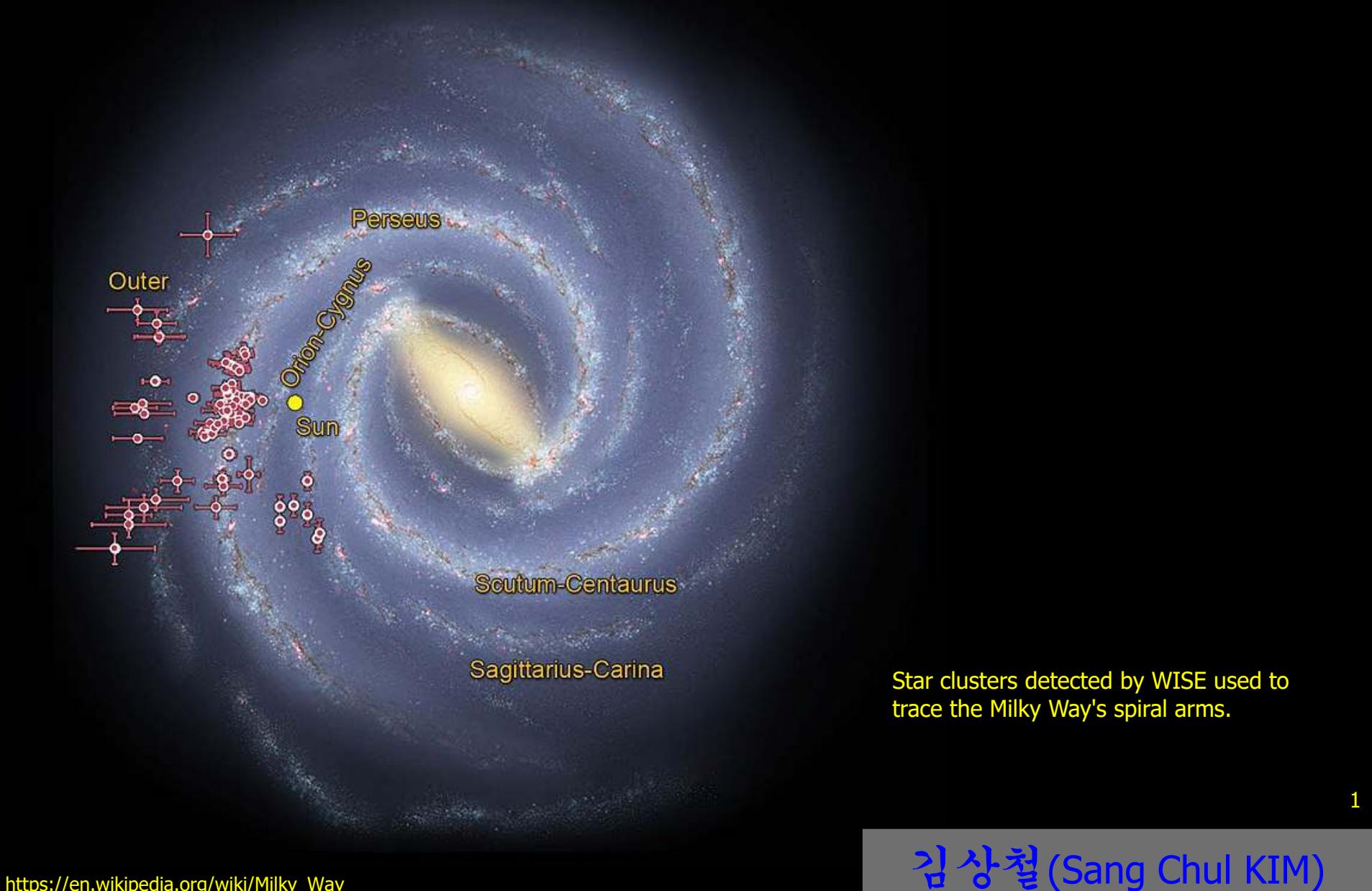


## 4. The Milky Way Galaxy (우리은하)

### 4.1 The MWG



# **Modern Astronomy**

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## **Part II. Stellar Evolution and the Milky Way Galaxy**

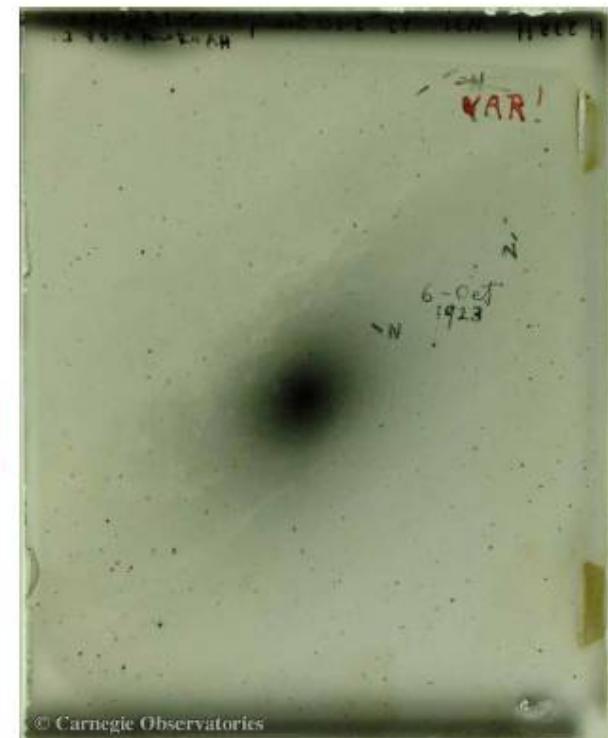
(항성진화와 우리은하)

- **Final exam** : April 28 (Fri) 10:30–11:30 AM
- LWCH room 220

# 1. Introduction

- Name : the Milky Way (MW), the Milky Way Galaxy (MWG), the Galaxy, our Galaxy '우리은하'
- Universe → MWG + External Galaxies (1923 Oct 5-6, Edwin P. Hubble's discovery of a Cepheid variable star in M31)
- General Properties :

| Property                               | Approximate Value                                     |
|--|---|
| Disk diameter                          | 50 kpc  |
| Halo diameter                          | 100 kpc   |
| Sun's distance from center             | $8.5 \pm 1.0$ kpc                                     |
| Height of Sun above disk               | 8 pc  |
| Total mass                             | $1.0 \times 10^{12} M_{\odot}$                        |
| Mass of gas                            | $8 \times 10^9 M_{\odot}$                             |
| Optical luminosity                     | $3 \times 10^{36} W = 3 \times 10^{43} \text{ erg/s}$ |
| Density of stars in solar neighborhood | $0.05 M_{\odot}/\text{pc}^3$                          |



[http://obs.carnegiescience.edu/PAST/m31var  
H335H\\_glass\\_0670\\_27\\_wm.jpg](http://obs.carnegiescience.edu/PAST/m31var/H335H_glass_0670_27_wm.jpg)

## 2. Shape of the Milky Way Galaxy

### Morphology

All-sky view :

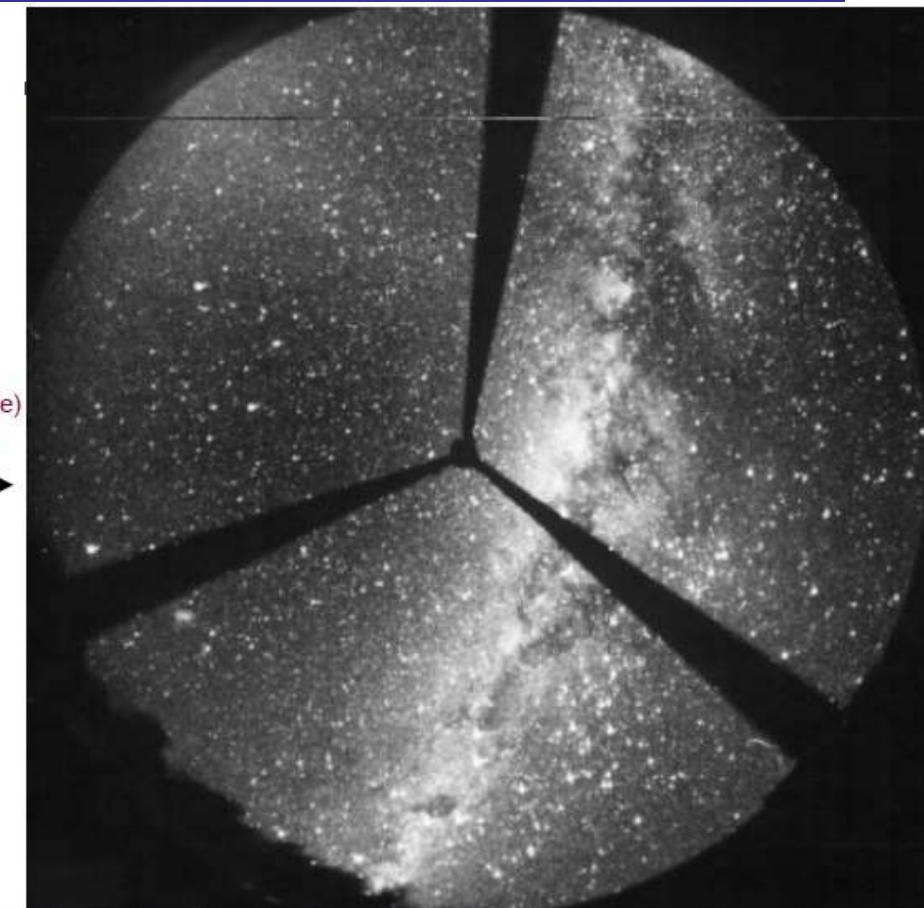
#### Visible

Plate 2: Galactic Bulge (between 285 and 65 degrees galactic longitude)

May 21/22, 1953, T. E. Houck and A. D. Code / Blue filter, 45 minute integration

Plate2.gif

<http://www.astro.wisc.edu/~dolan/constellations/mw/MilkyWay.htm>



#### Infrared

Image Credit: The COBE Project, DIRBE, NASA

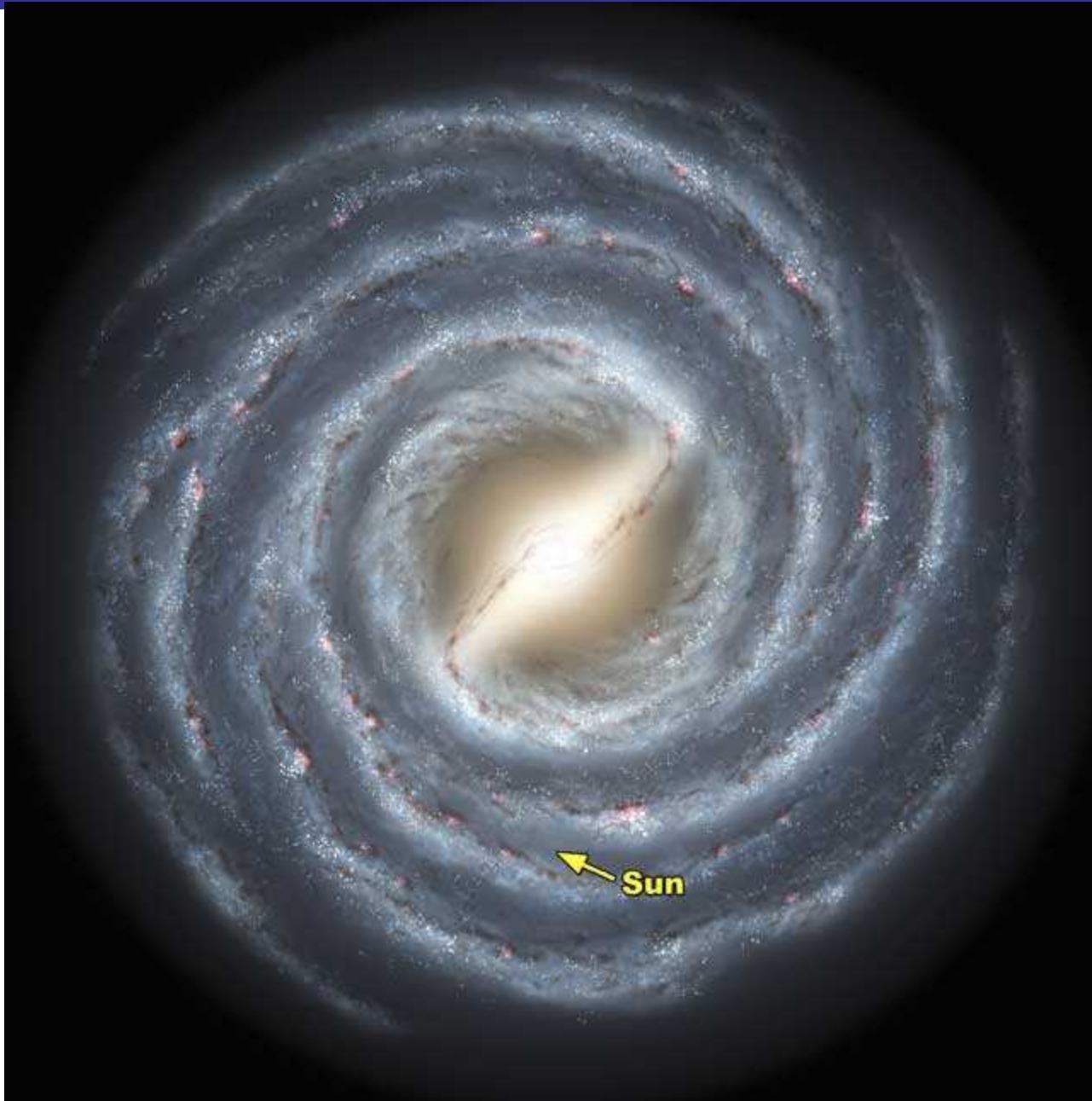
cobe\_milkyway.JPG

[http://imagine.gsfc.nasa.gov/features/cosmic/milkyway\\_info.html](http://imagine.gsfc.nasa.gov/features/cosmic/milkyway_info.html)



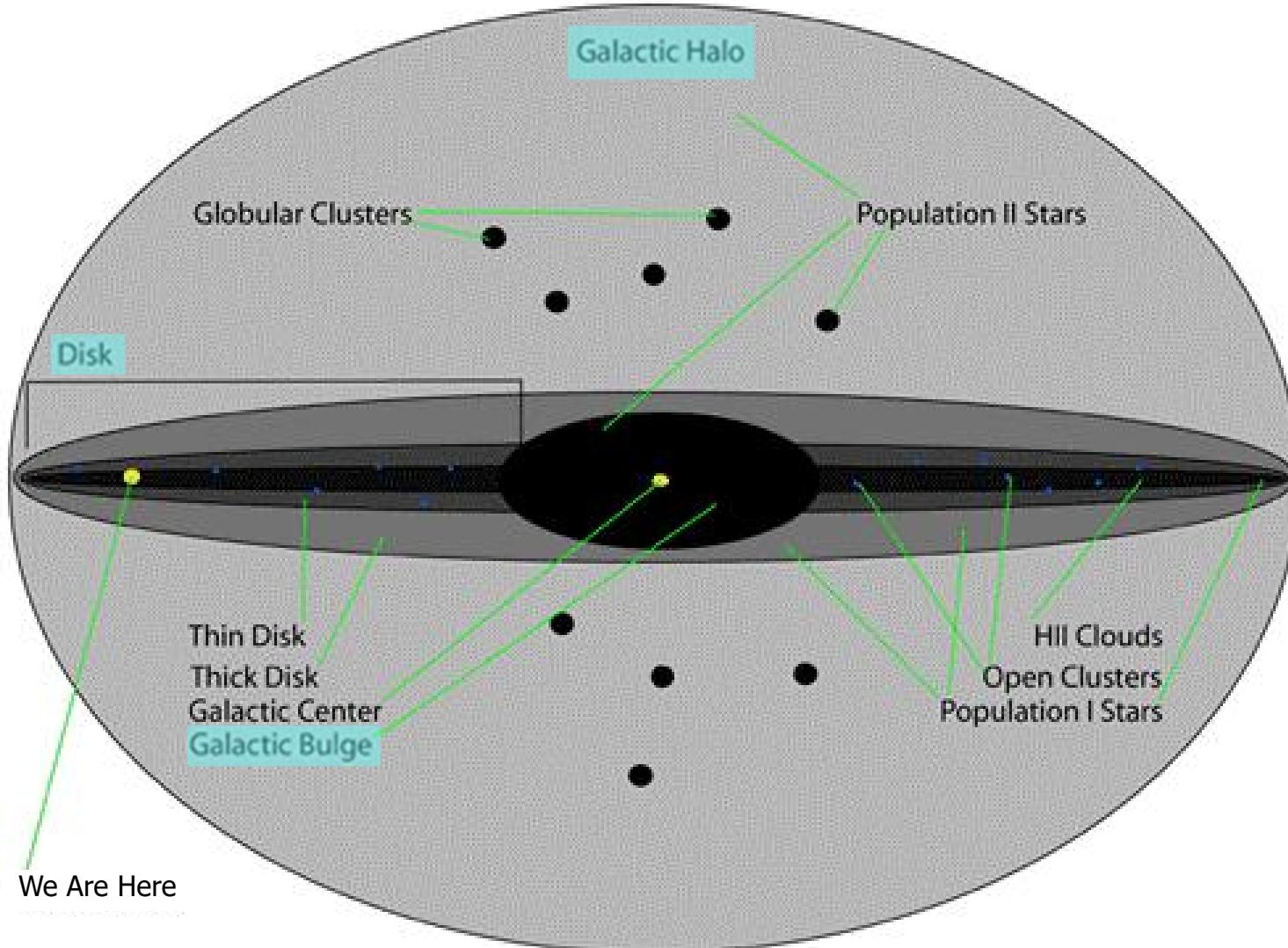
## 2. Shape of the Milky Way Galaxy

Face-on view:



## 2. Shape of the Milky Way Galaxy

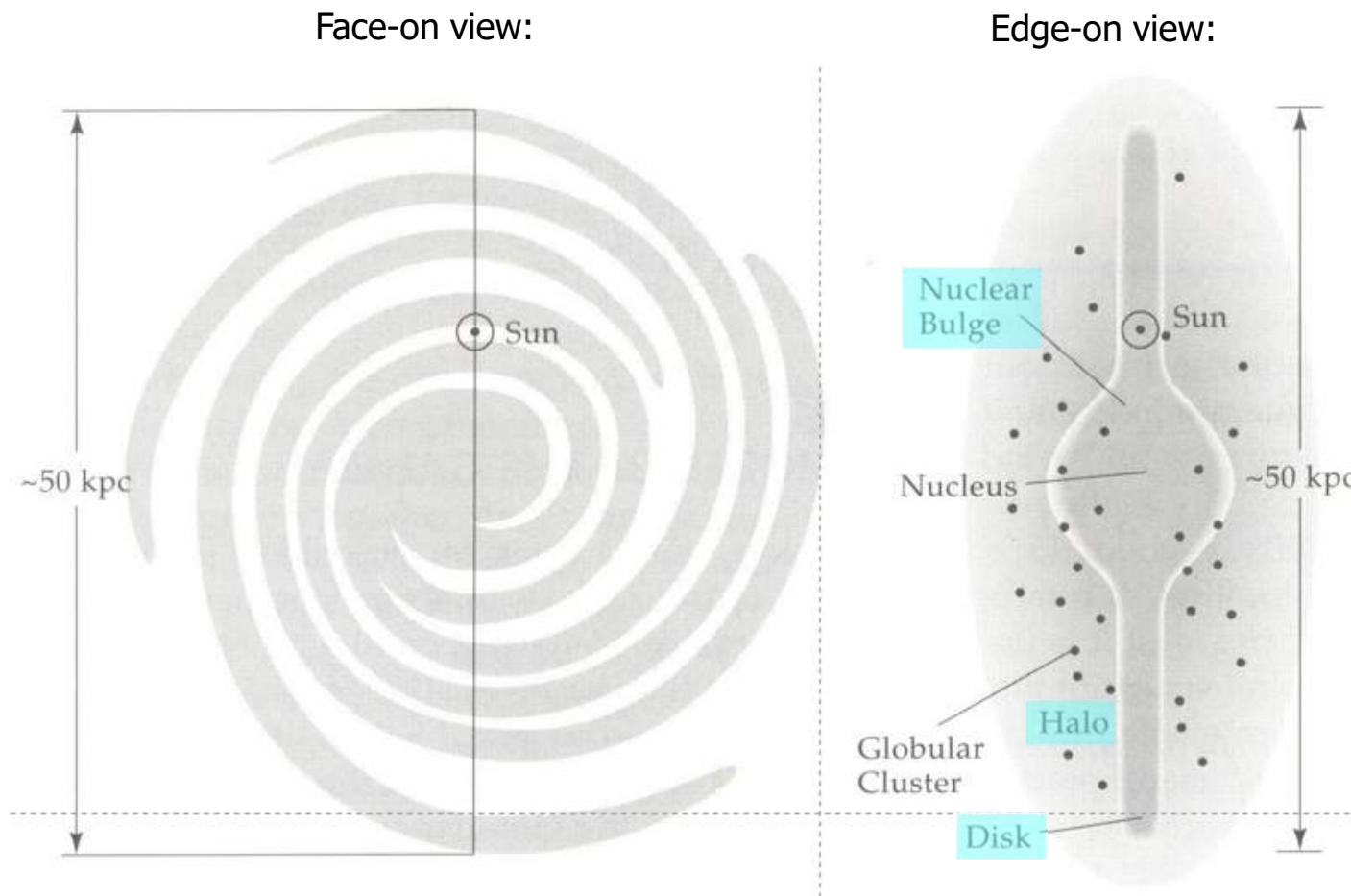
Edge-on view:



- Galactic plane (disk)
- thickness  $\sim 500$  pc
- diameter : thickness = 100 : 1

### 3. Structure of the Milky Way Galaxy

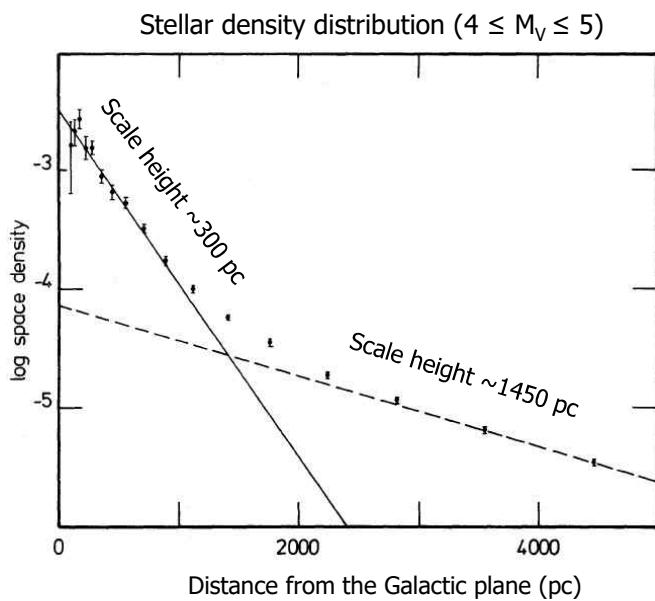
- 3 components : disk, bulge, halo
- Distance of the Sun from the Galactic center :  $8.5 \pm 1.0 \text{ kpc}$  ( $\sim 1/3$ )
- Galactic center: in the direction of the constellation of Sagittarius



