

恒星：从“本我”到“他我”

中国科学院大学 黄样

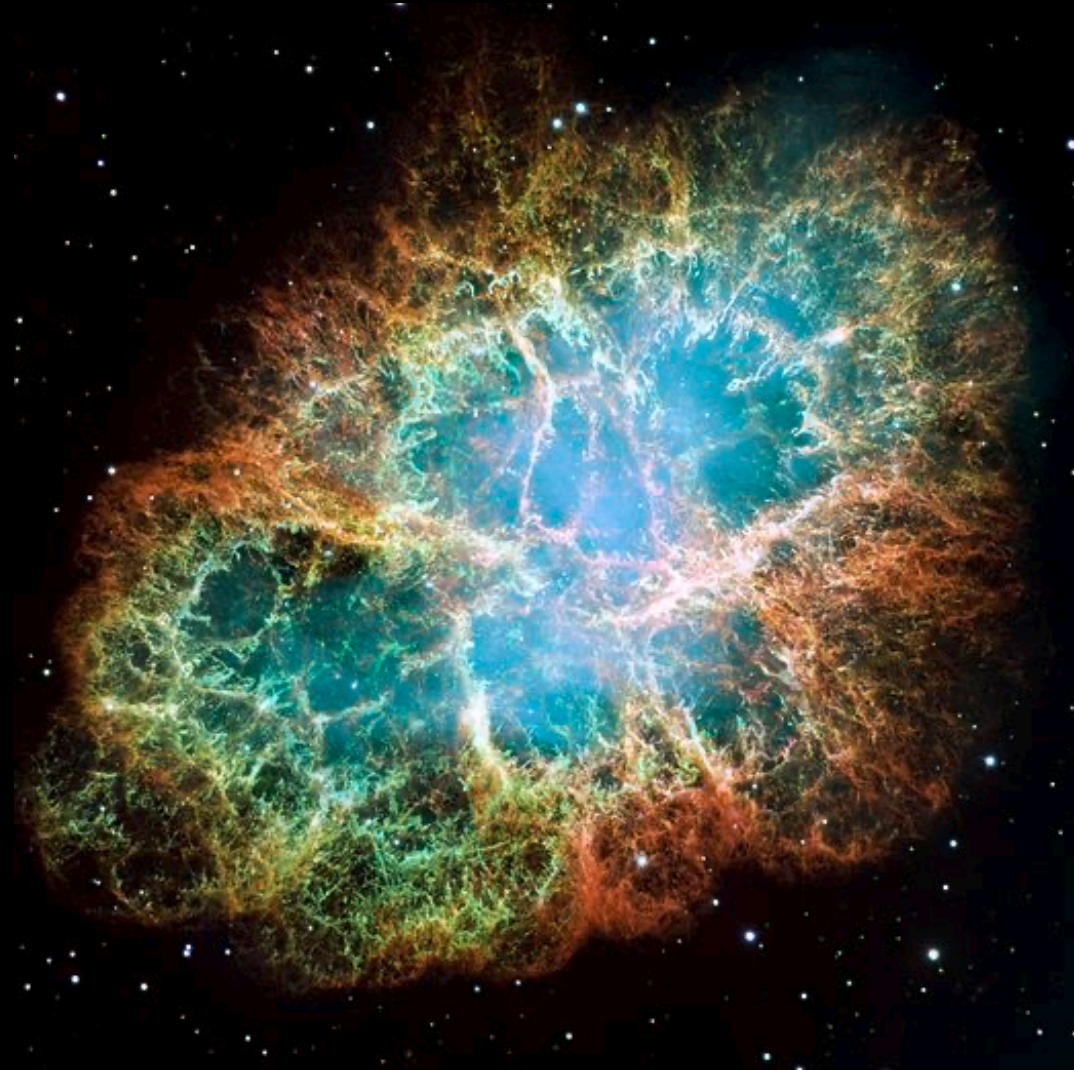
2026/08/15

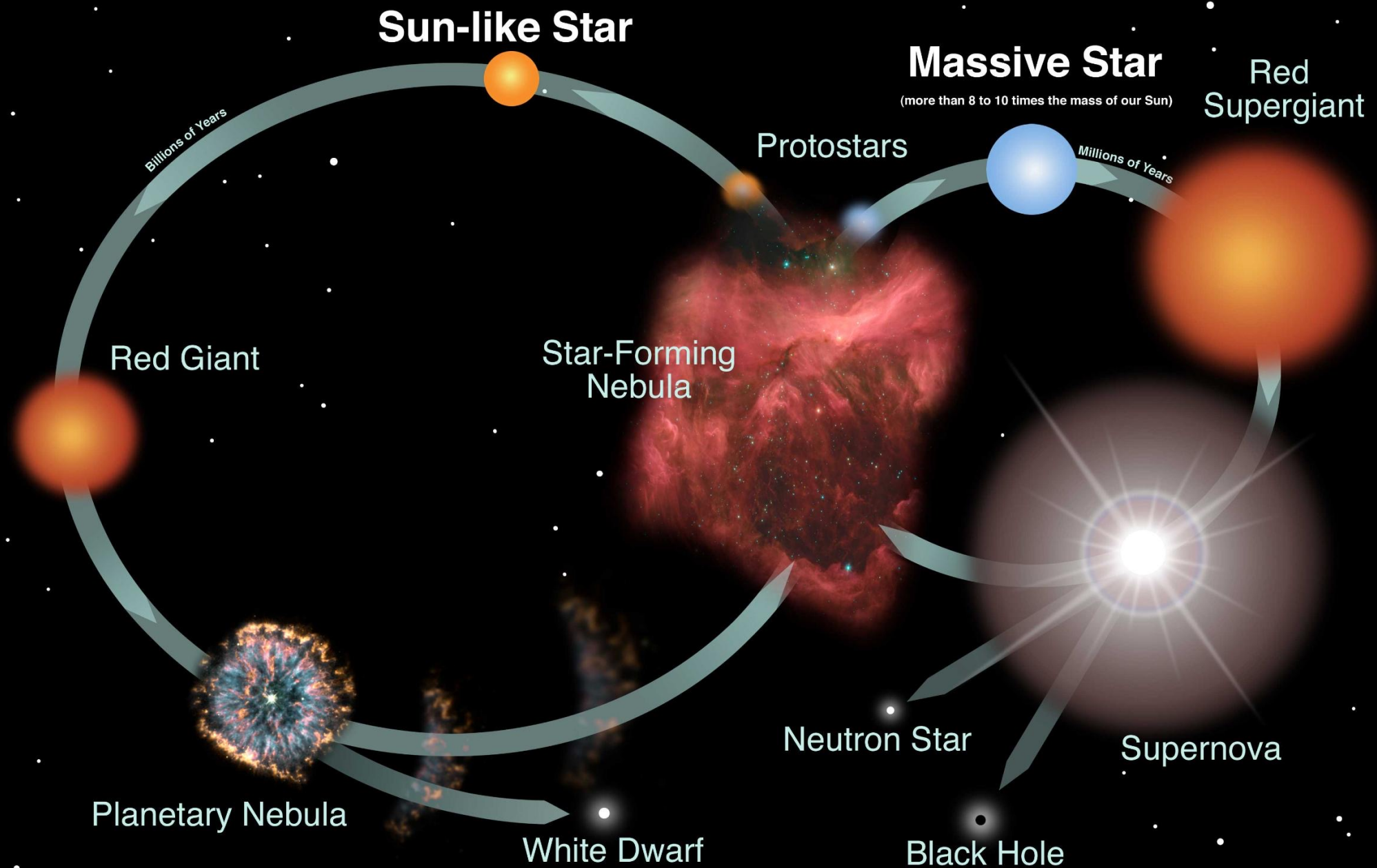
@中国科学院大学雁栖湖校区

本节课内容

- 生死之间，关乎宇宙（循环）
- 动静之间，亦双亦变（组合）
- 方寸之间，皆是物理（观测）
- 宇宙沙粒，永闪光辉（应用）

第一幕：生死之间





□ 恒星如何诞生？

□ 恒星如何演化？

□ 恒星如何死亡？

□ 在生死往复间又给宇宙留下了什么？

如何诞生？



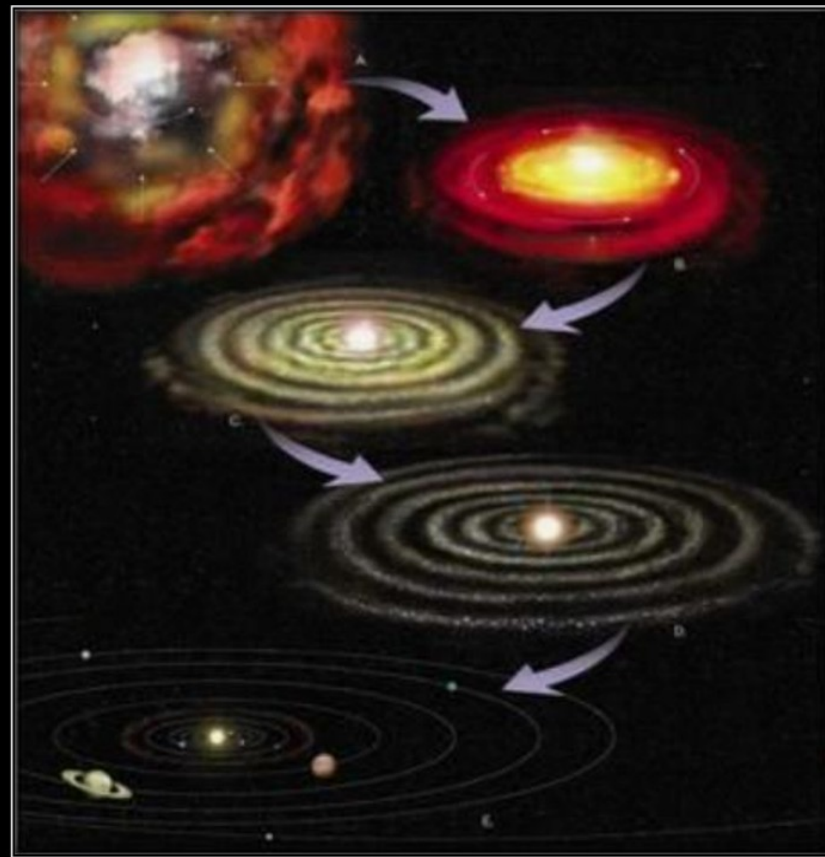
Emanuel
Swedenborg
17-18世纪
瑞典科学家
于1734年首次提出
恒星形成的星云假
说



康德
18世纪德国哲学家
在1755年发表的
《自然通史与天体
理论》一书中提出
星云假说而使其广
为人知

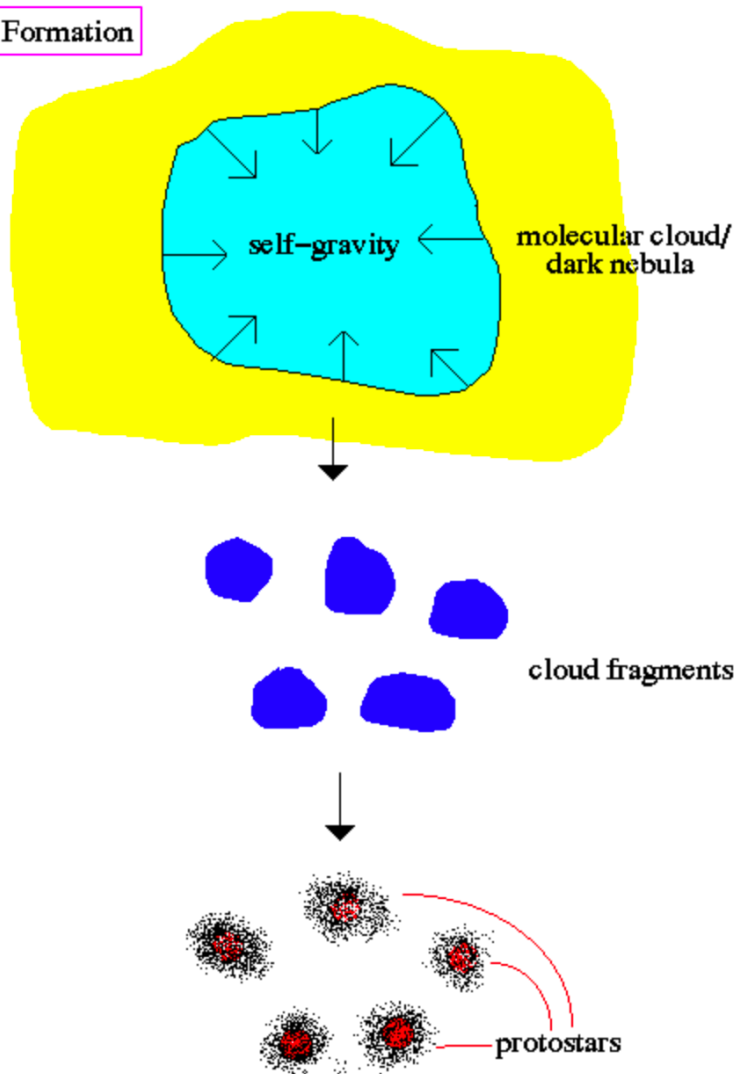


拉普拉斯
18-19世纪
法国科学家
在1796年出版的
《宇宙运行论》中
更加细致地发展了
星云假说



如何诞生？

Star Formation



金斯不稳定性

Jeans 1902

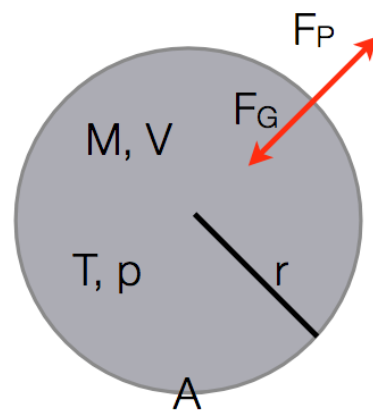
PHILOSOPHICAL TRANSACTIONS.

I. *The Stability of a Spherical Nebula.*

By J. H. JEANS, B.A., Fellow of Trinity College, and Isaac Newton Student in the University of Cambridge.

Communicated by Professor G. H. DARWIN, F.R.S.

Received June 15,—Read June 20, 1901. Revised February 28, 1902.



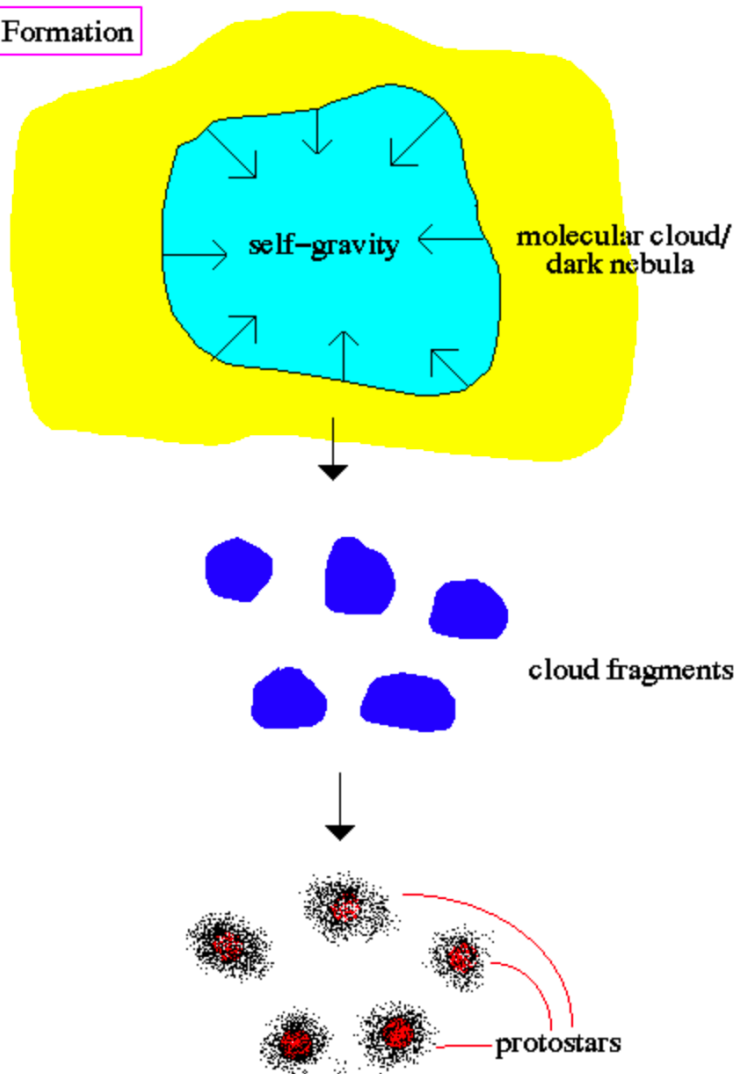
量级估计的方法来理解并尝试推倒金斯判据：

- 压力/热
- 引力/引力能
- 理想气体状态方程

如何诞生?

金斯不稳定性

Star Formation



Jeans 1902

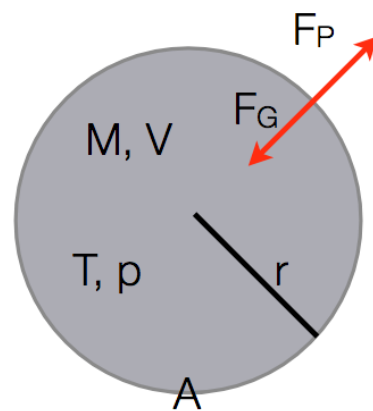
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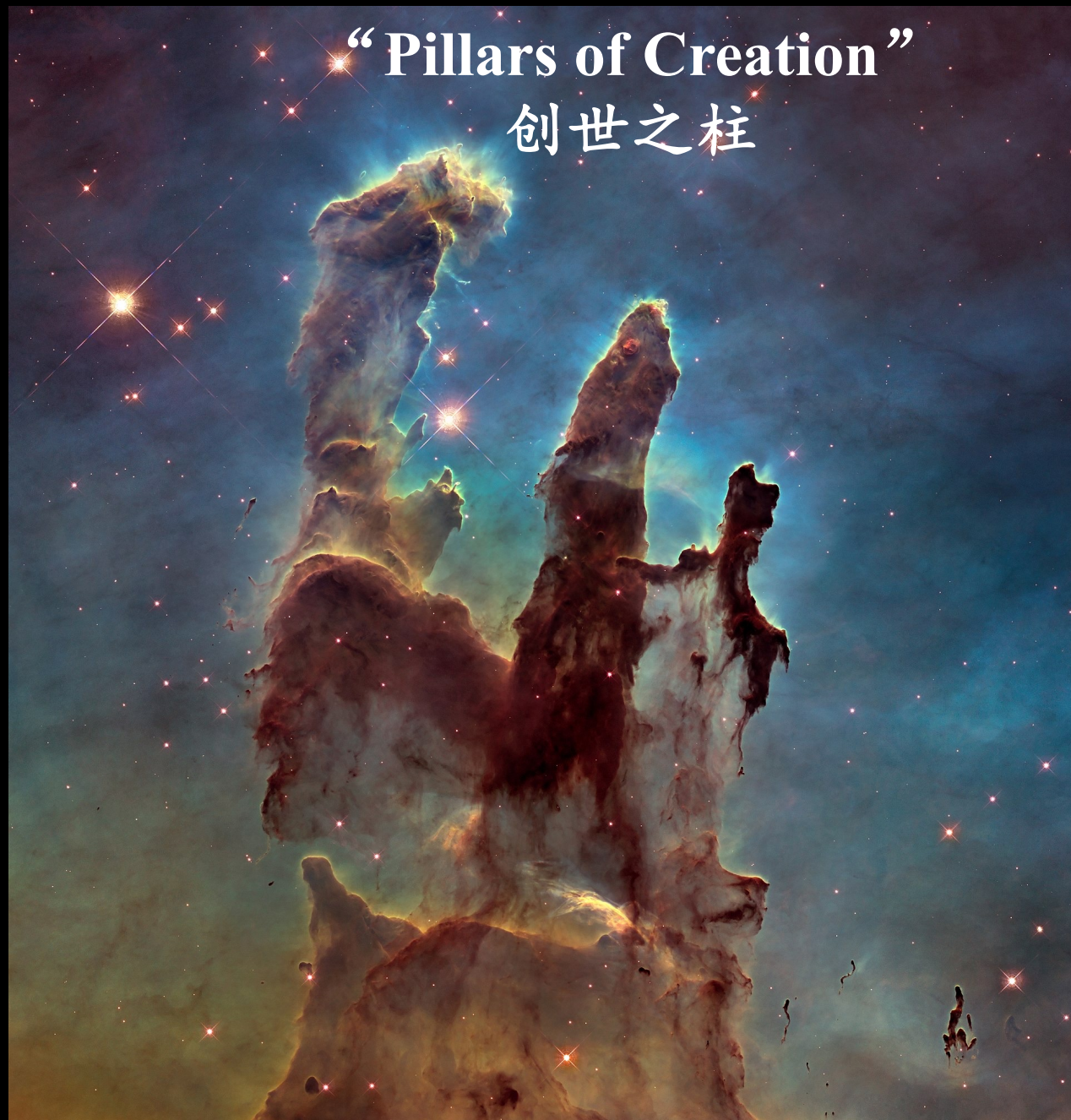
金斯长度和金斯质量:

- $L \sim (kT/G\rho m)^{0.5}$
- $M \sim \rho L^3 \sim T^{(3/2)} \rho^{(-0.5)}$

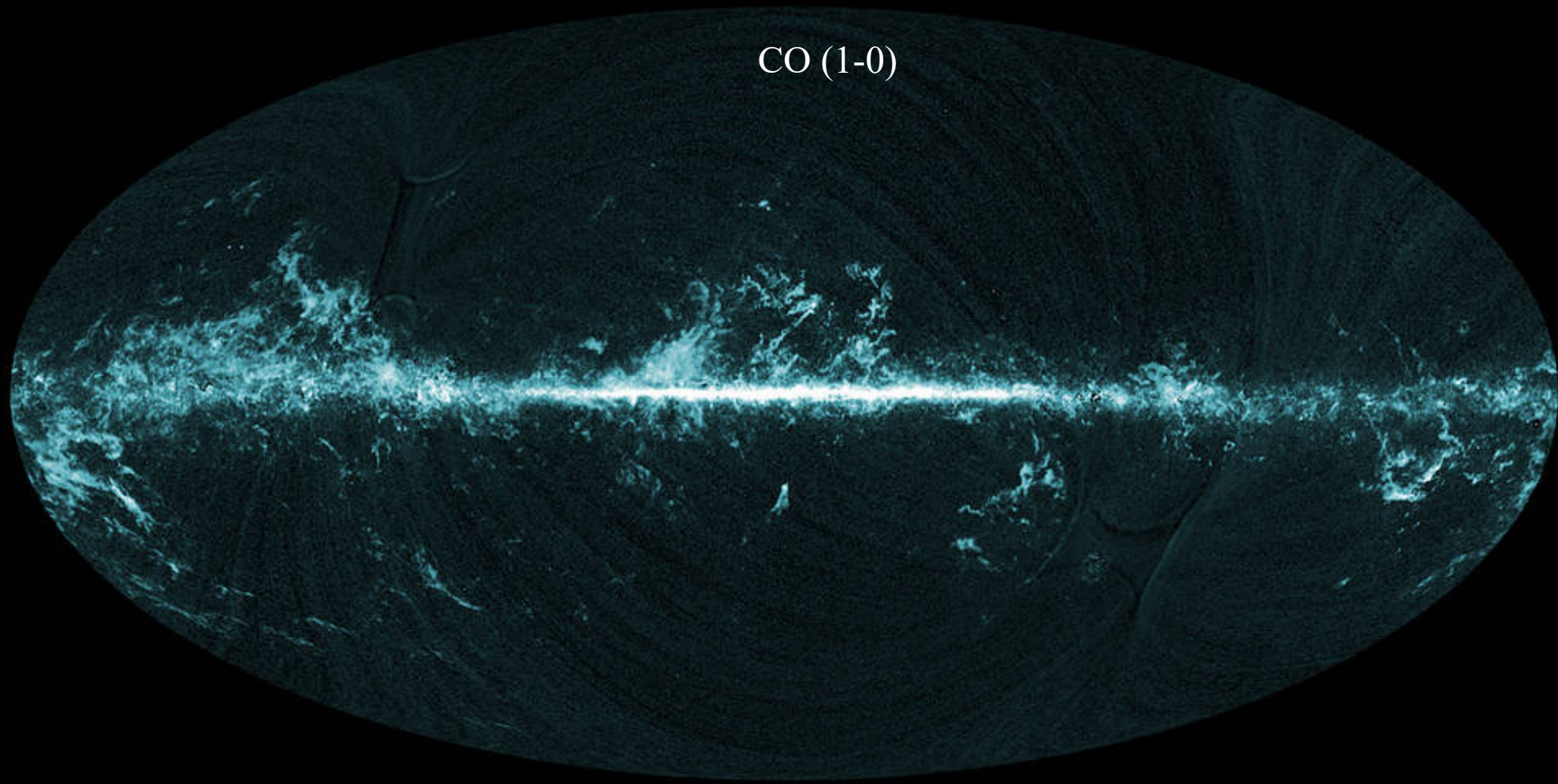
如何诞生？

星际介质 组分名称	气体 状态	温度 (K)	密度 (cm ⁻³)
分子气体 molecular	分子	10-20	10 ² -10 ⁶
冷中性气体 cold neutral	原子	50-100	20-50
温中性气体 warm neutral	原子	6000-10 ⁴	0.2-0.5
温电离气体 warm ionized	离子	8000	0.2-0.5
电离氢区 HII region	离子	8000	10 ² -10 ⁴
热电离气体 hot ionized	离子	10 ⁶ -10 ⁷	10 ⁻⁴ -10 ⁻²

**温度越低、密度越高，越有利于气体坍缩：
恒星诞生于分子云中！**



如何诞生?



Credits: ESA/Planck Collaboration

如何诞生？

实际情况远比金斯不稳定性复杂的多！

扩展阅读：

- 20世纪50-60年代：经典动力学理论 (Bonnor 1956 ; Ebert 1955等)
- 20世纪70-80年代：恒星形成标准理论 (Shu 1978, Shu+1987等)
- 21世纪初：湍流控制下的恒星形成理论 (Mac Low+04, McKee+07等)

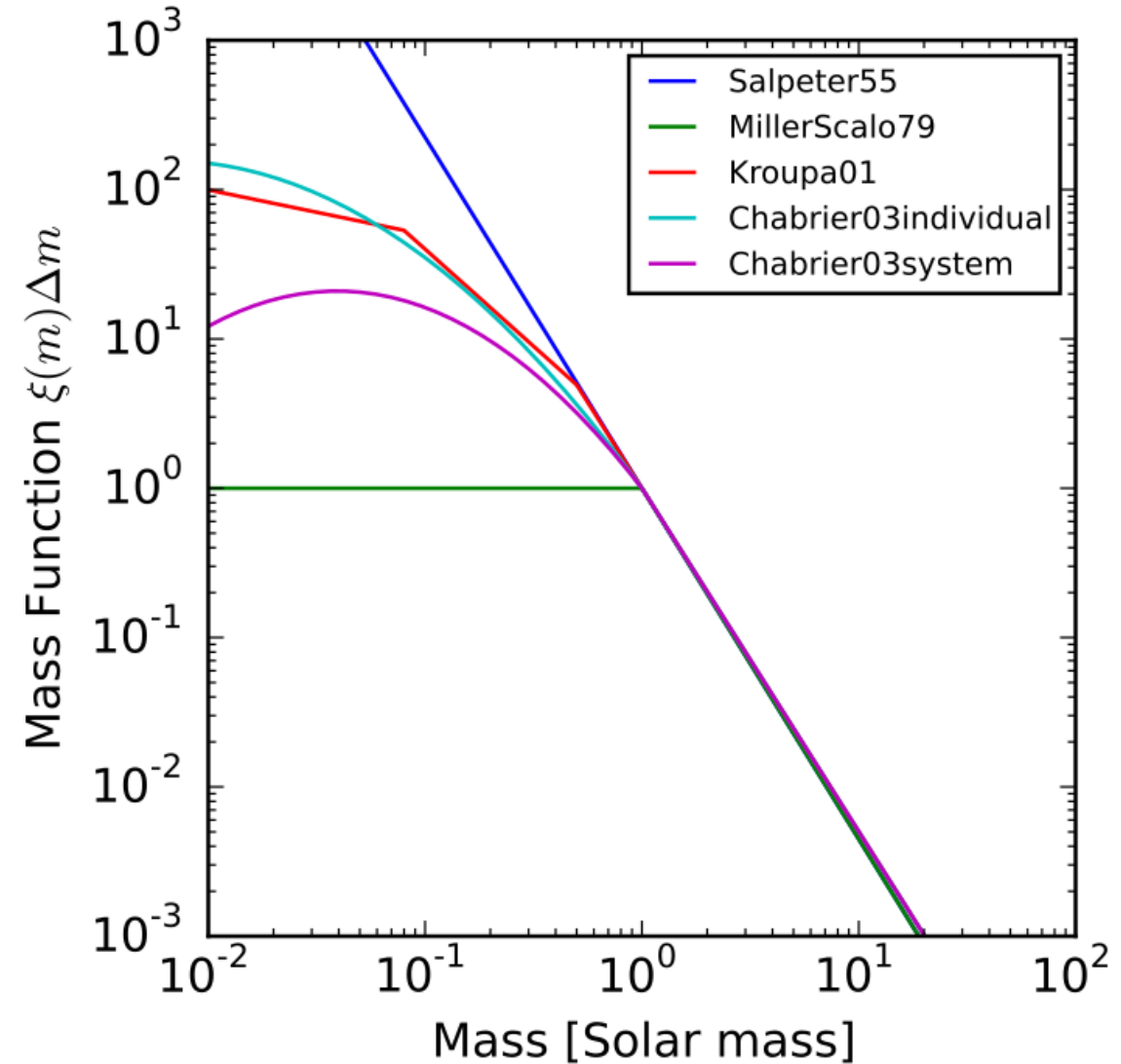
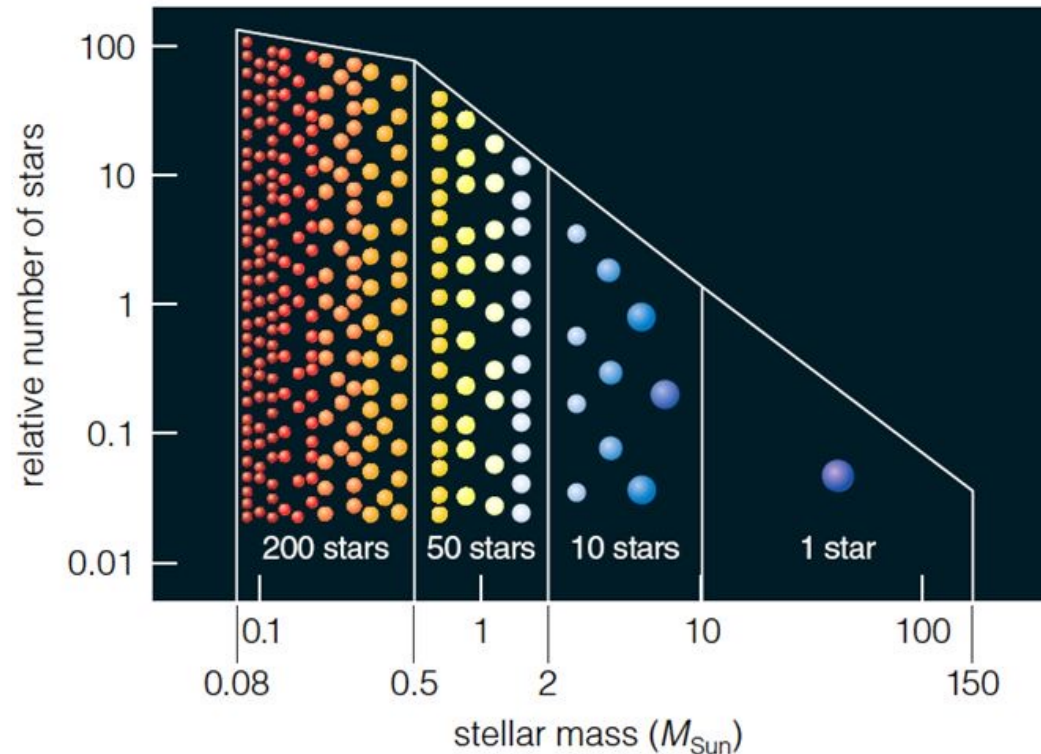


Frank H Shu
2009 Astronomy



如何诞生?

