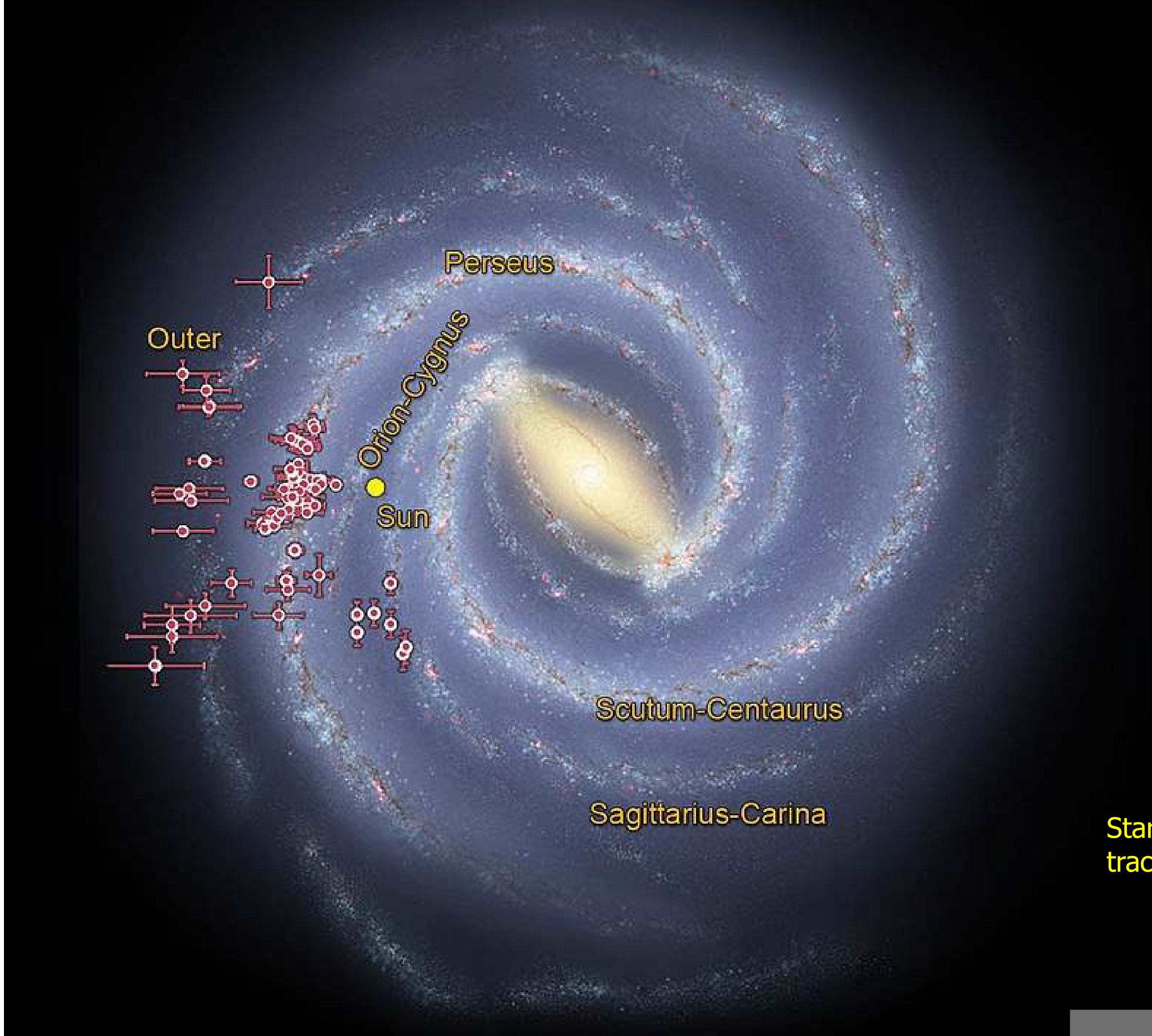
4. The Milky Way Galaxy (우리은하)
4.1 The MWG



Star clusters detected by WISE used to trace the Milky Way's spiral arms.

https://en.wikipedia.org/wiki/Milky_Way

김상철 (Sang Chul KIM)

Part II. Stellar Evolution and the Milky Way Galaxy (항성진화와 우리은하)

