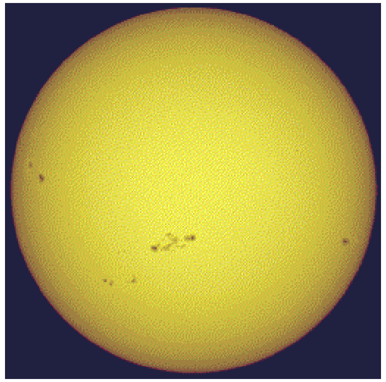
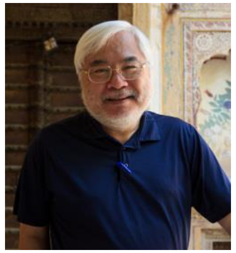


What Physicists May Care to Know about Stars

- 之於生：星際物質與恆星形成 Starbirth
- 之於老：恆星演化（平衡）Evolving
- 之於病：結構不穩 Ageing
- 之於死：衰亡與再生 Dying



陳文屏

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2023.03.17@NCHU Seminar

https://www.astro.ncu.edu.tw/~wchen/Tmp/starsPhysicists.pdf

Conclusion --- What is a star?

- A shining (gaseous) object in space … *Planets, meteorites?*

  … that derives energy from nuclear fusion reactions at the center … thereby

✓ maintaining a long-term structural stability, and

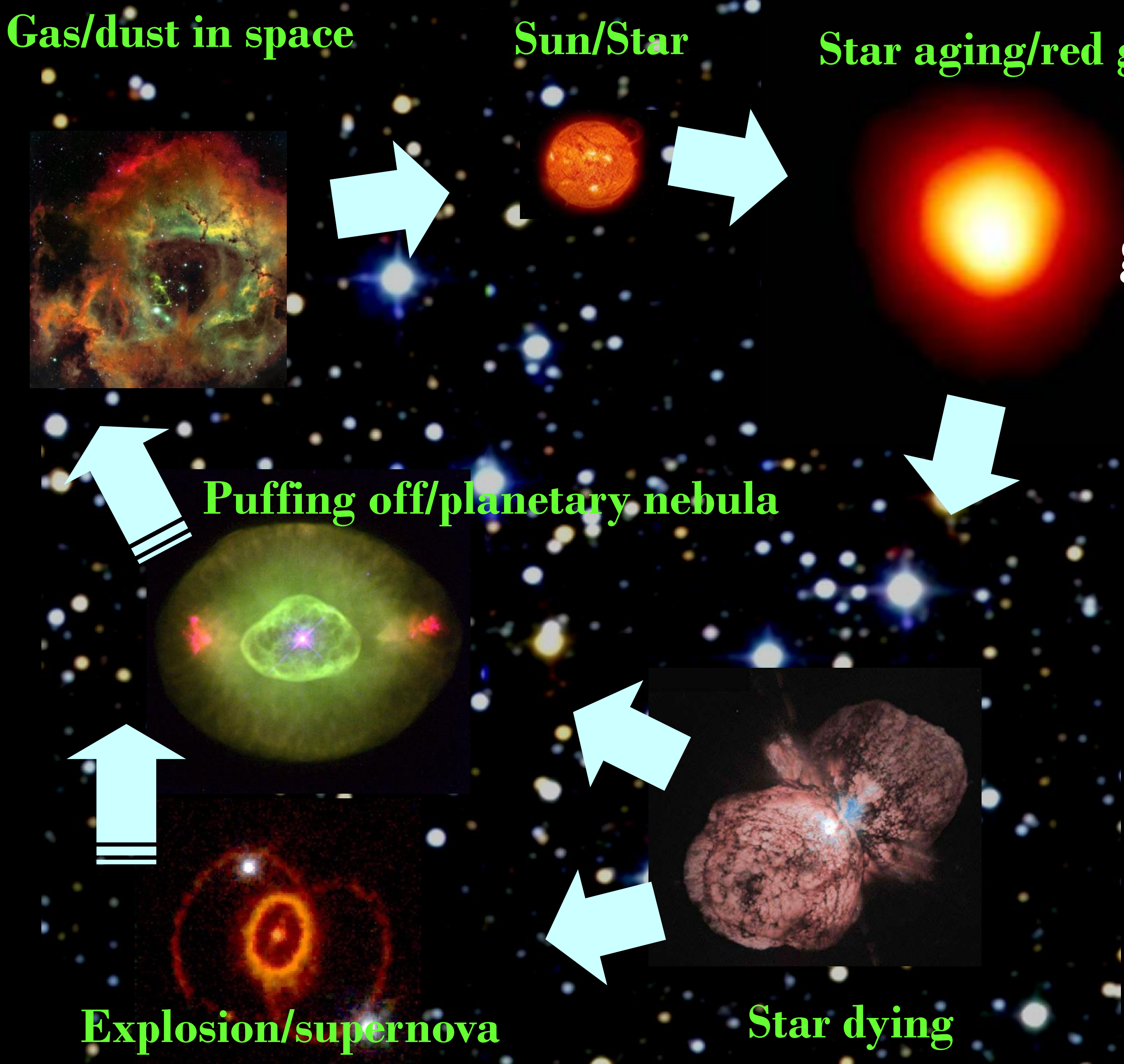
✓ radiating from the surface

How long has the Sun shone? How long will it last?

How do we know these?

Life Cycle of a Star

From dust to (richer) dust



Stars form in groups out of dense molecular clouds,

whereas **planets** form in young circumstellar disks.

星際物質與恆星形成
Interstellar matter and star formation

Interstellar Medium

Space is vastly, but not completely, empty. 太空不是真空

Air we breathe 10^{19} molecules/cc
Matter in space ~1 particle/cc

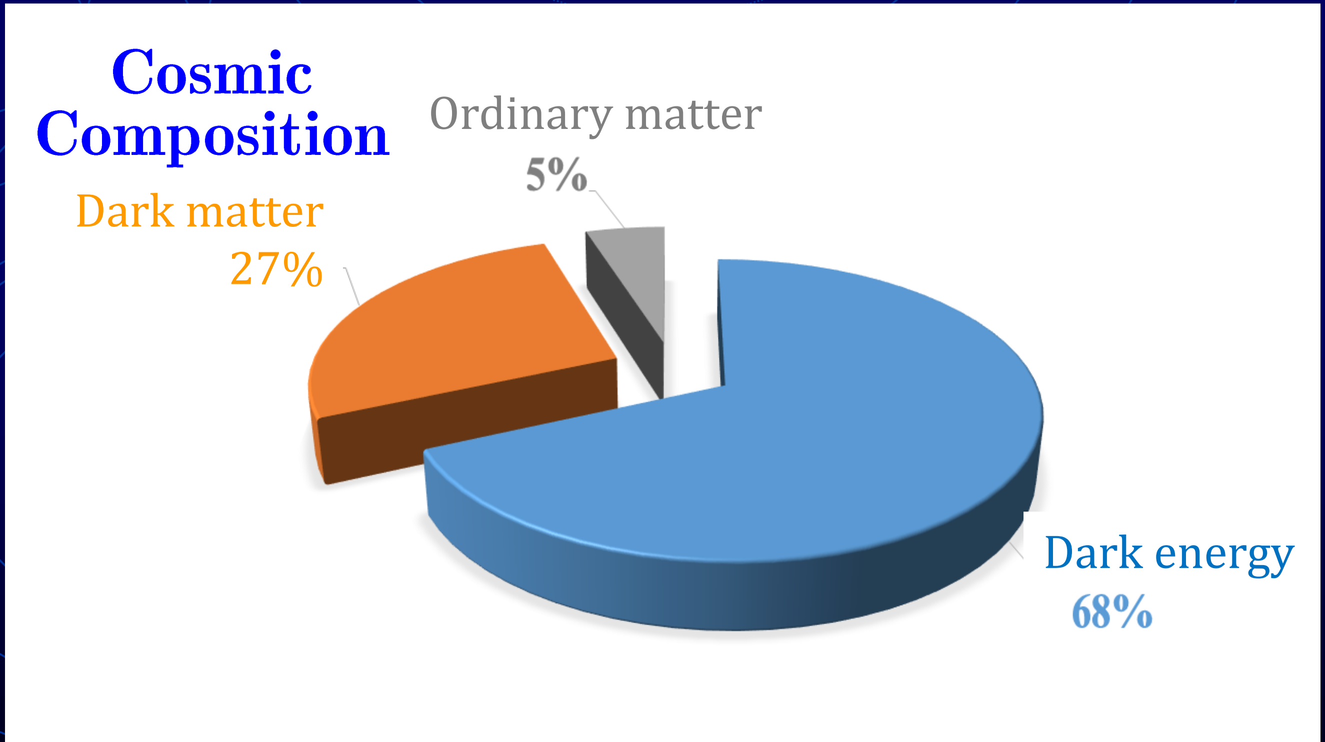
Gas plus dust (no liquid unless pressurized)
Mutual gravitational attraction → denser gas remains transparent; dusty clouds become ever more opaque blocking background stars or luminous gas

These dark clouds are dense ($\gtrsim 10^3 - 10^4\ \mathrm{cm}^{-3}$) and cold (~15 K)
→ supporting pressure force < contracting gravity
→ more compact and denser

The Milky Way galaxy contains 10% visible mass in ISM

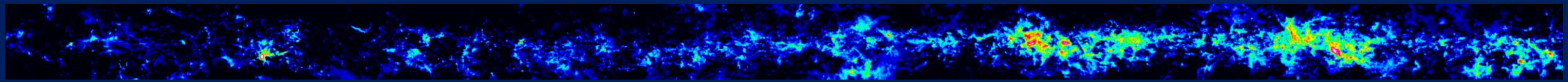
(the rest in stars, planets, cosmic rays, magnetic field …)

- ✓ Of which 90% in gas, 10% in solid
- ✓ Of the gas, 90% in H (mostly atomic H^0, the rest in ionized H^+, molecular H_2, or H^- …)

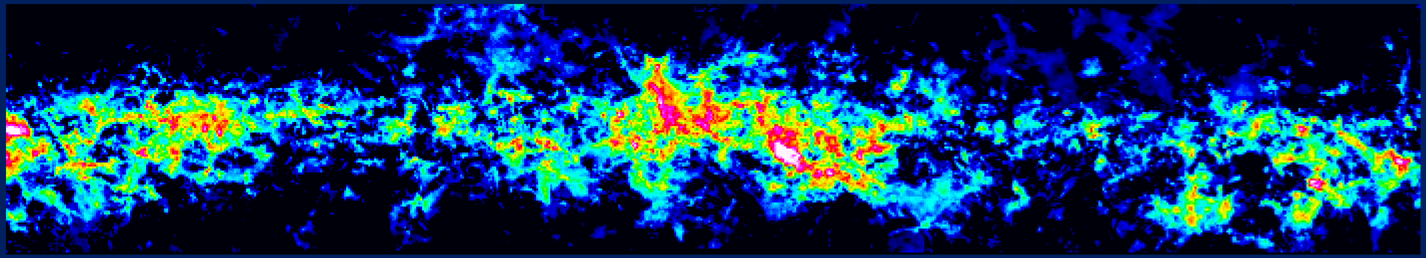


Mother nature via gravity makes stars (10^7 K at the center) out of (very) cold IS molecular clouds.

