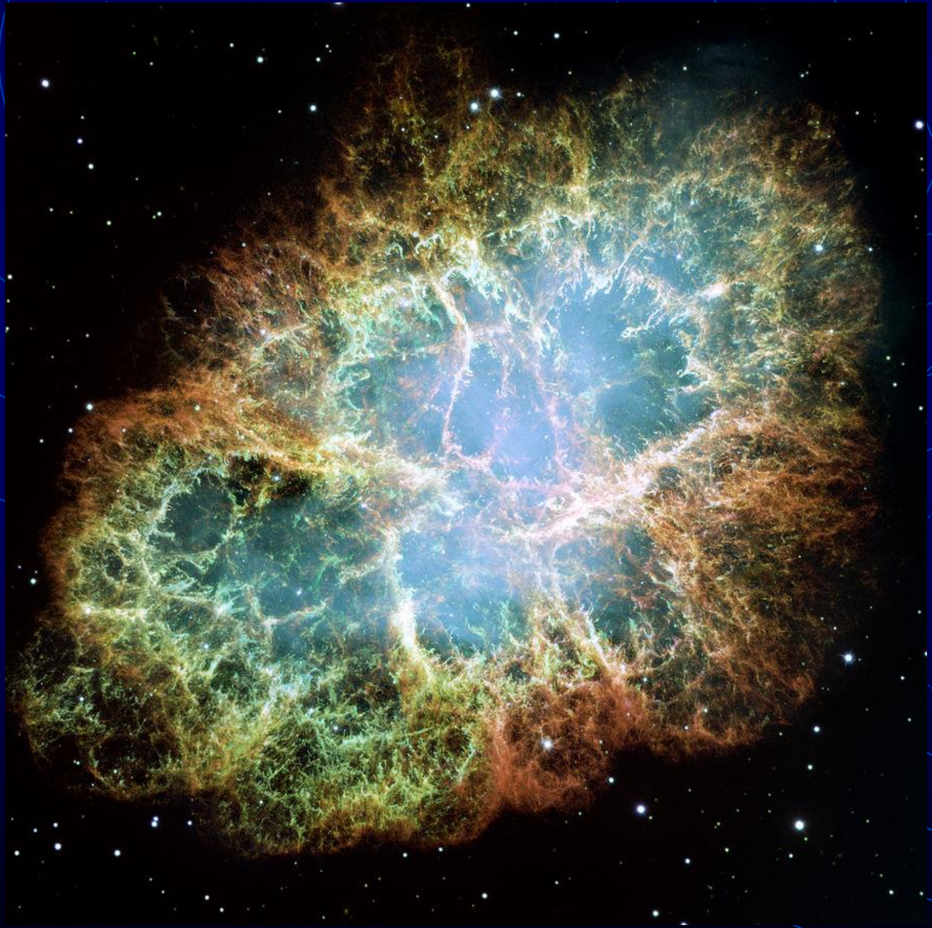
The Deaths of Stars
恒星的衰亡



最低質量（< 0.4 $M_\odot$）恆星（紅矮星），結構上大規模對流

→ 離開主序時，氫元素幾乎全部用罄，不會演化成巨星

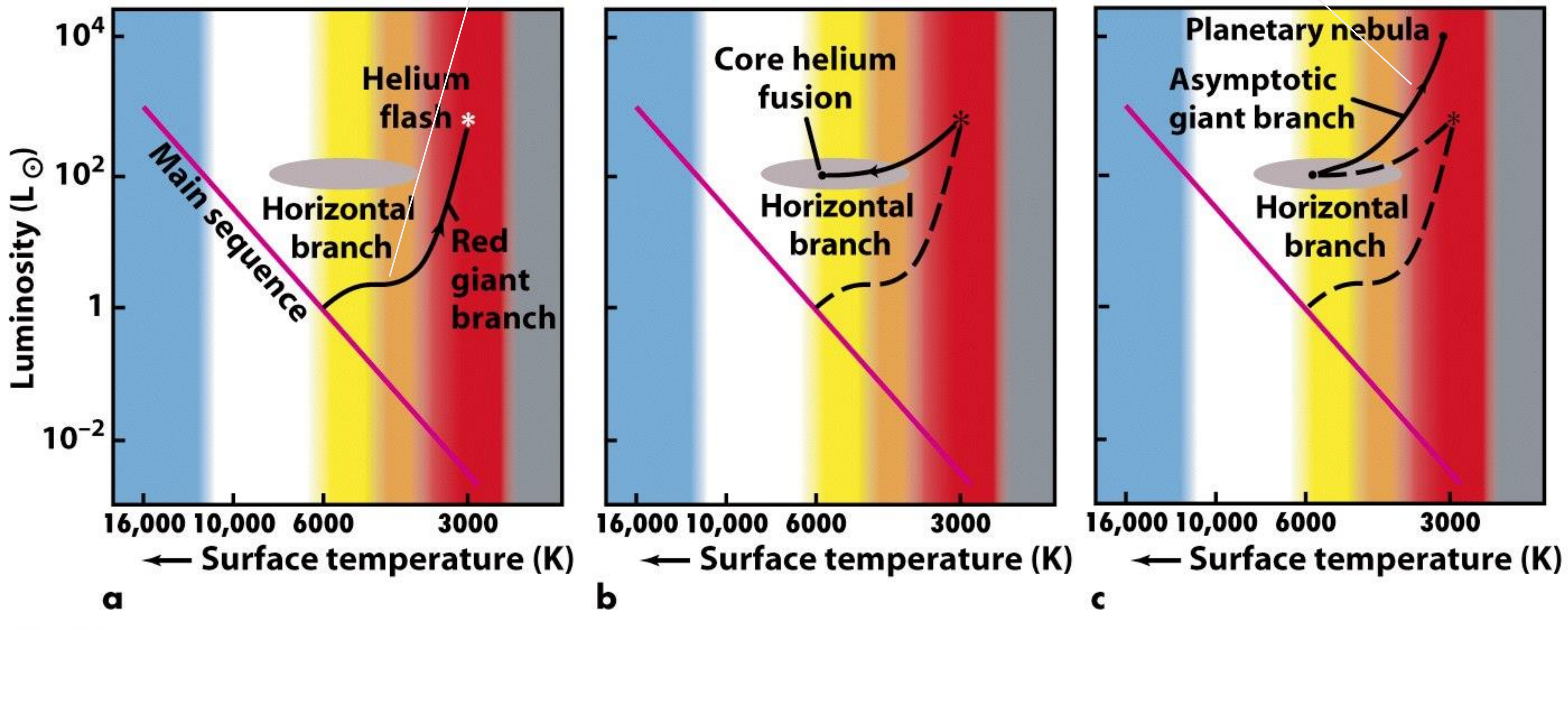
→ 星體冷卻，成為黑矮星

這種恆星壽命非常長，比宇宙現在年齡還長，意思是黑矮星都還沒死！

低質量 (0.4 to 8 $M_\odot$) 恆星晚年

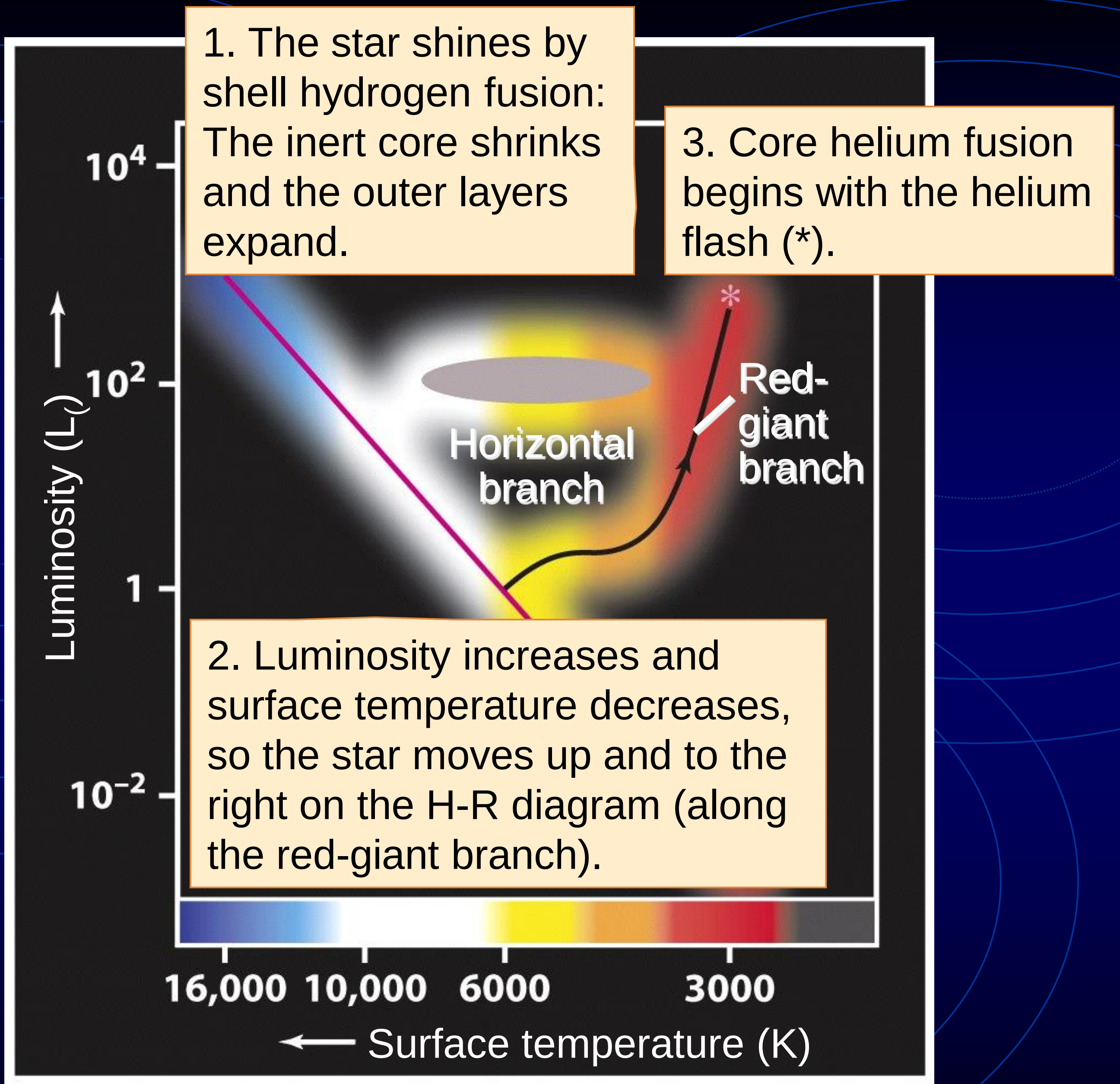
sion

Hydrogen shell fusion

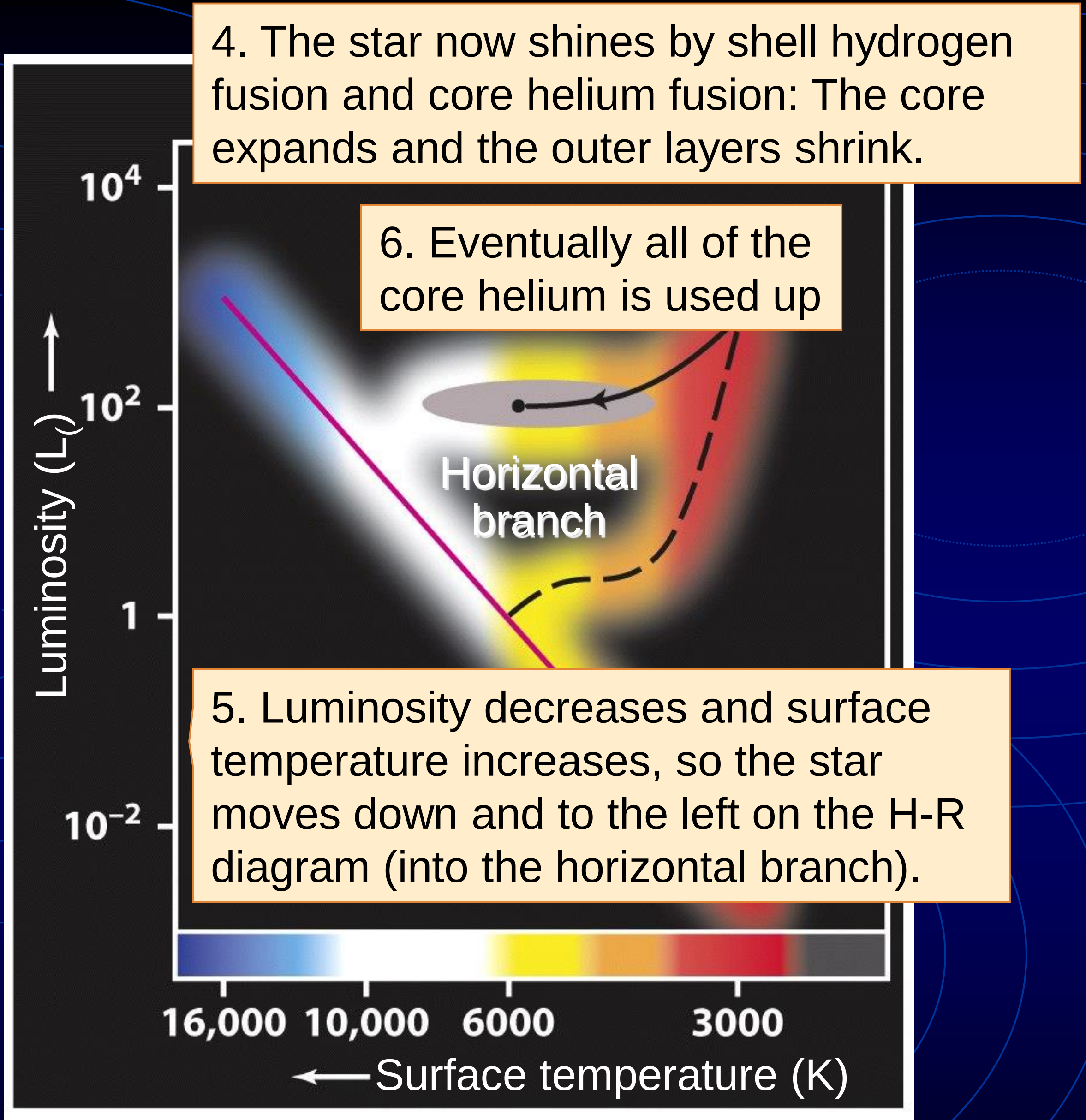


低質量 (0.4 to 8 $M_\odot$) 恆星晚年 II

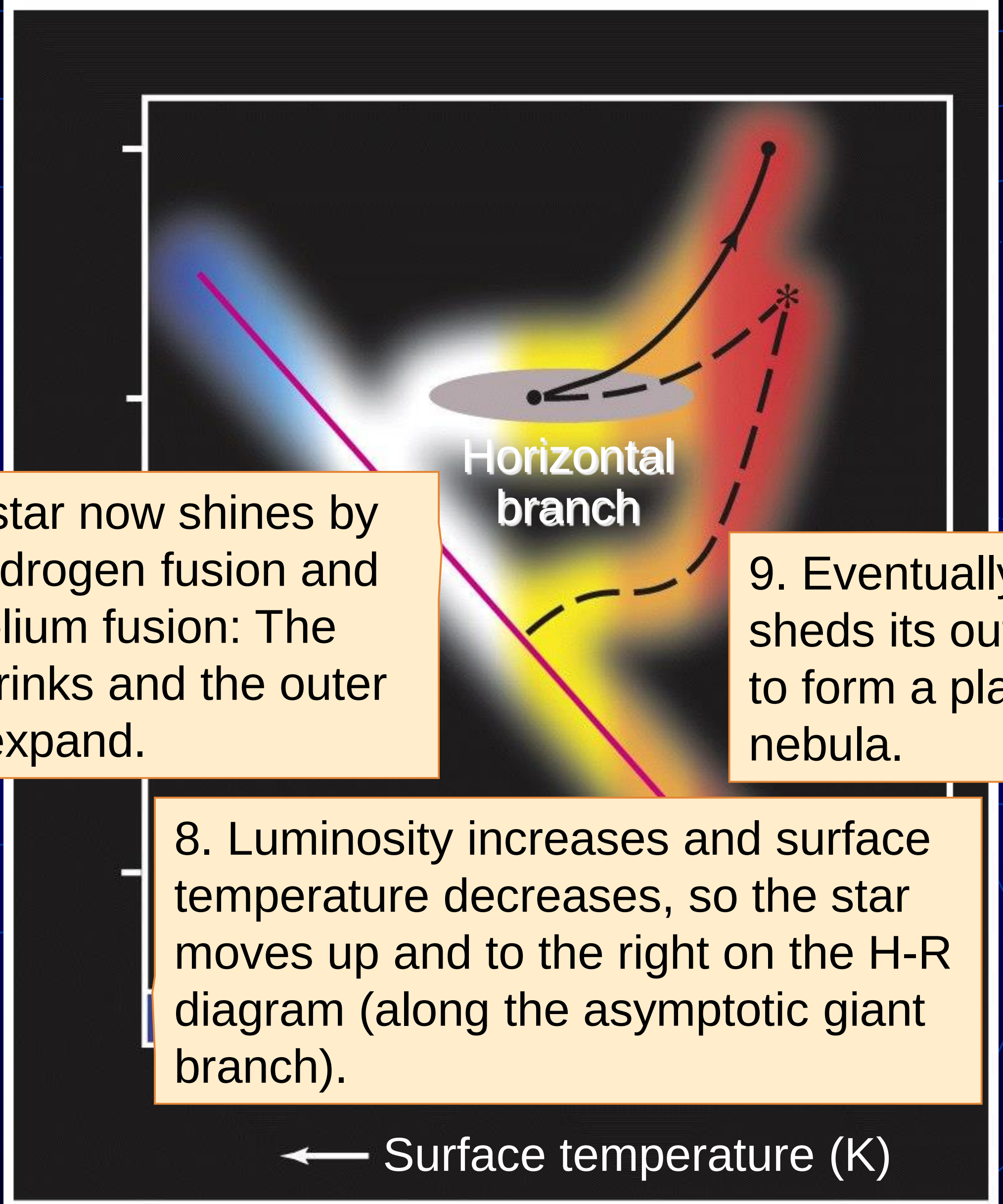
- 低質量水平分支的巨星，其核心溫度約2億 K，不足以點燃需要 6 億 K 的碳與氧的融合反應
  → 所以剩下 carbon-oxygen core
- 氦殼層融合 → 星體再次膨脹。由於有兩層融合反應，這次體積變得更大，演化進入
  asymptotic giant branch (AGB) 漸近巨星支
- 8 倍太陽質量的 AGB 星其半徑達火星軌道，光度達 $10^4 L_\odot$
- After being an AGB, the star becomes a supergiant （**超巨星**）