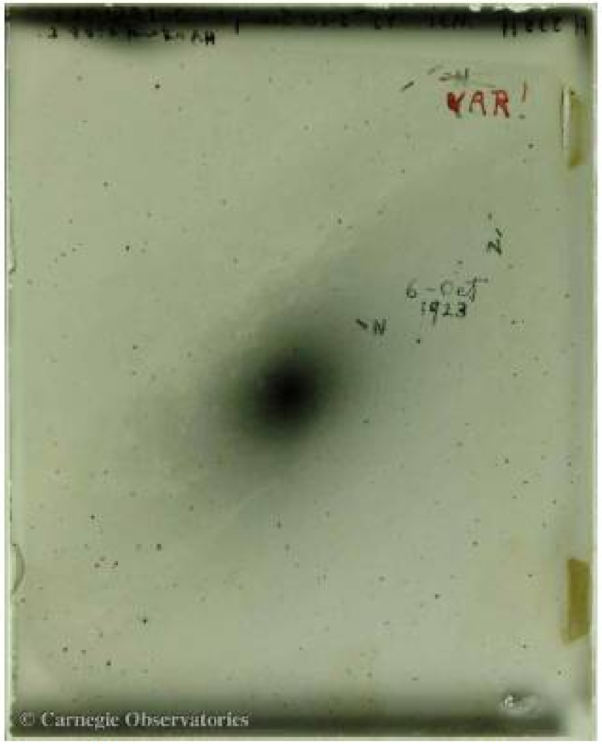
- **Exam** : April 23 (Wed) 10:30–11:30 AM
- 장영실홀(JYSH) room 329

- Calculator (계산기) not needed.
- Ruler (자) might be helpful.

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)
  → 1924 December, announcement a the AAS Meeting
- General Properties :

Property	Approximate Value
Disk diameter	50 kpc
Halo diameter	100 kpc
Sun’s distance from center	8.5 ± 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	3×10^{36} W = 3×10^{43} erg/s
Density of stars in solar neighborhood	$0.05\ M_\odot/pc^3$



http://obs.carnegiescience.edu/PAST/m31var
H335H_glass_0670_27_wm.jpg

Edwin P. Hubble

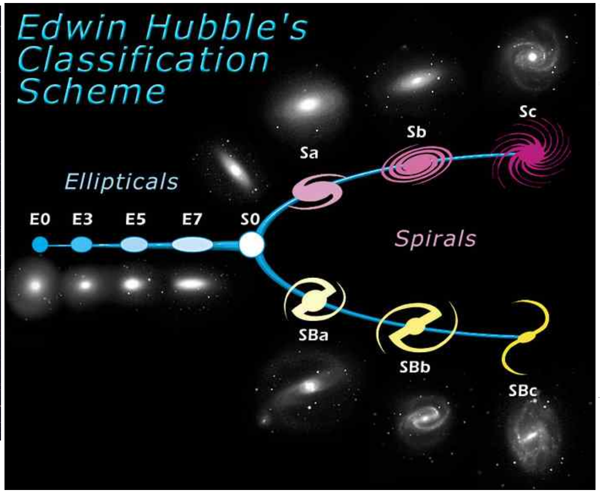
https://en.wikipedia.org/wiki/Edwin_Hubble

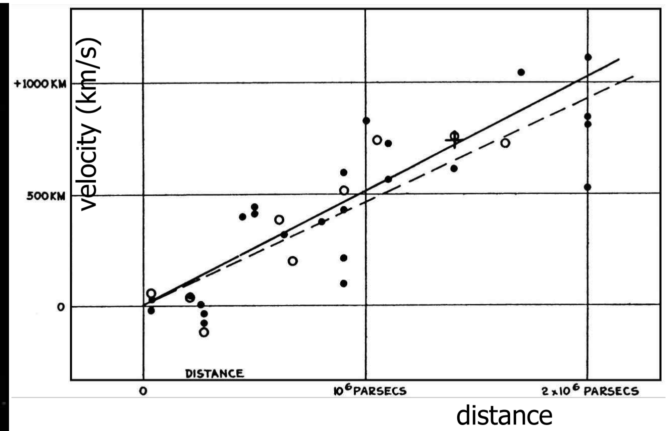
1924 Discovery of ‘external’ galaxies M31 (Andrometa galaxy)
→ began ‘extragalactic astronomy’

1926 Morphological classification scheme of galaxies

1929 Discovery of ‘expanding Universe’
“Hubble-Lemaître law” (1929, 1927) distance-redshift correlation : $v = c\,z = H_0\, d$