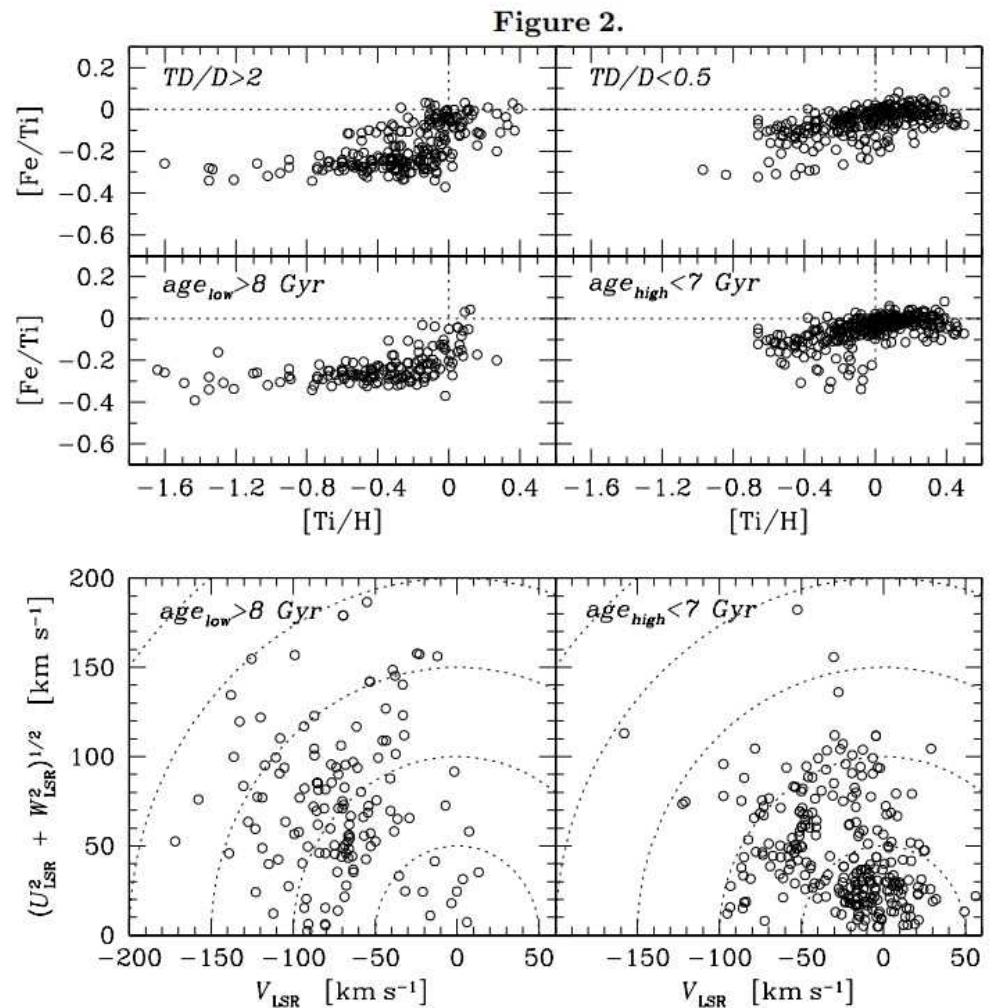
### 3. Structure of the Milky Way Galaxy

- Thin disk : scale height  $\sim 300$  pc
- Contain  $\sim 95\%$  of the disk stars
- Created from [gas accretion](#) at later stages of the MW formation  $\rightarrow$  metal-rich

- Thick disk : scale height  $\sim 1450$  pc
- mainly [old stars](#) made at early of the MW formation  $\rightarrow$  metal-poor



Gilmore & Reid 1983 (MN 202 1025)

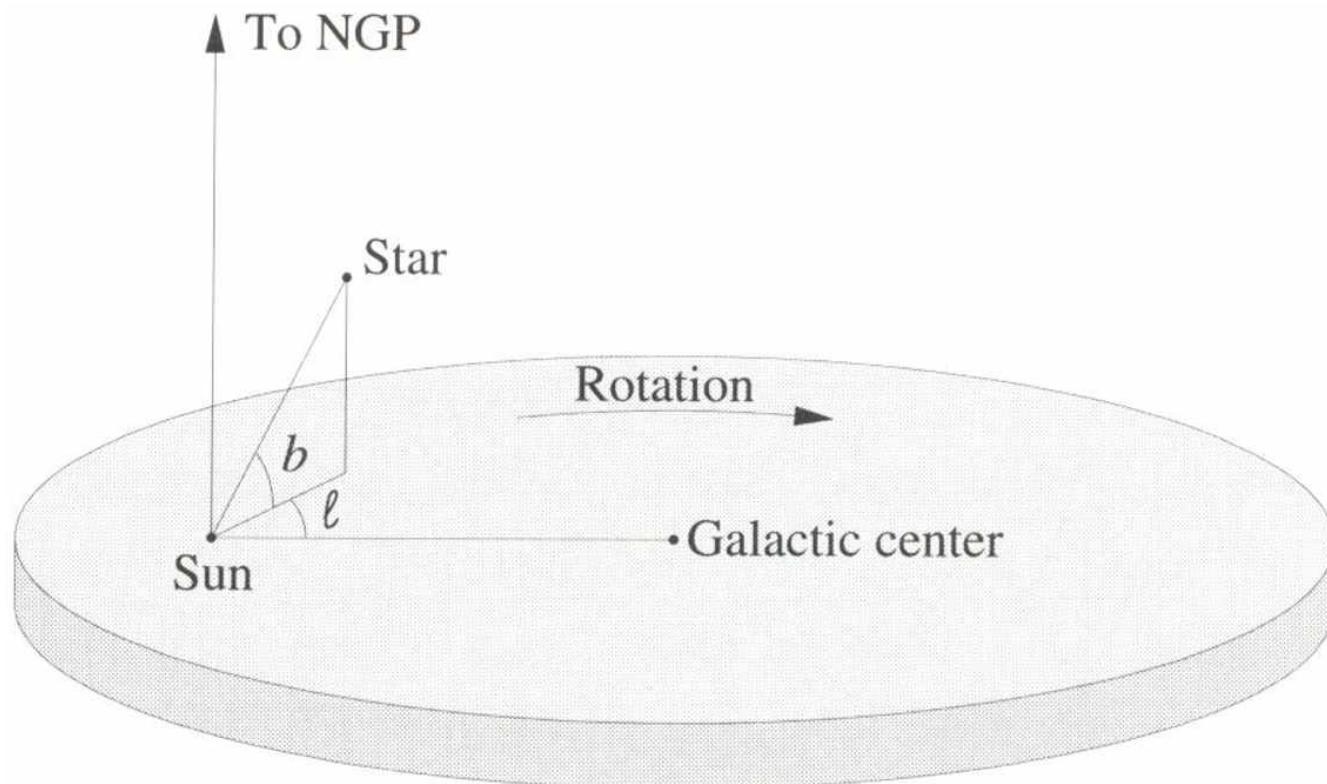


Bensby & Feltzing 2010 (IAUS 265, 300)

### 3. Structure of the Milky Way Galaxy

#### Galactic Coordinate System

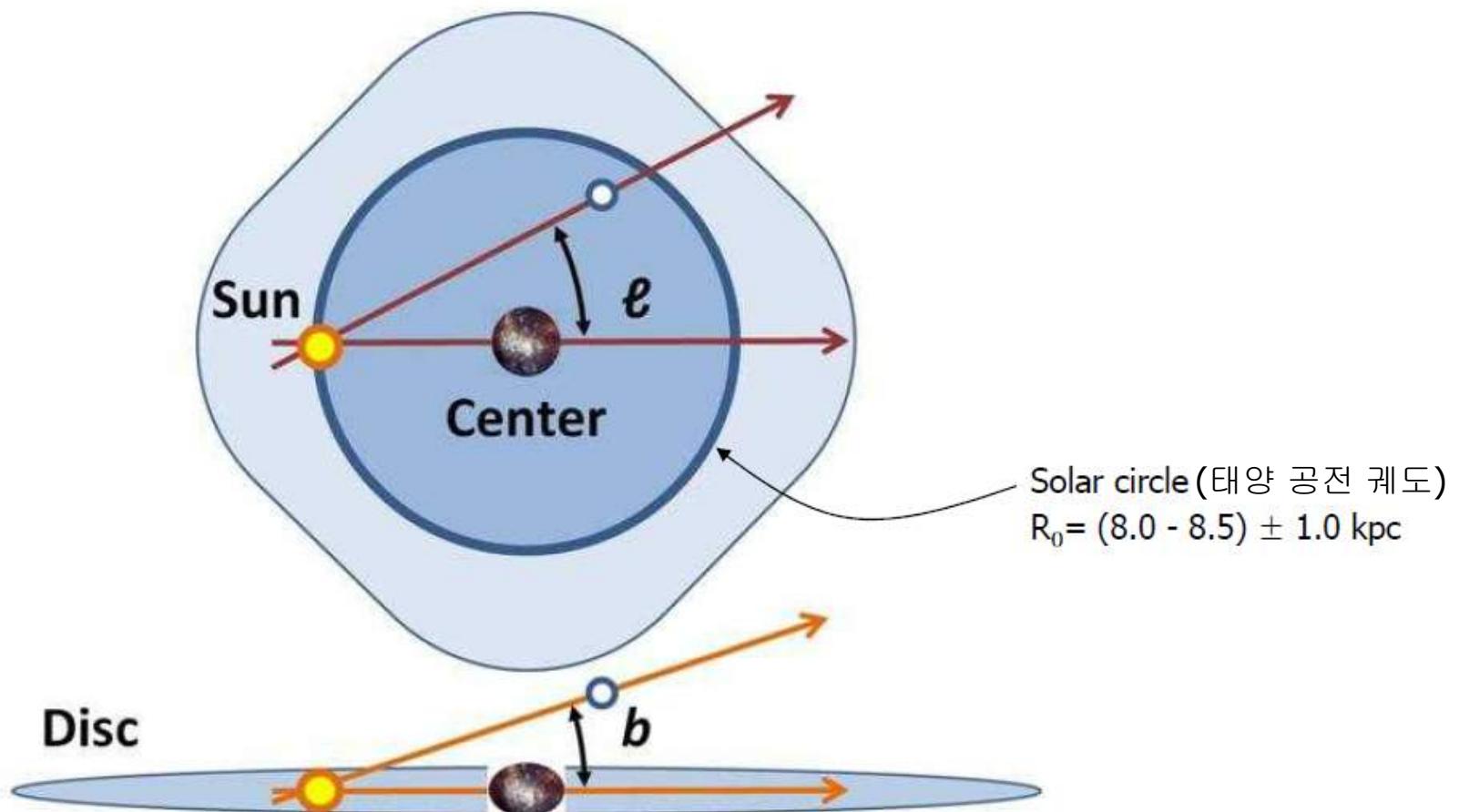
- Sun-centered (태양 중심)
- Galactic longitude (은경),  $\ell$  :  $0^\circ$  to  $360^\circ$
- Galactic latitude (은위),  $b$  :  $-90^\circ$  to  $+90^\circ$



### 3. Structure of the Milky Way Galaxy

#### Galactic Coordinate System

- Sun-centered (태양 중심)
- Galactic longitude (은경),  $\ell$  :  $0^\circ$  to  $360^\circ$
- Galactic latitude (은위),  $b$  :  $-90^\circ$  to  $+90^\circ$

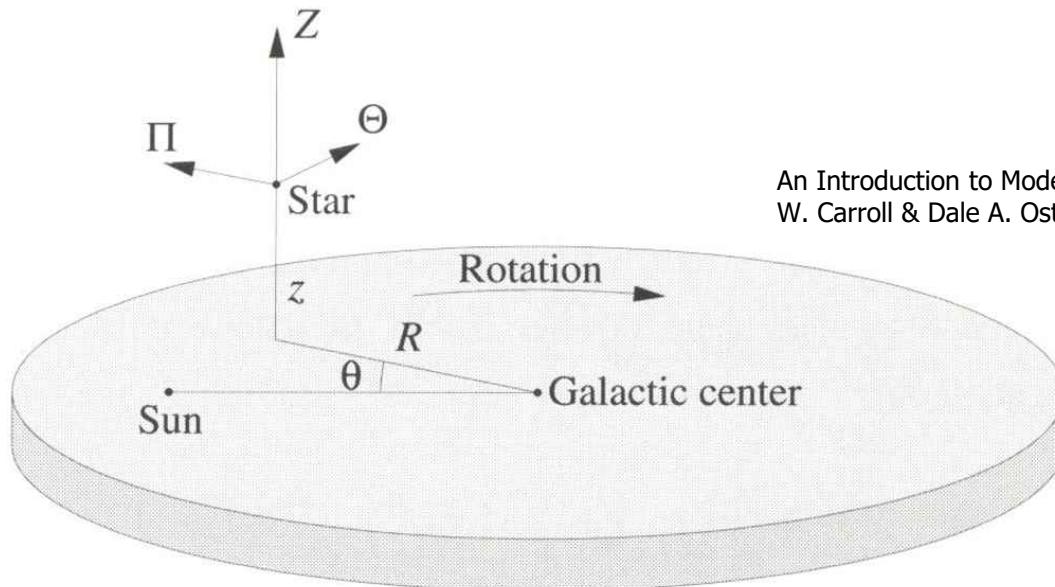


Galactic\_coordinates.JPG  
[https://en.wikipedia.org/wiki/Galactic\\_coordinate\\_system](https://en.wikipedia.org/wiki/Galactic_coordinate_system)

### 3. Structure of the Milky Way Galaxy

- Cylindrical Coordinate System  $\rightarrow (\Pi, \Theta, Z)$
- Velocity components :  $u, v, w$

#### Solar motion



An Introduction to Modern Astrophysics (2<sup>nd</sup> edition) Bradley W. Carroll & Dale A. Ostlie (1996) p. 941

- Orbital speed at  $R_0$  :  $\Theta_0(R_0) = 220$  km/s
- Solar motion :  $\sim 16.5$  km/s toward  $\ell = 53^\circ$ ,  $b = 25^\circ$  (a point in the constellation of Hercules)  
solar apex : the point toward which the Sun is approaching  
solar antapex : the point away from which the Sun is retreating (Columba, 비둘기, pigeon)
- Peculiar velocity:  
 $u_\odot = -9$  km/s (toward the Galactic center)  
 $v_\odot = 12$  km/s (more rapidly in the direction of Galactic rotation)  
 $w_\odot = 7$  km/s (north out of the Galactic plane)



### 3. Structure of the Milky Way Galaxy

#### Solar motion

- $v_{\odot} = 220 \text{ km/s}$ ,  $R_{\odot} = 8.5 \text{ kpc}$
- Assuming solar motion as a circular orbit →
- (centripetal acceleration maintaining the circular orbit) = (gravitational attraction between the inner mass and the Sun)

$$\frac{v_{\odot}^2}{R_{\odot}} = \frac{GM_G}{R_{\odot}^2}$$

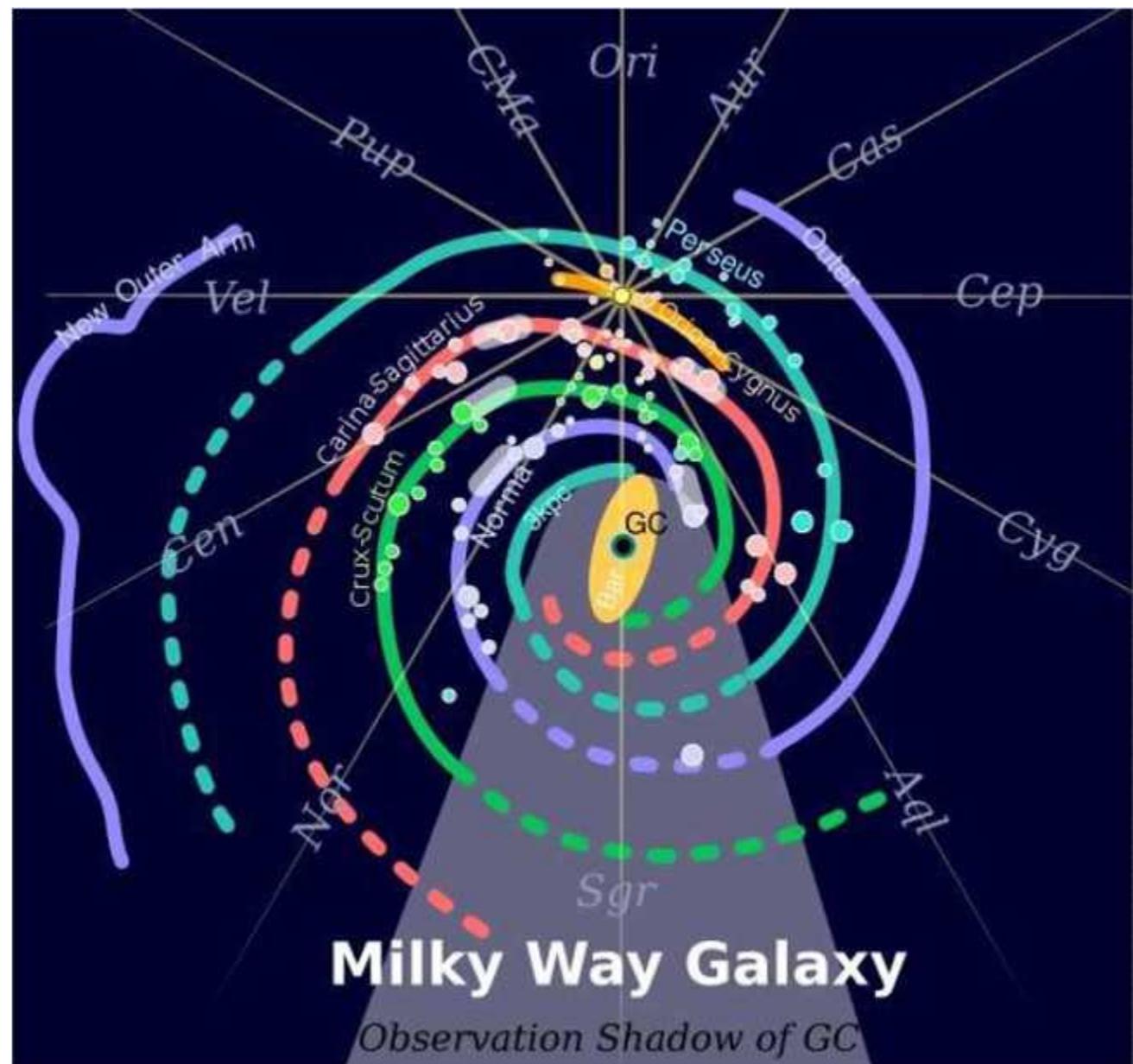
→ **mass of the Galaxy** within the solar orbit :

$$M_G = \frac{v_{\odot}^2 R_{\odot}}{G} = 1.9 \times 10^{44} \text{ g} \approx 10^{11} M_{\odot}$$

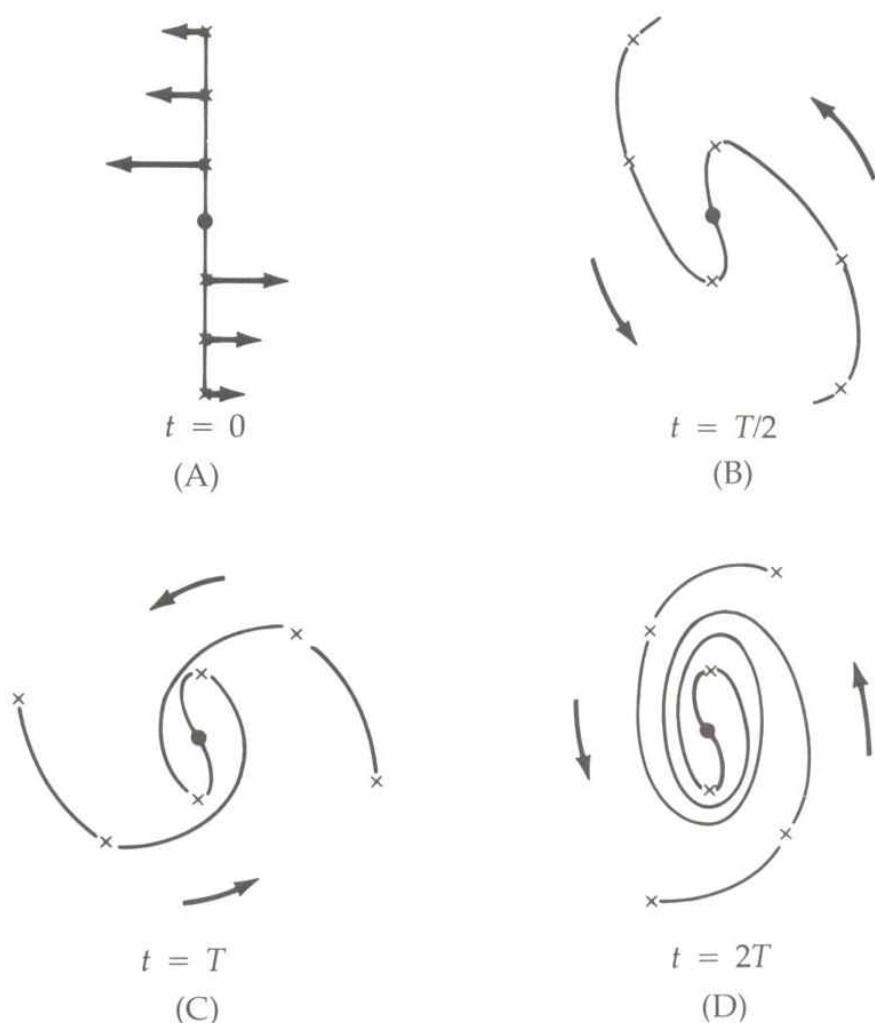
- Assuming an average stellar mass  $\sim 1 M_{\odot}$
- the Galaxy within the solar orbit =  $10^{11}$  stars

## 4. Spiral Arms of the MWG

- Spiral arm structure :  
observed : solid lines  
extrapolated : dotted lines



## 4. Spiral Arms of the MWG



- Spiral arms : believed to be produced by dynamical effects

- MW age  $\sim$  cosmic age ( $1.38 \times 10^{10}$  yr)

