Interstellar Medium, Star Formation, & Star Clusters

星際介質與恆星形成 + 星團 實作

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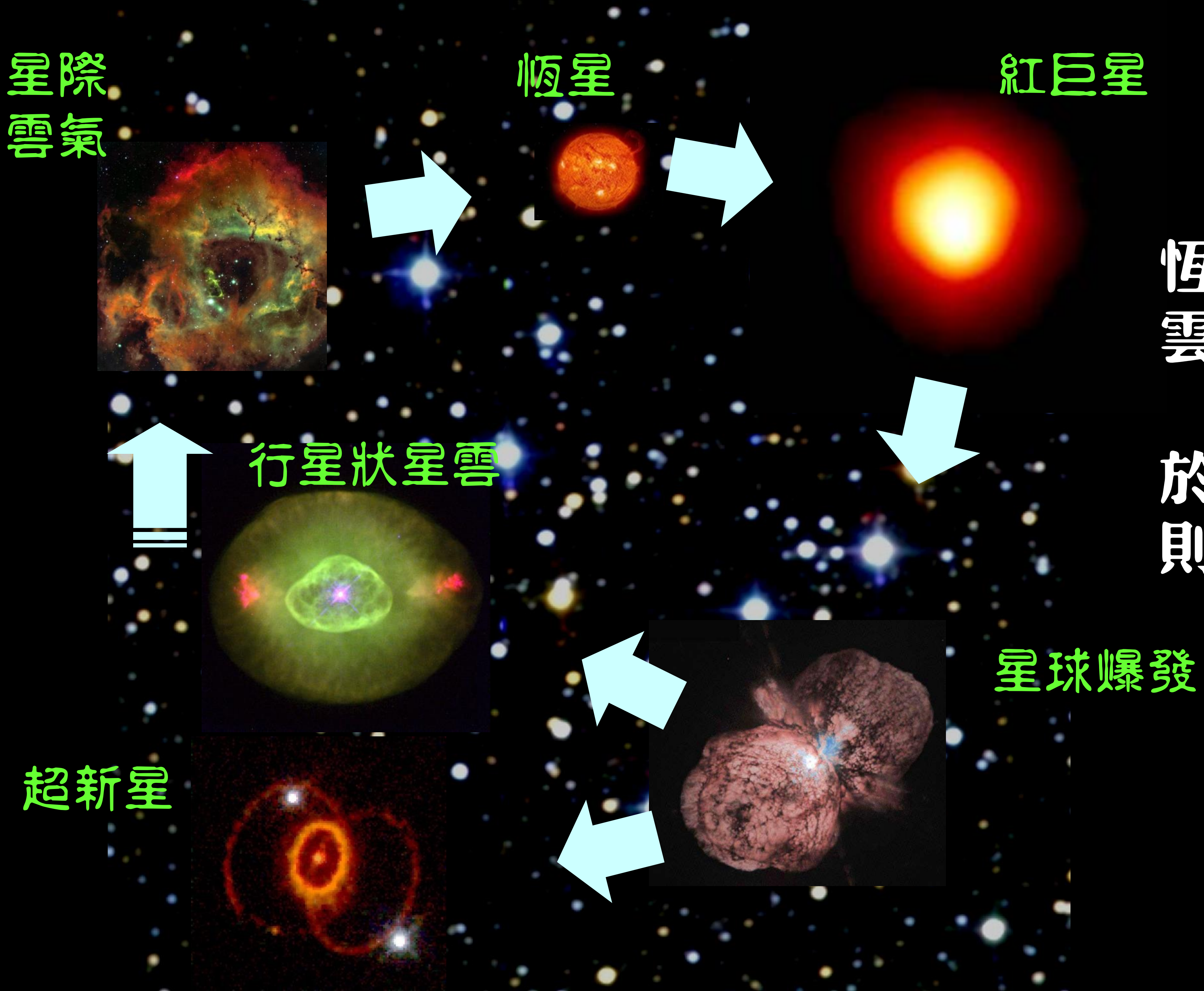
結論

- 太空不是真空。恆星間的物質密度極低，有各種溫度
- 這些物質有可能聚集起來，成為恆星、行星等天體
- 銀河系不斷誕生成群的恆星；隨著恆星老化、衰亡，星團也逐漸瓦解
- 有些星系當中有劇烈恆星形成活動，有些則已經不再製造恆星

恆星的生老病死

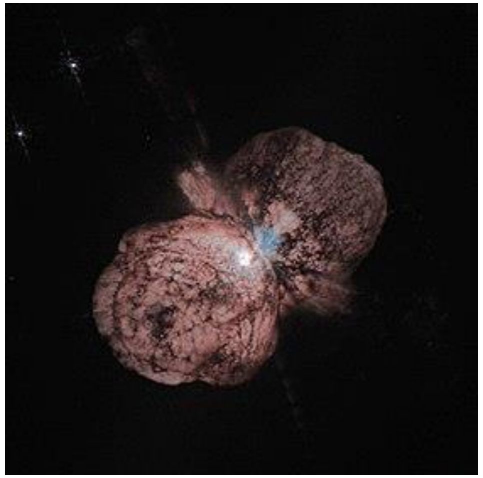


恆星在濃密分子雲核中成群誕生

於此同時，行星則在年輕環星盤中誕生

考前總複習

- 星際物質：氣體（原子、分子、離子）、固體（塵埃）；各種溫度、成分（星系際物質）
- 恆星源於重力塌縮的星際分子雲
  - ✓以成群的方式誕生
  - ✓恆星內部進行核反應，能源提供氣體熱壓力與重力平衡
- 行星誕生於個別初生恆星周圍的環星盤



星際物質

星星之間極其寬廣，但太空並非真空，而有星際物質

日常空氣每cc約含10^{19}個氣體分子
星際太空每cc約含 1 個氣體粒子

這些包含氣體與灰塵的雲氣彼此之間互相吸引（萬有引力），使得雲氣聚集，濃密的灰塵會擋住後面發光的氣體或星球

這些「星際暗雲」密度高（每cc超過數萬個分子）、溫度低（攝氏零下260幾度）

地球海平面 (STP) 空氣密度 ＝ 1.225 kg/m^3; ≈ 水的千分之一

星際物質為氣態或固態（雲氣＝氣體＋塵埃），因為太空壓力低，沒有液態

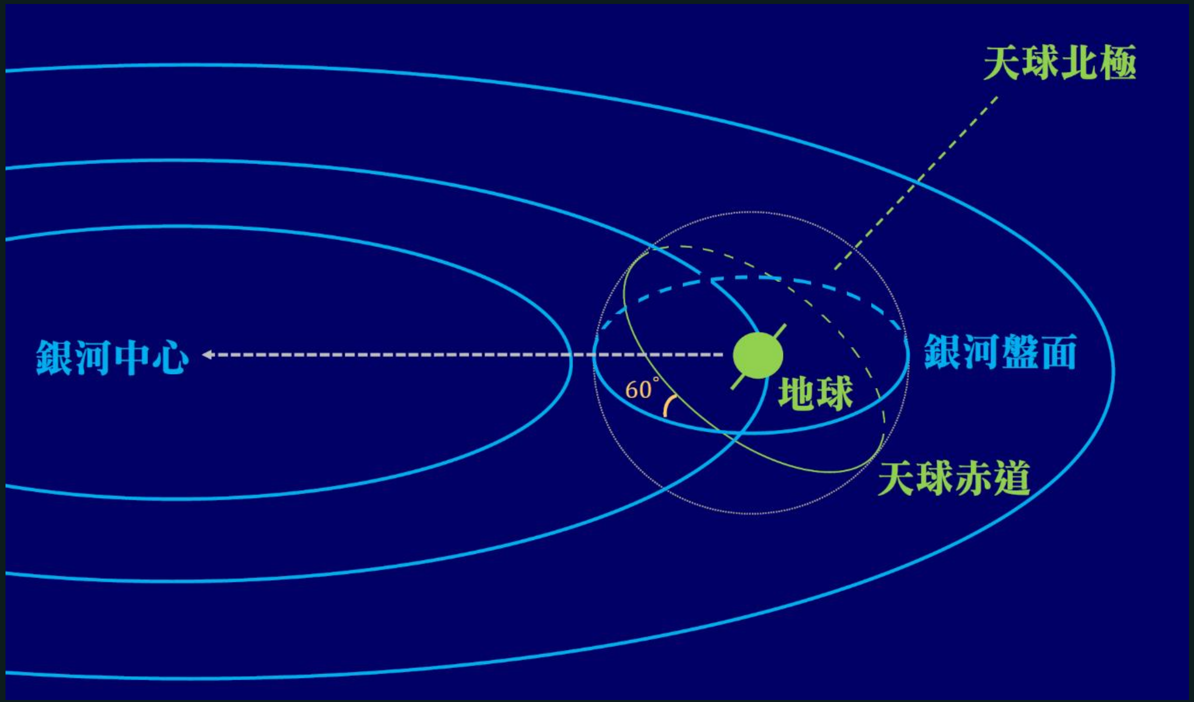
氣體可以是中性（原子或分子），或是游離態（離子＋電子＝電漿 plasma）

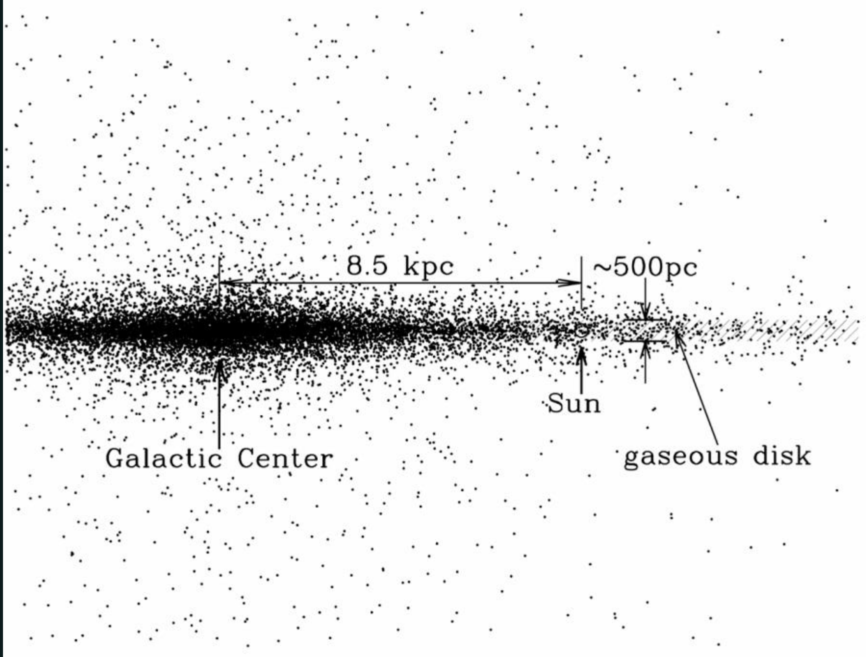
氣體多半透明

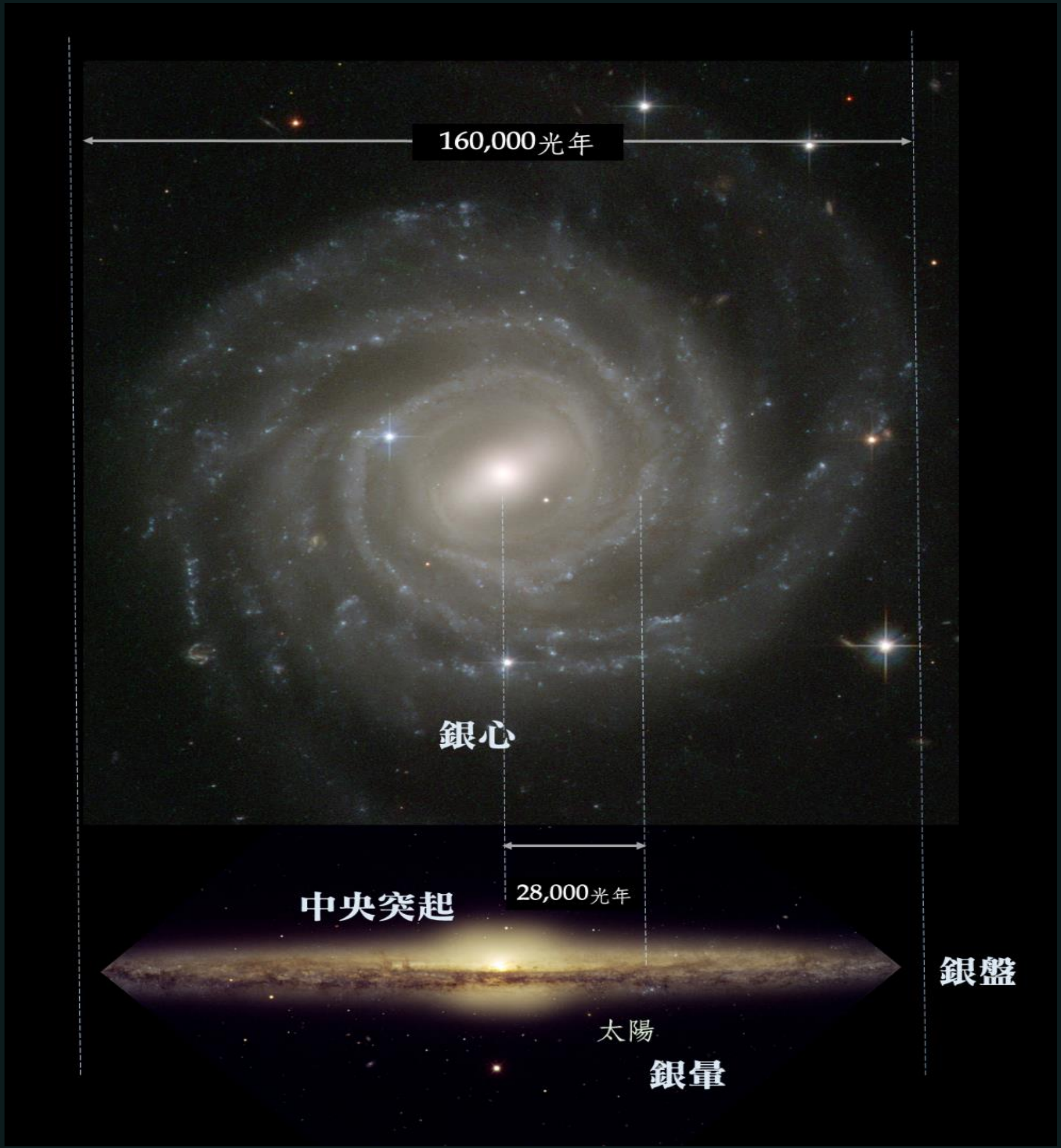
塵埃則會擋住光線 → 消光 (extinction)

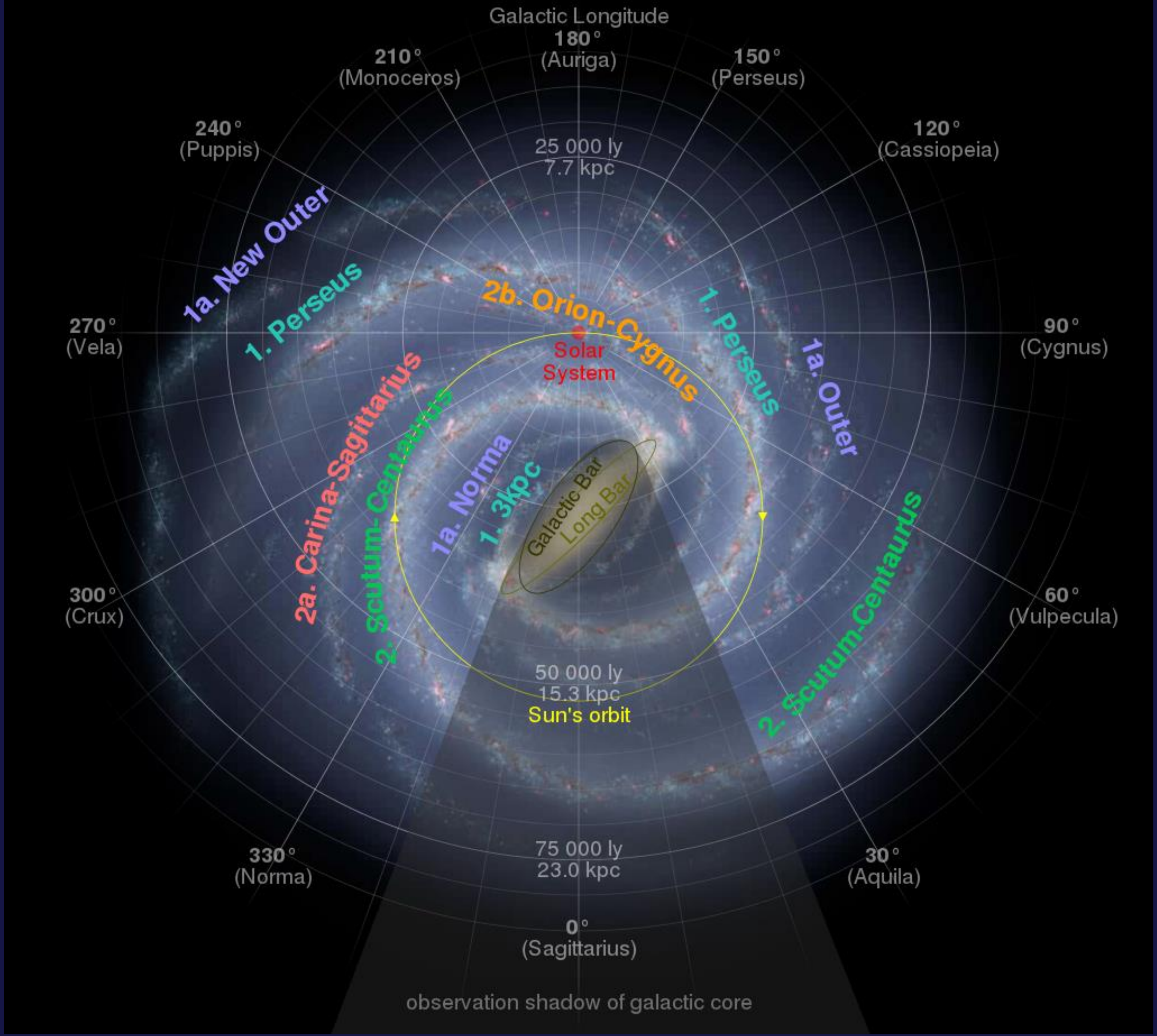
短波的光線擋光尤其明顯 → 紅化 (reddening)

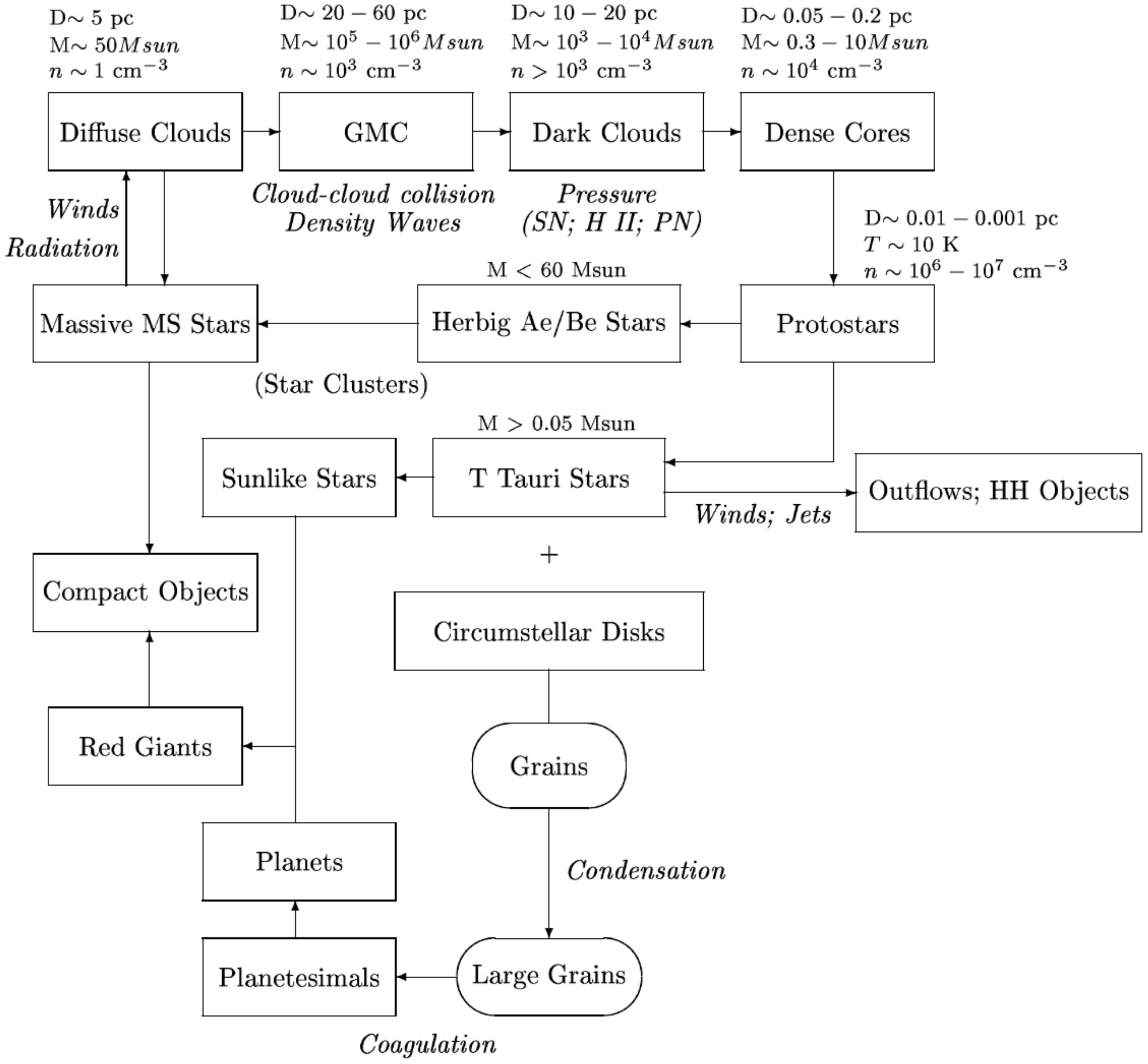
ISM 影響光線（能量）傳遞，也影響觀測結果


天球北極
銀河中心
銀河盤面
地球
60°
天球赤道


8.5 kpc
~500pc
Sun
Galactic Center
gaseous disk


160,000光年
銀心
28,000光年
中央突起
銀盤
太陽
銀暈


Galactic Longitude
180° (Auriga)
210° (Monoceros)
150° (Perseus)
240° (Puppis)
120° (Cassiopeia)
25 000 ly
7.7 kpc
270° (Vela)
90° (Cygnus)
1a. New Outer
1. Perseus
2b. Orion-Cygnus
Solar System
1. Perseus
1a. Outer
2a. Carina-Sagittarius
2. Scutum-Centaurus
1a. Norma
1. 3kpc
Galactic Bar
Long Bar
2. Scutum-Centaurus
300° (Crux)
60° (Vulpecula)
50 000 ly
15.3 kpc
Sun's orbit
330° (Norma)
75 000 ly
23.0 kpc
30° (Aquila)
0° (Sagittarius)
observation shadow of galactic core



Galactic Ecology 銀河系的生態系統

星際雲氣

氣體與塵埃

- **發射星雲 (emission nebula)**
  氣體受激發（星光照射、碰撞）
  自己發光。Balmer alpha → 紅色
- **反射星雲 (reflection nebula)**
  氣體反光（散射）→ 藍色
- **黑暗星雲 (dark nebula)**
  塵埃遮住背景光線
  （星光或發射星雲）→ 黑色

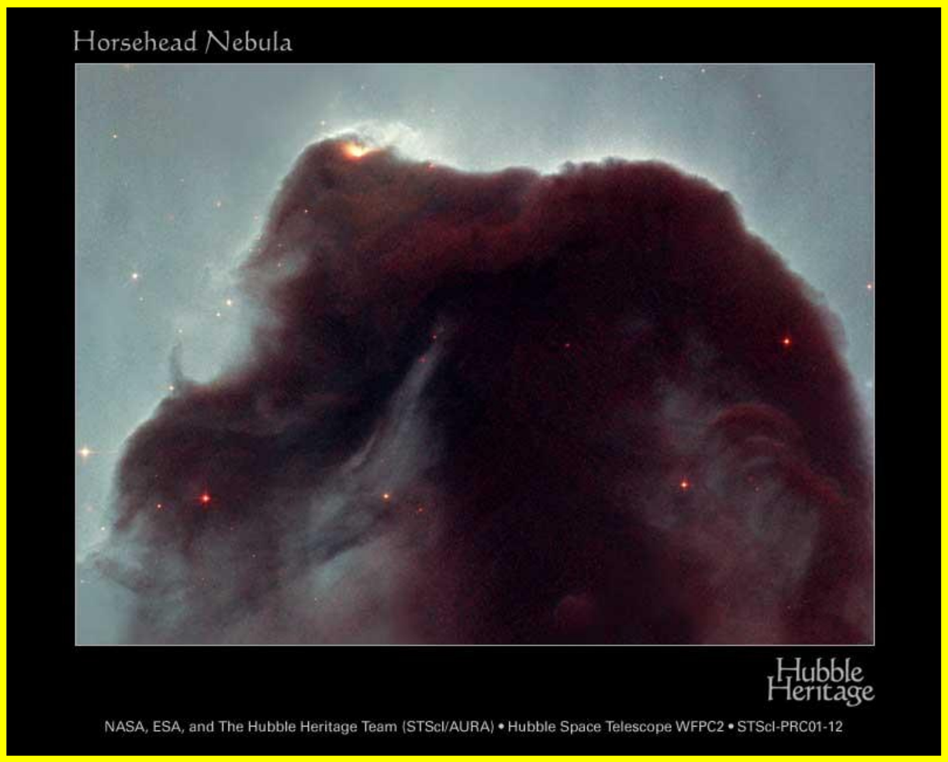
日光燈、LED 燈、 火焰

Interstellar Medium (ISM)

- 1811 William Herschel "*holes in the starry sky*"
- 1904 J. Hartmann "*stationary*" calcium lines in the spectroscopic binary δ Orionis → of interstellar origin
- 1919 Barnard catalog of dark nebulae
- Photography → emission and reflection nebulae; dark clouds
- 1930 Struve: absorption ↗ as distance ↗