What are the typical masses of newborn stars?



如何演化？



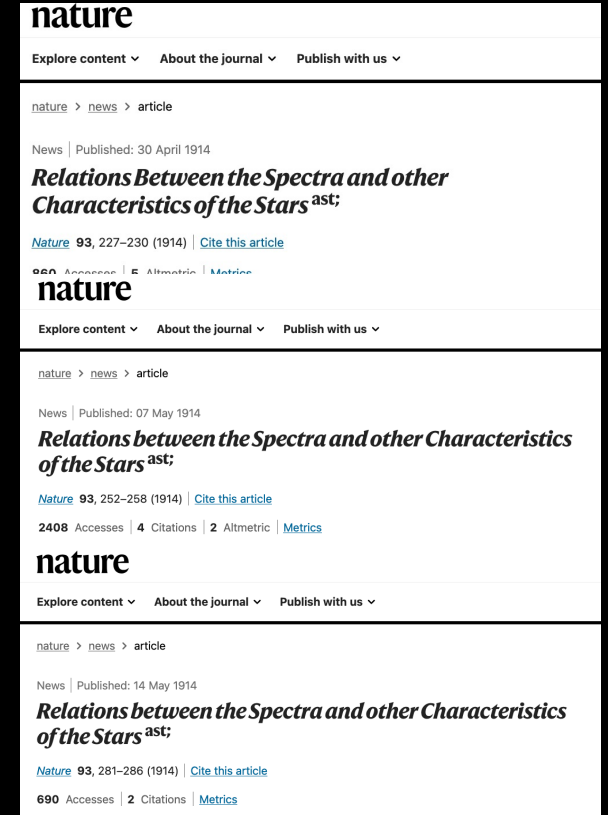
智人
(31万年前)



宋朝司天监
(1054年)



伽利略
(1609年)



罗素
(1914年)

如何演化？



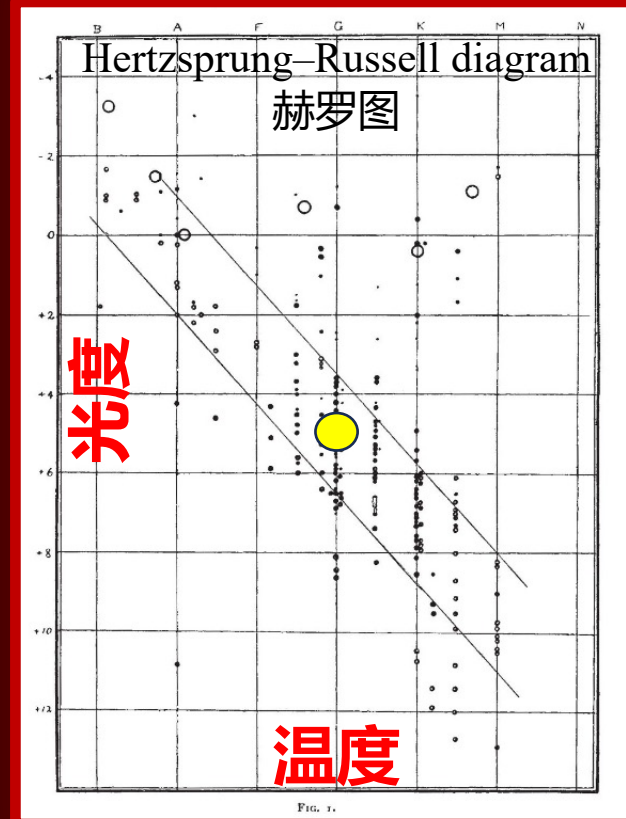
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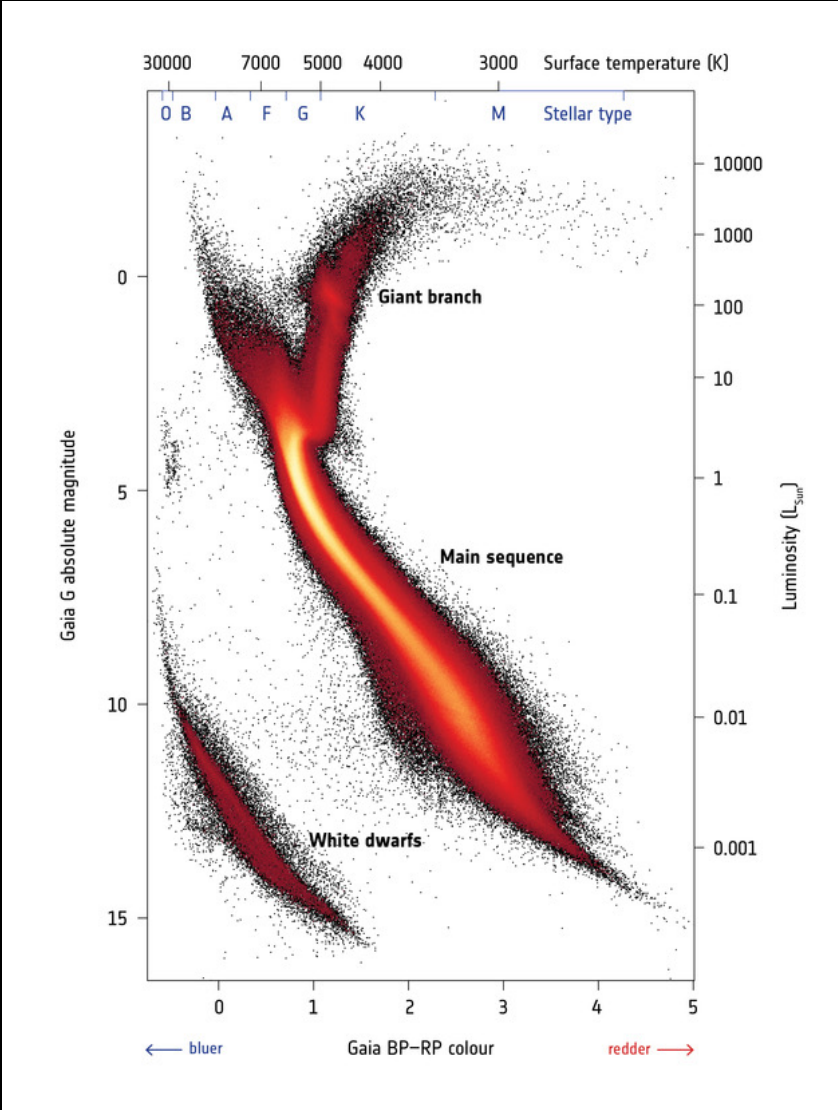
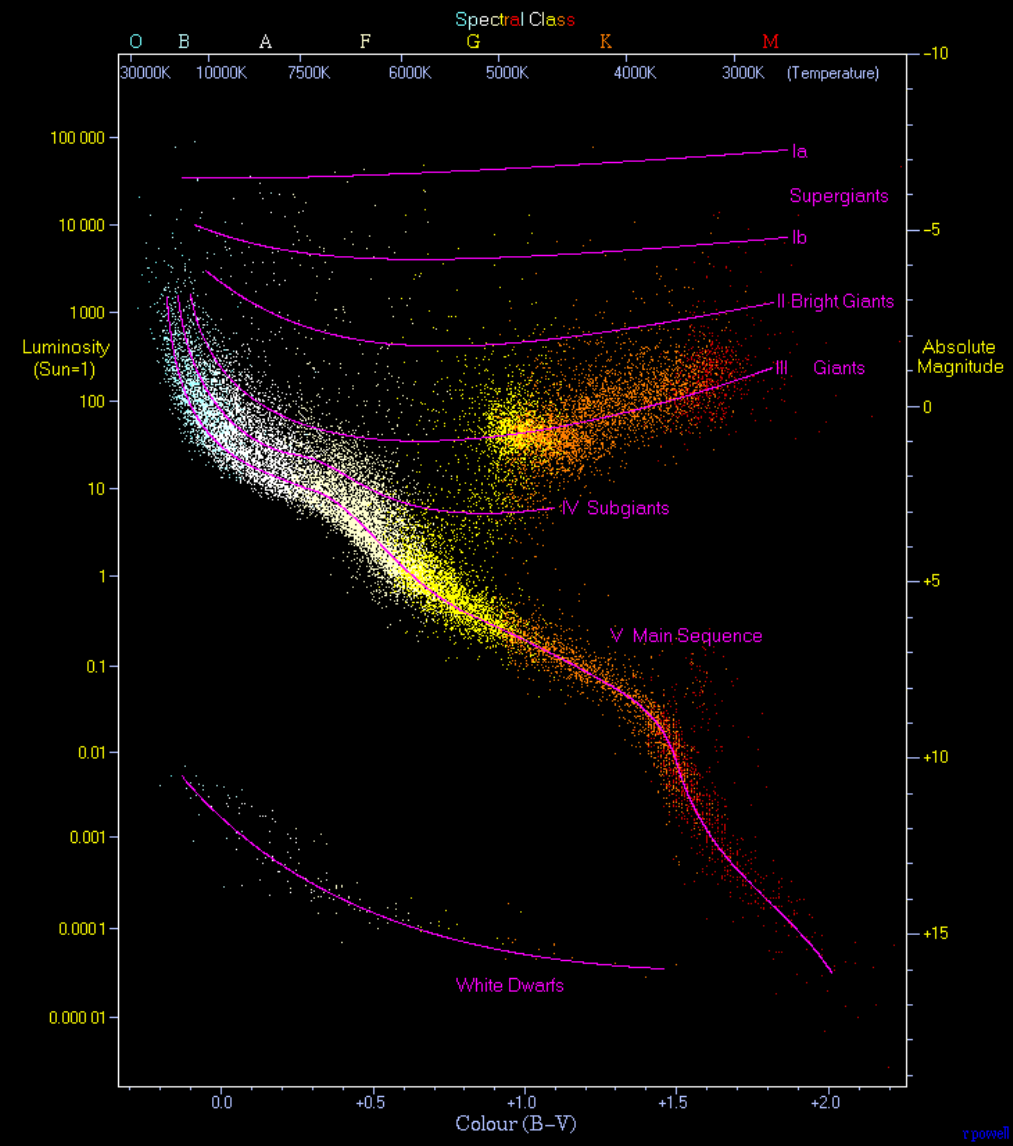


伽利略
(1609年)



罗素
(1914年)

Hertzsprung–Russell diagram



第一个恒星物理模型

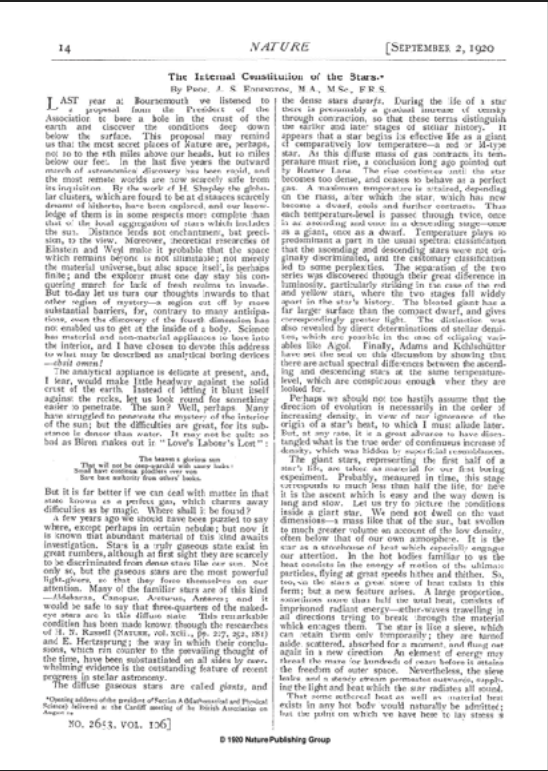


亚瑟·爱丁顿

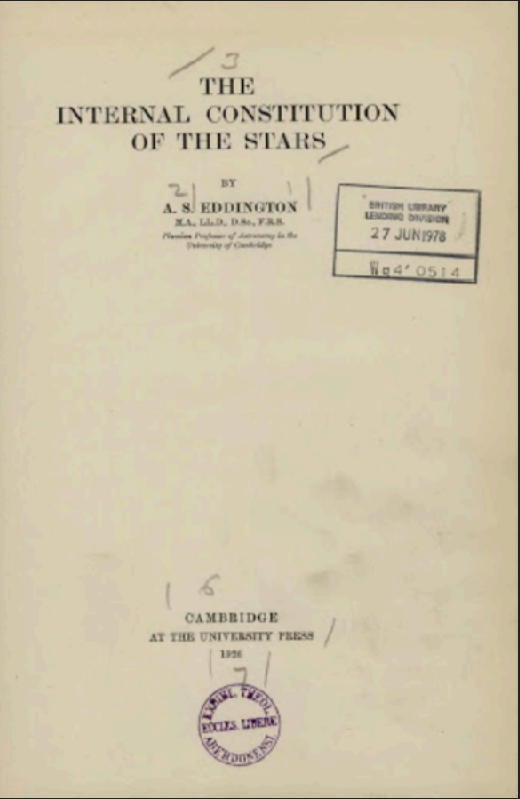
Arthur Eddington

(1882-1944)

Taken from Xiaoting



1920 年



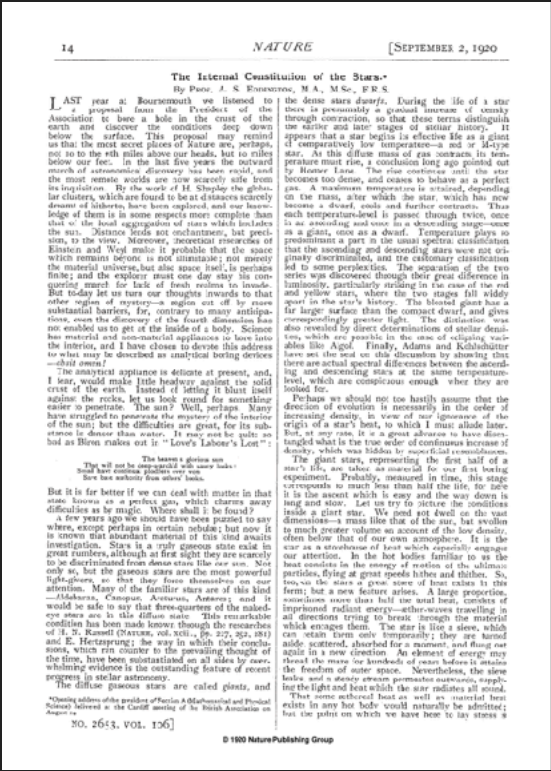
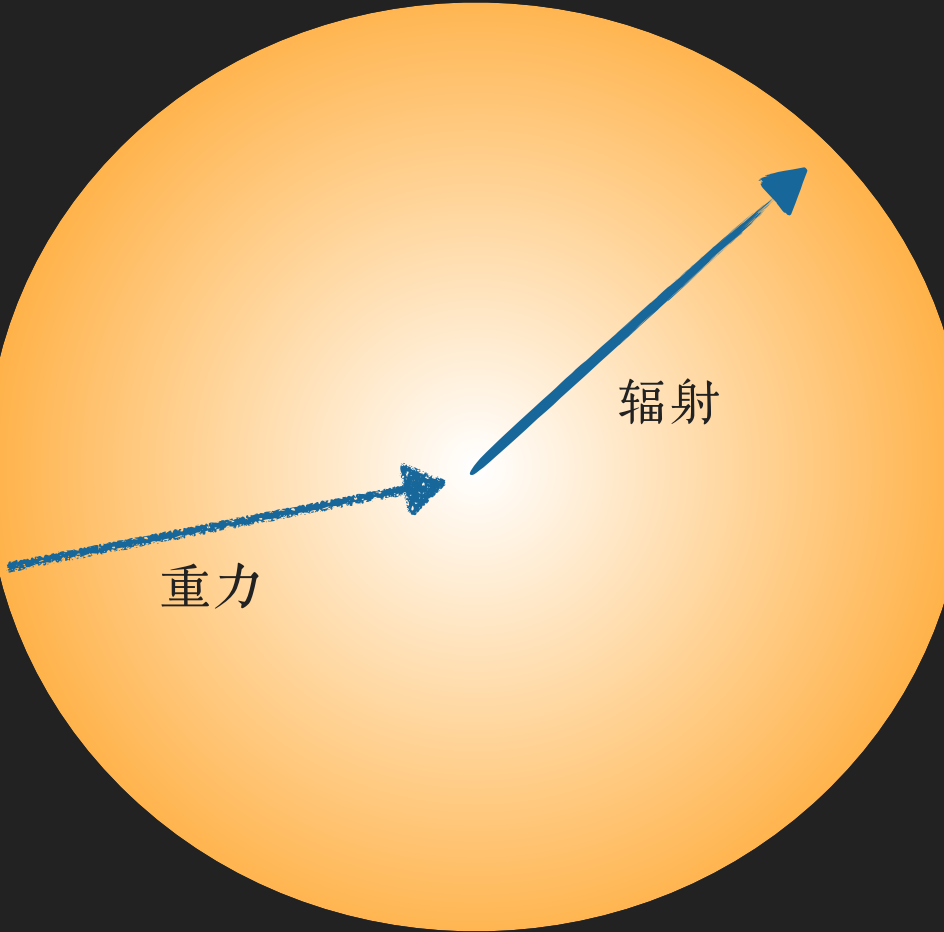
1926 年

第一个恒星物理标准模型

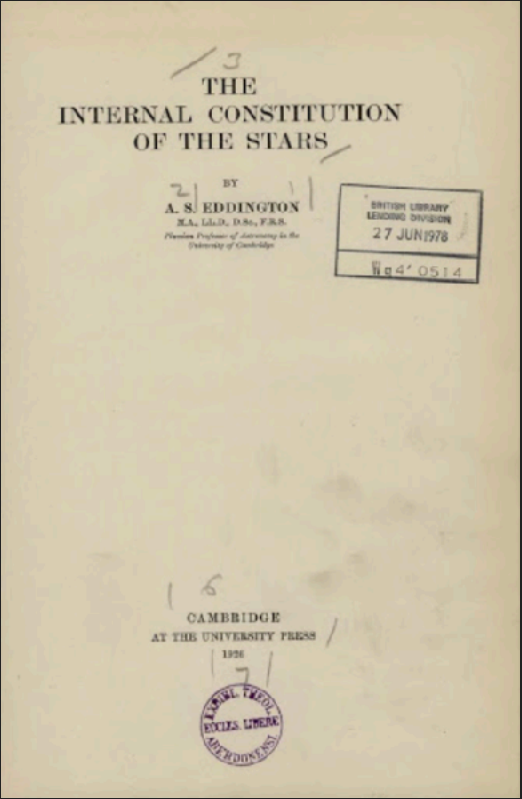
亚瑟·爱丁顿

恒星亮度取决于恒星质量

流体静力学平衡 & 辐射转移



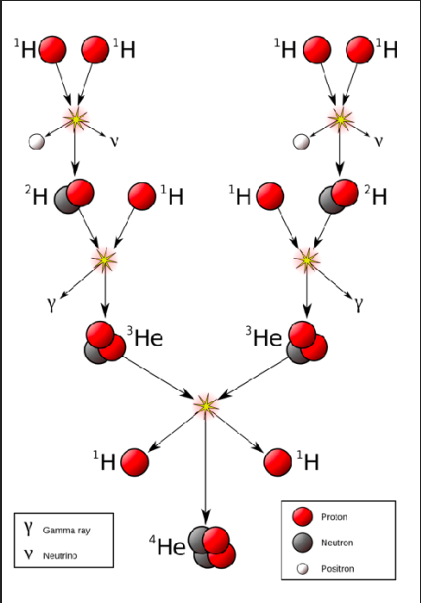
1920 年



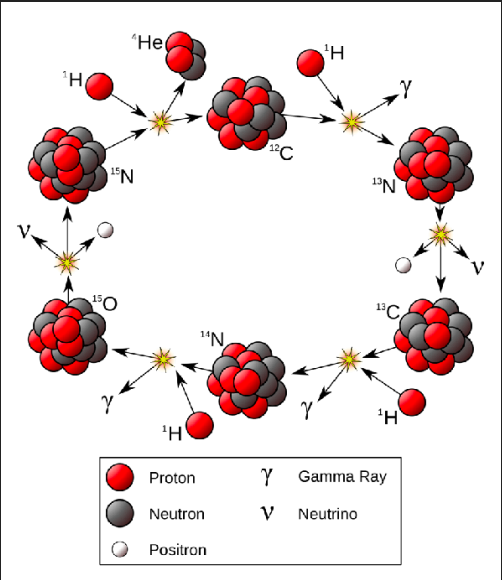
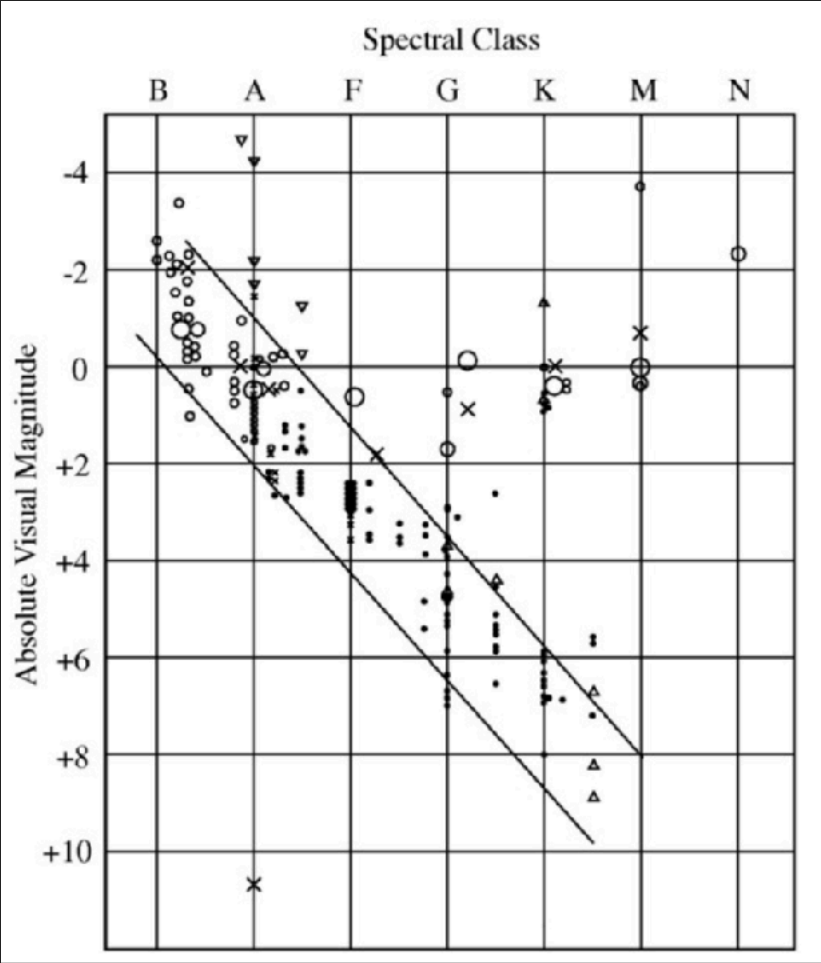
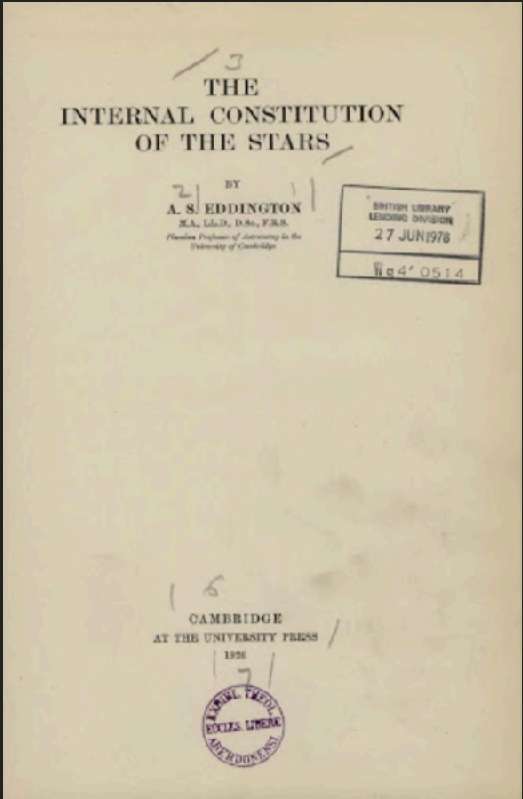
1926 年

恒星内部的能量哪里来？

质子-质子链 & 碳氮氧循环



+



谢谢量子物理学家、核物理学家、天体物理学家

恒星里其它元素哪里来的？

The B²FH paper, 1957

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and
Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
California Institute of Technology, Pasadena, California

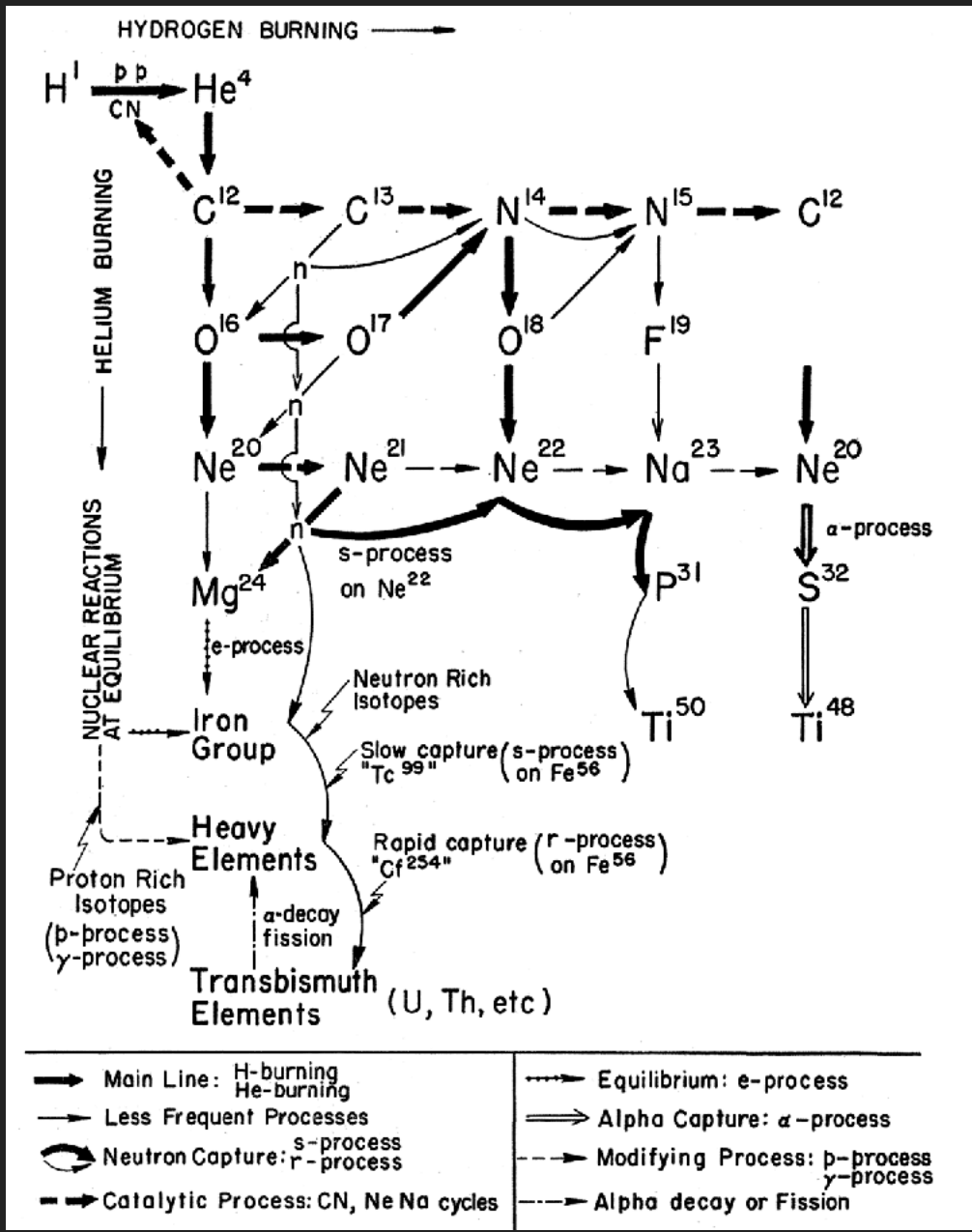
"It is the stars, The stars above us, govern our conditions";
(King Lear, Act IV, Scene 3)

but perhaps

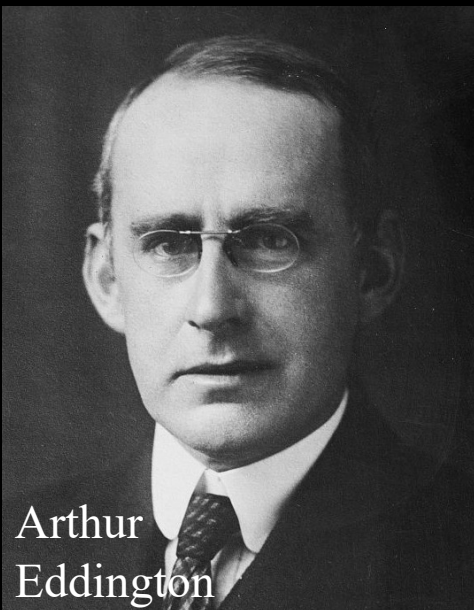
"The fault, dear Brutus, is not in our stars, But in ourselves,"
(Julius Caesar, Act I, Scene 2)