Before the helium flash: A red-giant star



After the helium flash: A horizontal-branch star

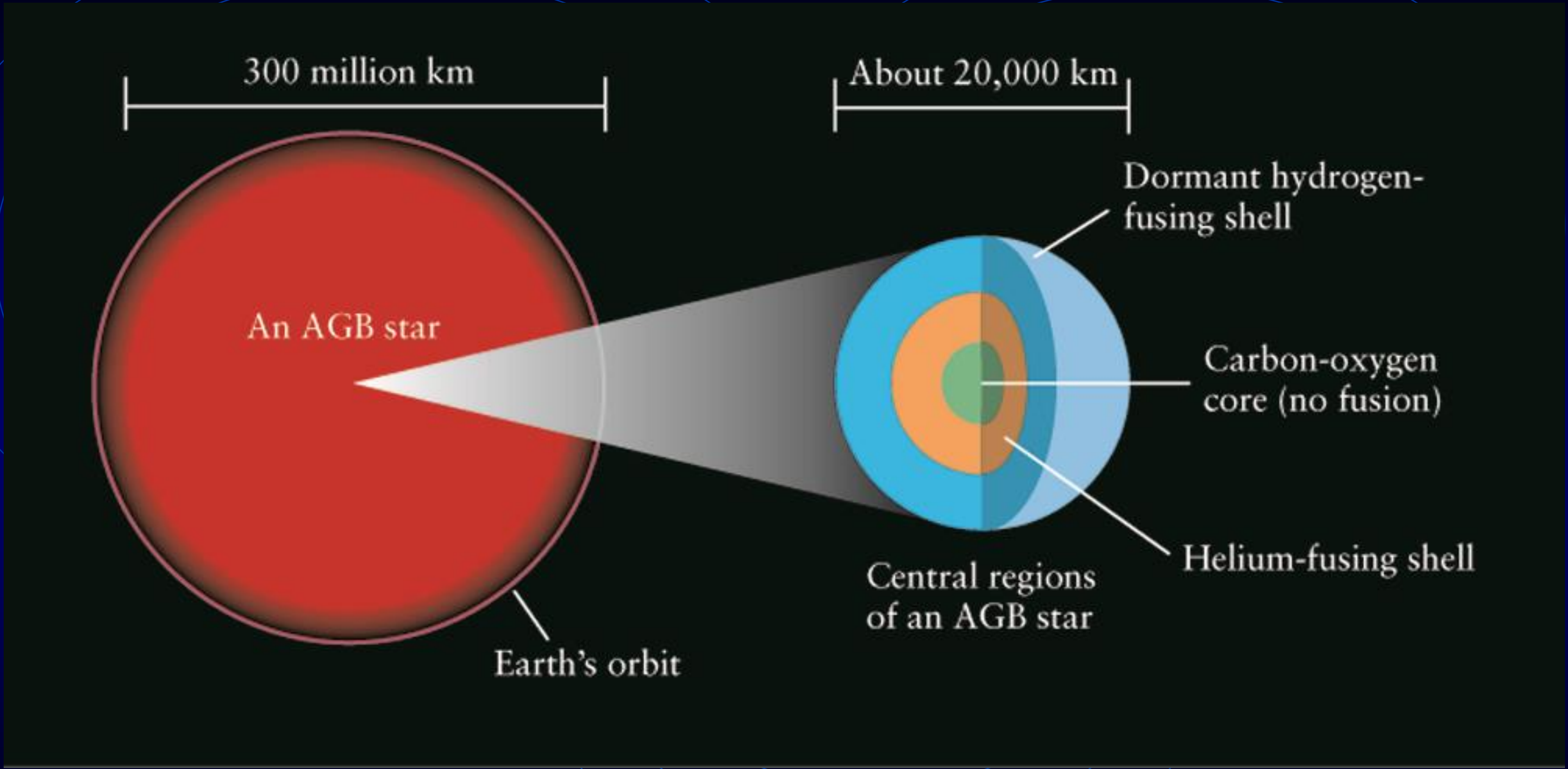


After core helium fusion ends: An AGB sta

7. The star now shines by shell hydrogen fusion and shell helium fusion: The core shrinks and the outer layers expand.

8. Luminosity increases and surface temperature decreases, so the star moves up and to the right on the H-R diagram (along the asymptotic giant branch).

9. Eventually the star sheds its outer layers to form a planetary nebula.

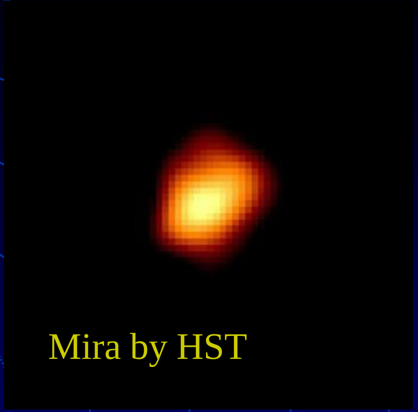

300 million km
About 20,000 km
Dormant hydrogen-
fusing shell
An AGB star
Carbon-oxygen
core (no fusion)
Helium-fusing shell
Central regions
of an AGB star
Earth's orbit

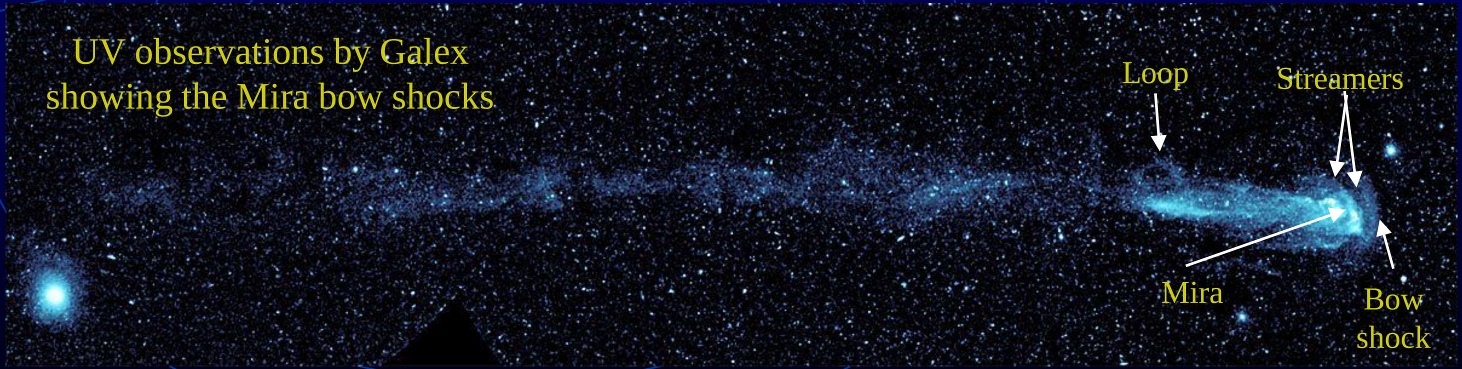
低質量 (0.4 to 8 $M_\odot$) 恆星晚年 III

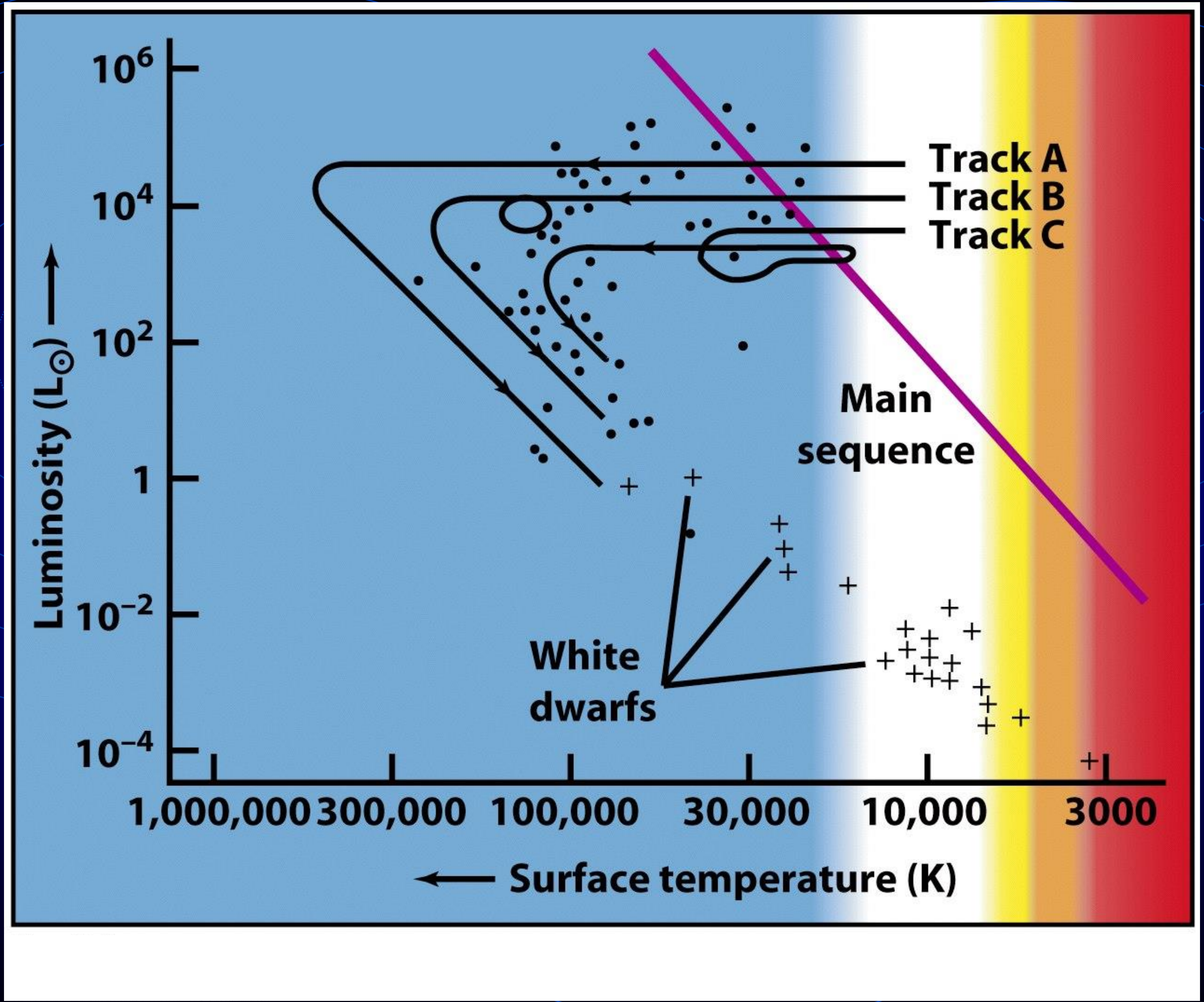
- Triple-alpha process 對溫度很敏感 (e.g., PP chain rate $\propto T^4$; triple-α $\propto T^{40}$), 只要溫度升高一點，融合速率便急遽加快 → 一系列的 helium shell flash (cf 之前在核心的 helium flash) → thermal pulses
- 最後超巨星外圍膨脹，溫度下降，電子與離子復合 (recombine)，放出光子，加上殼層氦閃發出的光子，光壓造成物質向外噴發，冷卻而凝固成塵埃。中心熾熱星體發光紫外線游離周圍氣體，使其發光，成為行星狀星雲 (planetary nebula) → HR 圖上向左移動

Mira Variables（米拉變星）

- Mira ("wonderful" in Latin)
- A pulsating red giant (M < 2 Msun) on the AGB
- P > 100 d, 1~3 mag variations ← size and temperature changes
- Significant mass loss (120 km/s), eventually becoming a planetary nebula

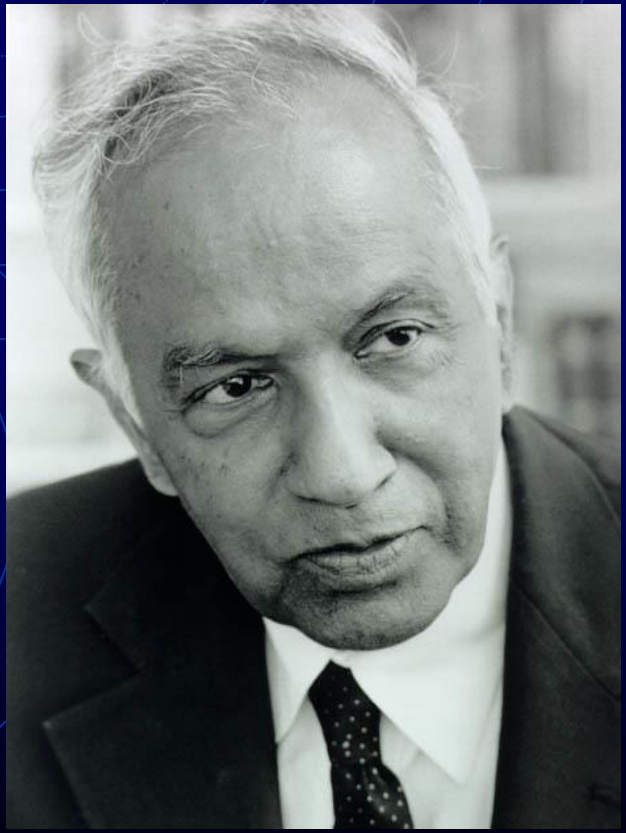


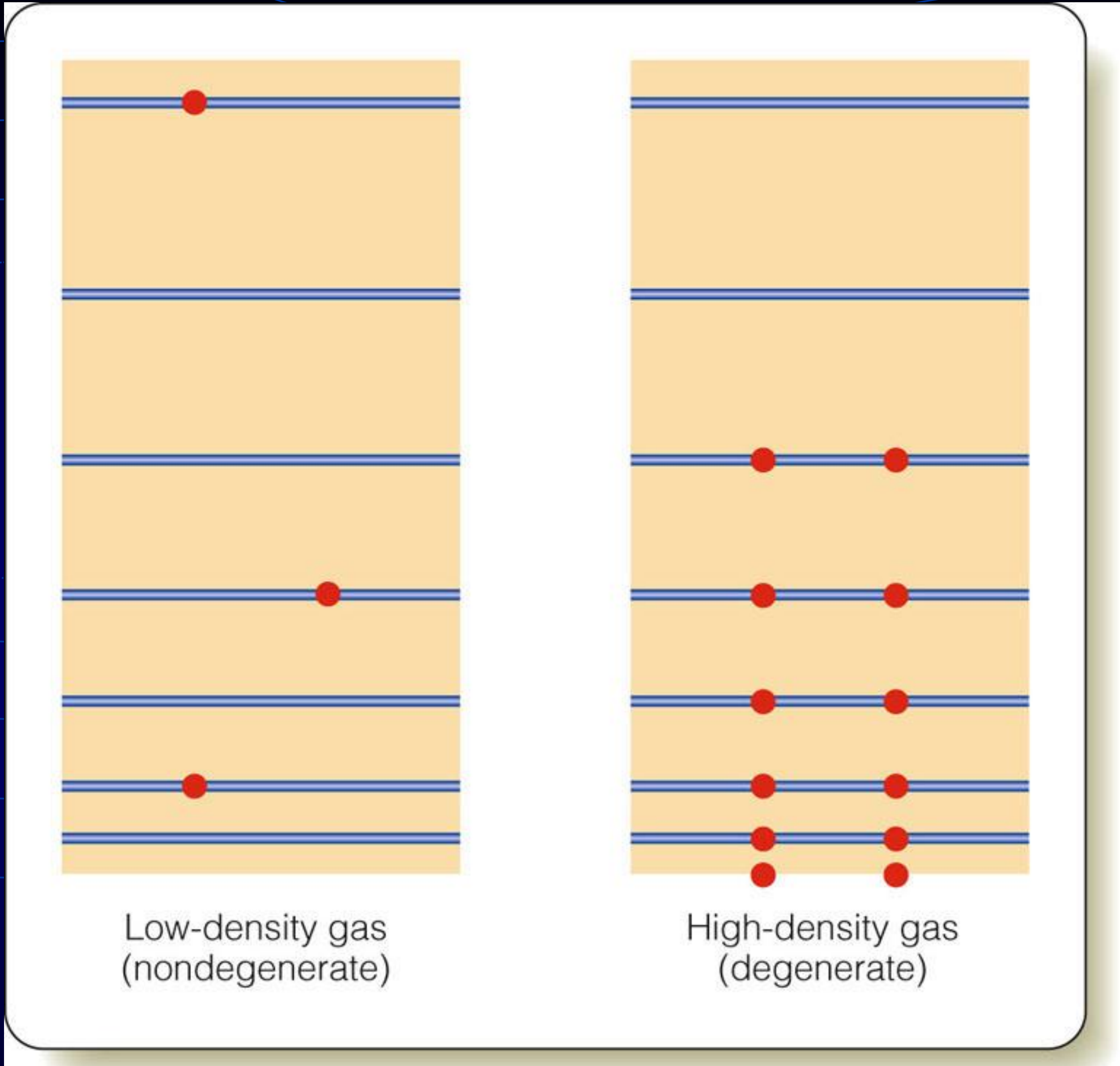




10^6
10^4
10^2
1
10^{-2}
10^{-4}
Luminosity ($L_{\odot}$)
Track A
Track B
Track C
Main sequence
White dwarfs
1,000,000
300,000
100,000
30,000
10,000
3000
Surface temperature (K)