Molecular Clouds in the Galactic Plane



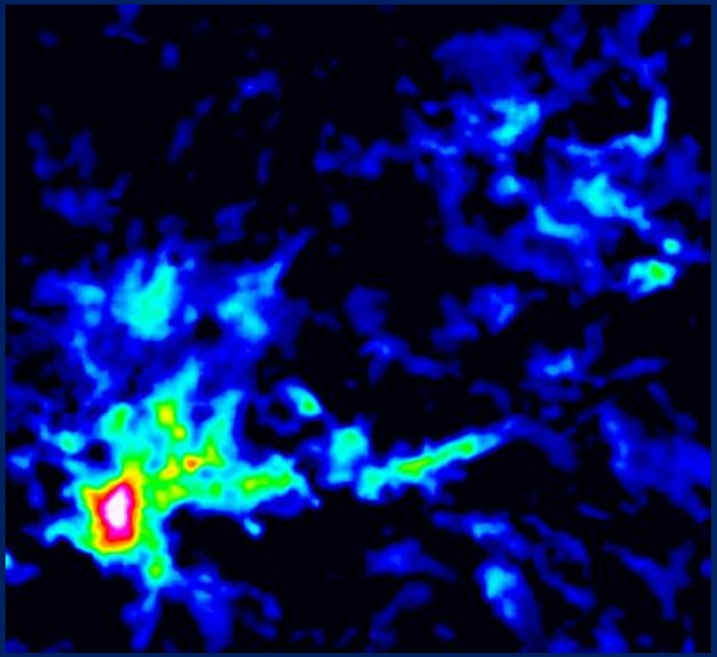
絲片狀
碎形結構



Filamentary fractals

巨型分子雲
(Giant mol. clouds)

$D \approx 20 \sim 100$ pc
$n \approx 10 \sim 300\ \mathrm{cm}^{-3}$
$\mathcal{M} \approx 10^5 \sim 10^6\ \mathcal{M}_\odot$
$T \approx 10 \sim 30$ K
$\Delta v \approx 5 \sim 15\ \mathrm{km}^{-1}$



分子雲團塊 (cloud clumps)

$D \approx 5$ pc
$n \approx 10^3\ \mathrm{cm}^{-3}$
$M \approx 10^3\ \mathcal{M}_\odot$

緻密分子雲核 (dense cores)

$D \approx 0.1$ pc
$n \gtrsim 10^4\ \mathrm{cm}^{-3}$
$M \approx 1 \sim 2\ \mathcal{M}_\odot$

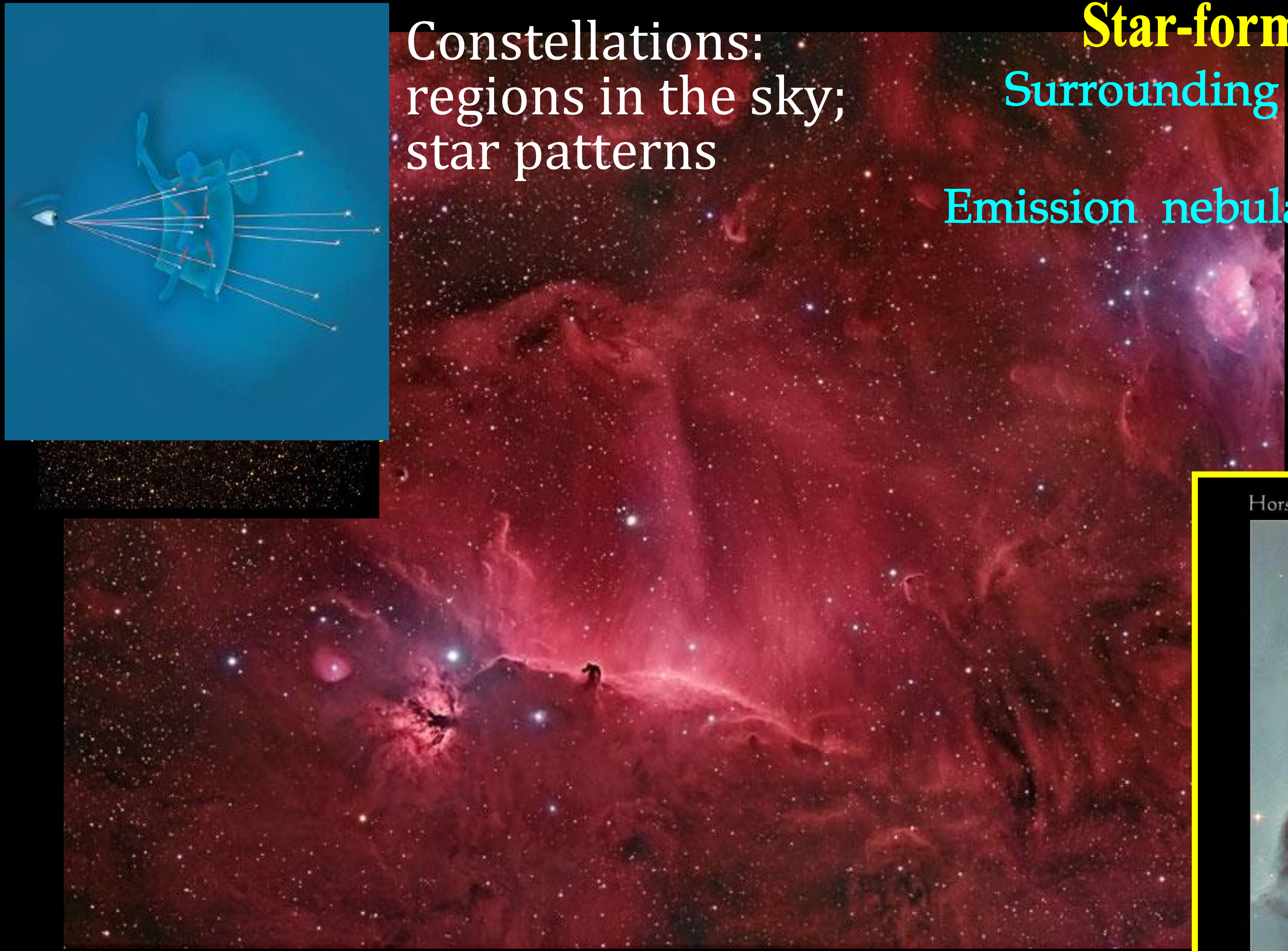
http://www.bu.edu/galacticring/outgoing/PressRelease/

Star-forming region toward Orion

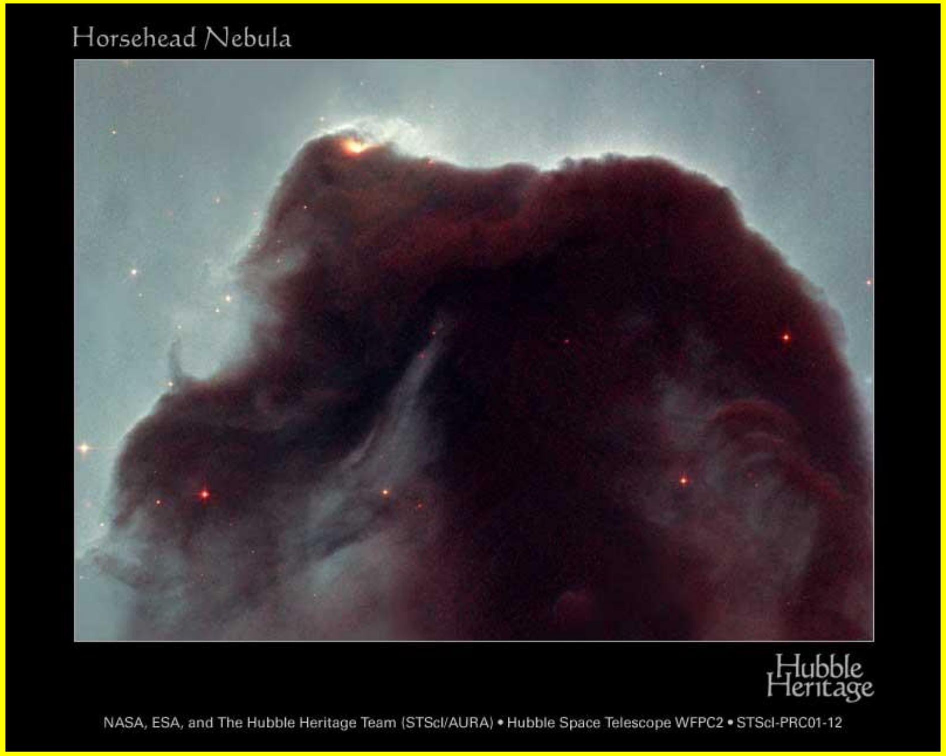
Surrounding gas (H) ionized/excited by star light, and radiates