- MW rotation period at the Sun's orbit

$$: 2.4 \times 10^8 \text{ yr } (= \frac{2\pi R_\odot}{v_\odot})$$

→ Spiral arms should be a steady dynamical feature

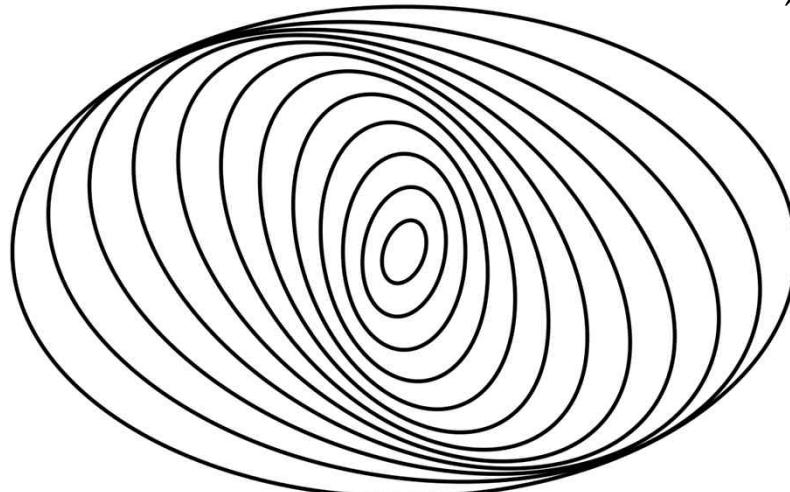
→ Manifestation of a rotating **density wave!**

- two hypothetical spiral arms + Kepler rotation
- After 2 cycles → arm configuration has disappeared into a tightly wound pattern

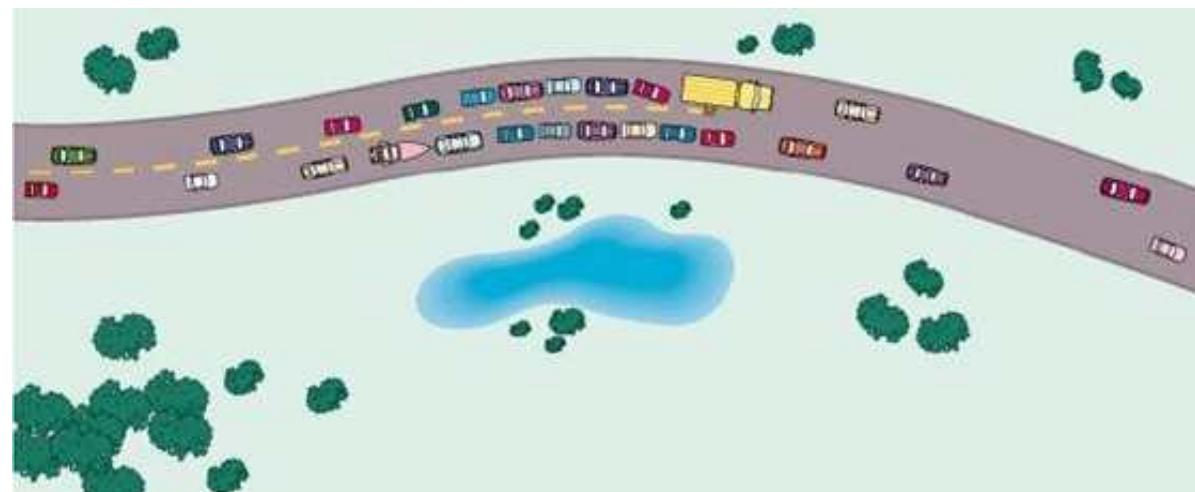
## 4. Spiral Arms – density wave

---

- MW rotation (spiral density wave)
  - dust and gas are compressed
  - High density, collisions of clouds, shock → new **star formation**
    - hot, **young population I** stars outline the spiral structure



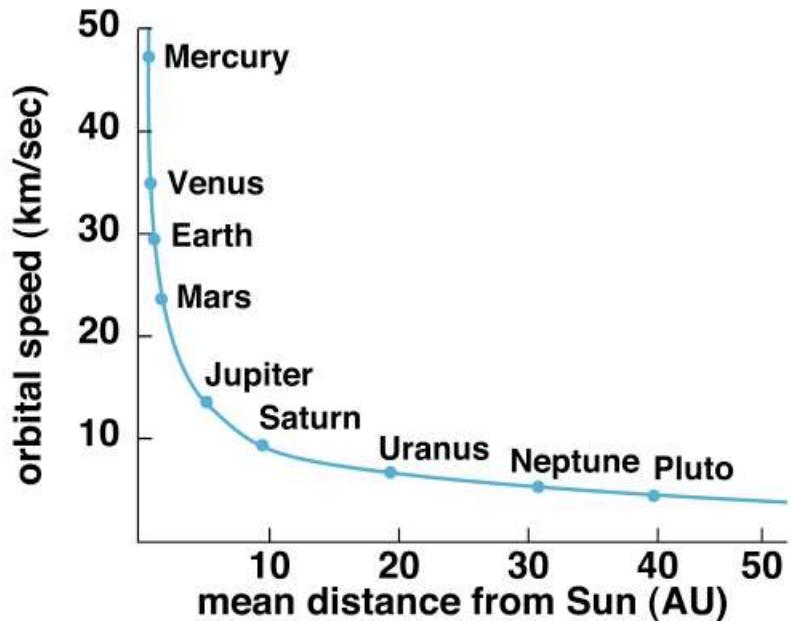
[https://en.wikipedia.org/wiki/Density\\_wave\\_theory](https://en.wikipedia.org/wiki/Density_wave_theory)



<http://frigg.physastro.mn.edu/~eskridge/astr101/week12.html>

## 5. MWG rotation curve

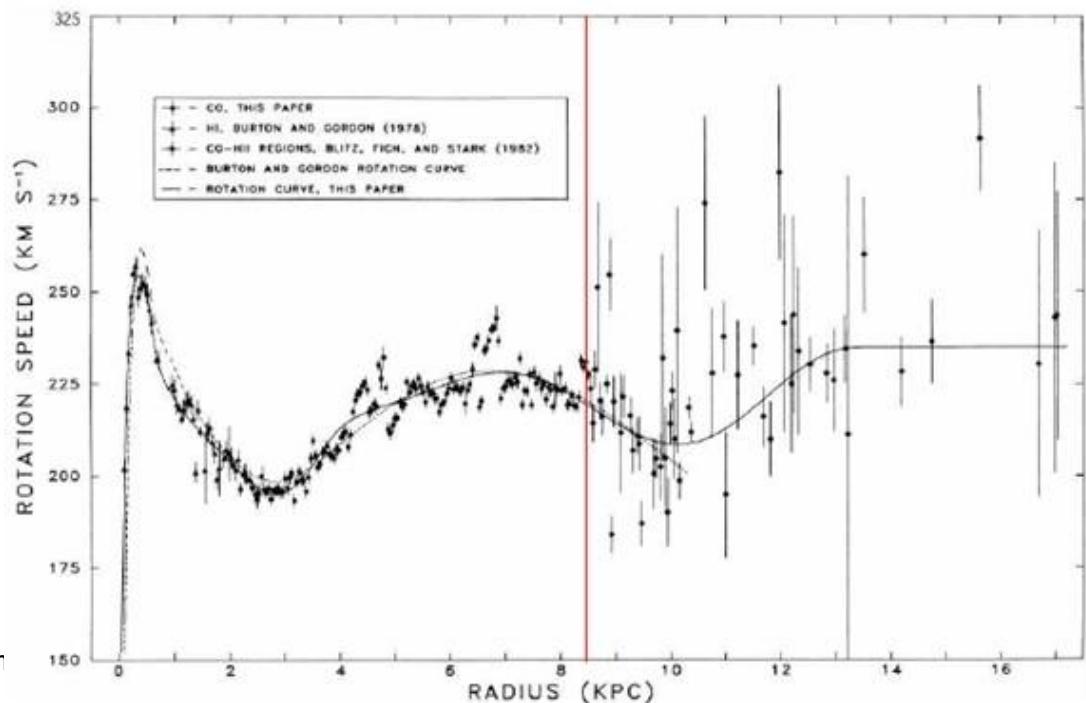
- Ordinary matter (planets, stars, gas) → Keplerian rotation
- Using  $R_0 = 8.5 \text{ kpc}$  and  $\Theta_0 = 220 \text{ km s}^{-1}$
- Observed Galactic rotation curve :  
Near the Galactic center → rigid-body rotation  
Outer region → roughly constant speed



(b)

Copyright © Addison Wesley

<http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/darkmatter.htm>



Clemens (1985 ApJ 295 422 – Massachusetts-Stony Brook Galactic plane CO survey – The Galactic disk rotation curve)

→ Dark Matter!

## 6. Stellar Populations

---

- Stellar 'populations'  
: families of stars with similar metal abundances and/or ages



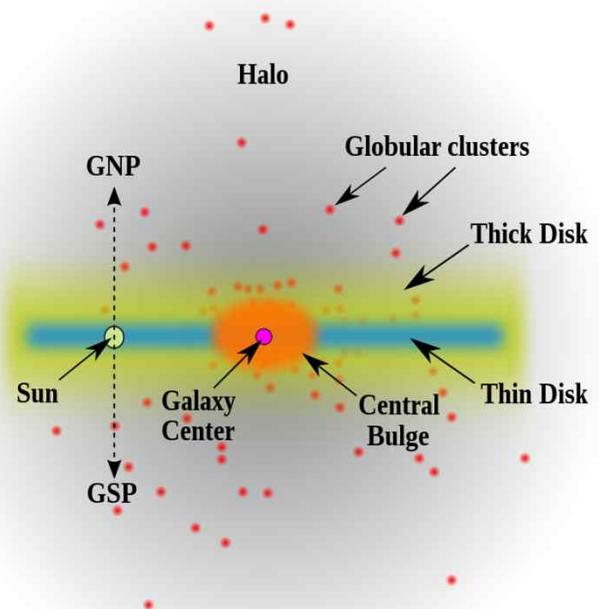
[https://en.wikipedia.org/wiki/Walter\\_Baade](https://en.wikipedia.org/wiki/Walter_Baade)

- Walter Baade : World War II in 1940's at Mount Wilson 2.5m telescope
  - MW GCs, M31 (Andromeda Galaxy), Galactic bulge [Baade's window], halo stars, etc.
  - 1944 : populations I and II



[https://en.wikipedia.org/wiki/Andromeda\\_Galaxy](https://en.wikipedia.org/wiki/Andromeda_Galaxy)

# 6. Stellar Populations



[https://en.wikipedia.org/wiki/Stellar\\_population](https://en.wikipedia.org/wiki/Stellar_population)

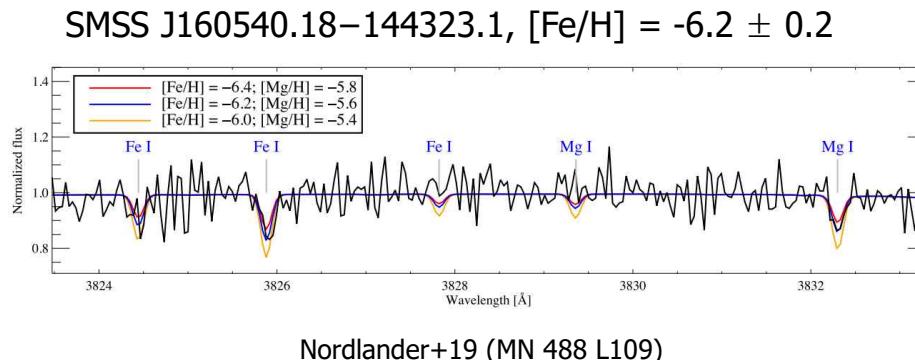
|                         | Population I                   | Population II     |
|-------------------------|--------------------------------|-------------------|
| Age                     | young                          | old               |
| Metallicity             | metal-rich                     | metal-poor        |
| Location in a galaxy    | disk (spiral arms)             | halo              |
| Related stellar systems | open clusters, OB associations | globular clusters |
| Evolutionary status     | ~main sequence stars           | ~giant stars      |
| Kinematics              | circular rotation              | random motion     |

Fossil properties (no change by galactic evolution)

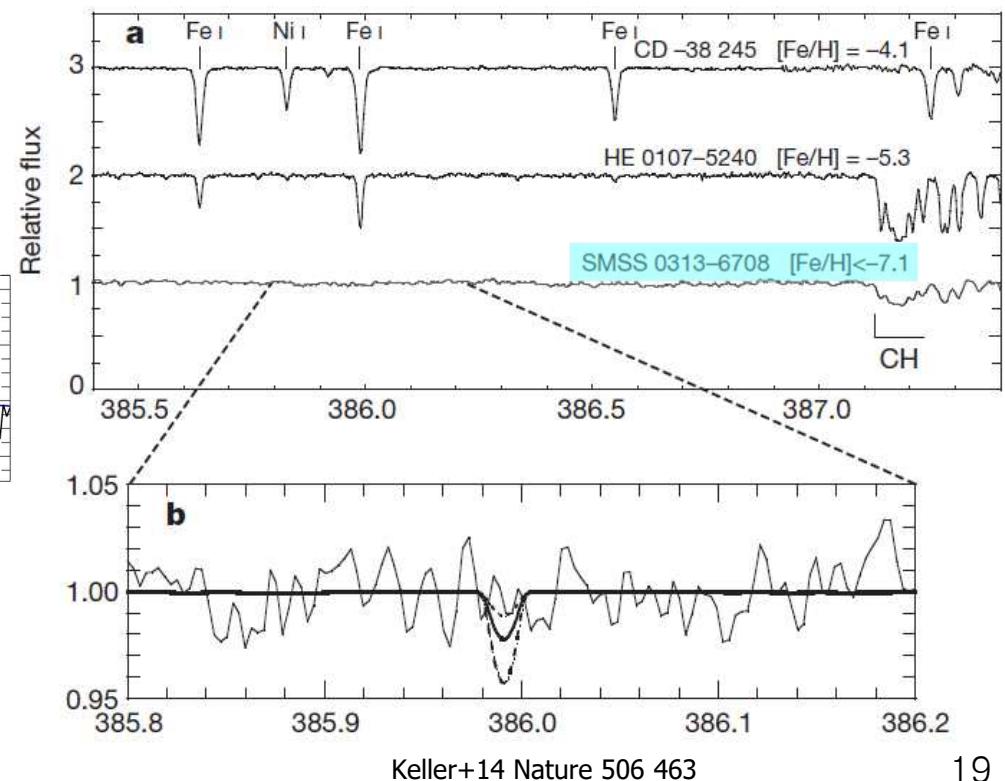
# 6. Stellar Populations

- Population III stars : first generation of stars in the history of the Universe with zero metal abundance
- Cosmic nucleosynthesis : not make appreciable amounts of heavy elements
- However, no pop III stars are discovered yet!

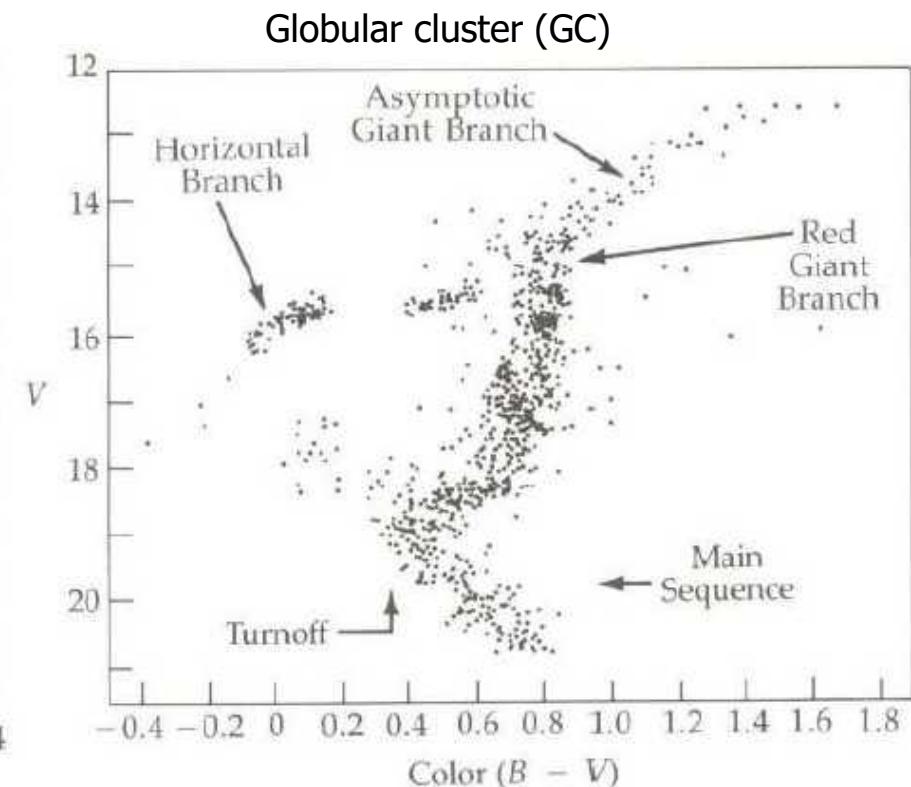
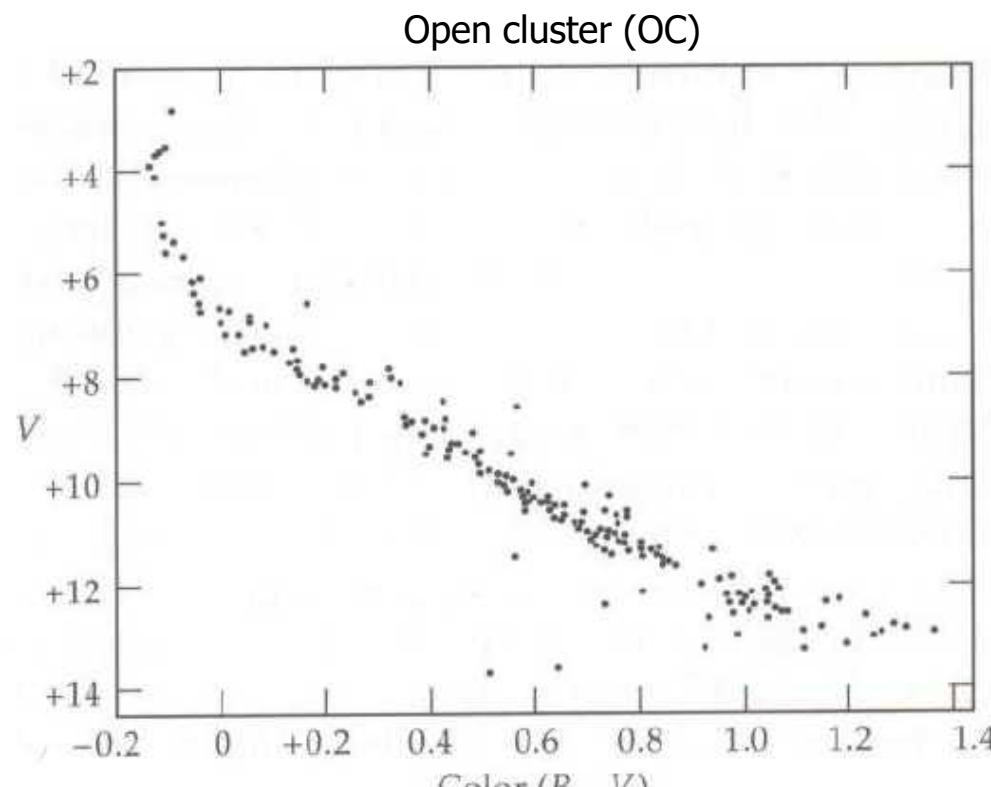
The most metal-poor halo stars :



SMSS J031300.362670839.3,  $[Fe/H] < -7.1$



## 6. Stellar Populations – Star Clusters



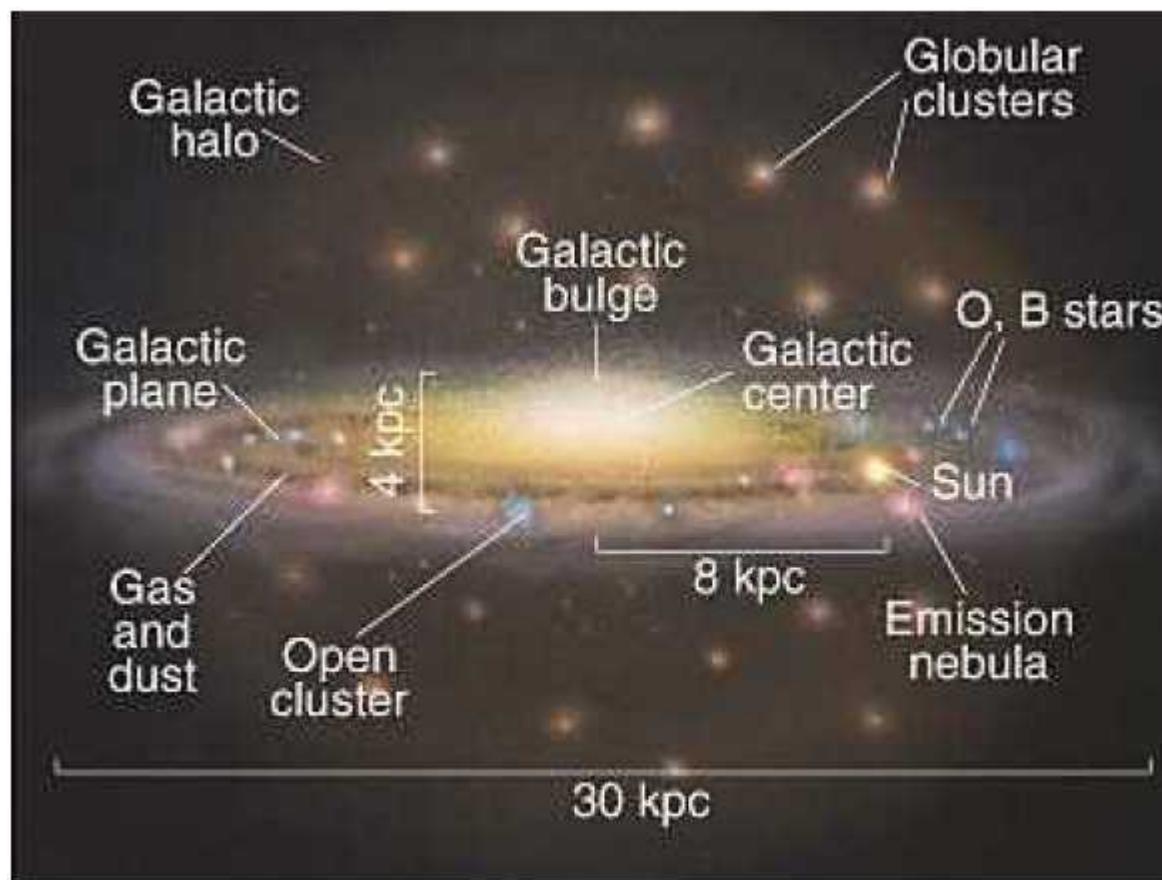
- Well-defined MS
- No giants (LC II to III)
- Curving up of the early end of the MS
- Stellar spectra  $\rightarrow$  high metal abundance ( $Z \approx 0.01$ )  
: population I

- MS :  $B-V \approx 0.4$  (turnoff)  $\rightarrow B-V = 0.8$
- Heavily populated giant branch
- High-luminosity branch running toward the left (HB, AGB)
- Stellar spectra  $\rightarrow$  very low metal abundance ( $Z \leq 0.001$ ) : population II