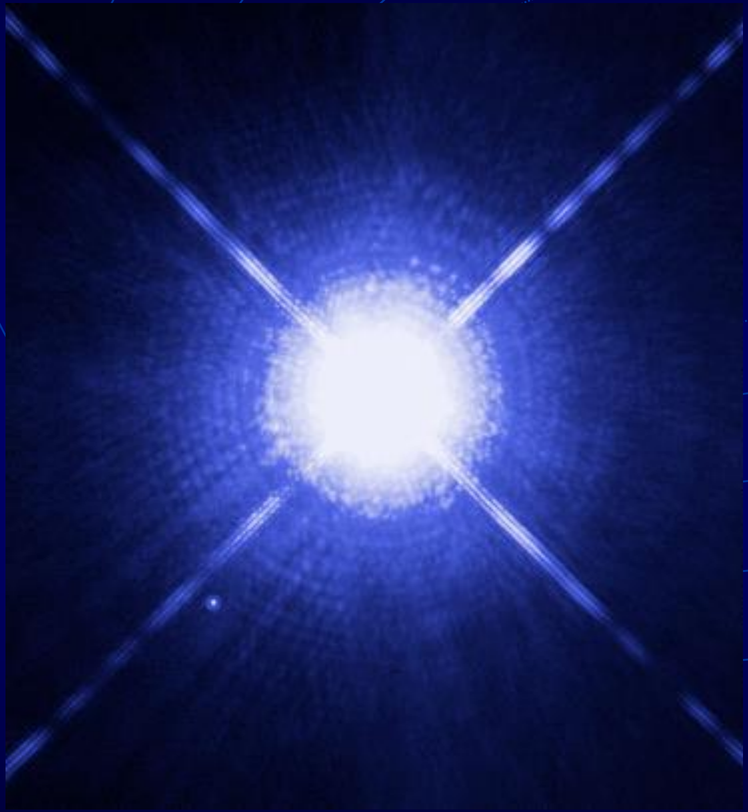
- 低質量恆星的外圍噴發出行星狀星雲，核心則演化成白矮星
- 白矮星以電子簡併壓力平衡萬有引力
- 質量（萬有引力）的上限稱為 **Chandrasekhar limit（錢氏極限）** ~1.4 $M_{\odot}$
- 白矮星的密度達 10^9 kg/m^3
- 超過此極限，連電子簡併壓力也無法抵擋引力，核心會繼續塌縮
- Subrahmanyan Chandrasekhar , 1990 Nobel Prize winner




Low-density gas
(nondegenerate)
High-density gas
(degenerate)

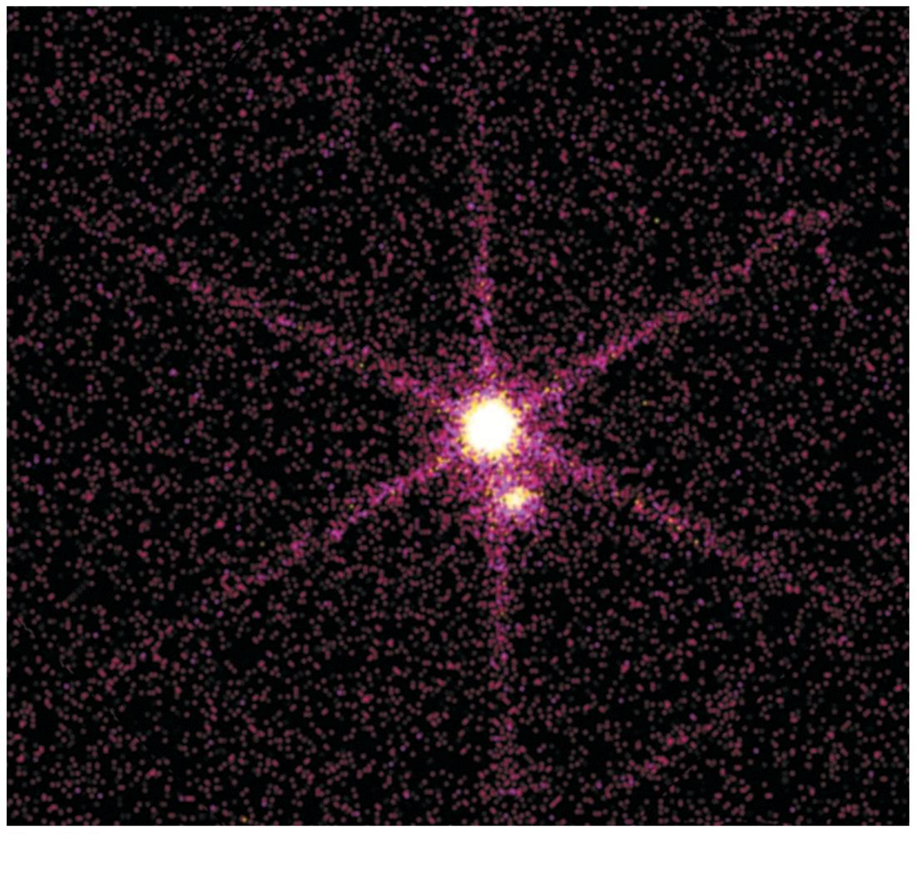
天狼星 (Sirius) 的伴星是顆白矮星。

Sirius A (11,000 K), Sirius B (30,000 K)

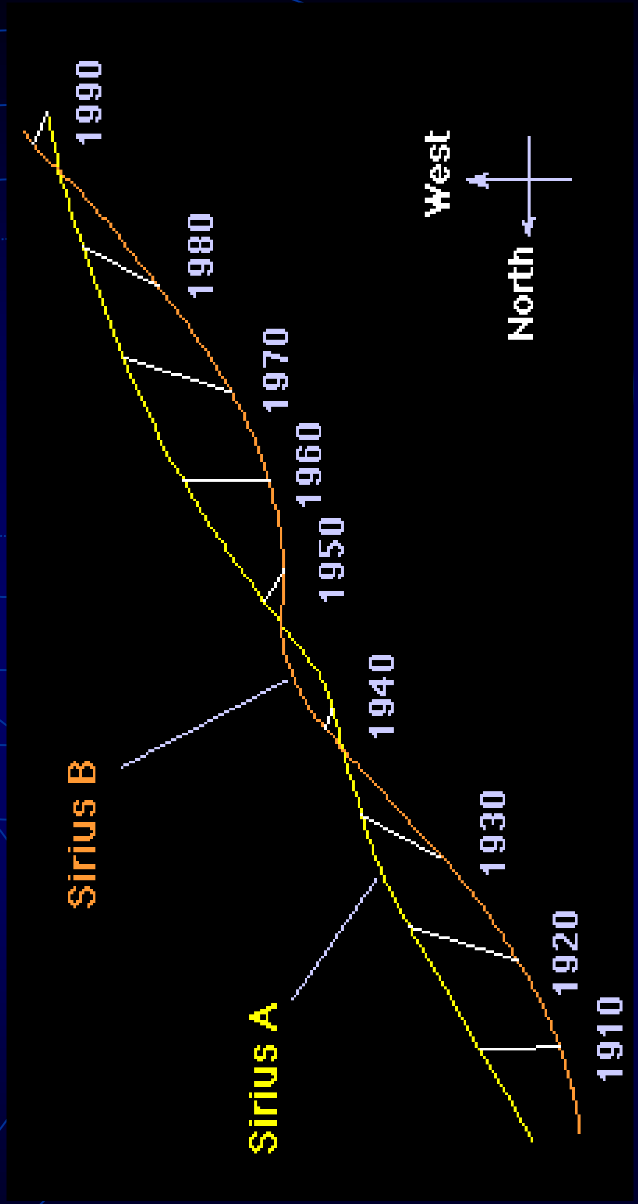


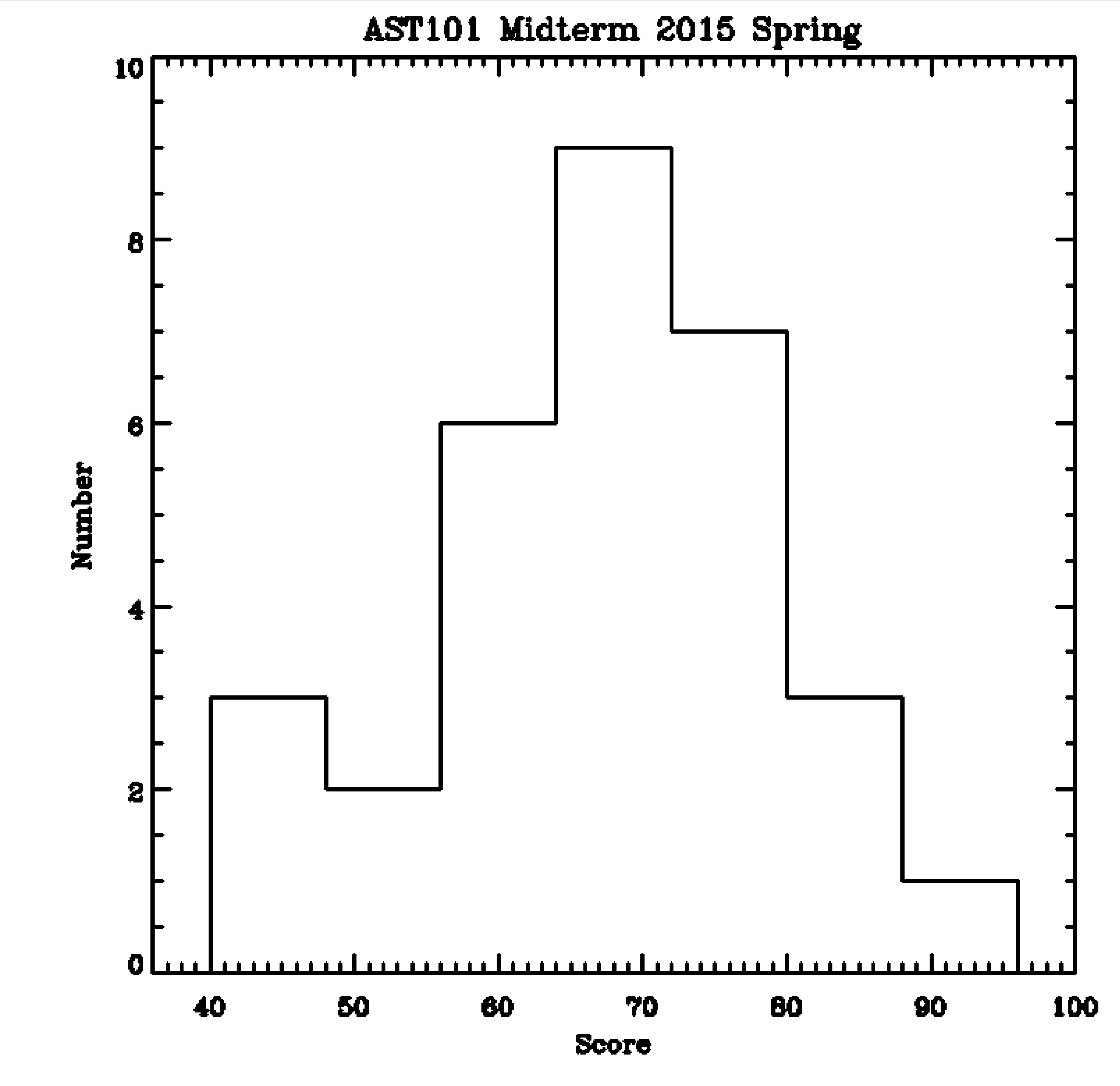
An optical image of Sirius A and Sirius B taken by the HST. Sirius B is seen to the lower left. The diffraction spikes and concentric rings are instrumental effects.

http://hubblesite.org/newscenter/archive/releases/2005/36/image/a/



An X-ray image by the Chandra Observatory. Sirius B is seen to the lower left. The diffraction spikes and concentric rings are instrumental effects. Sirius B is the brighter source.





AST101 Midterm 2015 Spring
Number
Score
0
2
4
6
8
10
40
50
60
70
80
90
100

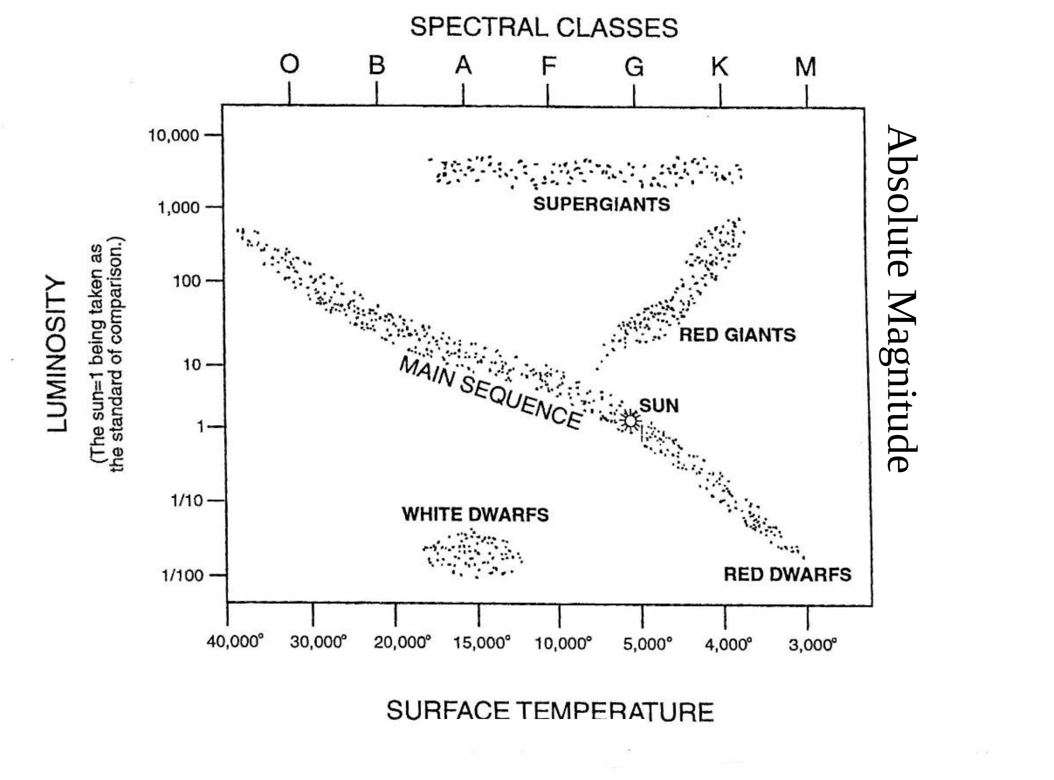
一、解釋下列名詞（3% each）

(1) brown dwarf; (2) limb darkening; (3) eclipsing binary; (4) Maunder diagram; (5) instability strip; (6) horizontal branch ; (7); proton-proton reaction; (8) interstellar reddening; (9) Population I star; (10) H II region

A star can be classified into one of the stellar spectral types of O, B, A, F, G, K, M, L, or T. (a) How does one tell which spectral type a particular star has? (b) What physical quantity does the spectral type sequence correspond to? (c) What is the spectral type of our Sun? (d) What is the luminosity class of the Sun? (20%)

Sol: (a) The spectral type of a star is determined by the stellar spectrum, by relative line strengths (type) and line width (luminosity class). (b) It is a temperature sequence, from the hottest O type stars to the coolest T. (c) The Sun is a G2 V star. (d) It is of luminosity class V, i.e., a main sequence star (also called "dwarf").

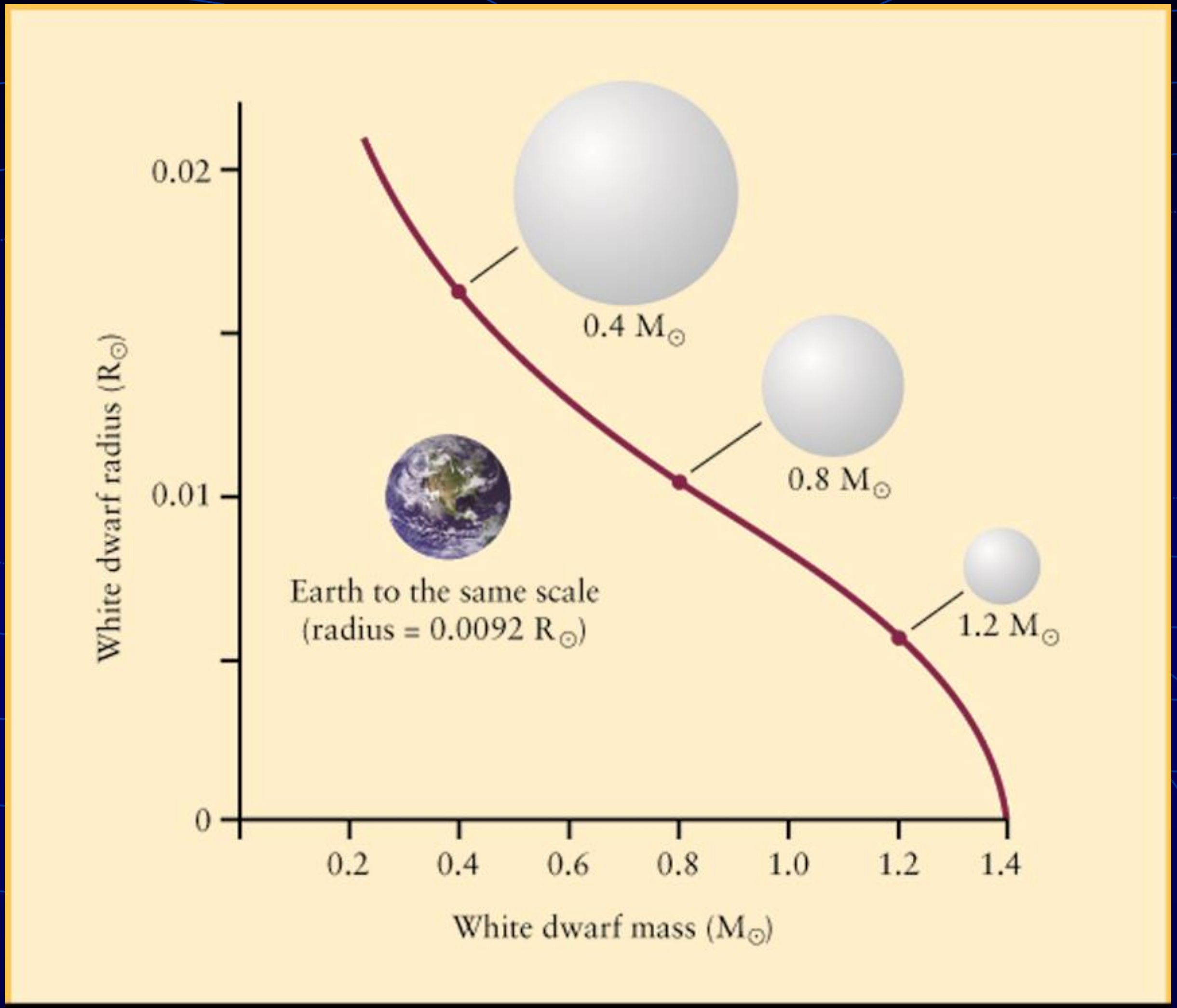
(a) Draw a Hertzsprung-Russell diagram. Clearly label and explain the physical quantity associated with each axis. (b) Draw the main sequence and mark where the Sun is in the diagram. (c) The Sun is estimated to be 5 billion years old. How is this known? (d) From our knowledge of the stellar evolution, the young Sun should be fainter by 30% than the current luminosity. Explain the physical reason of this inference. (20%)



<u>Sol</u>: (a) and (b) are as seen on the left. (c) The Sun is estimated to be about 5 billion years old, from the dating of materials on the Earth, from the Moon, and from the meteorites. The age is also consistent with our knowledge of stellar evolution. (d) The young Sun has more H than He in the core. With more particle numbers, there would be more thermal pressure to support, hence a lower energy output from, the core.