Emission nebulae interlaced with reflection nebulae and dark nebulae

Constellations:
regions in the sky;
star patterns

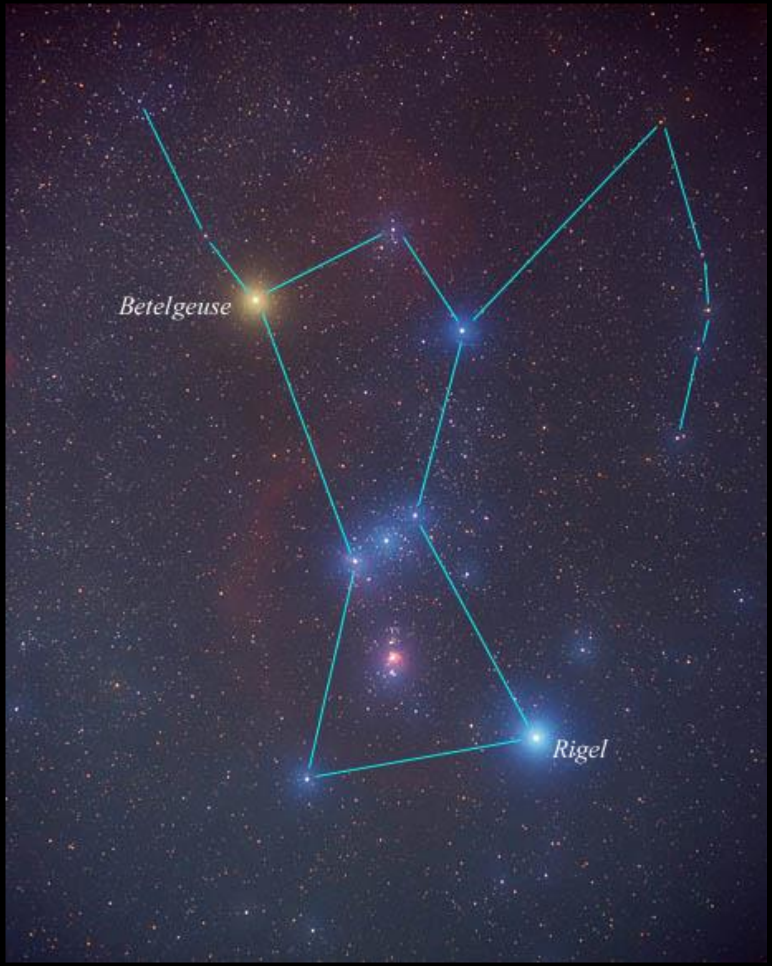


Star Shadows Remote Observatory



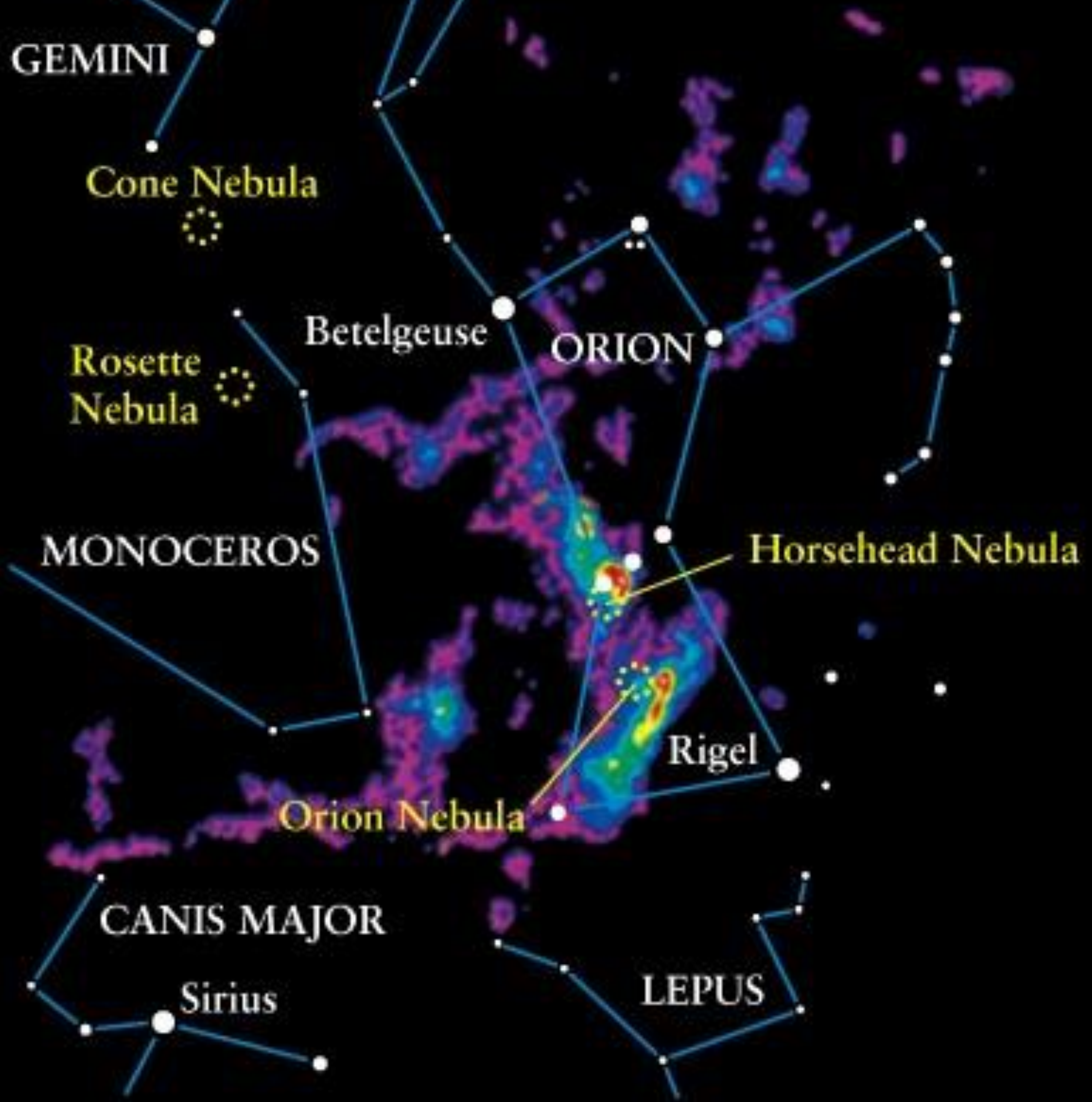
The “Hunter” seen in visible light emitted by stars

(star surface 2000 K to 30,000 K; Re. Wien’s displacement law)



… CO gas (as H_2 tracer) observed at radio wavelengths

(How does a molecule emit/absorb?)