Barnard 72 in Ophiuchus

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



Star Shadows Remote Observatory

(Bok) Globules silhouetted against emission nebulosity

© Anglo-Australian Observatory Photograph by David Malin

A dark cloud core seen against a star field

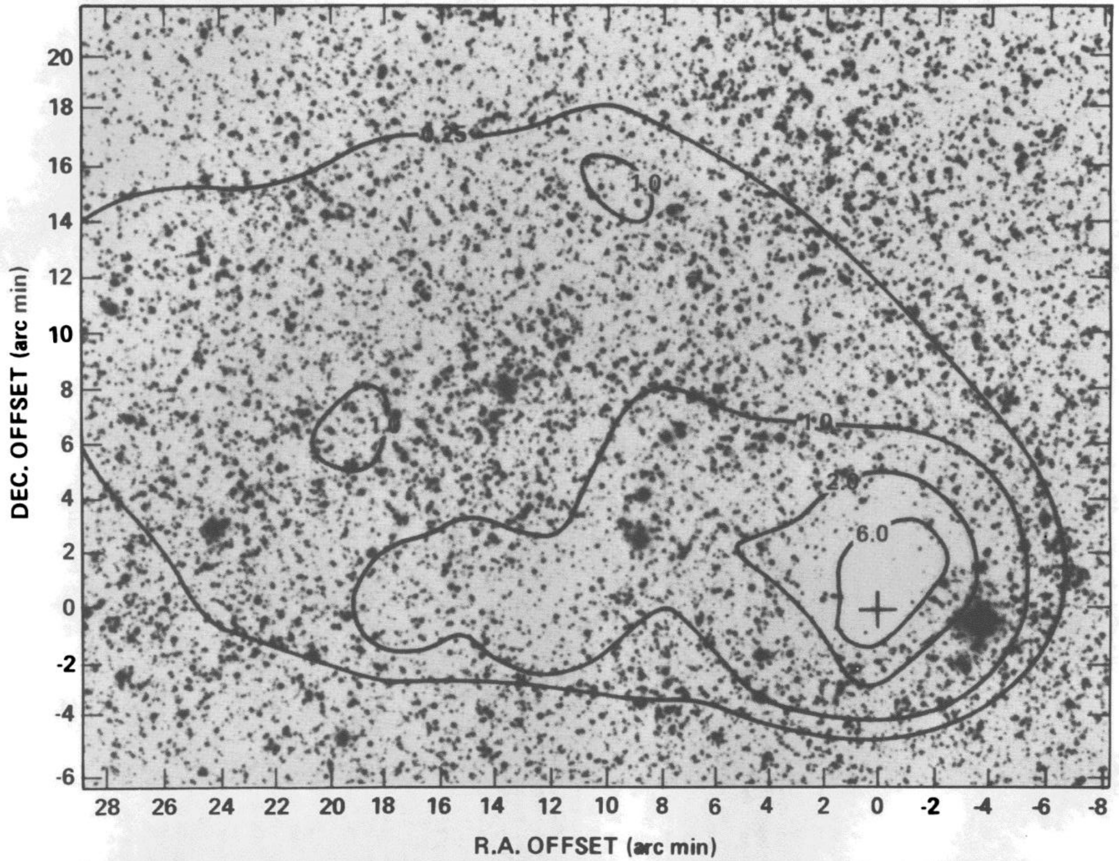
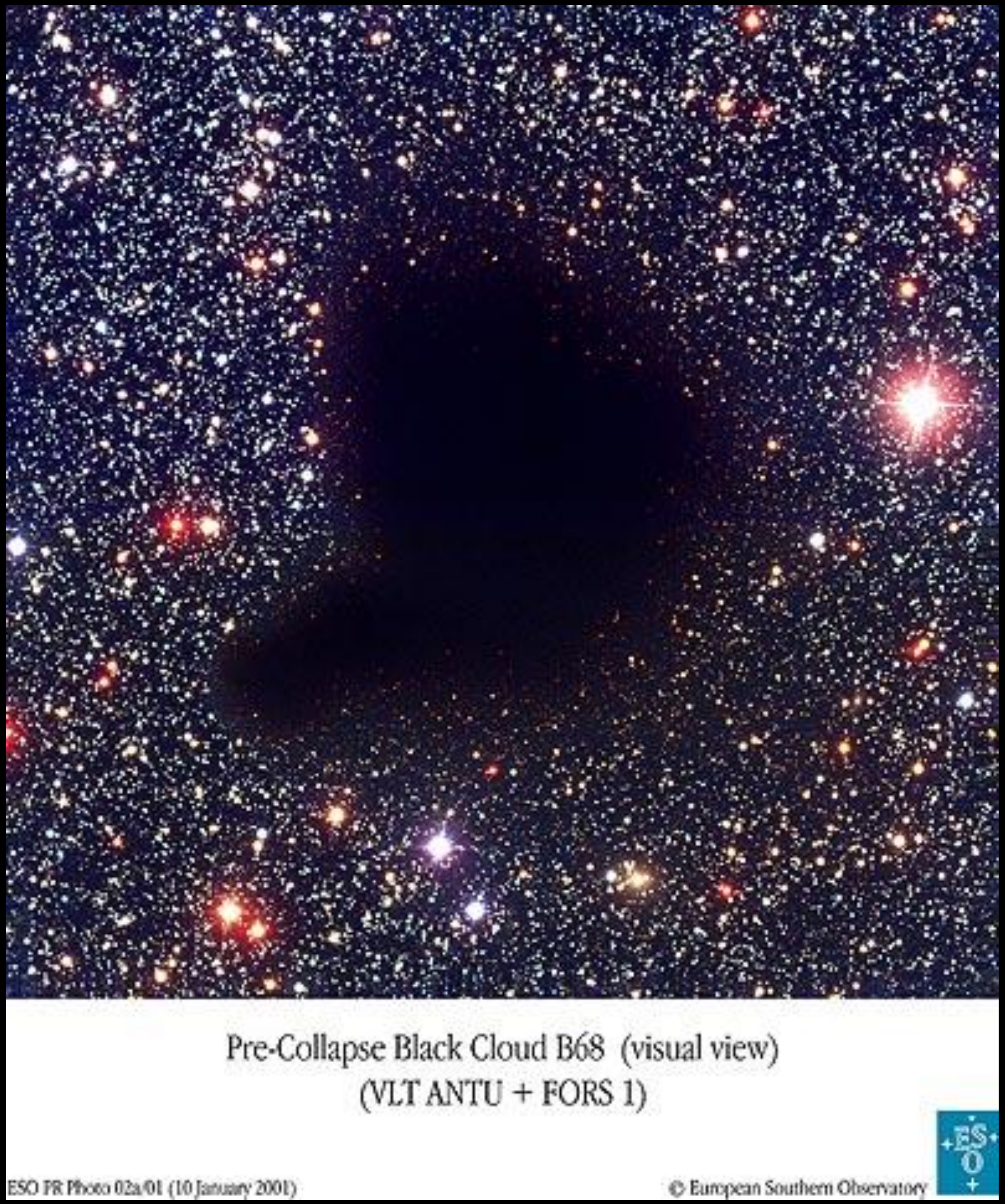


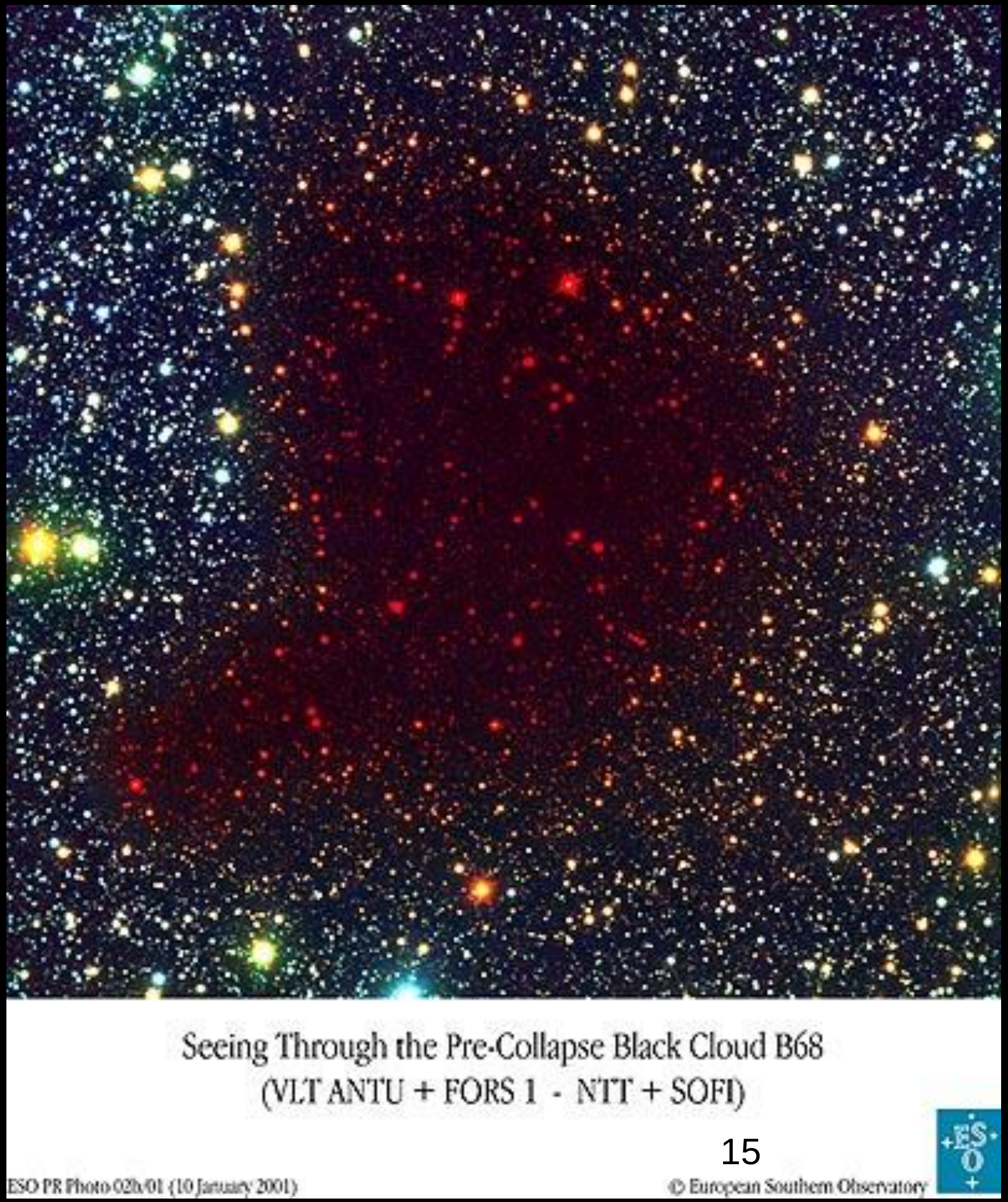
FIG. 1.—The optical image of B335 on the blue POSS print. Superposed on it are the $N(H_2)$ contours in units of 10^{21} cm^{-2}; the derivation of $N(H_2)$ is discussed in § IIIa(i). In the SW corner there is a highly obscured core region ~2′ × 3′ surrounded by an extended envelope covering ~34′ × 20′.

Frerking et al. (1987)

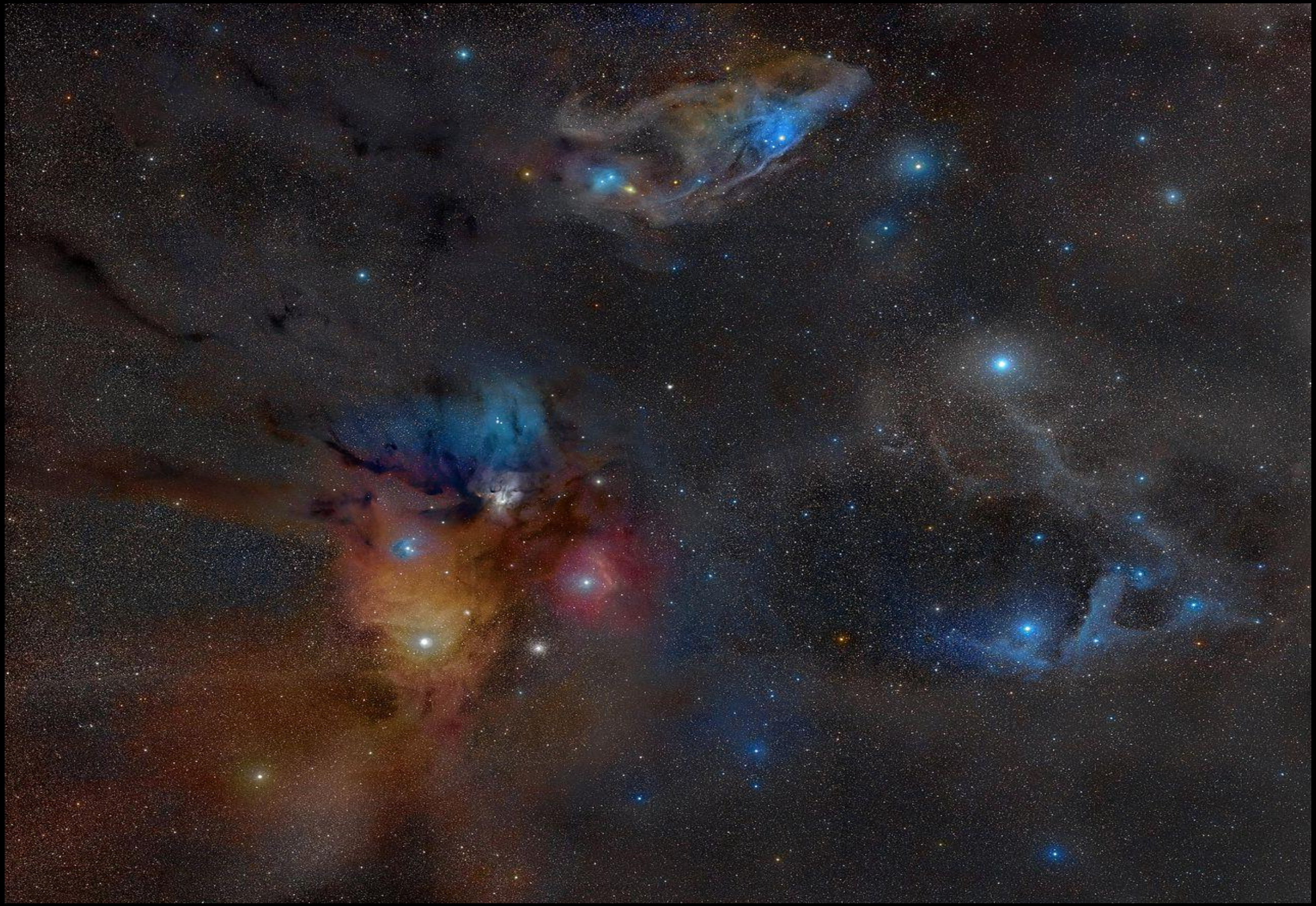
Optical Composite

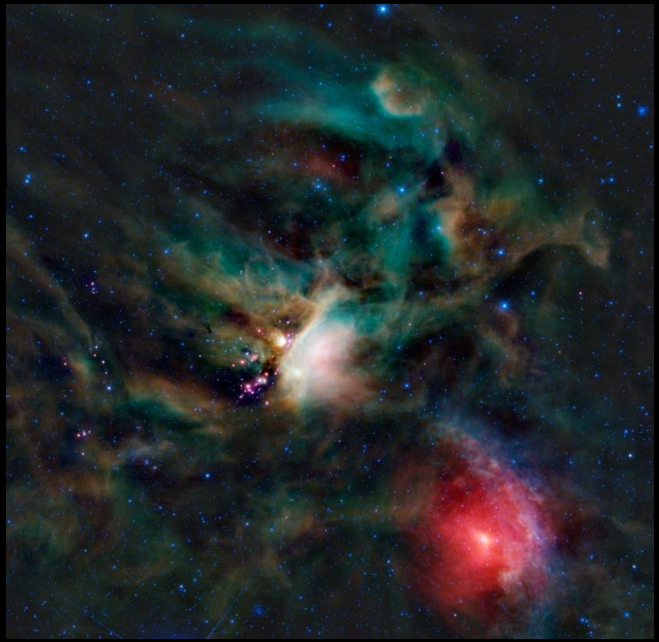
Optical/IR composite





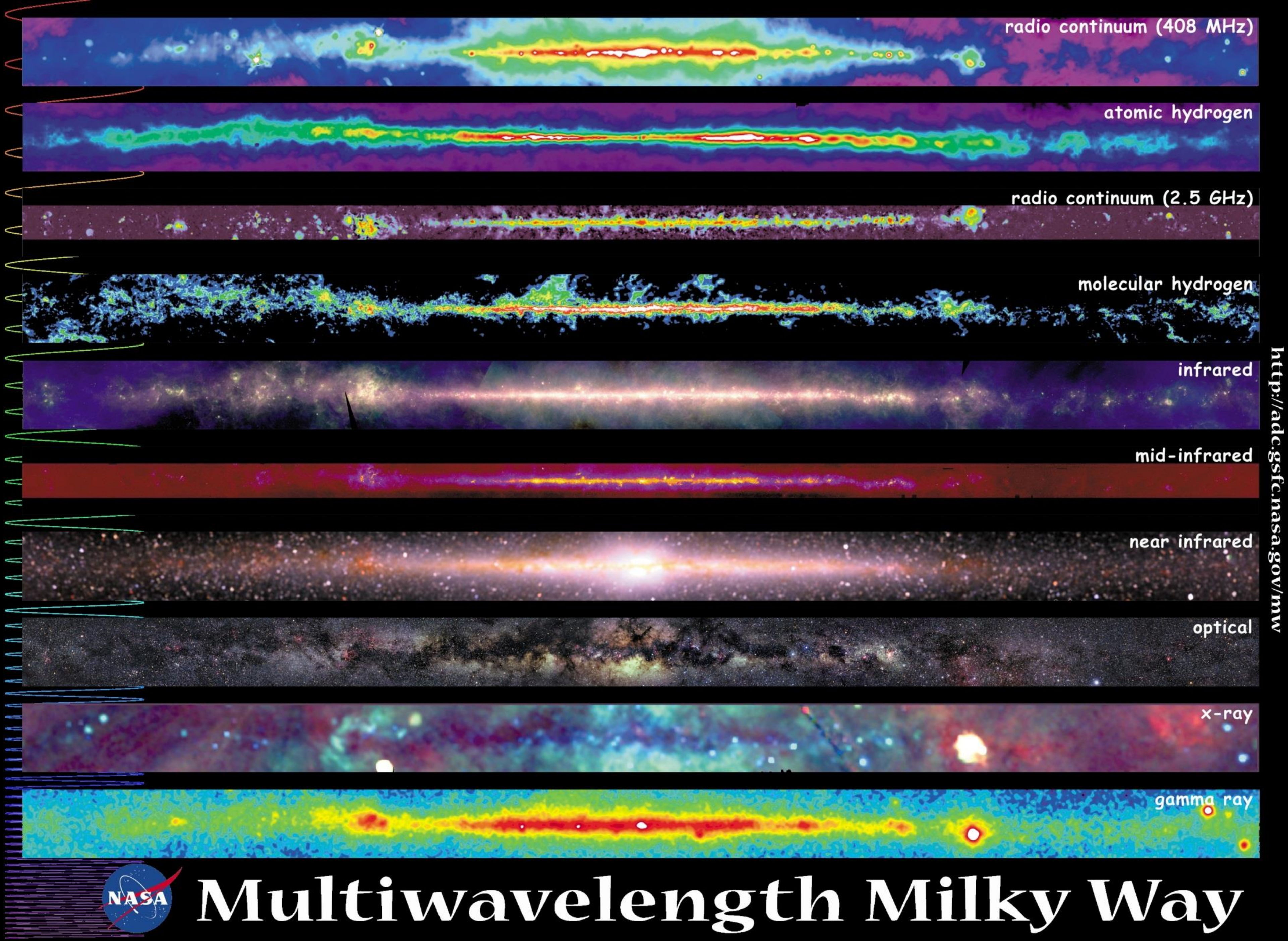
ρ Ophiuchi cloud complex



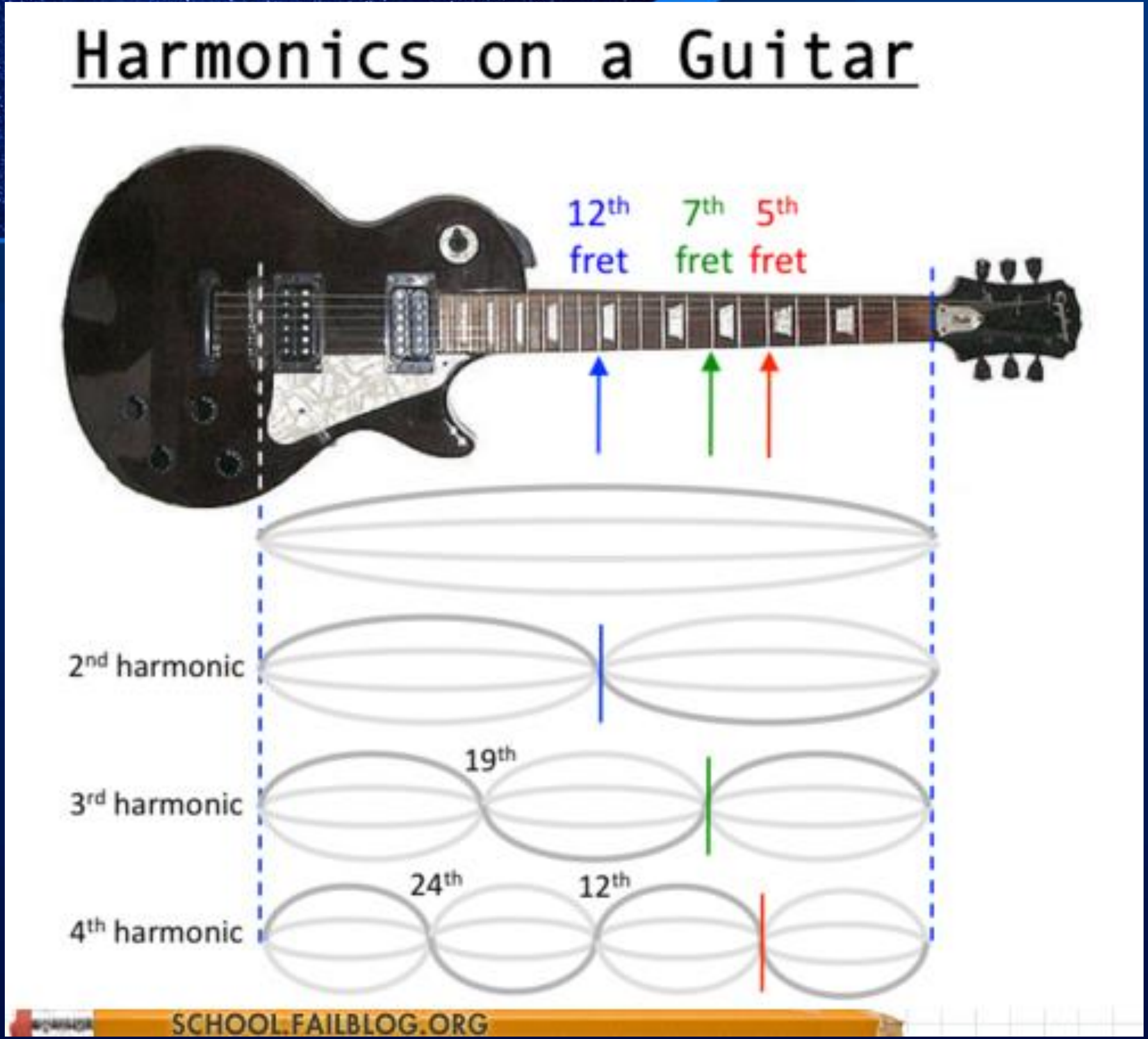


WISE

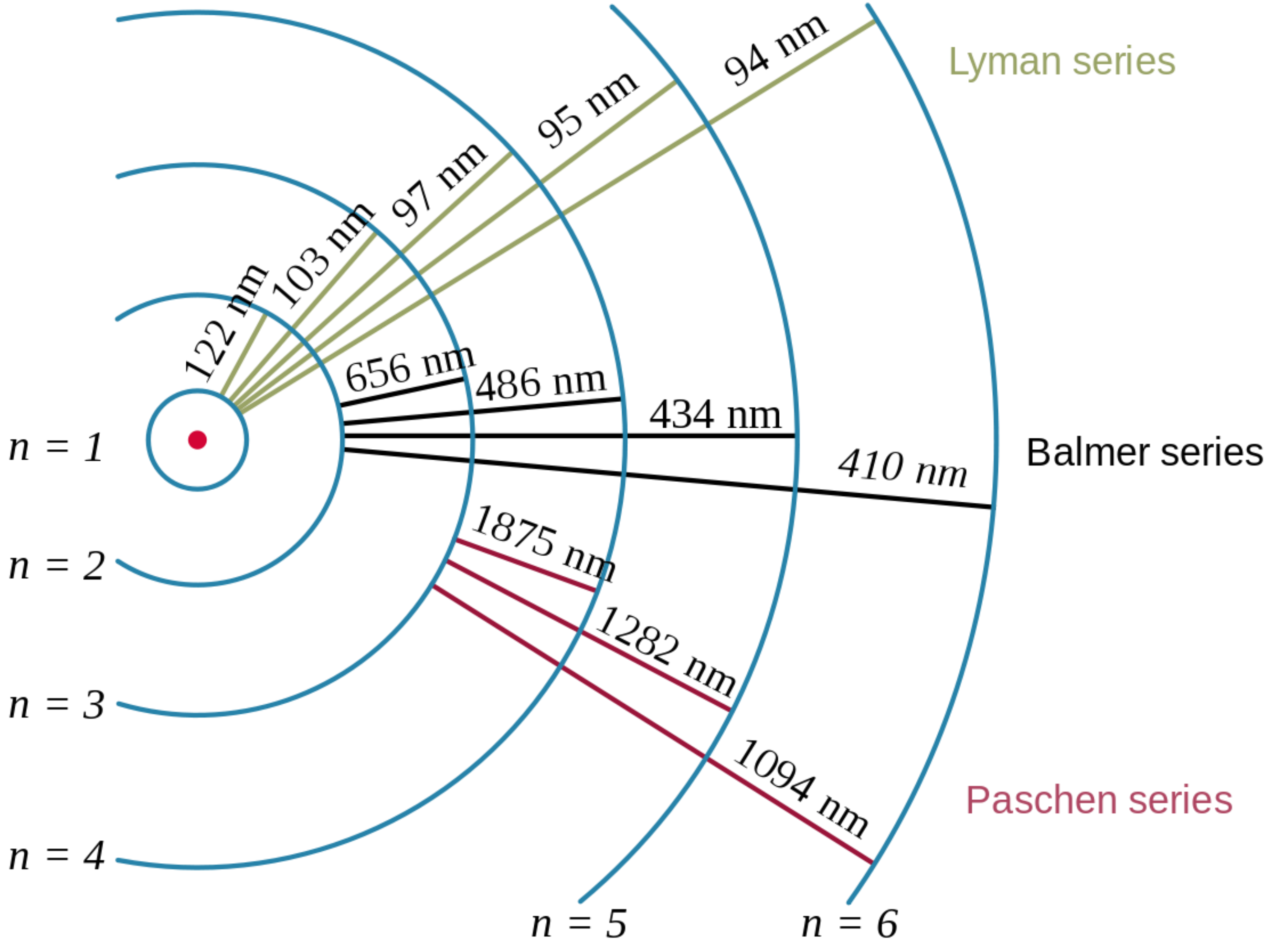
https://en.wikipedia.org/wiki/Rho_Ophiuchi#/media/File:Rho_Ophiucus_Widefield.jpg