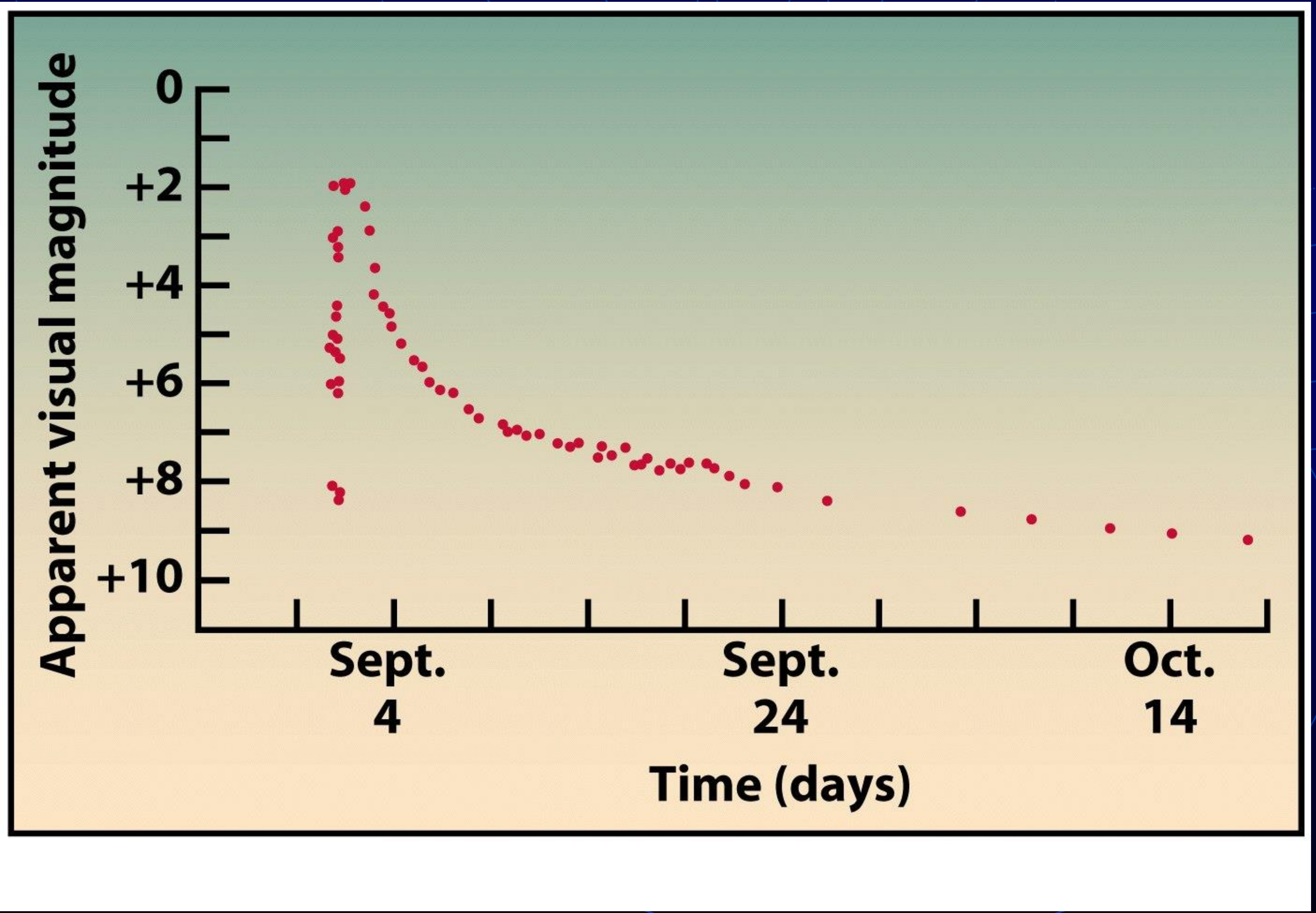
(a) What is the energy source of the Sun as a main-sequence star? State one piece of observational evidence to support your answer. (b) Stars like our Sun, after their main-sequence phase in evolution, will engage in an explosive event in their cores, called the "***helium flash***". Explain what a helium flash is, and why such an event occurs only in the core of a star with mass greater than about 0.5 $M_\odot$ and less than about 2.25 $M_\odot$. (20%)

Sol: (a) The energy source of a main-sequence star is the thermonuclear reactions in the core. Such reactions produce, in addition to energy, also neutrinos, which are detected. (b) Near the end of the main-sequence stage, the core contracts to become degenerate. Because the pressure of the degenerate matter does not increase when heated, unlike the normal ideal gas, the He core, when heated to 100 million K, is ignited in a violent way, This releases lots of energy in a short time, hence termed "helium flash". (c) The helium flash happens only in stars with masses in a certain range, because for a higher mass star, the core density is lower so it does not become degenerate when He burning starts, whereas for a lower mass star the core temperature never becomes hot enough to initiate the He fusion.

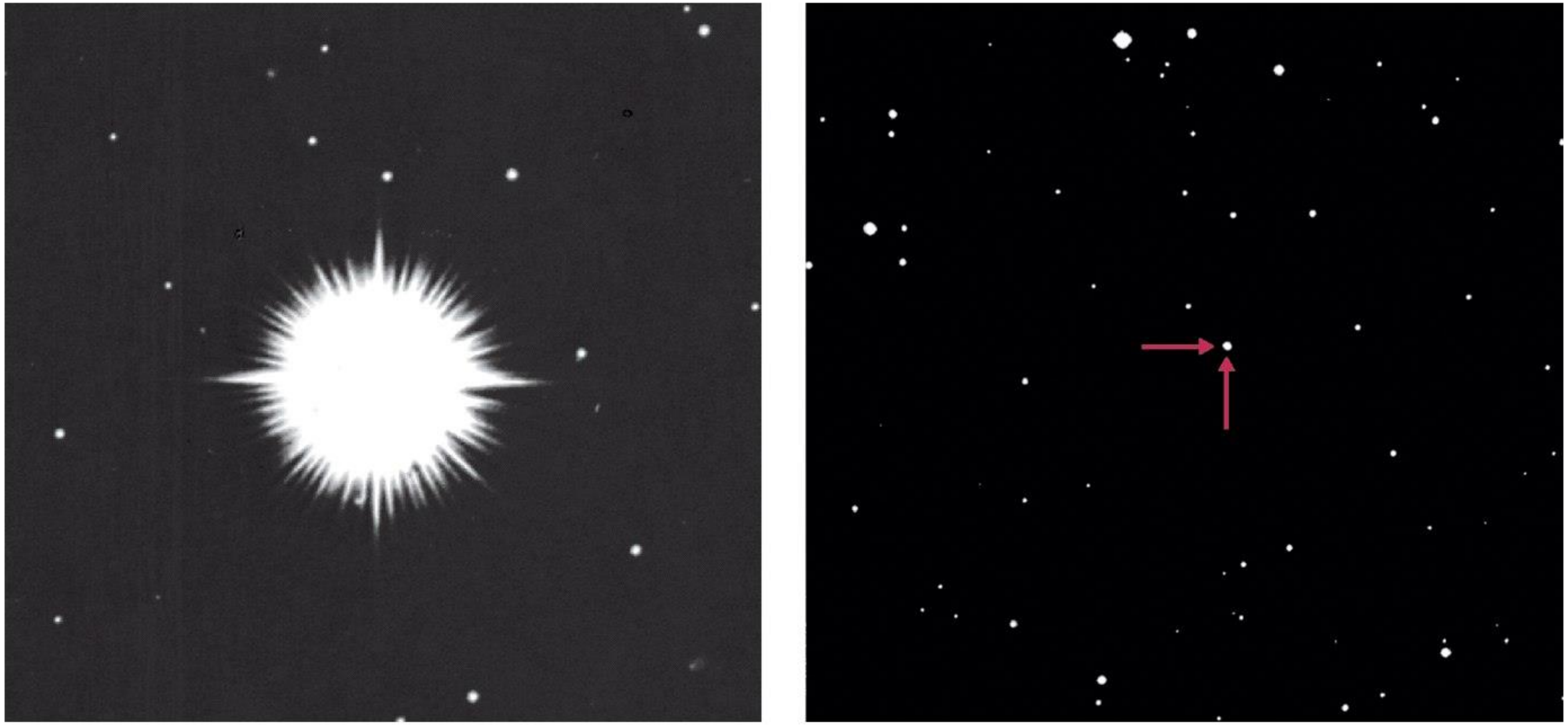


電子簡併壓力 ➔ 白矮星質量越大，直徑越小

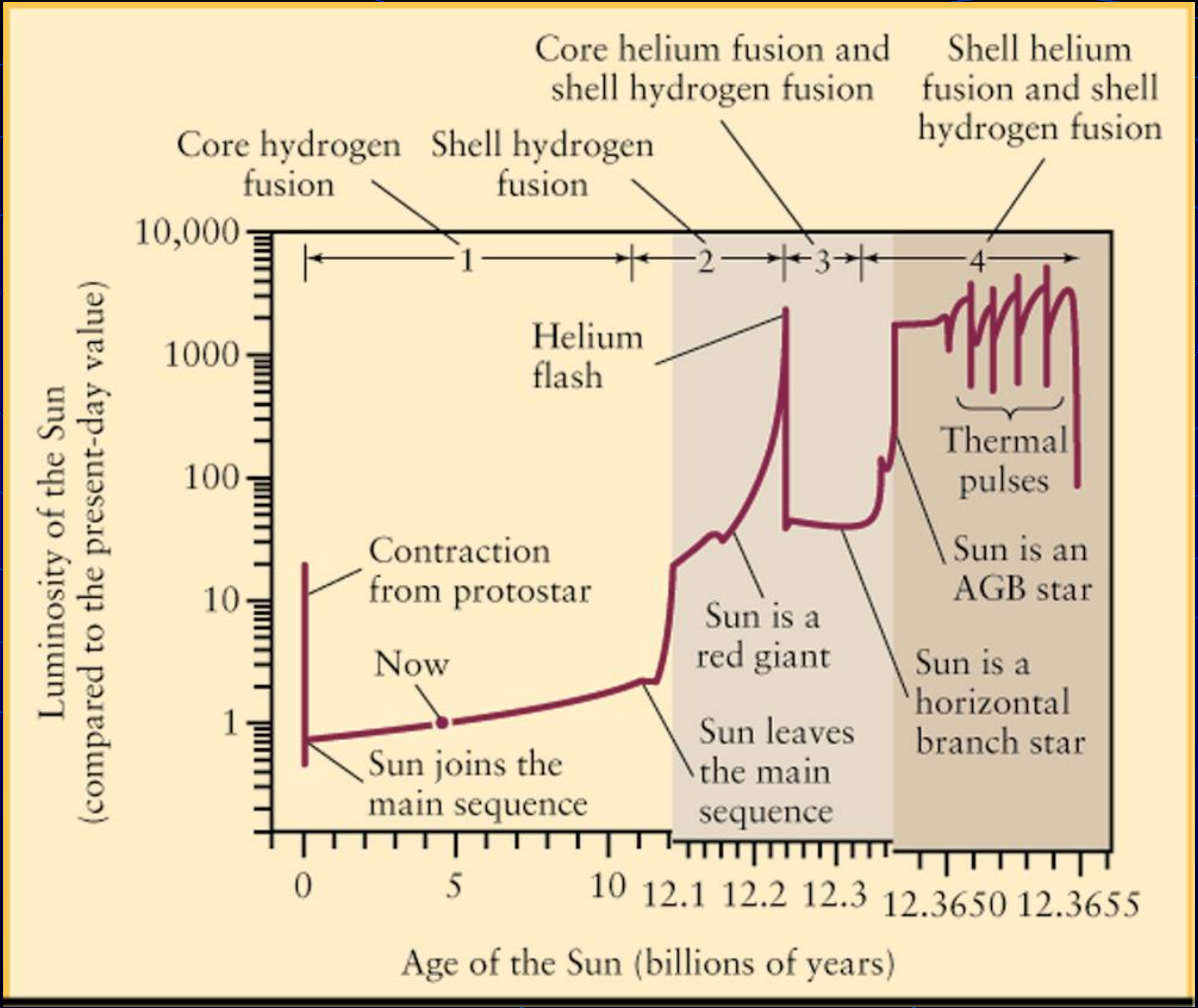
Nova（新星） is a close binary containing a white dwarf. The ordinary companion star fills its Roche lobe so deposits fresh H onto the WD.

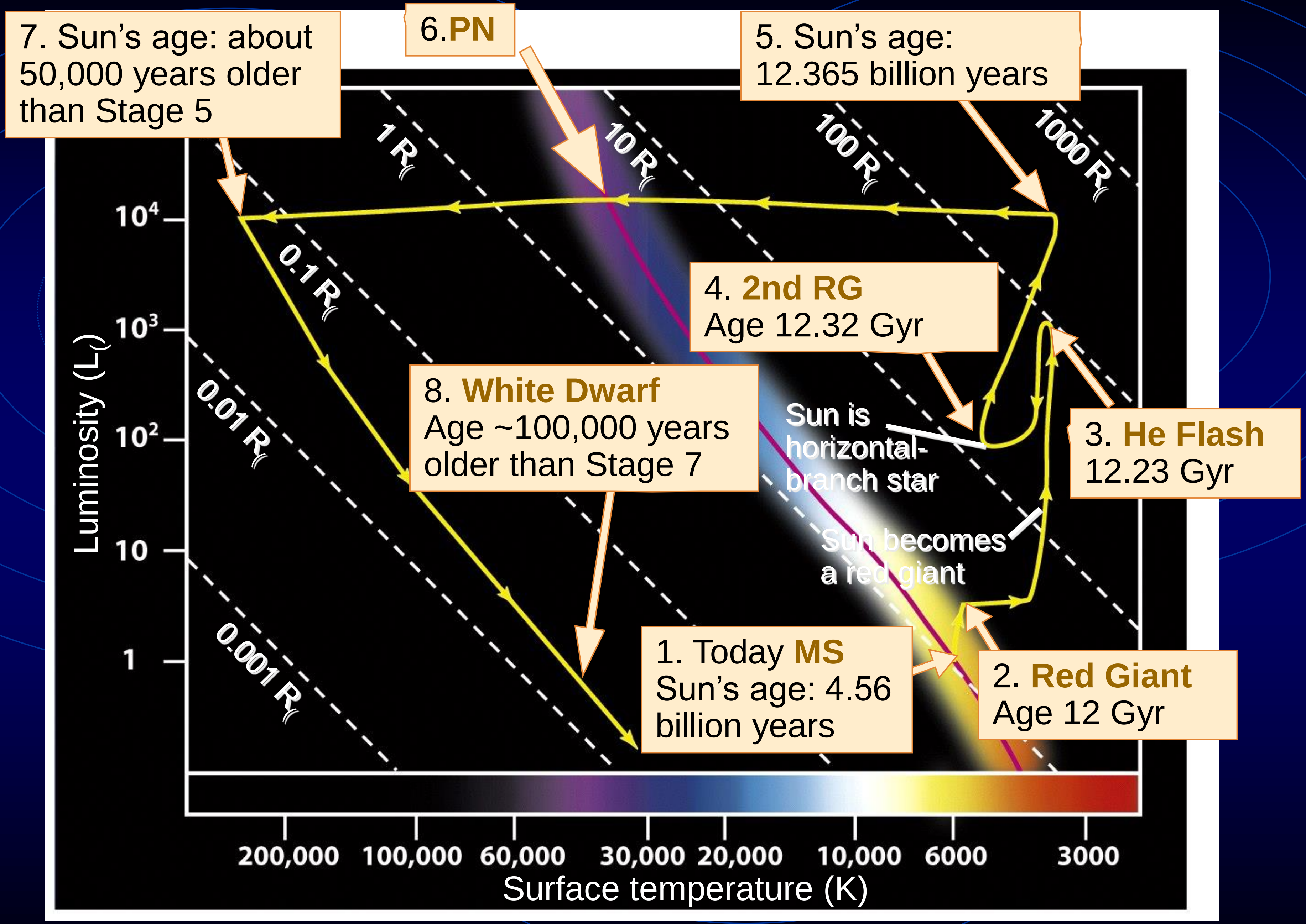


Nova Herculis 1934



during explosion (–3 mag) 2 months later (+12 mag)


Core hydrogen fusion
Shell hydrogen fusion
Core helium fusion and shell hydrogen fusion
Shell helium fusion and shell hydrogen fusion
1
2
3
4
10,000
1000
100
10
1
Helium flash
Thermal pulses
Contraction from protostar
Now
Sun joins the main sequence
Sun is a red giant
Sun leaves the main sequence
Sun is a horizontal branch star
Sun is an AGB star
0
5
10
12.1
12.2
12.3
12.3650
12.3655
Luminosity of the Sun (compared to the present-day value)
Age of the Sun (billions of years)