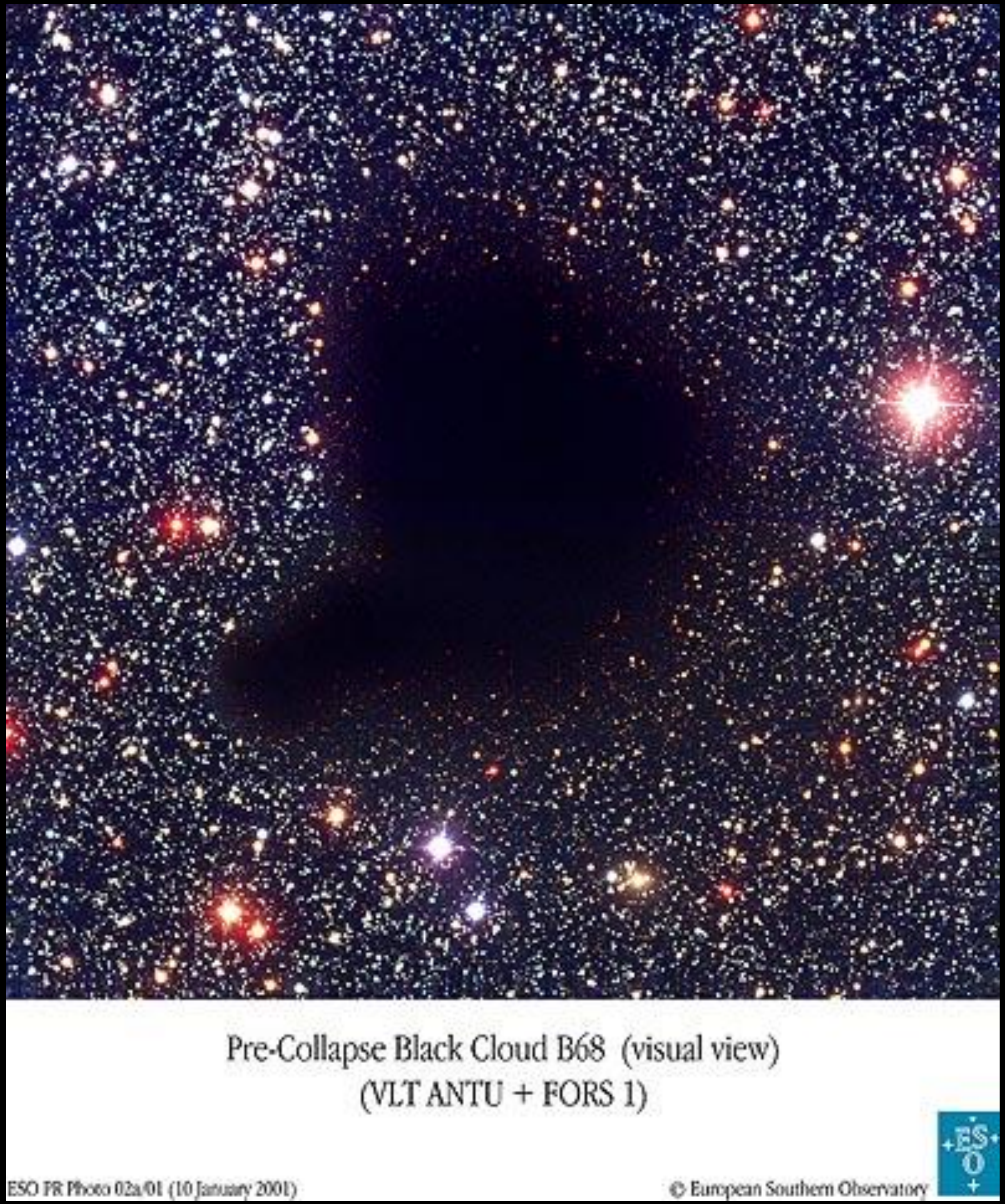


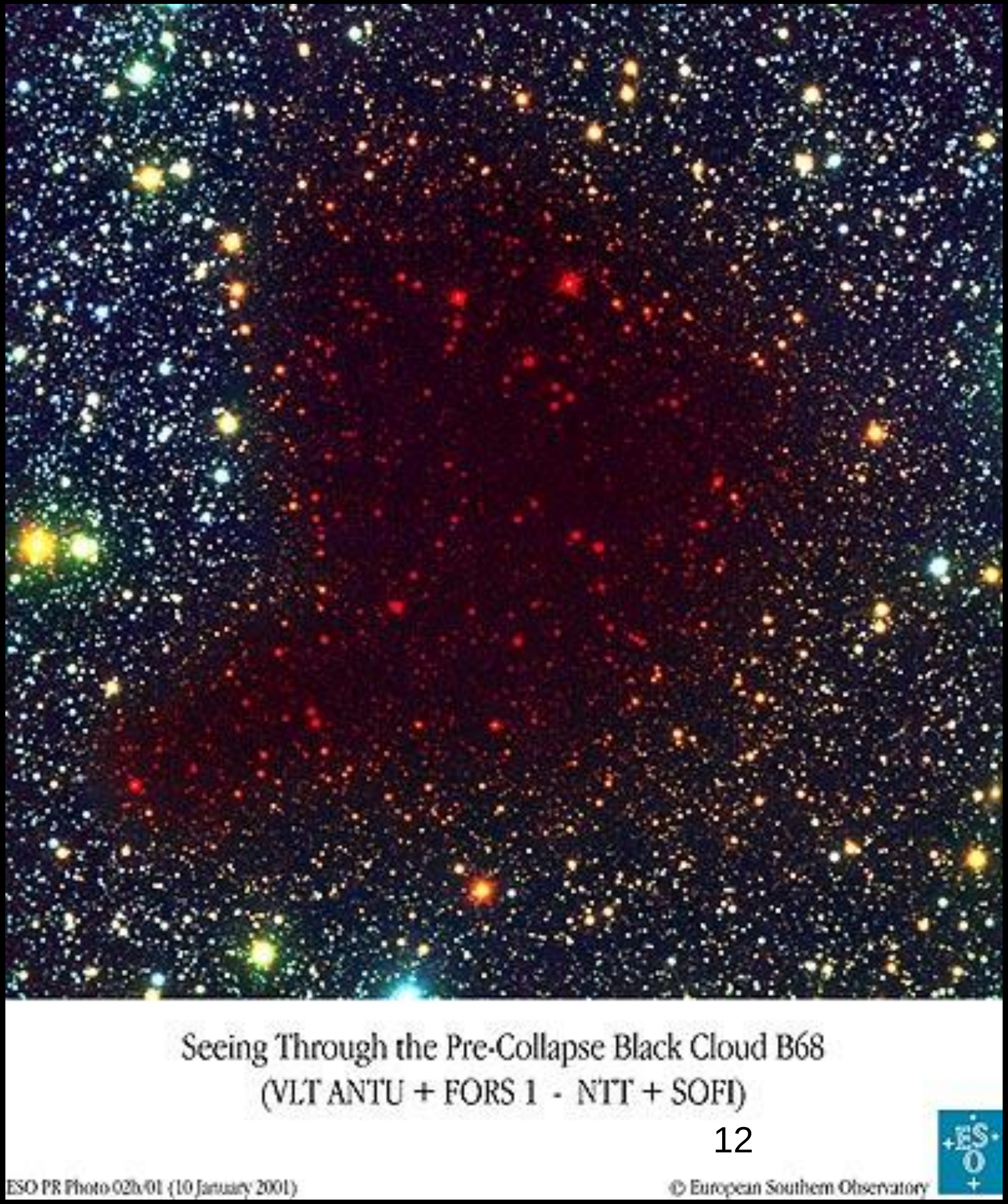
Dark clouds in Ophiuchus

http://www.robgendlerastropics.com/B72JMM.jpg

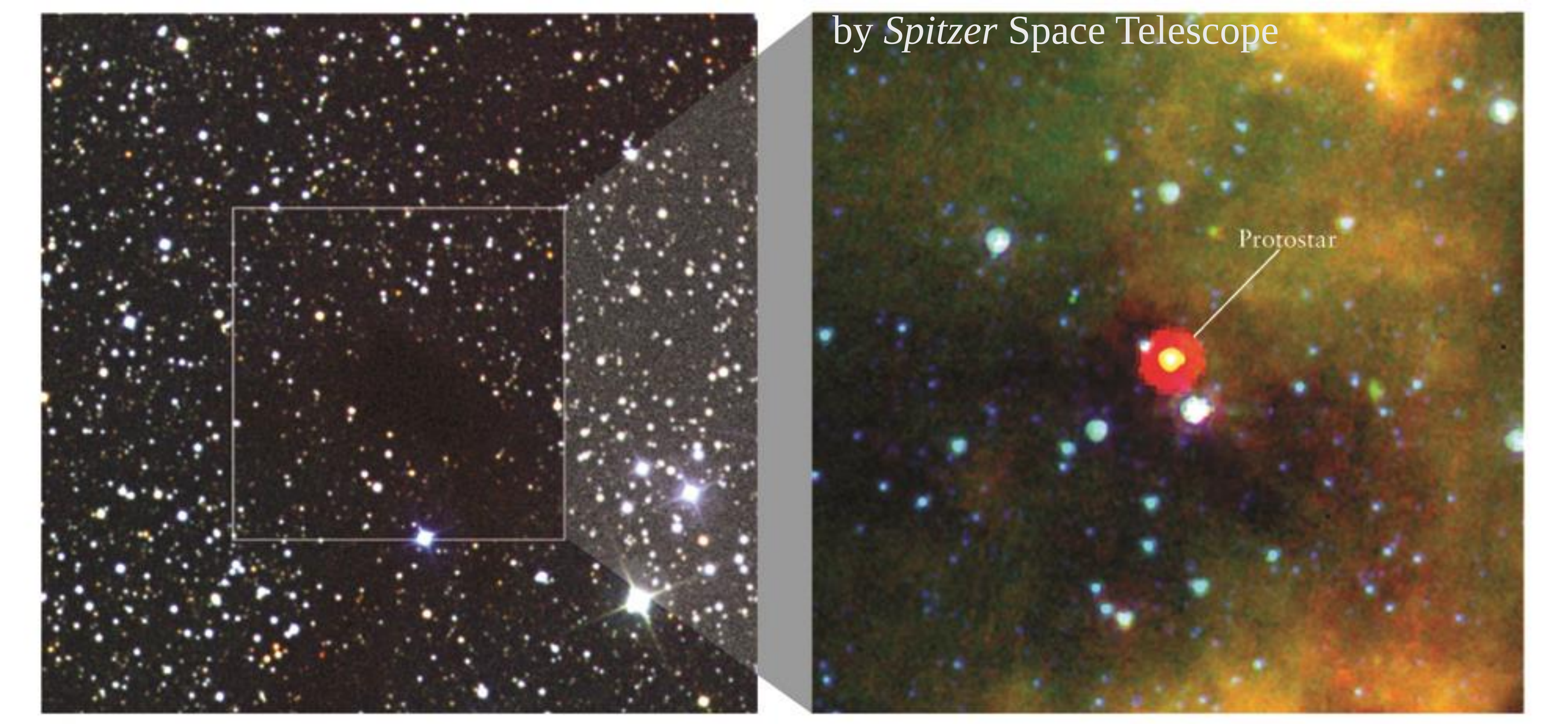
Barnard 72

Tri-color composite image … adding an infrared image





A protostar enshrouded in a dense cloud



(a) A dark nebula (b) A hidden protostar within the dark nebula

Not visible in optical … but prominent in infrared or longer wavelengths

L1014 in Cygnus

Initially, the cloud is optically thin (i.e., translucent)
contraction ⟶ more collisional excitation & radiative deexcitation
⟶ but the radiation escapes (isothermal)
⟶ Dynamical collapse

Eventually, the cloud becomes optically thick (opaque)
contraction ⟶ temperature increases (adiabatic contraction)

If cloud is not massive enough, contraction ⟶ cloud heated
⟶ thermal pressure increases to halt the contraction

But if the cloud mass exceeds the Jeans (critical) mass $M_J \propto T^{3/2}/\rho^{1/2}$
⟶ contraction continues … (the cloud fragments to form a cluster)
and if $T \gtrsim 10^6$ K …

Boom! A star is born.