- 预言各种元素的存在 ✓
- 各种同位素的存在 ✓
- 恒星稳定时期内部核聚变的产出 ✓
- 恒星爆炸时产生的元素 ✓

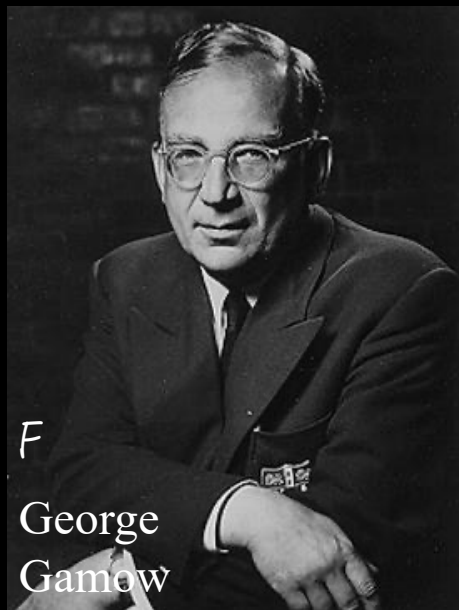
Taken from Xiaoting



如何研究恒星的一生？



Arthur Eddington

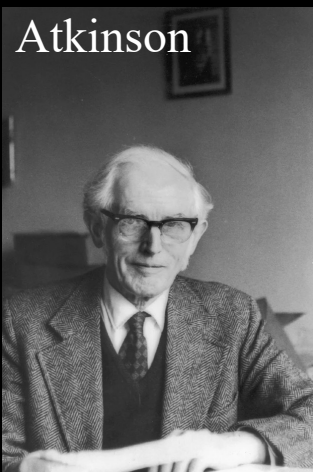


George Gamow

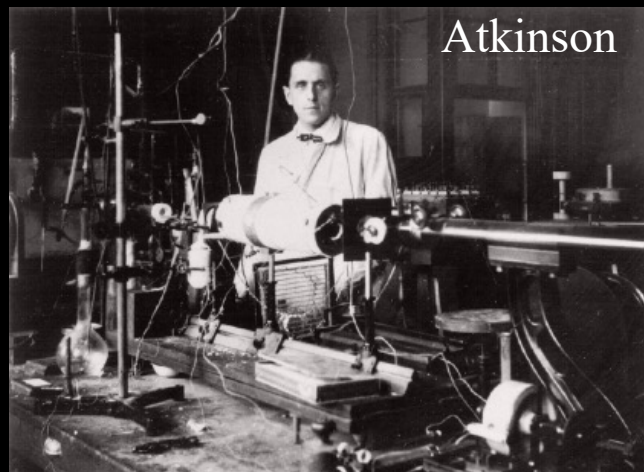


Hans Bethe

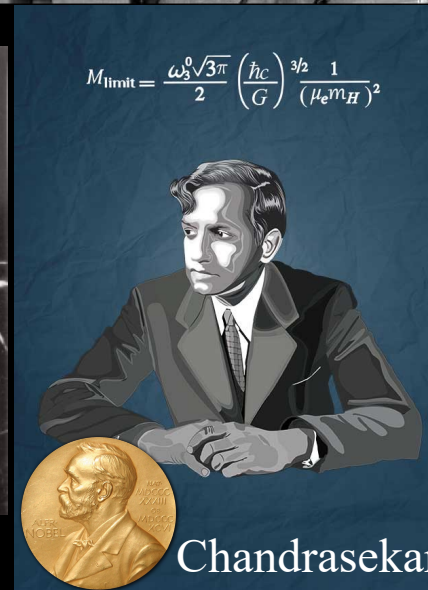
感谢这些先驱们！
(物理学家+核物理学家+天体物理学家)



Atkinson



Atkinson



Chandrasekar

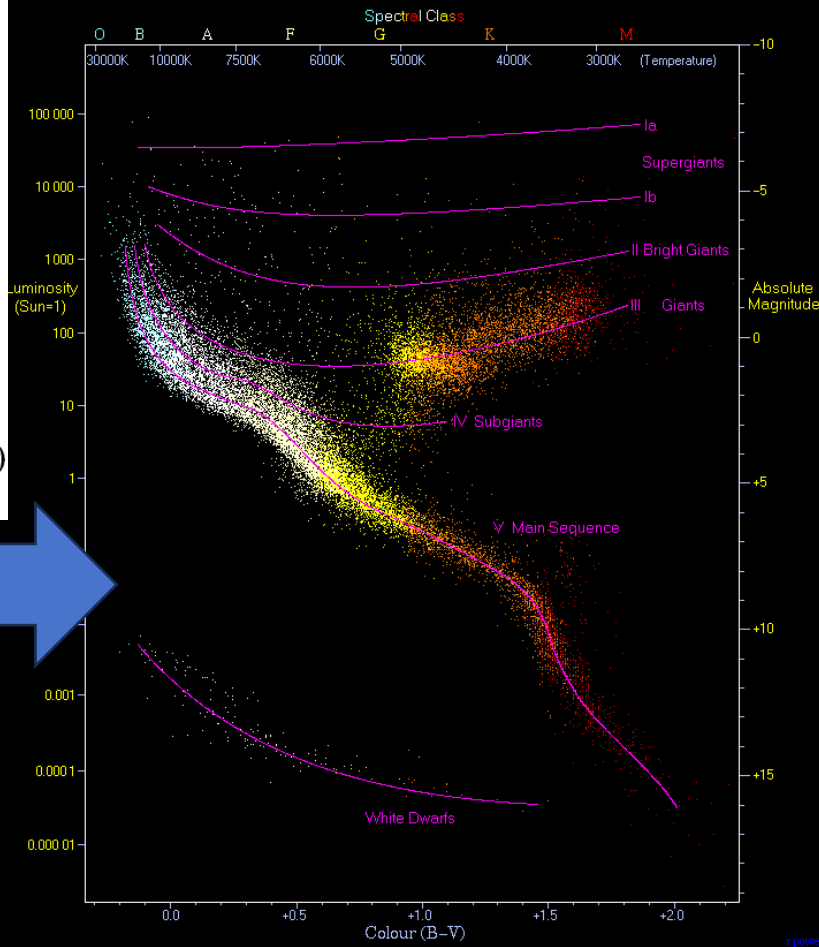
$$M_{\text{limit}} = \frac{\omega_3^0 \sqrt{3\pi}}{2} \left(\frac{\hbar c}{G} \right)^{3/2} \frac{1}{(\mu_e m_H)^2}$$



Margaret and Geoffrey Burbidge, Willy Fowler, and Fred Hoyle

如何研究恒星的一生？

基本方程	流体静力学平衡方程	$\frac{dP}{dr} = -G \frac{M_r \rho}{r^2}$	
	质量连续性方程	$\frac{dM_r}{dr} = 4\pi r^2 \rho$	
	能量守恒方程	$\frac{dL_r}{dr} = 4\pi r^2 \rho \epsilon$	
	能量传输方程	$\frac{dT}{dr} = -\frac{3}{4ac} \frac{\bar{\kappa} \rho}{T^3} \frac{L_r}{4\pi r^2}$ $= -\left(1 - \frac{1}{\gamma}\right) \frac{\mu m_H}{k} \frac{GM_r}{r^2}$	(radiation) (adiabatic convection)
辅助方程	物态方程	$P = P(\rho, T, \text{composition})$	
	不透明度公式	$\bar{\kappa} = \bar{\kappa}(\rho, T, \text{composition})$	
	产能率公式	$\epsilon = \epsilon(\rho, T, \text{composition})$	
边界条件	恒星中心	$M_r = 0, L_r = 0$	
	恒星表面	$M(r=R) = M, T = 0, P = 0$	



如何研究恒星的一生？



如何研究恒星的一生？

MESA

★ ⚙️ ✉️ 🔄

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✖️ + K

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Enterprise docs hosting Use any docs as code tool with custom builders, SAML SSO, and private repos.

Ad by EthicalAds

Modules for Experiments in Stellar Astrophysics

Note

🔗 Looking for the [KU Leuven 2025 summer school page?](#)

Modules for Experiments in Stellar Astrophysics (MESA) is an advanced, open-source 1D stellar evolution code. The code is developed and maintained by a globally distributed team of researchers. MESA is written primarily in Fortran with a modular, flexible design that facilitates easy interfacing.

🚀 New to MESA? Start with the [Quickstart](#) guide to set up and run your first models.

📖 Experienced users may find the [Reference and Defaults](#) page most valuable for exploring the code's features and input parameters. The [Test Suite](#) provides example problems for testing and showcasing MESA, serving as a project starting point but often requiring modifications for science-grade accuracy.

Check out the full documentation below.

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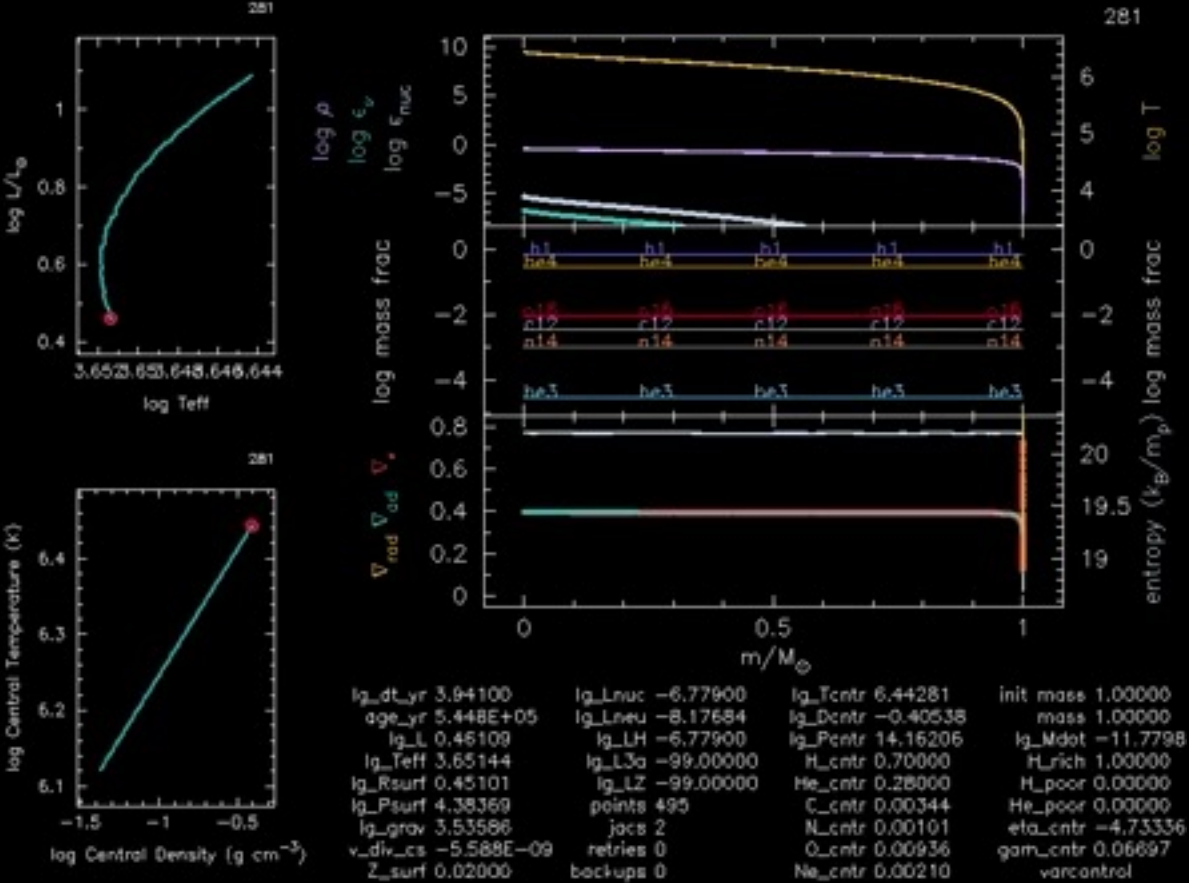
By The MESA Team

© Copyright 2025, The MESA Team.

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[Quickstart](#)

>



Next
[Quickstart](#)

如何研究恒星的一生？

PARSEC

PAdova TRieste Stellar Evolutionary Code

[HOME](#)[STELLAR TRACKS](#)[TOOLS](#)[PAPERS](#)

BRIEF OVERVIEW

Welcome to the PARSEC stellar tracks database.

The stellar evolution code PARSEC ([Bressan et al., 2012](#)) is an updated version of the Padova's stellar evolution code ([Bressan et al., 1993](#), [Girardi et al., 2000](#), [Marigo et al., 2001](#)). In PARSEC a detailed treatment of the input physics such as the equation of state, opacities, nuclear reaction rates, microscopic diffusion, allow us to compute stellar models from the pre-main sequence up to the most advanced evolutionary phases. The PARSEC stellar track database has grown significantly over the years in terms of mass and metallicity ranges, and, most recently, with the inclusion of rotation.

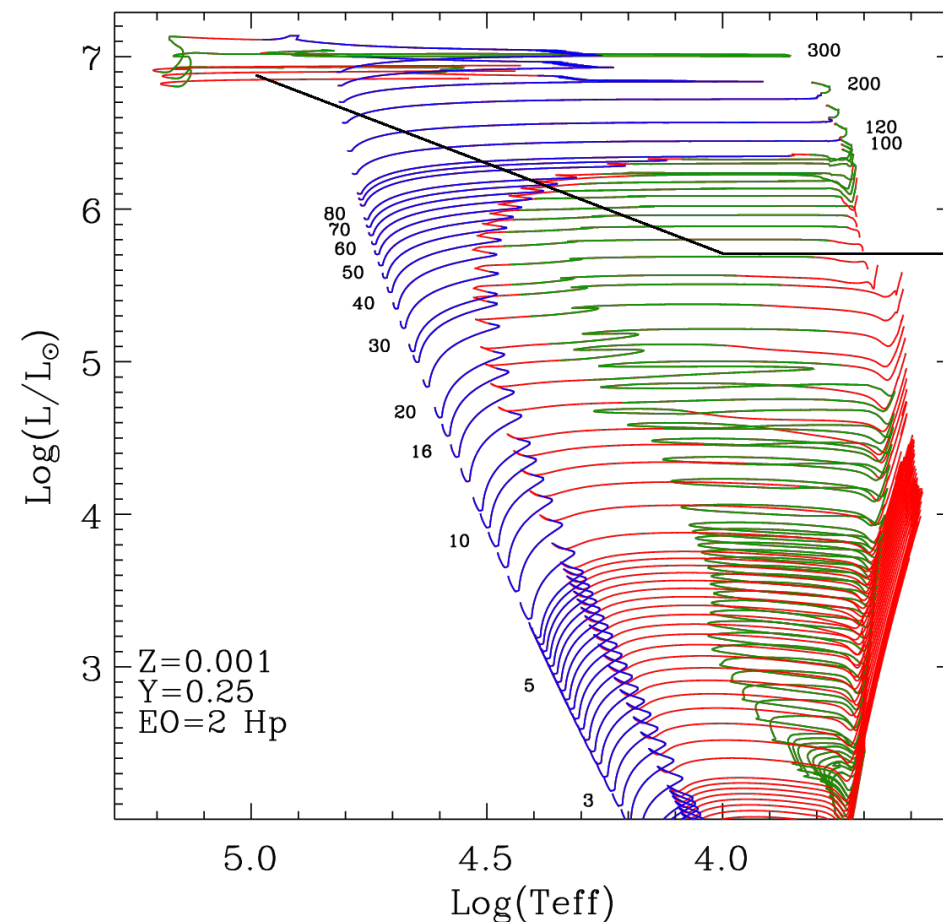
WHO WE ARE

PARSEC Team & Collaborators:

Alessandro Bressan (SISSA), Paola Marigo (UNIPD), Leo Girardi (INAF-OAPD), Guglielmo Costa (UNIPD), Thanh Chi Nguyen (SISSA), Guglielmo Volpato (UNIPD), Francesco Addari (SISSA), Kendall G. Shepherd (SISSA), Yang Chen (Anhui University), Xiaoting Fu (Purple Mountain Observatory), Michele Trabucchi (UNIPD), Giada Pastorelli (UNIPD), Diego Bossini (UNIPD), Alessandro Mazzi (UNIBO), Greta Ettore (UNIBO), Simone Zaggia (INAF-OAPD)

It's with deep sorrow that we announce the untimely passing of Prof. Paola Marigo on October 20th, 2024. As her group, we would like to express our deepest gratitude for her guidance, and our commitment to carry forward her legacy.

Evolutionary track



前主序星 (PMS)

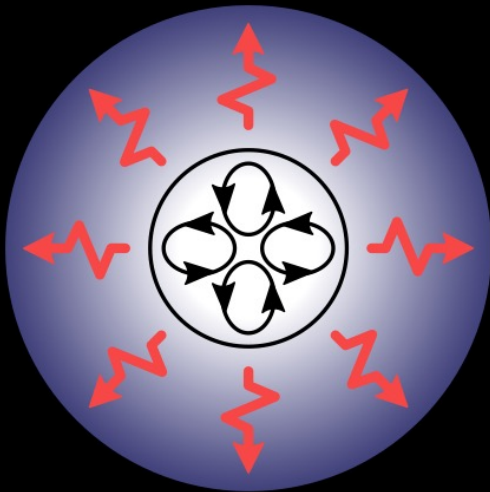
项目	Hayashi track	Heney track
适用恒星质量	低质量 ($\lesssim 1.5 M_{\odot}$)	中高质量 ($\gtrsim 1.5 M_{\odot}$)
主导输运方式	对流	辐射
HR图路径	近似垂直向下	近似水平向左
表面温度变化	变化小	持续升高
光度变化	明显下降	几乎恒定



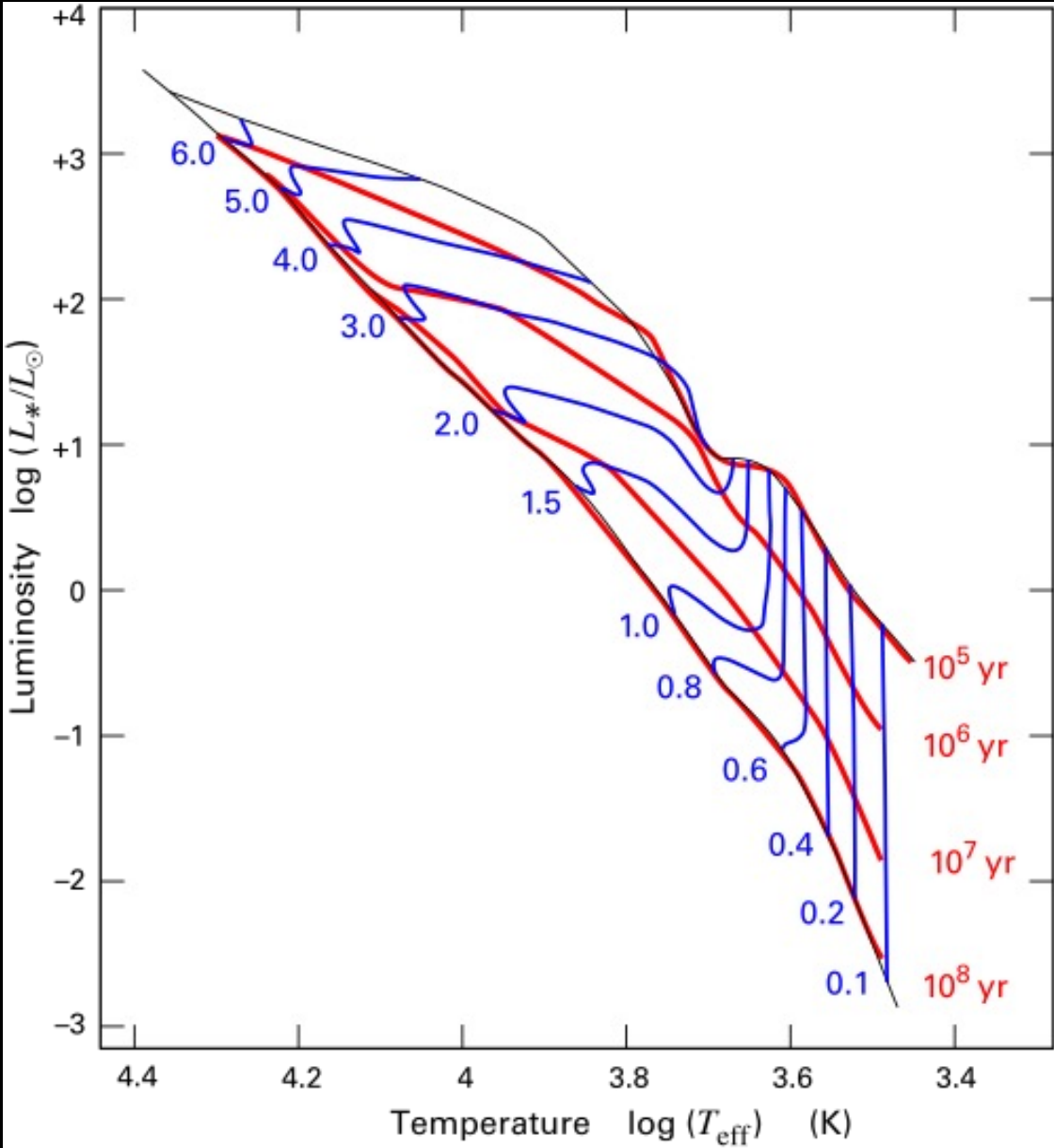
$M < 0.5 M_{\text{sun}}$



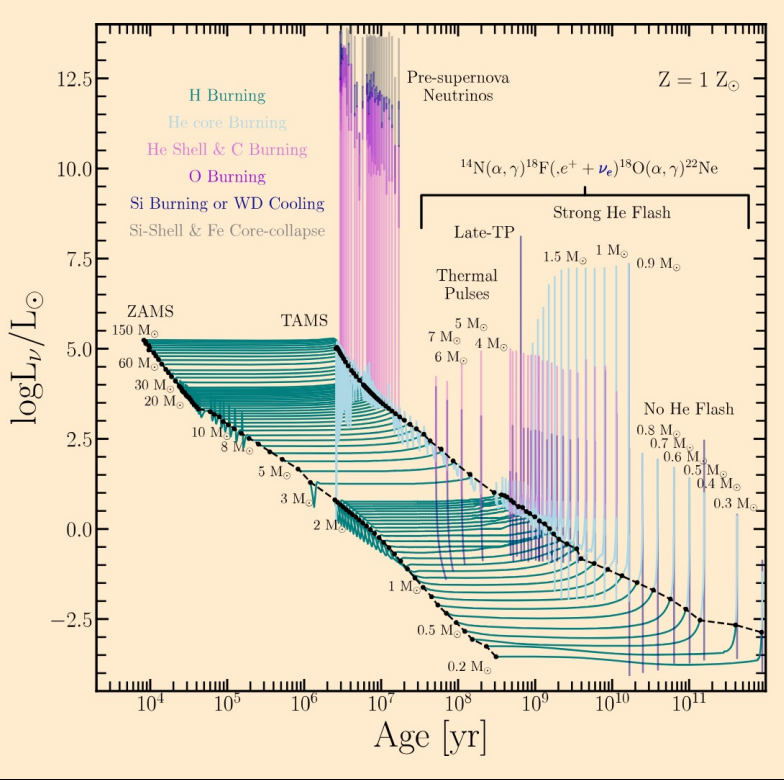
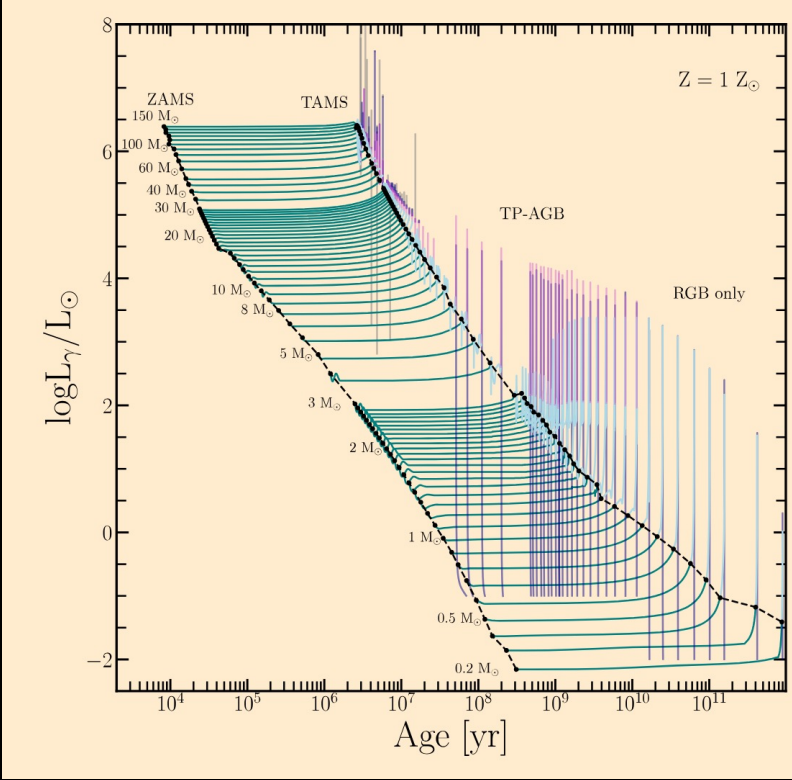
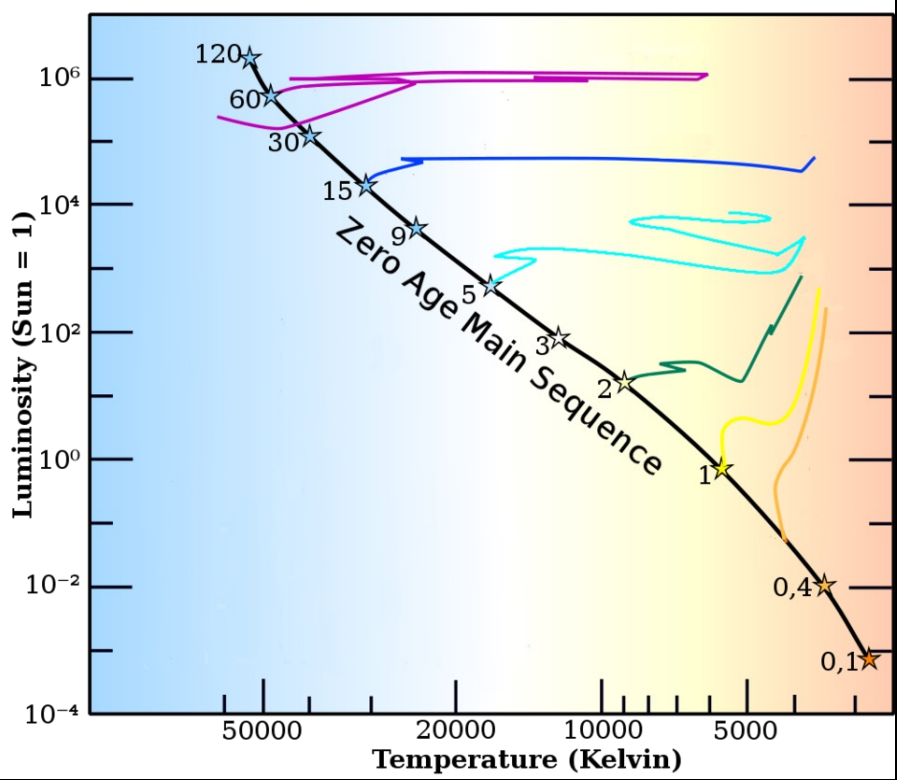
$0.5 < M < 1.5 M_{\text{sun}}$