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

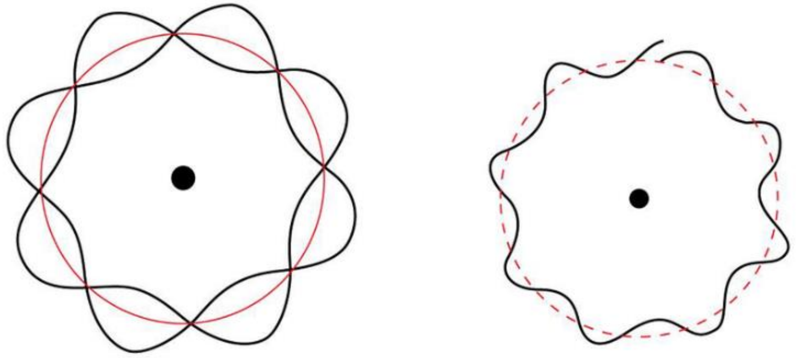
駐波


Harmonics on a Guitar
12th fret
7th fret
5th fret
2nd harmonic
3rd harmonic
19th
4th harmonic
24th
12th
SCHOOL.FAILBLOG.ORG

譜線是怎麼回事？

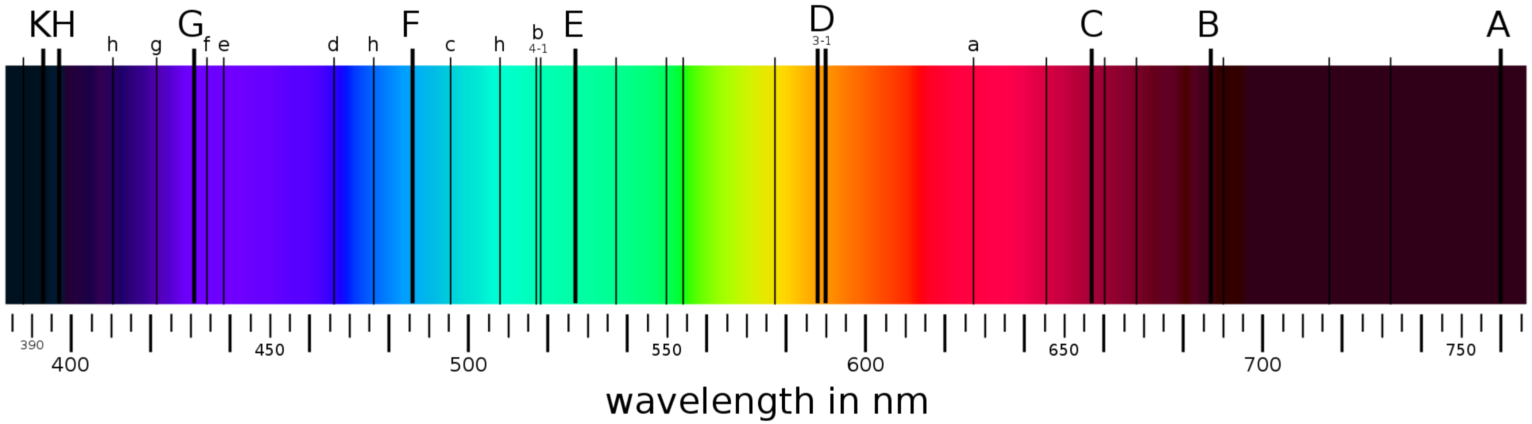


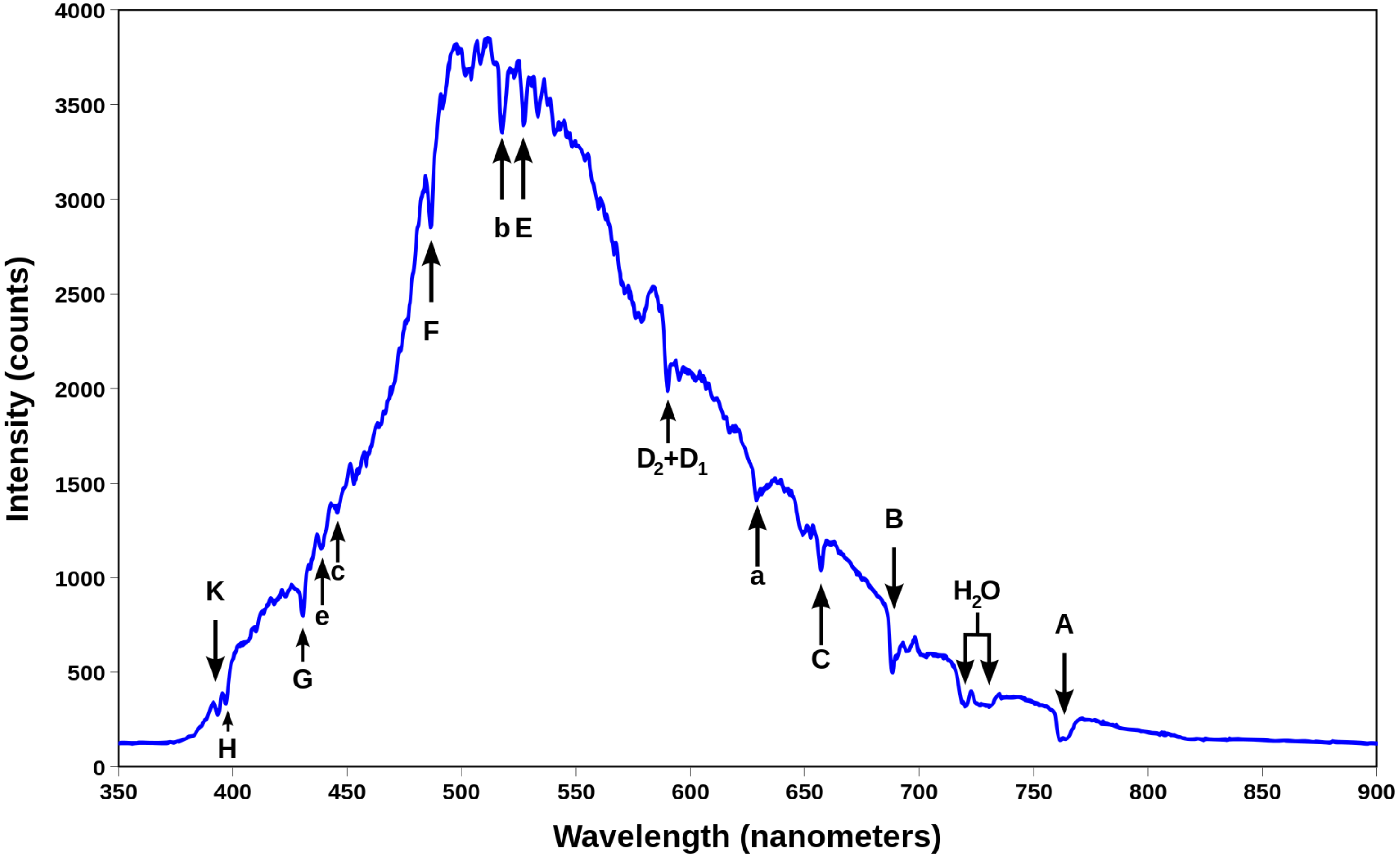
122 nm
103 nm
97 nm
95 nm
94 nm
Lyman series
656 nm
486 nm
434 nm
410 nm
Balmer series
1875 nm
1282 nm
1094 nm
Paschen series
n = 1
n = 2
n = 3
n = 4
n = 5
n = 6



顏色：
不同波長強度的比例

- ◆ 紅綠燈的顏色
- ◆ 衣服、牆壁的顏色
- ◆ 恆星的顏色





B33 (NOAO)

- 銀河系組成：恆星、行星、衛星、彗星（小行星）、星際物質、輻射、宇宙射線（高速帶電粒子）、磁場、暗物質…
- [恆星之間的距離] / [恆星本身直徑] ~ 1 pc/10^{11} cm ~$3\times10^{7}:1$　　以體積（空間）來說 ~ 10^{22}倍

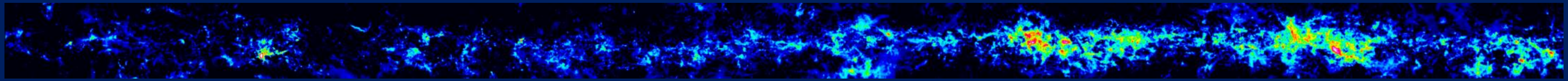
  ➔ 星際空間極其空曠

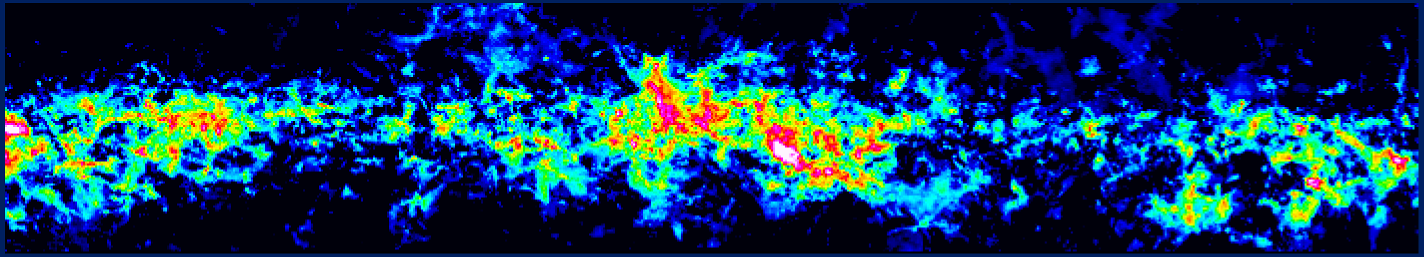
- 以質量來說　ISM ～10% 銀河系全部可見物質
  ISM本身 ～99% 為氣體；1% 為塵埃
- 氣體當中～90%為H；10%為He （就是整個宇宙的比例）
- 主要是氫原子 (H I; atomic)，另外是氫離子 (H II; ionized)，與氫分子 (H_2; molecular)

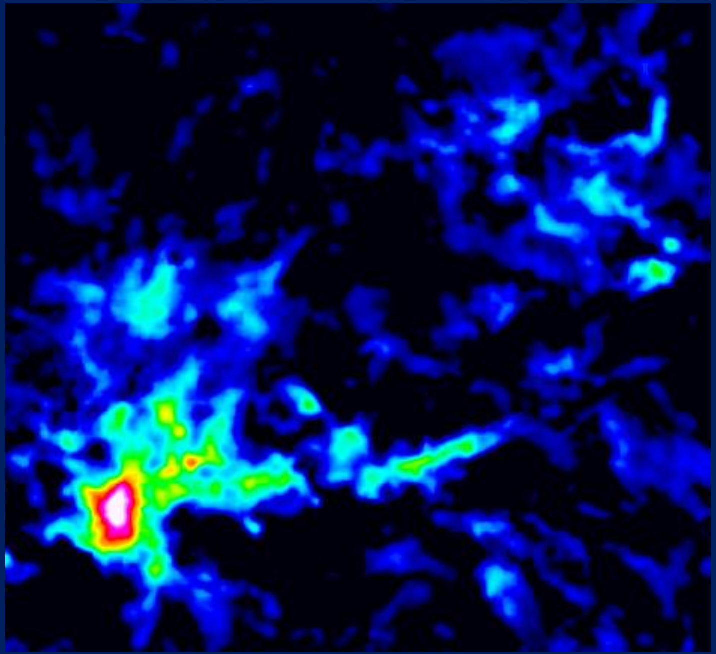
ISM密度不均勻

- □ 一般分布成**原子雲**；平均密度 1/cc; 溫度 100 K
  - ✓ 沒有激發，都處於最低能階 → 無法以原子光譜探測
  - ✓ 但即使在最低能階，與原子核自旋相同或不同，能量稍異，一旦改變狀態 → 波長為 21 公分的輻射
  - ✓ 以電波望遠鏡觀測 → 原子雲位置、大小、質量、溫度、運動
- □ 在低溫、高密度的環境，原子結合成分子，成為**分子雲**
  - ✓ 分子會震盪、擺動、旋轉，改變狀態 → 發出長波輻射
  - ✓ 向內引力大、向外熱壓力弱，這些分子雲容易塌縮形成恆星
- □ 在高溫恆星周圍的氣體，被紫外星光游離，成為**游離區** (H II region)

Filamentary Molecular Clouds







Molecular clumps/ clouds/condensations

$n \sim 10^3\ \mathrm{cm^{-3}}$, $D \sim 5$ pc,

$M \sim 10^3\ \mathrm{M_\odot}$

Dense molecular cores

$n \geq 10^4\ \mathrm{cm^{-3}}$, D ~ 0.1 pc,

$M \sim 1\text{-}2\ \mathrm{M_\odot}$

Giant Molecular Clouds

D=20~100 pc

$\mathcal{M} = 10^5 \sim 10^6\ \mathcal{M}_\odot$

$\rho \approx 10 \sim 300\ \mathrm{cm}^{-3}$

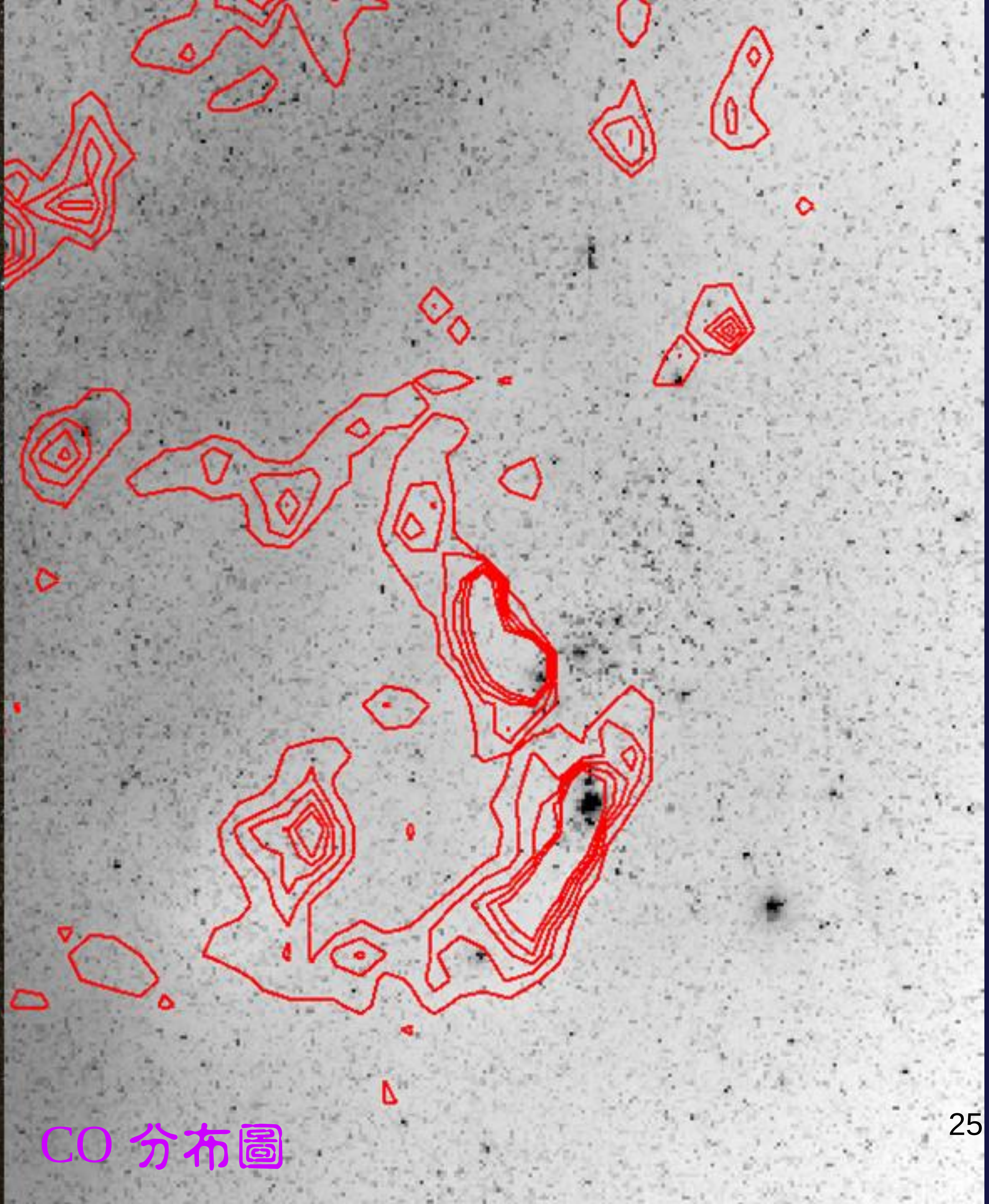
$T \approx 10 \sim 30$ K

$\Delta v \approx 5 \sim 15\ \mathrm{km}^{-1}$

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

獵戶

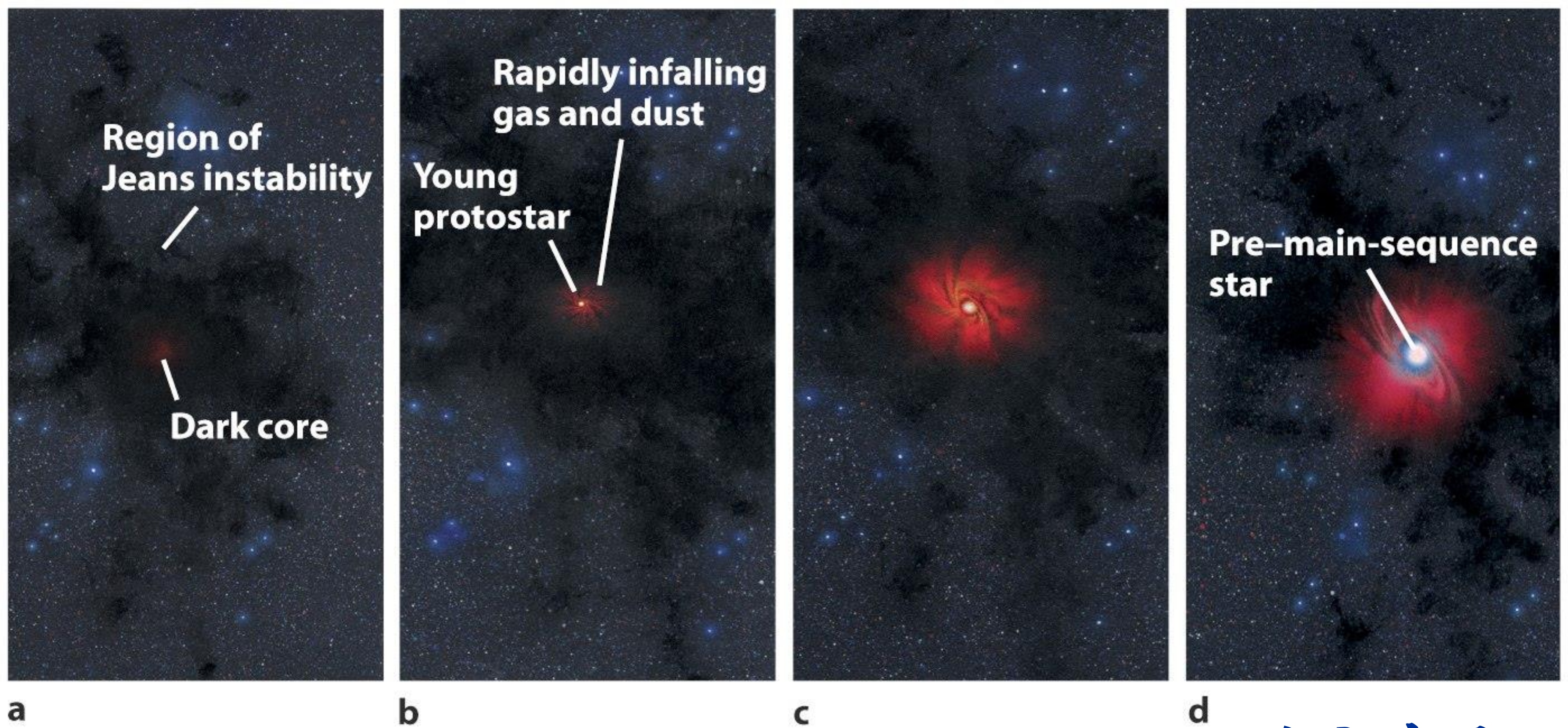
可見光照片



CO 分布圖

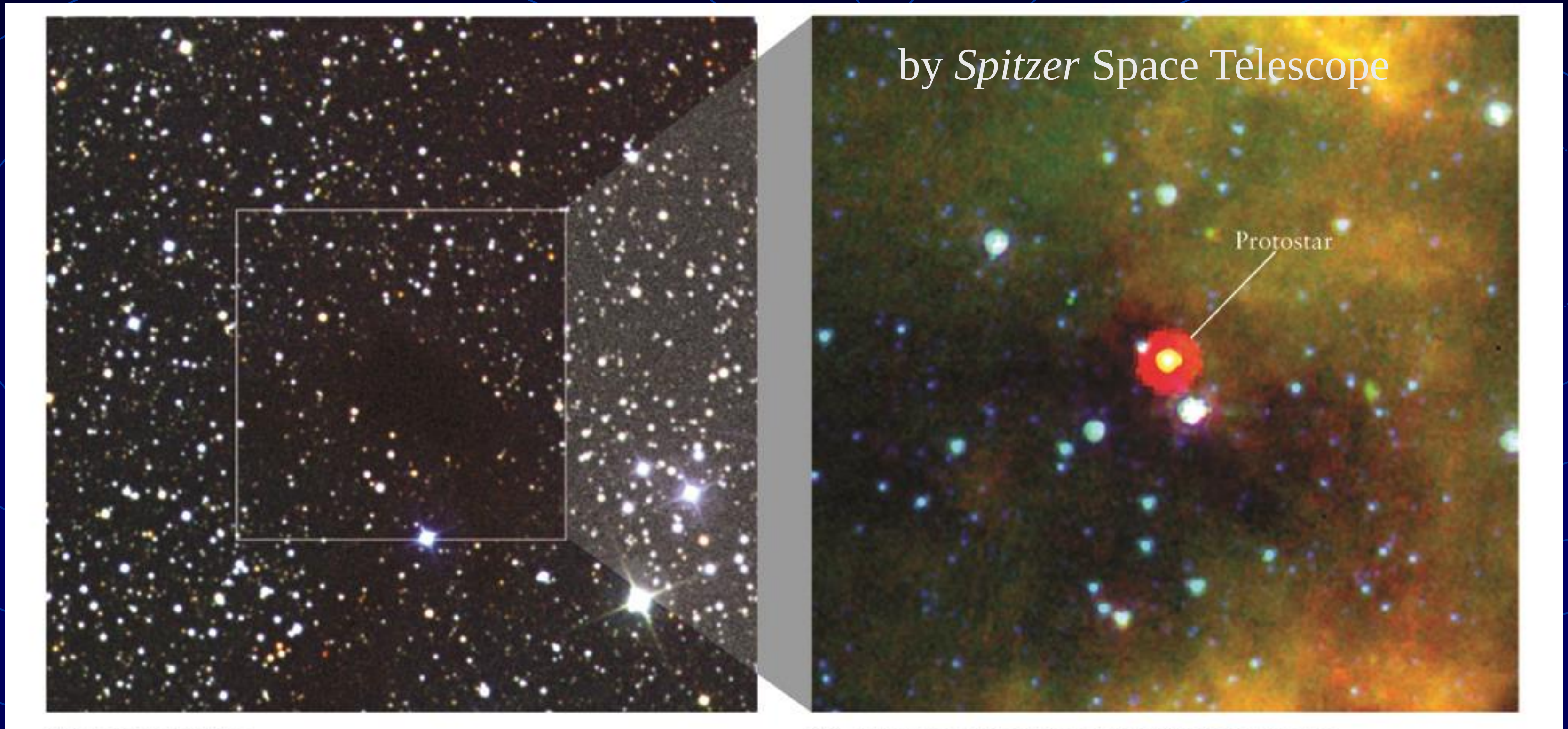
恆星源於分子雲核收縮

分子雲核要是密度高（因此萬有引力強）、溫度低（因此熱壓力弱）→ 引發重力塌縮形成**原恆星**



前主序星

原恆星仍被濃密的雲氣包圍



(a) A dark nebula

(b) A hidden protostar within the dark nebula

可見光影像顯示在暗雲中沒有恆星

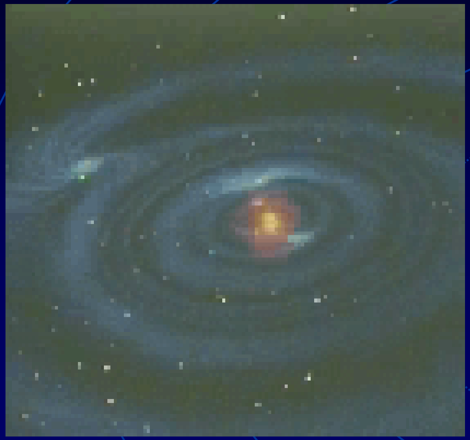
紅外光影像顯示在暗雲中存在原恆星

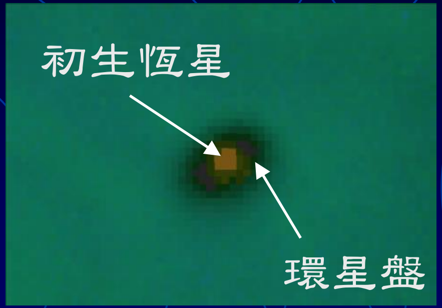
位於天鵝座方向的暗雲 L1014

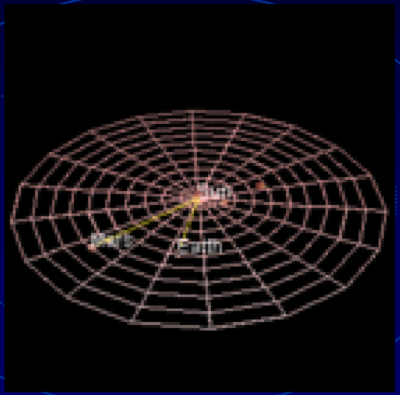
- 滿足臨界條件（溫度、密度→ 質量 Jeans mass）的分子雲核能夠塌縮，中央形成恆星，周邊形成環星盤
- 環星盤當中有濃密塵埃，遮住恆星的可見光，長波的星光比較有機會透射出來（紅外觀測）
- 塵埃受熱後自己也發熱 → 長波輻射（遠紅外、次／毫米波）