Hubble constant





https://pmc.ncbi.nlm.nih.gov/articles/PMC314128/

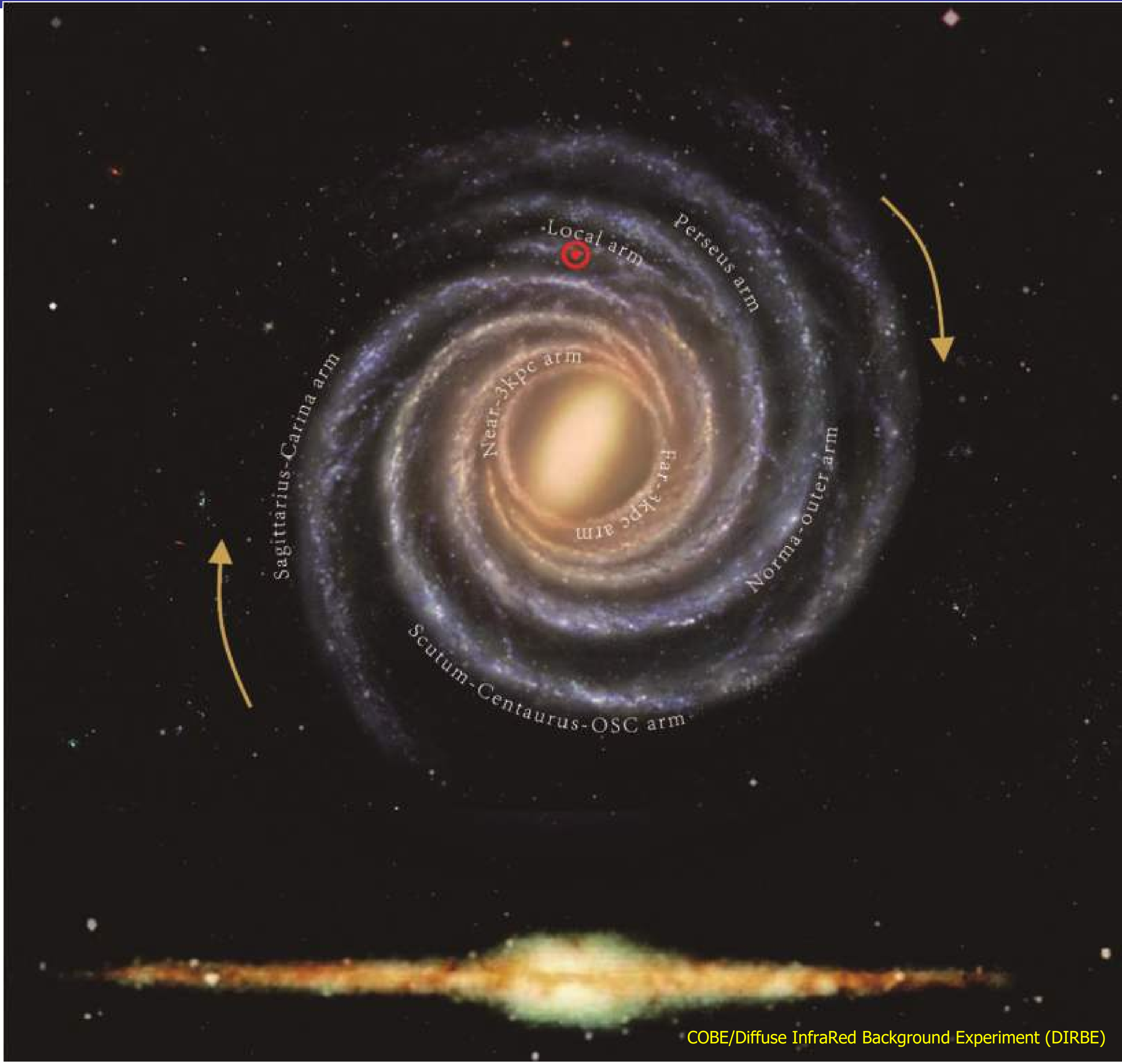
https://upload.wikimedia.org/wikipedia/commons/5/57/M31-Andromede-16-09-2023-Hamois.jpg
https://en.wikipedia.org/wiki/Edwin_Hubble#/media/File:Hubble_Tuning_Fork_diagram.svg
https://www.ncbi.nlm.nih.gov/core/lw/2.0/html/tileshop_pmc/tileshop_pmc_inline.html?title=Click%20on%20image%20to%20zoom&p=PMC3&id=314128_zpq0250332170001.jpg