# 6. Stellar Populations – Star Clusters

## Distribution in the Galaxy

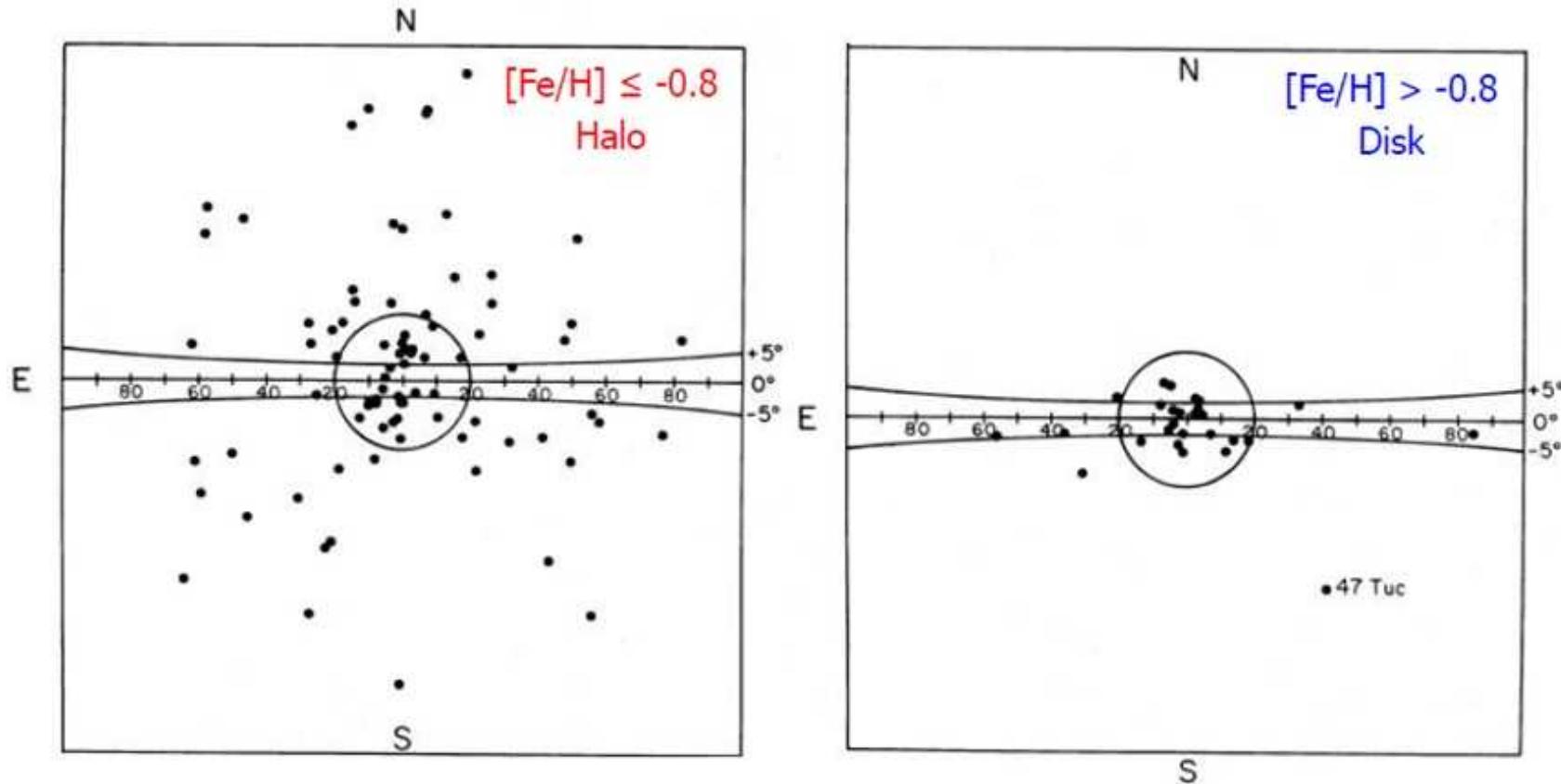
- Open clusters – disk
- Globular clusters – the whole galaxy (halo, bulge/disk)



[http://www2.astro.psu.edu/users/caryl/a10/lec13\\_2d.html](http://www2.astro.psu.edu/users/caryl/a10/lec13_2d.html)

## 6. Stellar Populations – Galactic Globular Clusters

### Distribution of GGCs in the Galaxy



Zinn 1985 (ApJ 293 424 – The GCS of the Galaxy. IV. The halo and disk subsystems) – Fig 3

|                                | Halo GCs | Disk GCs | Disk stars |
|--------------------------------|----------|----------|------------|
| [Fe/H]                         | -1.5     | -0.5     | 0.0        |
| $V_{\text{rotation}}$ [km/s]   | 45       | 185      | 220        |
| $V_{\text{dispersion}}$ [km/s] | 115      | 60       | 15         |

## 6. Stellar Populations in the MW

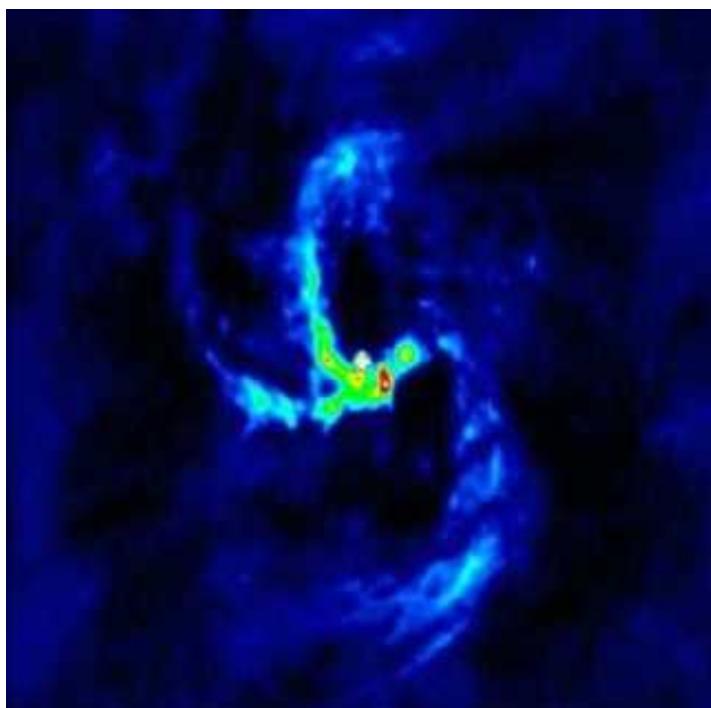
|                                       | Halo pop II  | Intermediate pop II  | Disk pop II   | Old pop I  | Extreme pop I   |
|---------------------------------------|--|--|---|--|---|
| Typical objects                       | GCs, <b>Extremely metal-poor stars</b> (subdwarfs), RR Lyrae stars ( $P > 0.4$ d), Pop II Cepheids | High-velocity stars ( $Z > 30$ km/s), Long period variables ( $P < 250$ d) | PNe, Novae, <b>Bright red giants</b> , Galactic bulge, Weak-line stars, RR Lyrae stars ( $P < 0.4$ d) | Sun, A-type stars, Strong-line stars, Me dwarfs, <b>Giants</b> , Older OCs | Gas, dust, O and B stars, supergiants, T Tauri stars, Young OCs, Classical Cepheids, H II regions |
| Mean age (Gyr)                        | $\geq 10$  | $\approx 10$   | 3-10  | 0.1-10   | < 0.1   |
| Distance from the Galactic plane (pc) | 2000   | 700  | 400   | 160  | 120   |
| Vertical velocity (km/s)              | 75   | 25   | 17  | 10   | 8   |
| Distribution                          | Smooth   | Smooth   | Smooth  | Patchy   | Extremely patchy in spiral arms   |
| Brightest stars ( $M_{vis}$ )         | -3   | -3   | -3  | -5   | -8  |
| Metal abundance, Z                    | 0.003  | 0.01   | 0.02  | 0.03   | 0.04  |
| Concentration to Galactic center      | Strong   | Strong   | Considerable  | Little   | None  |
| Galactic orbits                       | Highly eccentric   | Eccentric  | Slightly eccentric  | Almost circular  | Circular  |

Introductory Astronomy and Astrophysics (4th edition) Michael Zeilik & Stephen A. Gregory (1998) p. 398

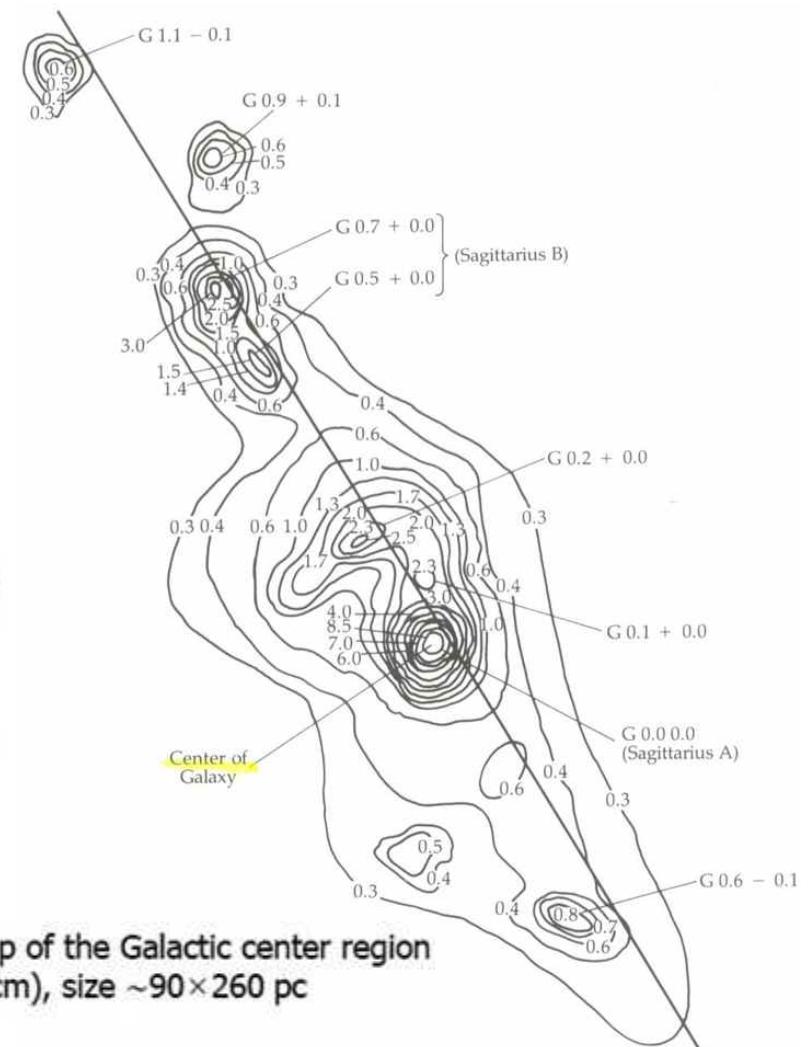
기본천문학 (Editors H. Karttunen, P. Kroger, H. Oja, M. Poutanen, K. J. Donner, 민영기 윤홍식 흥승수 공역, 형설출판사, 1991, p. 404)

## 7. Galactic center - Nucleus

- Great extinction → infrared, radio observations → very young O and M supergiants, molecular clouds, H II regions
  - ※ M31 nucleus : metal-rich giants, large number of low-mass dwarfs
- H I 21-cm observation → **3 kpc expanding arm**  
A gas cloud moving toward us at  $\sim 50$  km/s
- Continuous radio emission → an intense radio source, "**Sagittarius A**"  
→ nonthermal point-like source ( $D < 0.1''$ ), "**Sgr A\***"
- Gas motions → suggest high concentration of mass at the center, also a compact radio source ( $D < 140$  AU) →  
**Supermassive BH,  $M \sim 10^6 M_{\odot}$**



- Sgr A West,  $\sim 40''$  region – **mini-spiral**
- NRAO 3.6 cm image
- Sgr A\* is the bright white point source near the center.



## 7. Galactic center - Nucleus

---

2020 Nobel prize in Physics

**Roger Penrose**

University of Oxford, UK

*"for the discovery that black hole formation is a robust prediction of the general theory of relativity"*

and the other half jointly to

**Reinhard Genzel**

Max Planck Institute for Extraterrestrial Physics, Garching, Germany and University of California, Berkeley, USA

and

**Andrea Ghez**

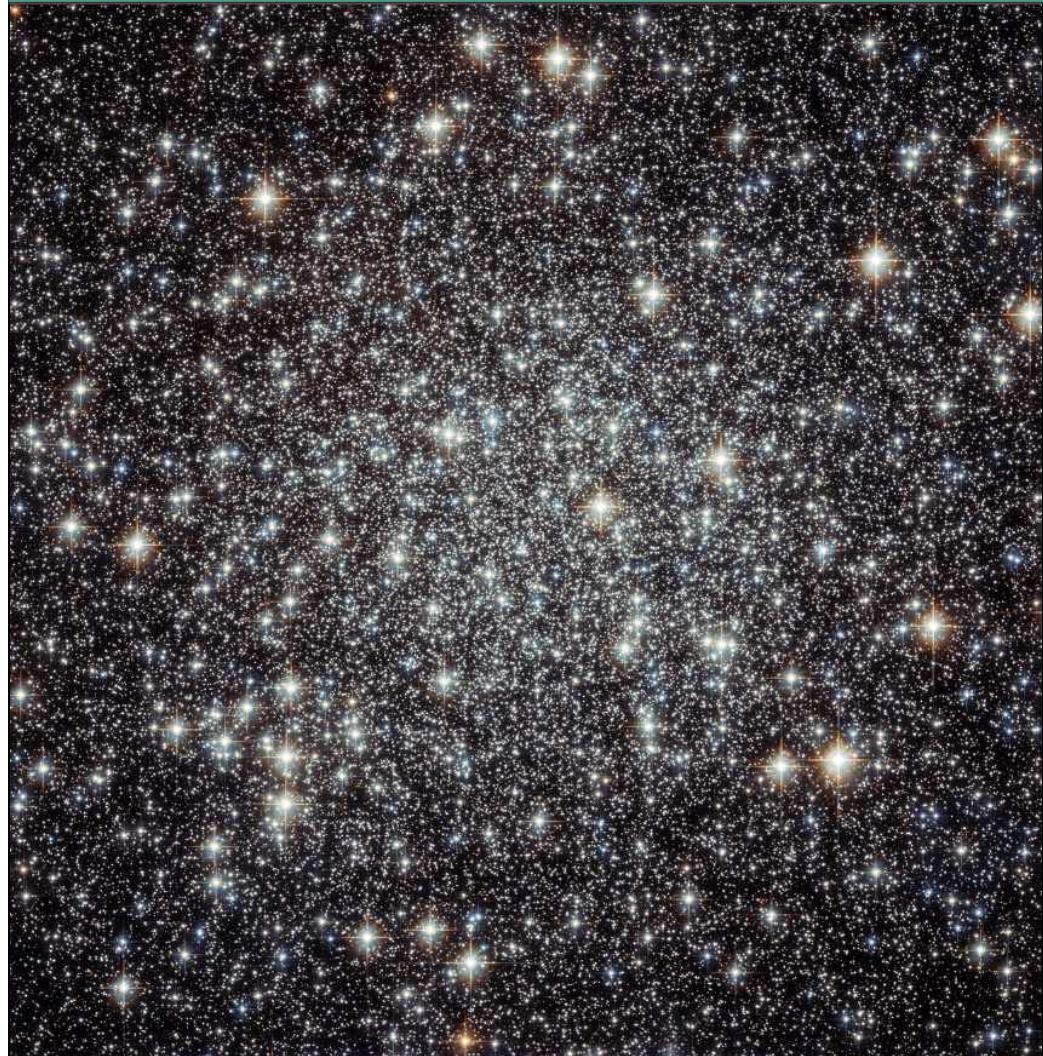
University of California, Los Angeles, USA

*"for the discovery of a supermassive compact object at the centre of our galaxy"*

## 4. The Milky Way Galaxy (우리은하)

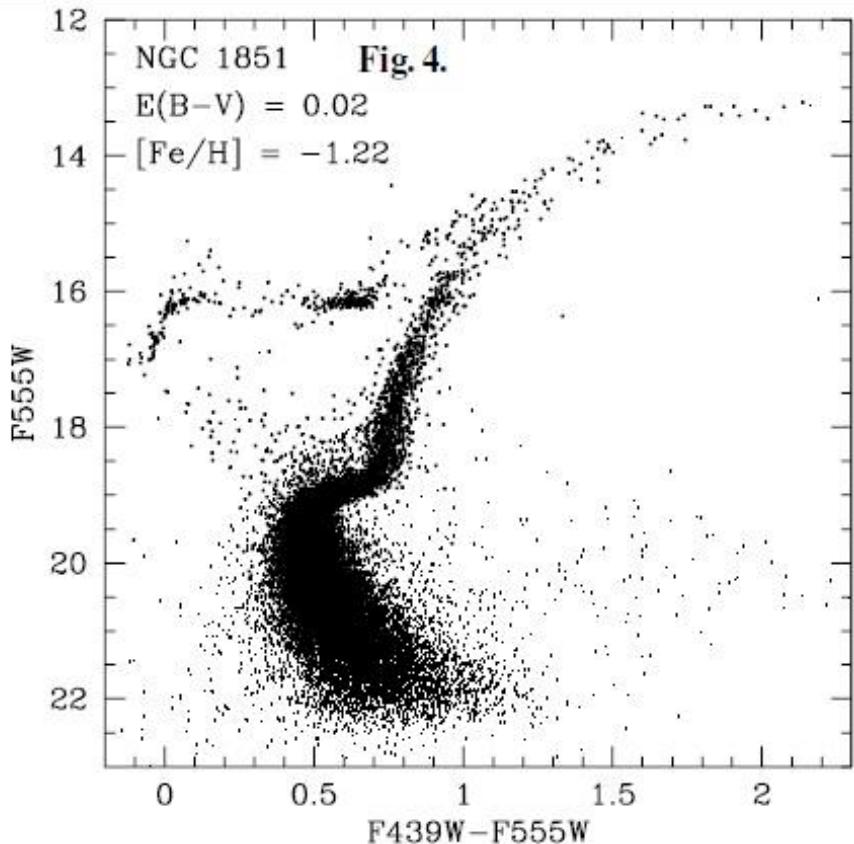
### 4.2 Star Clusters and the HR

#### Diagrams (성단과 HR도)



M22 = NGC 6656 (HST)

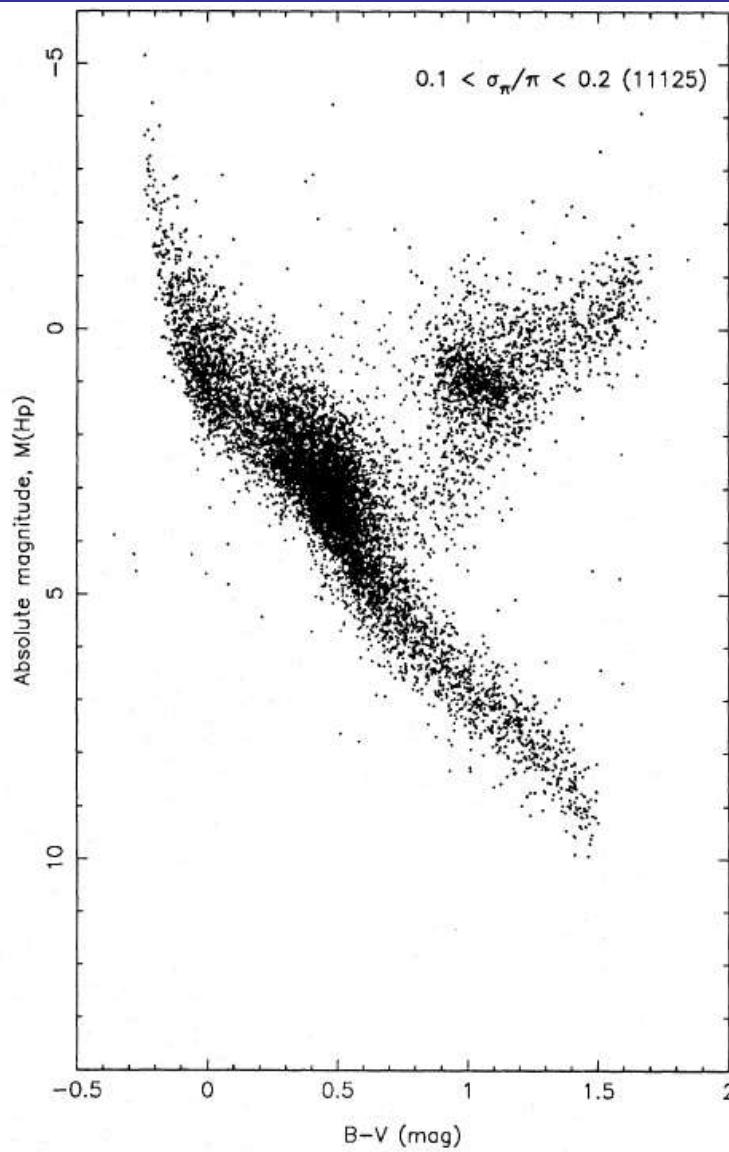
<http://www.space.com/29717-globular-clusters.html>



Piotto et al. (2002, A&A, 391, 945)

# Color-Magnitude Diagrams for Field Stars

11,125 stars with good Hipparcos parallaxes  
(MS/WD stars: p\_errors < 10%, RG stars : p\_errors <20%)



Perryman et al. (1995 A&A 304 69)

# Star Clusters

Open Cluster (OC, 산개성단)