7. Sun's age: about 50,000 years older than Stage 5
6. PN
5. Sun's age: 12.365 billion years
4. 2nd RG
Age 12.32 Gyr
3. He Flash
12.23 Gyr
2. Red Giant
Age 12 Gyr
1. Today MS
Sun's age: 4.56 billion years
8. White Dwarf
Age ~100,000 years older than Stage 7
Sun is horizontal-branch star
Sun becomes a red giant
1 R
10 R
100 R
1000 R
0.1 R
0.01 R
0.001 R
10⁴
10³
10²
10
1
Luminosity (L)
200,000
100,000
60,000
30,000
20,000
10,000
6000
3000
Surface temperature (K)

中質量 (8 to 25 $M_{\odot}$) 與 大質量(>25 $M_{\odot}$) 恆星晚年

- 核心消耗速度快，收縮快，以劇烈方式點燃下級核反應
- 核心萬有引力強，連擠壓原子的力量都撐不住 → 原來貼靠在原子核外面的電子被擠進原子核，結合成中子 （中子簡併狀態）

$$e^- + p^+ \rightarrow n^0 + \nu$$

→ **中子星 (neutron star)**

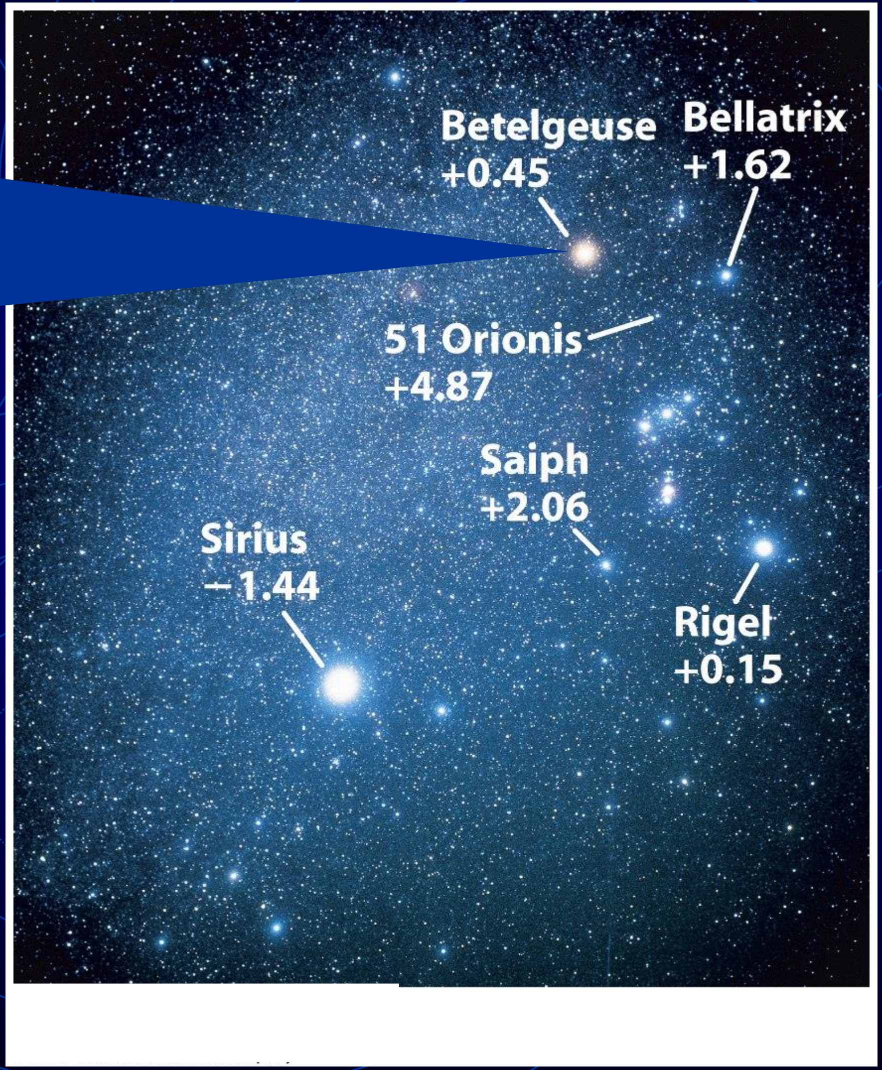
- 劇烈收縮造成強力反彈，把外層爆發開

→ **超新星爆發 (supernova explosion)**

- When a supernova explodes, it may outshine the entire host galaxy.

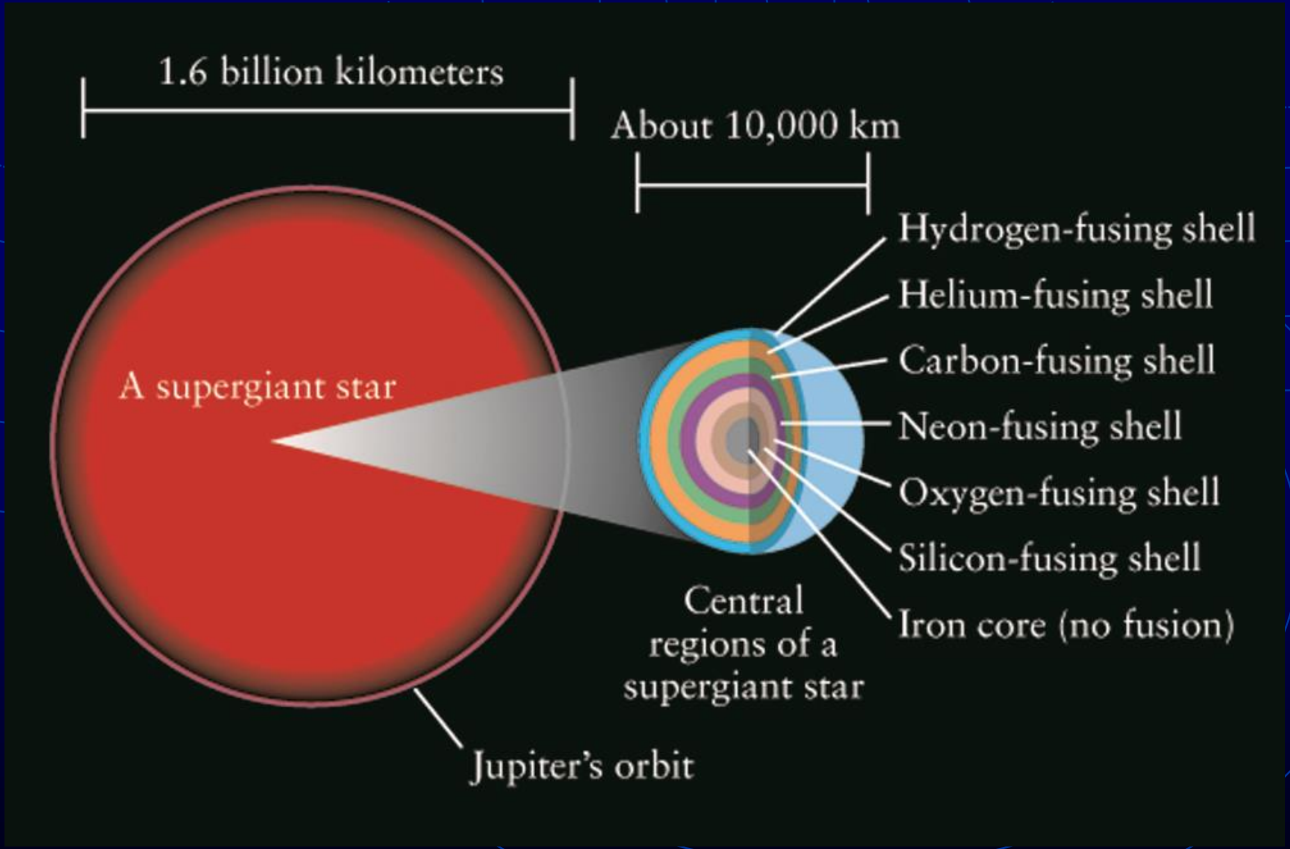
超巨星有強烈恆星風

例如 Betelgeuse 每年損失 $1.7 \times 10^{-7}\ M_{\odot}$，物質以 10 km/s 速率噴出，環繞在星球周圍達 1/3 光年。



中、大質量恆星演化晚期結構

- 外層成為超巨星，直徑相當於木星軌道
- 核心大小約如地球，有層層核反應（cf 洋蔥）



下一級核融合反應越來越快 矽核融合 → 鐵元素

鐵原子核當中的質子與中子已經縮得很緊，進一步核融合無法再釋放能量 → 鐵核塌縮
(D～3000 km, collapses in 0.1 s)

Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Central temperature (K)	Central density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 yr
Helium fusion	2×10^8	7×10^5	5×10^5 yr
Carbon fusion	6×10^8	2×10^8	600 yr
Neon fusion	1.2×10^9	4×10^9	1 yr
Oxygen fusion	1.5×10^9	1×10^{10}	6 mo
Silicon fusion	2.7×10^9	3×10^{10}	1 d
Core collapse	5.4×10^9	3×10^{12}	0.2 s
Core bounce	2.3×10^{10}	4×10^{17}	milliseconds
Supernova explosion	about 10^9	varies	10 seconds

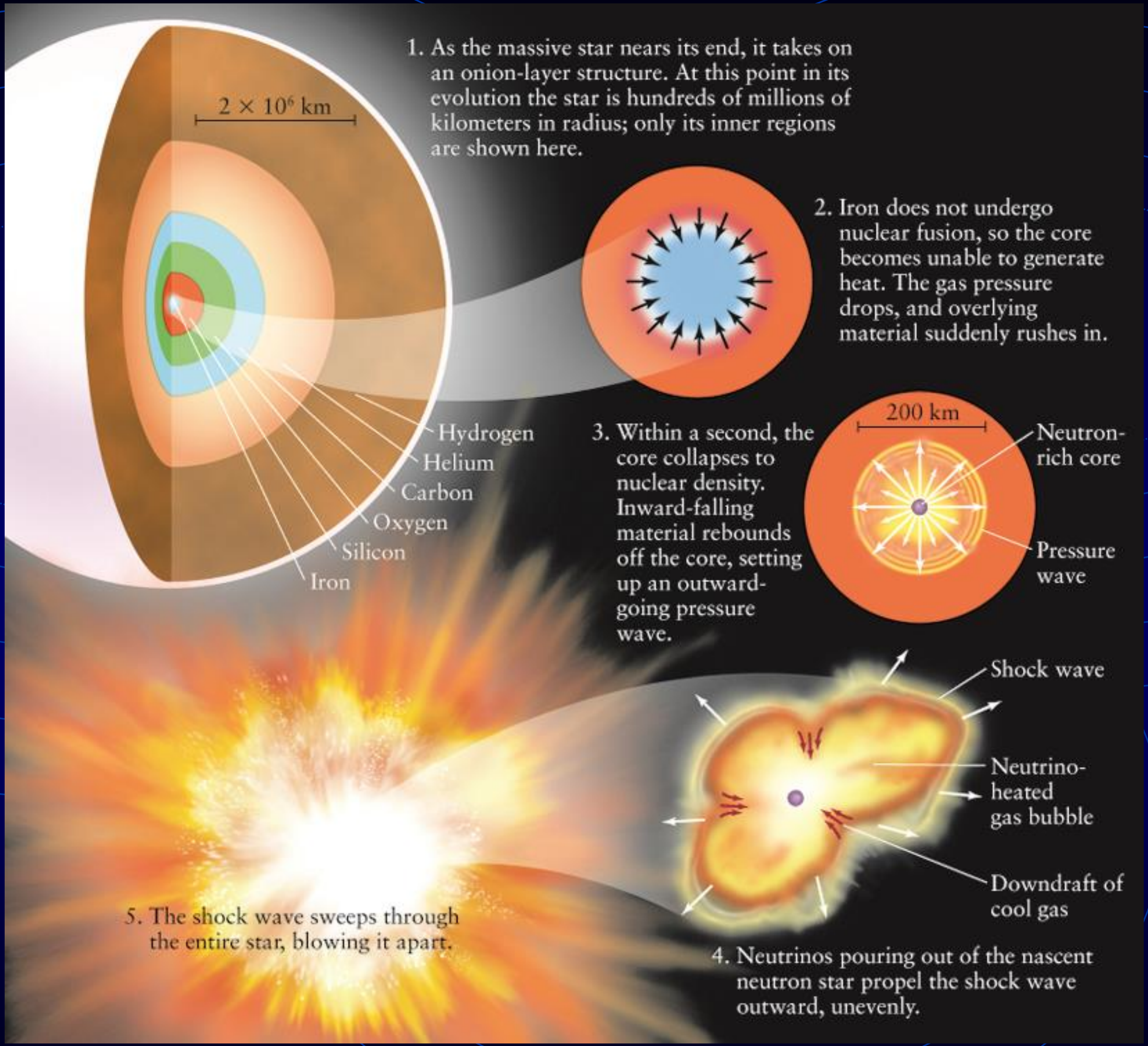
鐵核塌縮溫度達 5 billion K，極高能量的gamma rays 光子將鐵原子核**光分解 (photodisintegration)**

恆星花了數百萬年在主序上，將氫、氦融合成鐵，然後在不到一秒內，又將鐵元素分解成質子、中子與電子！

核心密度急速增大，在塌縮後1/4秒，密度達 4×10^{17} kg/m^3（相當於原子核的密度），電子與質子結合成中子，放出大量微中子 (neutrinos)。中子簡併壓力抗拒塌縮
→ **核心反彈 (core bounce)**
→ 超新星爆發 (supernova explosion)

雲消霧散後，成為超新星遺骸 (supernova remnant)

超新星不是「星」，就好像流星也不是，兩者都是「現象」


2 × 10⁶ km
1. As the massive star nears its end, it takes on an onion-layer structure. At this point in its evolution the star is hundreds of millions of kilometers in radius; only its inner regions are shown here.
Hydrogen
Helium
Carbon
Oxygen
Silicon
Iron
2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in.
3. Within a second, the core collapses to nuclear density. Inward-falling material rebounds off the core, setting up an outward-going pressure wave.
200 km
Neutron-rich core
Pressure wave
Shock wave
Neutrino-heated gas bubble
Downdraft of cool gas
4. Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly.
5. The shock wave sweeps through the entire star, blowing it apart.

AstroNews

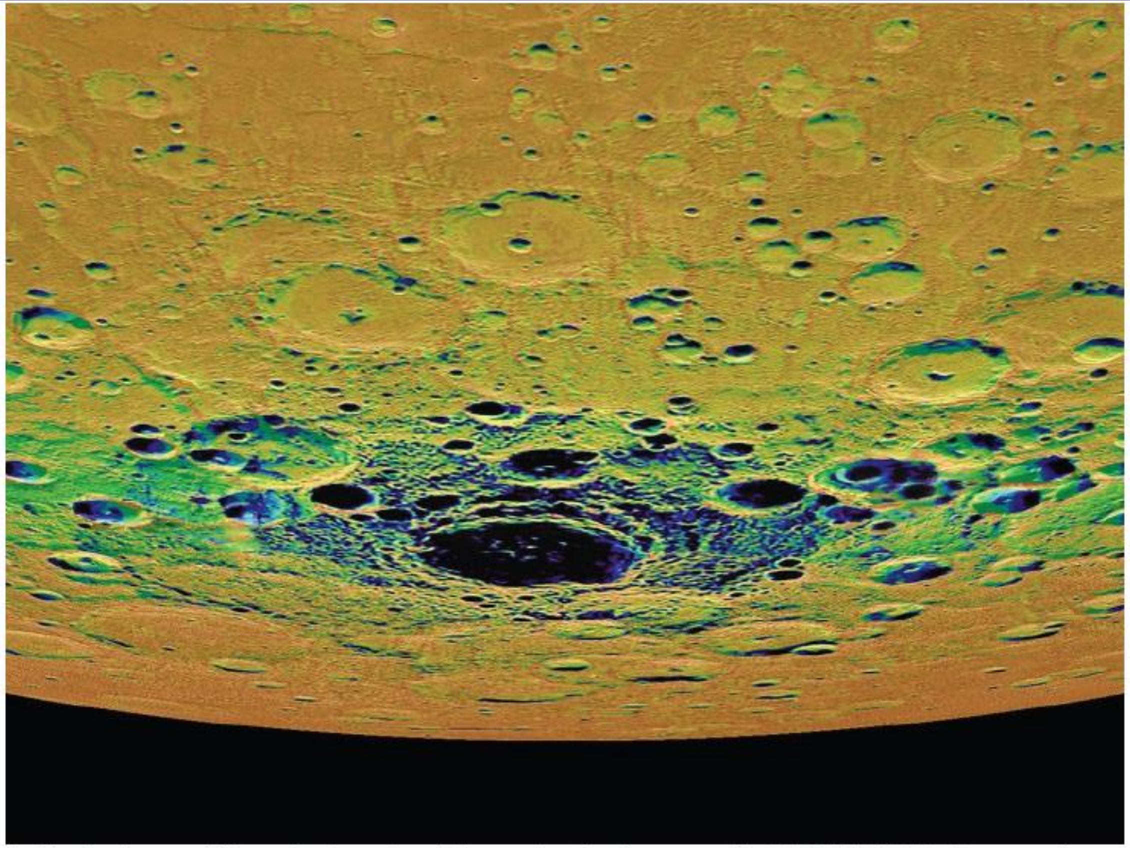
Messenger is scheduled to plunge onto Mercury on April 30.