  但是長波解析力不好，需要特殊技術，例如干涉術 (SMA, ALMA)
- 環星盤裡面的塵埃有機會繼續增長，最終形成行星

恆星與行星源於重力塌縮的雲氣



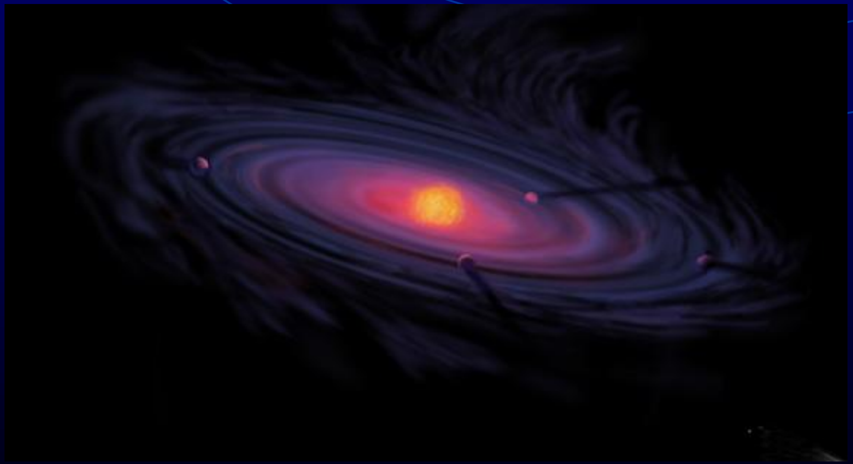




星際暗雲 —收縮 / 旋轉→ 初生星球 ＋ 扁盤 ＋ 剩下的塵氣

↓ 溫度上升、塵消氣散

年輕太陽 ＋ 盤狀物質



↓

塵埃 → 塵塊 → 小行星 → 行星

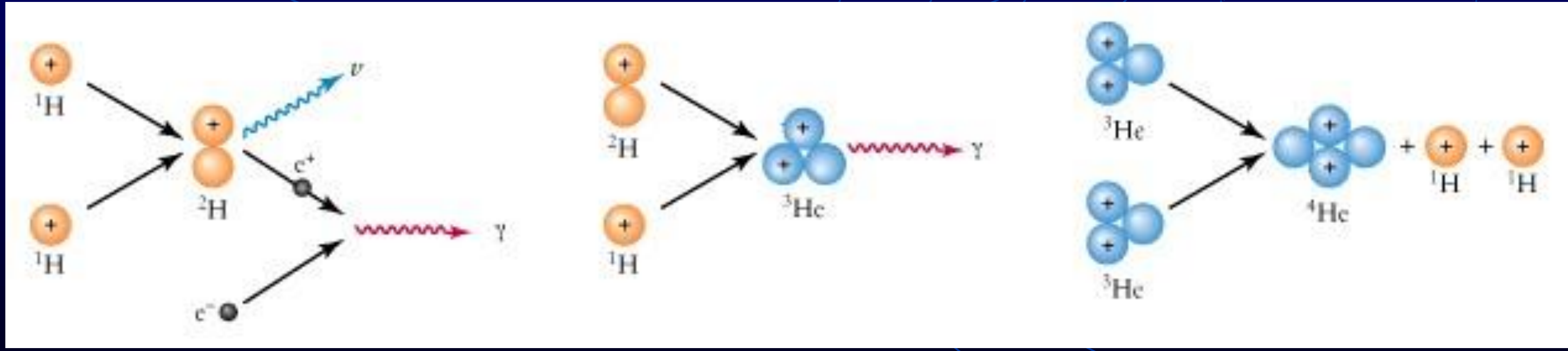
太陽（恆星）內部的核反應

簡單的原子核　　結合 → 較複雜的原子核

原子核強作用力把自己「抓得」比較緊

→ 放出能量（γ射線、X射線、光）

例如：（4個）氫原子核　→　（1個）氦原子核



這些能量讓氣體高速運動，彼此互推，產生（向外）高壓，抵抗（向內）萬有引力

怎麼樣會有核反應呢？

原子核帶正電，彼此排斥；越接近，靜電排斥力越強

但要是幾乎靠著了，原子核強作用力遠強於靜電力，而強作用是吸引力

→ 原子核互相吸引，放出能量（核子能）

那怎麼樣可以靠得很近呢？

太陽始於太空中一團收縮的雲氣，由於質量夠大，而持續收縮，費時3千萬年，終於溫度夠高，「點燃」氫元素的熱核反應

只有中央溫度夠高，產生的能量傳播到各部分，讓氣體高速運動，彼此碰撞的熱壓，平衡了向內的引力

熱融合不斷將氫原子核轉換成氦原子核 $E = \Delta mc^2$

太陽如此發光、發熱已經46億年，預計還可以存活50～70億年，直到中央不再有核反應

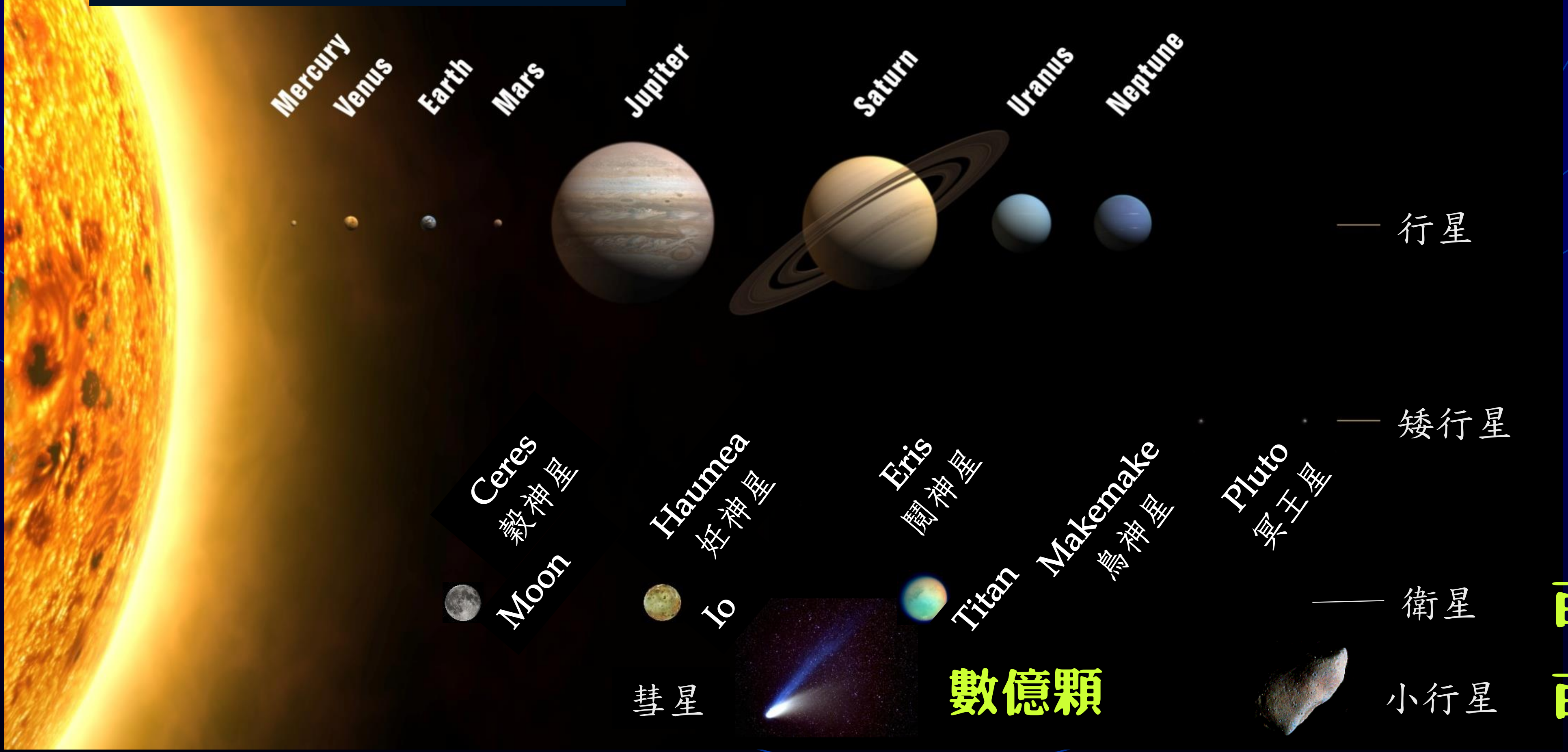
太陽系家族之「戶口名簿」

類地行星

靠內部的行星
（水、金、地、火）
體積小、岩石質

靠外部的行星
（木、土、天王、海王）
體積大、氣體、冰體

類木行星



八顆

五顆

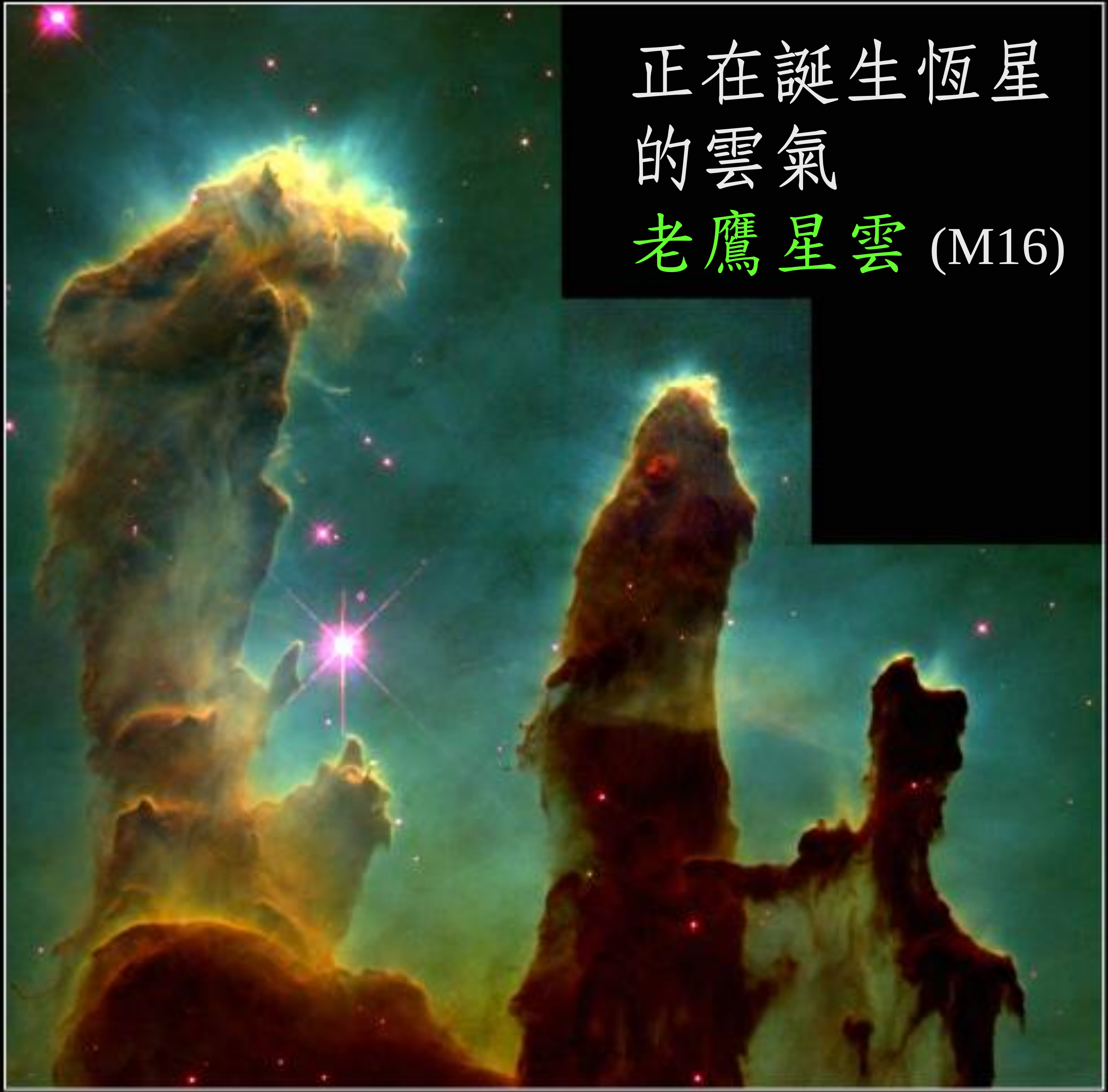
百來顆

數億顆

百萬顆

修改自IAU原圖

恆星風與輻射吹散周圍雲氣



正在誕生恆星的雲氣

老鷹星雲 (M16)

- 分子雲容易消散，成群誕生的恆星也跟著散開
- 維持重力束縛者（成員多、分布緊密、環境單純），成為目前看到的星團 star clusters
- 依照性質略分為疏散星團 **open cluster** 以及球狀星團 **globular cluster**
- 類似性質的恆星聚集在一起，稱為星協 (OB or T association; Reflection nebulae: R associations (e.g., Mon R2)
- 近期才瓦解的星團，成員星仍然分布在同樣區域，以相同的方式運動，稱為 **stellar associations** 或 **moving groups** (例如 Beta Pictoris MG, AB Doradus MG)
- 瓦解後的恆星成為場星，分布於銀河系各處

恆星成群形成

起初仍與雲氣共同存在而交互作用

太陽附近

大質量恆星形成區 massive star-forming regions

- *Orion OB Association* (350-400 pc)

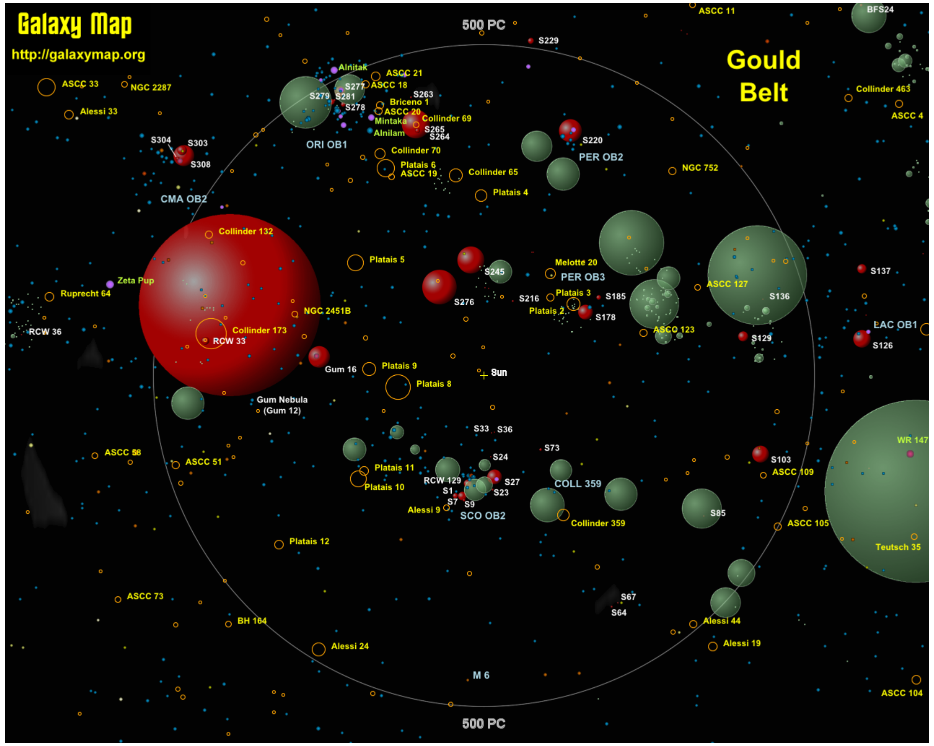
低質量恆星形成區 low-mass star-forming regions

- *Taurus Molecular Cloud (TMC-1)* (140 pc)
- *Rho Ophiuchi cloud* (130 pc)
- *Lupus* (140 pc)
- *Chamaeleon* (160 pc)
- *Corona Australis* (130 pc)

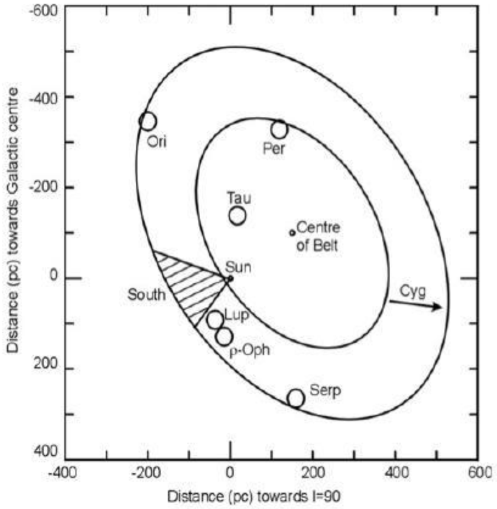
4/5 in the southern sky …
why?

The **Gould Belt**, a (partial) ring in the sky, ~1 kpc across, centered on a point 100 pc from the Sun and tilted about 20 deg to the Galactic plane, containing star-forming molecular clouds and OB stars (OMC, Sco-Cen OB, Cepheus OB2, Perseus OB2, TMC, parts of Serpens clouds) = local spiral arm

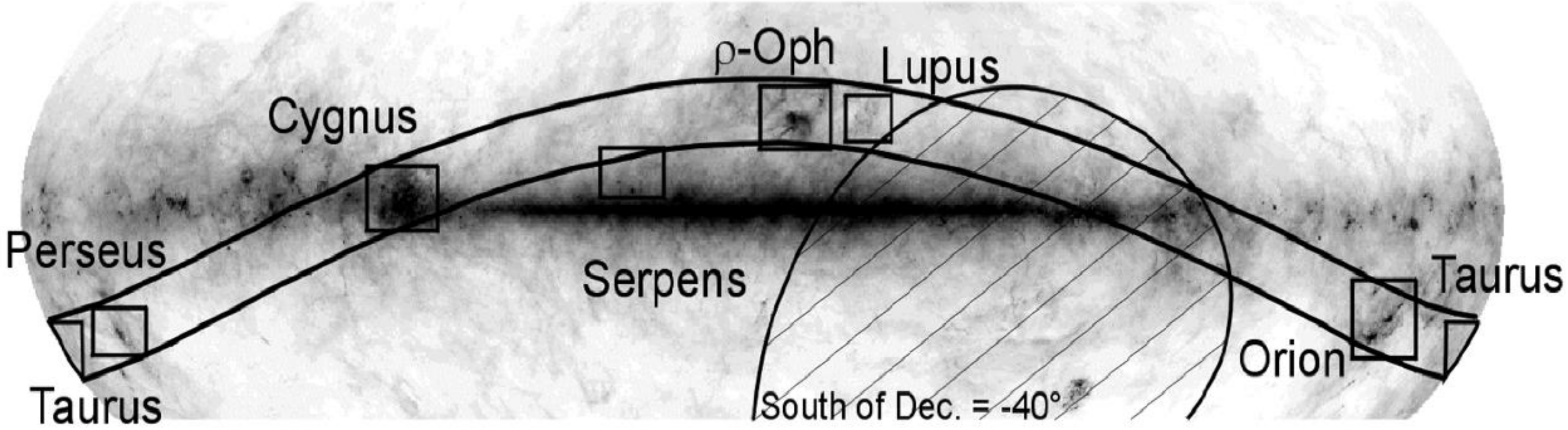
Origin unknown (dark matter induced star formation 30 Myrs ago?)



http://galaxymap.org/detail_maps/download_maps/gould.png

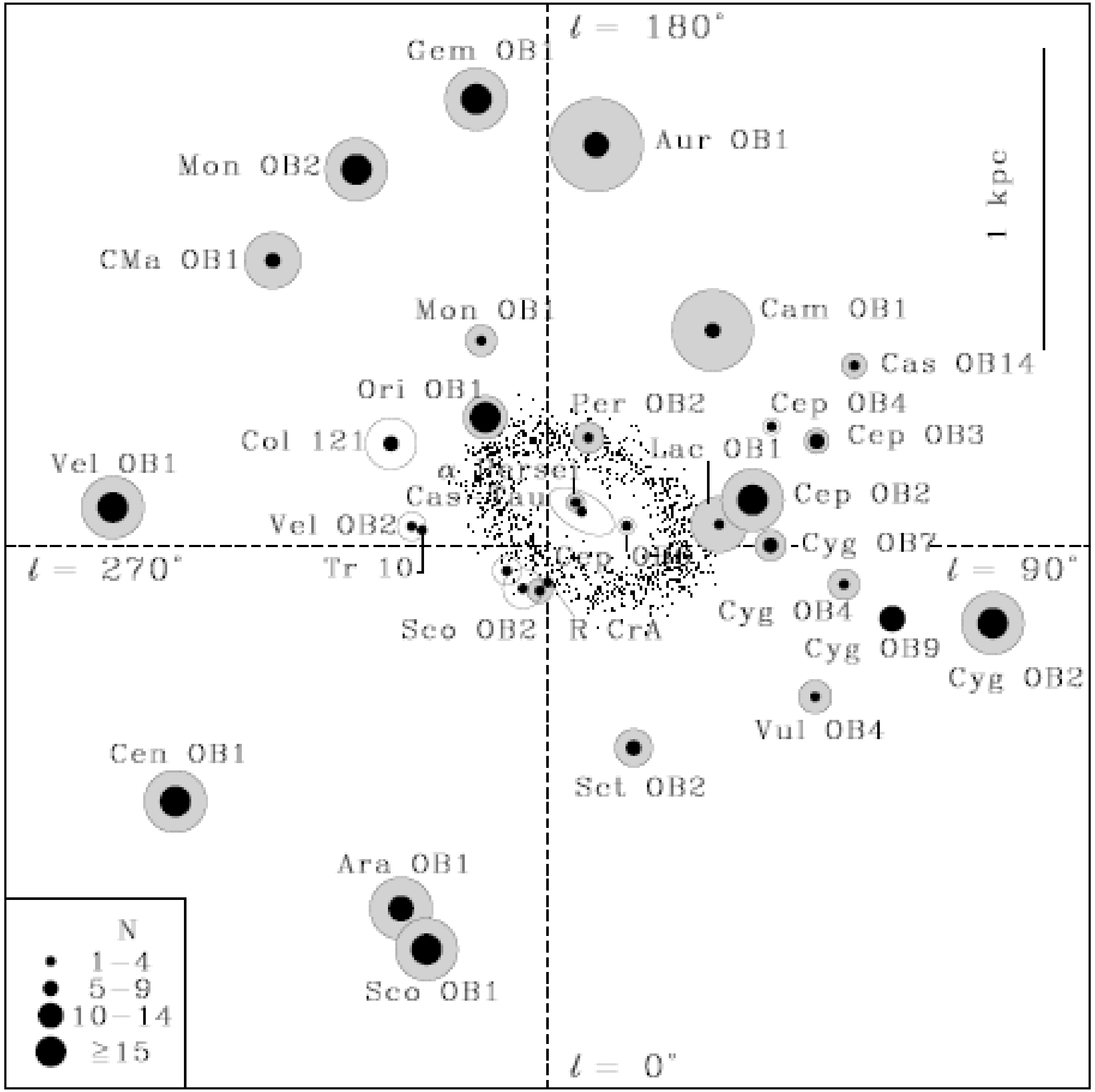


http://www.jach.hawaii.edu/JCMT/surveys/gb/



Gould's Belt superimposed on to an IRAS 100 micron emission map

Gould belt



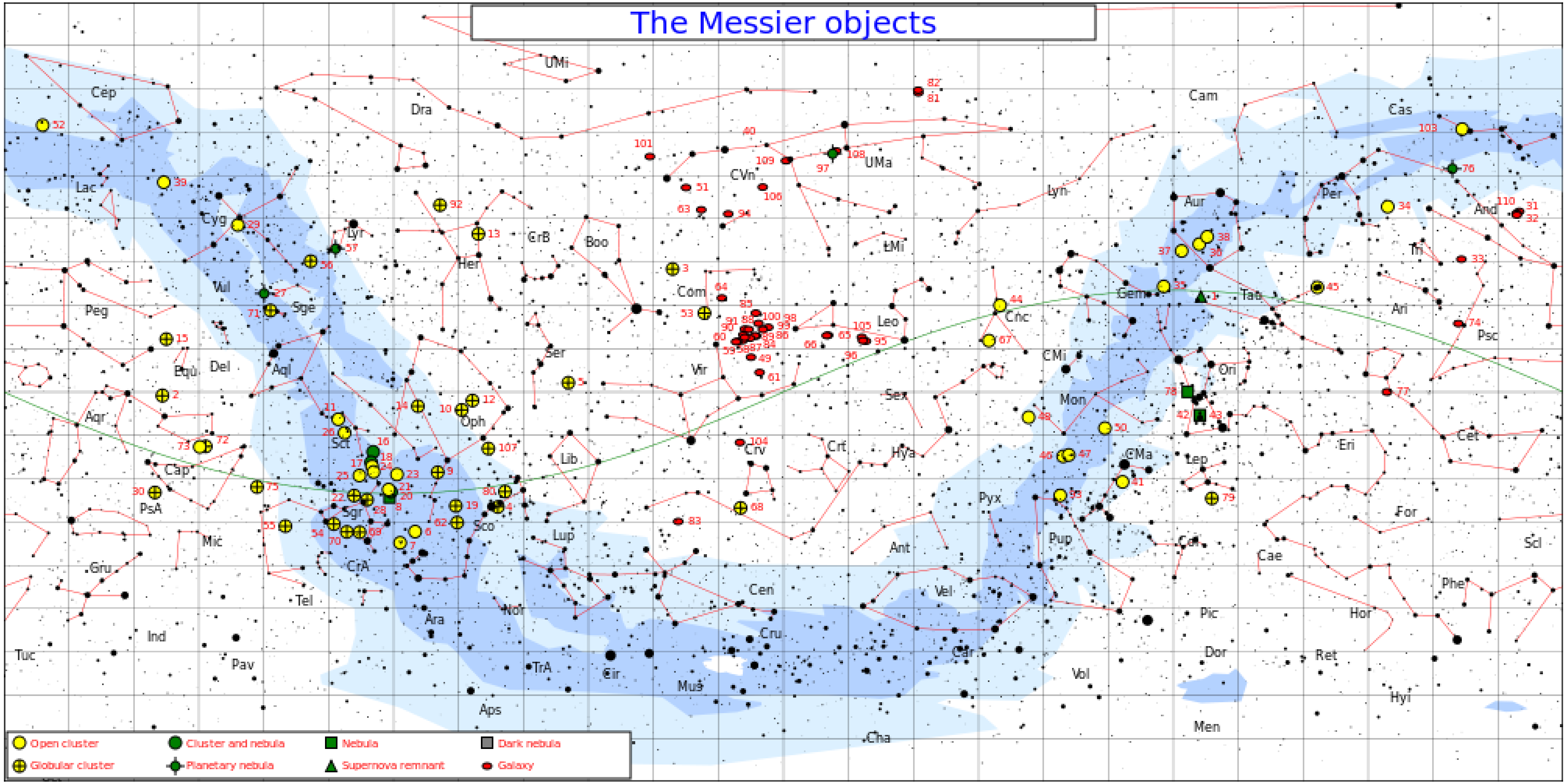
http://hera.ph1.uni-koeln.de/~heintzma/All/OB_stars.htm