2. Shape of the Milky Way Galaxy

Conceptual picture

face-on view

Visible



bar

spiral arms

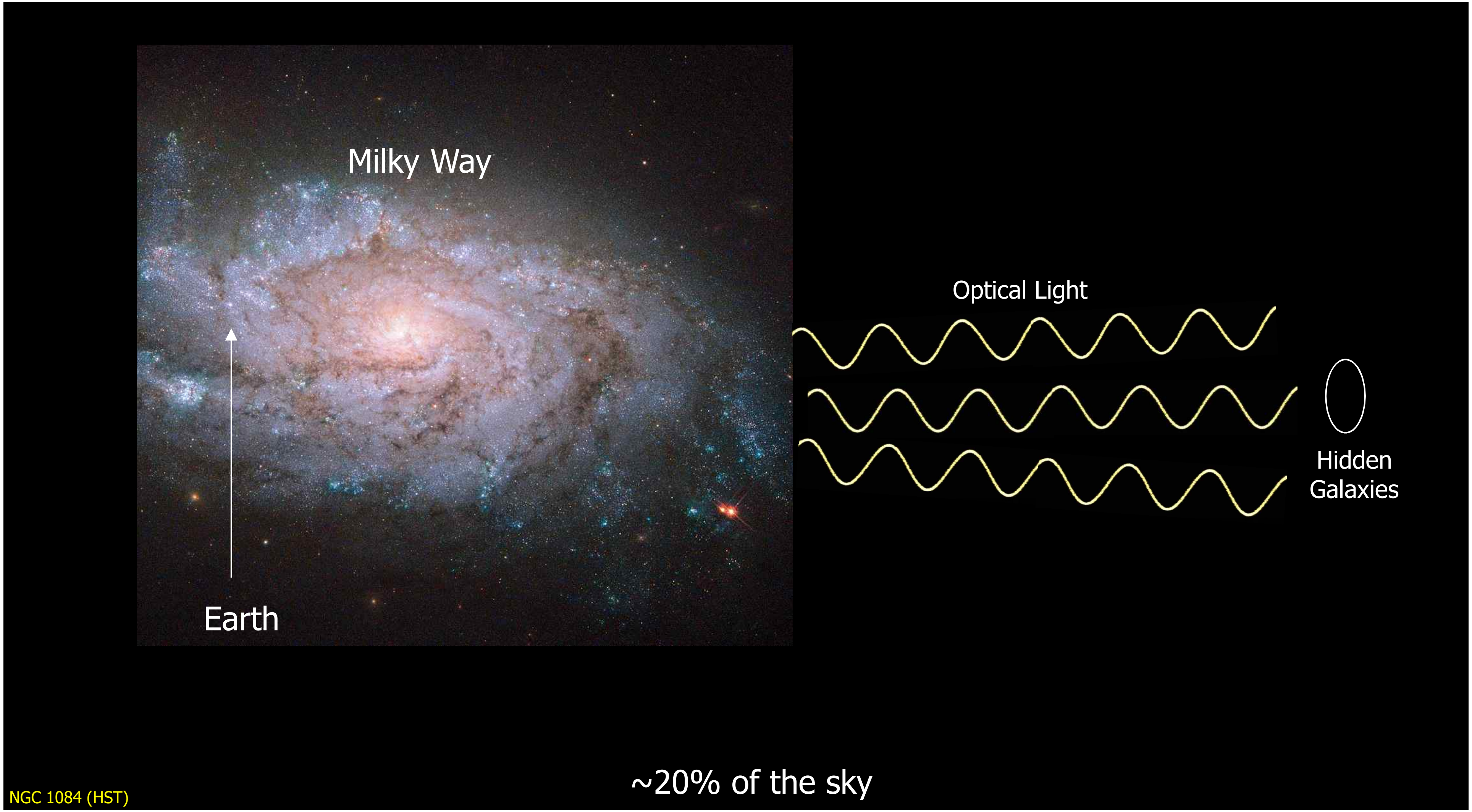
edge-on view

Infrared

Shen & Zheng 2020 RAA 20, 159