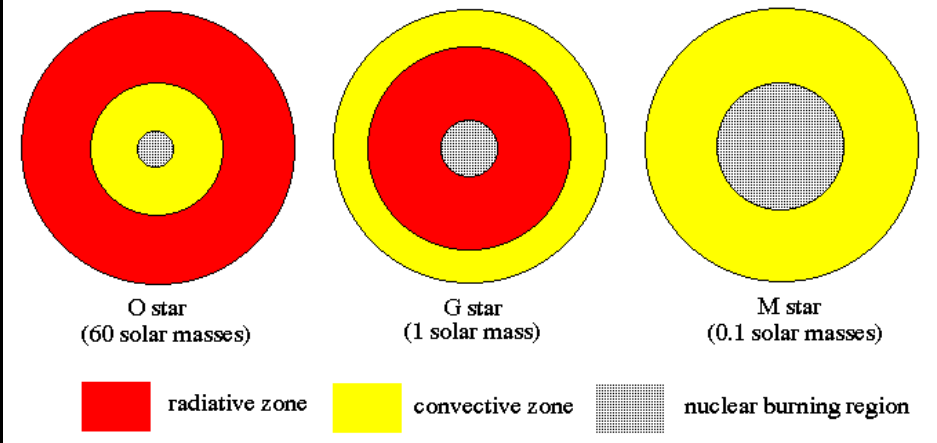
$M > 1.5 M_{\text{sun}}$



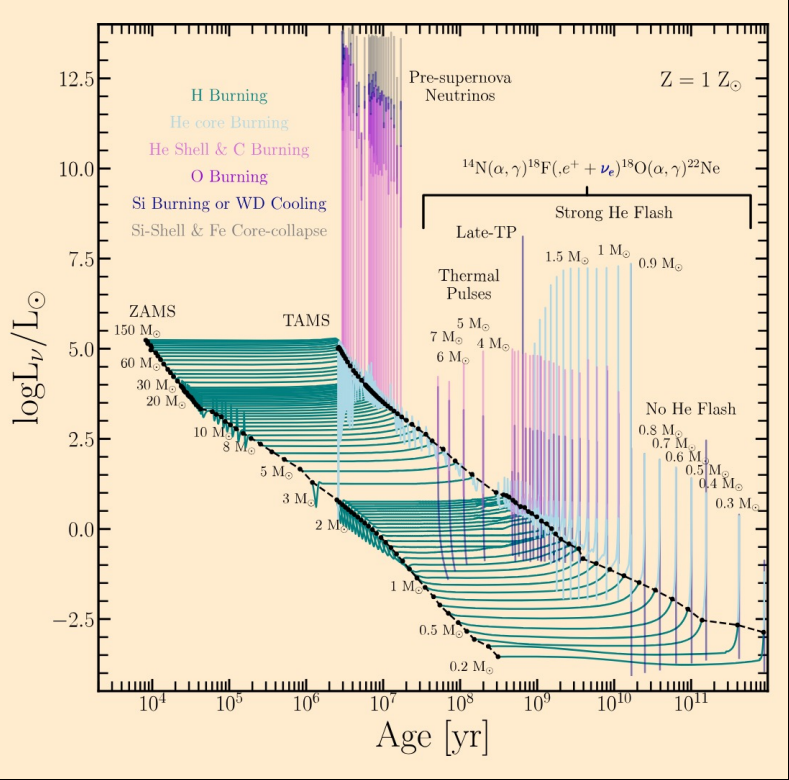
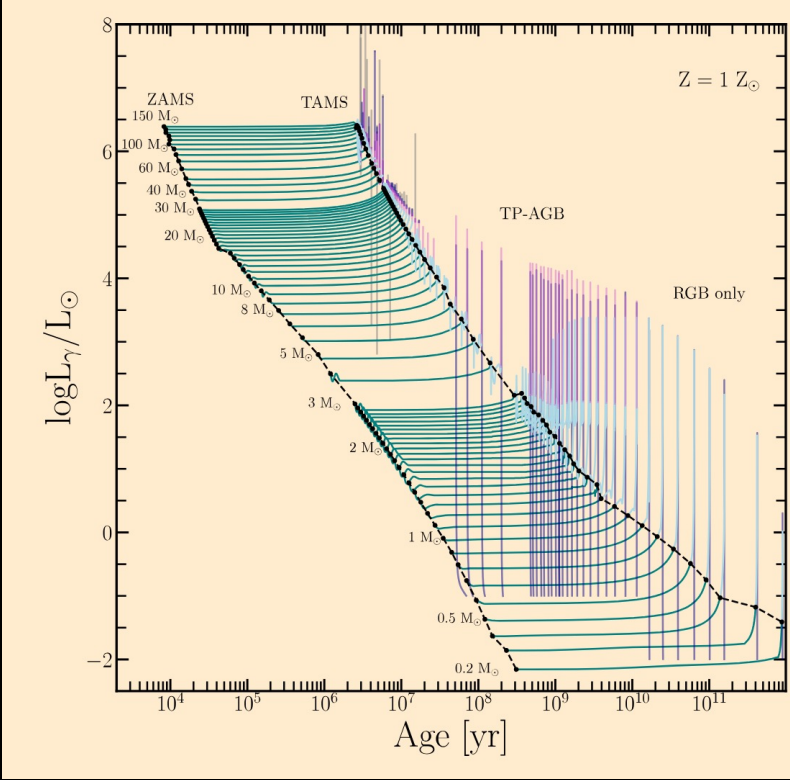
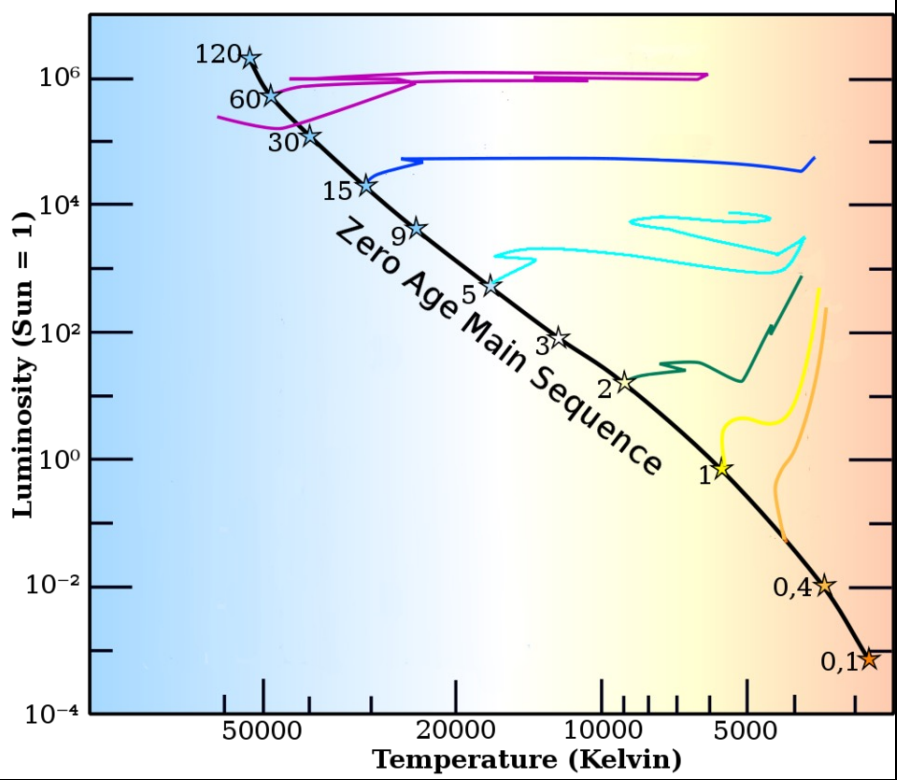
主序星 (MS)



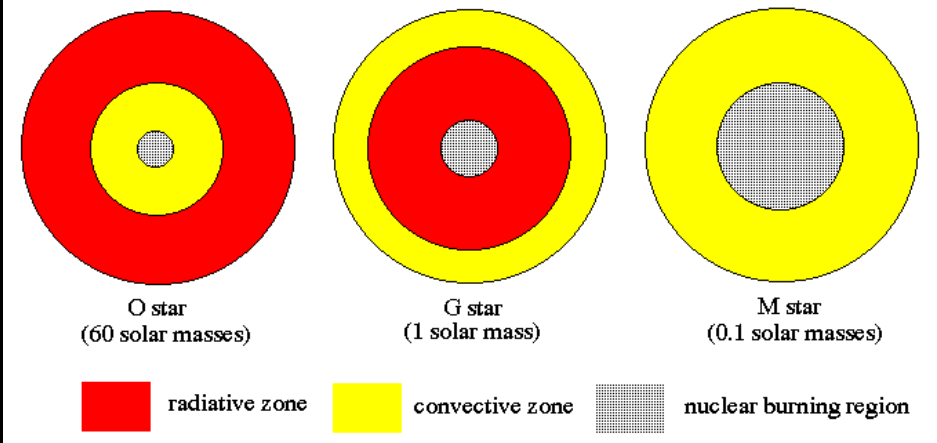
中心稳定燃烧氢



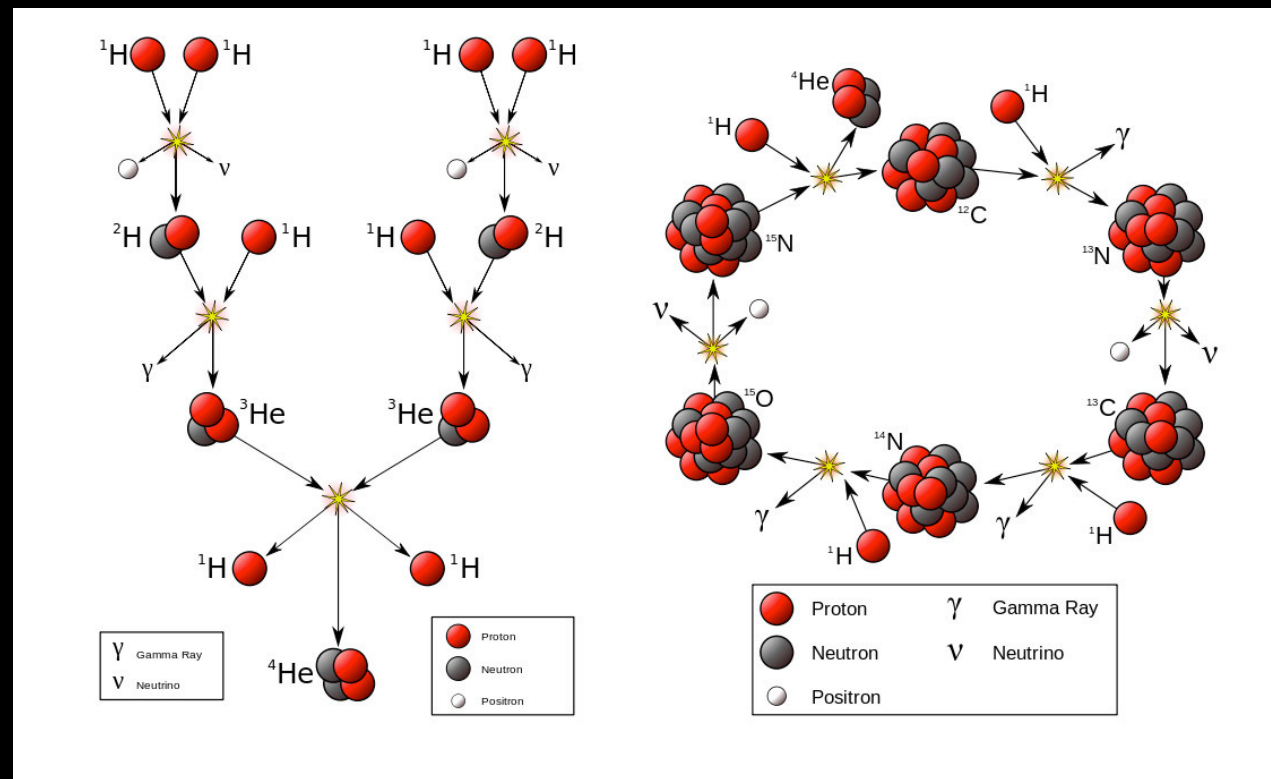
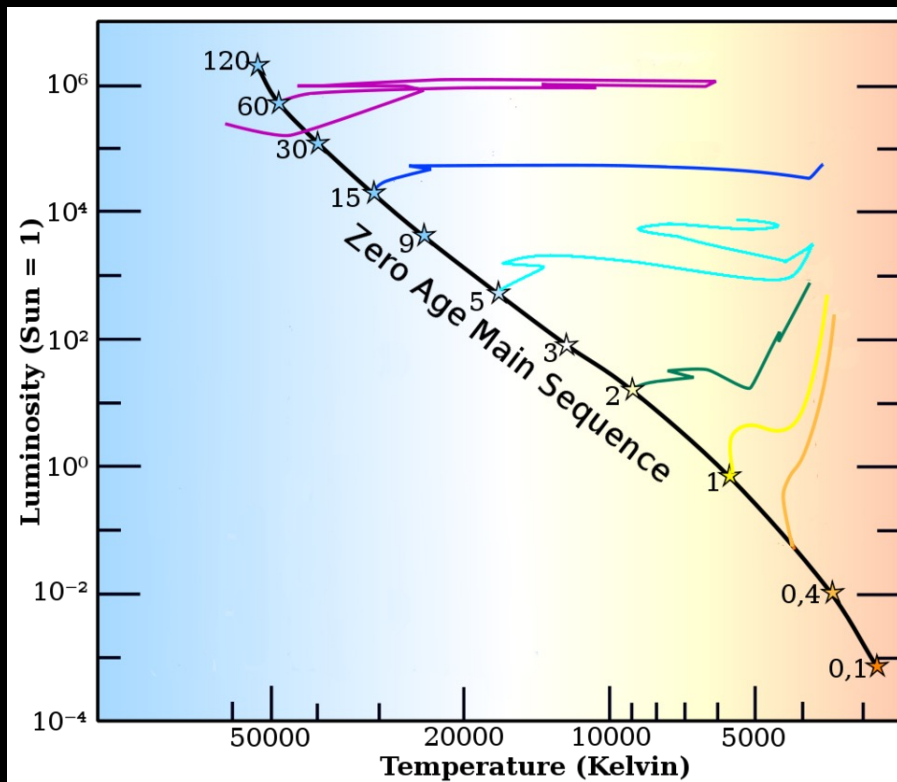
主序星 (MS)



中心稳定燃烧氢

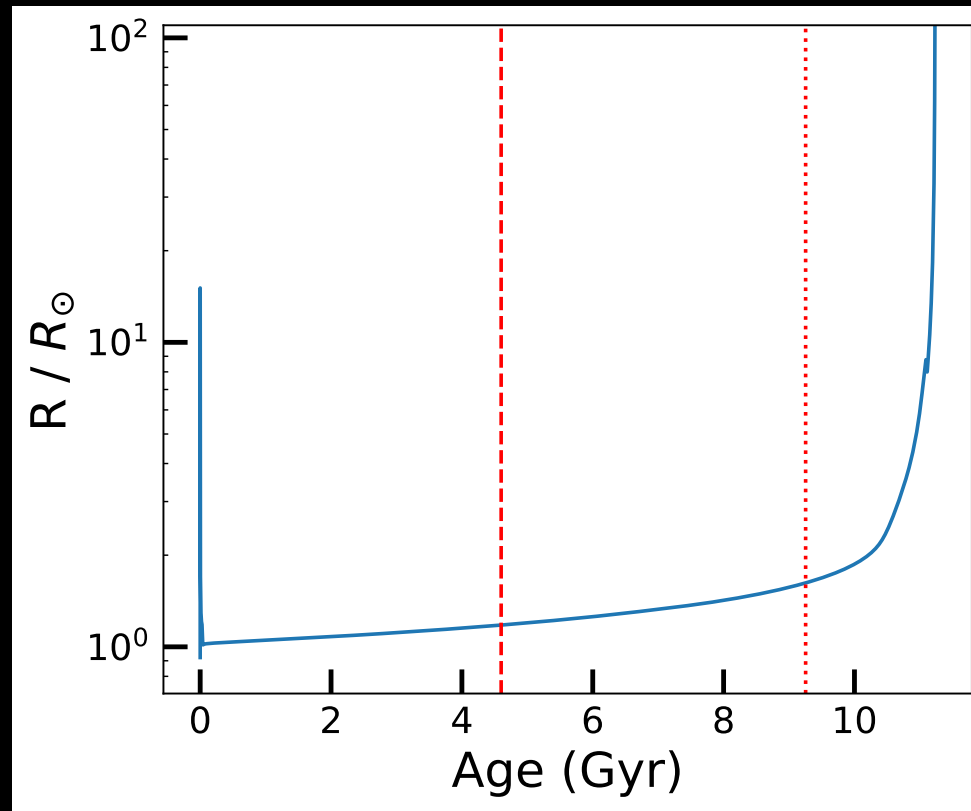
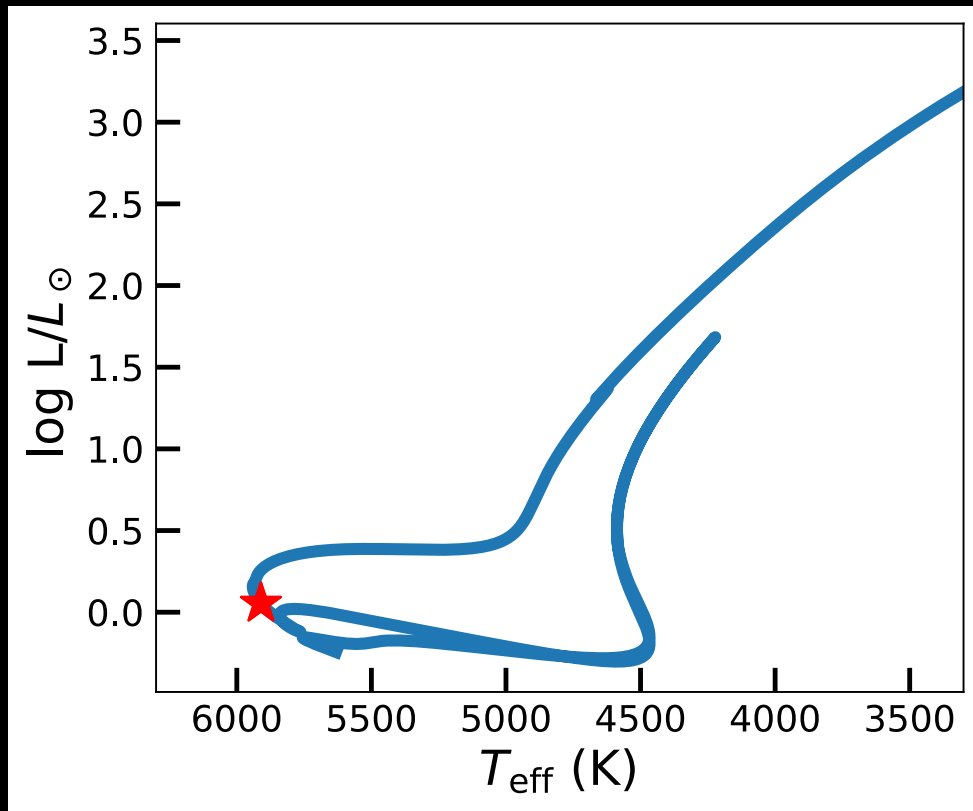


主序星 (MS)



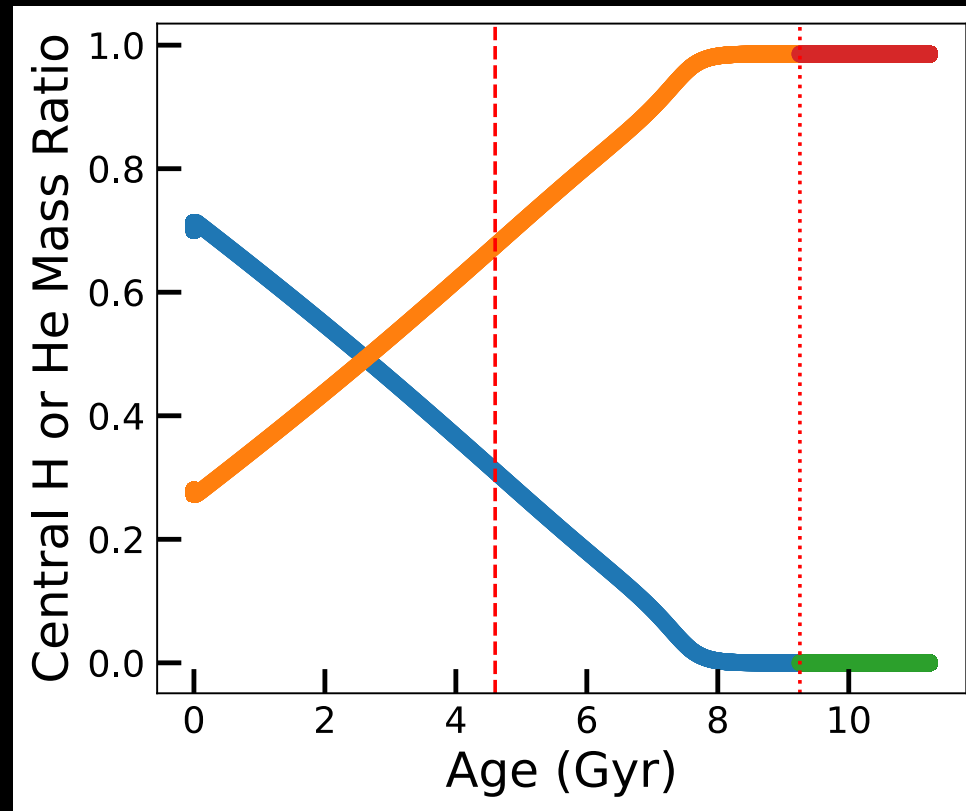
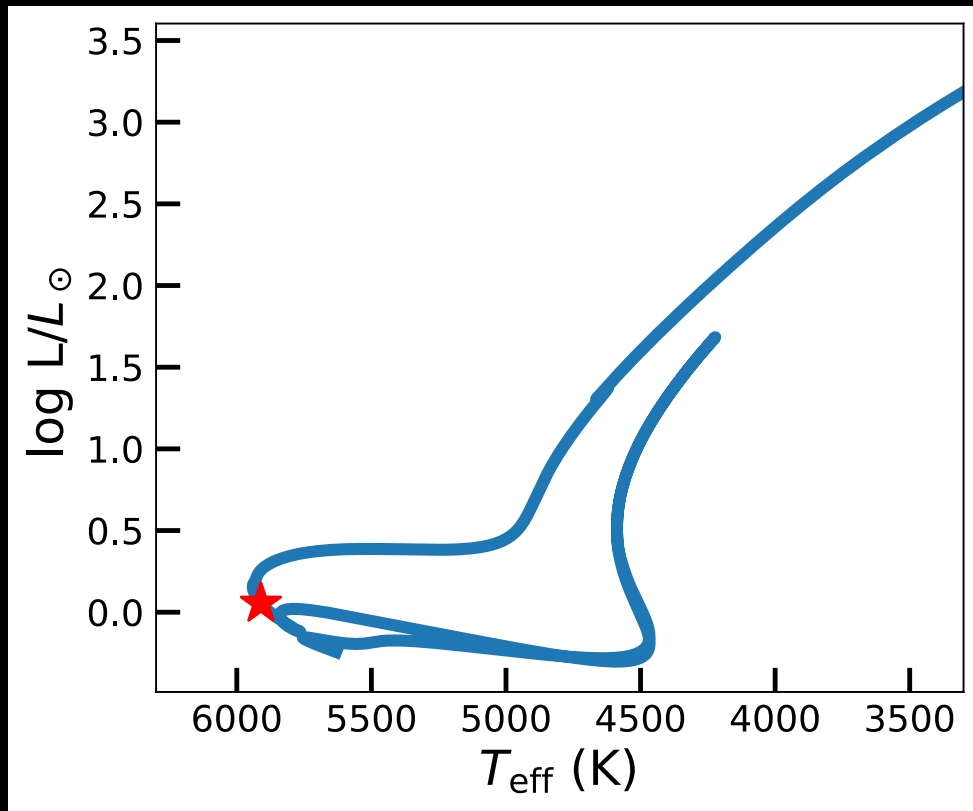
中心稳定燃烧氢

主序星 (MS)



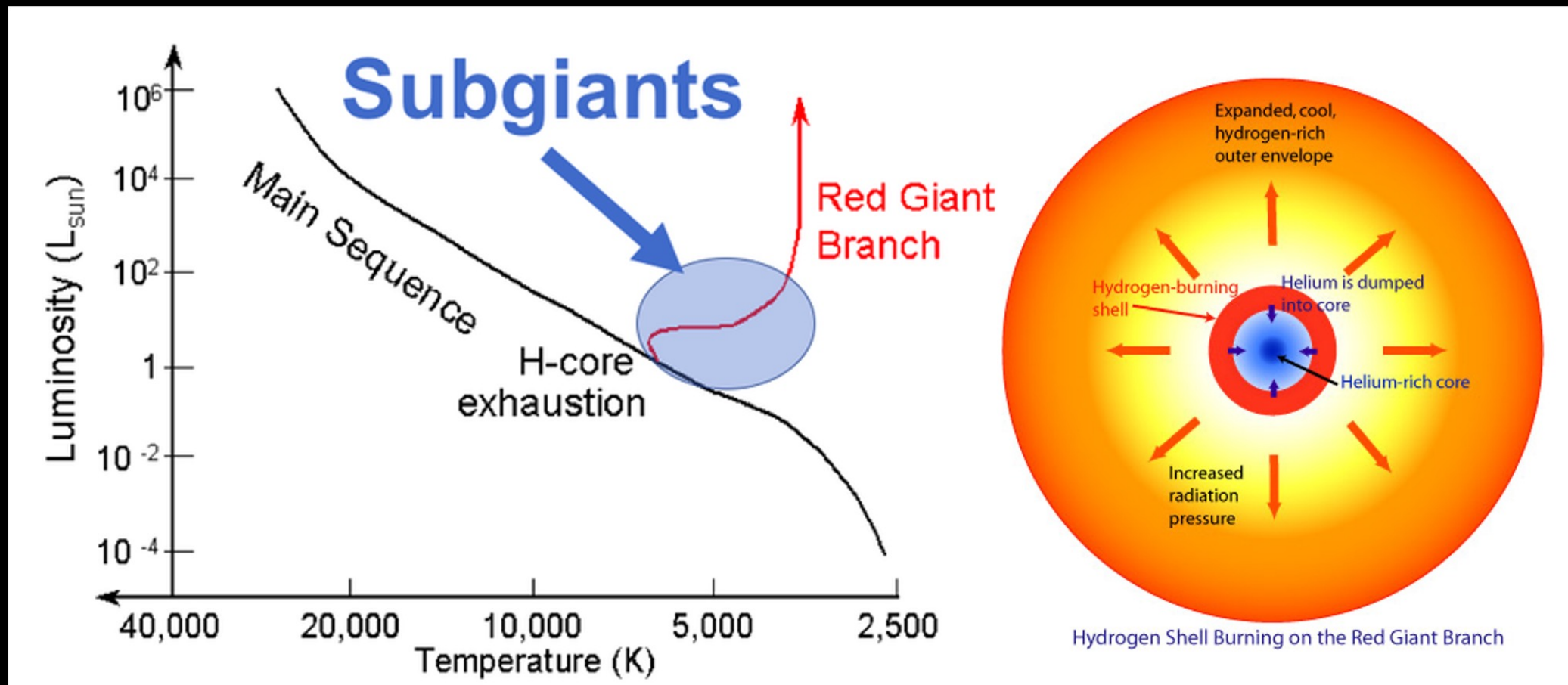
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主序星 (MS)



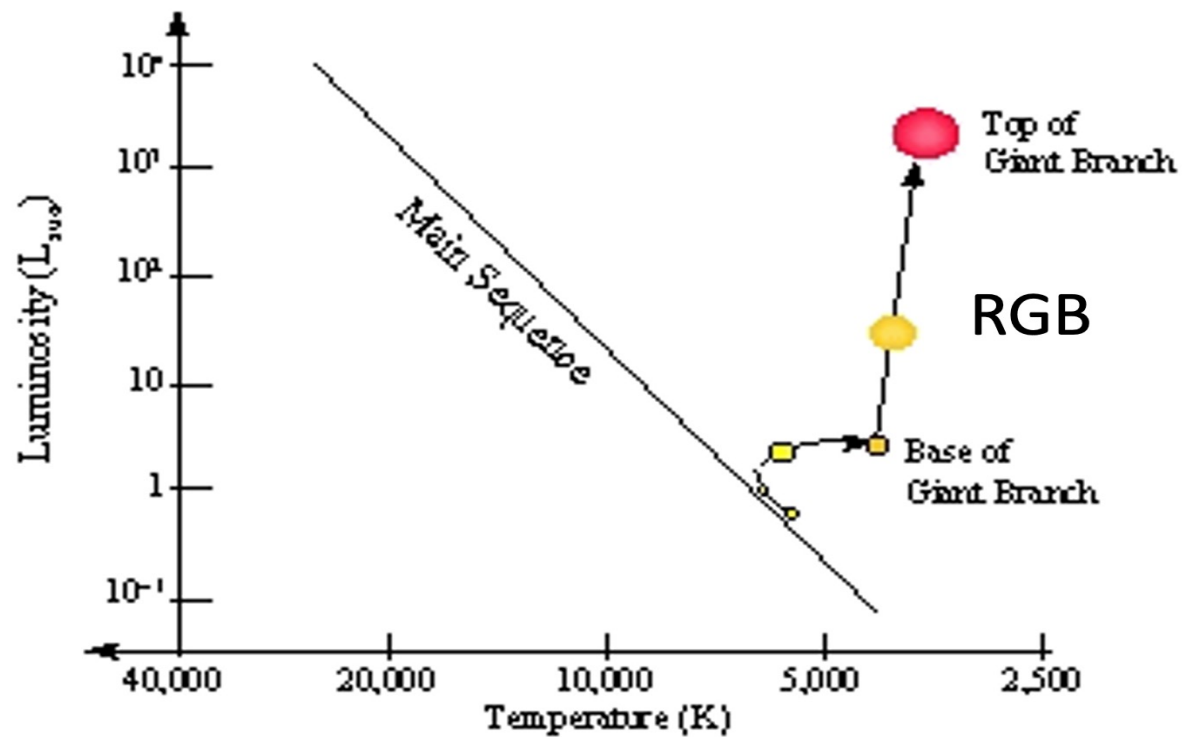
中心稳定燃烧氢

亚巨星 (SG)

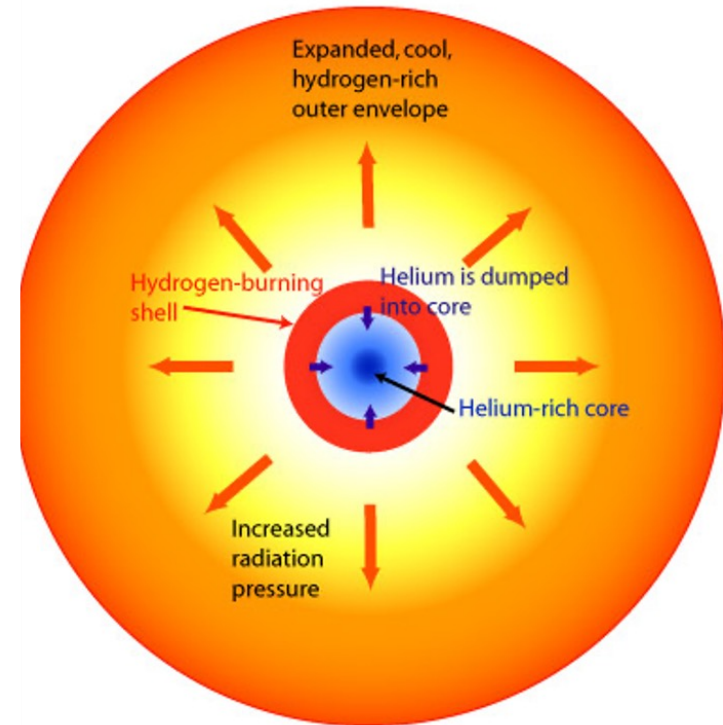


He核收缩
H壳层燃烧

红巨星支 (RGB)