Study of Star Clusters

- Historically one of the oldest subjects in astronomy, next to stars and planets, e.g., the Messier objects …
- Progress paused for a few decades because CCD sizes did not catch up
- Interest revived because of sky surveys and OIR wide-field imaging, and *Gaia* measurements
- Current Milky Way census: 3000+ open clusters,
100+ globular clusters
- Latest interests mainly in massive star clusters, dissolving/dissolved (extended clusters, moving groups), and extragalactic systems

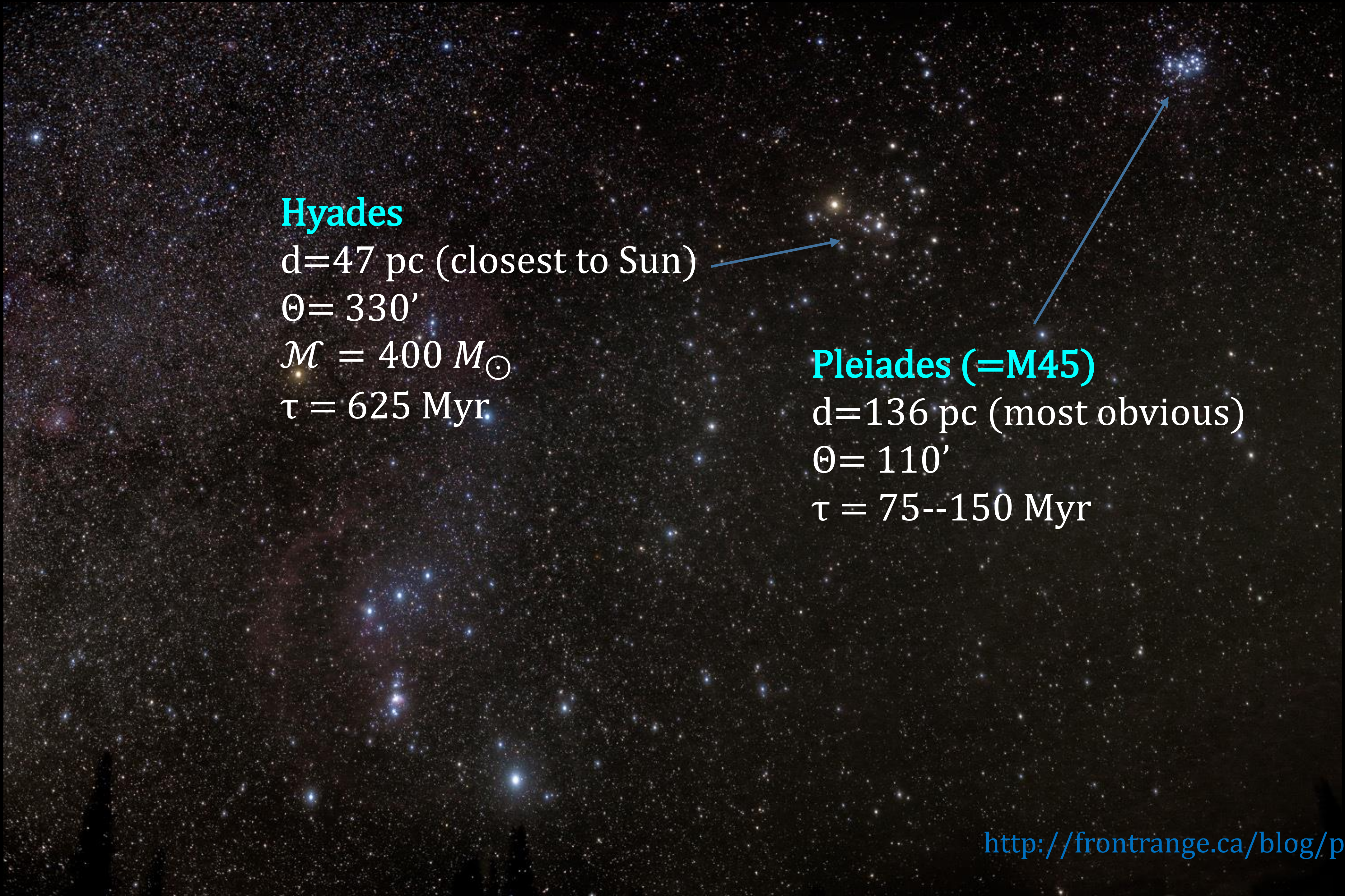
Star Clusters

- Long recognized by naked eyes in the night sky



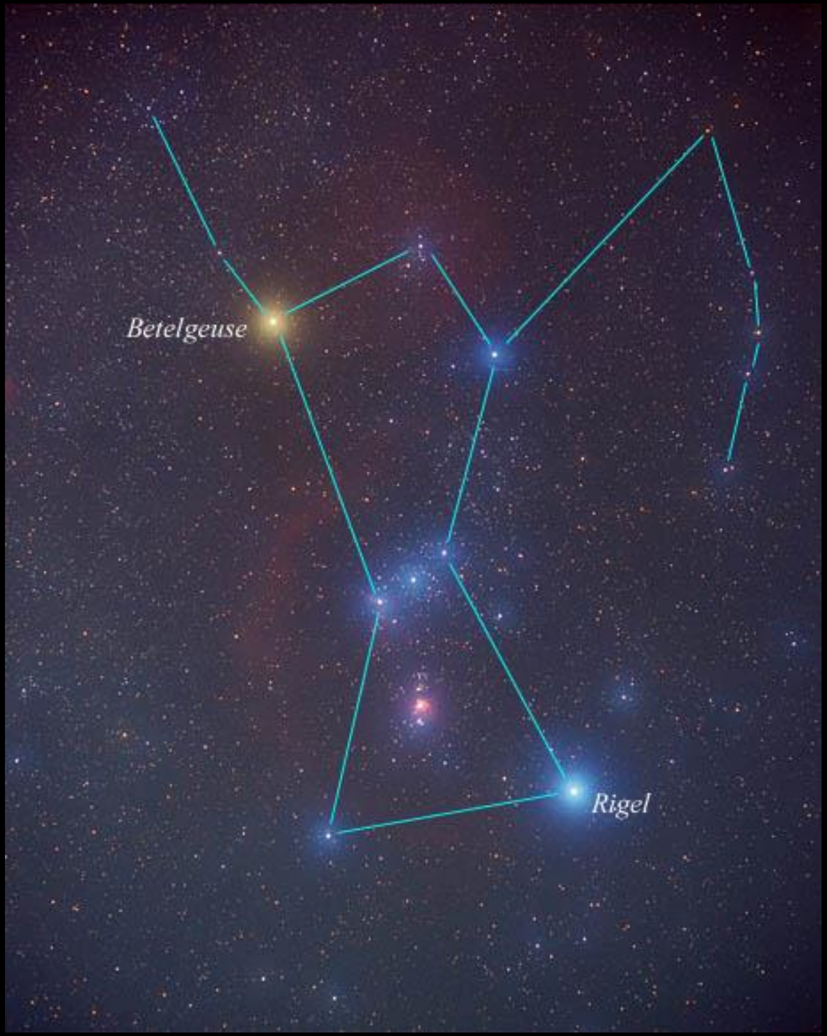
OCs: 26
GCs: 29

Messier "*Catalogue des Nébuleuses et des Ams e'Étoiles*" ("Catalogue of Nebulae and Star Clusters" (1771)

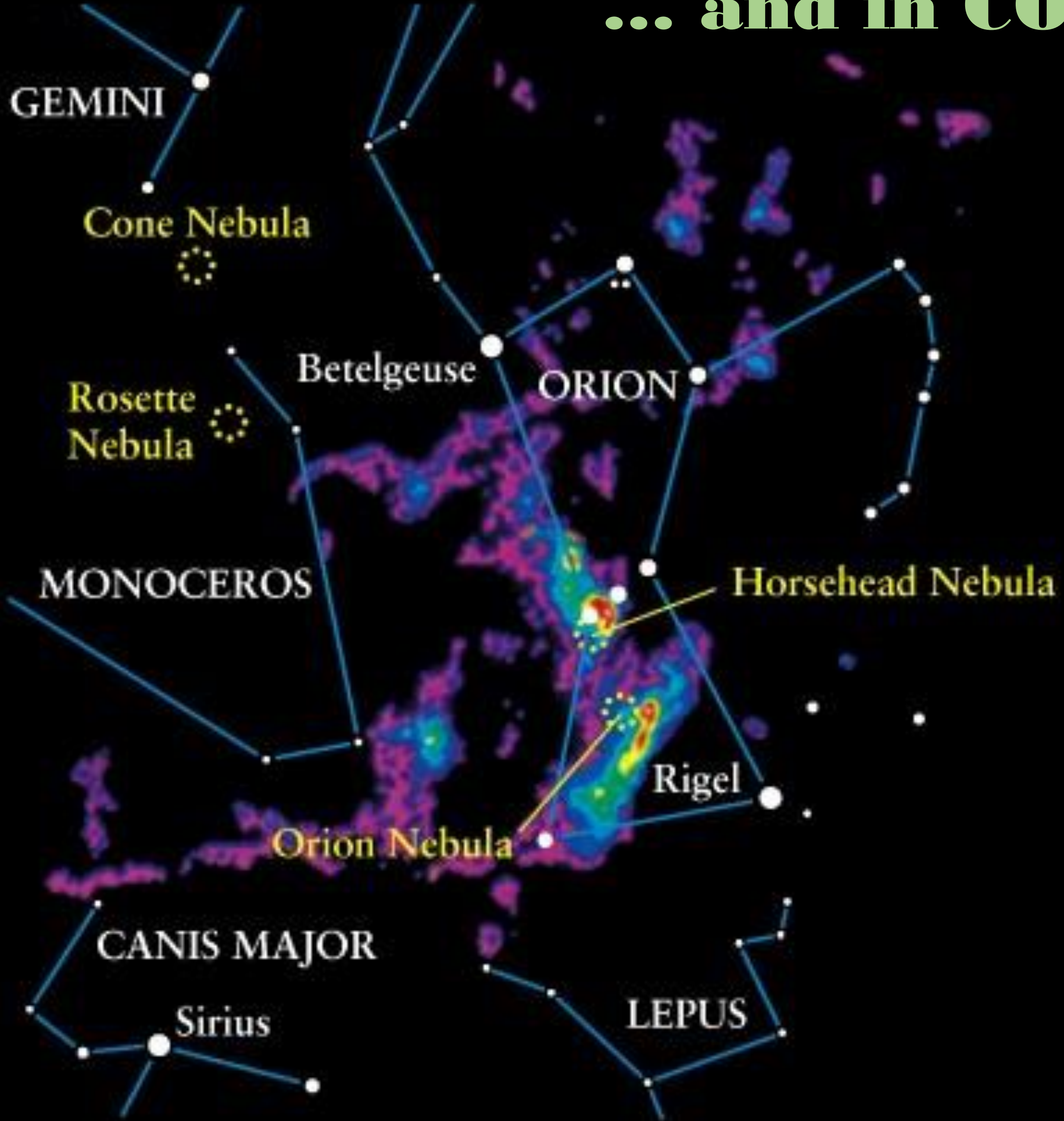

Hyades
d=47 pc (closest to Sun)
Θ= 330’
$\mathcal{M} = 400\ M_{\odot}$
τ = 625 Myr
Pleiades (=M45)
d=136 pc (most obvious)
Θ= 110’
τ = 75--150 Myr
http://frontrange.ca/blog/page/6/


Praesepe (=M44=Beehive)
d=177 pc
Θ= 95’
$\mathcal{M} = 500 - 600\ M_{\odot}$
$\tau = 600 - 700$ Myr

Orion in visible light



... and in CO



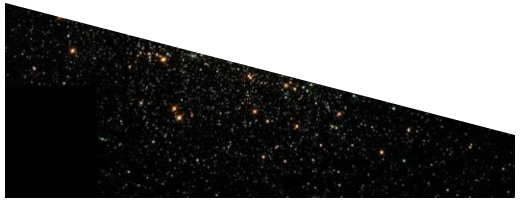
The division is not always clear. There are some clusters with properties of both kinds, and there are yet some falling in between.

Morph… there are two general kinds of star clusters

- Gala…
  - ✓Lo…
  - ✓10…
  - ✓Y…
  - ✓…

…2 m

- Globular…
  - ✓Spherically shaped, … concentrated
  - ✓10^4 to 10^6 members
  - ✓Old members; Pop II (“metal” poor)
  - ✓100s known; mostly in the halo , orbiting/concentrated toward the GC



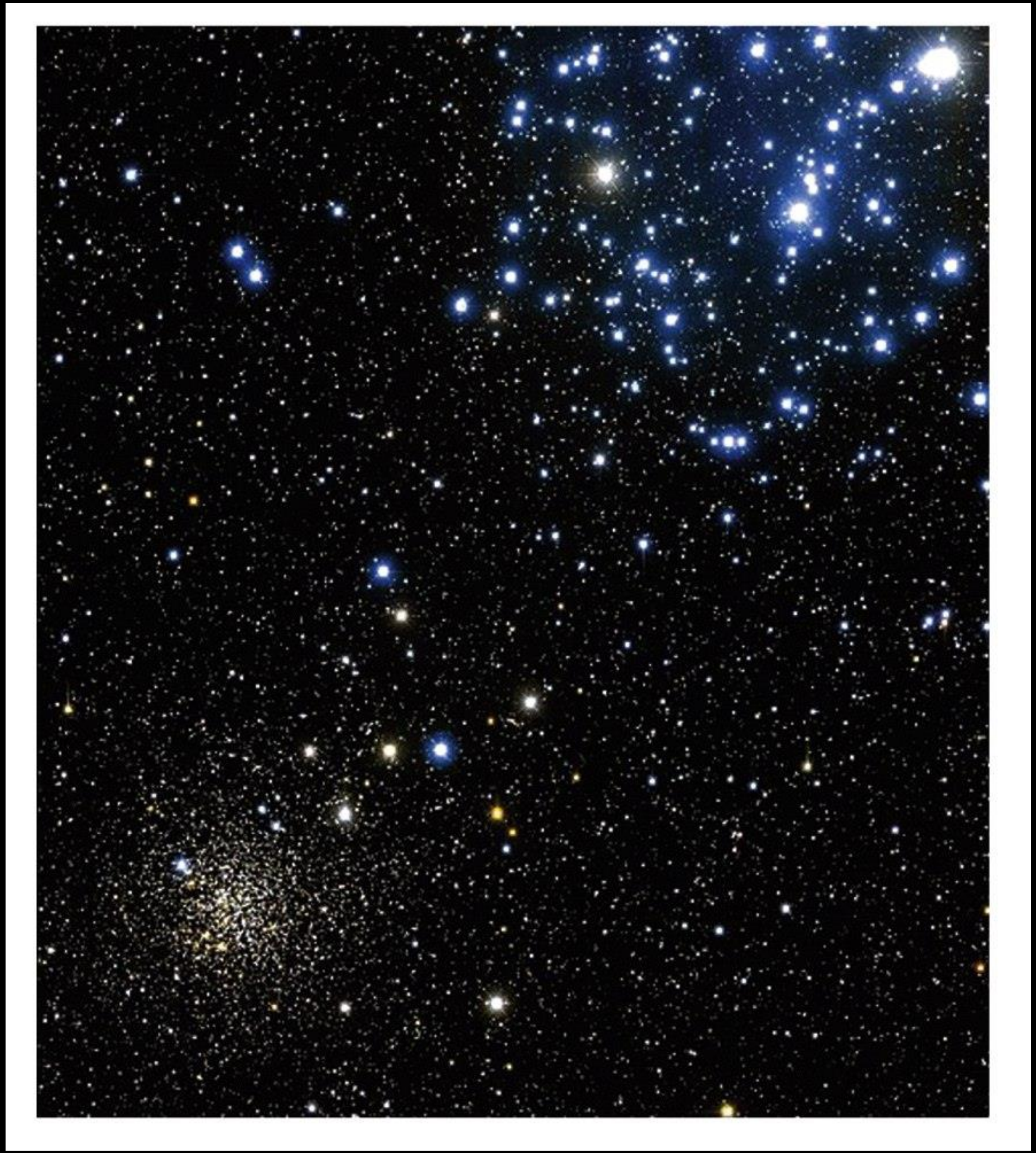
M80 HST

M31-G1 HST

M35

$d = 860$ pc

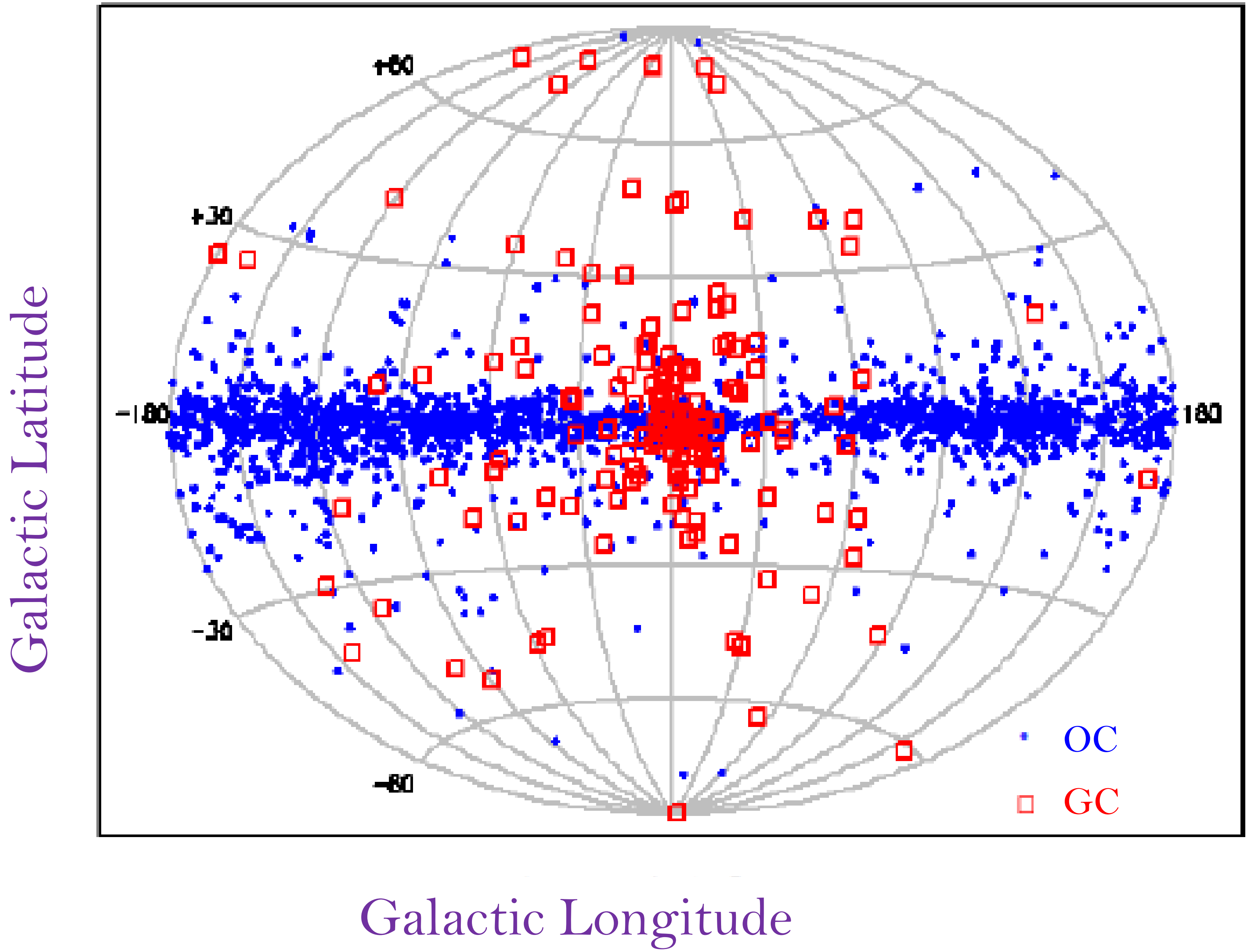
$\tau = 150$ Myr

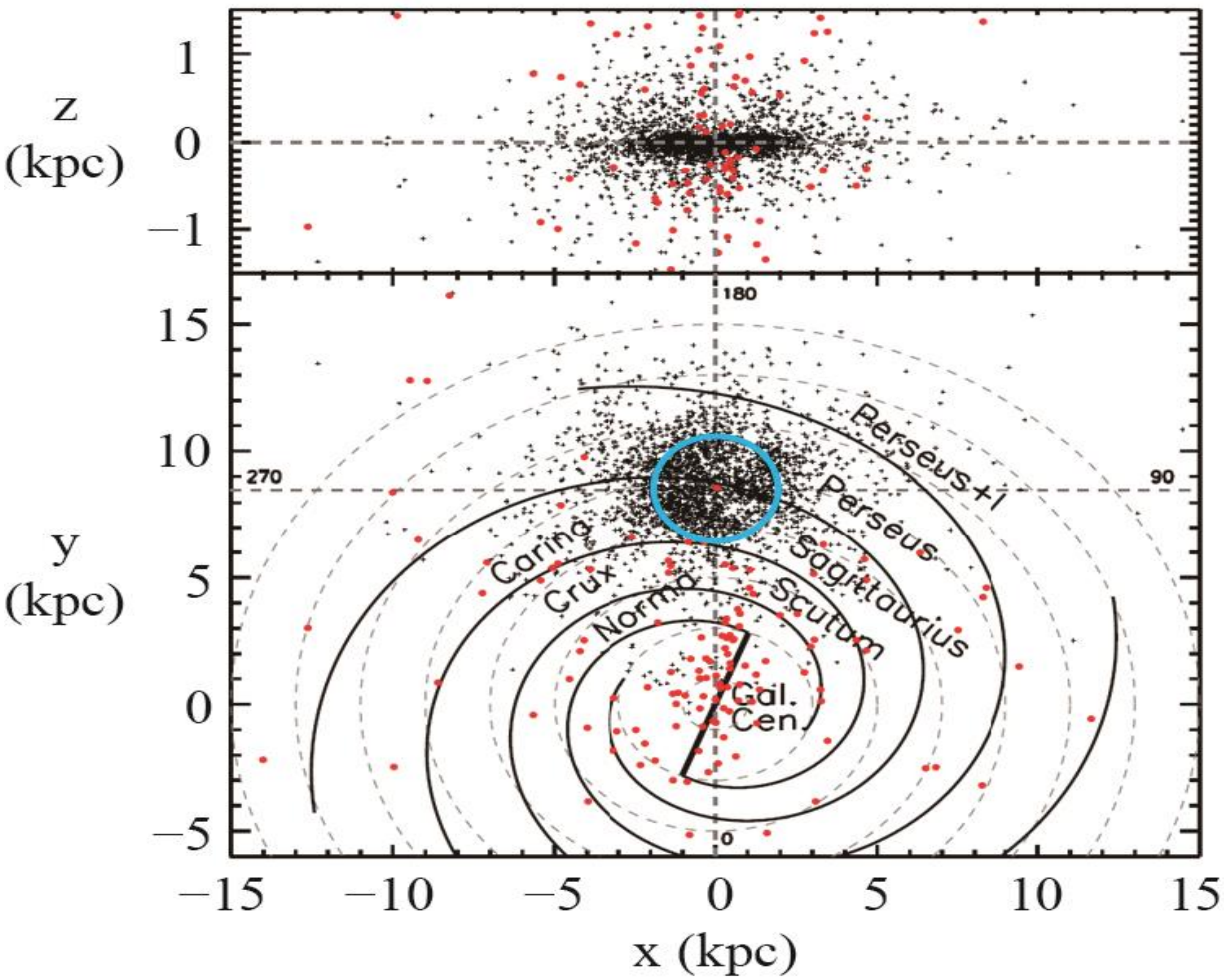


NGC 2158

$d = 5200$ pc

$\tau = 1.05$ Gyr


+60
+30
-180
180
-30
-60
OC
GC
Galactic Latitude
Galactic Longitude

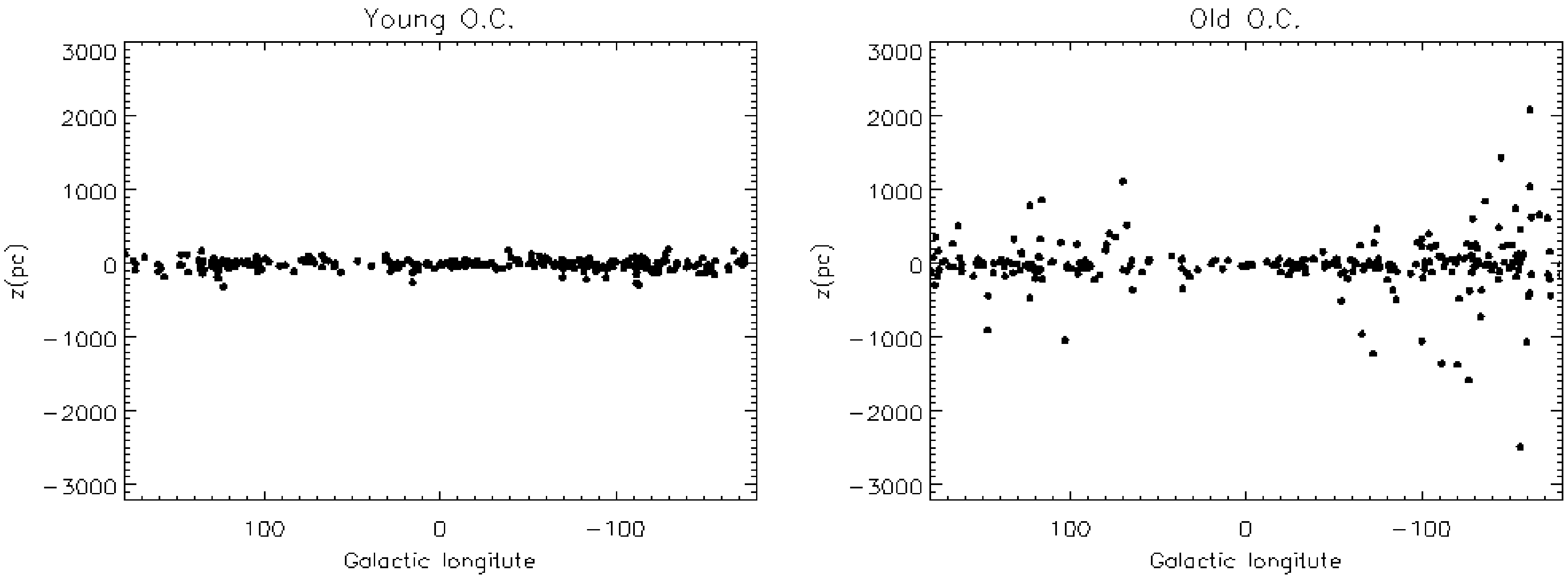


OCs preferentially on the disk plane

GCs preferentially away from the disk in the halo; centering around the Galactic center

Most known star clusters within 1-2 kpc (*why*?)