Virial theorem
$2K + \Omega = 0$

Thermonuclear reactions

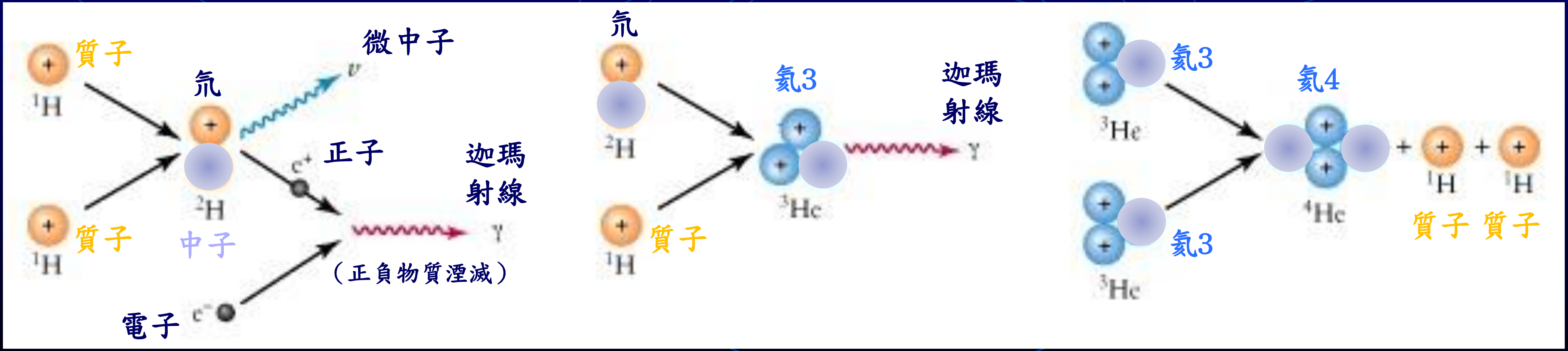
$4\ {}^{1}H \longrightarrow {}^{4}He$

4 H nuclei (protons) fuse $\xrightarrow{\text{Chain reactions}}$ 1 He nucleus

➔ **Energy is released** (γ rays)

(1) Keeping the structure stable; $\nabla P \leftrightarrow F_G$

(2) Radiating from the surface



Q: **How could the fusion proceed between positively charged nuclei?**

A: ***Short-range strong nuclear (attractive) force overcoming the repulsive Coulomb force***
$\longrightarrow$ ***Nuclear binding energy + complex elements***

Q: **How could the nuclei get close enough?** $E_{\text{kin}} \sim$ keV; $U_{\text{Coul}} \sim$ MeV;

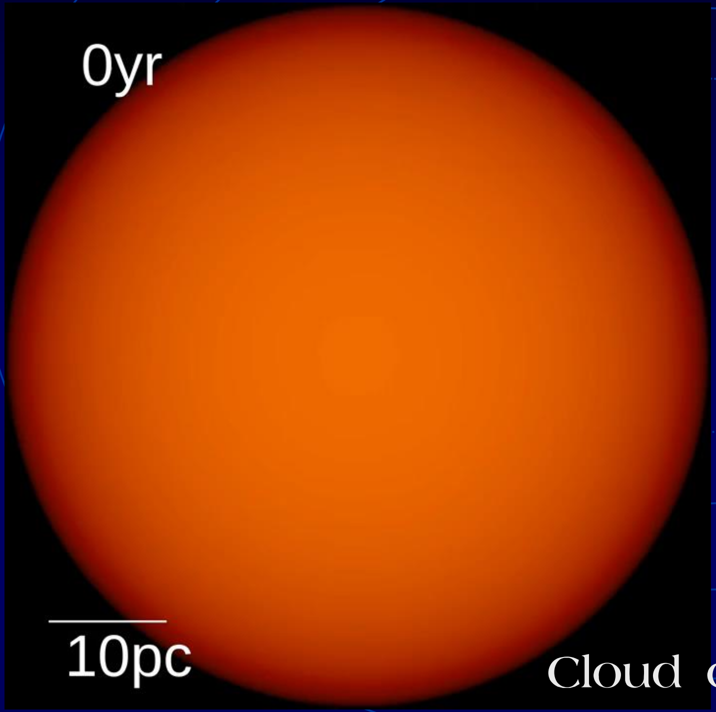
A: **High temperatures + QM tunneling effect**

Between protons > 5×10^6 K (within ¼ of solar radius)

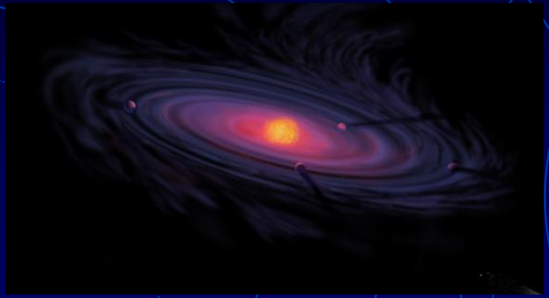
Between ^{3}He and ^{4}He; between ^{12}C, ^{14}N, ^{16}O and ^{1}H …

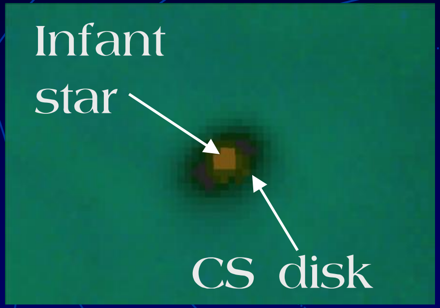
Stellar evolution = (con)sequences of nuclear reactions

Planets as byproducts of starbirth



Cloud collapse



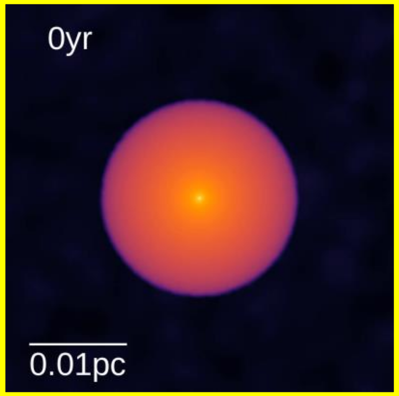


Contraction
Dark cloud ⟶ Protosun + Disk + Remnants
Rotation

Evaporation

Young sun + Protoplanetary disk

grains → Pebbles → Planetesimals → Planets



StarForge

Protostellar jets

結構靜力平衡
Hydrostatic equilibrium

The Hertzsprung-Russell (HR) Diagram（赫羅圖）

Stellar total luminosity (emitting power)

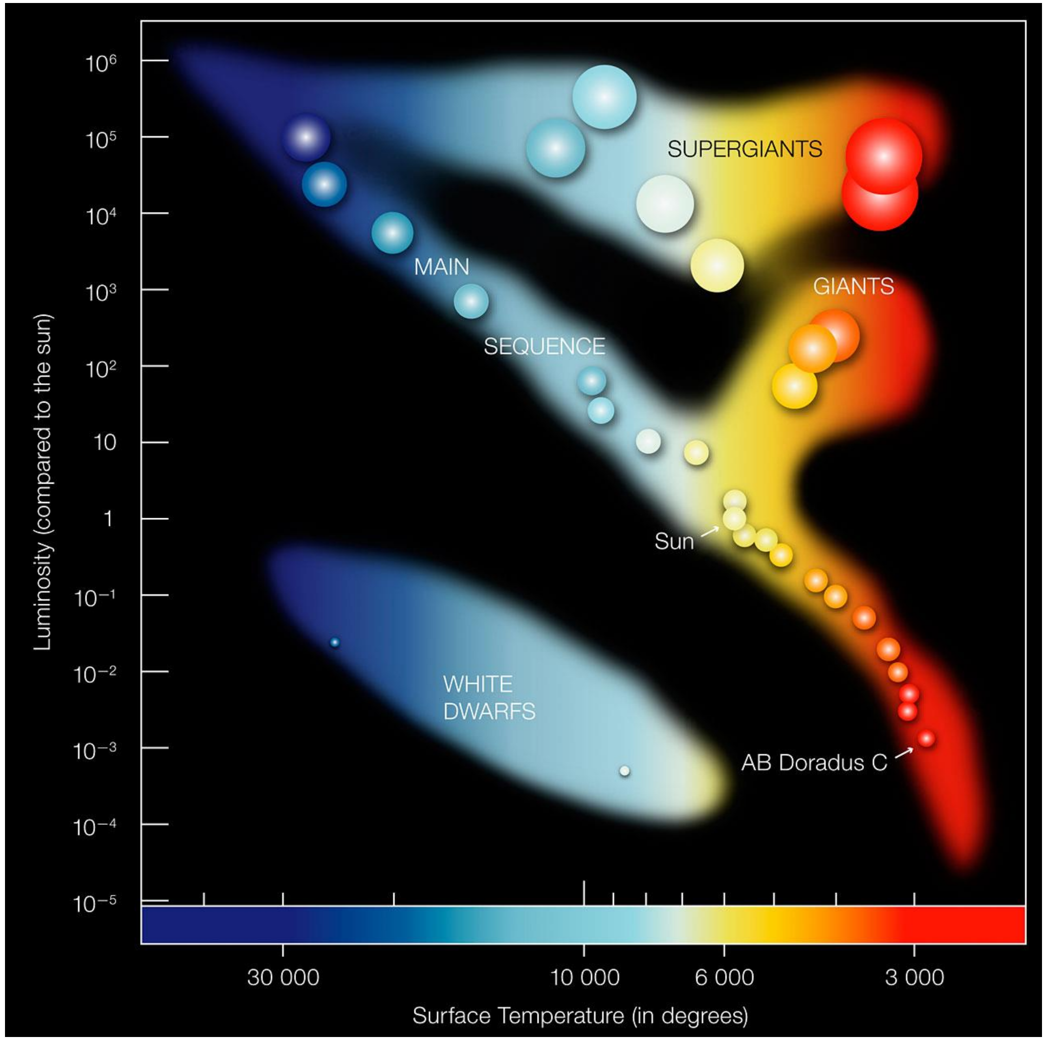
versus

Surface temperature

Both ‘external’ quantities; measurable

90% stars on the **main-sequence**; i.e., the hotter of an ordinary star, the brighter

Bright ← Luminosity → Faint



Hot/blue ← Surface Temperature → cold/red

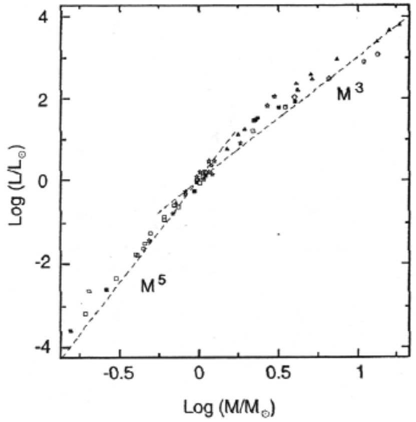
- ✓ $L = 4\,\pi\,R^2\,\sigma T^4$
- ✓ $\log L \leftrightarrow \log T$
- ✓ R ↗ dwarfs to giants
- ✓ MS: A mass sequence; undergoing core H fusion; stable and long lasting
- ✓ $L \propto M^{3-5}$