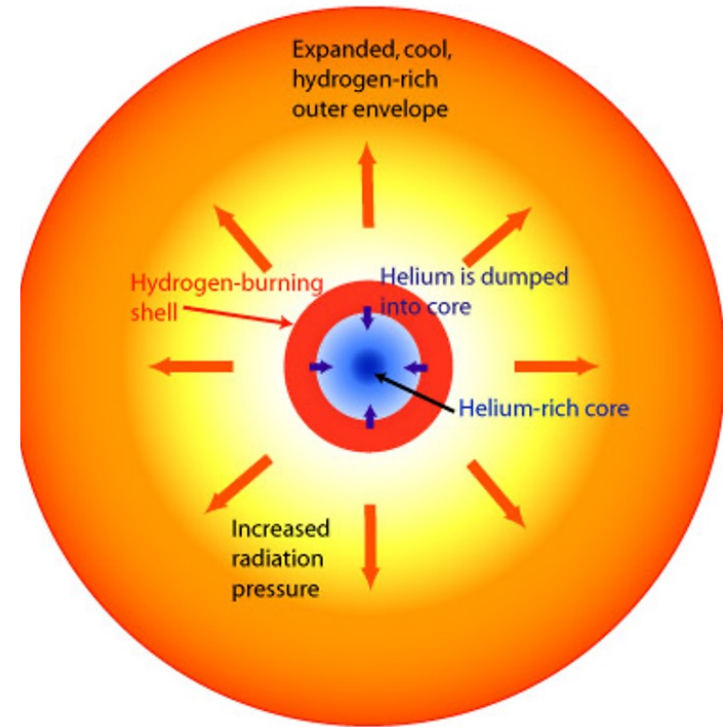
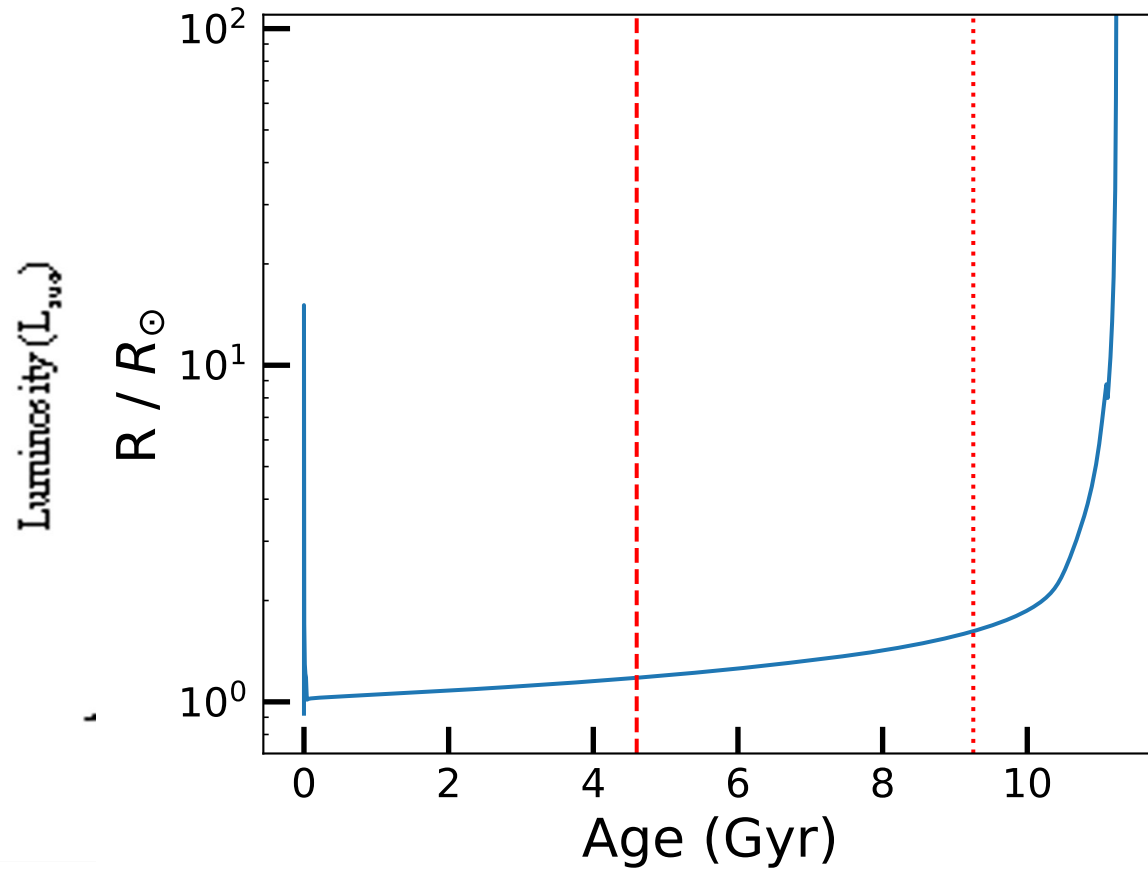
(Color on plot is not indicative of actual stellar color)



Hydrogen Shell Burning on the Red Giant Branch

He核收缩
H壳层燃烧

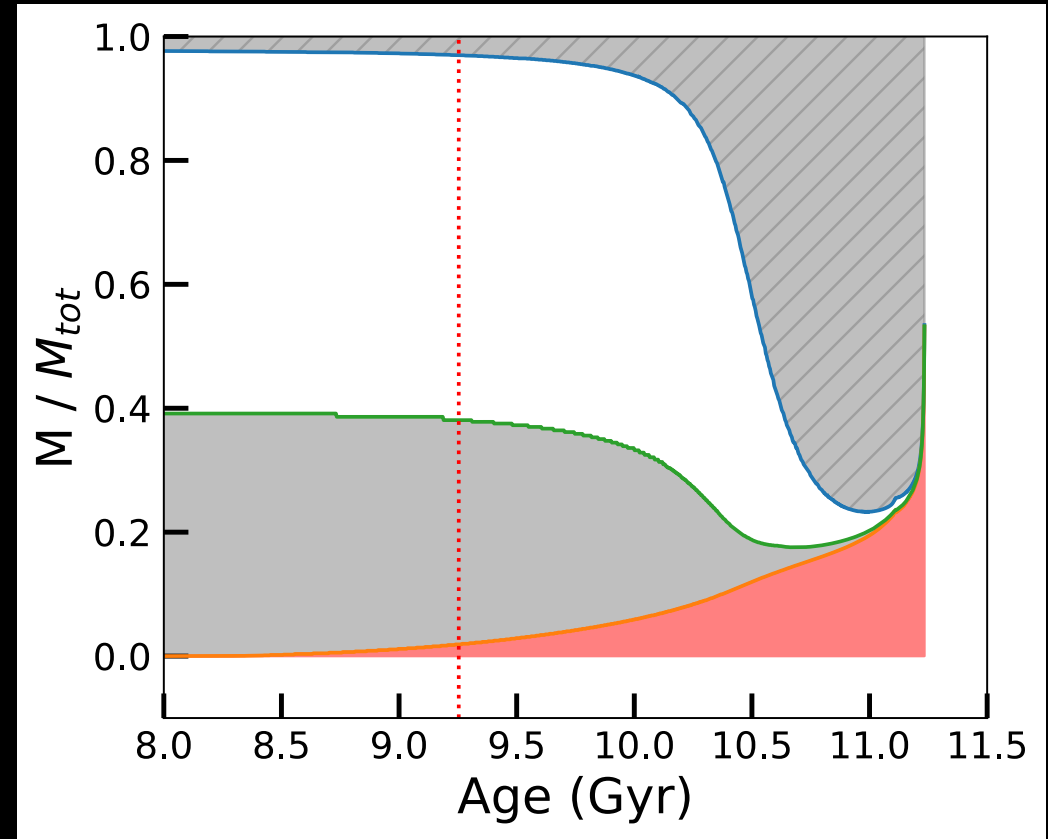
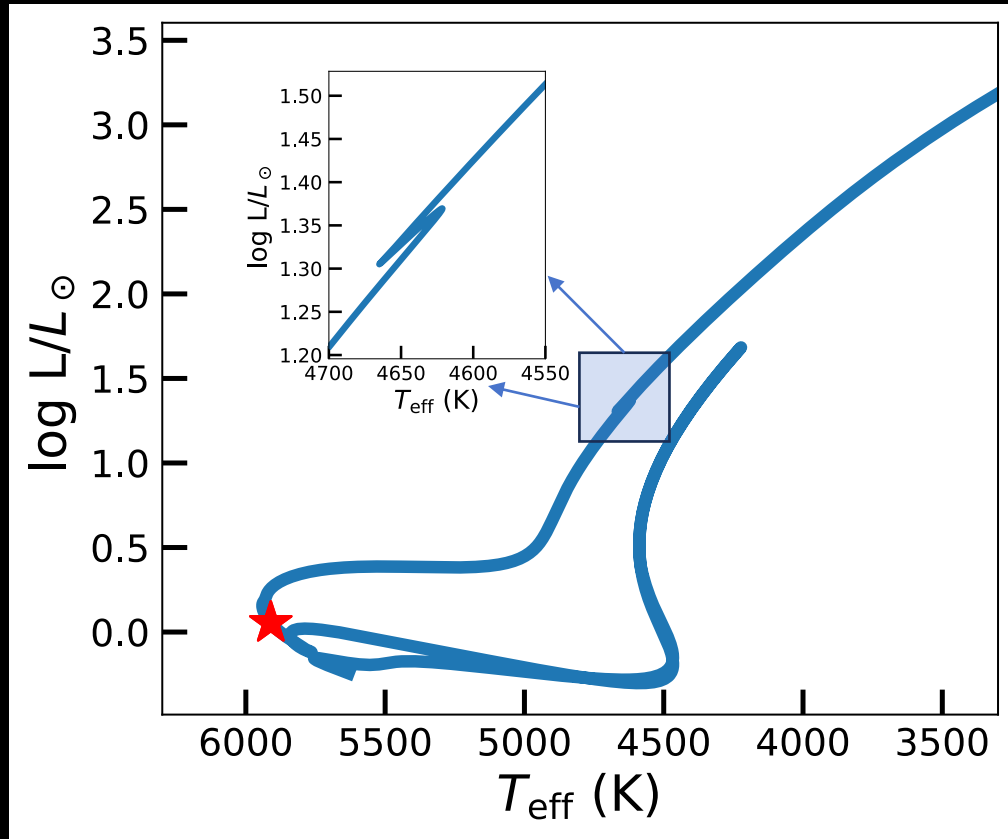
红巨星支 (RGB)



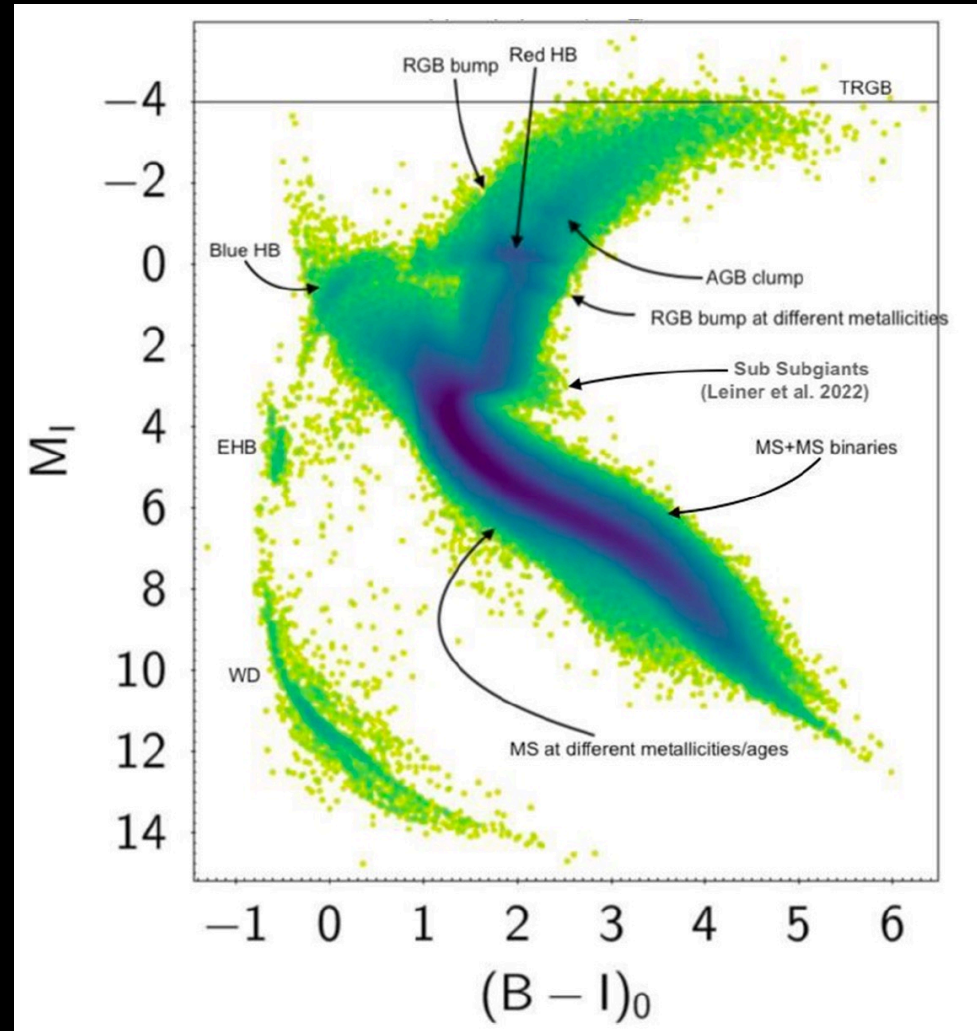
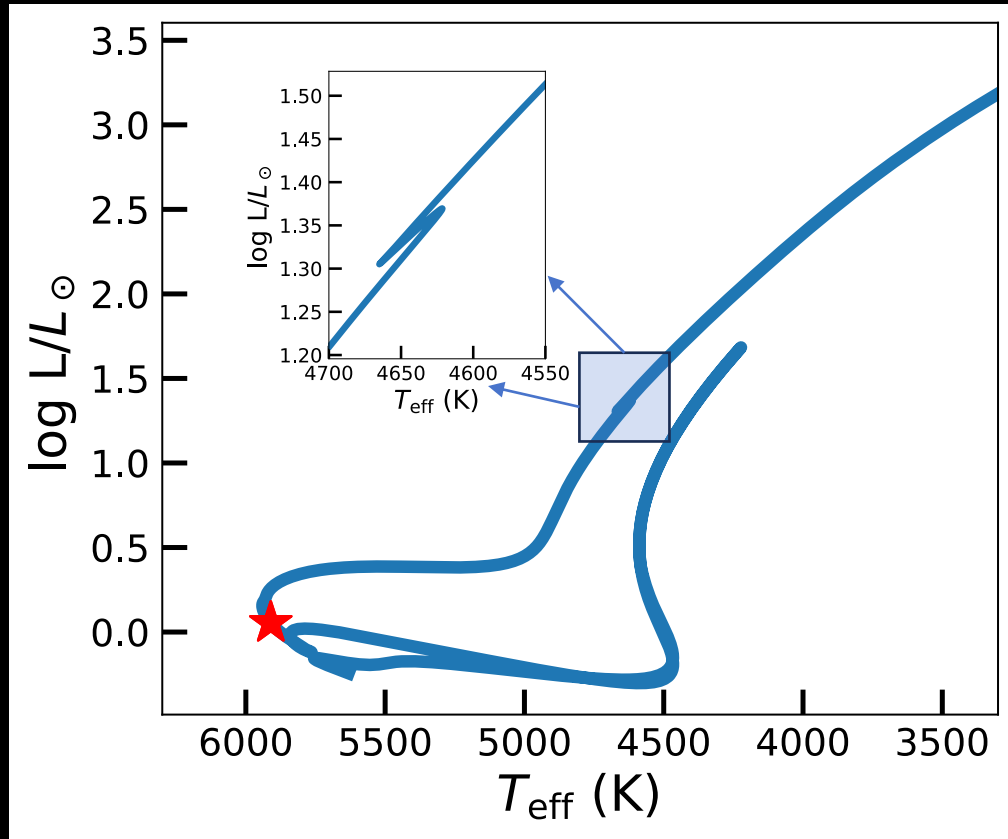
Hydrogen Shell Burning on the Red Giant Branch

He核收缩
H壳层燃烧

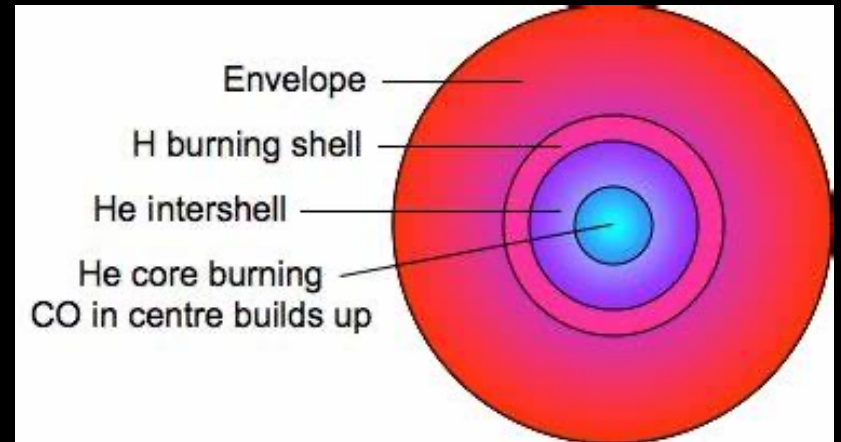
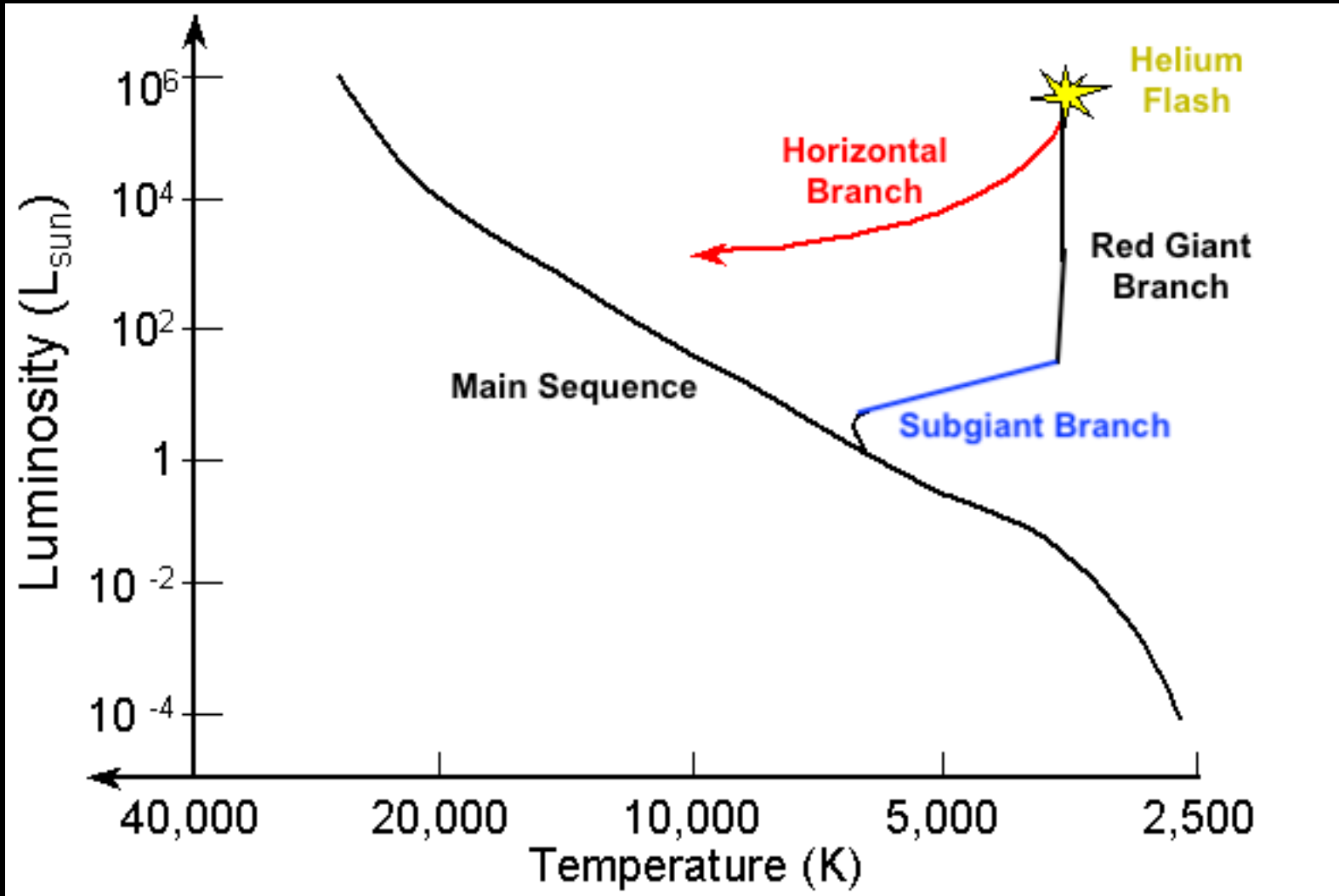
RGB Bump



RGB Bump

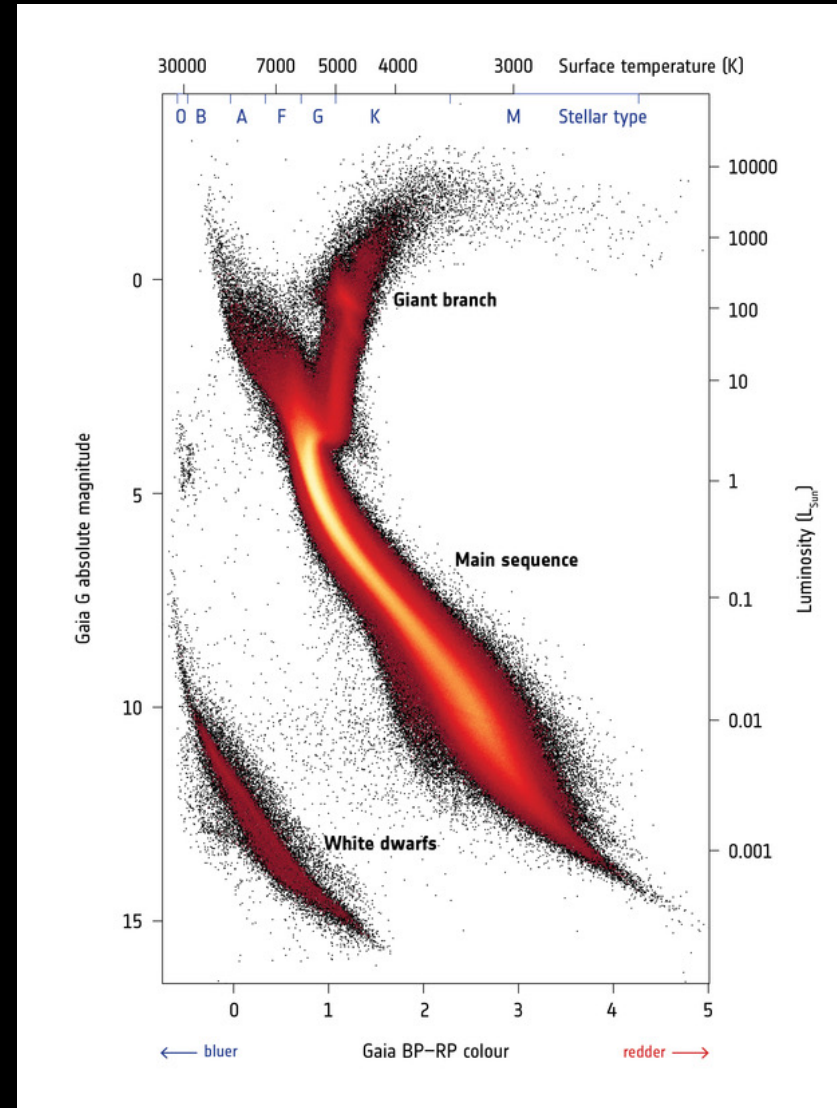
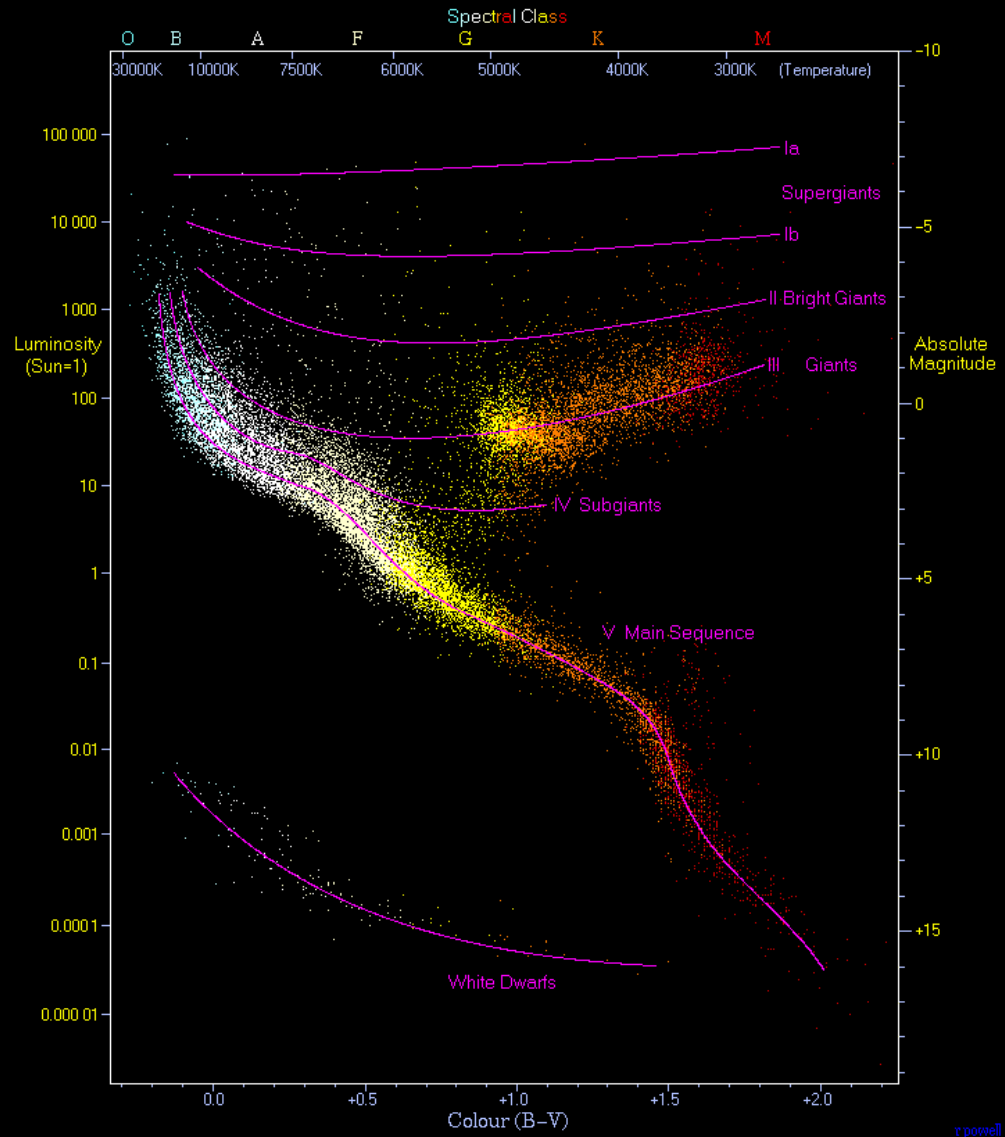


氦闪

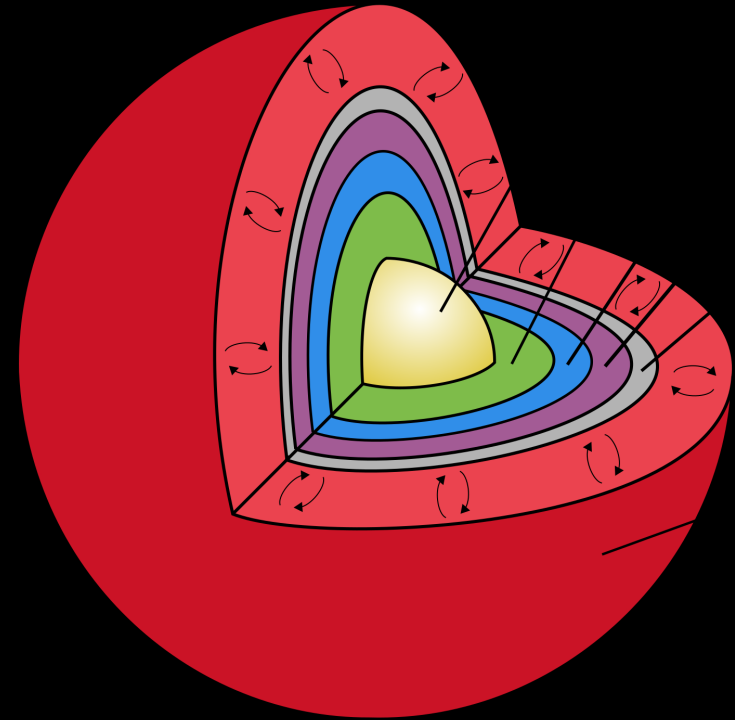
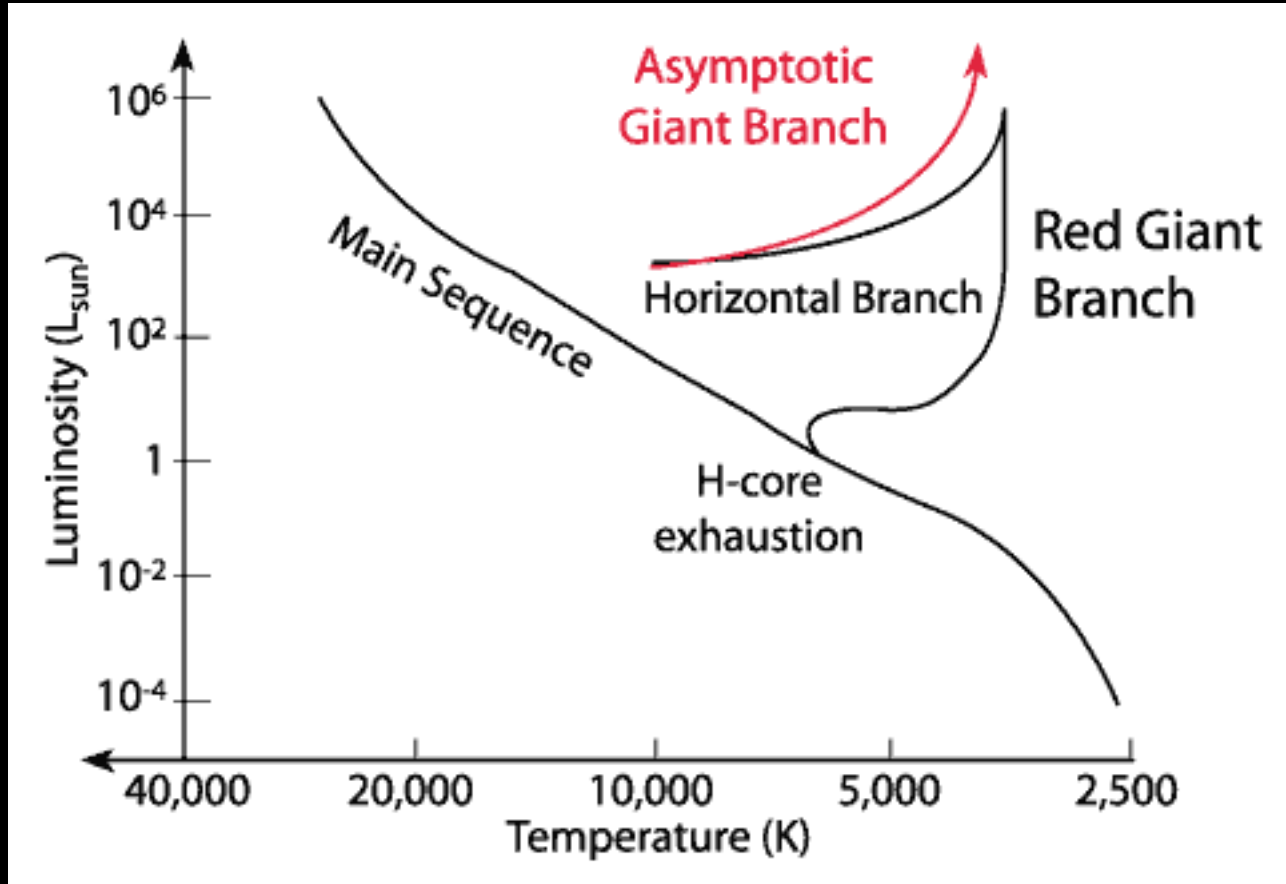