Spatial Distribution of Galactic Open Clusters



Young open clusters (< 100 Myr) are located near the Galactic plane. Older systems are more scattered above and below the plane.

Metallicity gradients

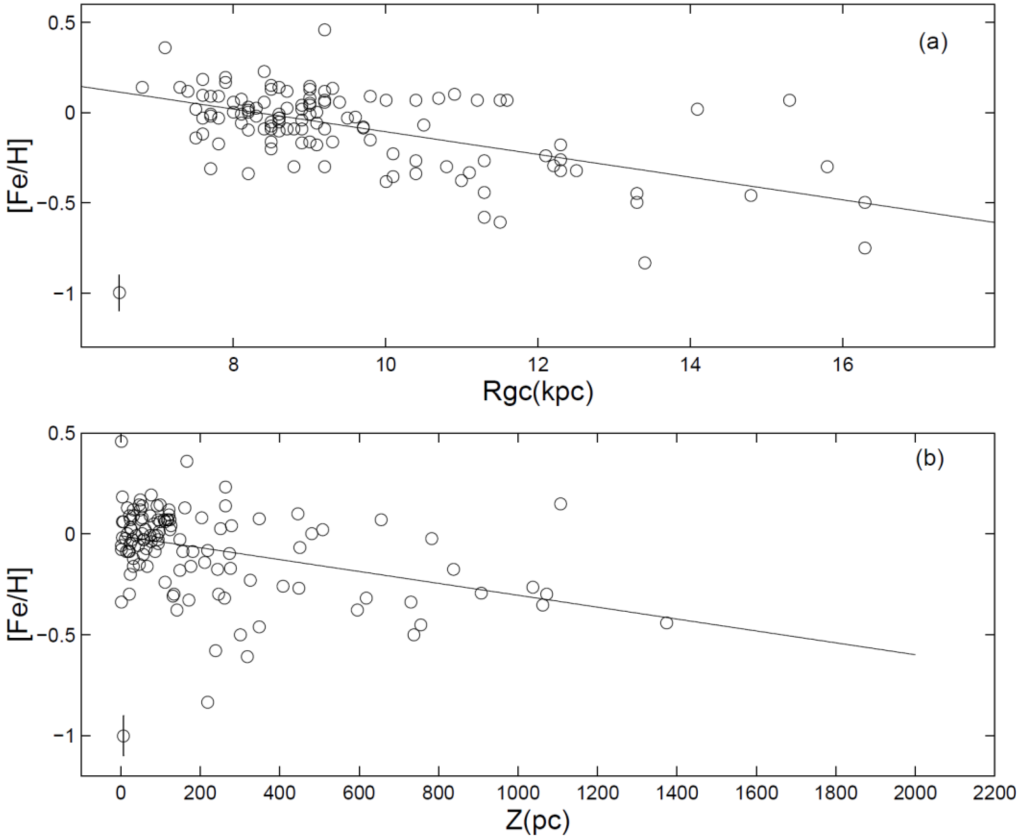


FIG. 8.—(*a*) Radial and (*b*) vertical abundance gradient for 118 open clusters. The least-square fitting results in a gradient of -0.063 ± 0.008 and -0.295 ± 0.050 dex kpc^{-1}, respectively. The typical error bar for [Fe/H] is about 0.1 dex, as shown in the lower left corner of the figures. In deriving the vertical gradient, the radial gradient has been corrected.

Age-Metallicity Relation

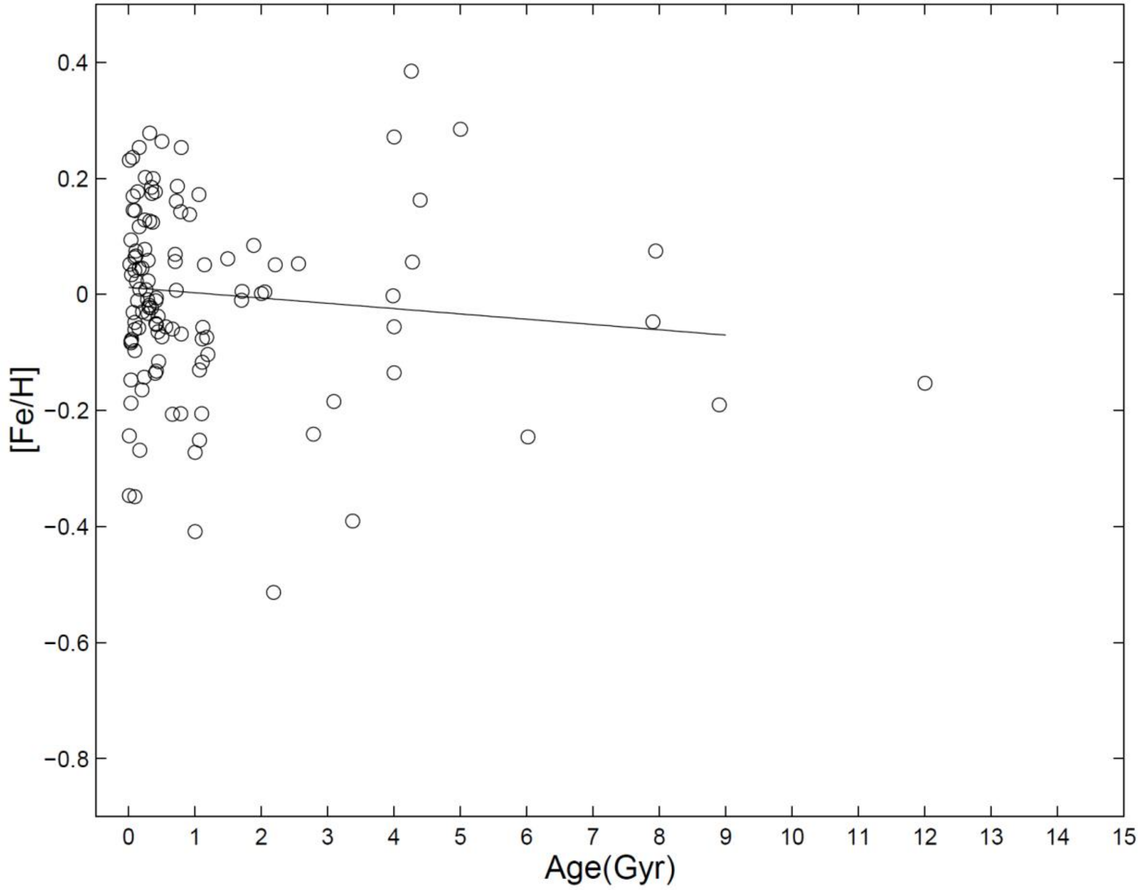
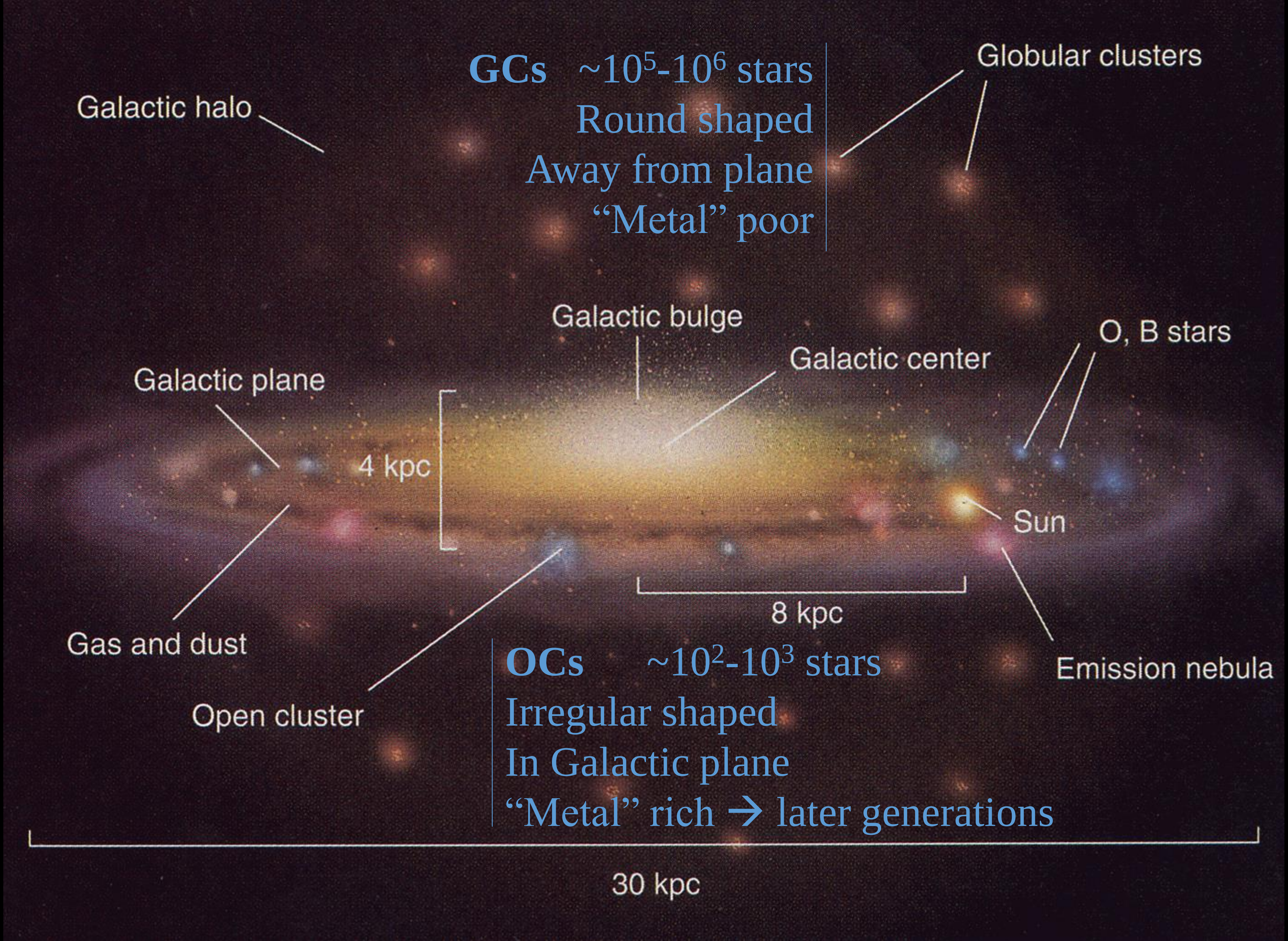


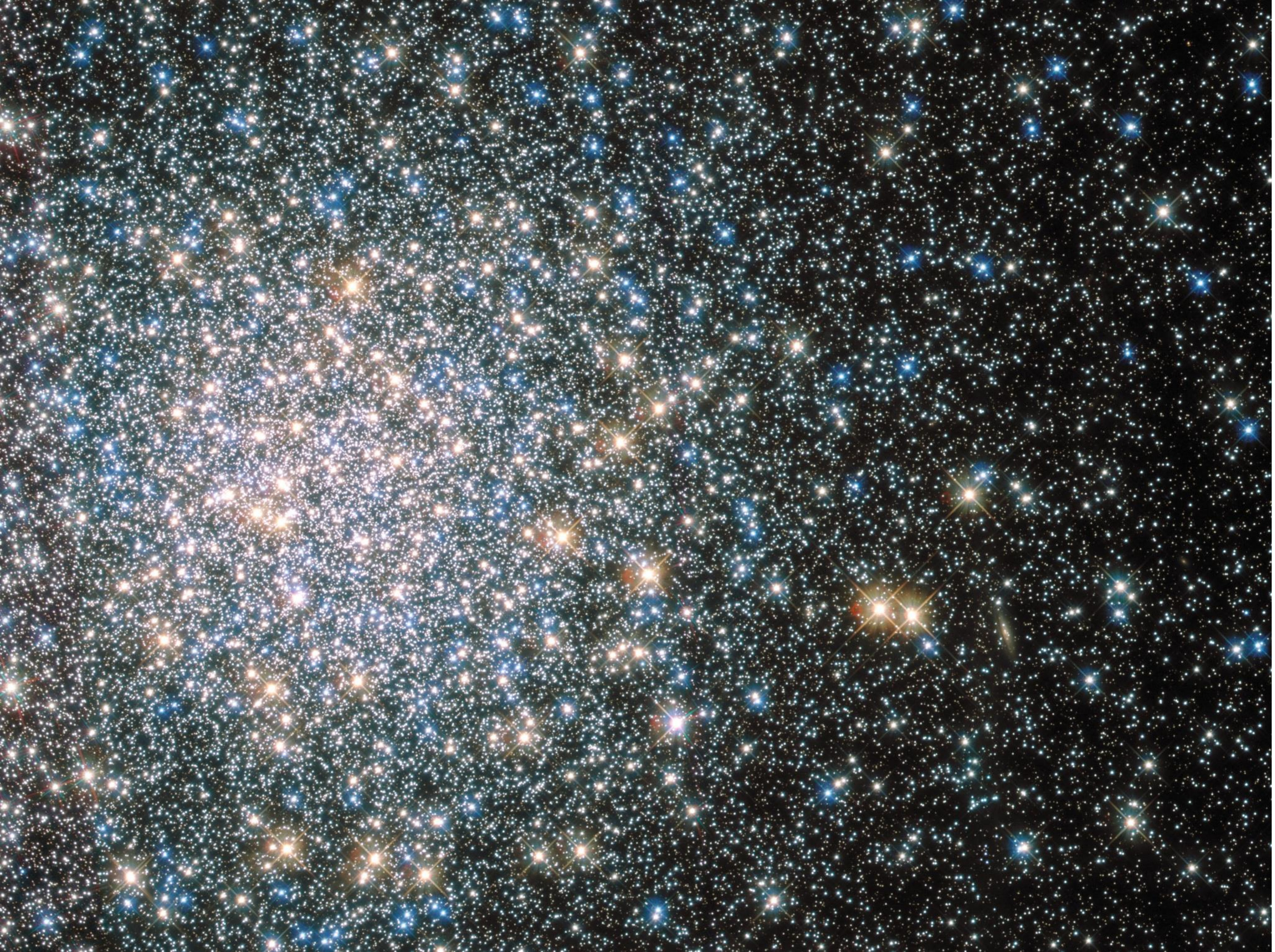
FIG. 10.—Age-metallicity relation (AMR) for the 118 open clusters after correcting for the radial gradient. The solid line is a least-square fit for the open cluster data.

Chen, L. + 2003



GCs ~10^5-10^6 stars
Round shaped
Away from plane
"Metal" poor

OCs ~10^2-10^3 stars
Irregular shaped
In Galactic plane
"Metal" rich → later generations



A globular cluster is very compact that even the *HST* cannot resolve individual stars near the core.

Messier 5 by HST
APOD 2014.04.25

Star Clusters
as
Targets of Investigation

How to determine the luminosity and surface temperature, chemical composition, etc., of a star? How to determine its distance and age of a star?

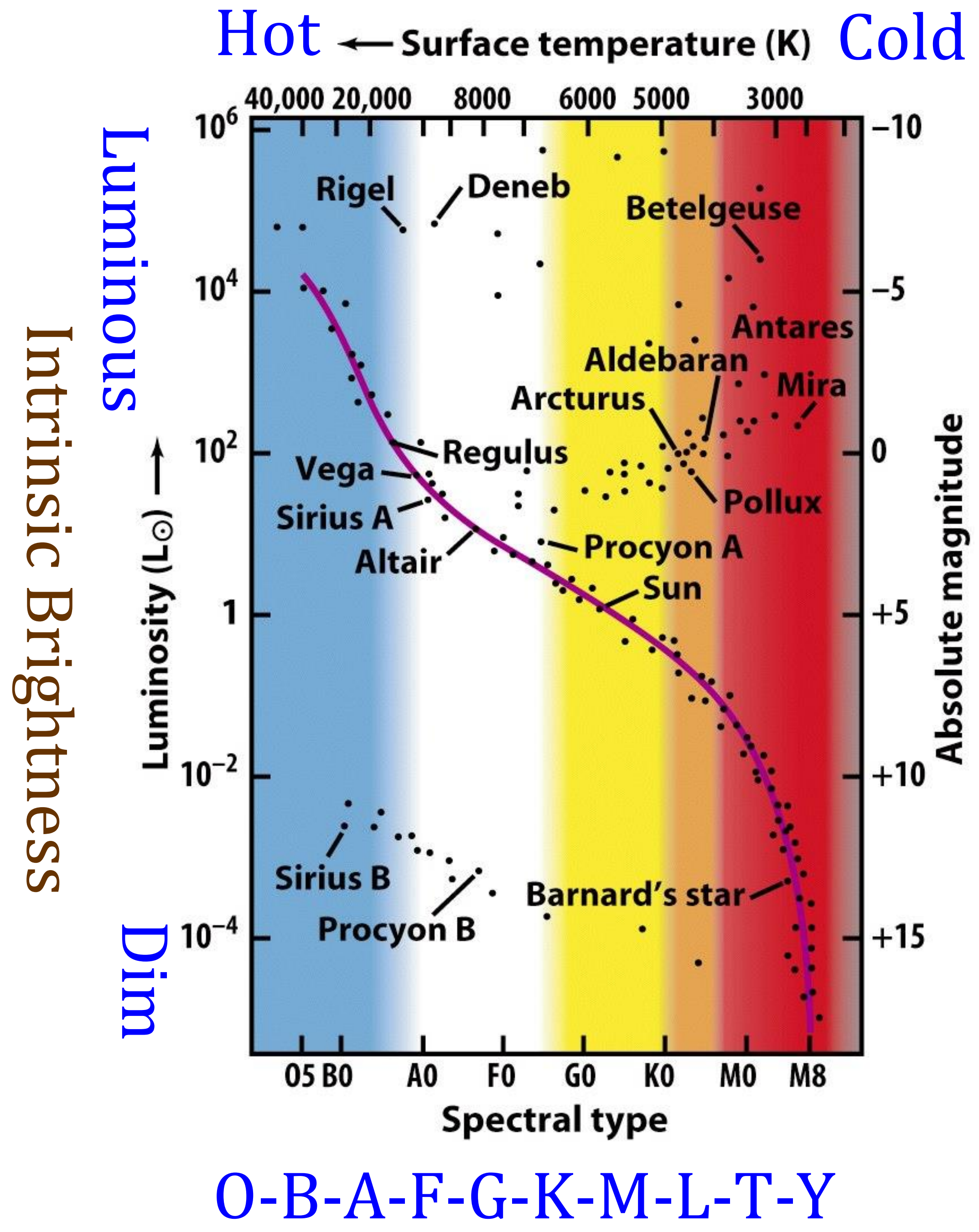
It is much easier if the star is a cluster member, because all the members were formed at the same time (coeval) out of the same molecular cloud, and at the same distance from us.

Stellar Properties in a Nutshell

A star generates energy by thermonuclear fusion reactions at its core → (outward) thermal pressure (gradient) to counteract (inward) gravitational pull

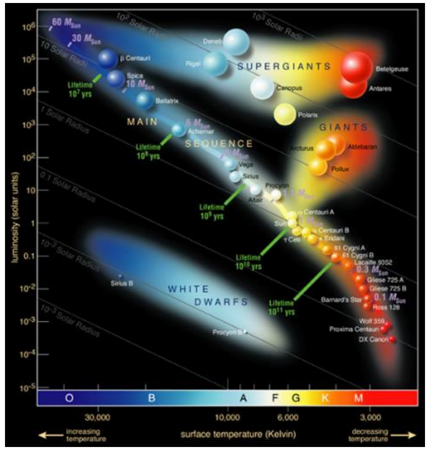
➔ **hydrostatic equilibrium** in every part of a star

Stars with stable supply of H as nuclear fuel → **main sequence stars** = normal stars



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

- $\mathcal{L}$: Stellar luminosity
- $4\,\pi\,\mathcal{R}^2$: Stellar surface area
- $\sigma\,T^4$: Blackbody radiation per unit area



$\uparrow \mathcal{L}$

$\leftarrow T$

$$\mathcal{L} \propto \mathcal{M}^{3.5\sim5.5}$$

Main-sequence stars

- ☐ core hydrogen fusion; a stellar mass sequence
- ☐ MS stars have similar radii.
- ☐ Massive stars → fusion rate ↑↑↑ at the core → luminous $\mathcal{L}$ ↑↑↑
  → large energy flux through stellar surface $4\,\pi\,\mathcal{R}^2$ → T↑

  Low-mass stars → moderate fusion rate → luminous $\mathcal{L}$ ↓
  → smaller flux through surface → T↓

→ A diagonal band in the **Hertzsprung-Russell (HR) diagram**

Stellar Evolution in a Nutshell

$\tau \propto \mathcal{M}/\mathcal{L} \propto \mathcal{M}^{-2.5}$

- Massive MS stars → fusion rate ↑↑↑ → luminous $\mathcal{L}$ ↑↑↑
  → nuclear fuel (H) used up rapidly → lifetime τ ↓↓

  Low-mass MS stars → moderate fusion rate → luminous $\mathcal{L}$ ↓
  → fuel used up slowly → τ ↑
- When central hydrogen exhausted (~10% for the Sun)
  → core contracts until being stopped
  - ✓ by next rounds of fusion

    Nuclear waste (e.g., He) → nuclear fuel
  - by electron degenerate pressure (a white dwarf)
  - by neutron degenerate pressure (a neutron star)
  - by spacetime singularity (a black hole)
- Disruptive/explosive ending → complex nuclei to ISM

Member stars in a star cluster are formed out of the same molecular cloud, so should have the same age, same chemical abundances, and at the same distance from us.

But …

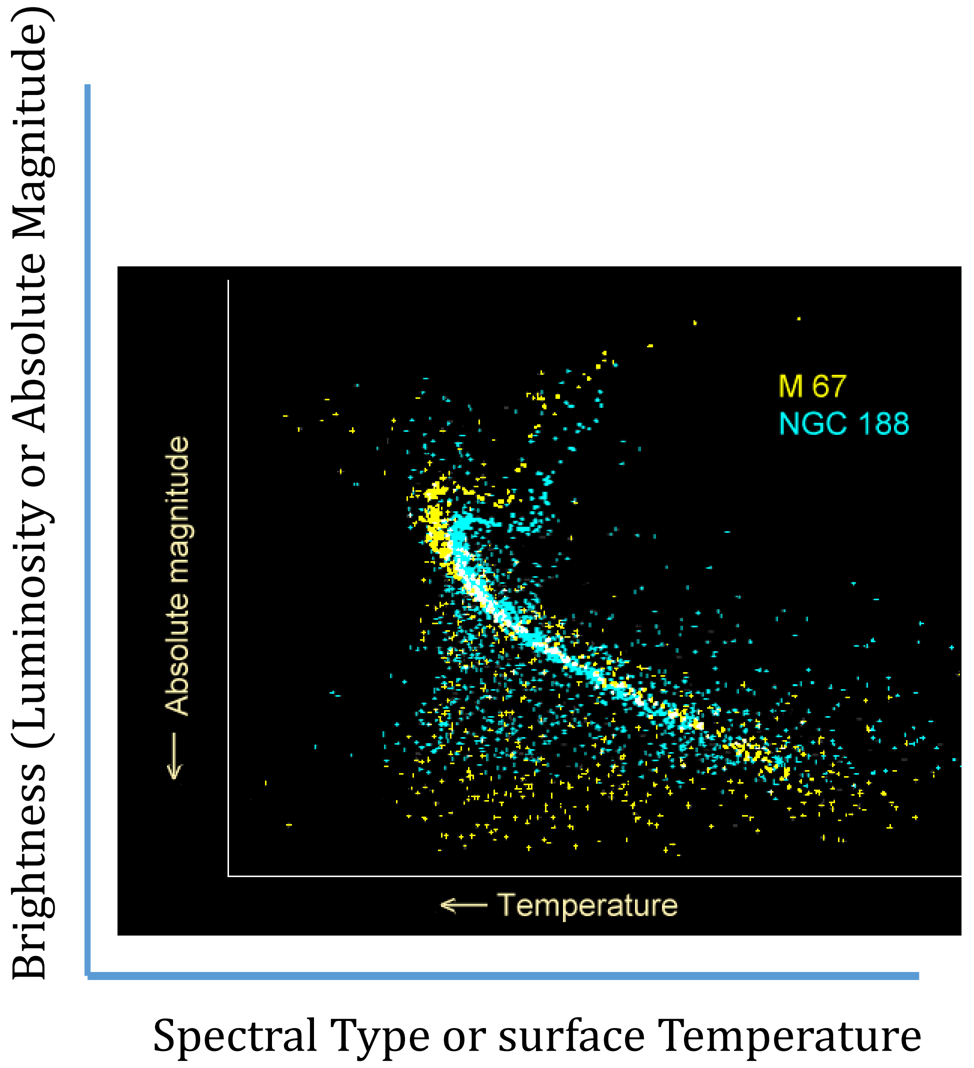
What if there is significant time lapse in star formation?
→ different ages