2015/4/30 MESSENGER Comes To a Crashing End on Thursday | Daily Planet | Air & Space Magazine

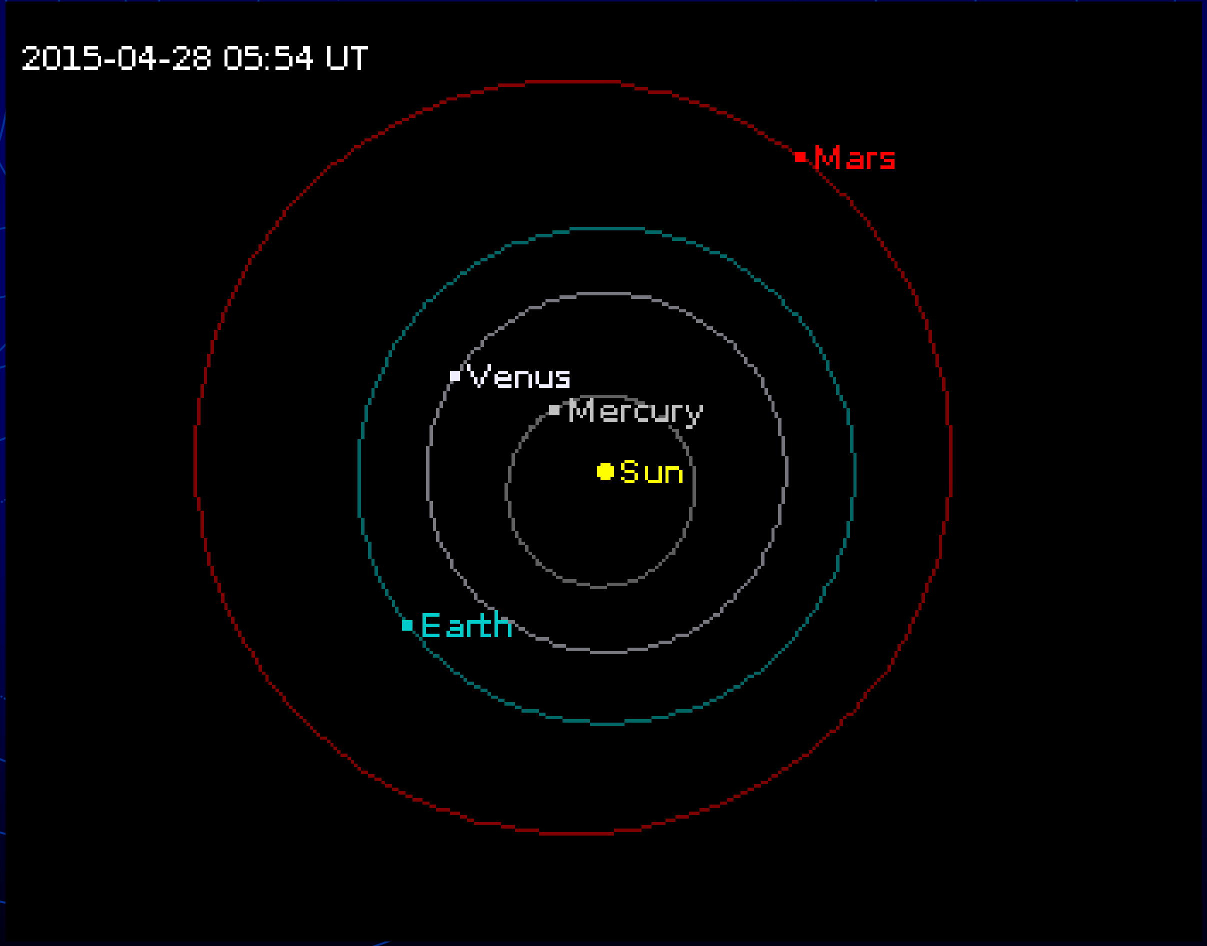
AirSpaceMag.com

MESSENGER Comes To a Crashing End on Thursday

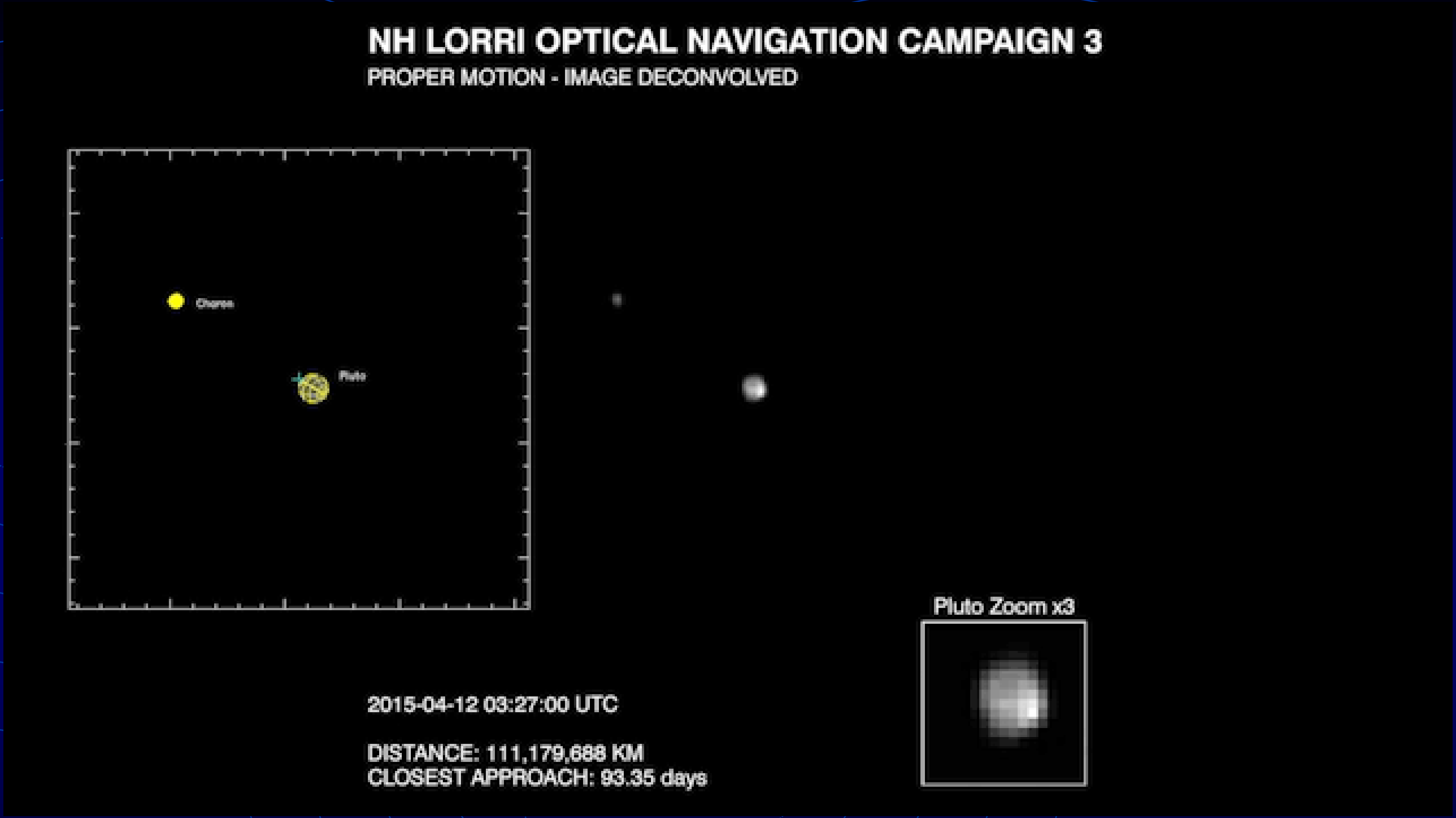
With its mission over, NASA's Mercury orbiter will slam into the planet it's been studying for years.



An illumination map of the south polar region of Mercury, based on data returned by MESSENGER. Black areas are in permanent shadow. (NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington)



AstroNews



New Horizons is expected to arrive at Pluto July 14, 2015.

Homework 150430   due in a week

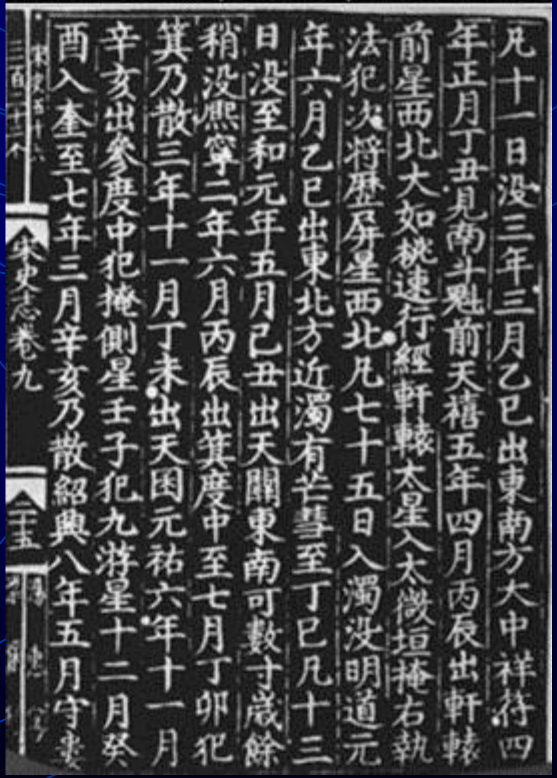
Write an essay about the *Messenger* project, about the spacecraft, its mission goals, schedule, and outcome.

位於金牛座方向的蟹狀星雲 (Crab Nebula)，距離我們 6000 光年，源於 AD1054年超新星爆發（當時中國天官記錄有詳細記載，故稱「中國超新星」。

星雲本身大小約7光年 ×10光年，以每秒1500公里速率向外膨脹

西元1054年七月（宋仁宗至和元年五月）金牛座超新星爆炸，據記載最明亮時相當於太白（金）星的光芒，長達23天在白天可見，直到1056年四月（宋嘉祐元年三月）肉眼才看不見。

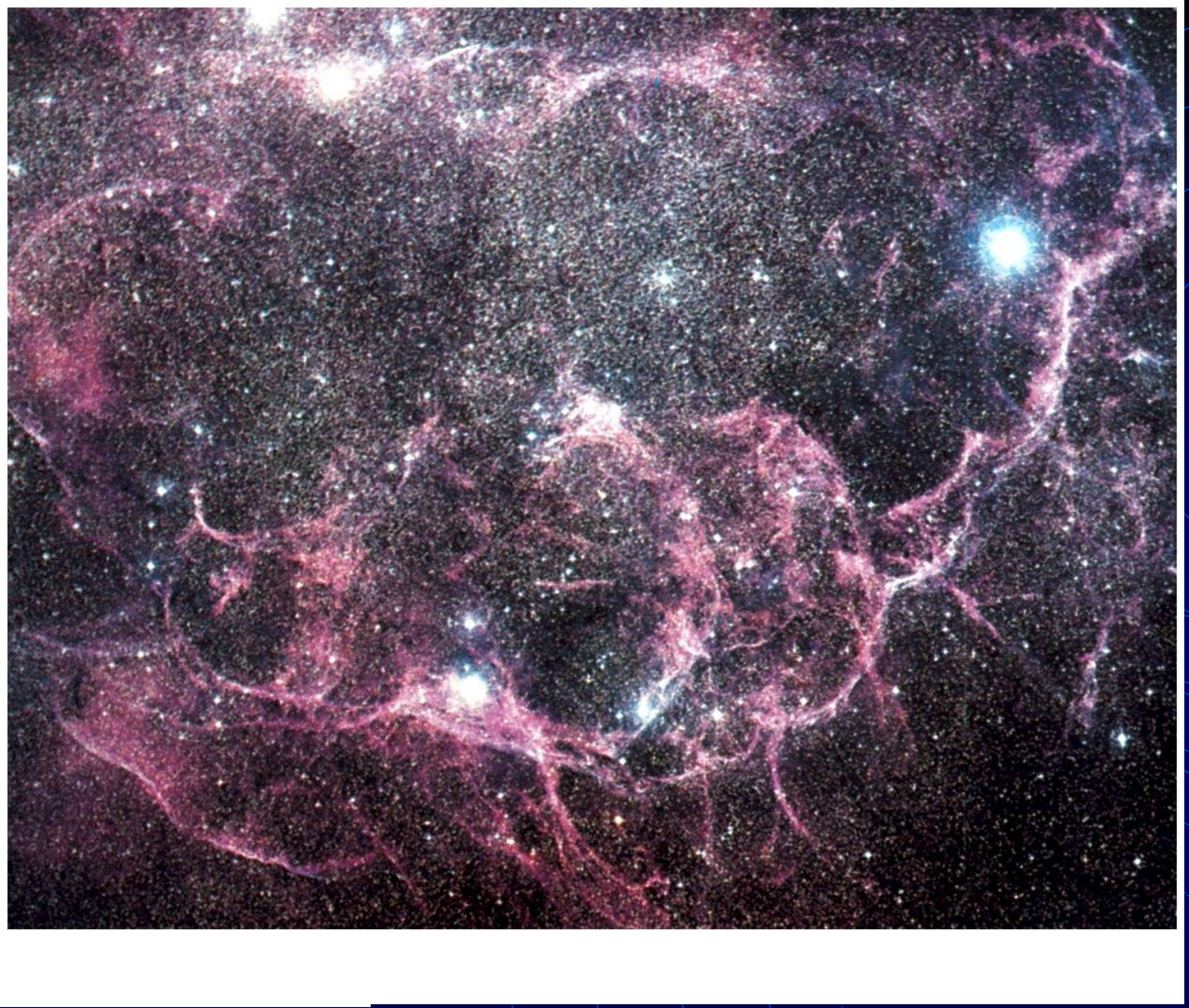
天關客星



凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

http://www.phys.ncku.edu.tw/~astrolab/e_book/history_c/captions/guest_star.html

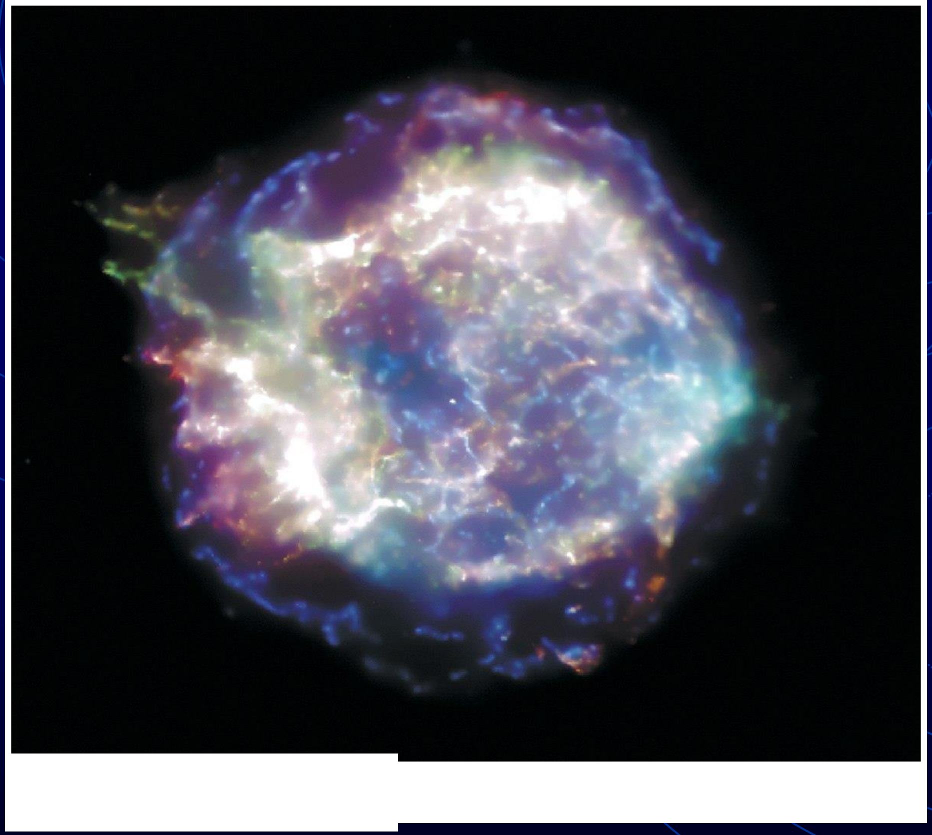


Gum Nebula 是全天空最大的超新星遺骸，來自 11,000 年前的超新星爆發。

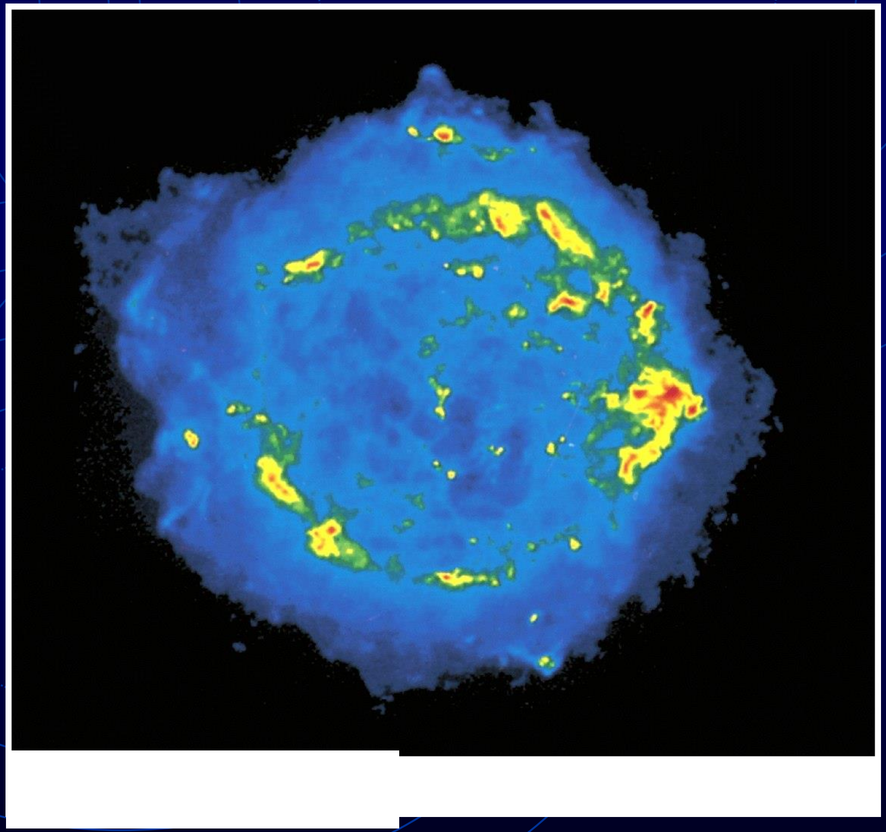
Gum Nebula 直徑超過2300光年，跨越天空60度，離我們最近的部分只有300光年

http://twanight.org/newTWAN/photos.asp?ID=3004052

Cassiopeia A 超新星遺骸，離我們10,000光年。地球應該於300年偵測到爆發事件，但歷史並無記載



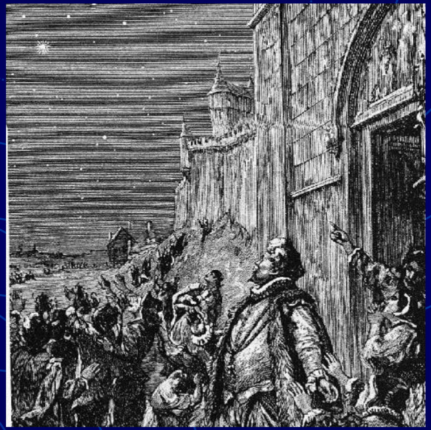
X 射線影像

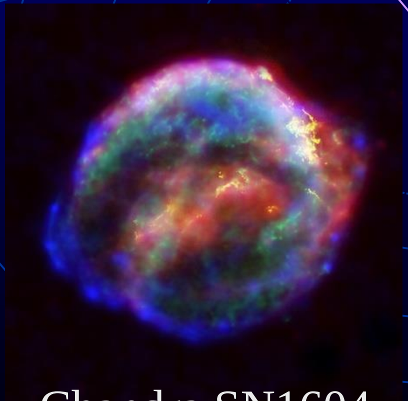


電波影像

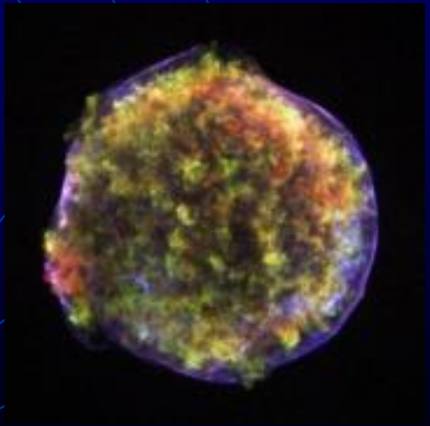
歷史上的超新星

- (OB association in Scorpius-Centaurus 在2百萬年前距離地球 < 150 光年，曾發生超新星爆發)
- 1054 AD 中國超新星
- 1572 Tycho supernova
- 1604 Kepler supernova
- 下一個？