红团簇星 (RC)

为什么是标准烛光？



渐进巨星支 (AGB)



星云与白矮星

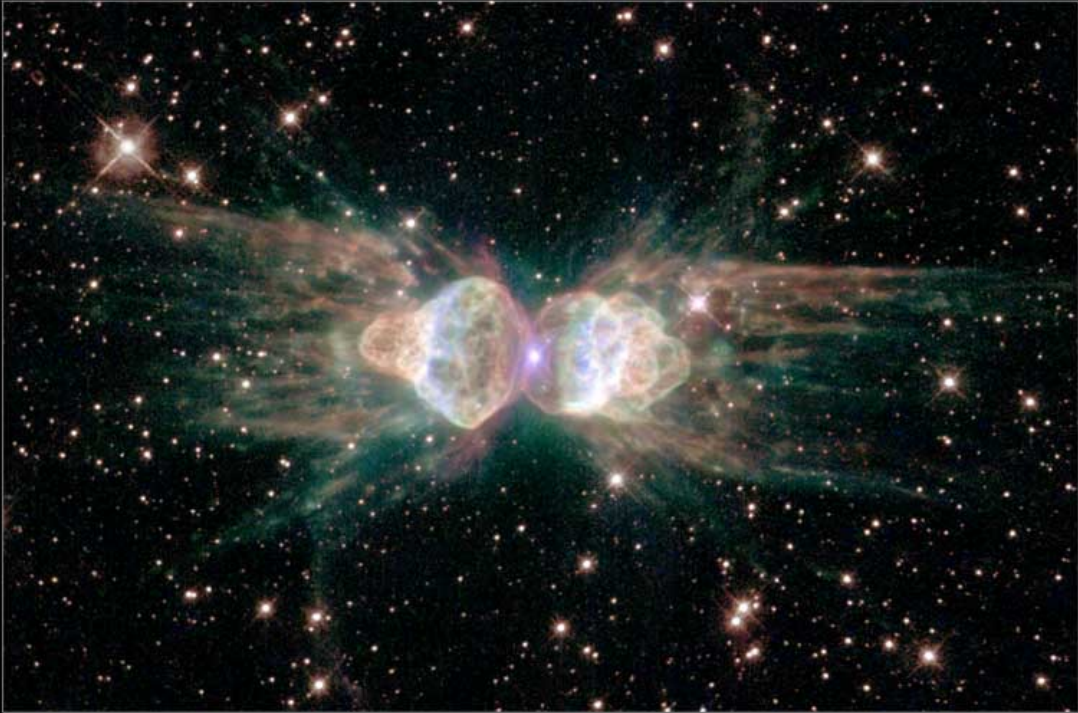
Planetary Nebula IC 418



Hubble
Heritage

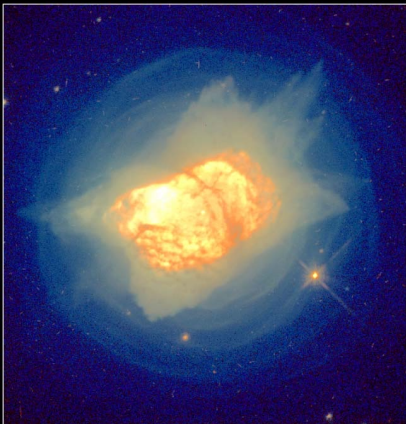
PRC00-28 • NASA and The Hubble Heritage Team (STScI/AURA) • HST/WFPC2

Planetary Nebula Mz3

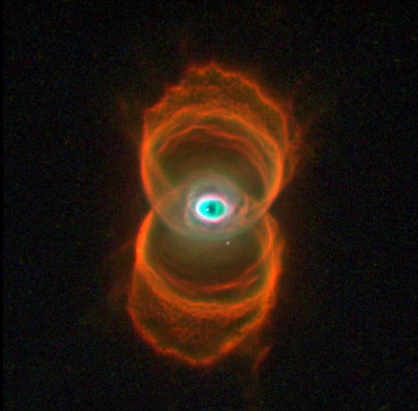


Hubble
Heritage

NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC01-05



Planetary Nebula NGC 7027 HST • WFPC2
PRC96-05 • ST ScI OPO • January 16, 1996 • H. Bond (ST ScI) and NASA

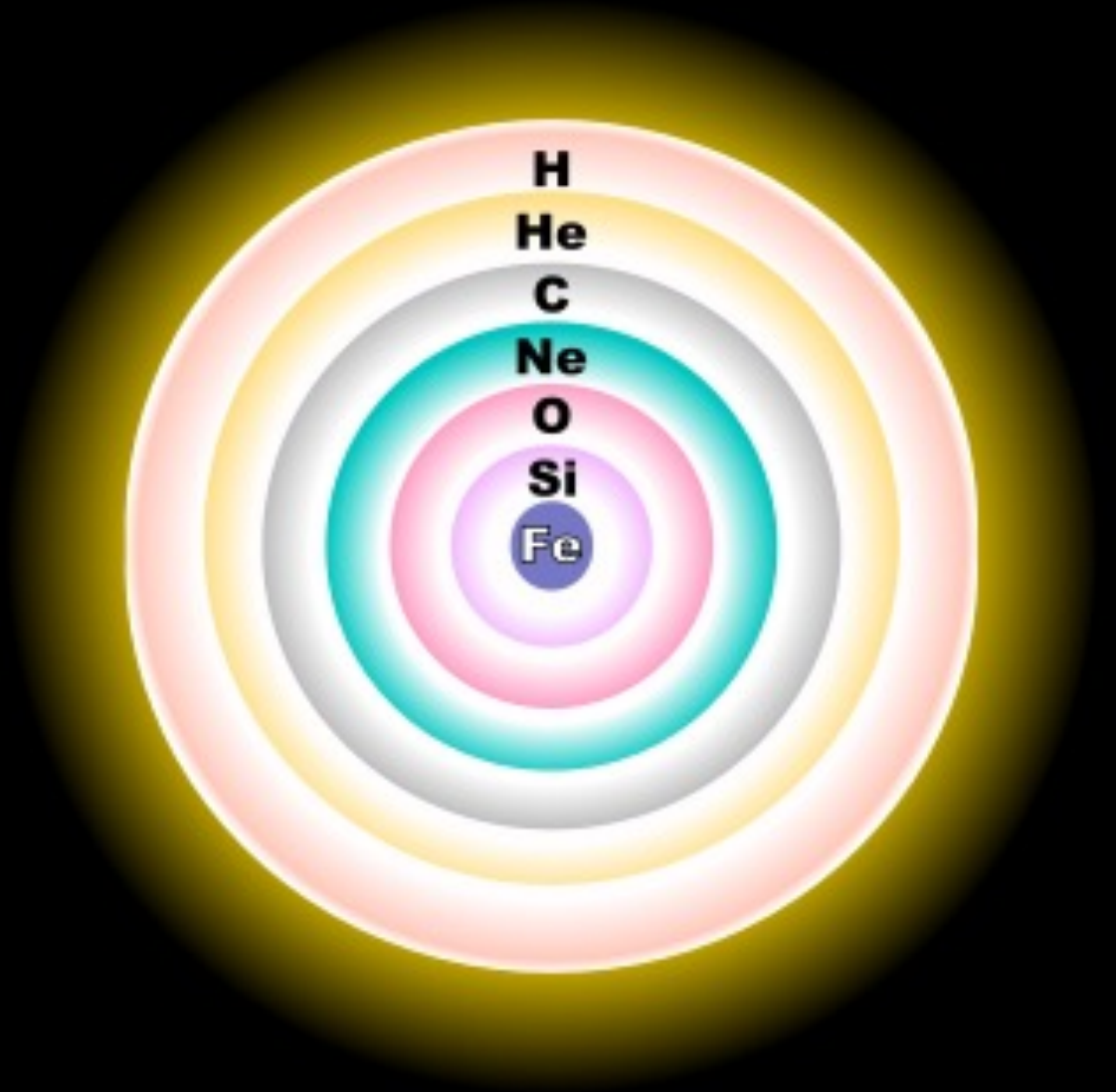
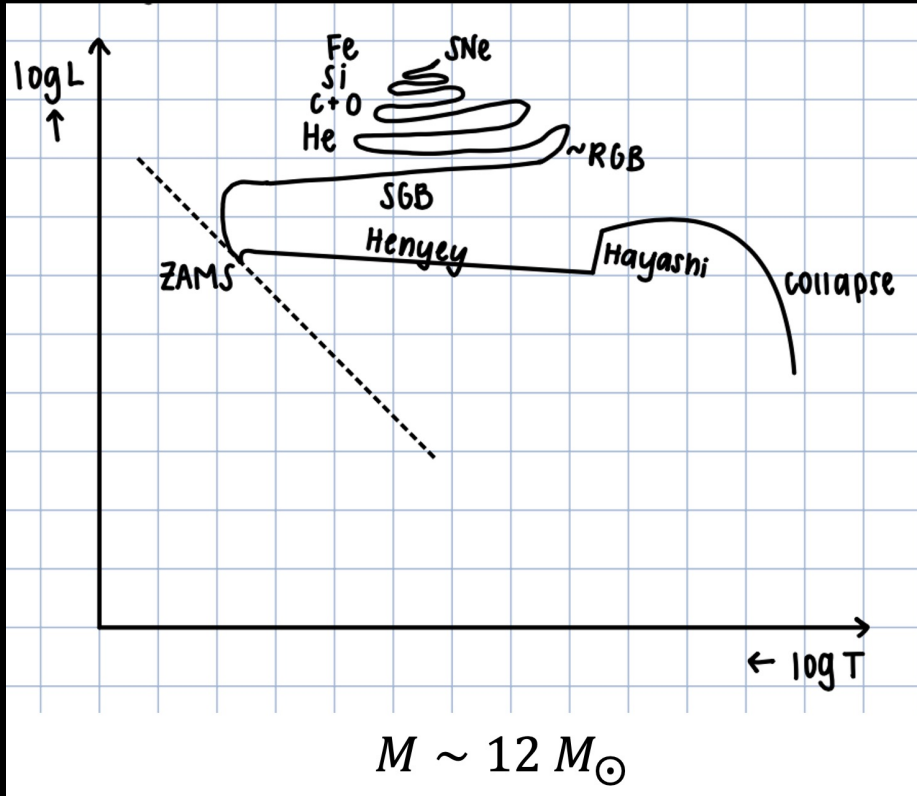


Hourglass Nebula • MyCn18 HST • WFPC2
PRC96-07 • ST ScI OPO • January 16, 1996
R. Sahai and J. Trauger (JPL), the WFPC2 Science Team and NASA

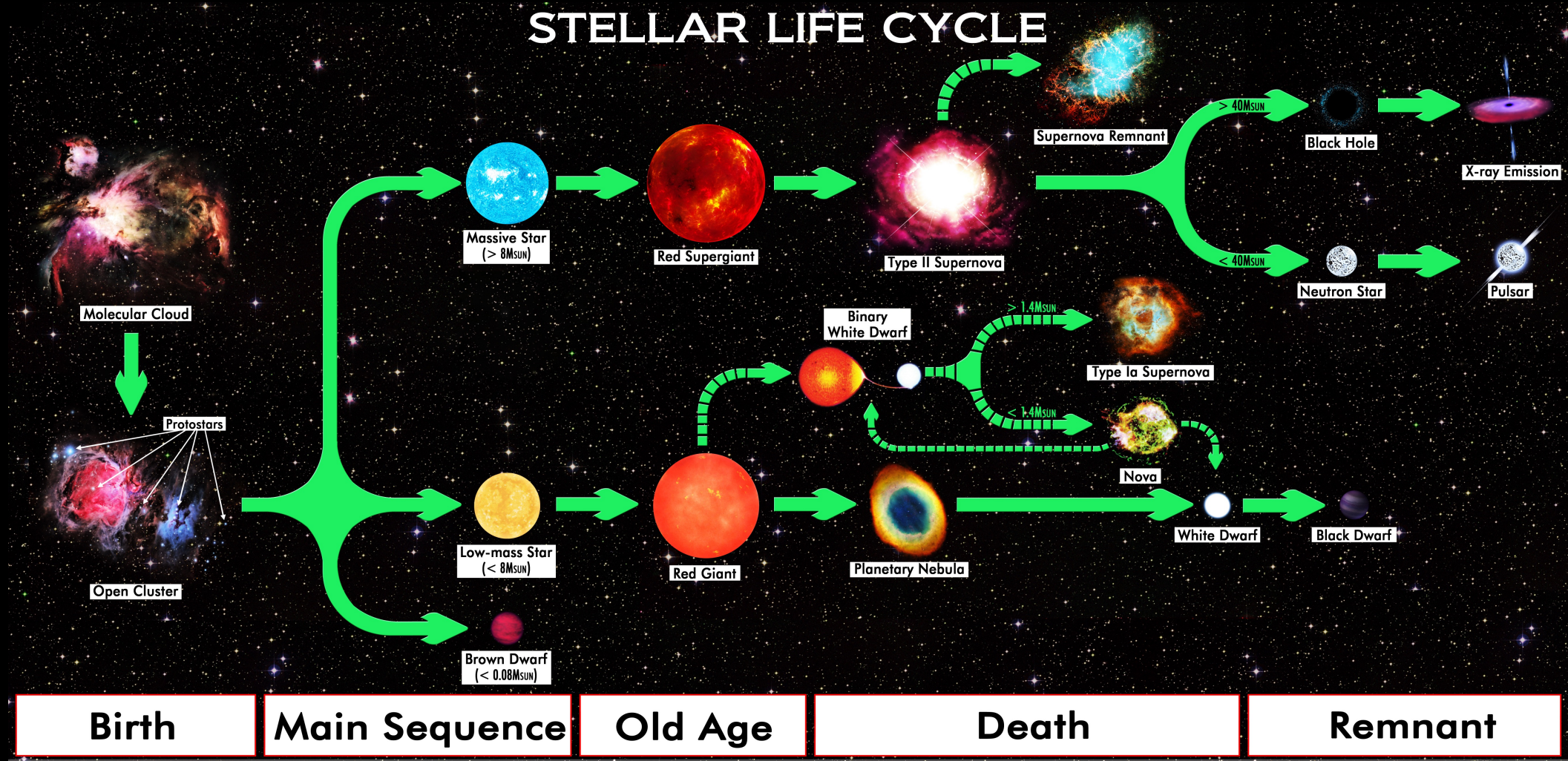


NGC 6543 HST • WFPC2
PR95-01a • ST ScI OPO • January 1995 • P. Harrington (J.M.D.), NASA
12/13/94 zip

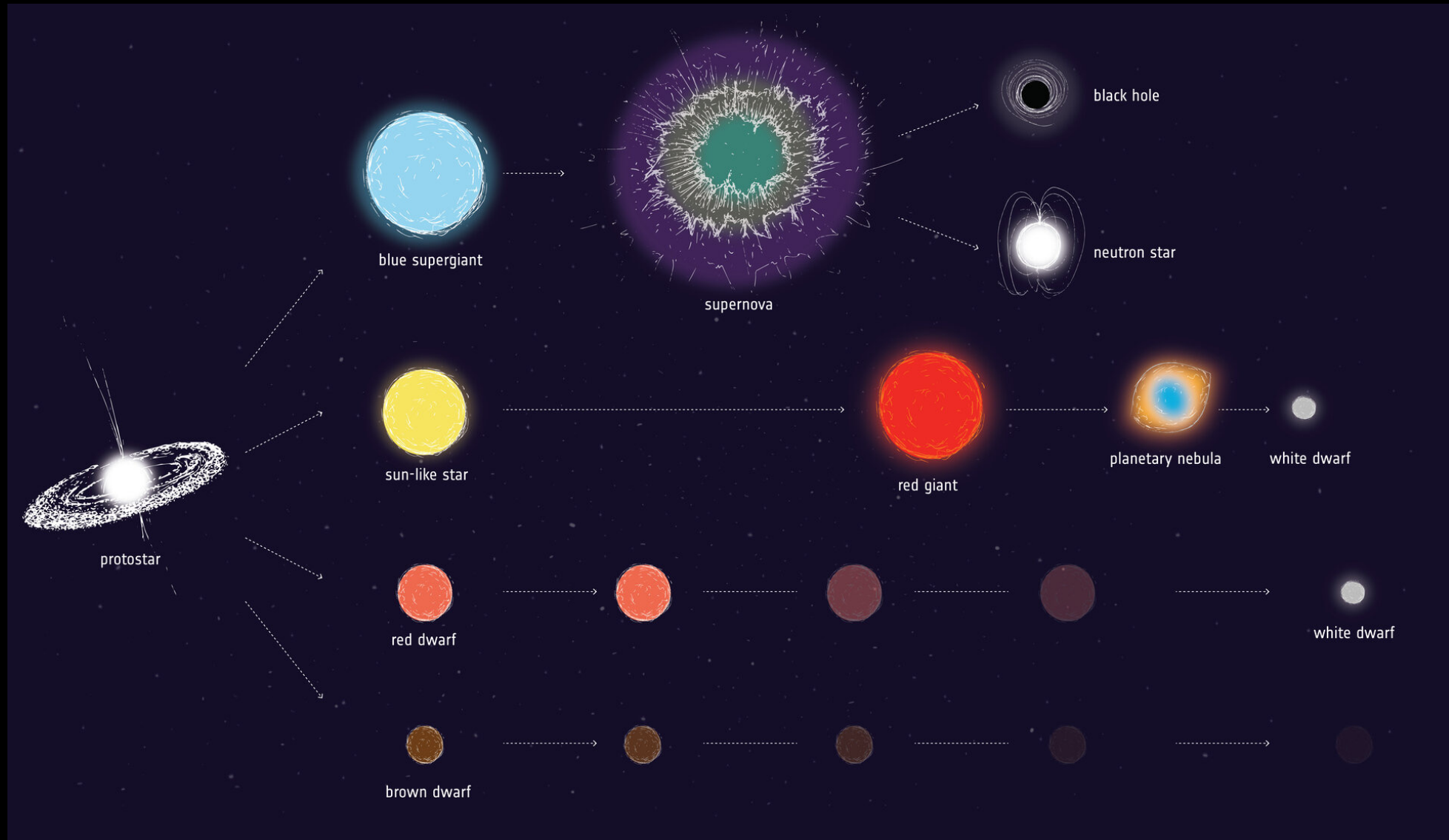
大质量恒星演化



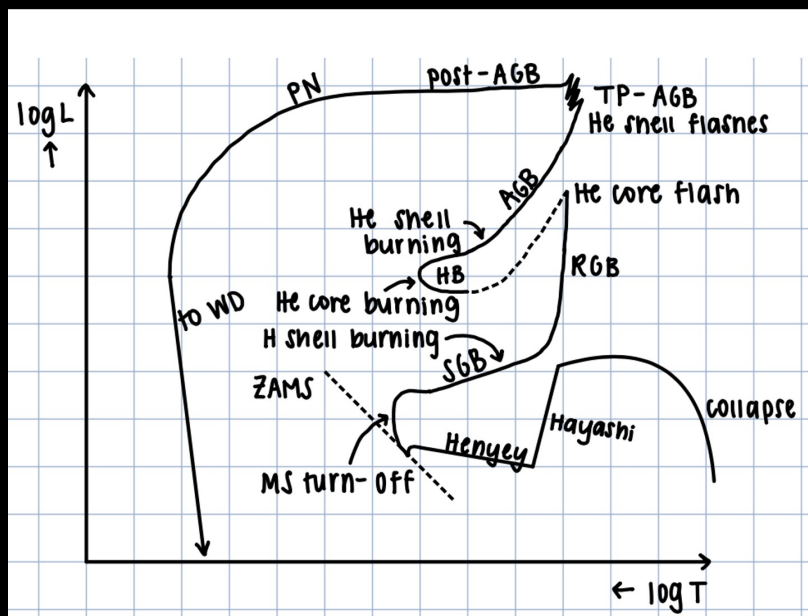
如何死亡?



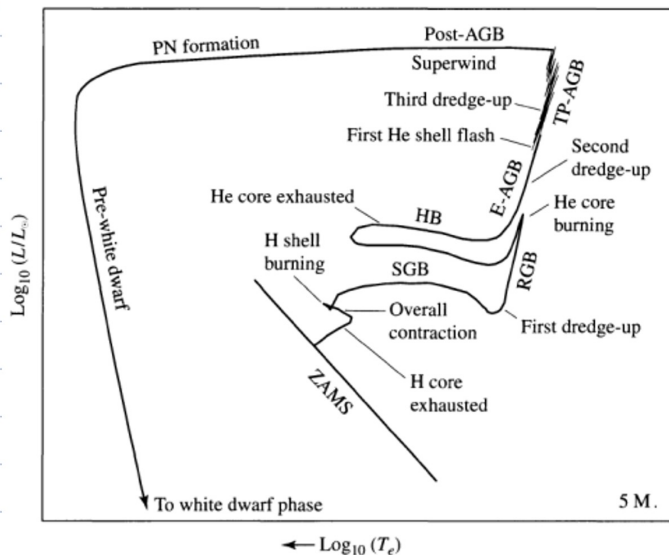
如何死亡?



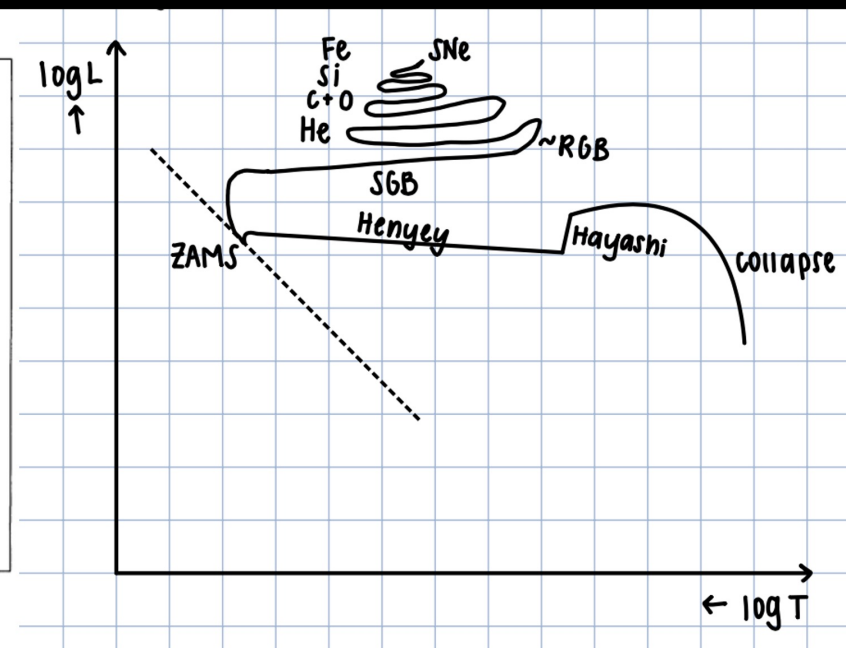
不同质量恒星的一生



$M \sim 1 M_{\odot}$



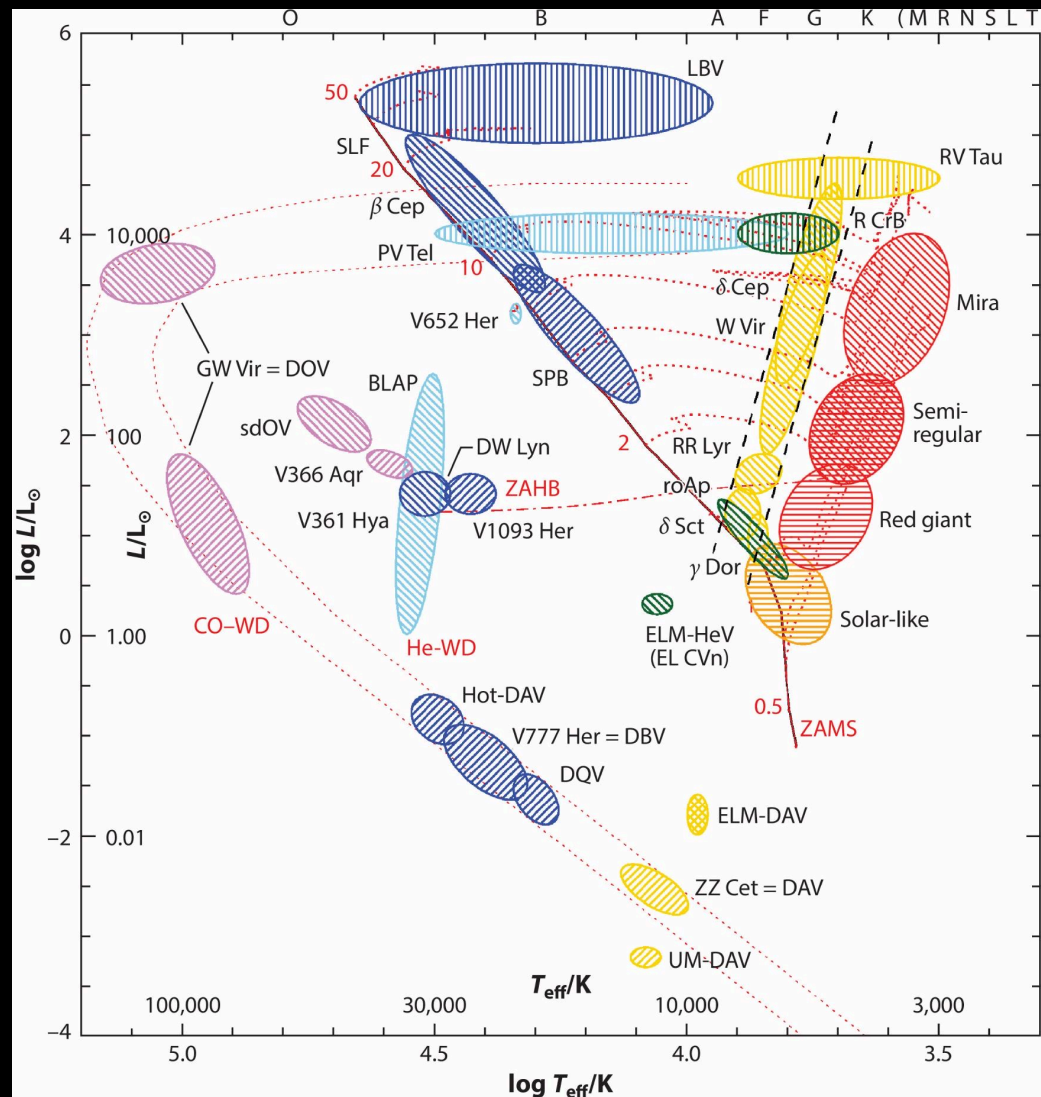
$M \sim 5 M_{\odot}$



$M \sim 12 M_{\odot}$

给定质量+化学组成，就可以预知它的一生了！

第二幕：动静之间



它们是很好的标准烛光，为什么？

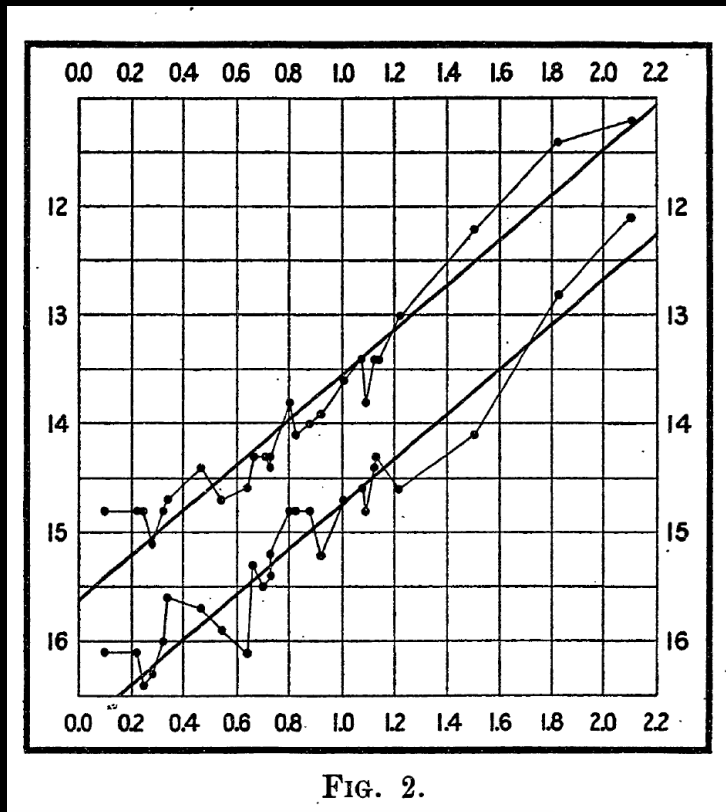
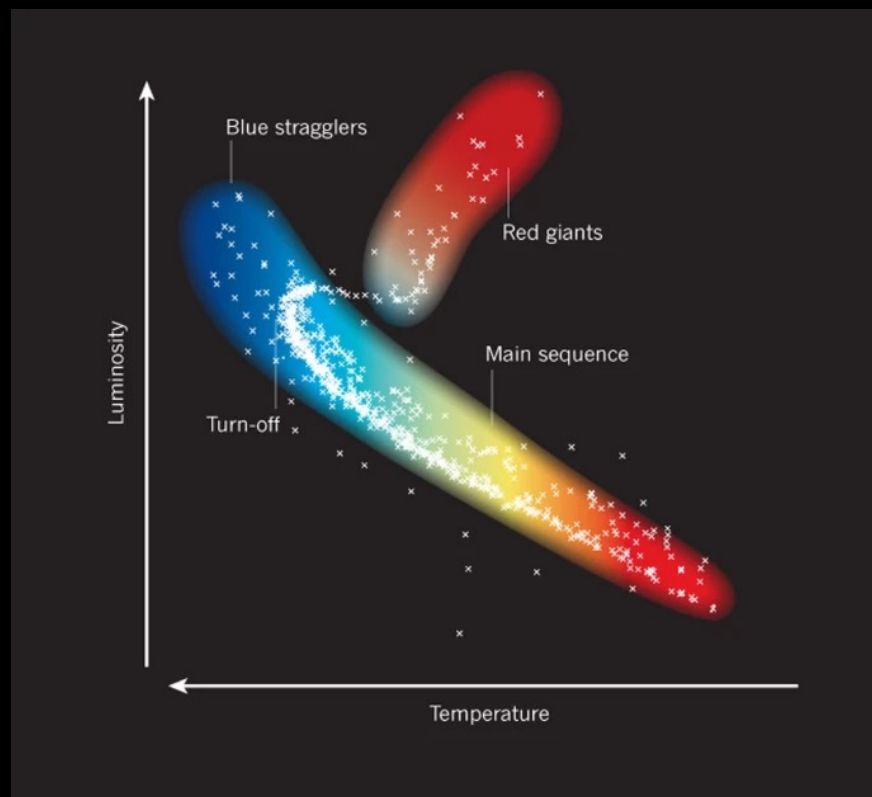


FIG. 2.