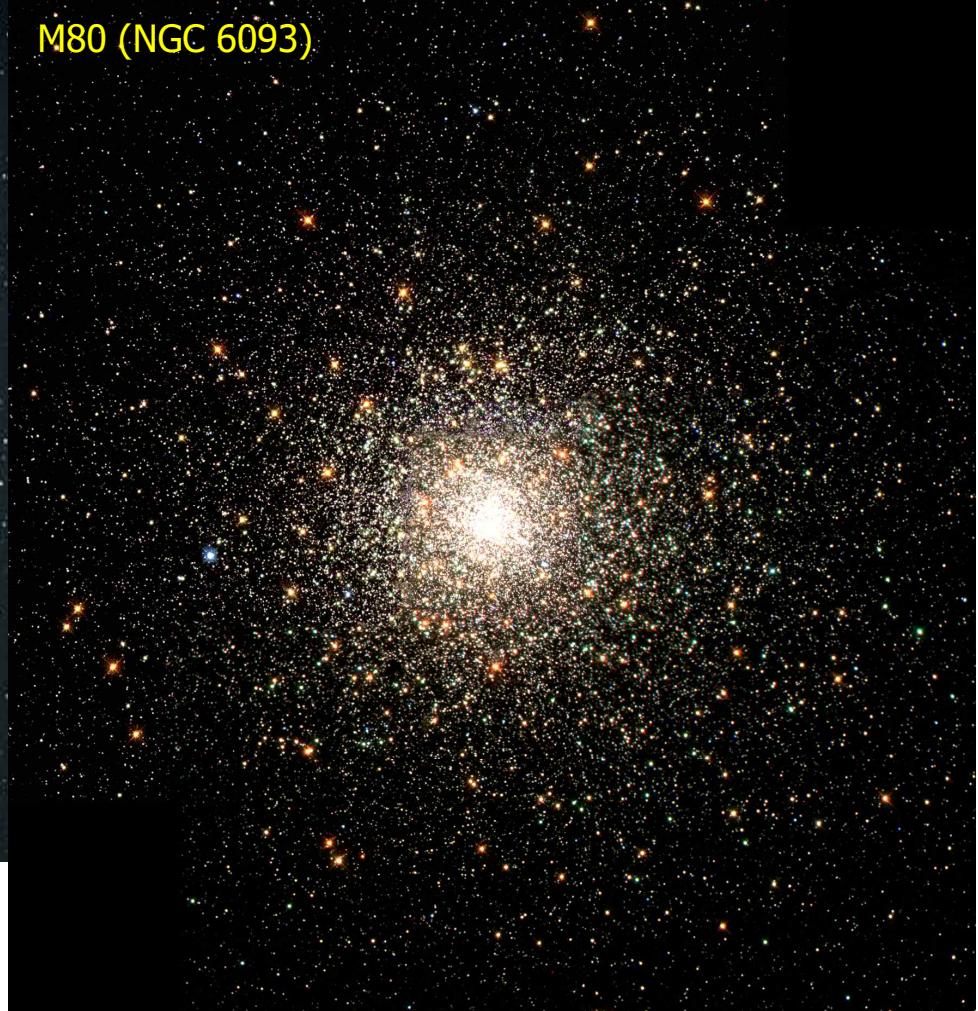
M45 (The Pleiades)



Canon 20D, 70-200mm(f/2.8) @200mm(f/3.5)  
AP1200DA, @iso800, 300s x2

Globular Cluster (GC, 구상성단)

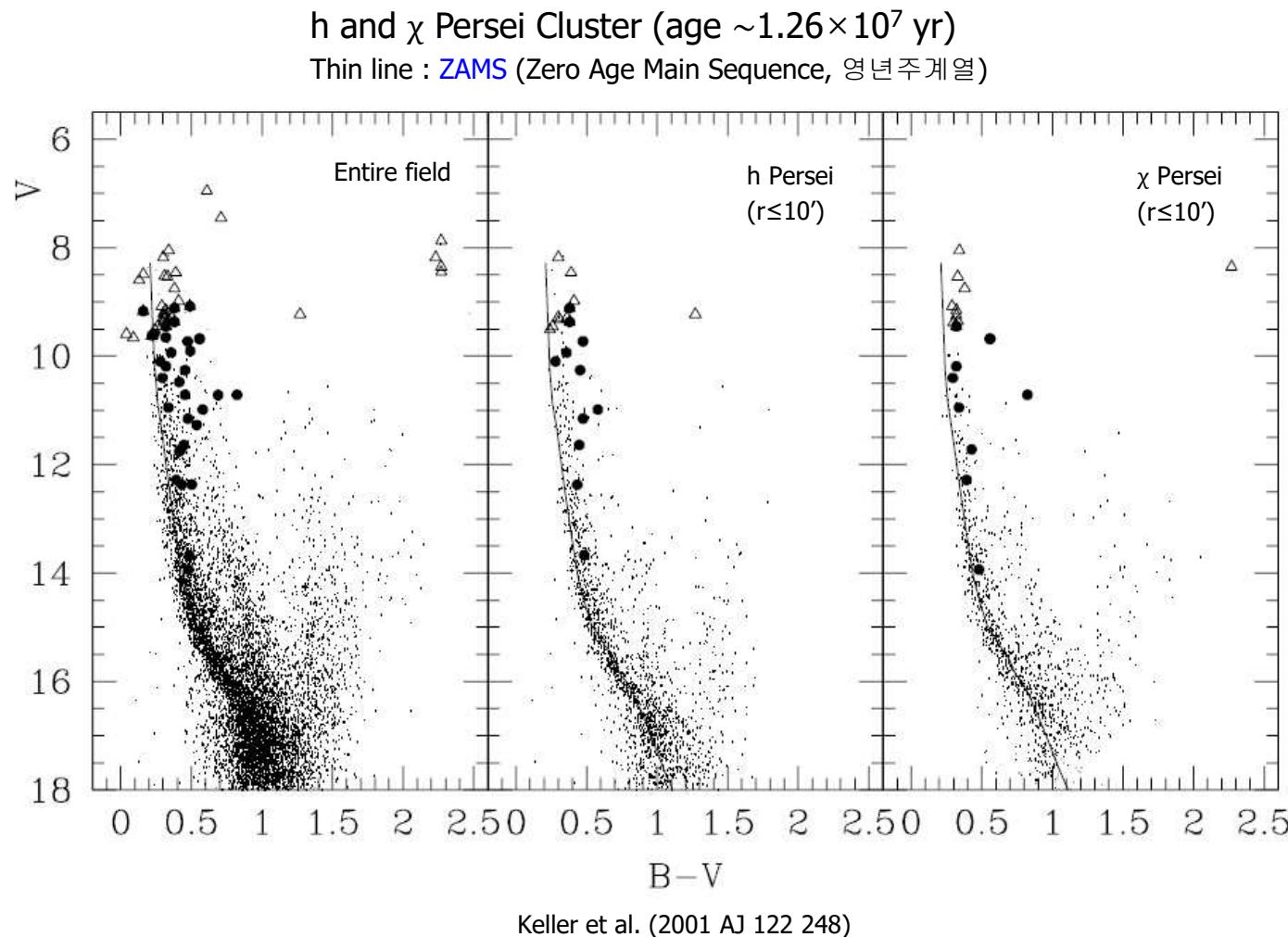
M80 (NGC 6093)



[https://en.wikipedia.org/wiki/Globular\\_cluster](https://en.wikipedia.org/wiki/Globular_cluster)

# Color-Magnitude Diagrams for Open Clusters (OCs)

- Open clusters (산개성단) = Galactic clusters
- CMD : well-defined MS, curving up of the early end of the MS, absence/small/large number of RGB stars

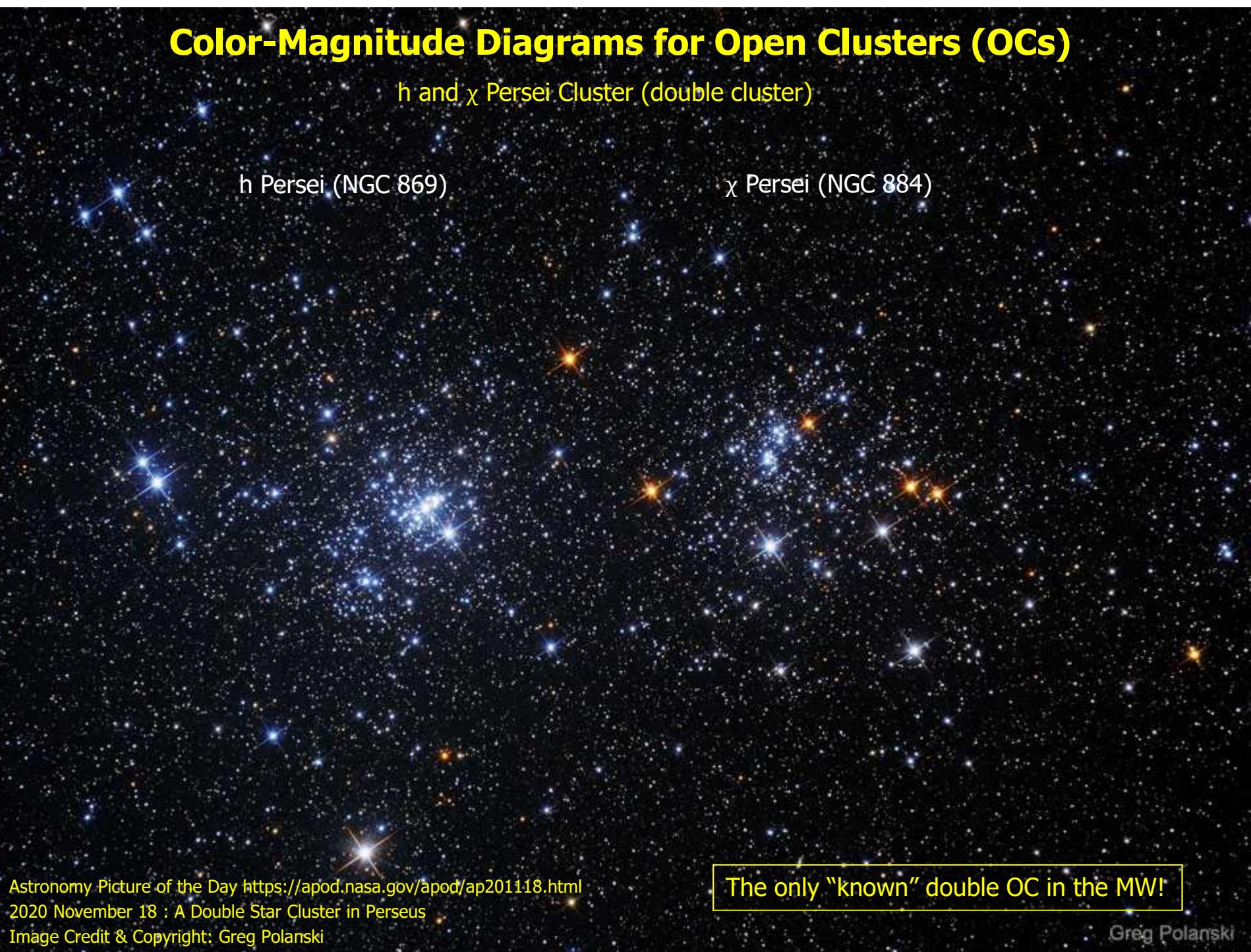


# Color-Magnitude Diagrams for Open Clusters (OCs)

h and  $\chi$  Persei Cluster (double cluster)

h Persei (NGC 869)

$\chi$  Persei (NGC 884)

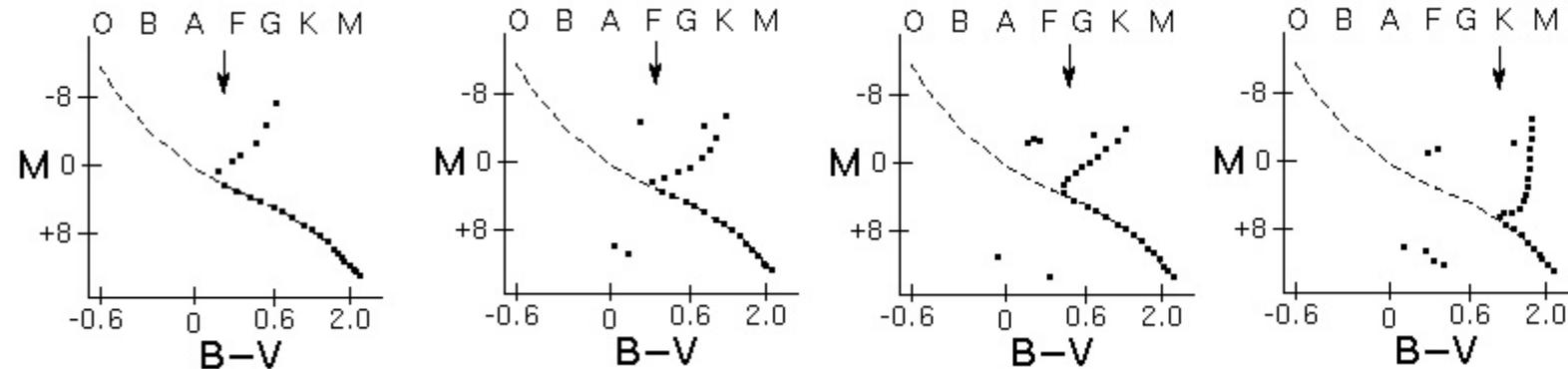


Astronomy Picture of the Day <https://apod.nasa.gov/apod/ap201118.html>  
2020 November 18 : A Double Star Cluster in Perseus  
Image Credit & Copyright: Greg Polanski

The only “known” double OC in the MW!

Greg Polanski

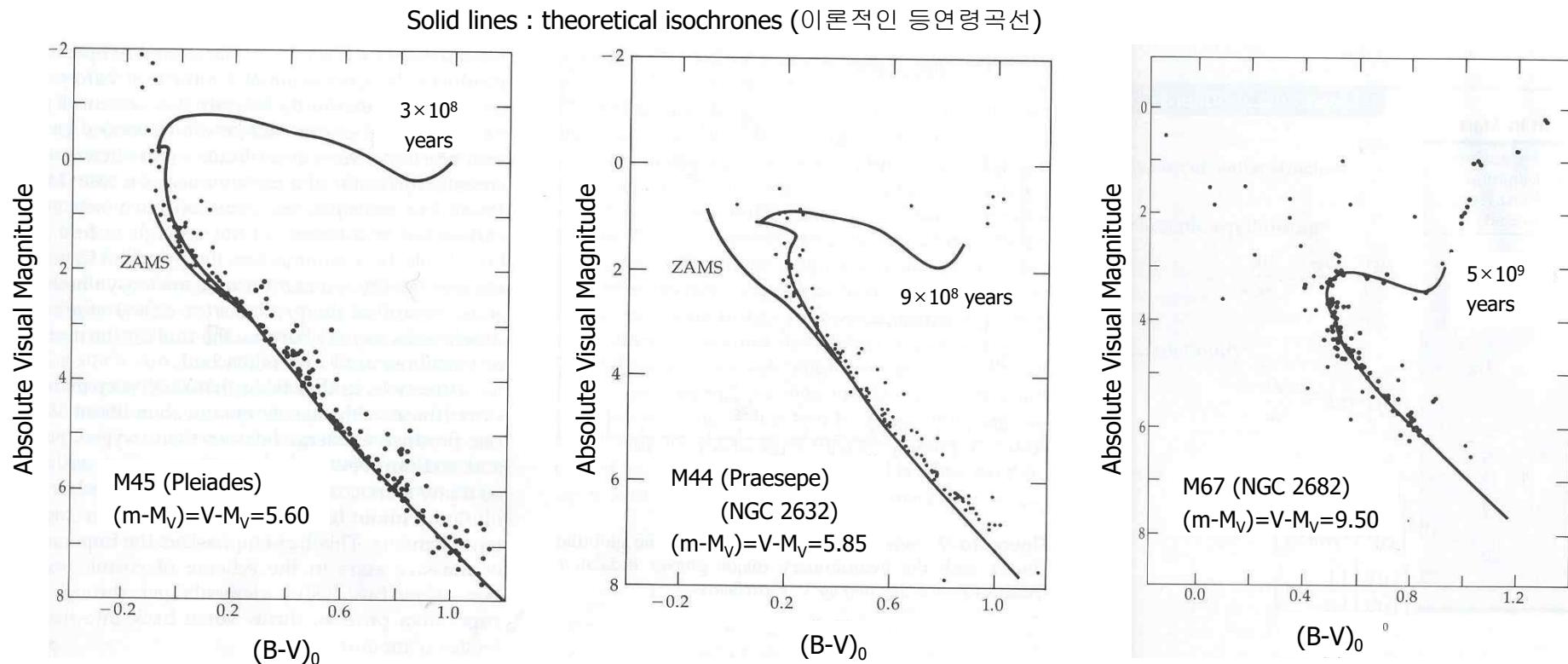
# Color-Magnitude Diagrams for Open Clusters (OCs)



<http://www.astronomynotes.com/evolutn/s9.htm>

- Arrows : main sequence turnoff point (MSTO, 전향점)
  - : stars at this point are leaving the MS
  - : time elapsed since the stars first arrived on the ZAMS

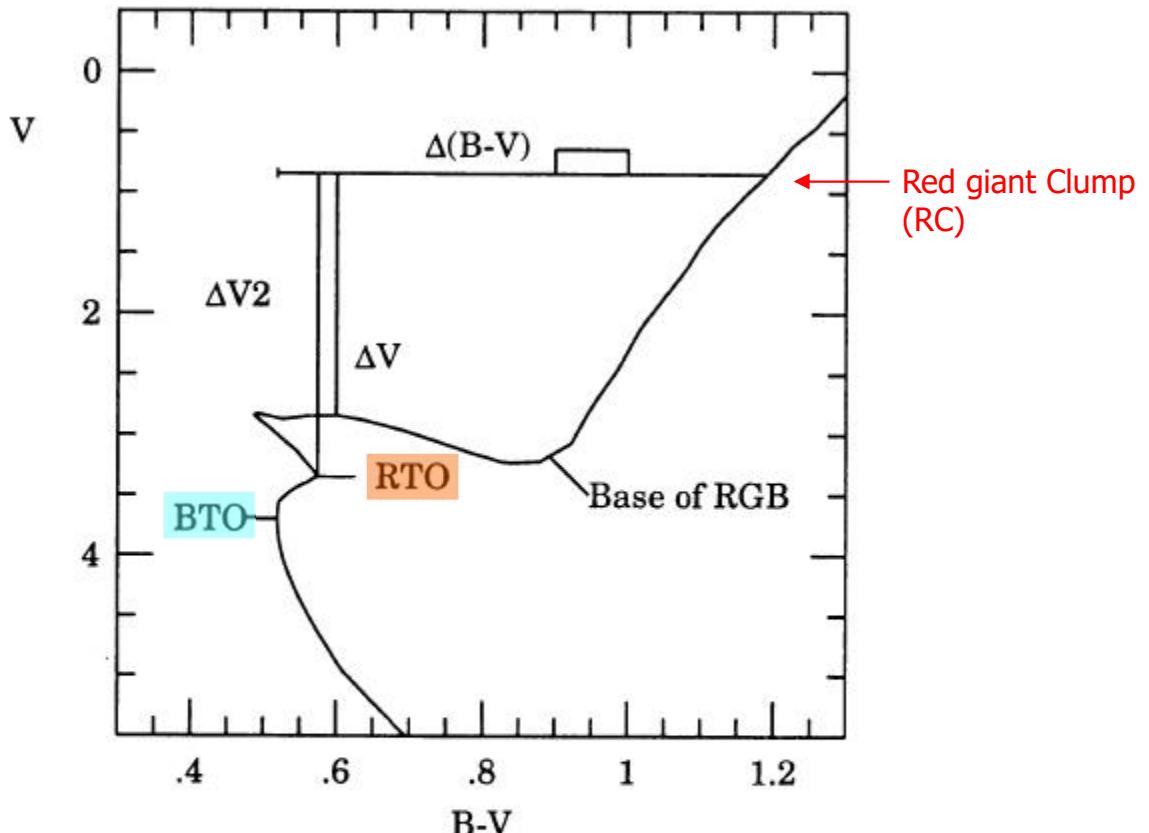
# Color-Magnitude Diagrams for Open Clusters (OCs)



- Observed turnoff points → approximate **ages** of the OCs (성단의 나이)

# Color-Magnitude Diagrams for Open Clusters (OCs)

- MSTO for **old** OCs
- Blue turnoff (BTO)
  - Red turnoff (RTO)

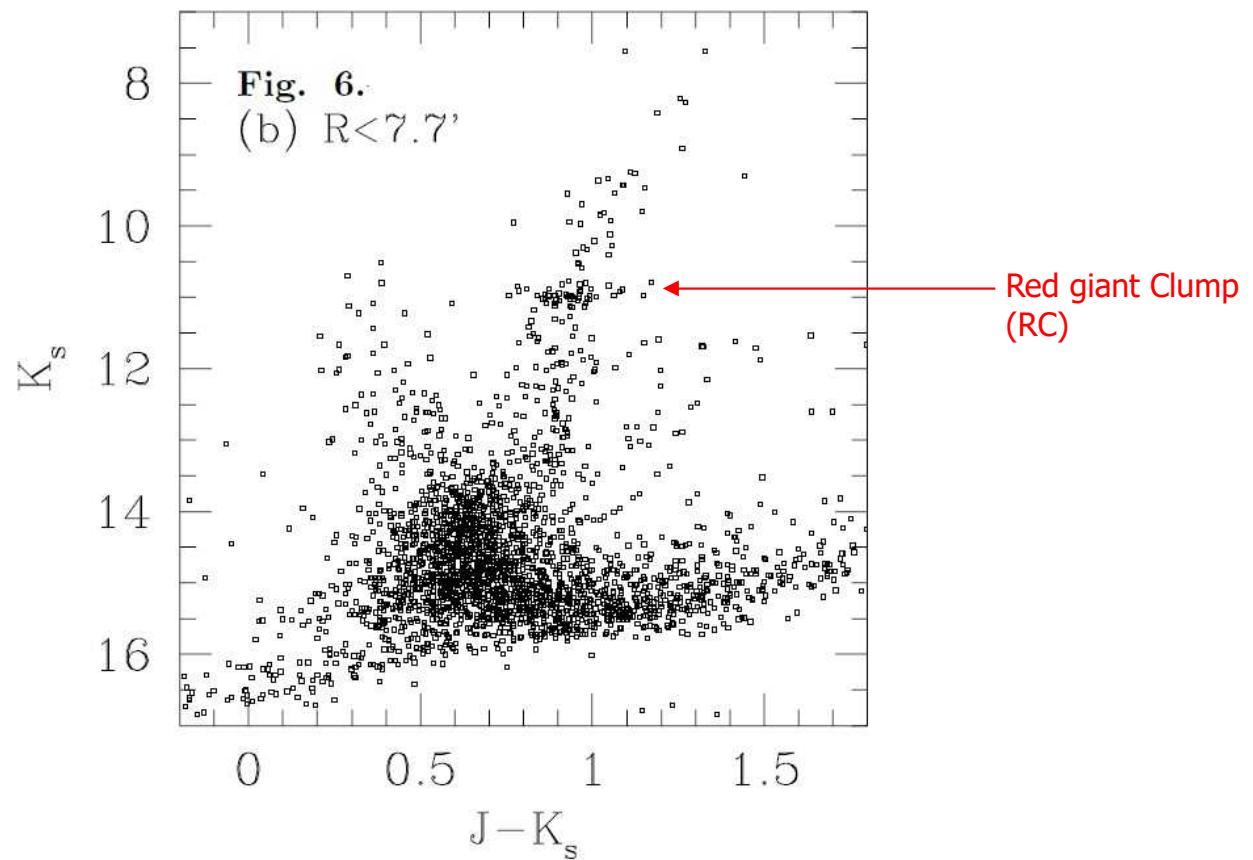


**Fig. 2.** Theoretical isochrone for stars of solar metallicity and age = 4Gyr (Meynet et al. 1993). Positions of the blue turnoff (BTO), the red turnoff (RTO) and the base of the red giant branch (RGB) are marked. The location of the red giant branch clump is marked with a rectangle

Kaluzny 1994 (A&AS 108 151 – CCD photometry of distant OCs. I. Berkeley 22, Berkeley 29 and Berkeley 54)