For nearby systems, the depth may no longer be negligible
→ different distances

What if member stars are not from the same cloud?
→ different abundances

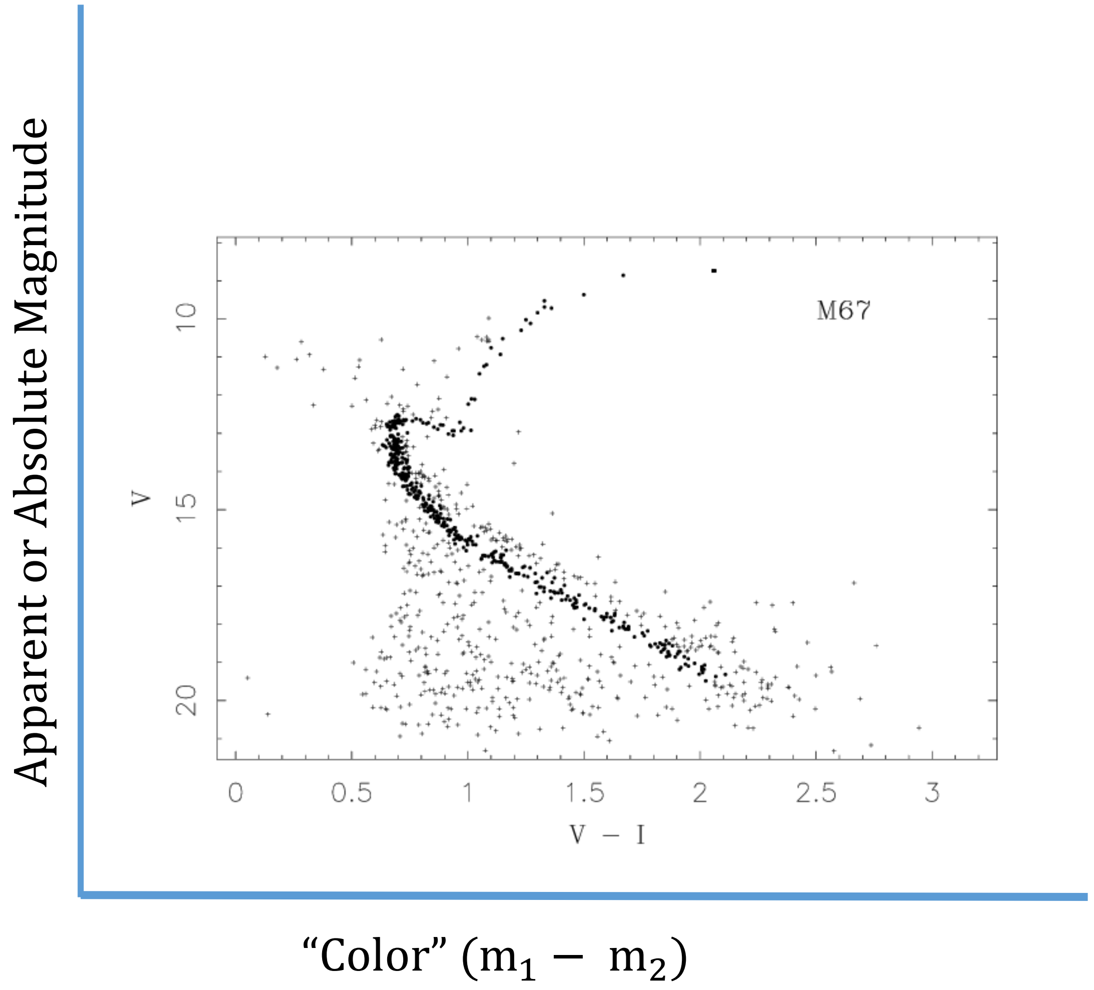
Hertzsprung-Russell Diagram

(physical)



Color-Magnitude Diagram (CMD)

(observational, a proxy of the HRD)



To Determine the Distance of a cluster

Main Sequence Fitting

$$m_\lambda - M_\lambda = 5 \log d_{\rm pc} - 5 + A_\lambda$$

$$(m_{\lambda 1} - m_{\lambda 2}) = (M_{\lambda 1} - M_{\lambda 2}) + E(\lambda 1 - \lambda 2)$$

$$E(\lambda 1 - \lambda 2) \equiv A_{\lambda 1} - A_{\lambda 2}$$

ISM (dust) reddening

More distant → fainter and redder

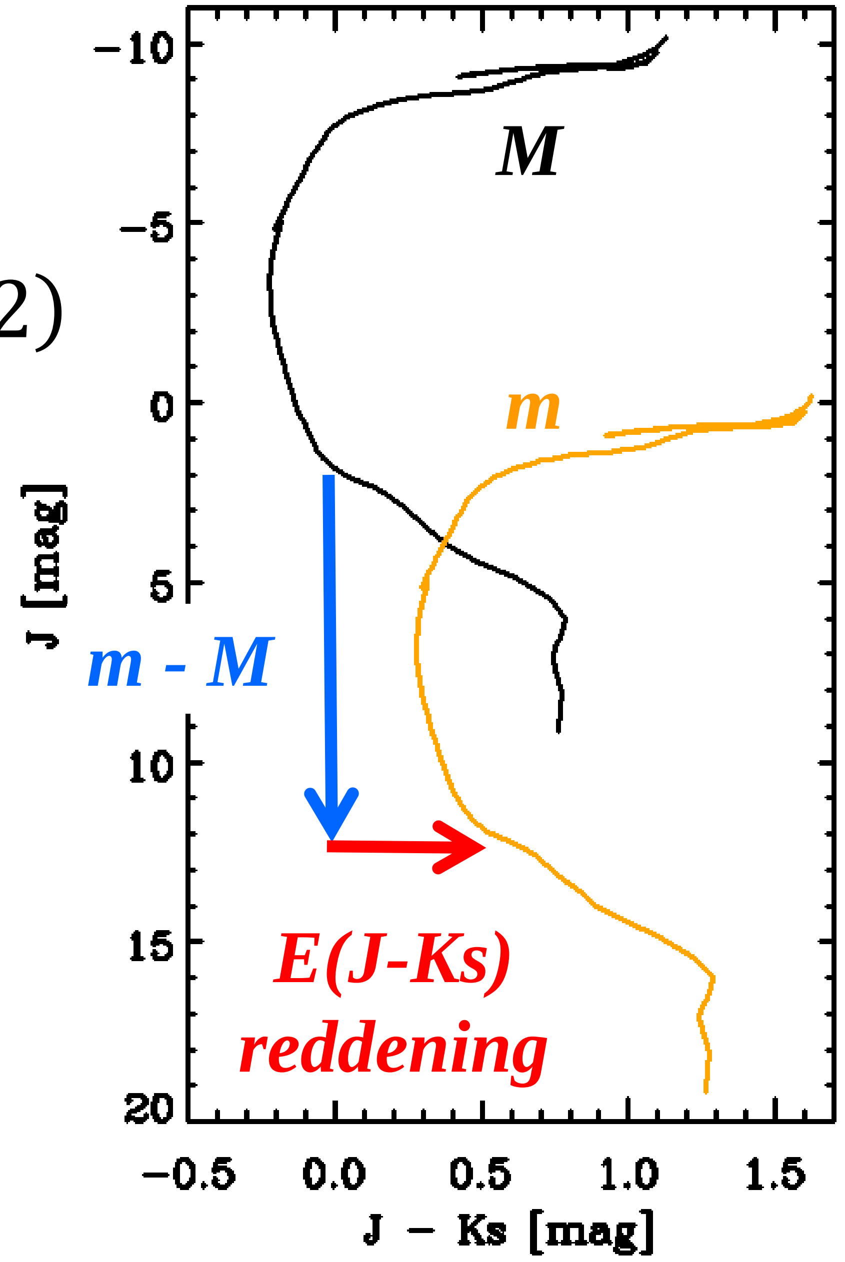
ISM "**Reddening law**" (Rieke & Lebofsky 1985)

$$A_B = 1.324\, A_V$$

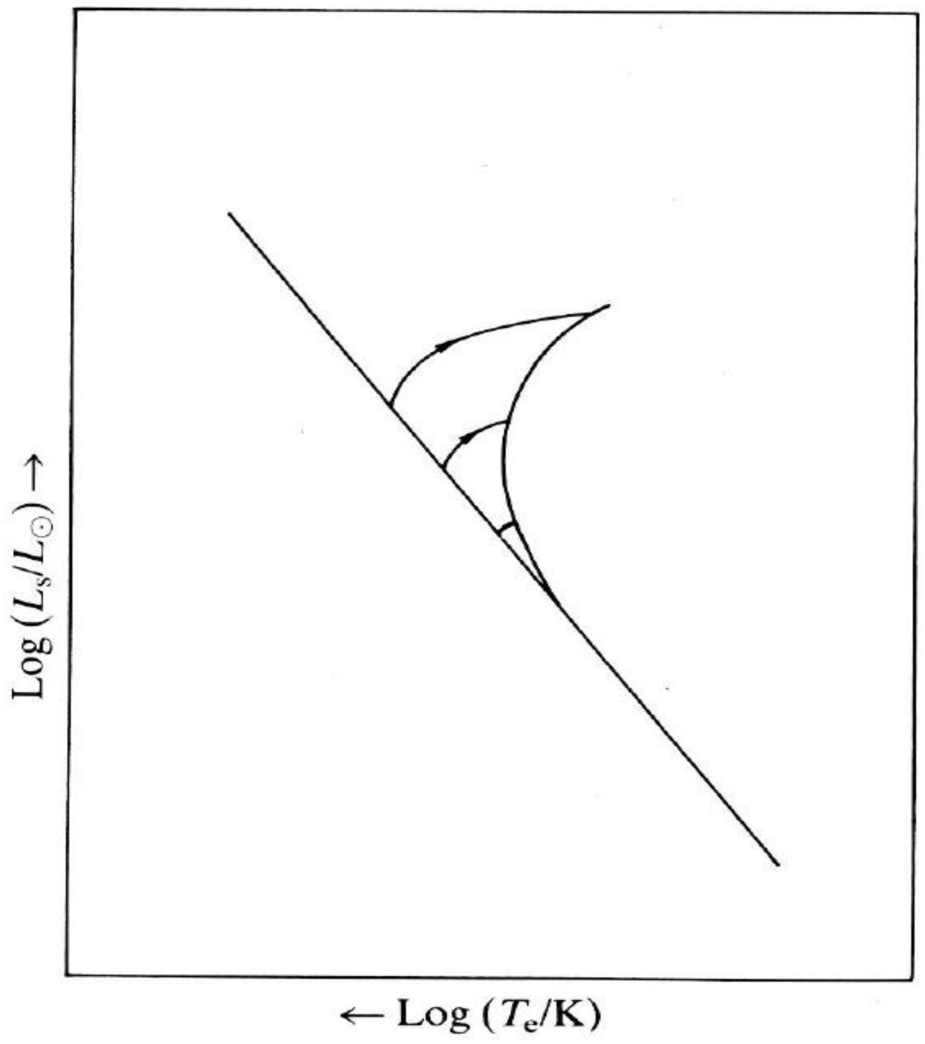
$$A_J = 0.282\, A_V$$

$$A_K = 0.112\, A_V$$

$$R \equiv A_V / E(B-V) \approx 3.1$$



To Determine the Age of a Star Cluster

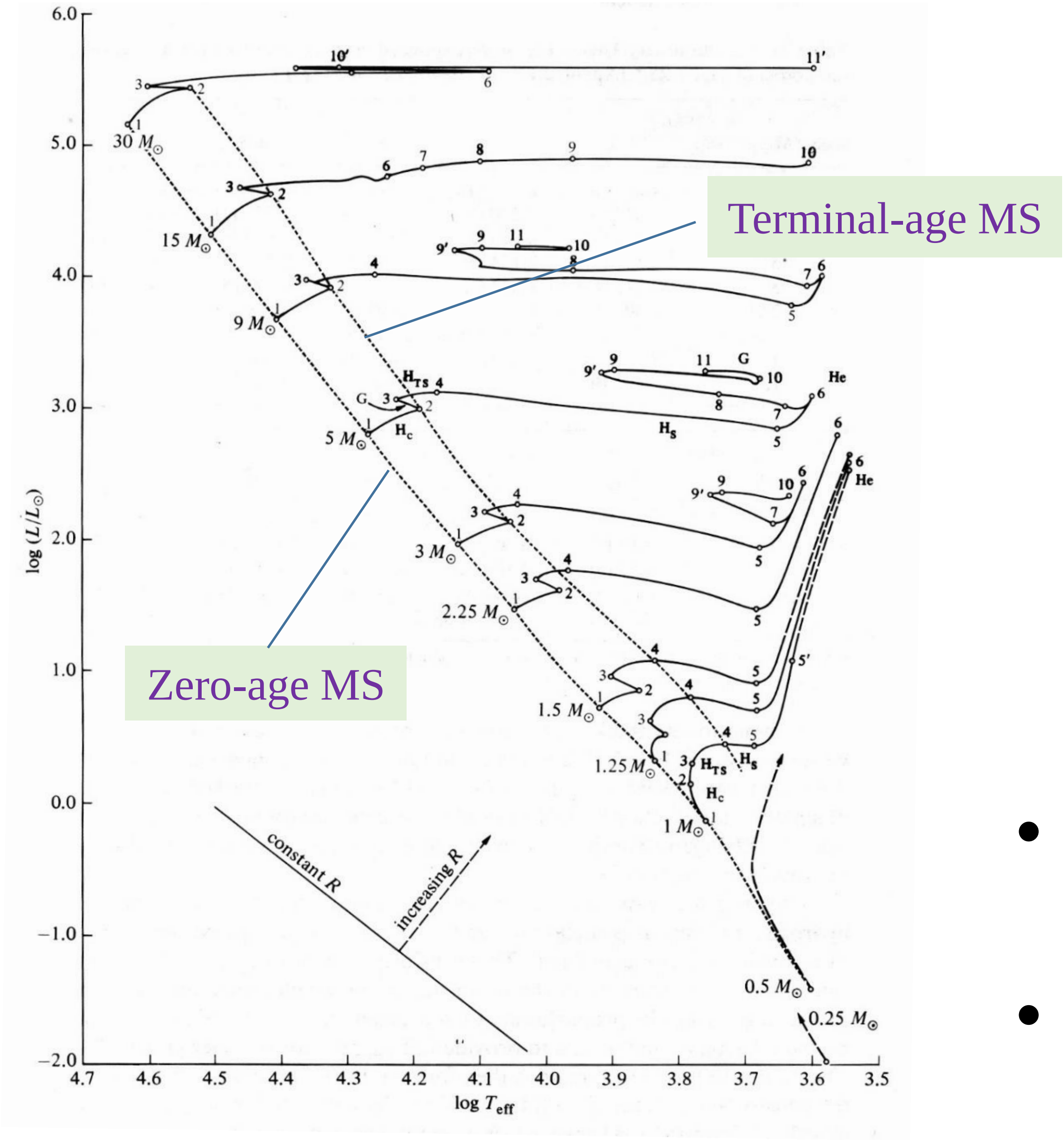


As a cluster (its member stars) ages, massive stars leave the MS first and evolve to the post-main sequence phase, then progressively followed by lower-mass members.

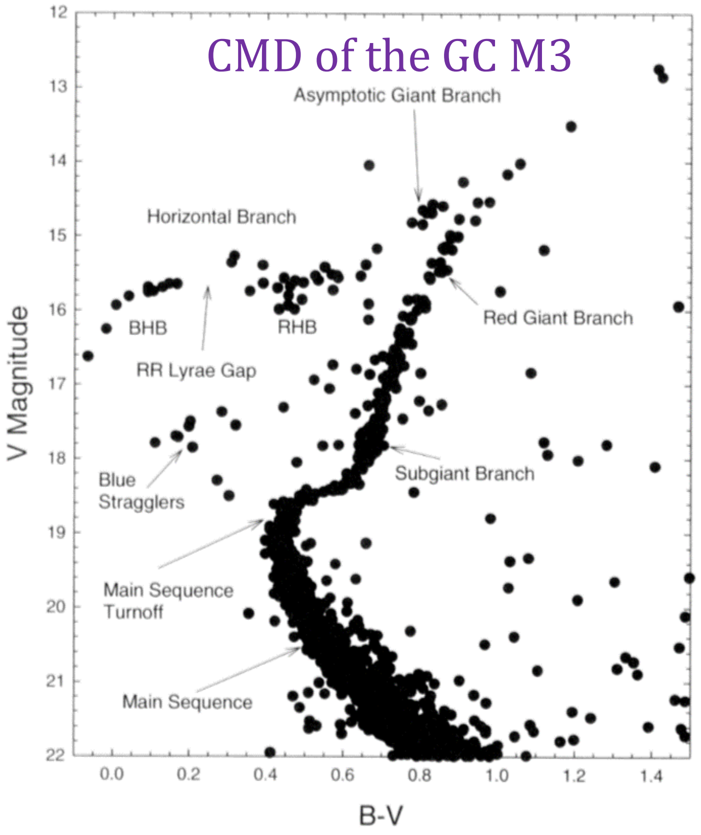
The MS is "peeled off" from the top (upper MS) down.

Only the low-mass stars remain on the MS.

Evolution of individual stars of different masses

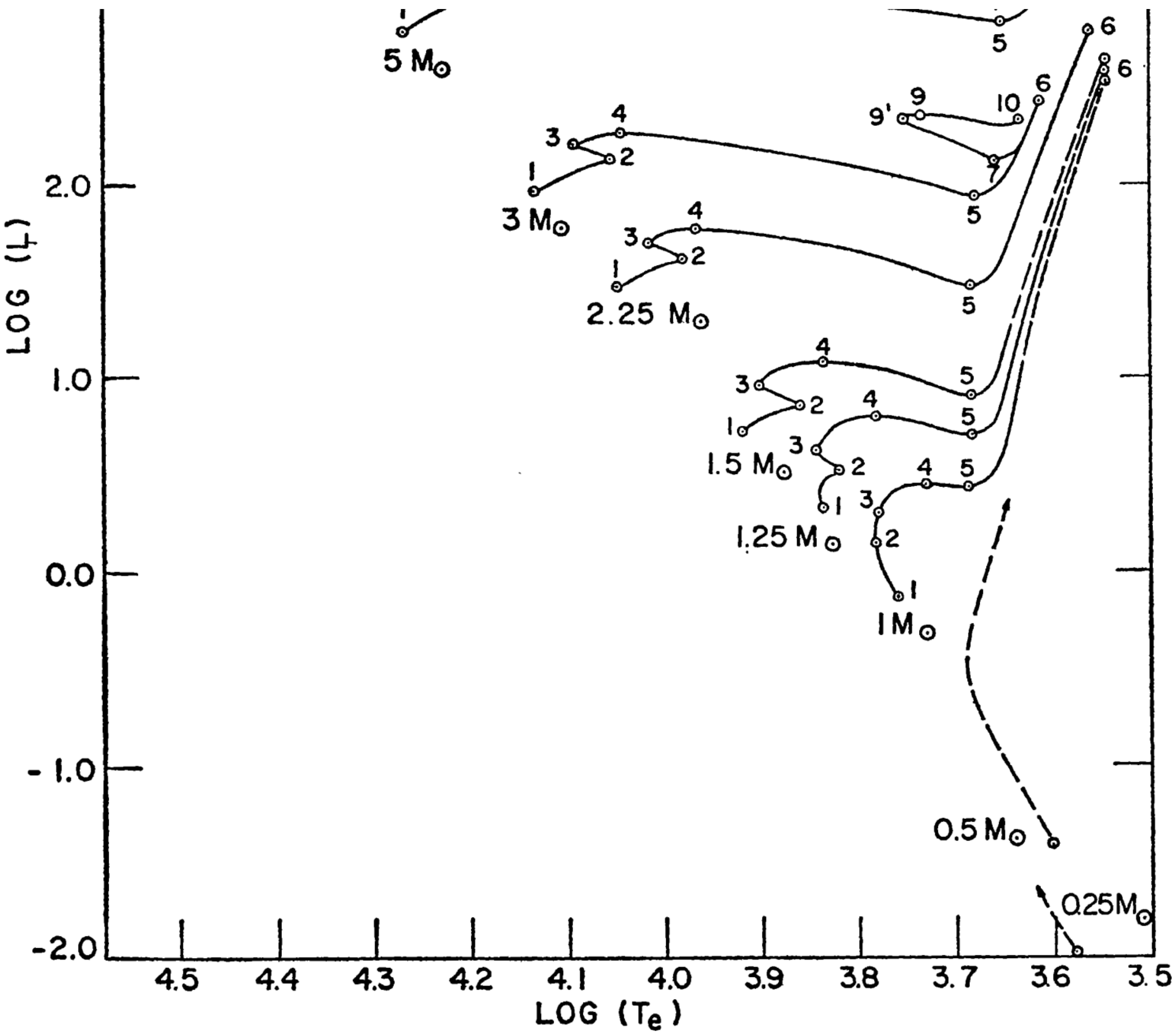


A collection of stars at different evolutionary stages

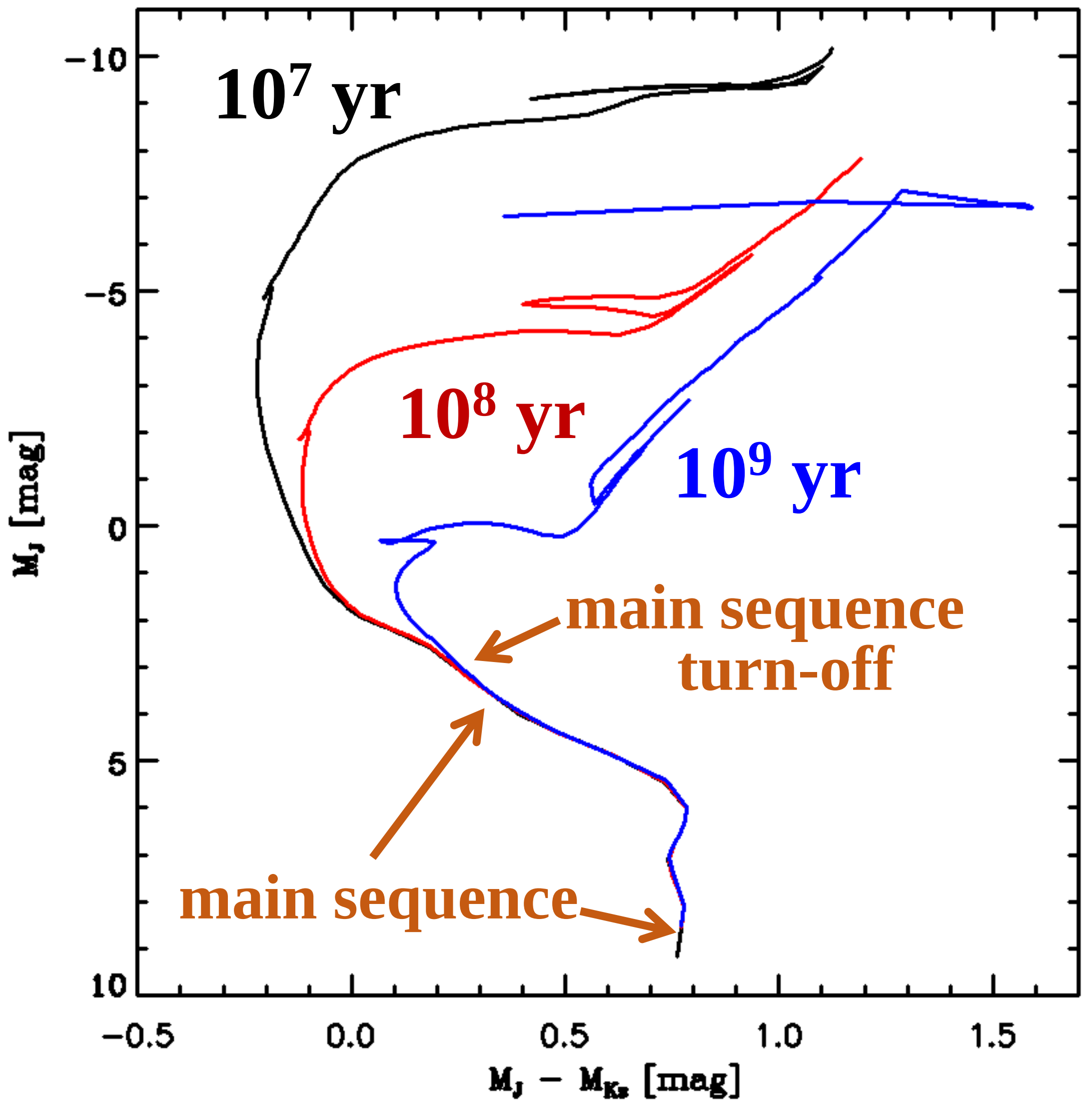


- Snapshot of different stellar masses at this age
- Star clusters at different ages → theory of stellar evolution

1-2 main sequence
2-3 overall contraction
3-4 H <u>thick</u> shell burning
5-6 H <u>thin</u> shell burning
6-7 red giant
7-10 core He burning
8-9 envelope contraction



Theoretical isochrones



Assumptions:

✓coeval star formation

✓same metallicity

✓same distance

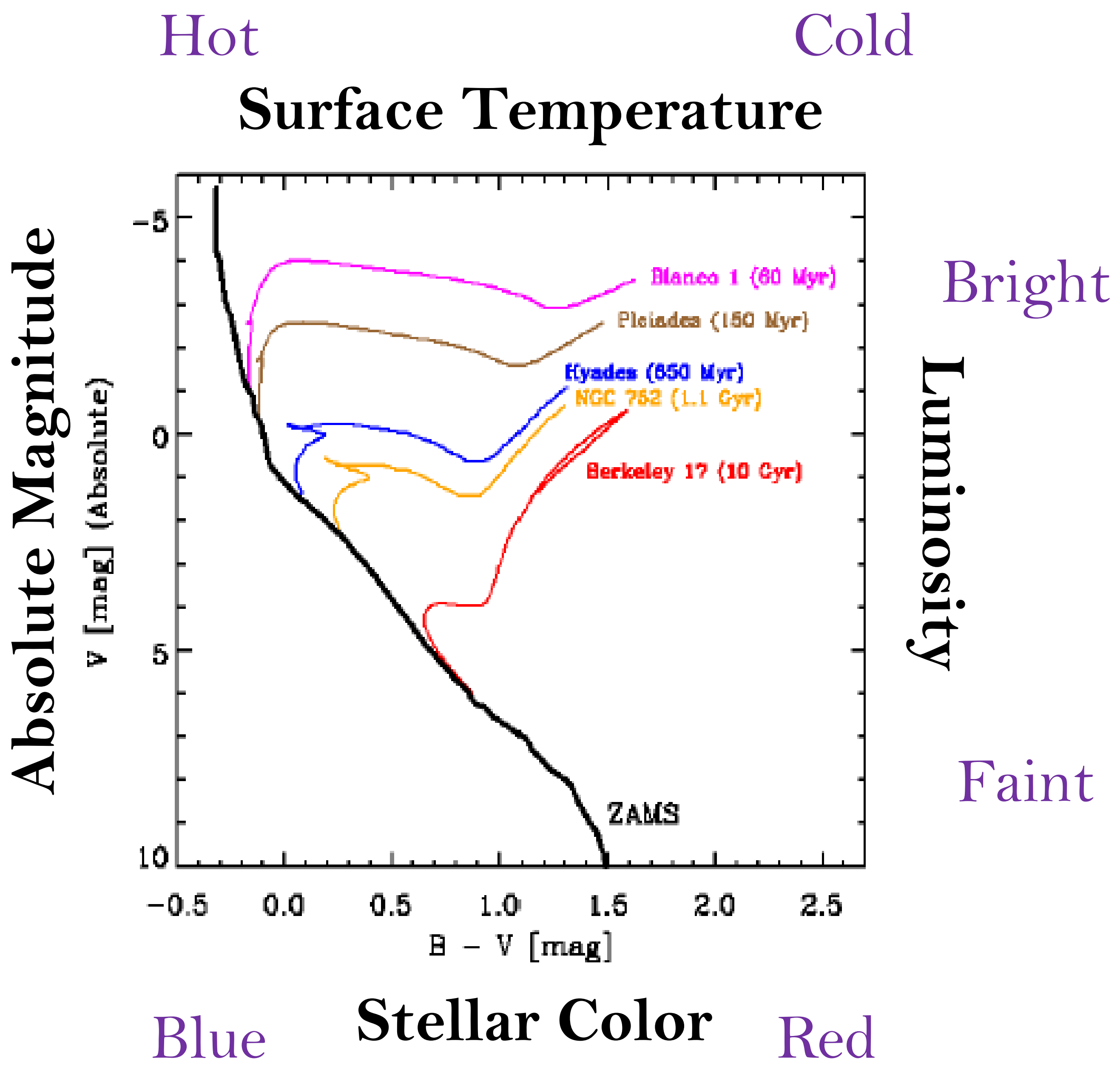
How good are these …

Age of the cluster

= the main sequence lifetime of stars at the MSTO

Post-MS members, while rarer than MS, are useful.