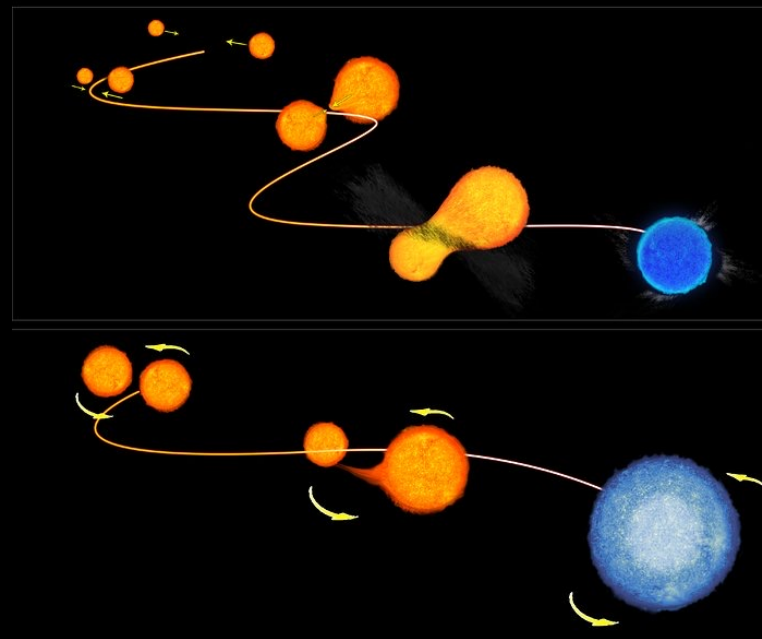
Leavitt 1912

第二幕：动静之间



给定质量+化学组成，就可以预知它的一生了！

如何破除宿命论/决定论？

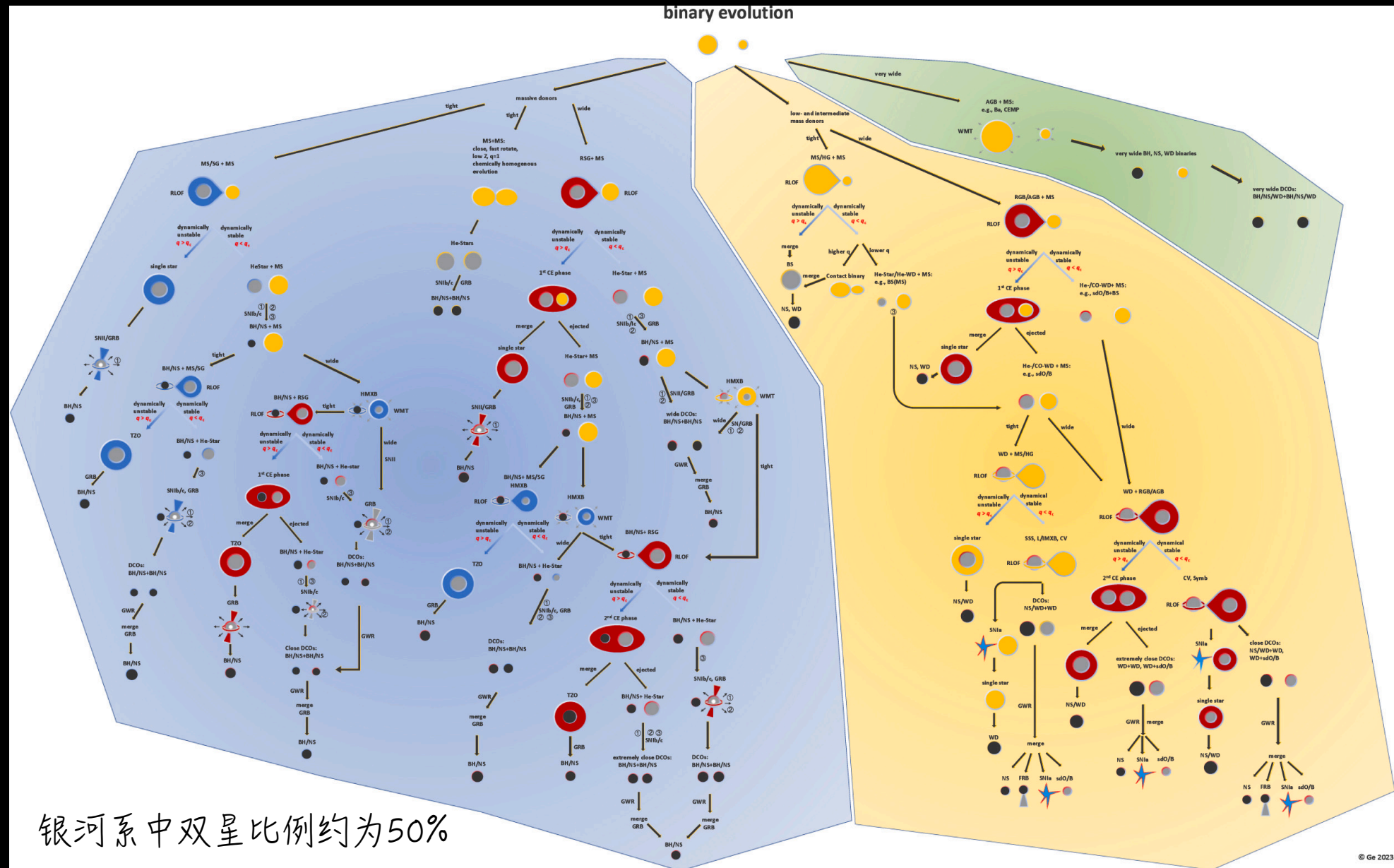


逆天改命！

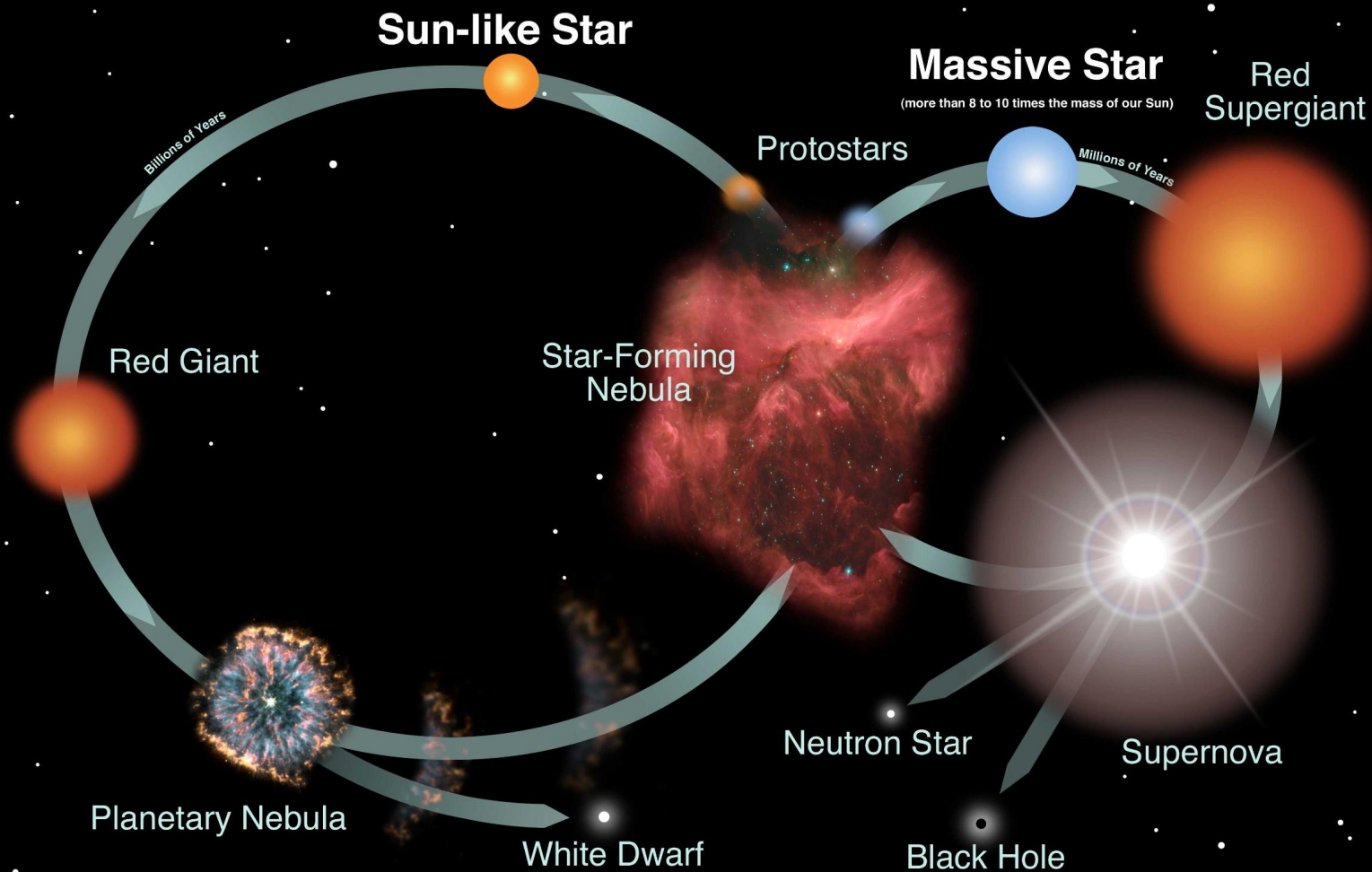


第二幕：动静之间

Han et al. 2020



第二幕：动静之间



在生死往复间又给宇宙留下了什么？

- ✓ 遗传 (尘归尘)
- ✓ 杂交 (双星组合)

第三幕：方寸之间

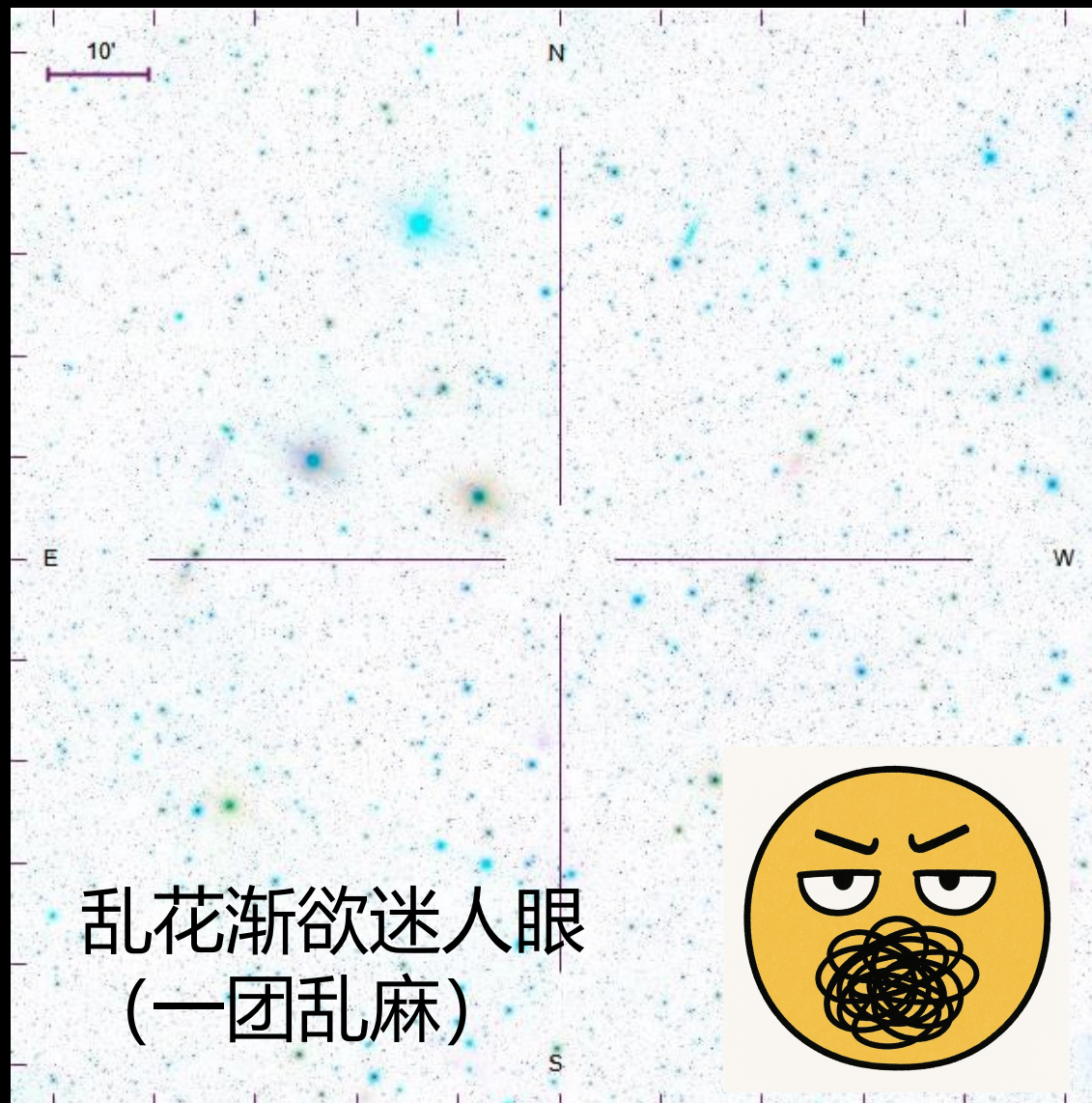
星海浮沉



第三幕：方寸之间

- 亮暗？
- 色彩？
- 远近？
- 大小？
- 轻重？
- 年纪？
- 组成？
- 快慢？
- 孤偶？

。 。 。 。 。 。



第三幕：方寸之间

“本我” 与 “他我”

“本我”：

- a) 质量 (IMF)、化学组成 (出生条件)
- b) 有效温度、半径、光度 (当前状态)
- c) 年龄、磁场、自转、活动性 (当前脾气)

“他我”：

a) **作为家庭的成员**

- ① 伴星：质量比，间距，周期等
- ② 母星：“本我”性质和宜居性

b) **作为家族的一员**

- ① 星团成员/前成员

c) **作为星系的一员：** $f(\vec{x}, \vec{v}, Z|t)$

第三幕：方寸之间

“本我”与“他我”

“本我”：

- a) 质量 (IMF)、化学组成 (出生条件)
- b) 有效温度、半径、光度 (当前状态)
- c) 年龄、磁场、自转、活动性 (当前脾气)

“他我”：

- a) 作为家庭的成员
 - ① 伴星：质量比，间距，周期等
 - ② 母星：“本我”性质和宜居性
- b) 作为家族的一员
 - ① 星团成员/前成员
- c) 作为星系的一员： $f(\vec{x}, \vec{v}, Z|t)$

一、恒星形成与演化

观测发现/约束

二、行星形成与演化

行星统计与族群

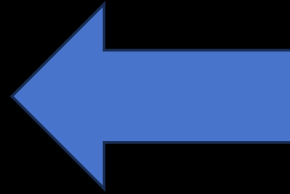
三、银河系集成历史

星口普查

第三幕：方寸之间

恒星物理参数:

- 光度
- 有效温度
- 表面重力加速度
- 半径
- 质量
- 年龄
- 化学组成
- 速度
- 磁场/活动性等
- 孤偶



观测:

- 位置
- 多波段星等
- 光谱
- 干涉 (纹)
- 偏振
- 以上量随时间的变化
 - 视差
 - 自行
 - 光变 (星震)
 - 视像速度曲线
 - ...

第三幕：方寸之间

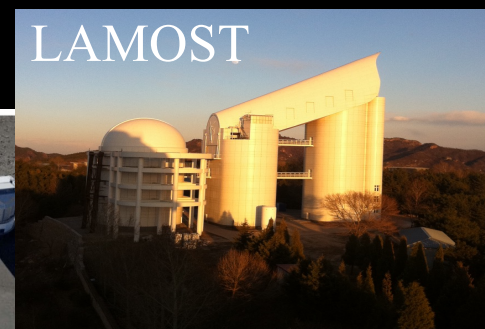
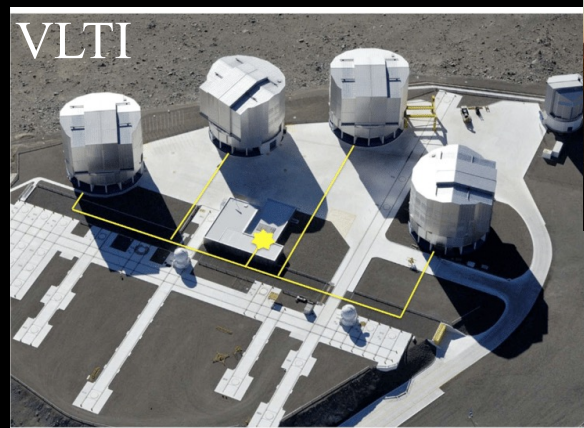
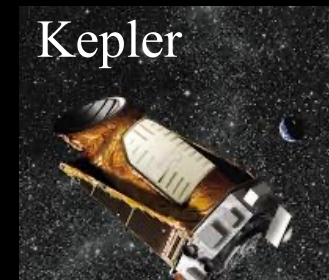
天测：位置、自行、三角视差

测光：位置、多波段星等
自行、光变曲线（时域）
星震（超高精度光变曲线）

光谱：视向速度、元素丰度

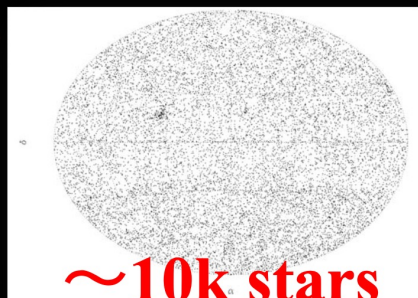
干涉：半径

偏振：磁场

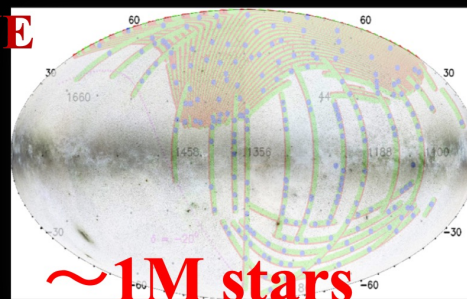


第三幕：方寸之间

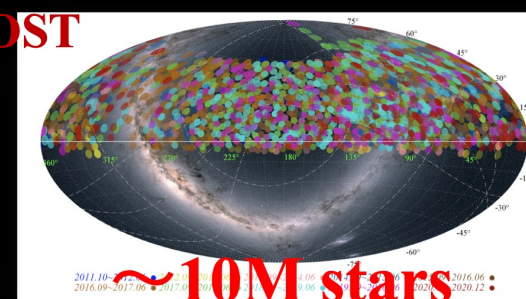
GCS



SEGUE



LAMOST



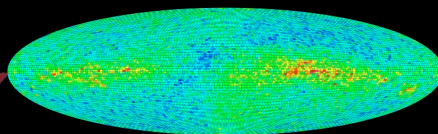
2000年 ●

2010年 ●

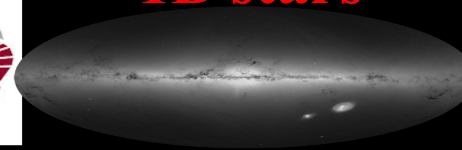
2020年 ●



~10k stars



>1B stars



第四幕：宇宙沙粒，永闪光辉

丈量宇宙史：
从“银河系全景图”到“哈勃常数危机”

第四幕：宇宙沙粒，永闪光辉

序幕：银河系全景图

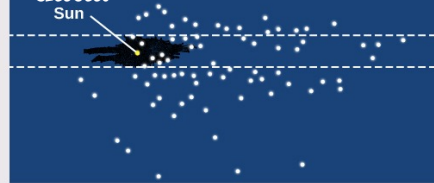


Source: *On the Construction of the Heavens*. By William Herschel, Esq. F. R. S. Philosophical Transactions of the Royal Society of London, Vol. 75. (1785), pp. 213-266.

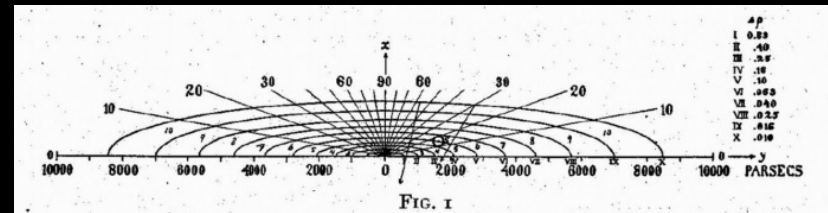


(a)

Source: Graph based on Shapley's original **1918** globular cluster data.



(b)



Source: Kapteyn's Universe from his 1922 publication of his photographic star count survey.

第四幕：宇宙沙粒，永闪光辉

序幕：银河系全景图

勒维特与她的量天尺

HARVARD COLLEGE OBSERVATORY.

CIRCULAR 173.

PERIODS OF 25 VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

The following statement regarding the periods of 25 variable stars in the Small Magellanic Cloud has been prepared by Miss Leavitt.

A Catalogue of 1777 variable stars in the two Magellanic Clouds is given in H.A. 60, No. 4. The measurement and discussion of these objects present problems of unusual difficulty, on account of the large area covered by the two regions, the extremely crowded distribution of the stars contained in them, the faintness of the variables, and the shortness of their periods. As many of them never become brighter than the fifteenth magnitude, while very few exceed the thirteenth magnitude at maximum, long exposures are necessary, and the number of available photographs is small. The determination of absolute magnitudes for widely separated sequences of comparison stars of this degree of faintness may not be satisfactorily completed for some time to come. With the adoption of an absolute scale of magnitudes for stars in the North Polar Sequence, however, the way is open for such a determination.

Fifty-nine of the variables in the Small Magellanic Cloud were measured in 1904, using a provisional scale of magnitudes, and the periods of seventeen of them were published in H.A. 60, No. 4, Table VI. They resemble the variables found in globular clusters, diminishing slowly in brightness, remaining near minimum for the greater part of the time, and increasing very rapidly to a brief maximum. Table I gives all the periods which have been determined thus far, 25 in number, arranged in the order of their length. The first five columns contain the Harvard Number, the brightness at maximum and at minimum as read from the light curve, the epoch expressed in days following J.D. 2,410,000, and the length of the period expressed in days. The Harvard Numbers in the first column are placed in Italics, when the period has not been published hitherto. A remarkable relation between the brightness of these variables and the length of their periods will be noticed. In H.A. 60, No. 4, attention was called to the fact that the brighter variables



亨丽爱塔·斯万·勒维特：1868-1921

- 哈佛天文台计算员
- 发现造父变星周光关系

第四幕：宇宙沙粒，永闪光辉

序幕：银河系全景图

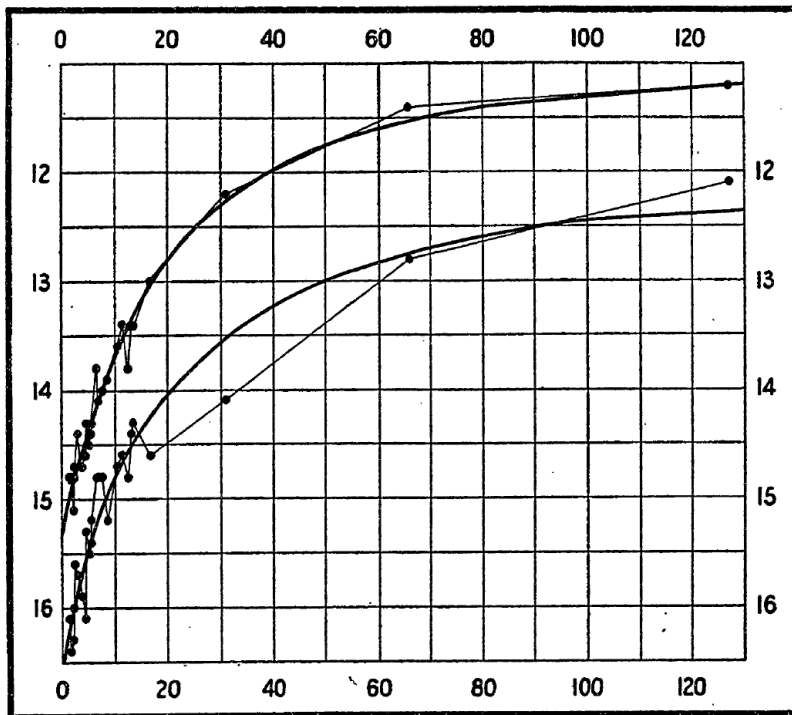


FIG. 1.

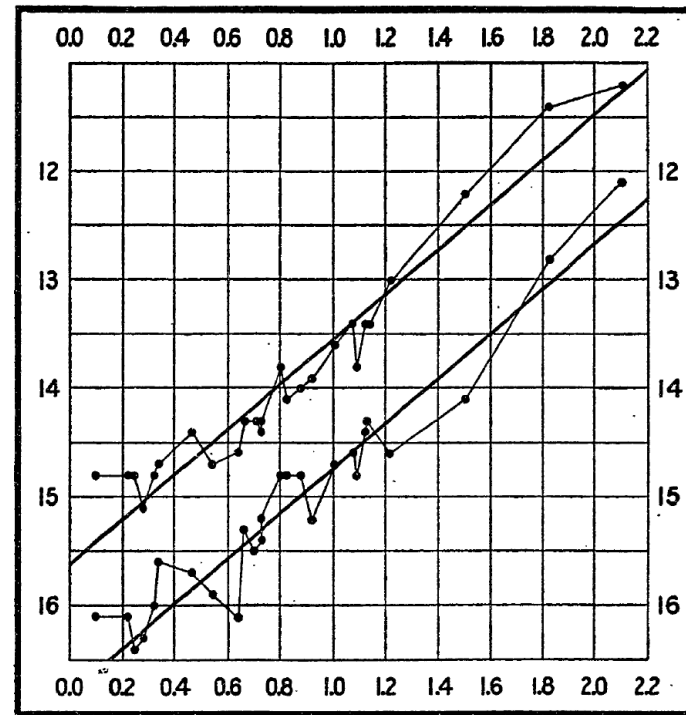


FIG. 2.

Leavitt 1912

第四幕：宇宙沙粒，永闪光辉

第一章：世纪大辩论

The Shapley - Curtis Debate in 1920



[Harlow Shapley](#)



[Heber D. Curtis](#)

哈罗·沙普利：1885-1972
(1914年普林斯顿博士毕业；
Willson天文台研究员)

希伯·柯蒂斯：1872-1942
(1902年维吉尼亚大学博士毕业；
利克天文台)

The Scale of the Universe

[What the Great Debate was, how it was resolved, and why it was important.](#)

A subjective abstract in three short paragraphs.

[Published version of the 'Great Debate.'](#) This is a reprint of the texts of Great Debate published in 1921 in the Bulletin of the National Research Council

[The 'Great Debate:' What Really Happened](#) by Michael Hoskin, editor of the Journal for the History of Astronomy. This is a reprint of an article appearing

["The 1920 Shapley-Curtis Discussion: Background, Issues, And Outcome".](#) This excellent review of the historical context, personalities, and scientific is

[A long bibliography for the 1920 Great Debate.](#) This collection of over one hundred articles and books was compiled by Robert W. Smith, a historian wo

[A short bibliography for the 1920 Great Debate.](#) Five key books and articles about the Great Debate.

A [lesson plan](#) for teaching undergraduates about the Great Debate. The lesson plan consists of an outline, a lecture, suggested classroom uses for the plan

[A Glossary of terms used in the Great Debate.](#)

https://apod.nasa.gov/diamond_jubilee/debate20.html

MONDAY, APRIL 26

MORNING SESSION

10.30 a. m.—12.30 p. m.

JOHN M. CLARKE: Conservation of natural resources as a proper function of the National Academy. (15 minutes.)
RAYMOND PEARL: On the rate of growth of the population of the United States since 1750 and its mathematical expression (illustrated). (15 minutes.)
FRANZ BOAS: Growth and development as determined by environmental influences. (15 minutes.)
CHARLES B. DAVENPORT: Plural births in man (illustrated). (12 minutes.)
SAMUEL J. MELTZER: The importance of the presence of both sympathetic superior cervical ganglia to the maintenance of life; and their possible relations to respiratory diseases. (15 minutes.)
CHARLES D. WALCOTT: Structure of Marrella and allied Middle Cambrian crustaceans. (15 minutes.)
JAMES K. ANGELL: The National Research Council (illustrated). (20 minutes.)
ROBERT M. YERKES (introduced by E. L. Thorndike): A psychological study of the medical officers in the Army. (15 minutes.)

AFTERNOON SESSION

2.00 p. m.—4.30 p. m.

ROBERT W. WOOD: Spectroscopic phenomena of very long vacuum tubes (illustrated). (25 minutes.)
L. F. E. THOMPSON, C. N. HICKMAN and N. RIPPOLD (introduced by Arthur G. Webster): The measurement of small time intervals and some applications, principally ballistic. (10 minutes.)
ROBERT A. MILLIKAN: The effect of molecular structure upon the reflection of molecules from the surface of liquids and solids (illustrated). (12 minutes.)
ARTHUR G. WEBSTER: The Springfield rifle and the Leduc formulae. (5 minutes.)
ARTHUR G. WEBSTER: Some new methods in internal ballistics of the Springfield rifle. (15 minutes.)
GEORGE E. HALE: The 100-inch Hooker telescope of the Mt. Wilson Observatory (illustrated). (15 minutes.)
A. A. MICHELSON: The vertical interferometer. Preliminary tests in an attempt to measure the diameter of the stars. A modification of the Foucault method adapted to long-distance measurement of the velocity of light (illustrated). (30 minutes.)
ARTHUR G. WEBSTER: Preliminary measurements on the pressures in the "Onde de Choc." (15 minutes.)
ARTHUR G. WEBSTER: On the connection of the specific heats with the equation of state of a gas. (10 minutes.)
EDWIN H. HALL: Thermal conductivity of metals. (15 minutes.)

8.15 p. m.

WILLIAM ELLSWORTH HALE LECTURES. Discussion: The Scale of the Universe. By Harlow Shapley, Mount Wilson Solar Observatory, and Heber D. Curtis, Lick Observatory. (Illustrated), (open to the public), U. S. National Museum (main auditorium).

9.30 p. m.

Conversazione. Galleries, U. S. National Museum.