Yellow dwarf; red dwarf; brown dwarf; white dwarf; black dwarf …

$\mathcal{L} = 4\,\pi\,\mathcal{R}^2\,\sigma\,T^4$

Stellar Luminosity | Total Surface area | Power emitted per area

$\mathcal{L}$



$\mathcal{M}$

Deciphering the HRD

Main-Sequence Stars ≡ core H fusion, highly T sensitive

☐ More massive, size similar, but much brighter

- ✓ Massive MS stars → Fusion much faster → $\mathcal{L}\uparrow\uparrow\uparrow$
  - → Energy passing through $4\,\pi\,\mathcal{R}^2$ → $T\uparrow$
- ✓ Low-mass stars → Fusion much slower → $\mathcal{L}\downarrow$ → $T\downarrow$

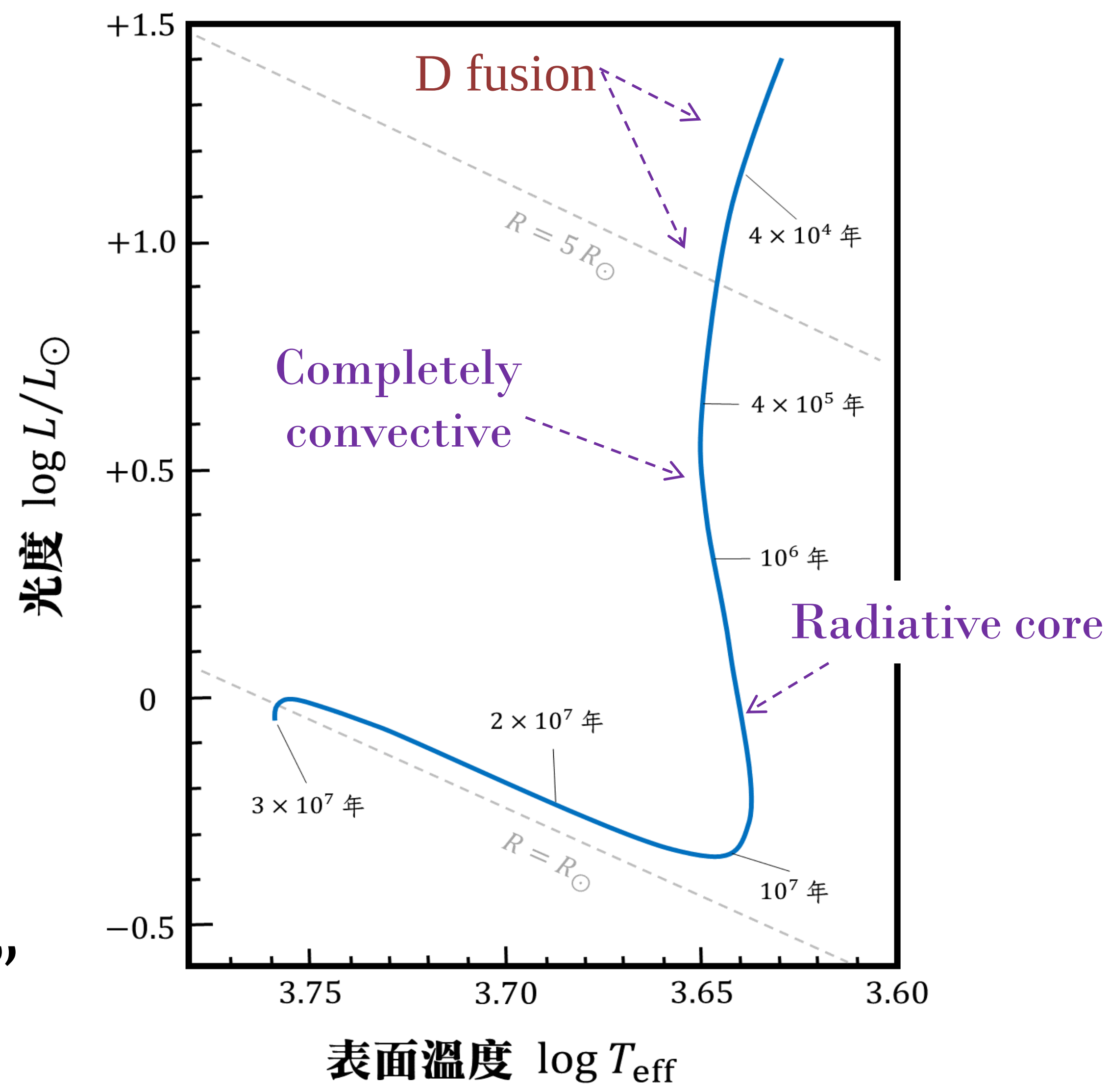
➔ Upper-left (hot and bright) to lower-right (cool and faint) band

MS: a mass sequence

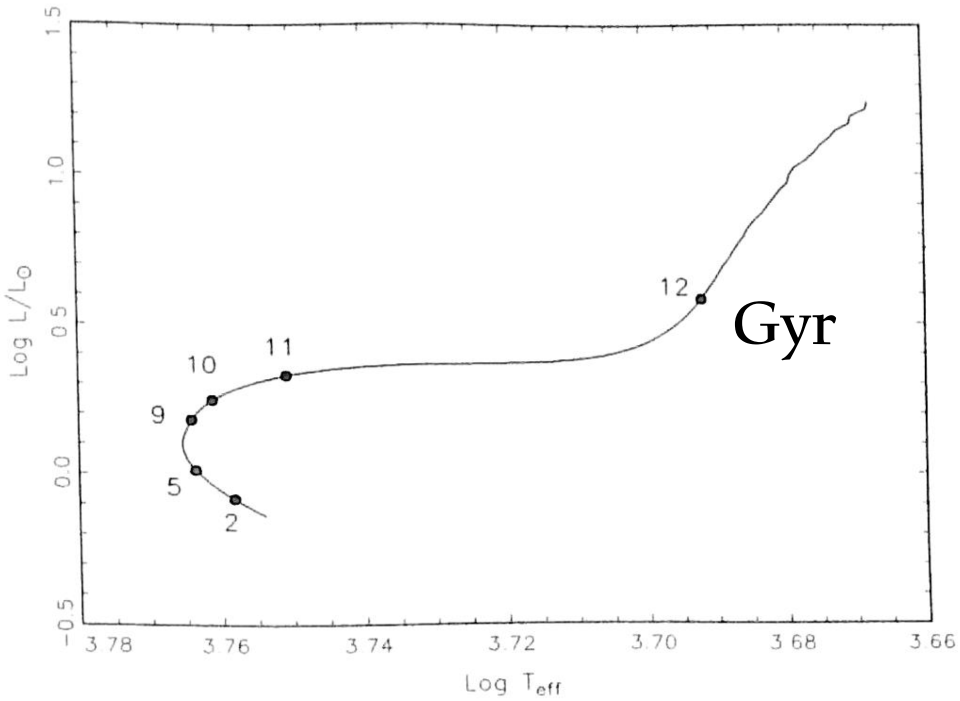
Mass-luminosity relation $\mathcal{L} \propto \mathcal{M}^{3\sim5}$

Early Evolution

- A cloud core free-fall collapse
  $\longrightarrow$ inside-out collapse $\tau_{ff} \propto 1/\sqrt{G\rho}$
  $\longrightarrow$ accretion $E_{Grav} \rightarrow E_{kin} \rightarrow E_{thermal}$
  $\longrightarrow$ a protostars (warm, embedded)
- Quasistatic contraction $E_{Grav} \rightarrow E_{int}$
  $\longrightarrow$ ionization of H, He, He^{+}
  $\longrightarrow$ $T_{surface} \approx$ const (4000 K)
  $\longrightarrow$ but radius drops, and so does the brightness Hayashi tracks
- It took the Sun ~30 Myr to "ignite" H fusion (to reach the MS), maintaining $T_{surface} \approx 5800$ K



Evolution on the MS



- ✓ Ideal gas $P = n\, k_B\, T$
- ✓ MS $4\text{H} \rightarrow \text{He}$

  $n \downarrow \;\Longrightarrow\; P \downarrow$
- ✓ Core contraction $\Longrightarrow T \uparrow$