Observed CMDs



Effect of Metallicity

"metals" → low ionization/excitation potentials → effective coolants

Given the same mass, a metal poorer star is bluer and brighter.

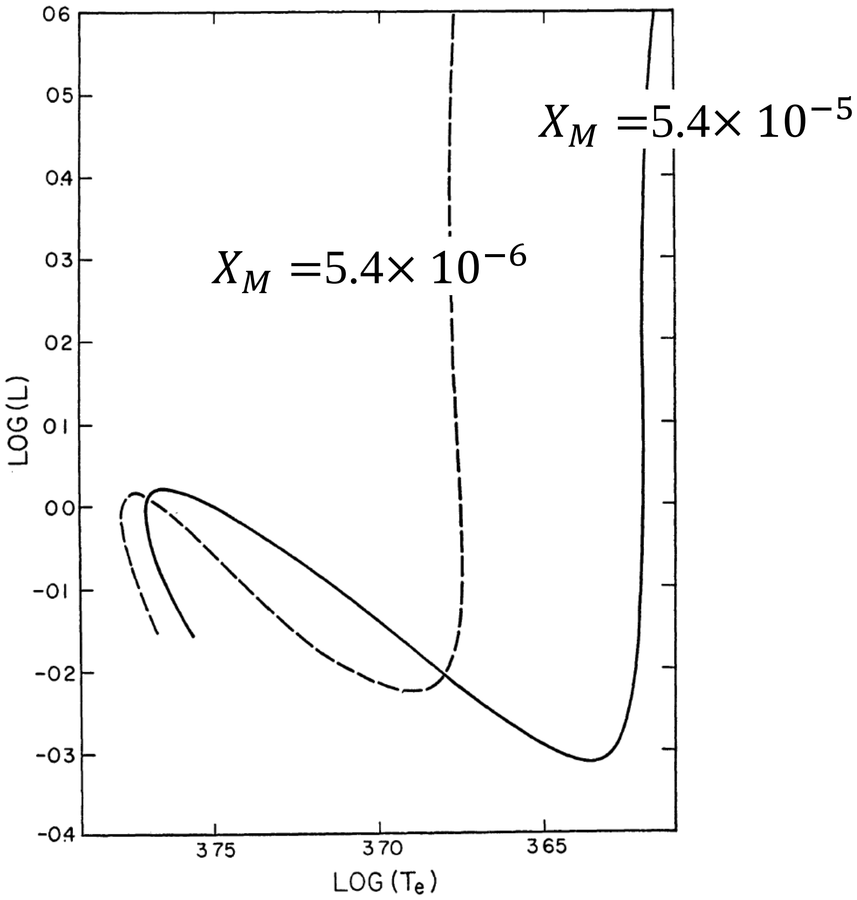
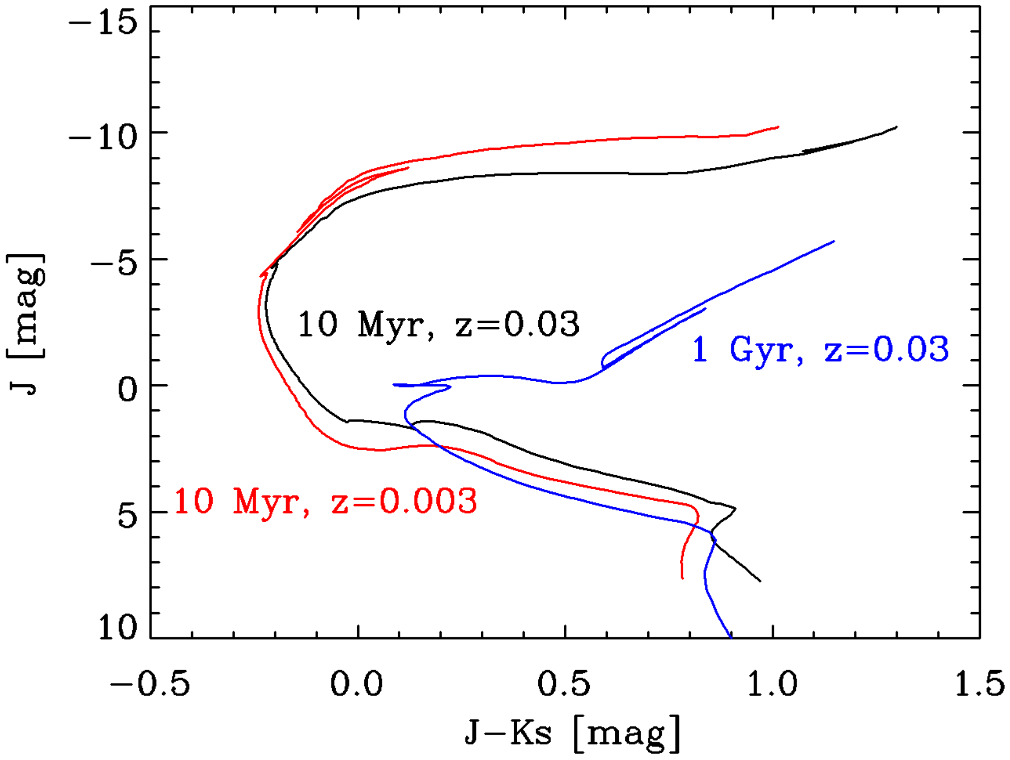


FIG. 1.—Paths in the theoretical Hertzsprung-Russell diagram for $M = M_\odot$. Luminosity in units of $L_\odot = 3.86 \times 10^{33}$ erg/sec and surface temperature T_e in units of ° K. Solid curve constructed using a mass fraction of metals with 7.5-eV ionization potential, $X_M = 5.4 \times 10^{-5}$. Dashed curve constructed with $X_M = 5.4 \times 10^{-6}$.

Iben (1965)

A metal poorer cluster → bluer



A younger cluster retains a longer upper MS, and even contains some PMS stars.

HB stars:
He core burning,
RR Lyrae variables

Blue stragglers ...
An extension of MS beyond the MSTO. They should not exist according to "standard" stellar evolution theory.

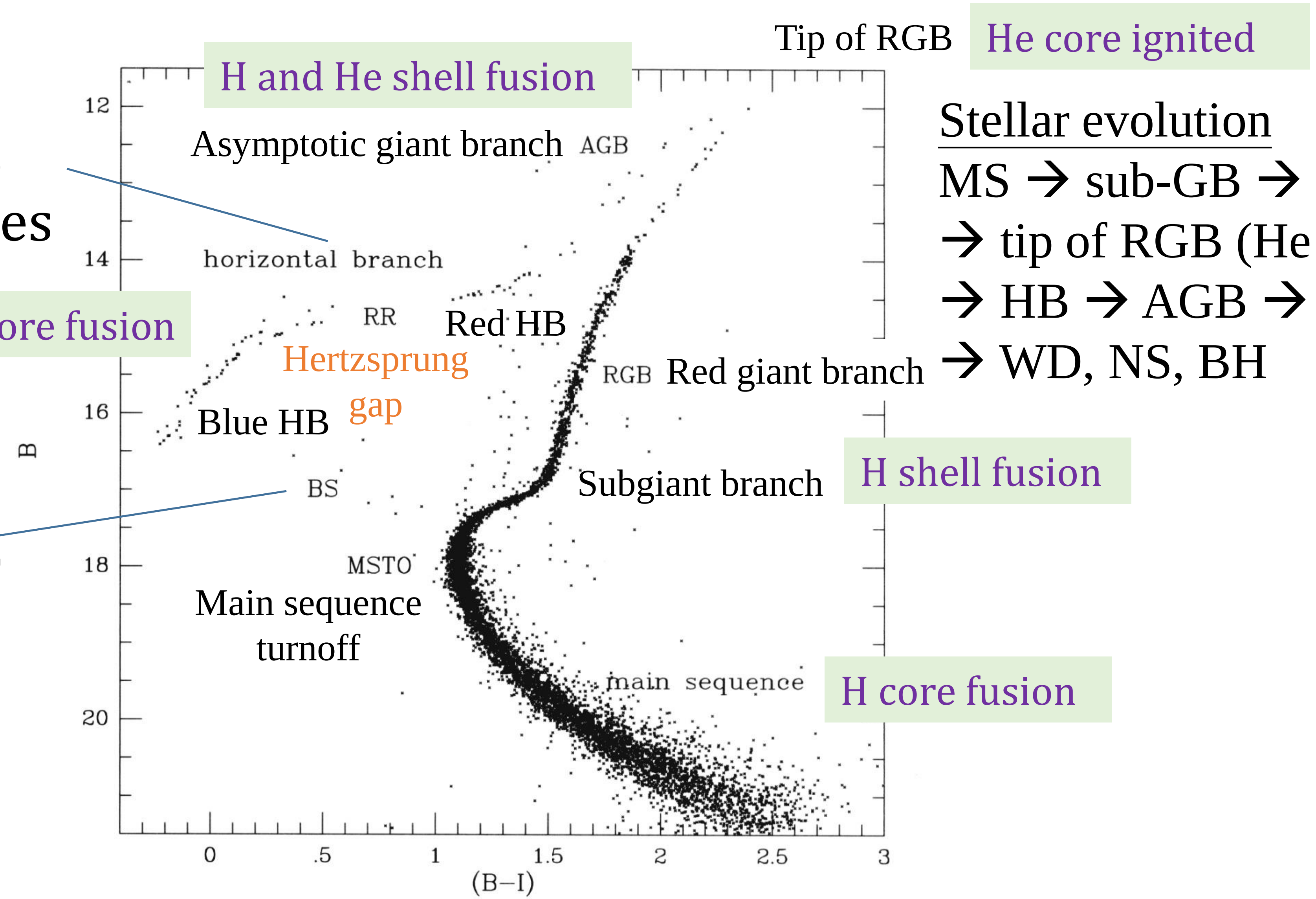


Fig. 2.1. The color–magnitude diagram of M5. The horizontal branch and main sequence are labeled. Also shown are: the RR Lyrae gap or instability strip (RR); the Red Giant Branch (RGB); the asymptotic giant branch (AGB); the main-sequence turn-off (MSTO); and blue stragglers (BS). (From data supplied by M. Bolte.)

Stellar evolution

MS → sub-GB → RGB
→ tip of RGB (He flash?)
→ HB → AGB → (PN, SN)
→ WD, NS, BH

Ashman & Zepf (1998)

Blue Stragglers

Common among GCs, even in some OCs.

Possible mechanisms of formation

- ✓ They formed later, therefore live longer (Roberts 1960)?
  But the age difference would have been large, and GCs do not seem to contain much gas.
- ✓ Binary merging as a result of mass transfer between equal-mass components (Iben 1986) ?
- ✓ Stellar collisions (Hills & Day 1976) ?
- ✓ Prolonged MS lifetimes due to rotation or ***B*** field (Wheeler 1979) ?
- ✓ Do not suffer as much mass loss as normal stars (slow rotators) ?

Horizontal Branch

Bright and distinct
→ extragalactic distance indicator

Different morphologies of GCs …

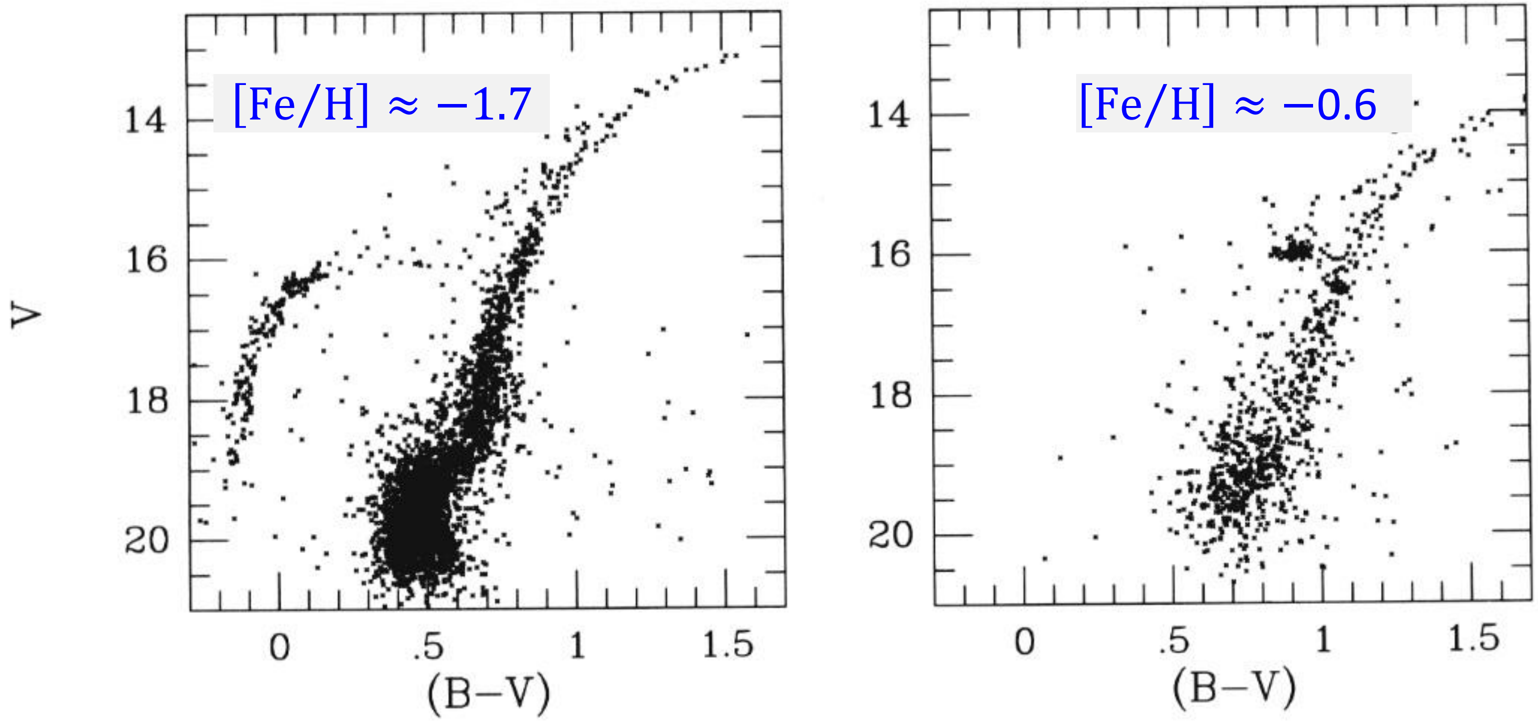


Fig. 2.2. The color–magnitude diagrams of NGC 1904 (left) and NGC 6637 (right) illustrating differences in horizontal branch morphology and the location of the main-sequence turn-off. (From data supplied by R. Buonanno and A. Sarajedini.)

Metallicity as the "first parameter"; higher z → redder

But not every metal-poor GC has an extended blue HB tail!

All [Fe/H] ≈ −1.6

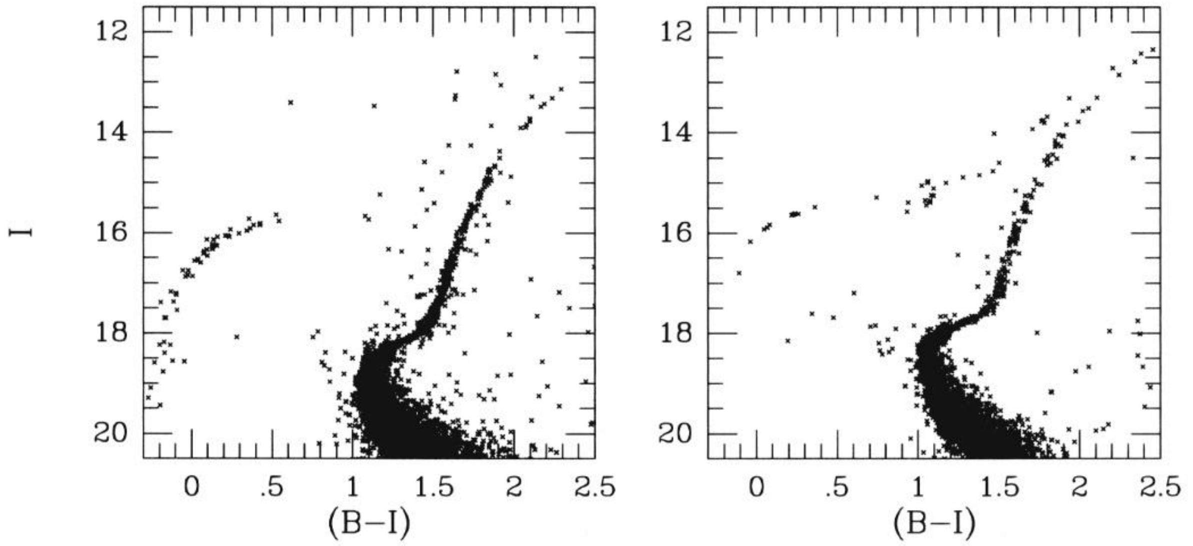


Fig. 2.3. The color–magnitude diagrams of M2 (left) and M3 (right). (From data supplied by P. Stetson.)

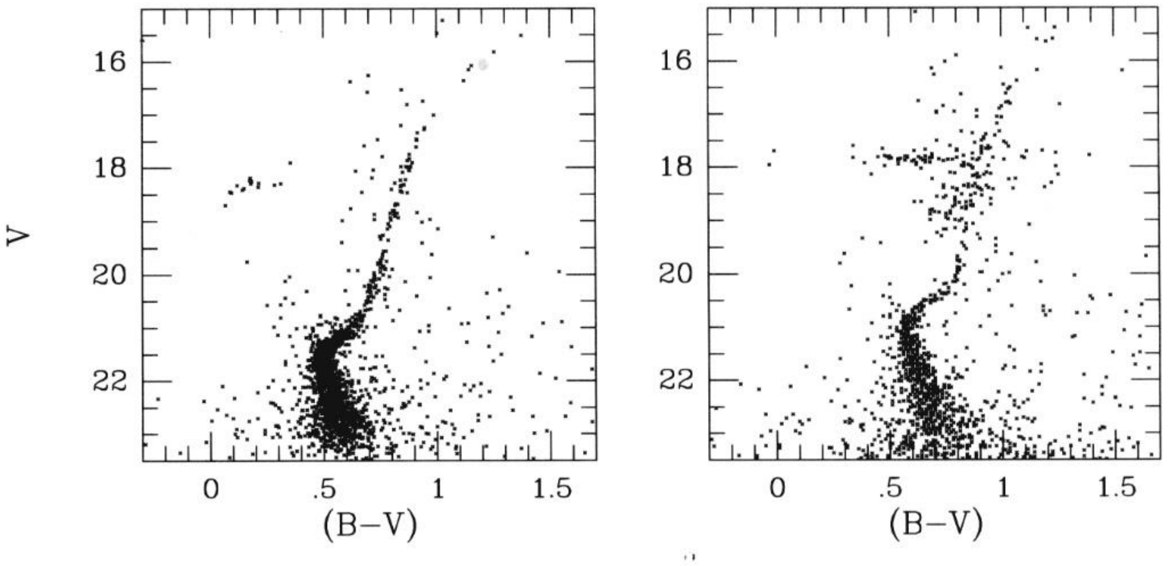
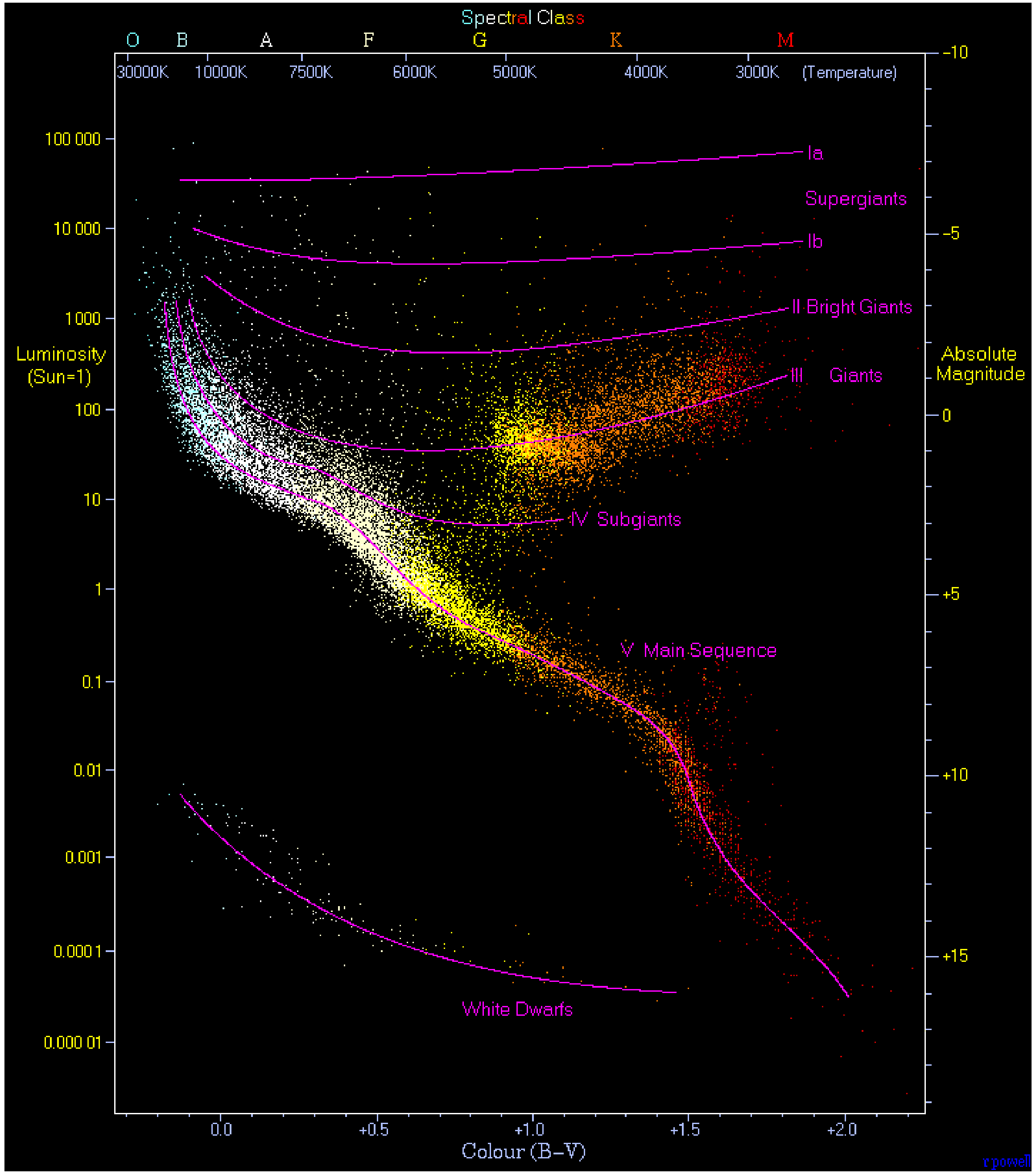


Fig. 2.4. The color–magnitude diagrams of Arp 2 (left) and Ruprecht 106 (right). (From data supplied by R. Buonanno.)

The "**second parameter**"

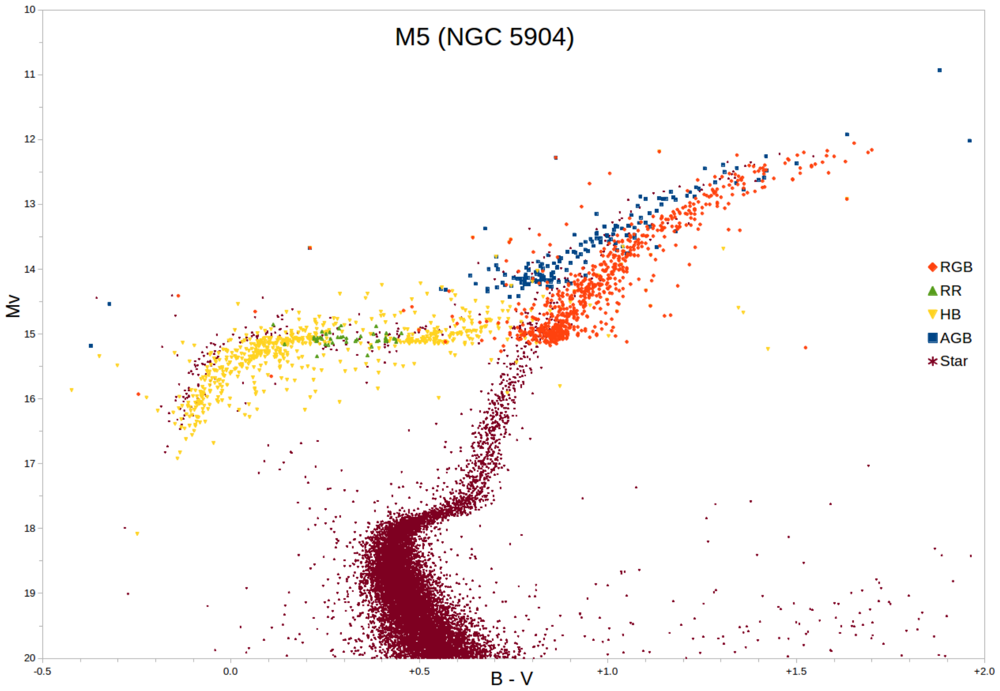
- ✓ age (older → bluer)?
- ✓ mass loss on RGB?
- ✓ He abundance??



Red Clump

Clustering of cool horizontal-branch giants (core He fusion, metal-rich)

… 5,000 K and $M_V \sim 0.5$



https://en.wikipedia.org/wiki/Subgiant#/media/File:M5_colour_magnitude_diagram.png