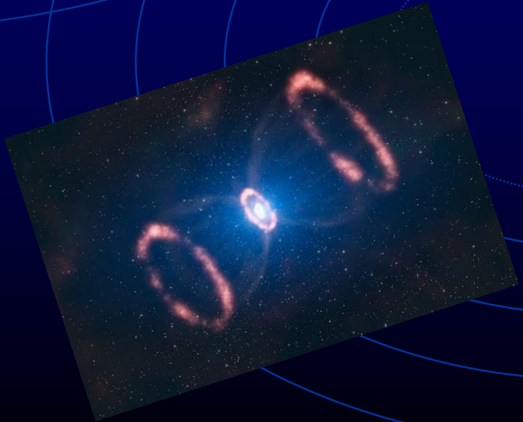


Chandra SN1604



Chandra SN1572

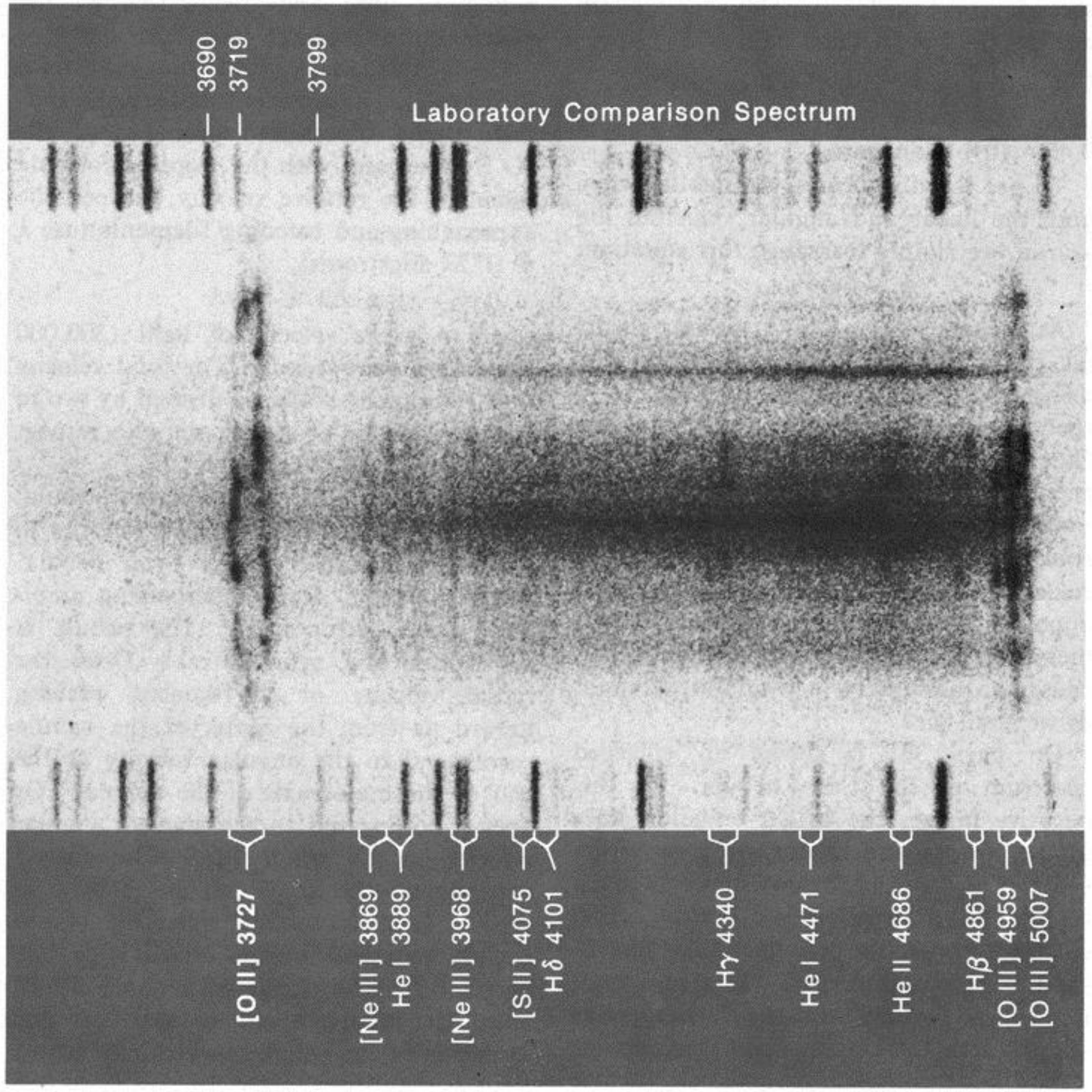

銀河系鄰近的星系 Large Magellanic Cloud 當中，原來不起眼的某顆星，於1987年2月在地球上看到其爆發，耀眼異常，稱為 **SN1987A**




王為豪 拍攝

http://www.astrographics.com/GalleryPrintsIndex/GP1614.html

The Expanding Crab Nebula
1973 to 2001



The spectrum of the Crab nebula, obtained at Lick Observatory by N. U. Mayall with the Crossley reflector. The spectrograph slit was aligned with the major axis of the nebula (here vertical), to record velocity differences along that axis. These are best shown by the necklace shape of the 3727-angstrom oxygen line. A laboratory spectrum of palladium, tin, and lead flanks that of the Crab to give a wavelength scale; nebular lines are identified at bottom.

超新星的種類

- 單一大質量恆星衰亡後，核心變成超新星

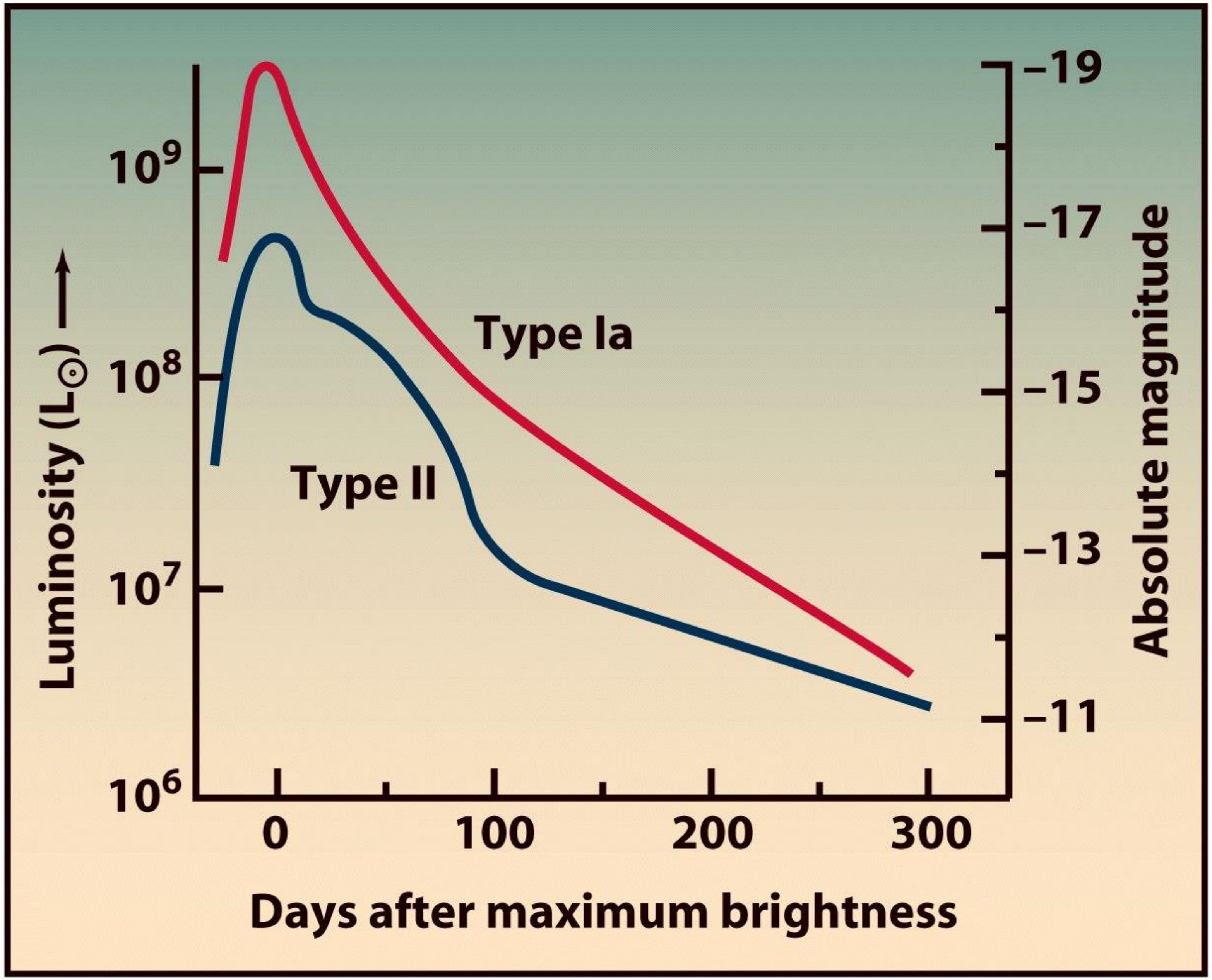
  ➔ **Type II supernovae**

  - 光譜裡有明顯氫線
  - 最亮時達絕對星等 −17 等，光度變暗有急緩

- Semi-detached 雙星系統中白矮星可能藉由吸積伴星物質，造成核心碳融合，而引發超新星爆發

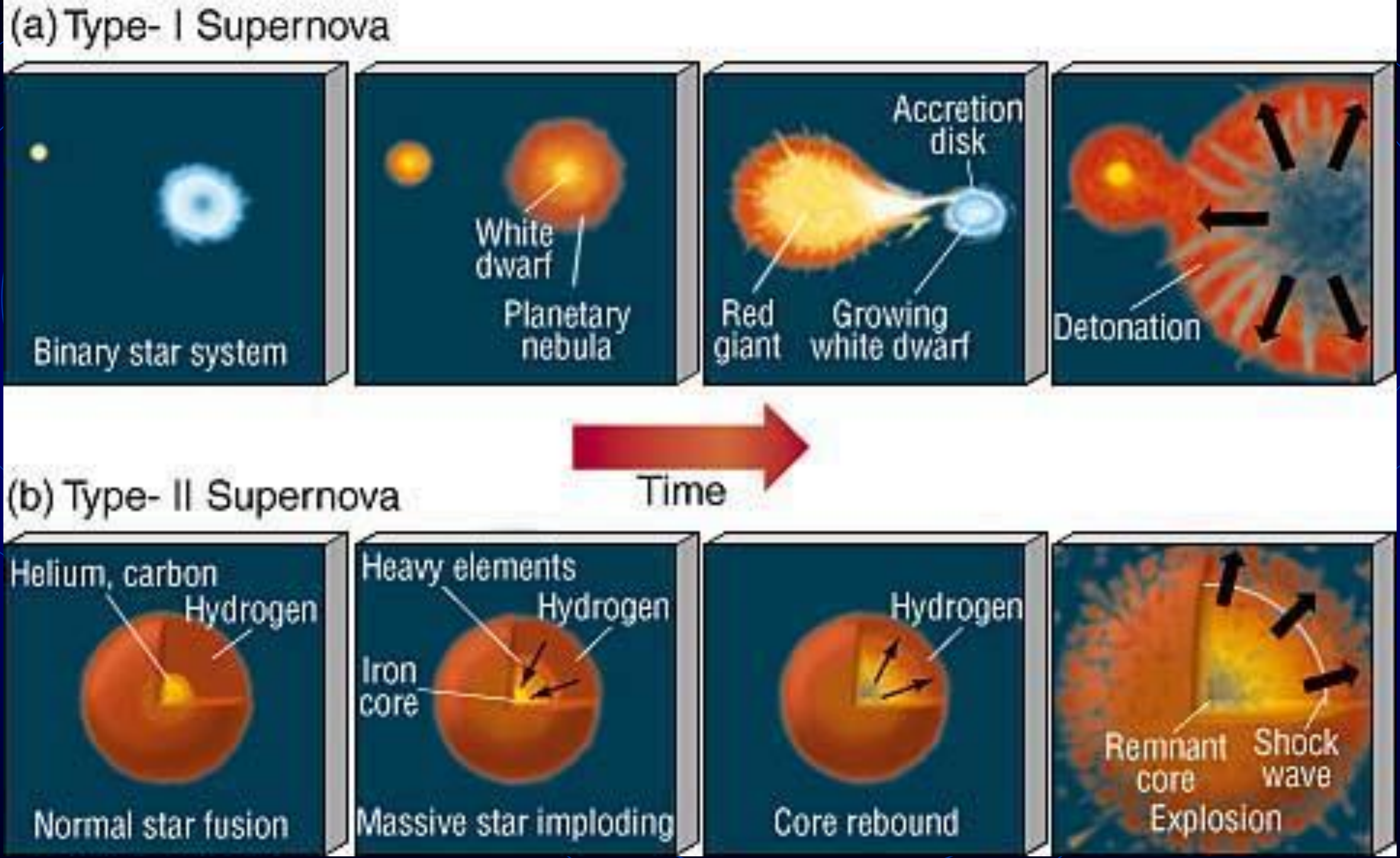
  ➔ **Type Ia supernovae**

  - 光譜裡沒有氫線
  - 最亮達 M~ −19 等，之後緩緩（1 年）變暗



Luminosity ($L_\odot$)
10^9
10^8
10^7
10^6
Type Ia
Type II
0
100
200
300
Days after maximum brightness
−19
−17
−15
−13
−11
Absolute magnitude

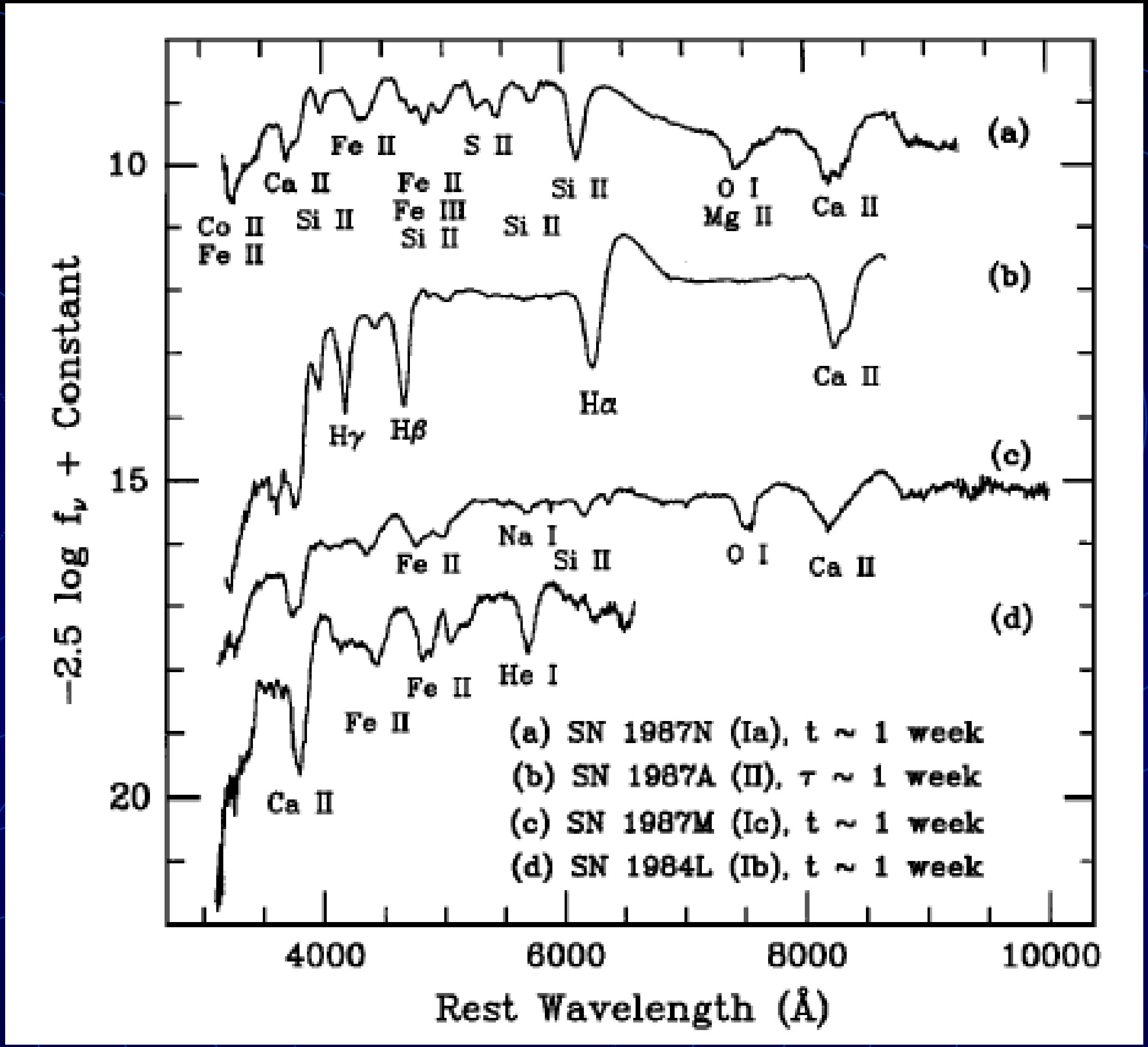
Supernova	Type Ia	Type II
來源	接近 Chandrasekhar 極限的白矮星吸積 ➔ 老年恆星附近	大質量恆星演化的結果 ➔ 年輕恆星附近
光譜	沒有氫氣，有很多其他元素譜線	主要為氫氣
極亮星等	−19 to −20	−17
全部爆發能量	5 x 10^{43} joules	10^{44} joules
噴發出的質量	0.5 $M_{\odot}$	5 $M_{\odot}$
噴發速率	10,000 km/s	5,000 km/s


(a) Type- I Supernova
Binary star system
White dwarf
Planetary nebula
Accretion disk
Red giant
Growing white dwarf
Detonation
Time
(b) Type- II Supernova
Helium, carbon
Hydrogen
Normal star fusion
Heavy elements
Hydrogen
Iron core
Massive star imploding
Hydrogen
Core rebound
Remnant core
Shock wave
Explosion

超新星爆發的能量來源

- 一個 1.4 $M_{\odot}$ 的星體塌縮成 R～15 km（也就是中子星）為例
- $E_{grav} = GM^2/R = 6.6 \times 10^{-11}$ N m^2/kg^2 $\times$ ($1.4 \times 2 \times 10^{30}$ kg)^2 / 15×10^3 m $= 4 \times 10^{46}$ joules
- So, the gravitational energy is sufficient to power an SN.