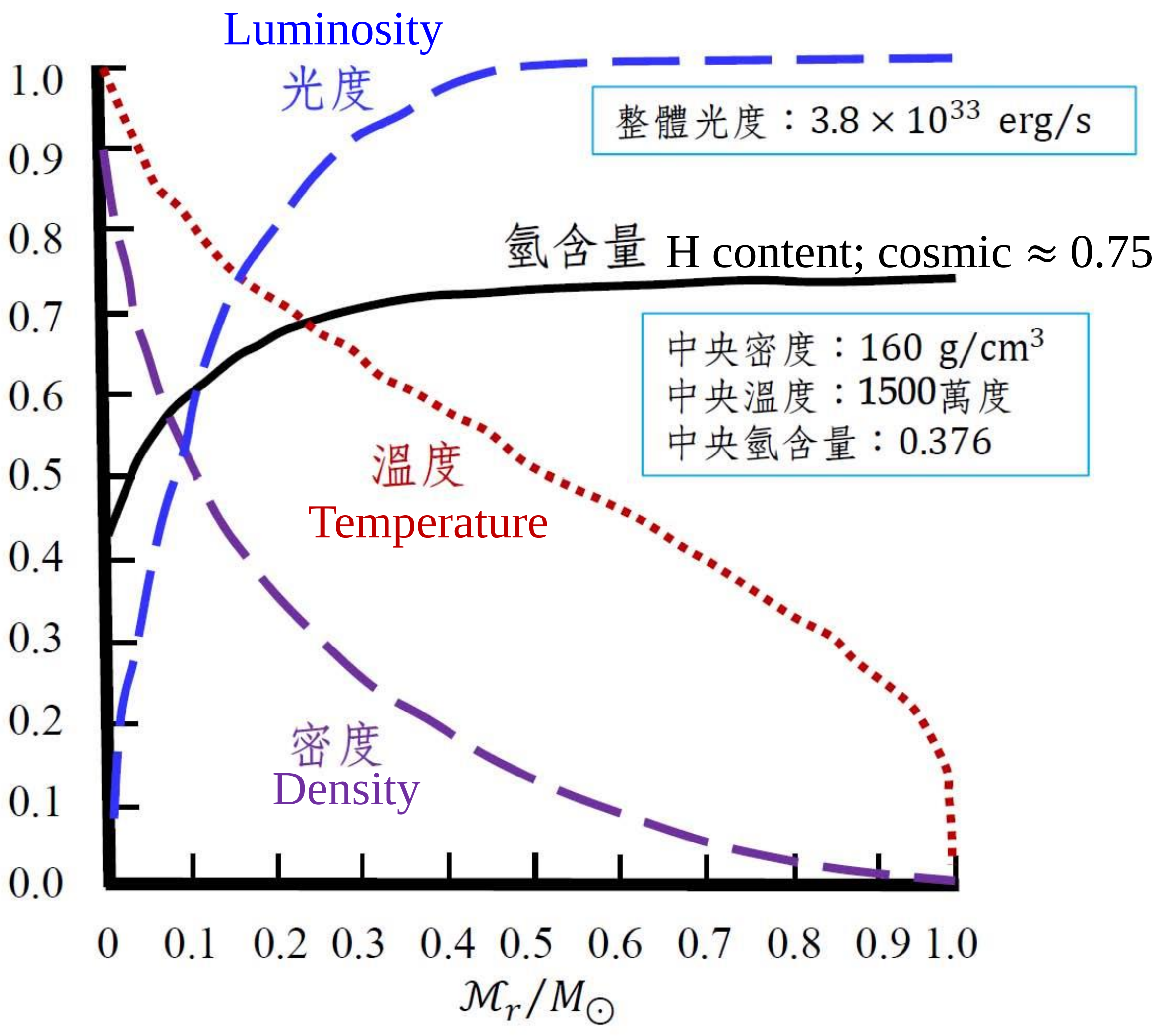
  Nuclear reaction rate $L \uparrow\uparrow\uparrow$

- ☐ Sun on MS for ~5 Gyr 太陽已經發光發熱約50億年
- ☐ Keeps brightening on the MS 亮度持續增亮 *Faint young Sun paradox*
- ☐ Total MS lifetime 10～12 Gyr 還有50～70億年主序壽命
- ☐ Core eventually exhausted of H; left with all He

太陽的（主序）年齡 How old is the Sun?

- 恆星理論預期太陽主序壽命約100億年 Stellar theory
- 已經活了約50億年 5 Gyr now
  - ✓ 地球、月球、隕石定年；太陽應該起碼一樣年紀 Earth, moon, asteroids
  - ✓ 太陽理論模型顯示中央的氫元素含量只有原來（宇宙）的一半 H left half at core
  - ✓ 偵測到的微中子，日震推測的太陽結構支持理論 Neutrino, helioseismology data

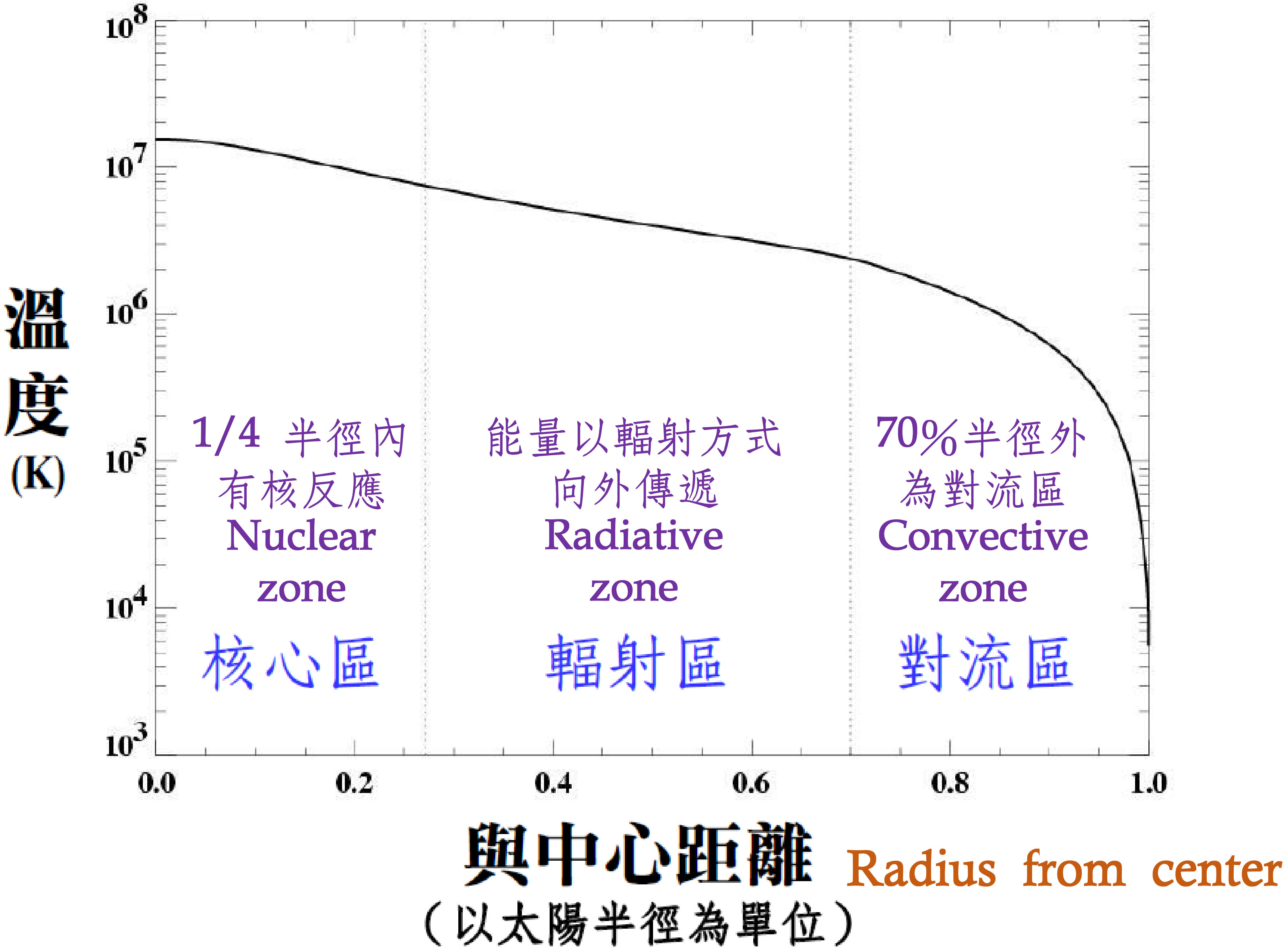
年齡46億年（當今）的太陽數值模型



The Present Sun

25%半徑 radius

70%半徑 radius



恆星演化與衰亡
Steller Evolution & Death

Stellar Evolution

- More fuel? *Yes* → Balance
  No → Contraction → Additional fuel *Yes* → Balance
  No → ...

- Possible balancing mechanism
  - ✓ Advanced fusion, e.g., He + He + He ⟶ C if $T \gtrsim 10^8$ K
    C + He, O + He, N + He (multiples of 4; cosmic abundances)
  - ✓ "Matter force", e.g., electron degenerate pressure

- Massive stars → fusion rate ↑↑↑ → hot and v. bright $\mathcal{L}$ ↑↑↑
  → lots of fuels, but used up quickly → τ_{MS} ↓↓

  $\mathcal{L} \propto \mathcal{M}^{3.5}$

  Low-mass stars → warm and faint → long-lived τ_{MS} ↑↑

$\tau_{\mathrm{MS}} \propto$ [fuel]/[consumption rate] $\propto \mathcal{M}/\mathcal{L} \propto \mathcal{M}^{-2.5}$

- When core H exhausted (becomes He; ～10% of total H)
  → Out of balance → core contracts, heated

  The immediate outer layer, then insufficiently hot to burn H, now manages to do so (extra energy) → H shell burning

  → The envelope expands and cools ⟹ A big, cool red giant 紅巨星

- If the core not massive enough, He never ignited
  → cools to become a black dwarf

  If He fusion starts (nuclear waste becomes fuels)
  → balance regained, but He in short supply and used up rapidly

  More massive cores → … C, N, O, S, … Fe

  When no more fusion whatsoever, core collapses

  If $M_{core} \lesssim 1.4\ M_\odot$ Chandrasekhar limit 錢氏極限 → a **white dwarf** 白矮星 supported by P_{deg}^{e-} $\rho \approx 10^9\ \mathrm{kg\ m^{-3}}$

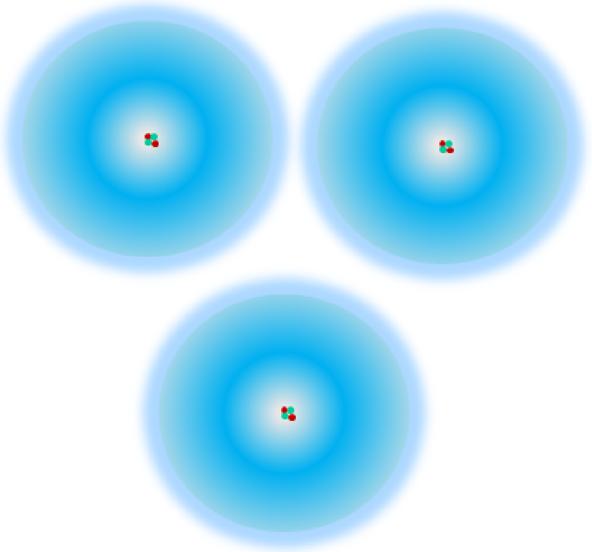
  ✓ Or else, halted by P_{deg}^{n} → a **neutron star** 中子星 $\rho \approx 5 \times 10^{17}\ \mathrm{kg\ m^{-3}}$