# Color-Magnitude Diagrams for Open Clusters (OCs)

Core He-burning stars



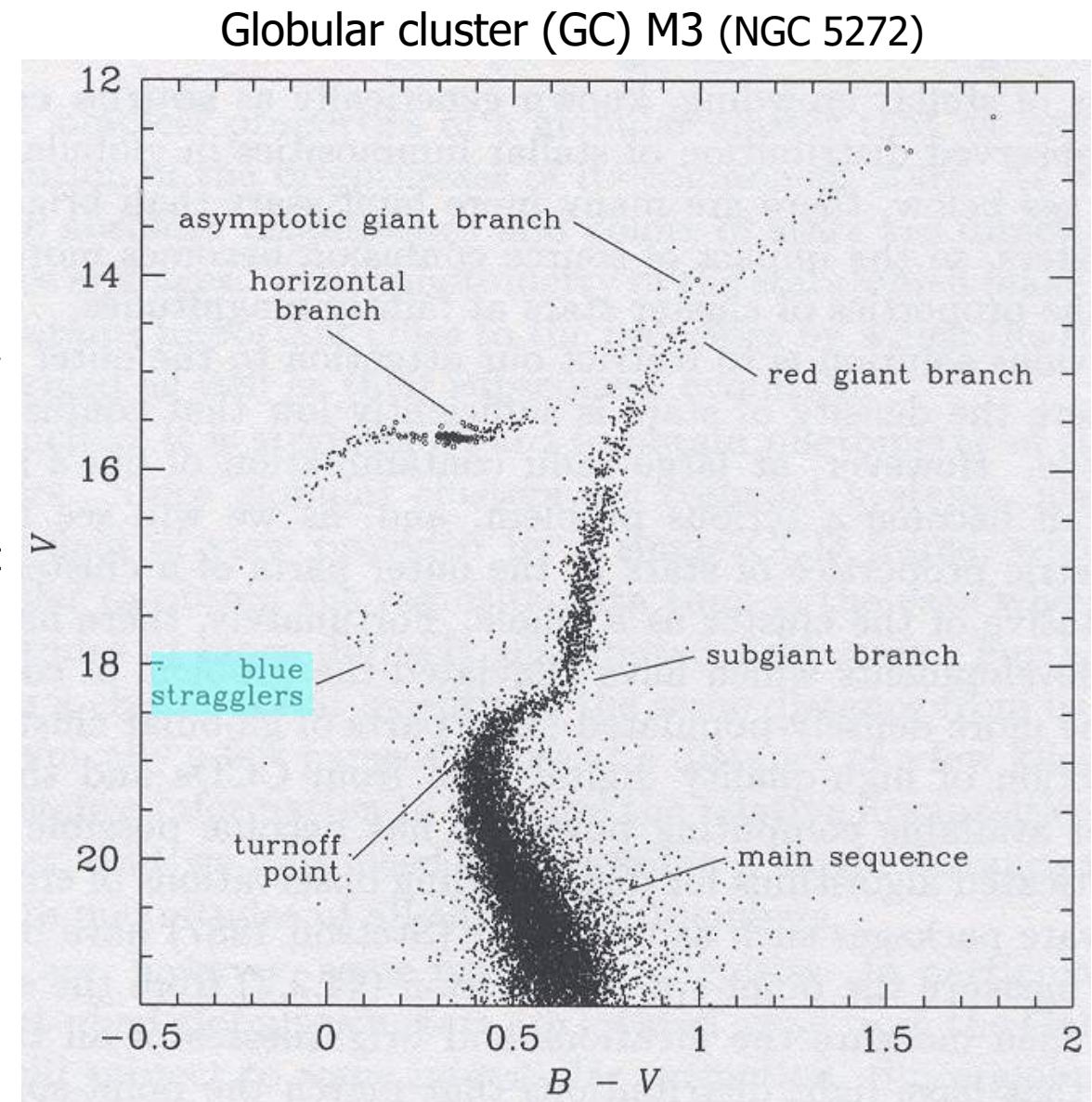
OC Trumpler 5

S. C. Kim et al. (2009, J. Korean Astron. Soc. 42, 135)

# Blue stragglers (BSs)

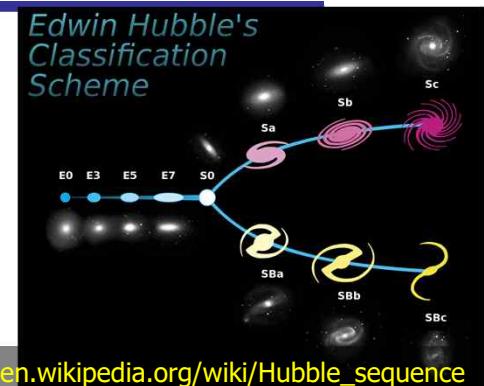
네가 왜 거기서 나와?  
Why are you coming out there?

- Should have left the MS
- Probably
  - Mass exchange with a binary companion
  - Merger with a close companion
  - Internal chemical mixing that provided more H fuel to the core



## Stellar populations – Simple Stellar Population (SSP)

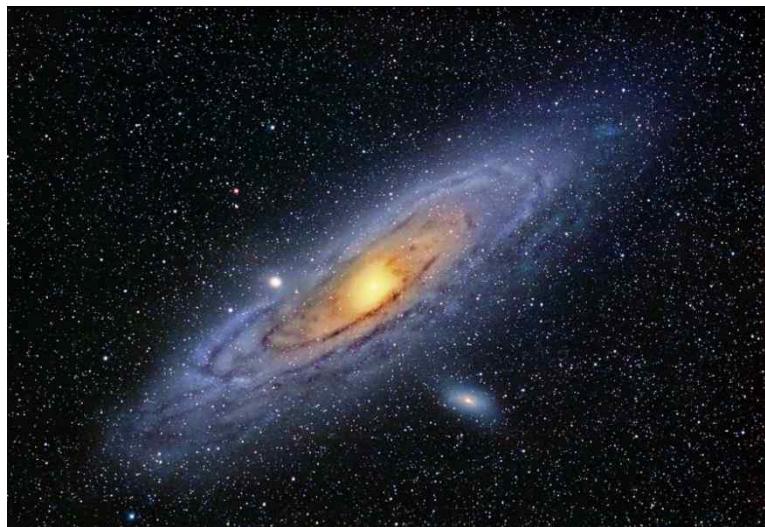
- Star clusters (SCs)
- Open clusters (OCs)
- Globular clusters (GCs)
- Populous clusters (부자성단, 富者星團)



[https://en.wikipedia.org/wiki/Hubble\\_sequence](https://en.wikipedia.org/wiki/Hubble_sequence)

## Stellar populations – Multiple Stellar Populations

- galaxies
- Giant galaxies – elliptical galaxies (E), lenticular galaxies(S0)
  - Early-type galaxies
- spiral galaxies (S : Milky Way Galaxy), irregular galaxies
  - late-type galaxies
- dwarf galaxies – dwarf elliptical galaxies (dE), dwarf spheroidal galaxies (dSph), dwarf irregular galaxies (dI, dIrr), blue compact dwarf (BCD) galaxies



M31\_GS.jpg <http://www.astroimages.com/m31.htm>



Fornax [https://en.wikipedia.org/wiki/Dwarf\\_spheroidal\\_galaxy](https://en.wikipedia.org/wiki/Dwarf_spheroidal_galaxy)

## (young) populous clusters

- Populous clusters (부자성단, 富者星團)
- Large Magellanic Cloud (LMC), Small MC(SMC)

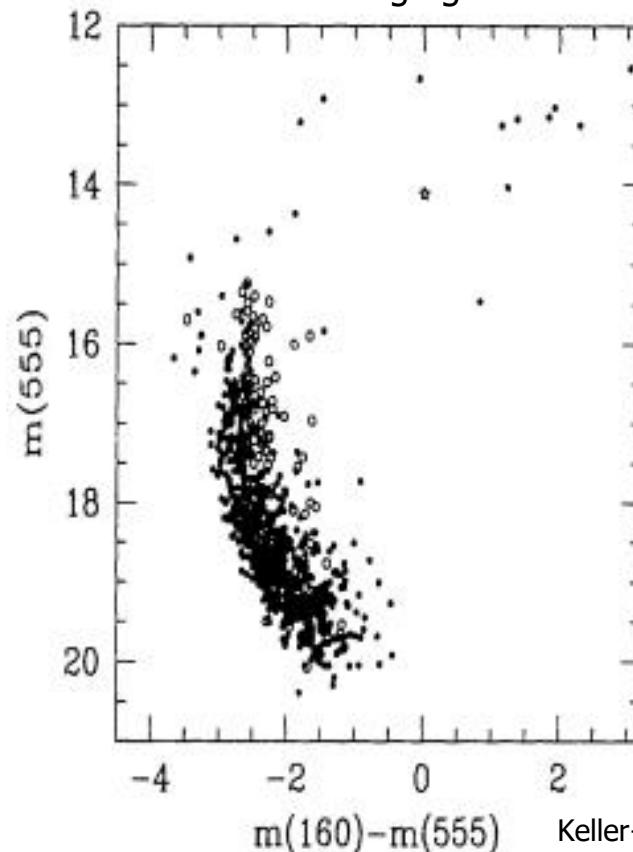
NGC 330 (SMC)



[https://en.wikipedia.org/wiki/NGC\\_330](https://en.wikipedia.org/wiki/NGC_330)

GC-like

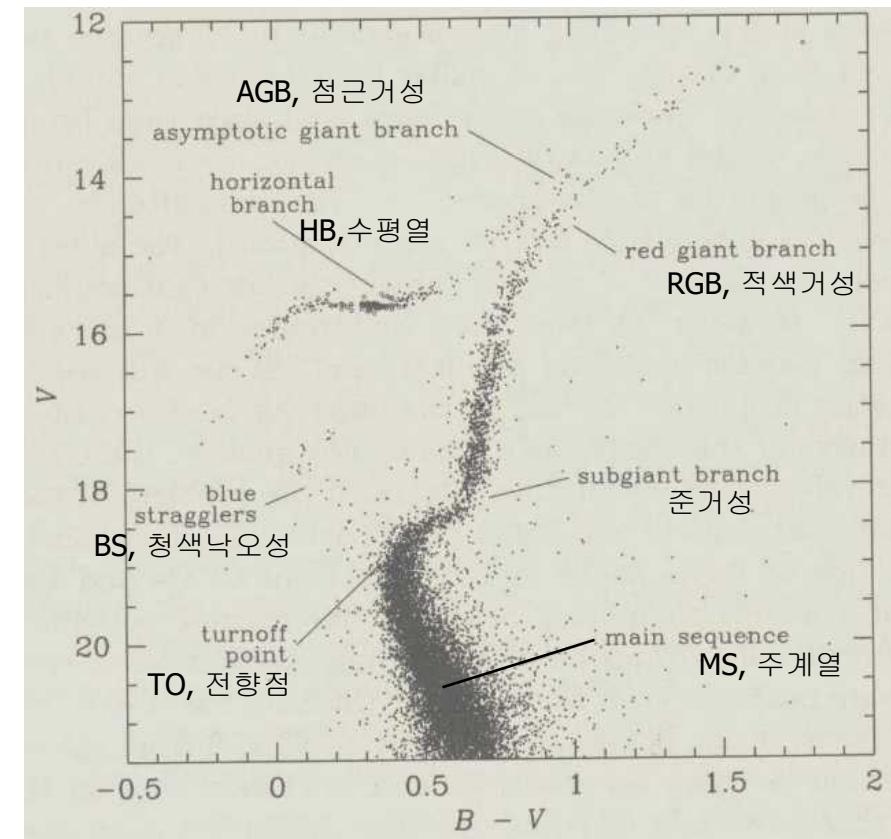
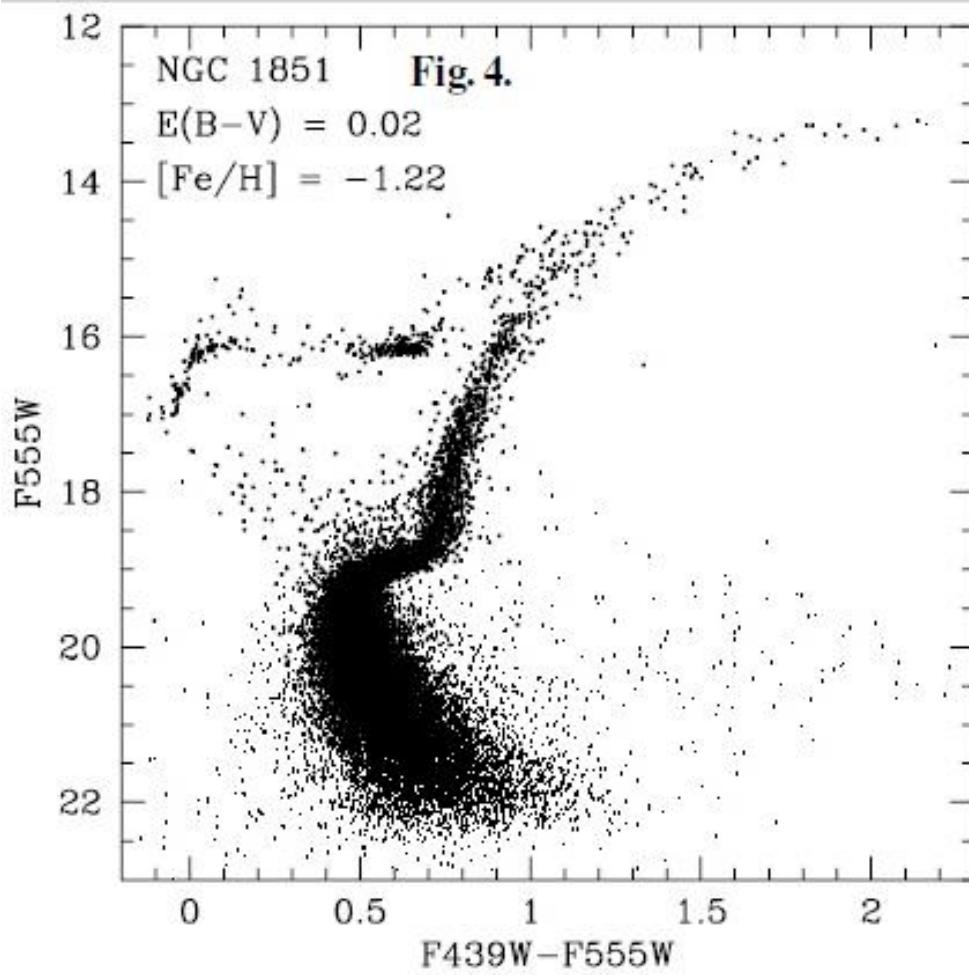
Young age



Keller+00 (ASPCS 211, 124)

$t=4 \times 10^7$  years  
(Song+ 21 MNRAS 504 4160)

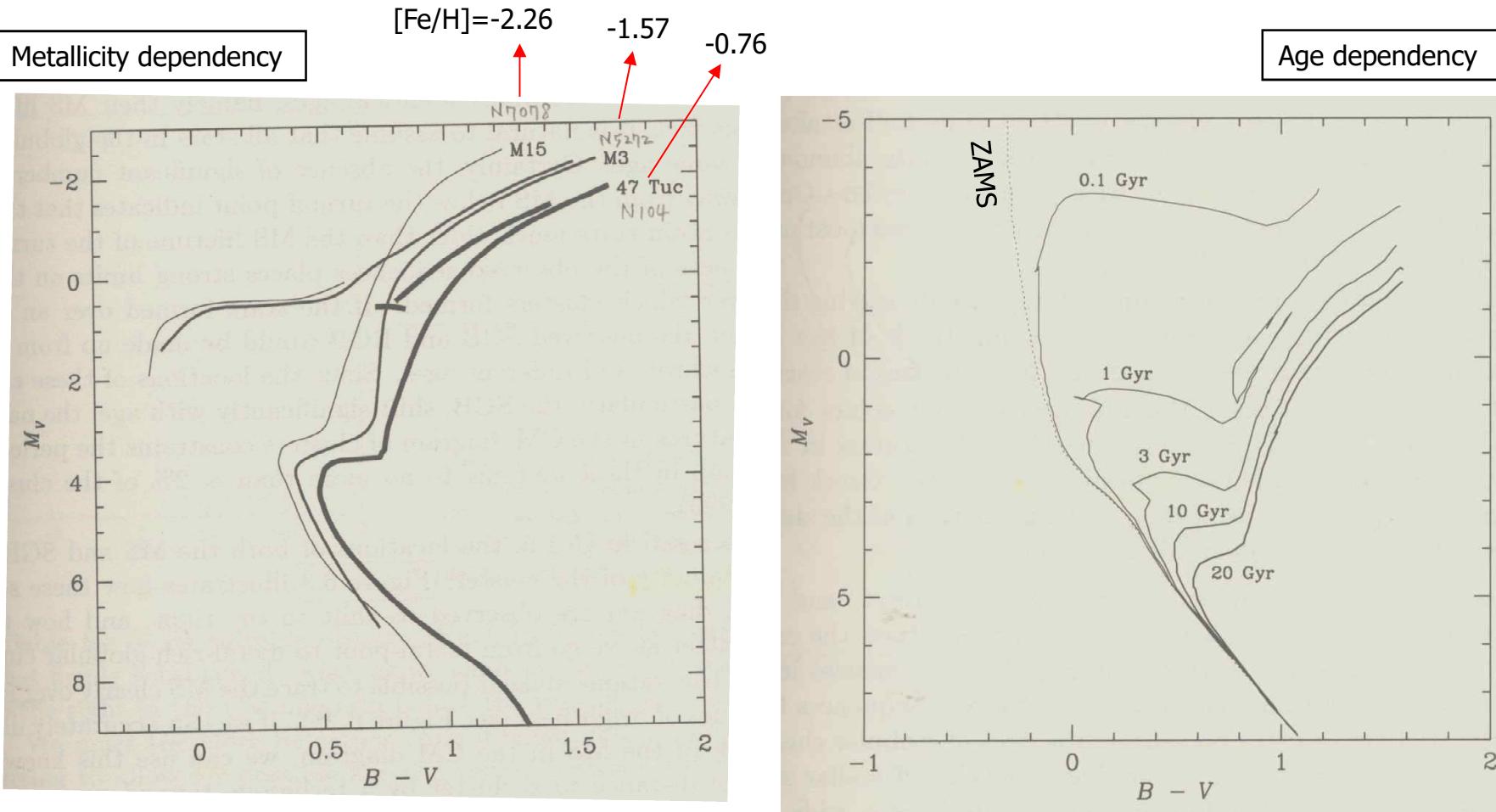
# Color-Magnitude Diagrams for globular clusters (GCs)



GC M3 (NGC 5272)  
(variables=open circles)

- Mostly **old** stars
- MS, RG :  $(B-V)_0 \geq 0.4$
- $[Fe/H] = -1.34$  dex

# Globular Cluster (GC) – metallicities and ages

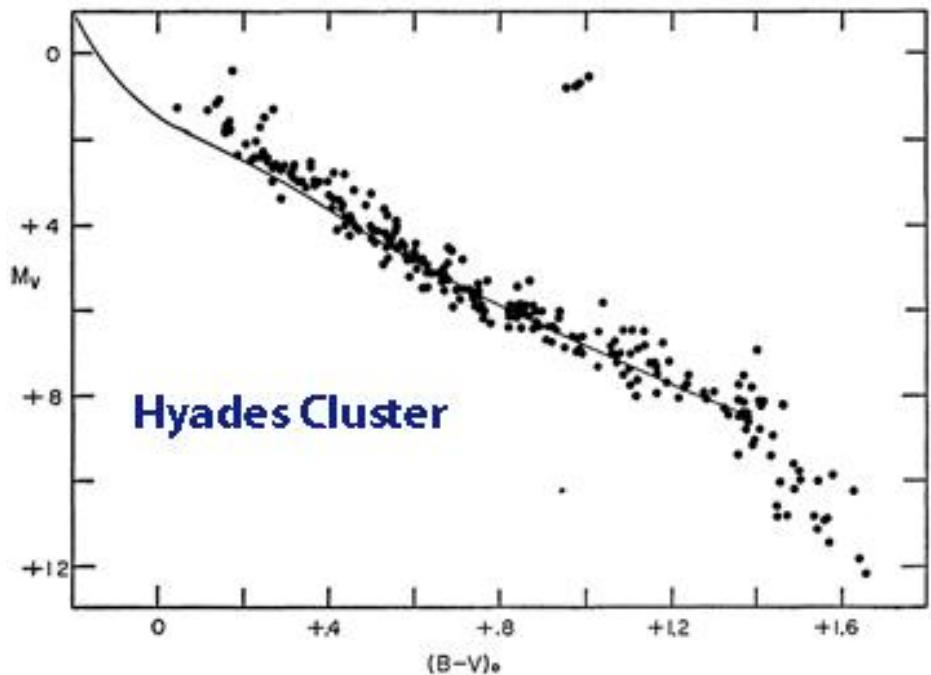


Bertelli + (1994, A&AS, 106, 275)  
Padova isochrones, Z=0.004, Y=0.24

→ Best-fitting isochrones for GCs (MS, SGB) :  
between 10-20 Gyr

# Globular Cluster (GC) - introduction

산개성단  
(散開星團,  
open cluster)



[http://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution\\_pleiadesact.html](http://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_pleiadesact.html)