第四幕：宇宙沙粒，永闪光辉

第二章：哈勃发现宇宙膨胀

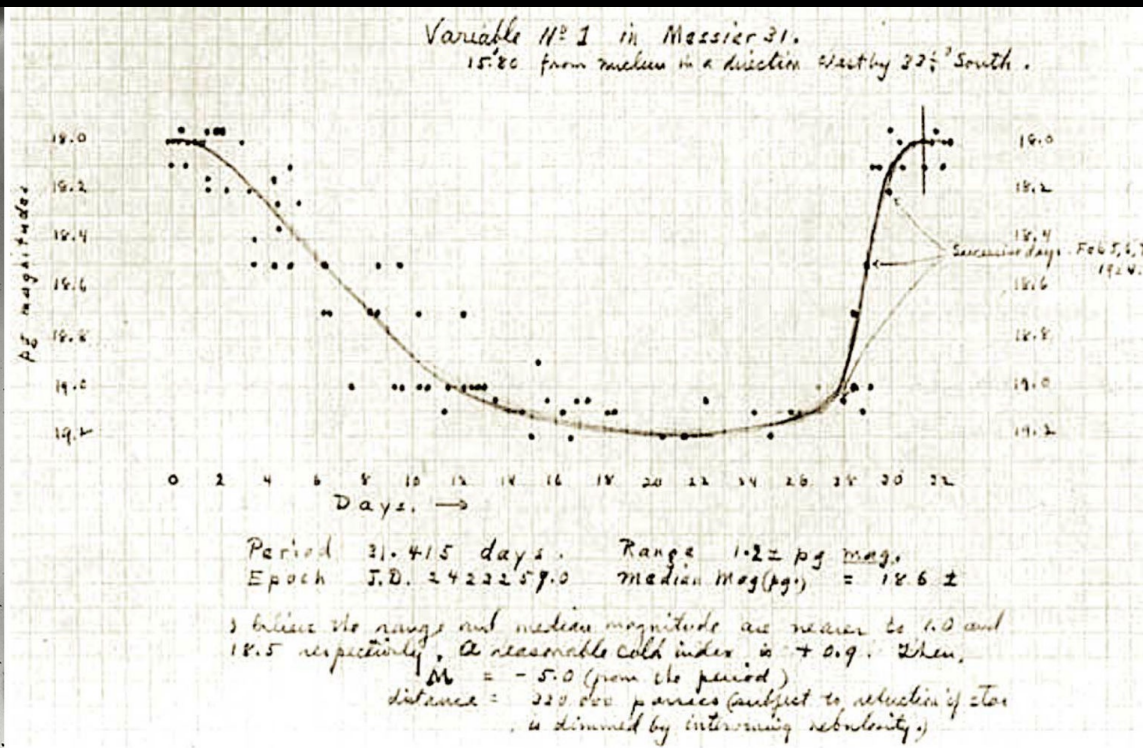
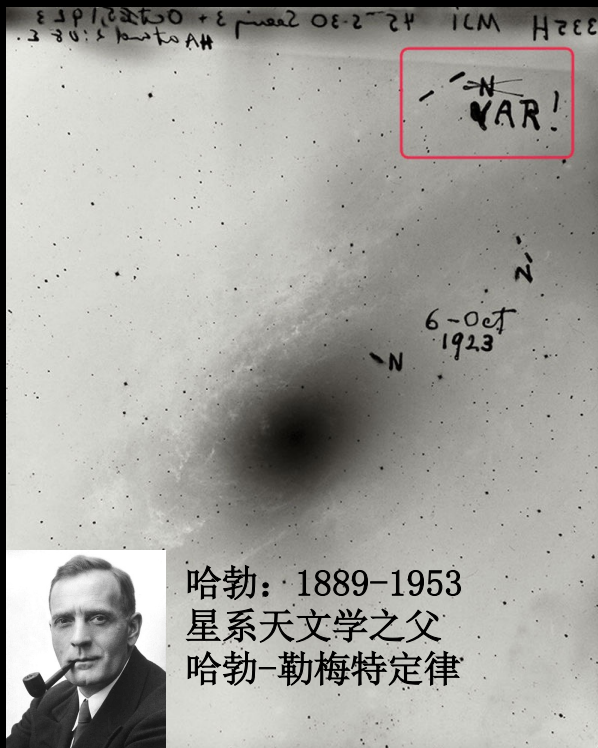
- 1 ☐ 1929PNAS...15..168H 1929/03 cited: 1006   
A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae
Hubble, Edwin
- 2 ☐ 1929ApJ....69..103H 1929/03 cited: 249   
A spiral nebula as a stellar system, Messier 31.
Hubble, E. P.



哈勃：1889-1953
星系天文学之父
哈勃-勒梅特定律

第四幕：宇宙沙粒，永闪光辉

第二章：哈勃发现宇宙膨胀



第四幕：宇宙沙粒，永闪光辉

第二章：哈勃发现宇宙膨胀

Hubble, ApJ, 1929

A SPIRAL NEBULA AS A STELLAR SYSTEM, MESSIER 31¹

By EDWIN HUBBLE

Distance of M 31 derived from Cepheid criteria.—Comparisons of period-luminosity diagrams indicate that M 31 is about 0.1 mag. or 5 per cent more distant than M 33, and about 8.5 times more distant than the Small Magellanic Cloud. Using Shapley's value for the Cloud, we find the *distance of M 31* to be 275,000 parsecs.



哈勃：1889–1953
星系天文学之父
哈勃-勒梅特定律

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
Days. →

Period 31.415 days. Range 1.2 ± pg mag.
Epoch J.D. 2422259.0 median mag(pg) = 18.6 ±

I believe the range and median magnitude are nearer to 1.0 and 18.5 respectively. A reasonable color index is +0.9. When $M = -5.0$ (from the period) distance = 320,000 parsecs (subject to reduction of star is dimmed by intervening nebulosity).

第四幕：宇宙沙粒，永闪光辉

第二章：哈勃发现宇宙膨胀

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a K term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results have not been convincing. The present paper is a re-examination of the question, based on only those nebular distances which are believed to be fairly reliable.

Distances of extra-galactic nebulae depend ultimately upon the application of absolute-luminosity criteria to involved stars whose types can be recognized. These include, among others, Cepheid variables, novae, and blue stars involved in emission nebulosity. Numerical values depend upon the zero point of the period-luminosity relation among Cepheids, the other criteria merely check the order of the distances. This method is restricted to the few nebulae which are well resolved by existing instruments. A study of these nebulae, together with those in which any stars at all can be recognized, indicates the probability of an approximately uniform upper limit to the absolute luminosity of stars, in the late-type spirals and irregular nebulae at least, of the order of M (photographic) = -6.3 .¹ The apparent luminosities of the brightest stars in such nebulae are thus criteria which, although rough and to be applied with caution,



$$V = H_0 D$$

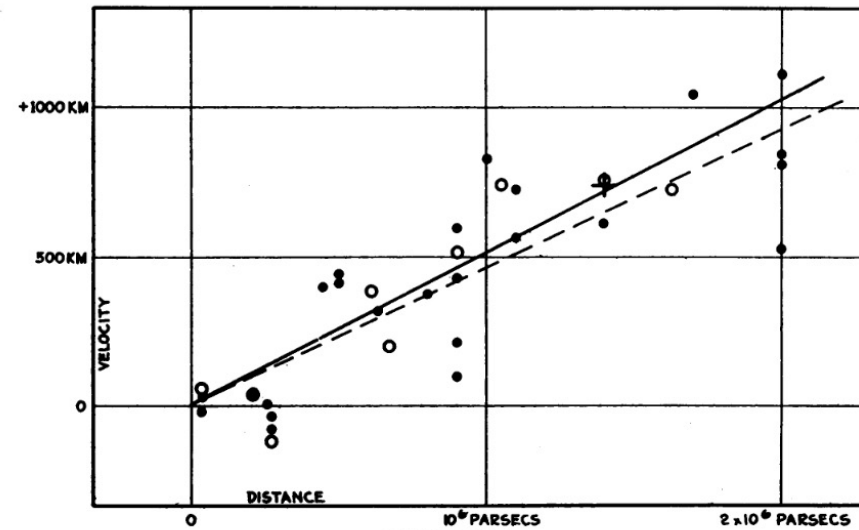


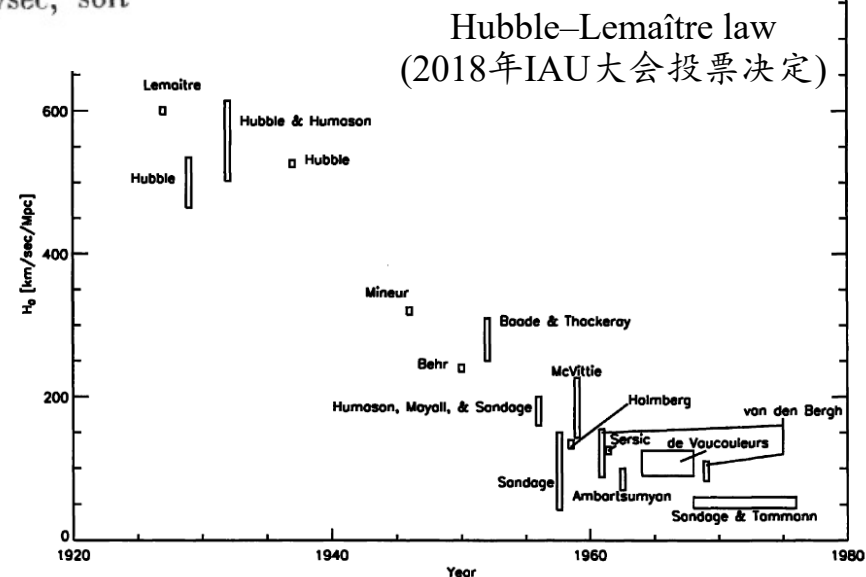
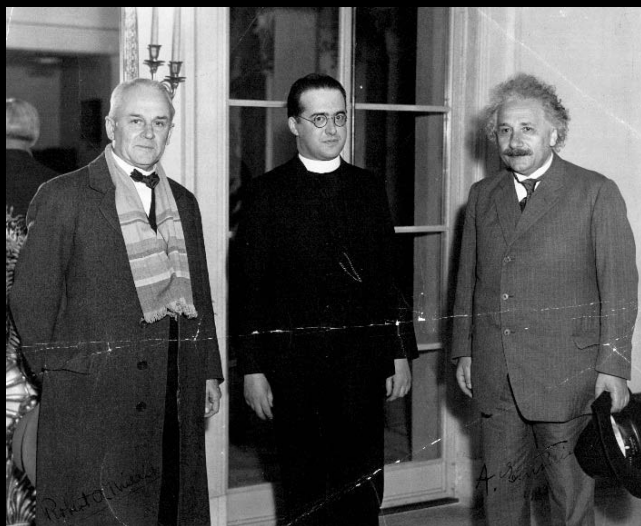
FIGURE 1

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— 36 — Lemaître 1927

Utilisant les 42 nébuleuses figurant dans les listes de Hubble et de Strömberg ⁽¹⁾, et tenant compte de la vitesse propre du soleil (300 Km. dans la direction $\alpha = 315^\circ$, $\delta = 62^\circ$), on trouve une distance moyenne de 0,95 millions de parsecs et une vitesse radiale de 600 Km./sec, soit 625 Km./sec à 10^6 parsecs ⁽²⁾.



Trimble 1966

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第三章：宇宙加速膨胀

宇宙如何膨胀？
减速？匀速？加速？

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$$q \stackrel{\text{def}}{=} - \frac{\ddot{a}a}{\dot{a}^2}$$

TABLE 1 Published Results of q_0

TYPE	AUTHOR	REF.	SET	N	INDICATOR/CLASSIFIER	q_0
Luminosity classifier	Setti & Woltjer (1973)	/3,4/	1	81	Steep-spectrum radio sources	~ 1
	Davidson et al.(1977)	/5/	2	6	QSOs with same width of $L\alpha$	~ 1
	Qu et al.(1979)	/6/	3	27	Strong scintillation	$\sim 1.4^*$
	Yang et al.(1980)	/7/	4	24	Small optical variation	*
	Zhang (1980)	/8/	5	8	VLBI-resolved compact sources	*
	Cheng (1982)	/9/	6	15	Strong scintillation and small optical variation	1.9
	Bachcall & Hills (1973)	/17/	7	7	Brightest QSOs in equal redshift interval	~ 1
Luminosity indicator	Fang et al.(1976,1979, 1980)	/10-12/	8	17	Maximum separation of radio components	0.9~1.5
	Baldwin et al.(1977, 1978)	/13-14/	9	31	Emission line width (CIV).	~ 2
	Kiang & Cheng (1981)	/1/	10	33	ibid	1.1
	" " "	"	11	44	ibid (C IV & Mg II)	2.1
	" " "	"	12	53	ibid (C IV & Mg II & $L\alpha$)	1.9

N = sample size

Cheng, Kiang & Fang 1982

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Relative quasar luminosities determined from emission line strengths

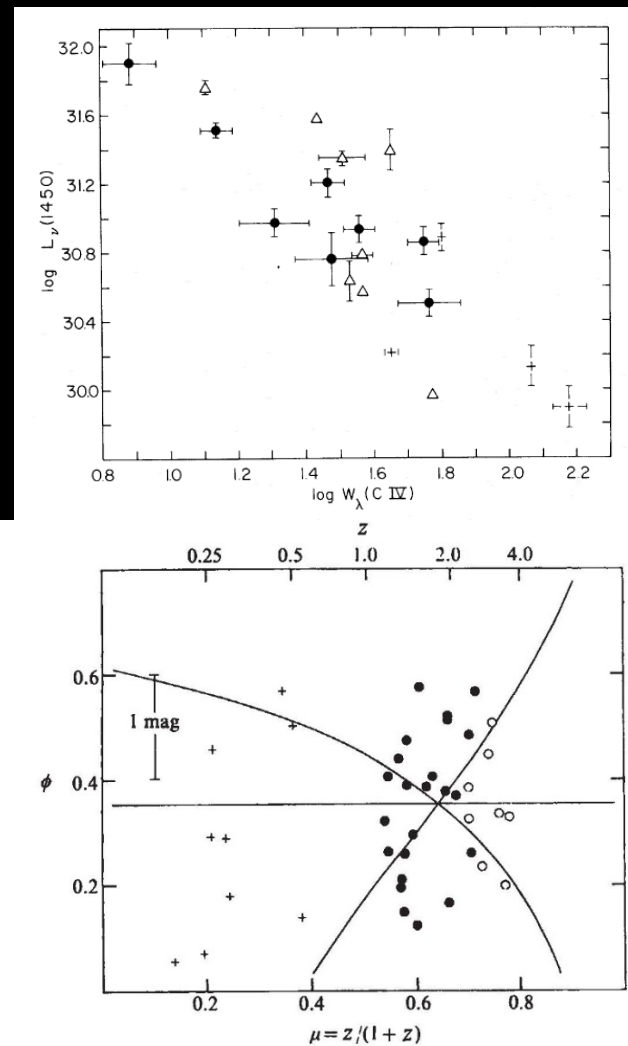
[Jack A. Baldwin](#), [William L. Burke](#), [C. Martin Gaskell](#) & [E. J. Wampler](#)

[Nature](#) **273**, 431–435 (1978) | [Cite this article](#)

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Abstract

Observations of flat radio spectrum QSOs selected from complete samples confirm the strong correlation between continuum luminosity and emission line equivalent width. The r.m.s. scatter about a mean relationship is about 0.6 mag. The data indicate that the luminosity of QSO emission lines increase as the 1/3 power of the continuum luminosity. Unless the zero point of the relationship between emission line equivalent width and continuum luminosity depends on redshift, both the local hypothesis and zero pressure models of the Universe in which $q_0 \approx 0$ are ruled out by the data at about the 99% confidence level.



Baldwin et al. 1977, 1978

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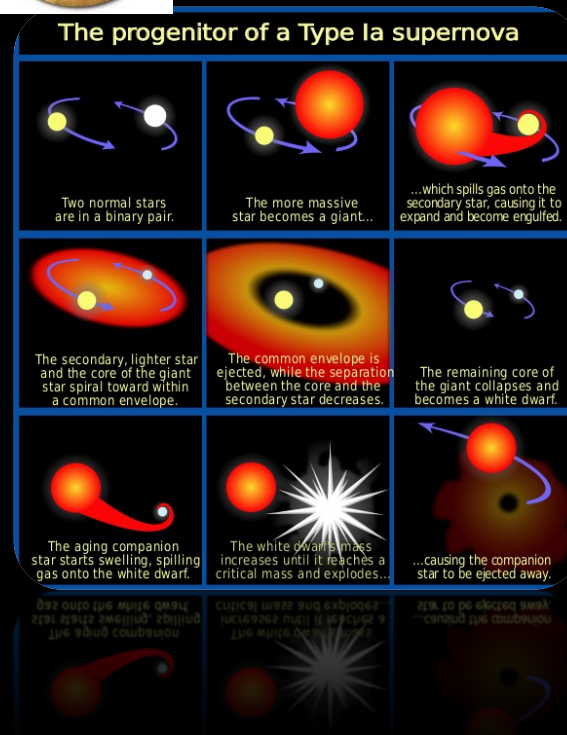
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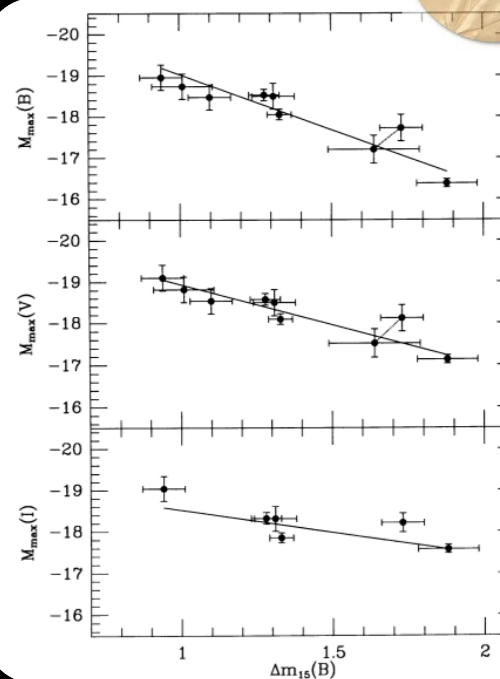
$$M_{\text{limit}} = \frac{\omega_3^0 \sqrt{3\pi}}{2} \left(\frac{\hbar c}{G} \right)^{3/2} \frac{1}{(\mu_e m_H)^2},$$



1983 Nobel Prize



Phillips 1993



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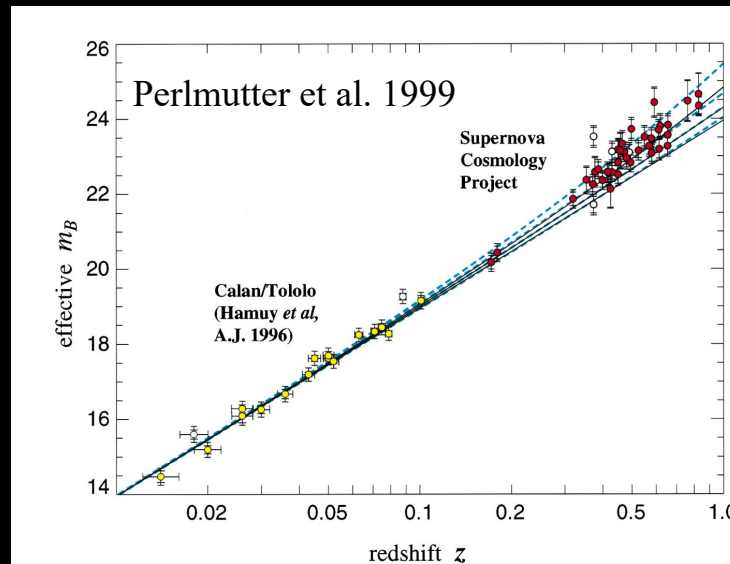


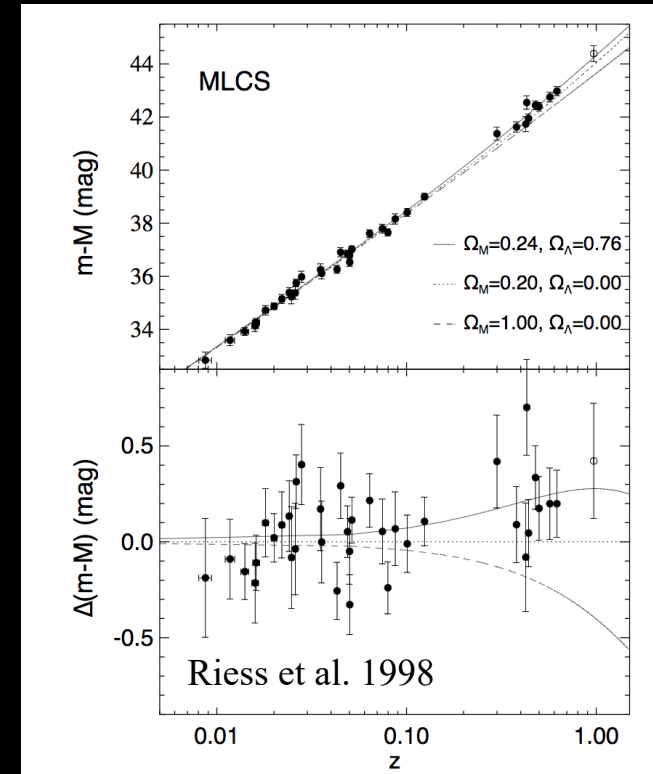
Photo: U. Montan
Saul Perlmutter
Prize share: 1/2



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Prize share: 1/4



Photo: U. Montan
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Prize share: 1/4



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Conference Highlights

Quasars as Standard Candles for Cosmology¹

JOSEPH WAMPLER
Santa Cruz, CA

It has been 22 years since Jack Baldwin first noticed that there was an inverse correlation between the equivalent width of the C IV emission line and the apparent luminosity of bright quasars. (See J. A. Baldwin, E. J. Wampler, & C. M. Gaskell, ApJ, 338, 630 [1989] for a review and further references.) By using this “Baldwin effect” correlation to calibrate the relative luminosity of quasars, the scatter in the quasar Hubble diagram can be reduced by about a factor of 10. For high-redshift quasars, the data have sufficiently low scatter to discriminate between the different popular cosmologies at high redshift. Early efforts, which ignored possible redshift evolution in the Baldwin effect, give Hubble diagrams that require a high value for q_0 ($q_0 \sim 5$). This means that either the Baldwin effect has strong redshift evolution or the high-redshift quasars are telling us that there was a strong deceleration during the early expansion of the universe.

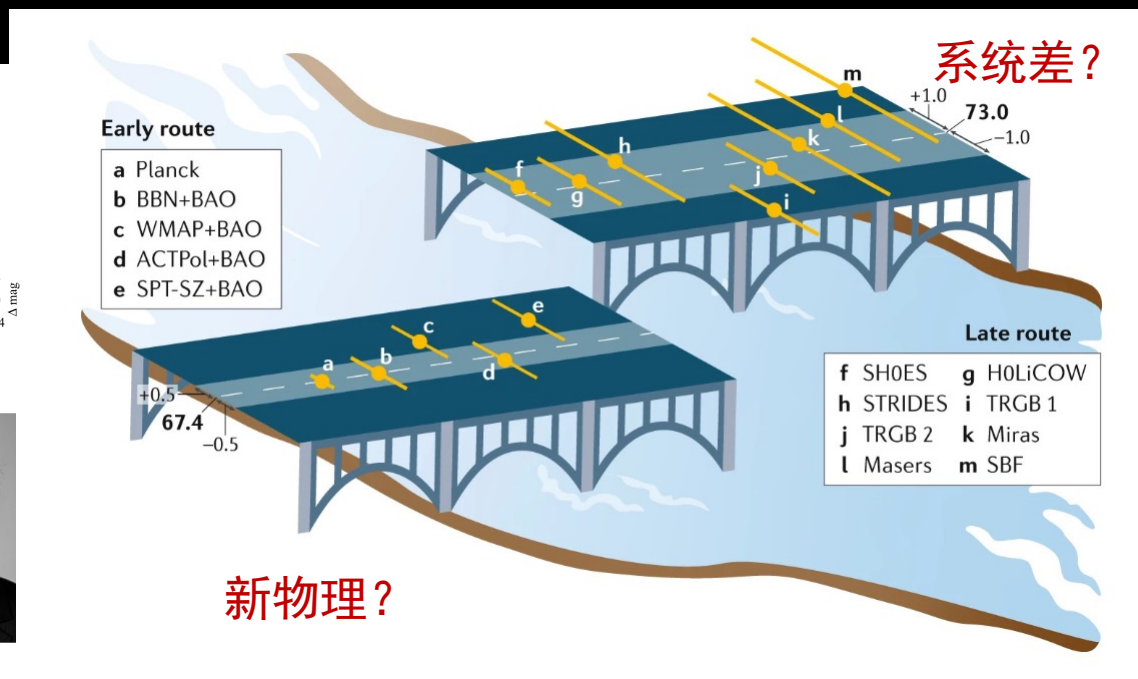
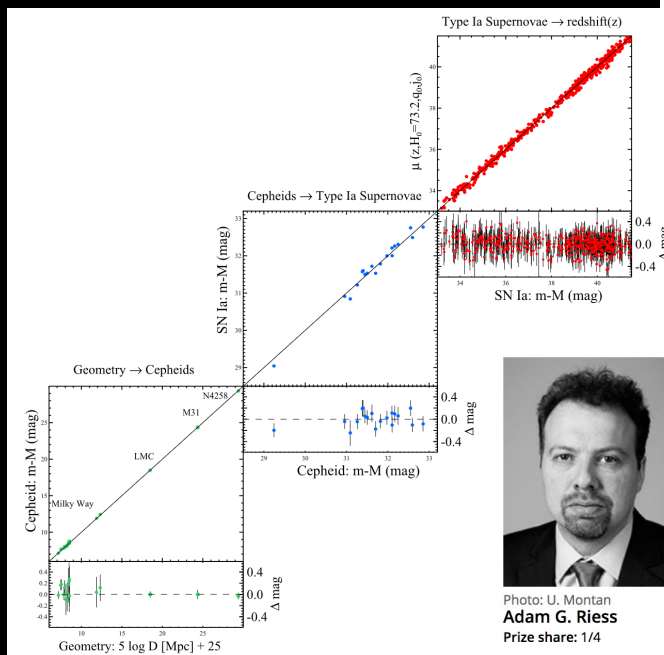
At the end of 1998 May an international conference on the Baldwin effect, “Quasars as Standard Candles for Cosmology,” was held in La Serena, Chile, to review the progress in our understanding of the physical processes important in quasar nuclei where the broad emission lines are formed. It is hoped that with a deeper understanding of quasar central engine chemistry and physics, the source of the Baldwin effect can be identified and understood. It would then be possible to identify any agents that could lead to systematic differences between quasars at different redshifts.

In the first talk of the conference, Nick Suntzeff reviewed the new, very accurate data from the distant supernovae (SNe) programs. These data, which have now reached SNe out to redshift 1, indicate that q_0 is very small, or possibly negative. If both the quasar data and the SN data are to be believed, then the universe has evolved from an early decelerating universe to the present accelerating universe. The SN data are very convincing. While the scatter in the quasar data is much larger, at redshifts above 2, different models of the universe give very different Hubble diagrams, and small scatter is not needed to distinguish between the models. A much more serious concern is the possible evolution of the Baldwin effect with redshift. Malmquist bias is not likely to be important because quasar subsamples, selected in narrow redshift intervals, show similar Baldwin effect slopes. The zero-point offset of the different

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Riess et al. 2016, ApJ, 826,
56 (>2000 citations)



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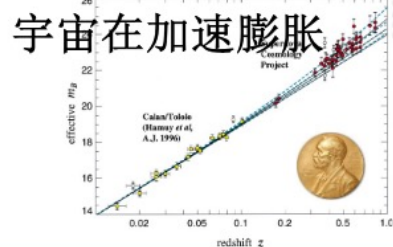
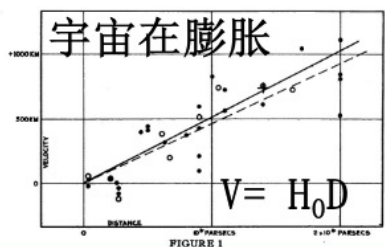
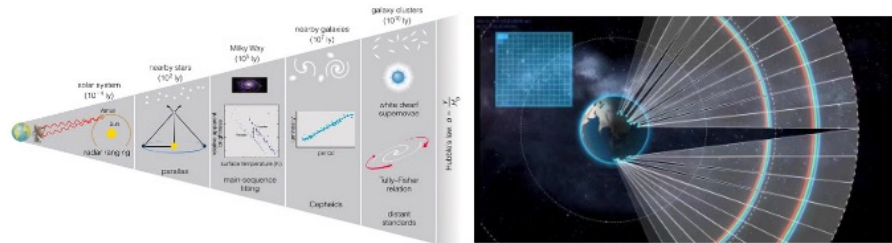
执尺丈天涯

- 宇宙有多大？
- 如何存在？
- 如何演化？

第一张银河系全景图

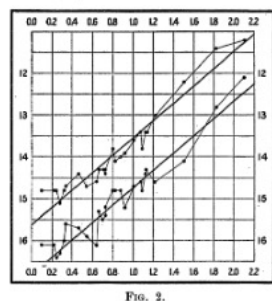
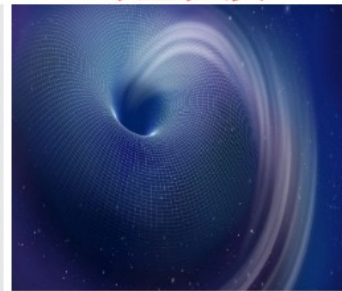


William Herschel 1785

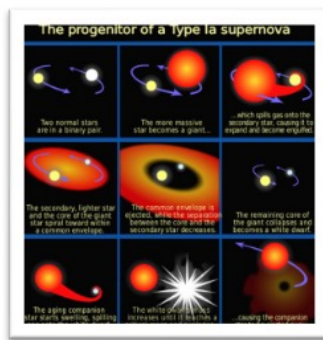


布阵控寰宇

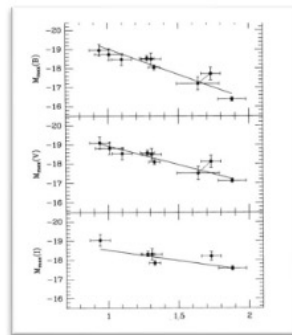
- 引力检验、物质存在形式
 - 新天体、新现象、新物理
- 物态方程 时空性质



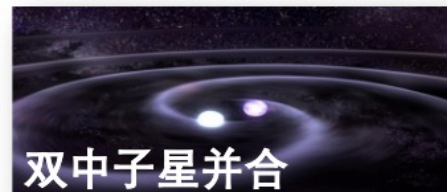
造父变形的
周光关系



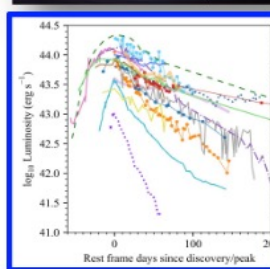
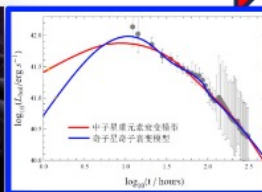
白矮星质量上限



Phillips关系



双中子星并合



潮汐瓦解事件

天语解物

执尺丈天涯
四百年，始末恒变
布阵控寰宇
朝夕间，物态时空

谢谢！