  ✓ Or else → a spacetime singularity, a **black hole** 黑洞

（理想）氣體，溫度高、密度高
→ 彼此碰撞 → 熱壓強

簡併氣體，壓強不靠碰撞，而
來自不相容原理（鳩佔鵲巢）
→ 壓強只跟密度有關

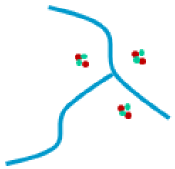
正常物質



電子以波動機率，分布在
原子核之外特定的軌域內

土壤密度：3×10^{-3} kg/cc
空氣密度：10^{-6} kg/cc

電子簡併態
（白矮星）



強大引力將原子核
緊密排列，自由電
子則交錯分布

物質密度：1000 kg/cm^3

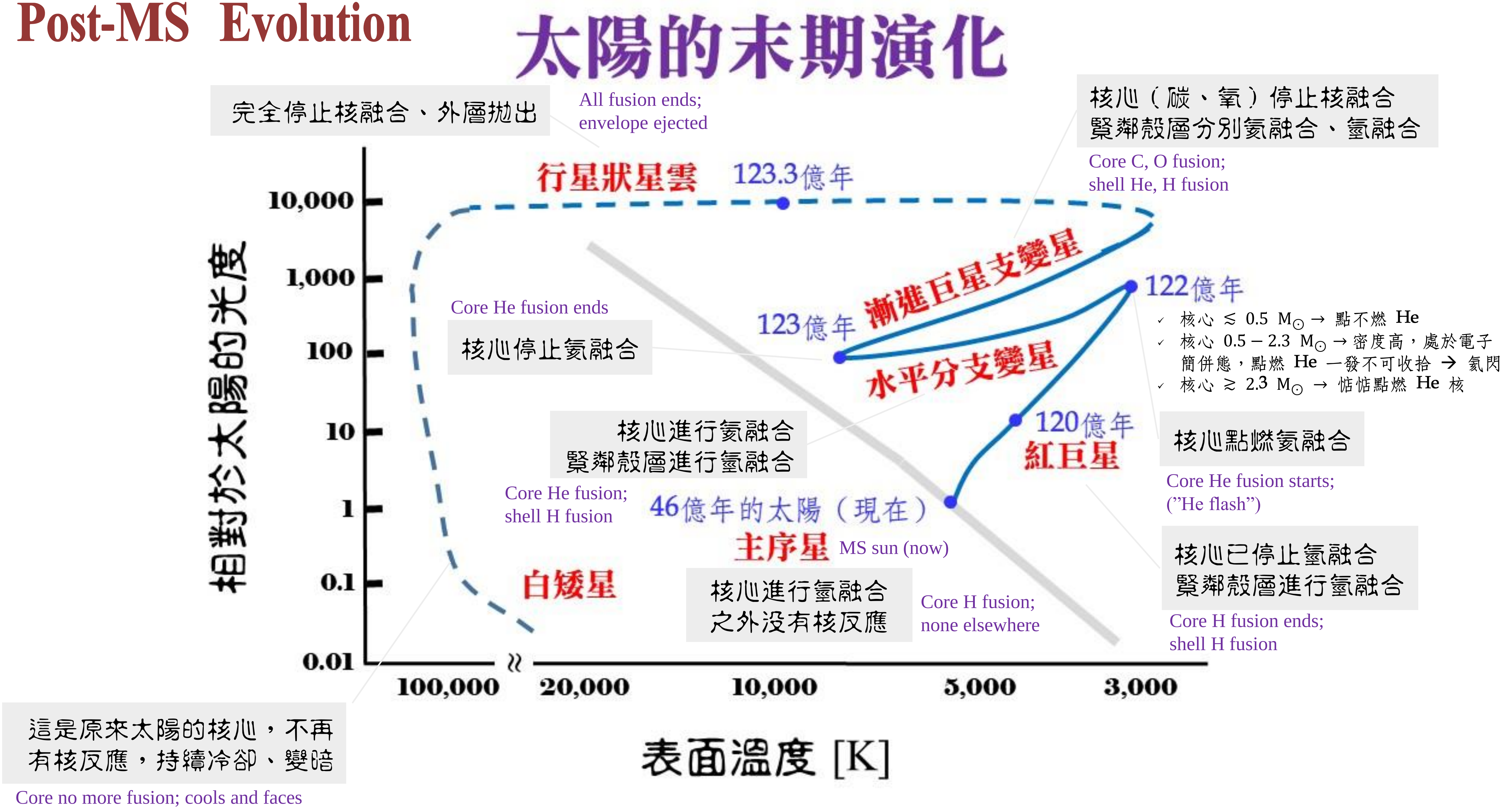
中子簡併態
（中子星）

電子與質子結合成為中子

物質密度：5×10^{11} kg/cm^3
每cc重達5億公噸

（此為示意圖，未照比例繪製）

Post-MS Evolution



- ☐ Low-mass stars: core thermally pulsed and eventually puffing the envelope out → a planetary nebula 行星狀星雲

nothing to do with planets; dim & fuzzy


- ☐ Massive stars: core highly compressed and bounced, exploding the envelope 超新星 *(not new, not a star)*

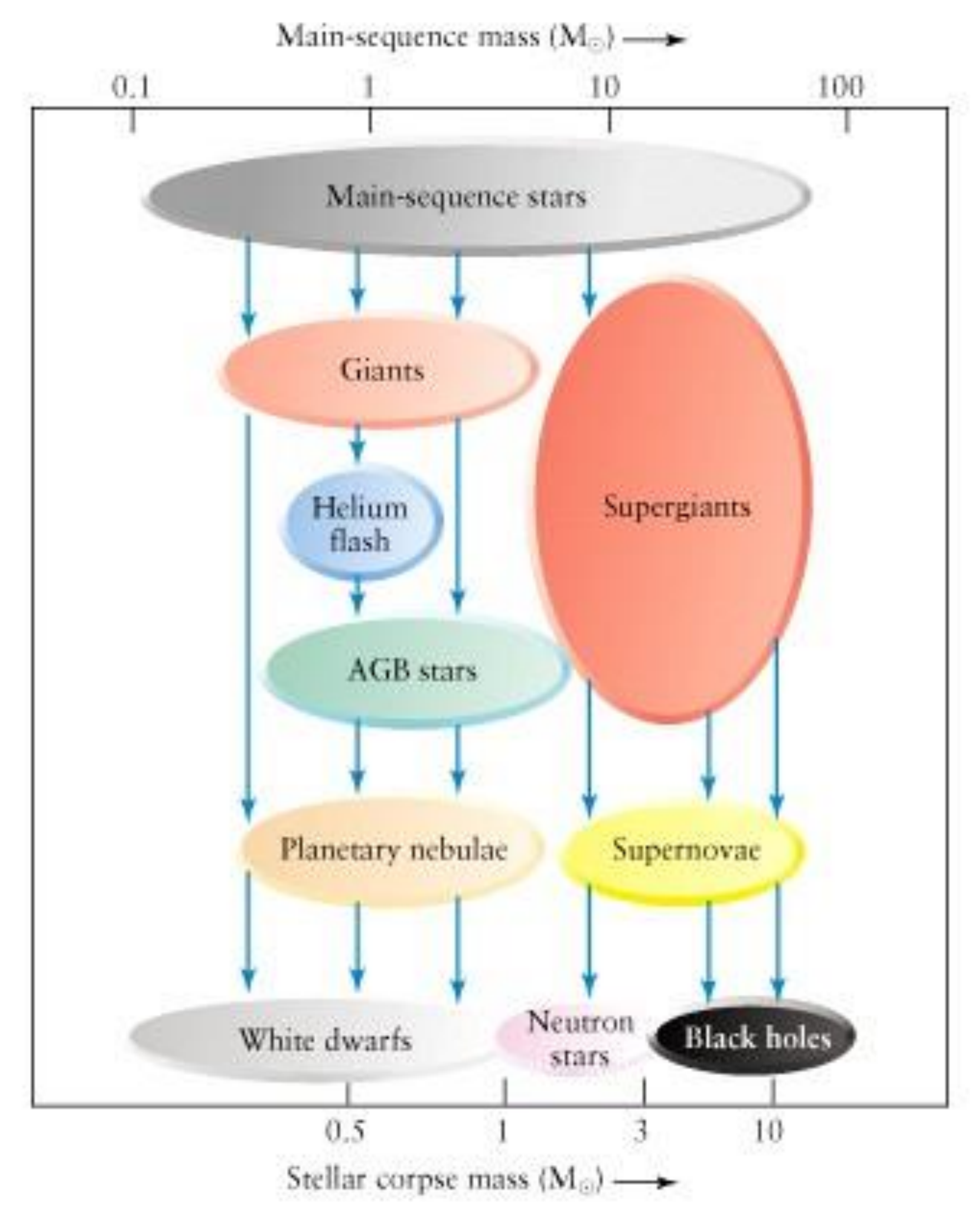

⟹ ISM enriched with "complex elements" for next-generation stars; producing nuclei heavier than Fe

We owe ourselves and the complexity of the world to stars; we are all their offspring, from stardust back to stardust …

恆星在主序時的質量

質量流失

恆星死亡時（核心）的質量



結論：所謂「恆星」種種 …

- 太空中極冷的環境，誕生出極熱的東西 … 自我引力 … 核反應 … 靜力平衡 … 穩定發光發熱
  Stars made in coldest space; energy engines and element factories
- 壽命百萬年到百億年，製造複雜元素 *shine for Myr to 100s Gyr*
- 提供地球生命（及宇宙）重要的能量來源 *sustaining earthlings*
- 我們這種生命以天體演化的時間尺度發展出來
  so we evolve with cosmic timescales
- 我們藉星光了解大半的宇宙（總有暗勢力）
  so we comprehend the cosmos

"The most incomprehensible thing about the Universe is that it is comprehensible." - Albert Einstein

「宇宙最讓人無法理解之處，就是其居然可以理解」

—愛因斯坦