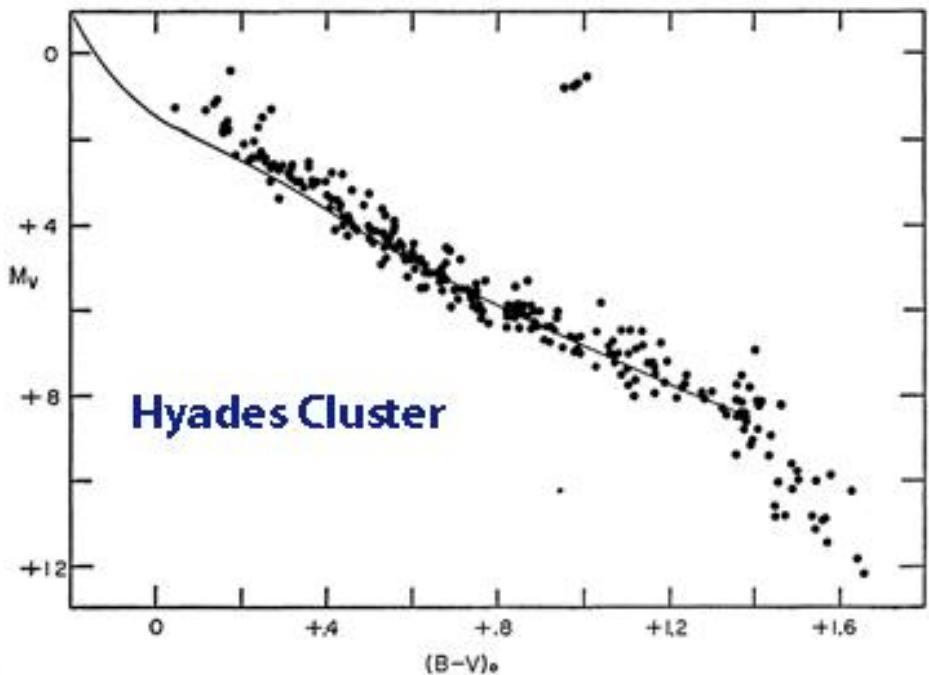
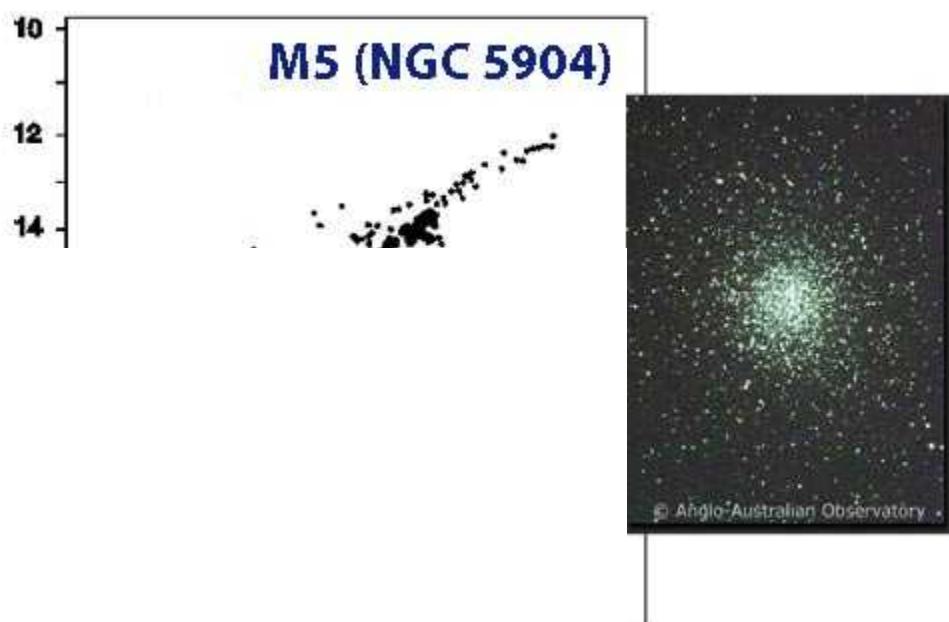


<http://www.daviddarling.info/encyclopedia/H/Hyades.html>

# Globular Cluster (GC) - introduction

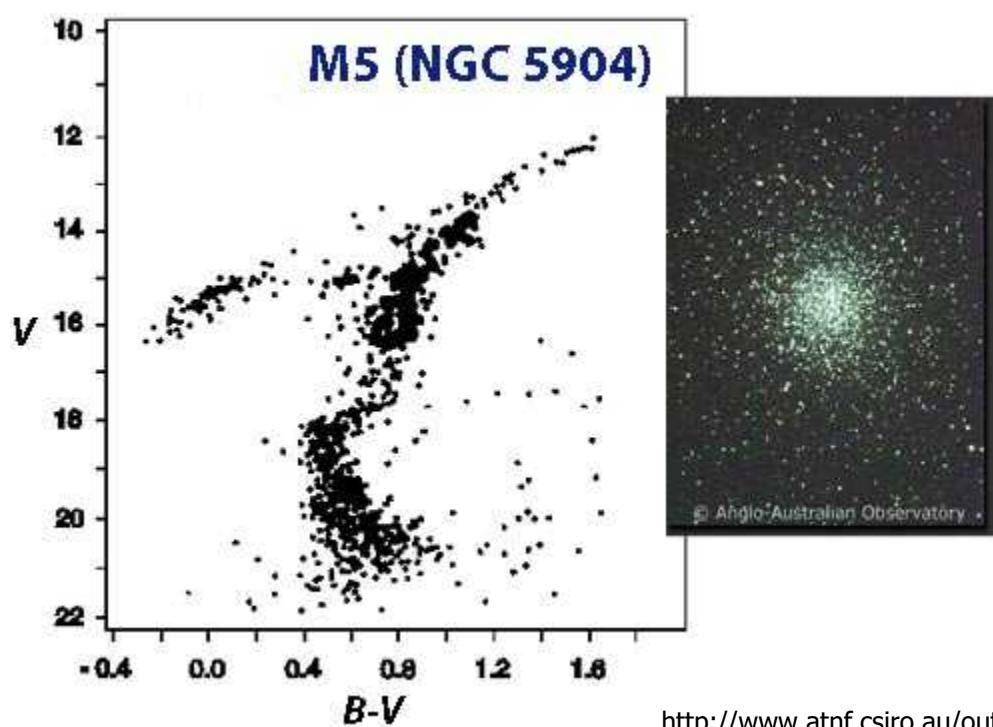
산개성단  
(散開星團,  
open cluster)

구상성단(球狀星團,  
globular cluster)



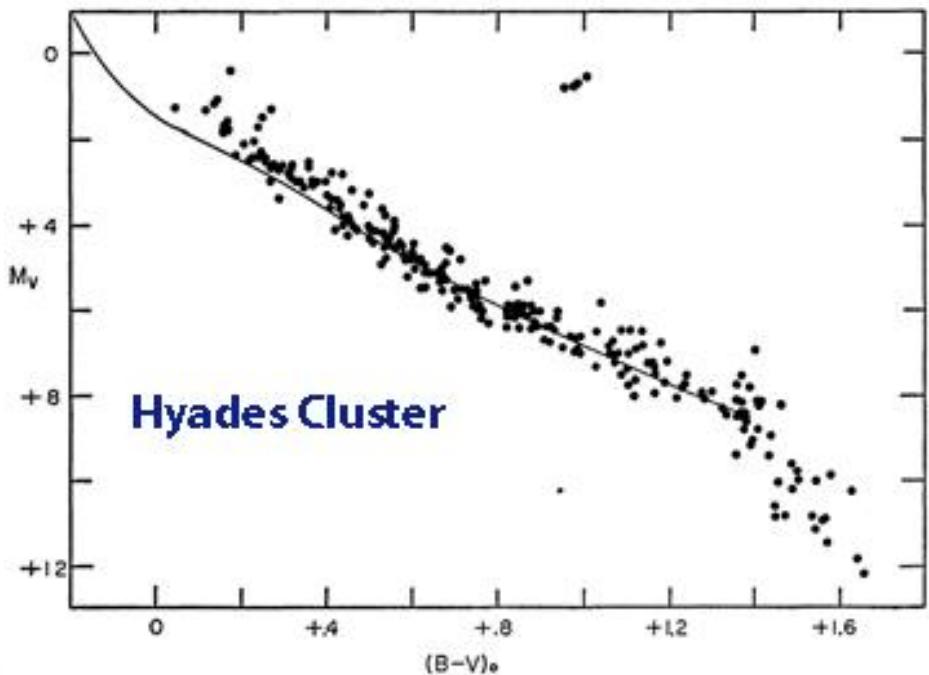
<http://www.daviddarling.info/encyclopedia/H/Hyades.html>

# Globular Cluster (GC) - introduction



산개성단  
(散開星團,  
open cluster)

구상성단(球狀星團,  
globular cluster)



<http://www.daviddarling.info/encyclopedia/H/Hyades.html>

# Globular Cluster (GC) - definition

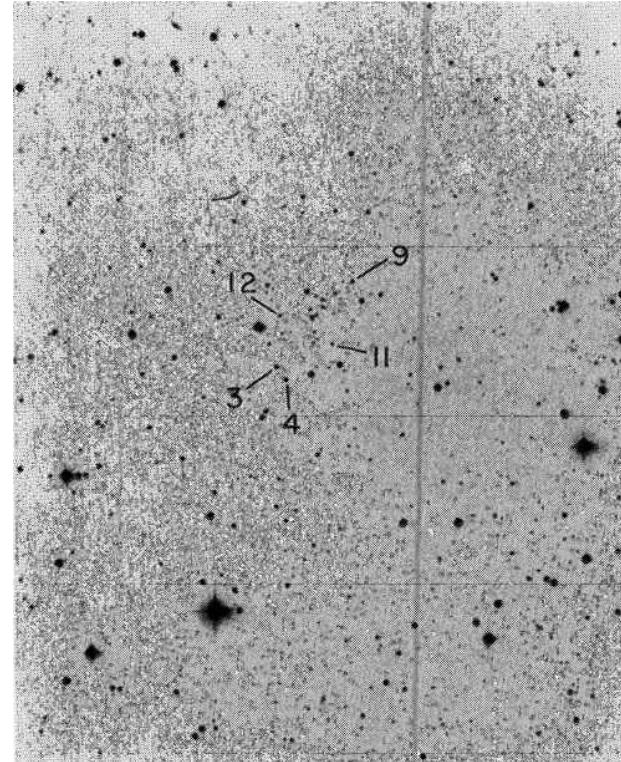
구상성단(球狀星團) = globular cluster

※ globular : shaped like a ball, 공 모양의



M80

[https://en.wikipedia.org/wiki/Messier\\_80#/media/File:A\\_Swarm\\_of\\_Ancient\\_Stars\\_-\\_GPN-2000-000930.jpg](https://en.wikipedia.org/wiki/Messier_80#/media/File:A_Swarm_of_Ancient_Stars_-_GPN-2000-000930.jpg)



Palomar 13

Hodge (1988, PASP, 100, 568 - Star Clusters in Galaxies)

globular cluster definition : structure, age, metallicity, mass, luminosity...

→ Age (> 10 Gyr)

# Galactic SCs – General Characteristics

|                             | Globular clusters         | Open clusters           |
|-----------------------------|---------------------------|-------------------------|
| Mass                        | $6 \times 10^5 M_{\odot}$ | $250 M_{\odot}$         |
| Lifetime                    | 10-15 Gyr                 | $10^6 - 10^8$ yr        |
| Mass-to-light ratio         | $2 M_{\odot}/L_{\odot}$   | $1 M_{\odot}/L_{\odot}$ |
| Central density             | $8000 M_{\odot}/pc^3$     | $100 M_{\odot}/pc^3$    |
| Core radius ( $r_c$ )       | 1.5 pc                    | 1 pc                    |
| Half-light radius ( $r_h$ ) | 10 pc                     | 2 pc                    |
| Tidal radius ( $r_t$ )      | 50 pc                     | 10 (-20) pc             |
| Central velocity dispersion | 7 km/s                    | 1 km/s                  |

$r_c$  : radius at which the **surface brightness** has fallen to half of its central value

$r_h$  : radius within which half the **total luminosity** from the cluster is received

$r_t$  : truncation radius, beyond which the external **gravitational field** of the galaxy dominates the dynamics

Number of GCs :

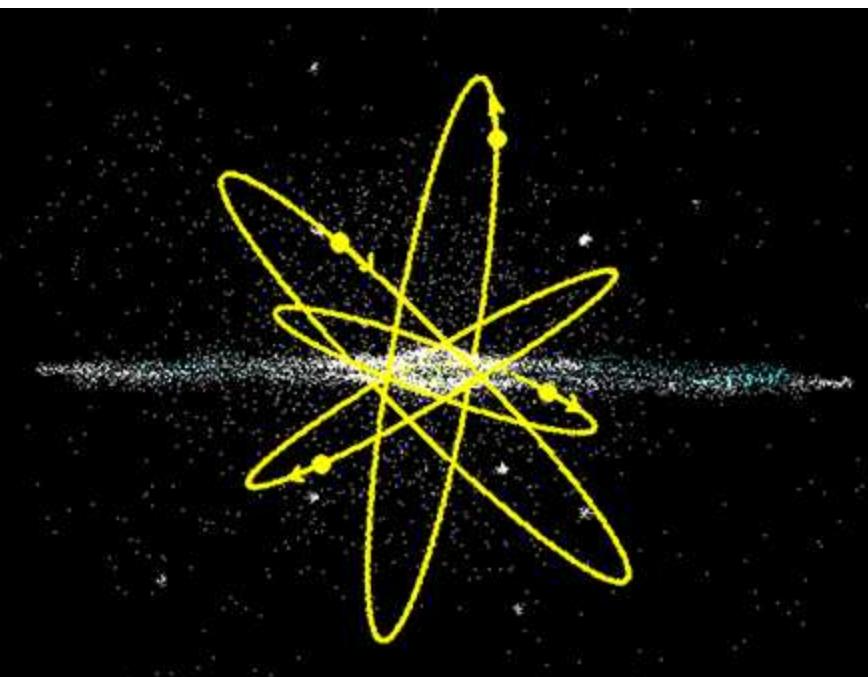
MWG :  $N \sim 150$

M31 :  $N \sim 245$  (only confirmed GCs) ← Revised Bologna Catalogue V.5 (Aug 2012)  
[\(http://www.bo.astro.it/M31/\)](http://www.bo.astro.it/M31/)

$N \sim 2060$  (all GCs and GC candidates)

# GCs and OCs in the MW

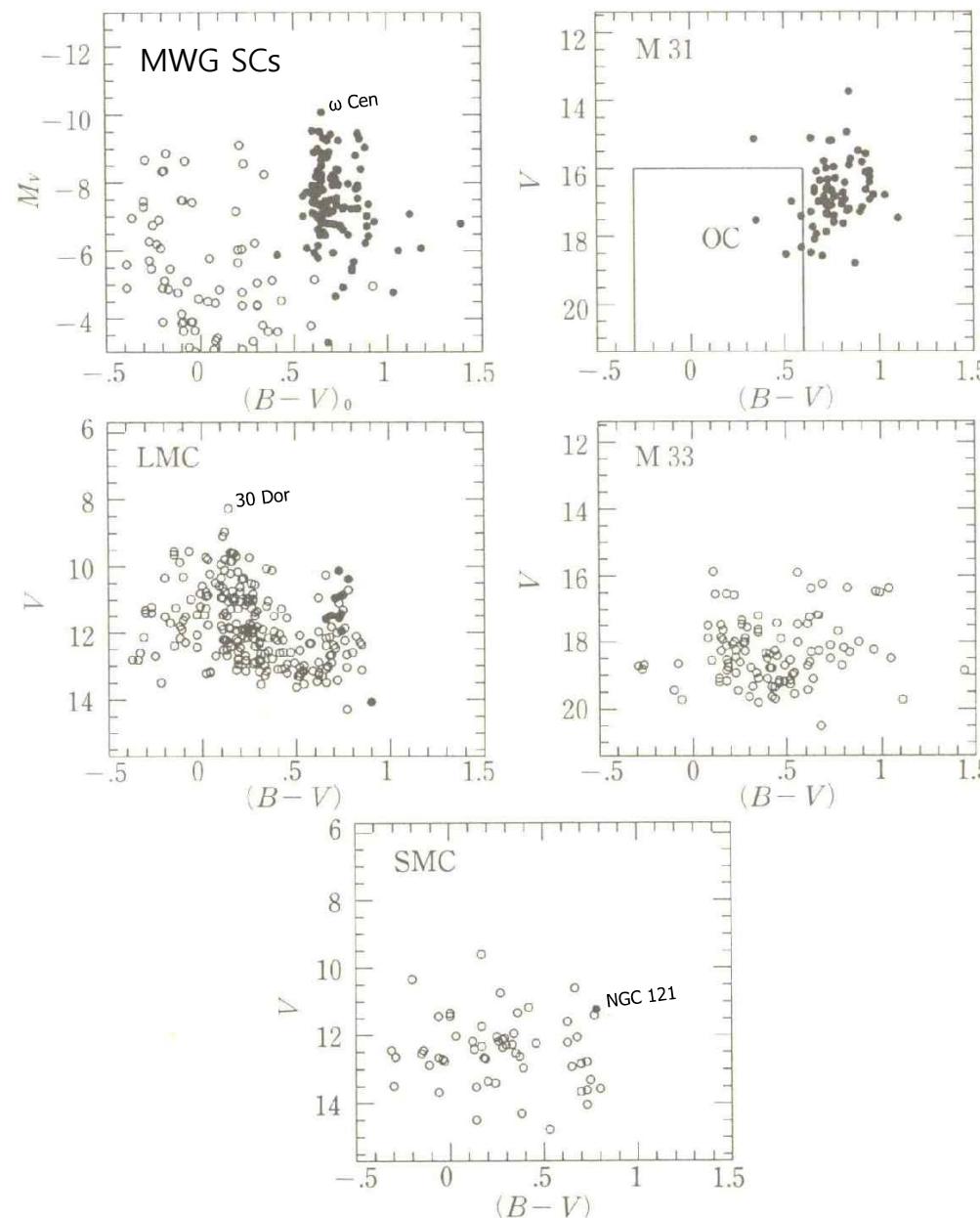
GCs : high velocity dispersion, eccentric orbits



OCs →  
: circular rotation  
in the disk

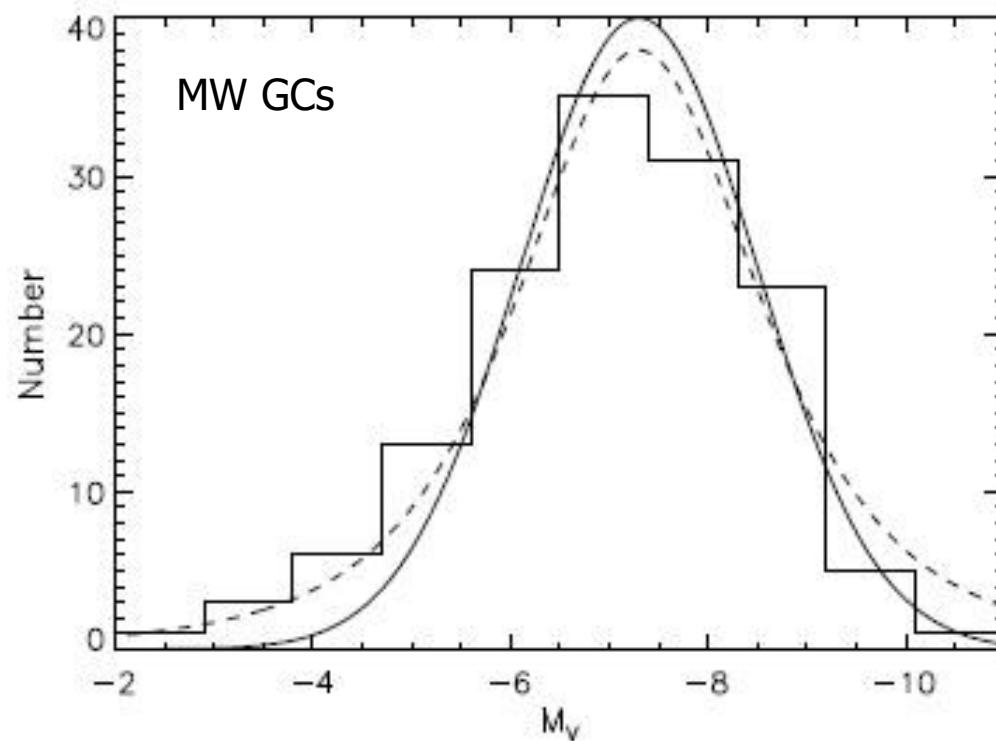
# GCs and OCs in the MW

- : GCs
- : young SCs



# GC luminosity function (GCLF)

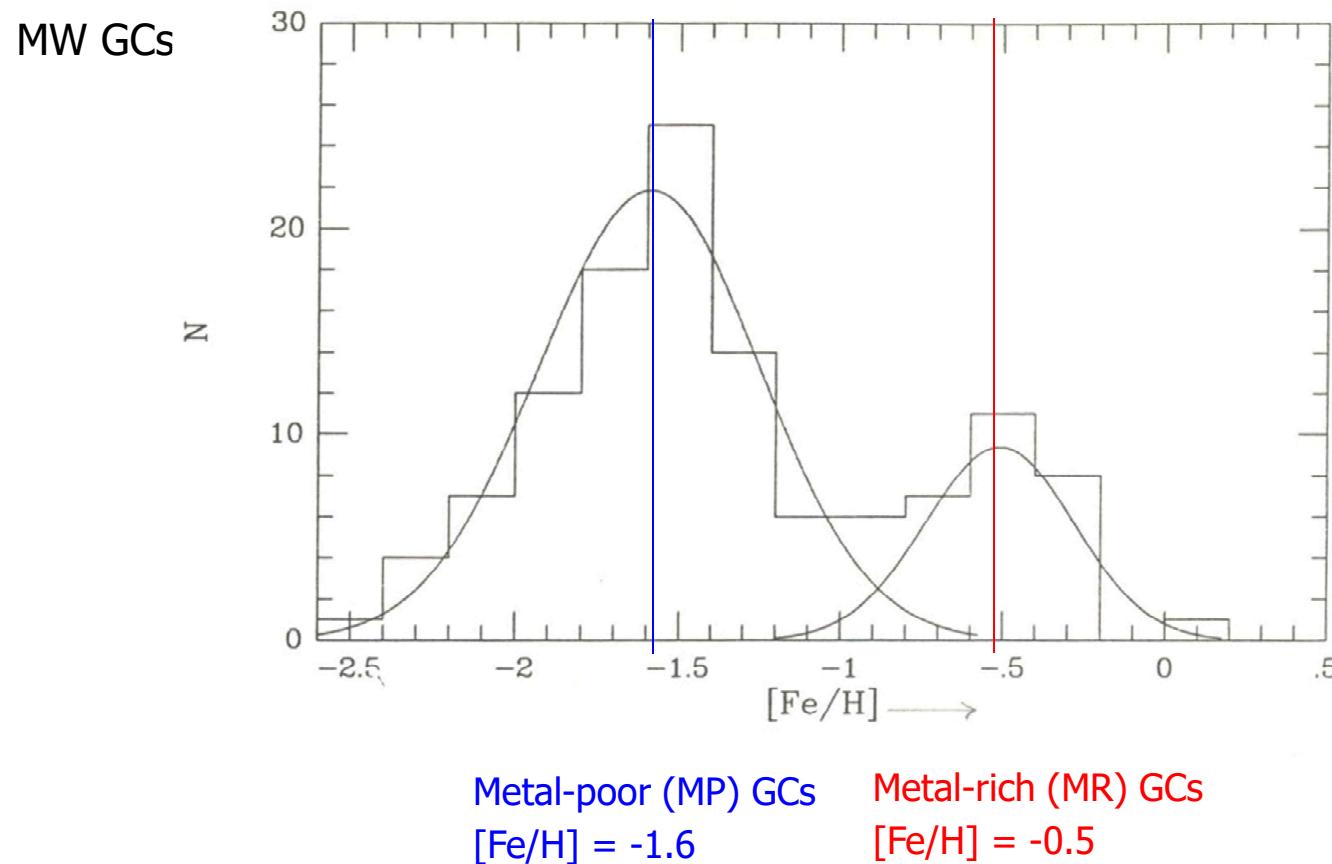
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Rejkuba (2012, Ap&SS, 341, 195 – GCLF as distance indicator) – Fig. 3

$$\langle M_V \rangle = -7.3, \sigma = 1.4$$

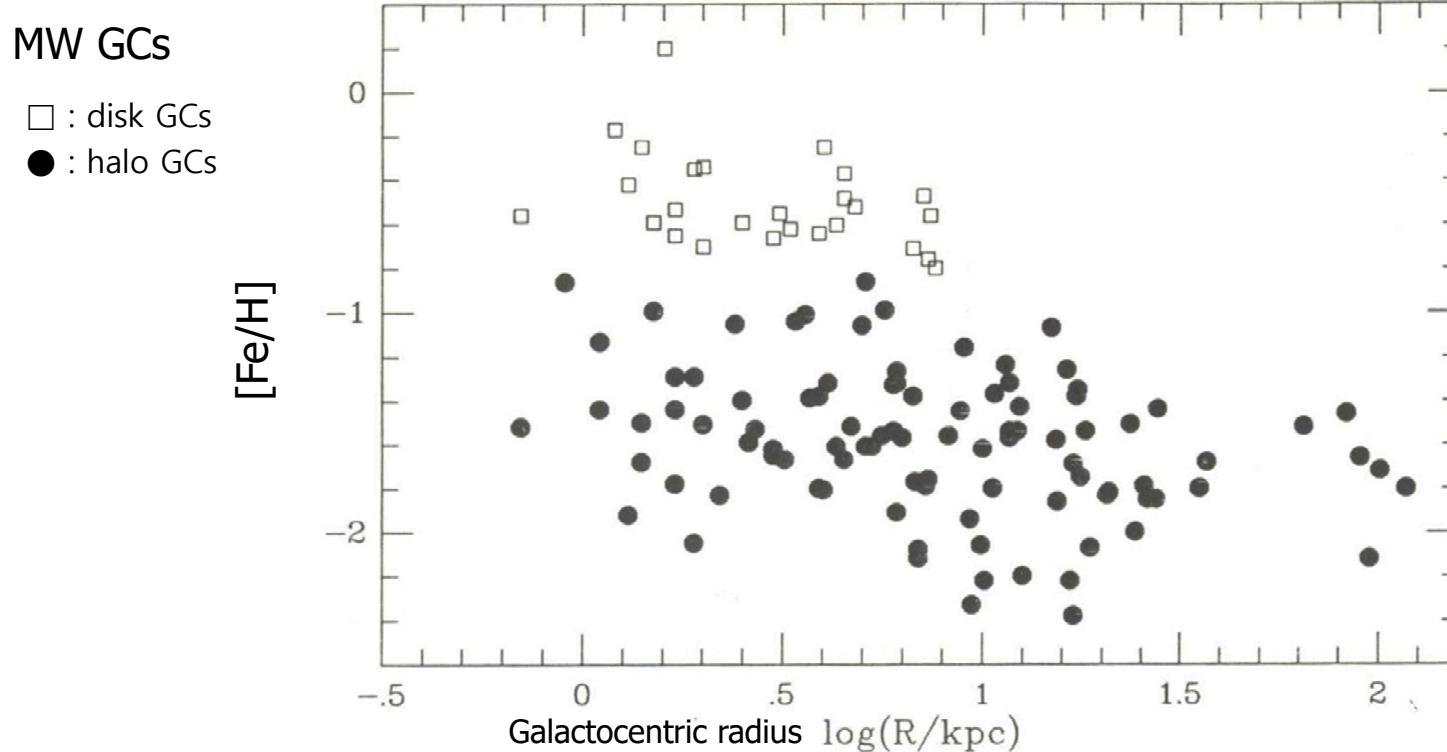
# Metallicity Distribution Function (MDF)