2. Shape of the Milky Way Galaxy

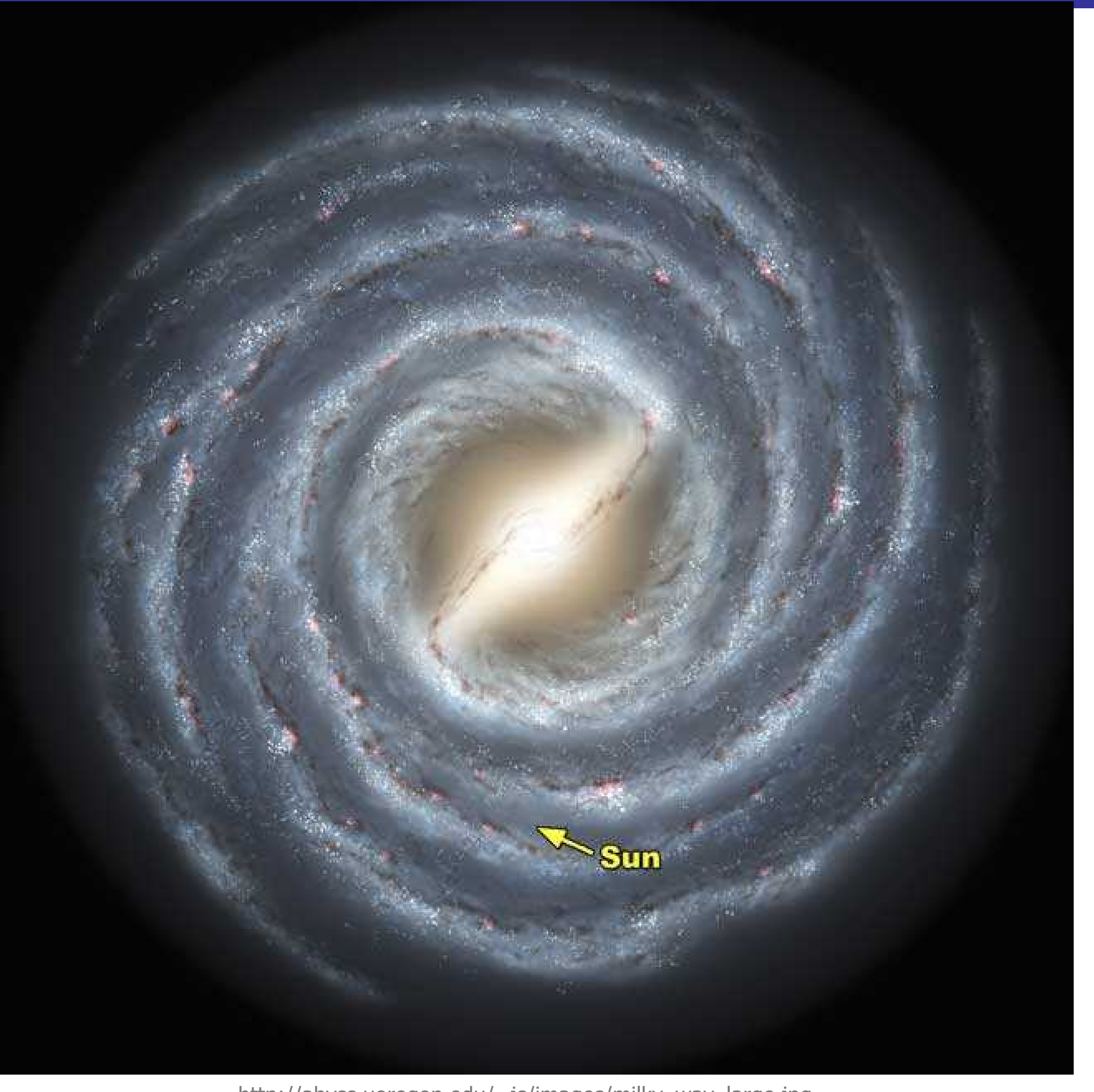
Zone of avoidance (ZoA, ZOA, 회피대)



https://en.wikipedia.org/wiki/Spiral_galaxy#/media/File:A_spiral_home_to_exploding_stars.jpg