發現超新星——
比對星系影像



超新星爆發早期光譜 (Filippenko 1997, ARAA 35, 309)

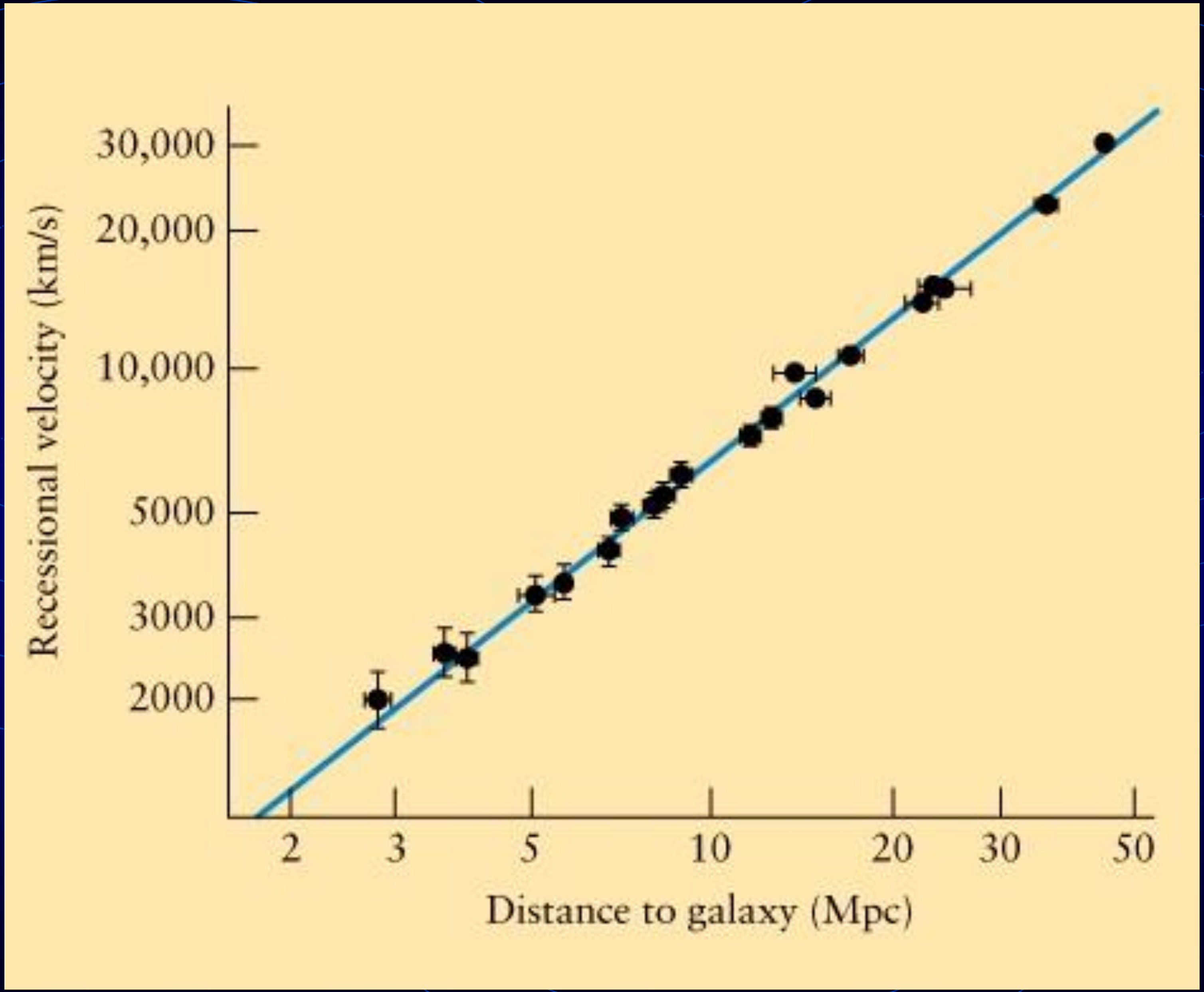
Useful web reference

http://www.arikah.com/encyclopedia/Supernova

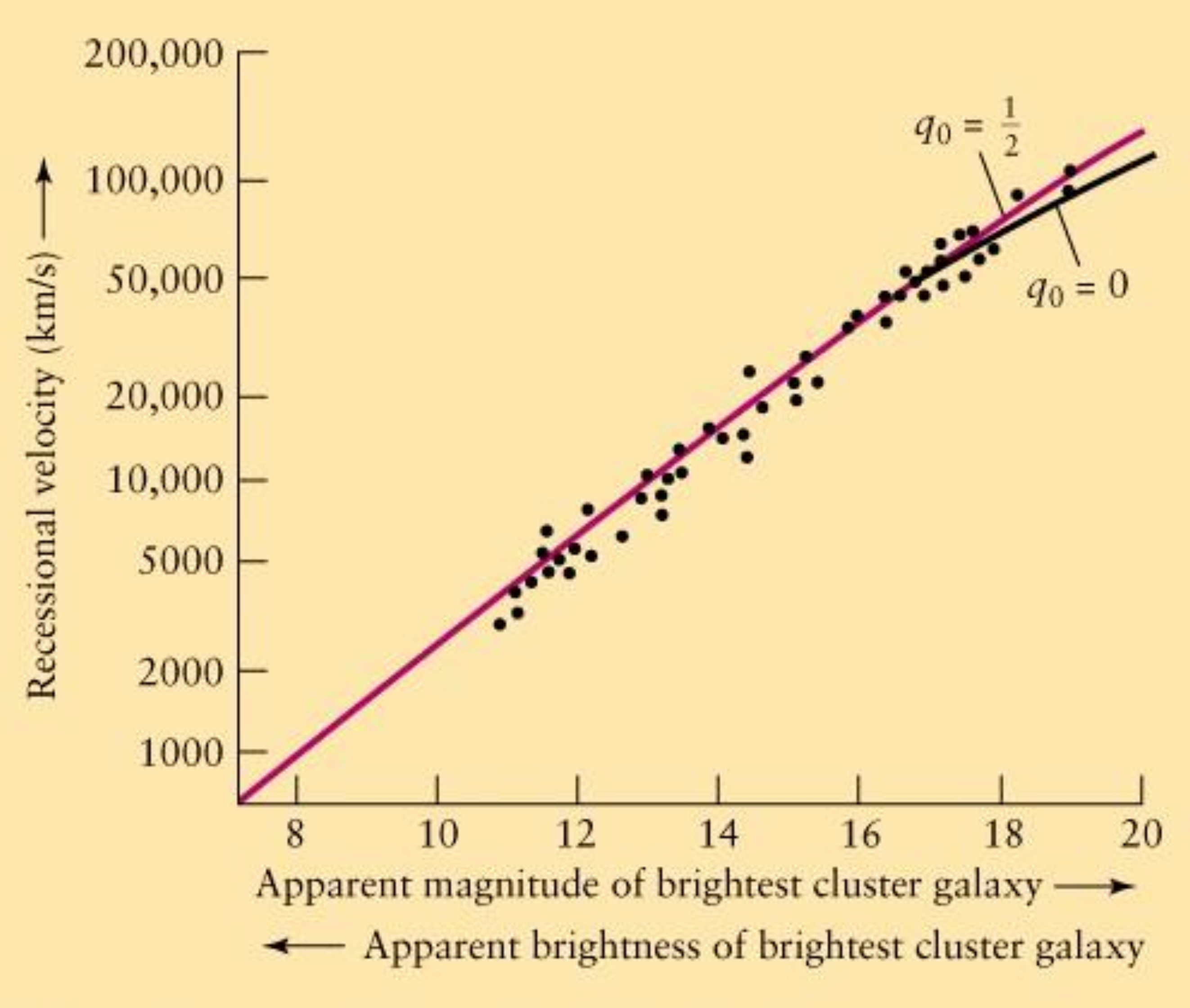
- Ia 型超新星能量來自核融合，爆發產生多種 radioactive isotopes , e.g., nickel 衰變成 cobalt
- 目前已經觀測到（別的星系中）超過數千顆超新星
- 銀河系當中應該每 36 年有顆 Type Ia SN，每 44 年有顆 Type II SN
- 那麼每個世紀應該看到約5顆超新星 ...

Q：爲什麼沒有看到那麼多呢？

- Ia 型超新星爆發為「臨界現象」，一旦條件足夠發生，便有相同的現象
- Ia type supernovae may have very similar intrinsic luminosities. If so, they will serve as good cosmic ‘standard’ candles that allow us to measure their distances (and the distances of their host galaxies) on cosmic scales.

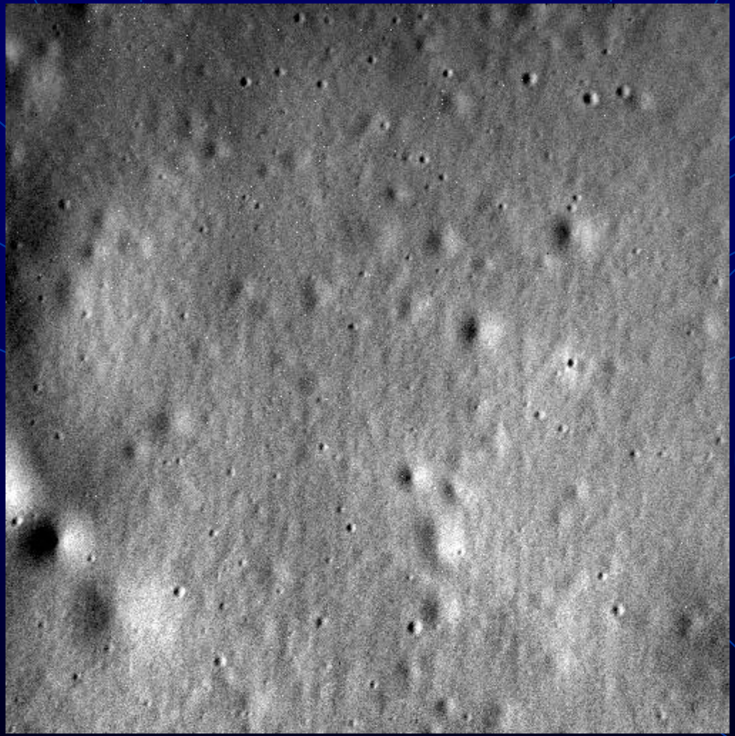


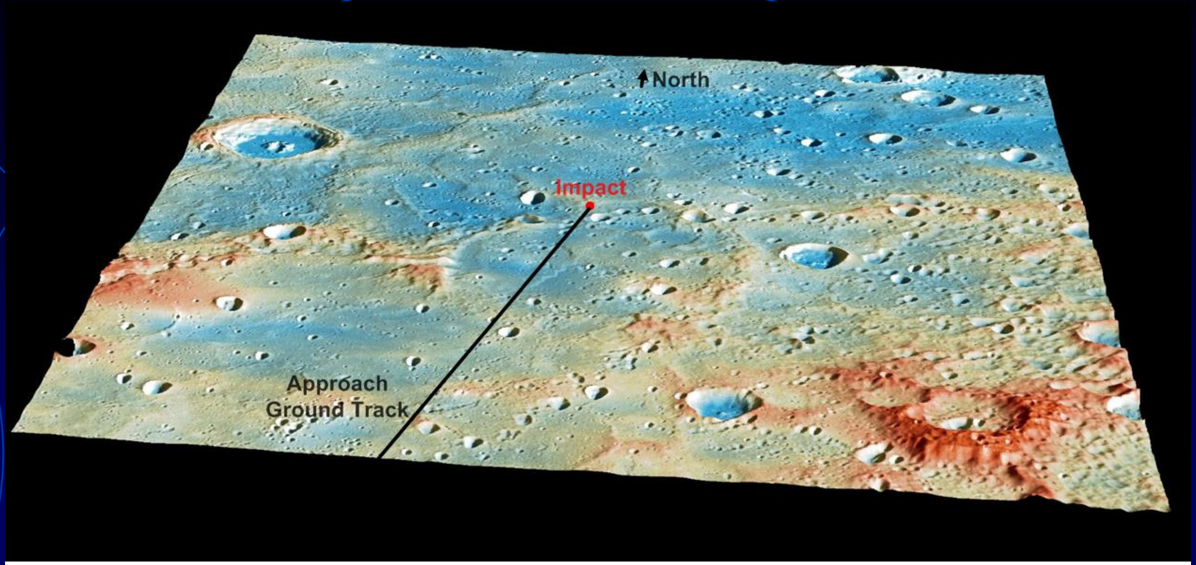
Recessional velocity (km/s)
30,000
20,000
10,000
5000
3000
2000
2
3
5
10
20
30
50
Distance to galaxy (Mpc)

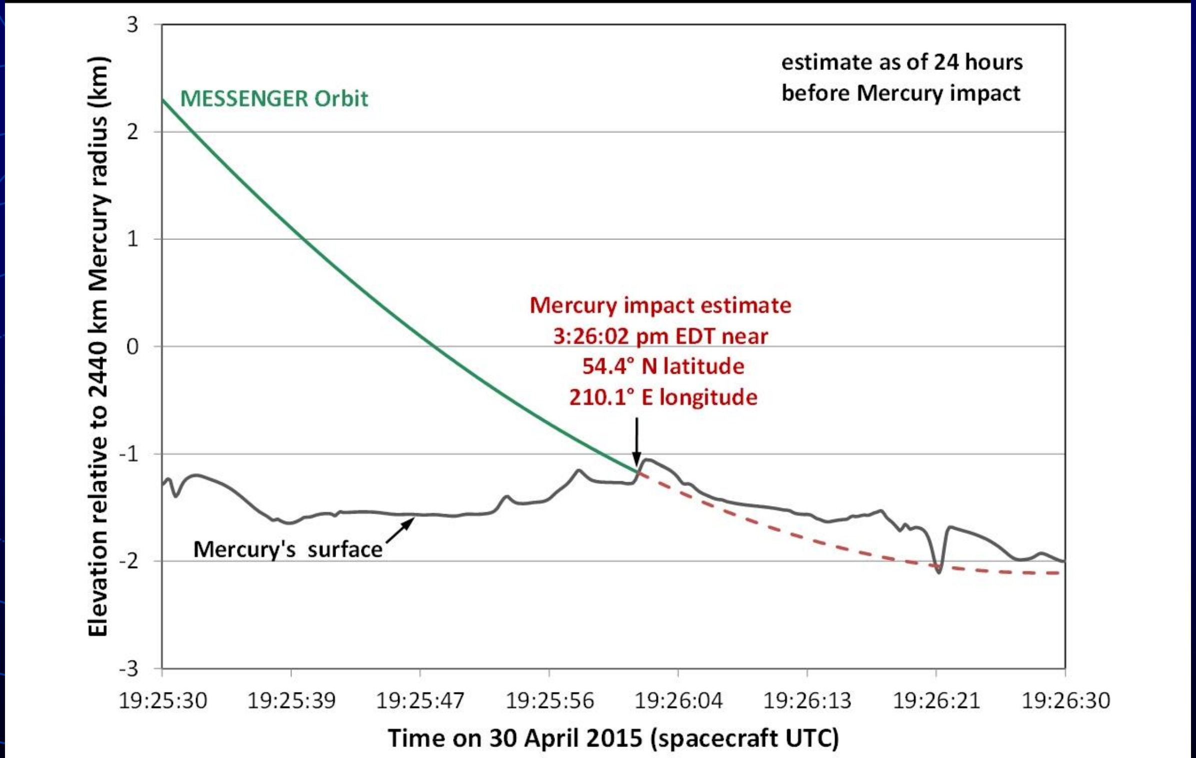


200,000
100,000
50,000
20,000
10,000
5000
2000
1000
Recessional velocity (km/s)
8
10
12
14
16
18
20
Apparent magnitude of brightest cluster galaxy
Apparent brightness of brightest cluster galaxy
$q_0 = \frac{1}{2}$
$q_0 = 0$

MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft impacted the surface of Mercury, as predicted, at 3:26 p.m. EDT (3:34 p.m. ground time) on April 30, 2015.







http://messenger.jhuapl.edu/