Different origins  
(Formation mechanisms)

Globular Cluster Systems (1998, K. M. Ashman & S. E. Zepf, p. 37)

# Radial metallicity distribution



- Metallicity gradient – mainly due to MR GCs at  $R \leq 8$  kpc
- Slight metallicity gradient in the halo GCs

# GCs : ellipticity (타원율)

$\omega$  Cen (Omega Centauri) = NGC 5139

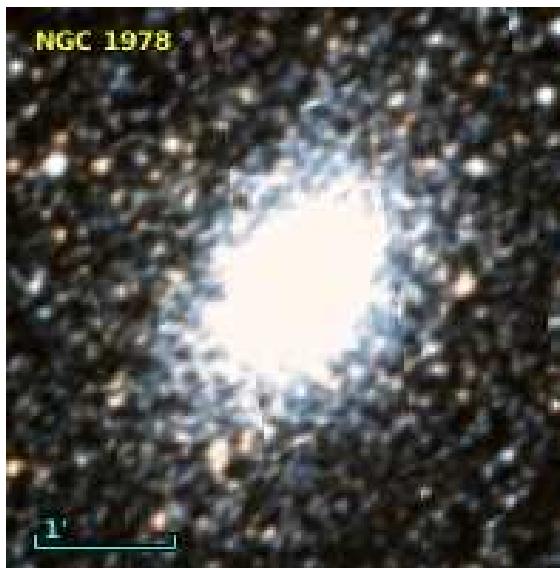
$\epsilon=0.19$ ,  $M_V = -10.1$ , slow rotation



<http://www.sidleach.com/ngc5139.htm>

NGC 1978 (LMC)

$\epsilon=0.33$ ,  $M_V = -8.0$ ,  $t = 2.5$  Gyr



<http://aladin.u-strasbg.fr/simbad-thumbnails/thumbnails23.html>

NGC 121 (SMC)

$\epsilon=0.26$ ,  $M_V = -7.7$ ,  $t = 1.2$  Gyr



HST

[https://pl.wikipedia.org/wiki/NGC\\_121](https://pl.wikipedia.org/wiki/NGC_121)

G1 = Mayall II (M31)

$\epsilon=0.22$ ,  $M_V = -11.0$

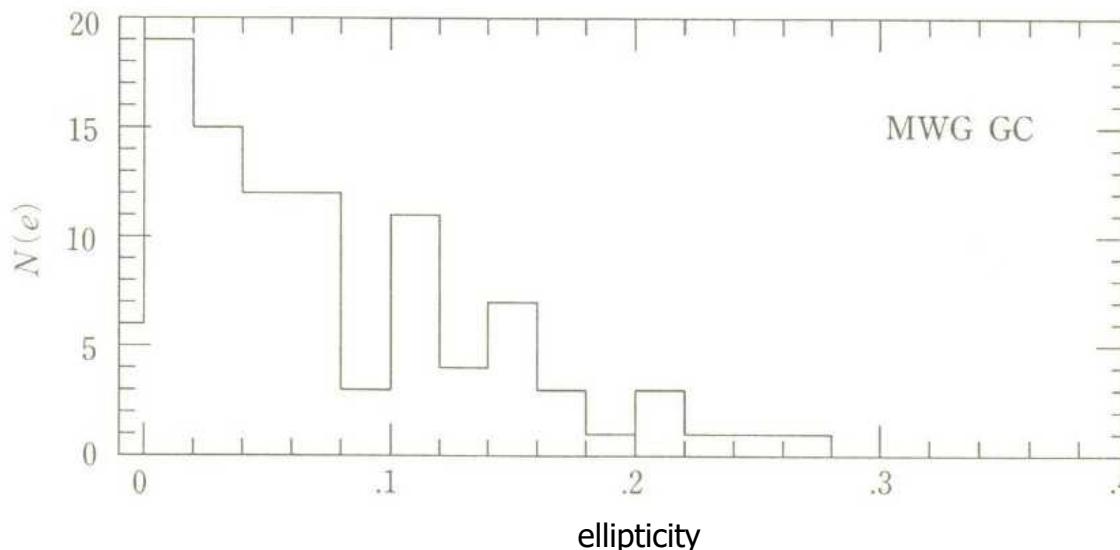
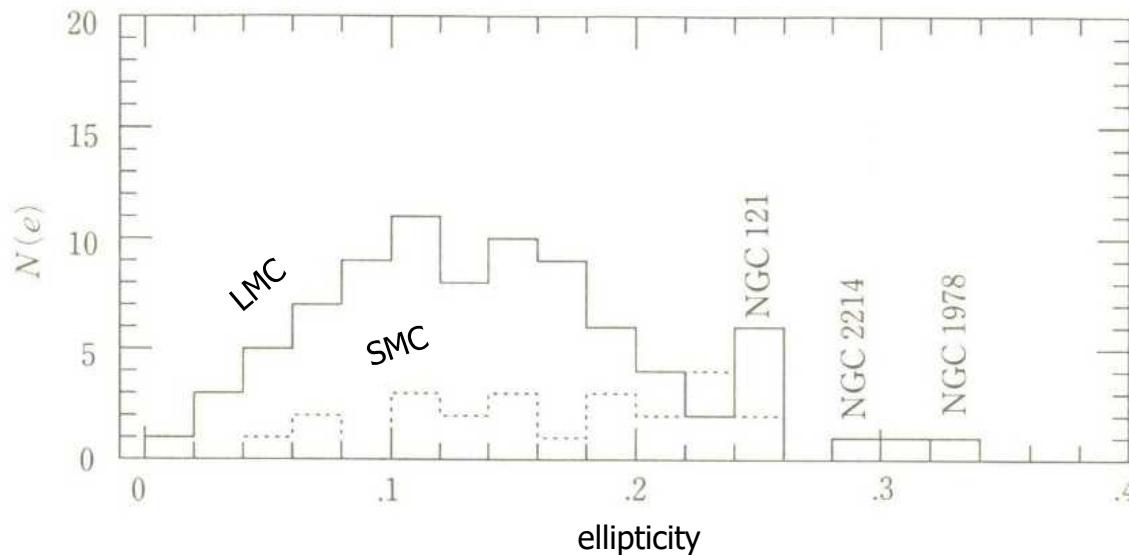
HST

[https://en.wikipedia.org/wiki/Mayall\\_II](https://en.wikipedia.org/wiki/Mayall_II)



# GCs : ellipticity (타원율)

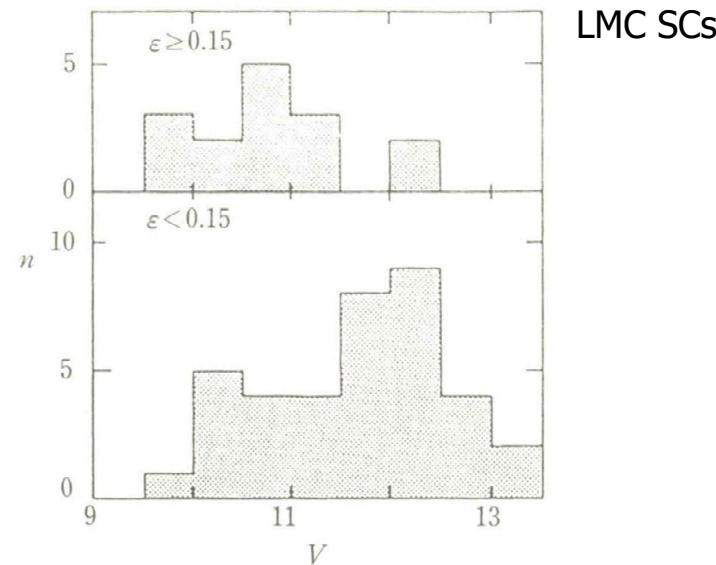
- Brightest GCs in galaxies  $\sim$  large ellipticities
- MCs : larger ellipticities than MW
- Largest  $\epsilon$  in MCs » largest  $\epsilon$  in MWG



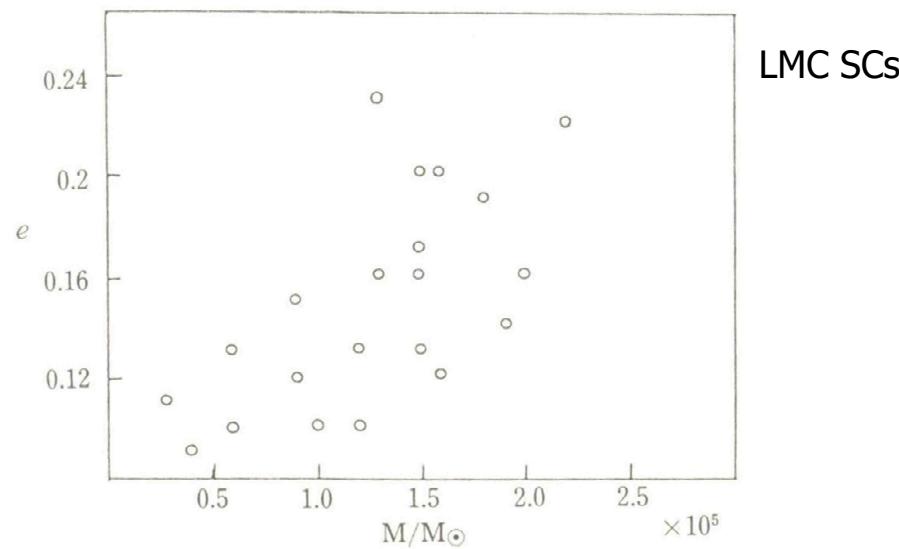
구형항성계의 진화(1997,  
안홍배 오갑수 이명균 등, p. 67)

# GCs : ellipticity (타원율)

Brighter GCs  $\sim$  larger  $\epsilon$

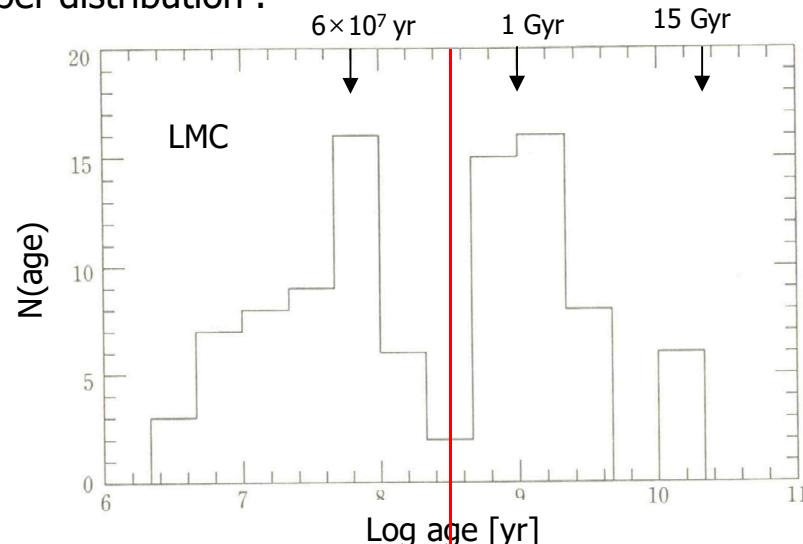


massive GCs  $\sim$  larger  $\epsilon$

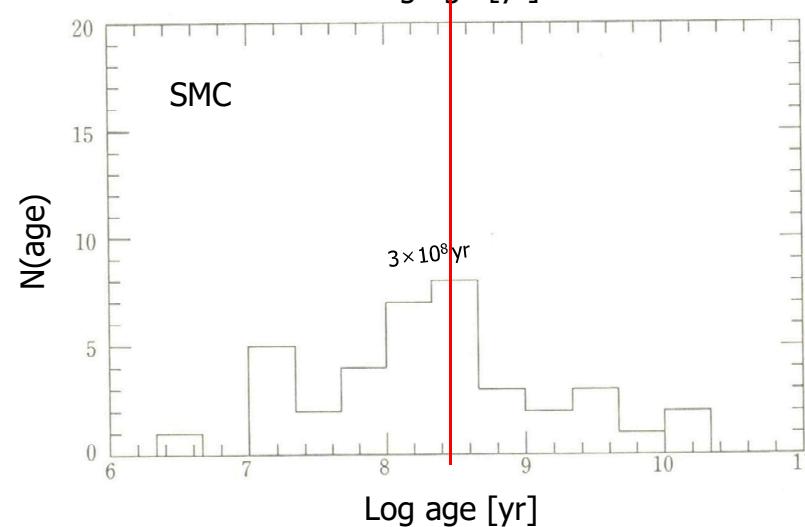


# GCs : age distribution

Number distribution :



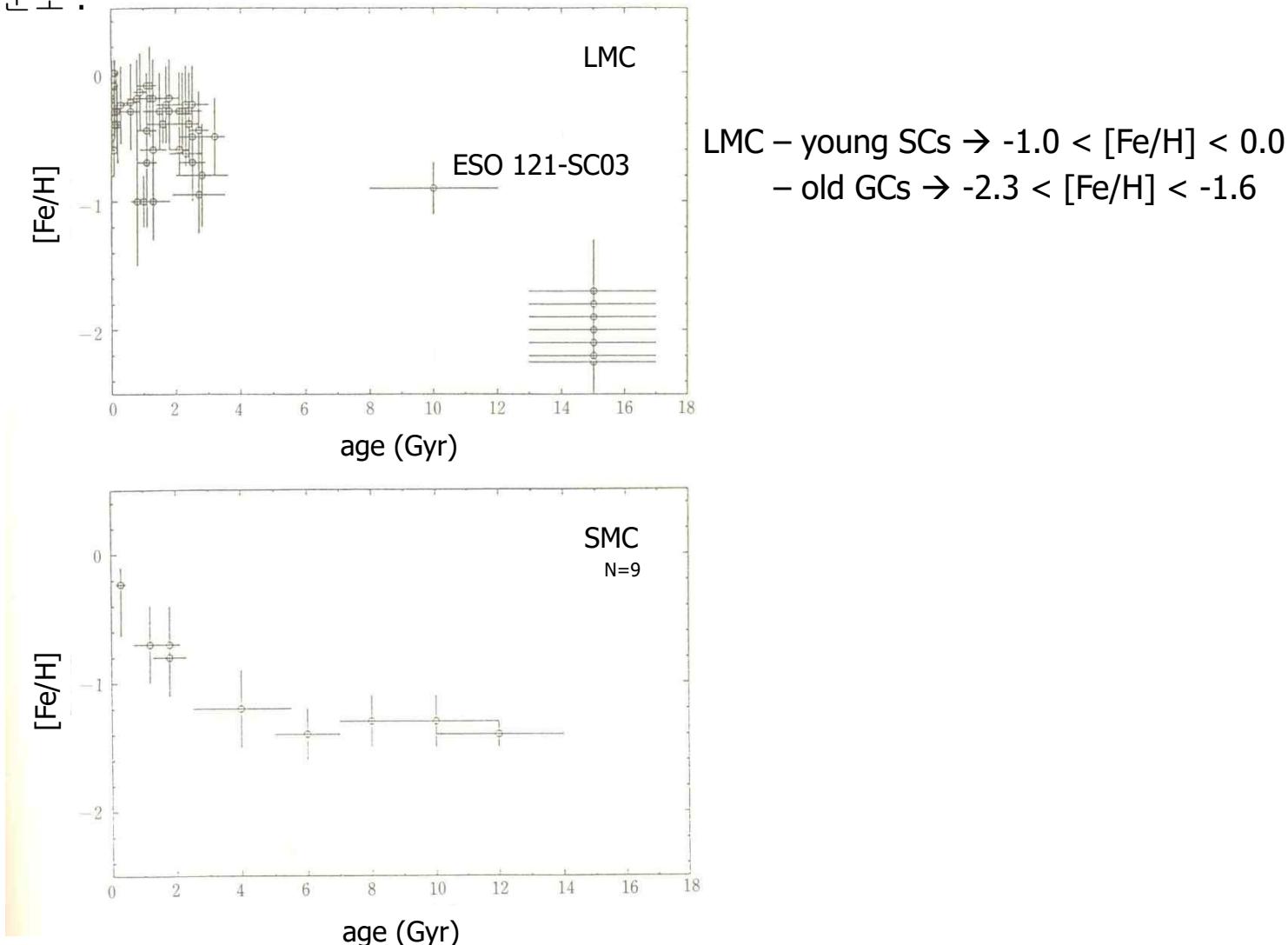
LMC – 3 peaks ( $6 \times 10^7$  yr, 1, 15 Gyr)  
– 2 valleys



SMC – peak at  $3 \times 10^8$  yr

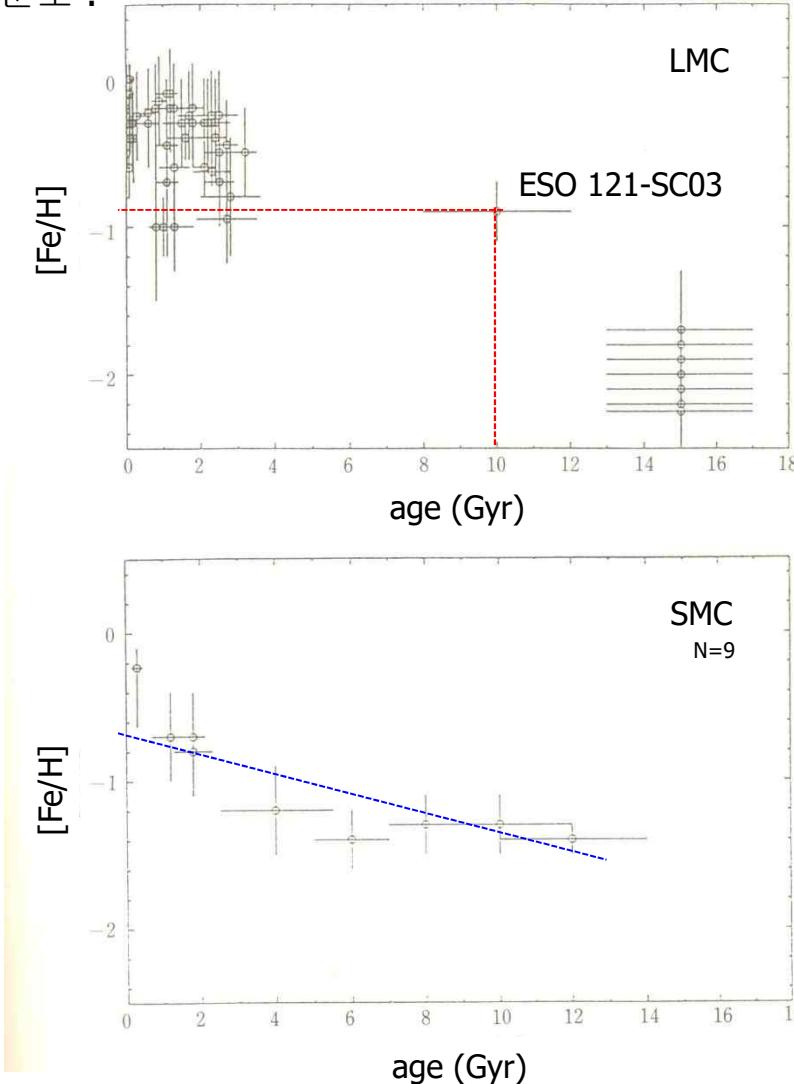
# GCs : age-metallicity

개수 분포 :



# GCs : age-metallicity

개수 분포 :



LMC – young SCs  $\rightarrow -1.0 < [Fe/H] < 0.0$   
– old GCs  $\rightarrow -2.3 < [Fe/H] < -1.6$

→ correlation between age-metallicity

# **Summary**

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**Star Clusters are  
“laboratory for stellar evolution”**

- Star clusters : **single** stellar population (i.e. formed in just ONE event)
- Stars in a star cluster : same **age**, same **distance**
- **Evolutionary** differences – solely due to **stellar initial mass**