2. Shape of the Milky Way Galaxy

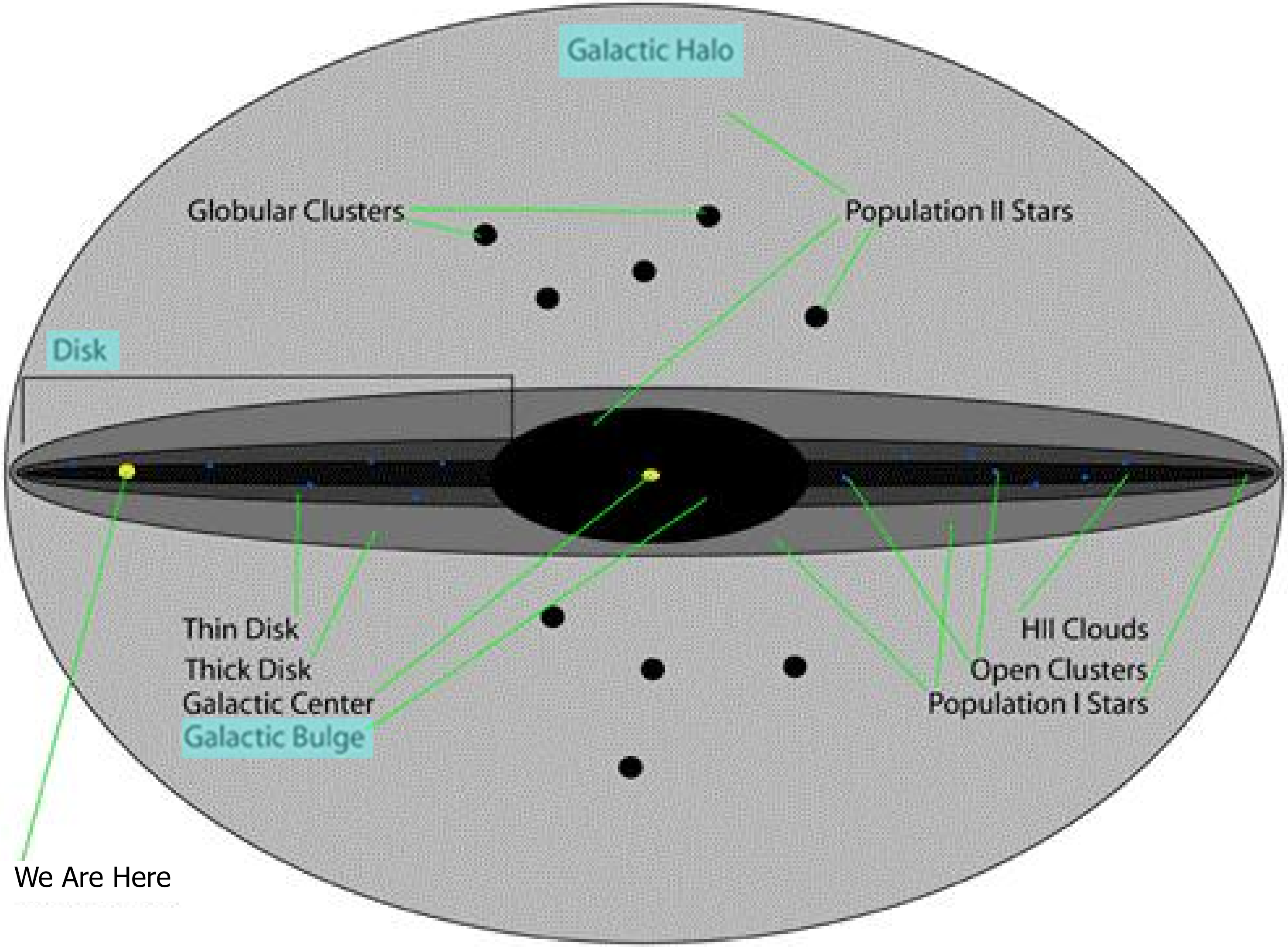
Face-on view:



http://abyss.uoregon.edu/~js/images/milky_way_large.jpg

2. Shape of the Milky Way Galaxy

Edge-on view:



Galactic plane (disk)
•thickness ~ 500 pc
•diameter : thickness = 100 : 1

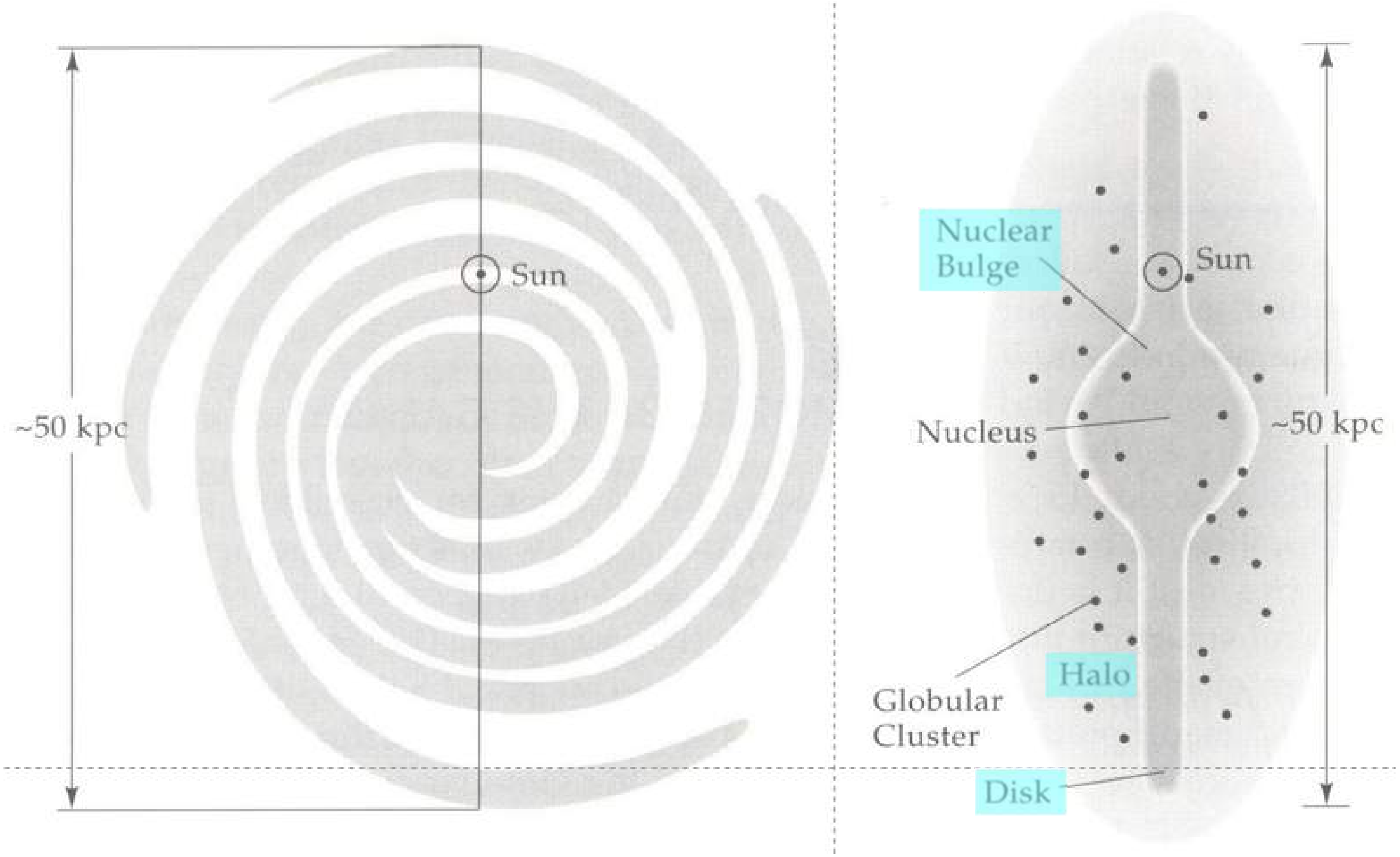
http://astronomyonline.org/images/ImagesFromPapers/GalaxyDiagram.gif

3. Structure of the Milky Way Galaxy

- 3 components : disk, bulge, halo
- Distance of the Sun from the Galactic center : 8.5 ± 1.0 kpc (~1/3)
- Galactic center: in the direction of the constellation of Sagittarius

Face-on view:

Edge-on view:

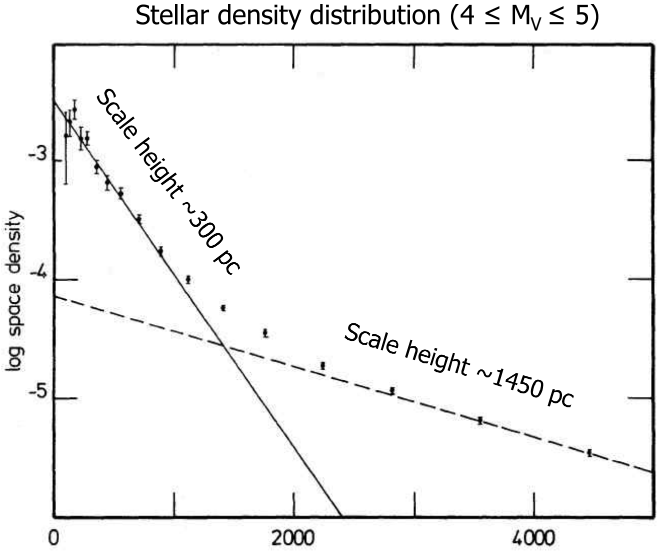


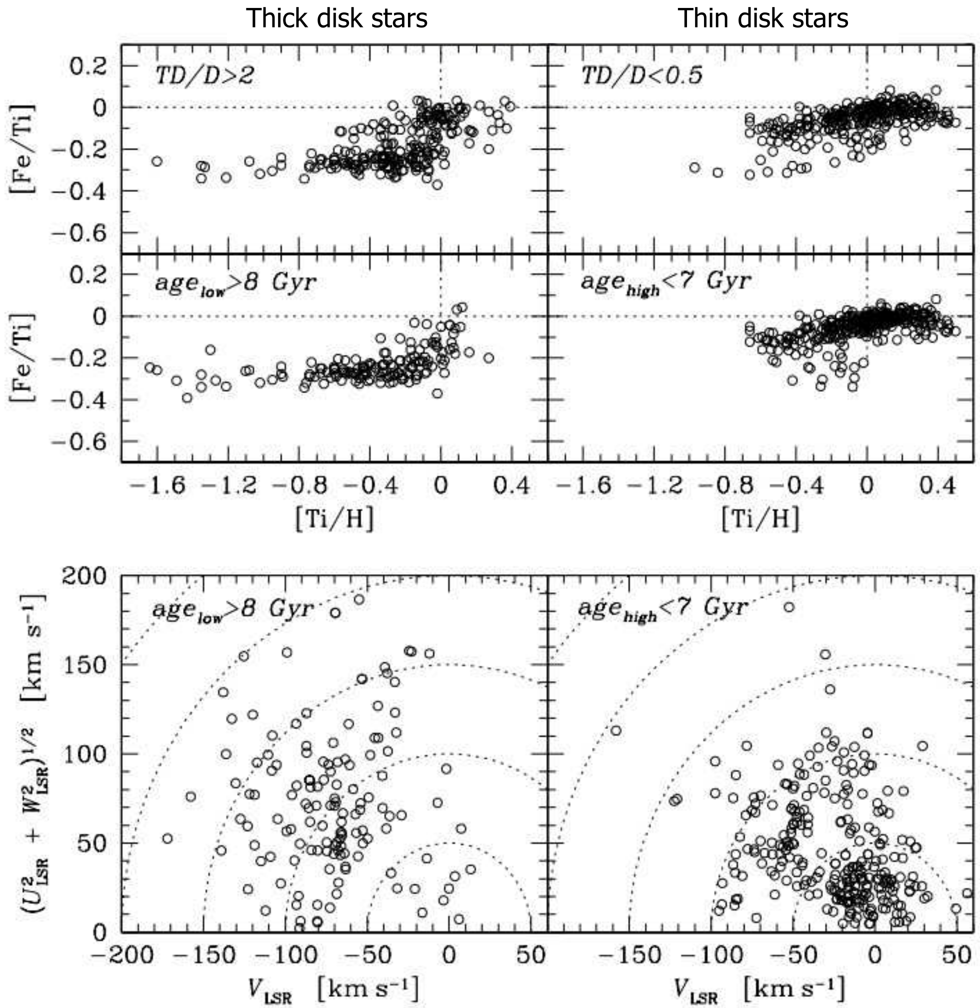
Introductory Astronomy and Astrophysics (4th edition) Michael Zeilik & Stephen A. Gregory (1998) p. 280

3. Structure of the Milky Way Galaxy

- Thin disk : scale height ~300 pc
- Contain ~95% of the disk stars
- Created from gas accretion at later stages of the MW formation → metal-rich

- Thick disk : scale height ~1450 pc
- mainly old stars made at early of the MW formation → metal-poor





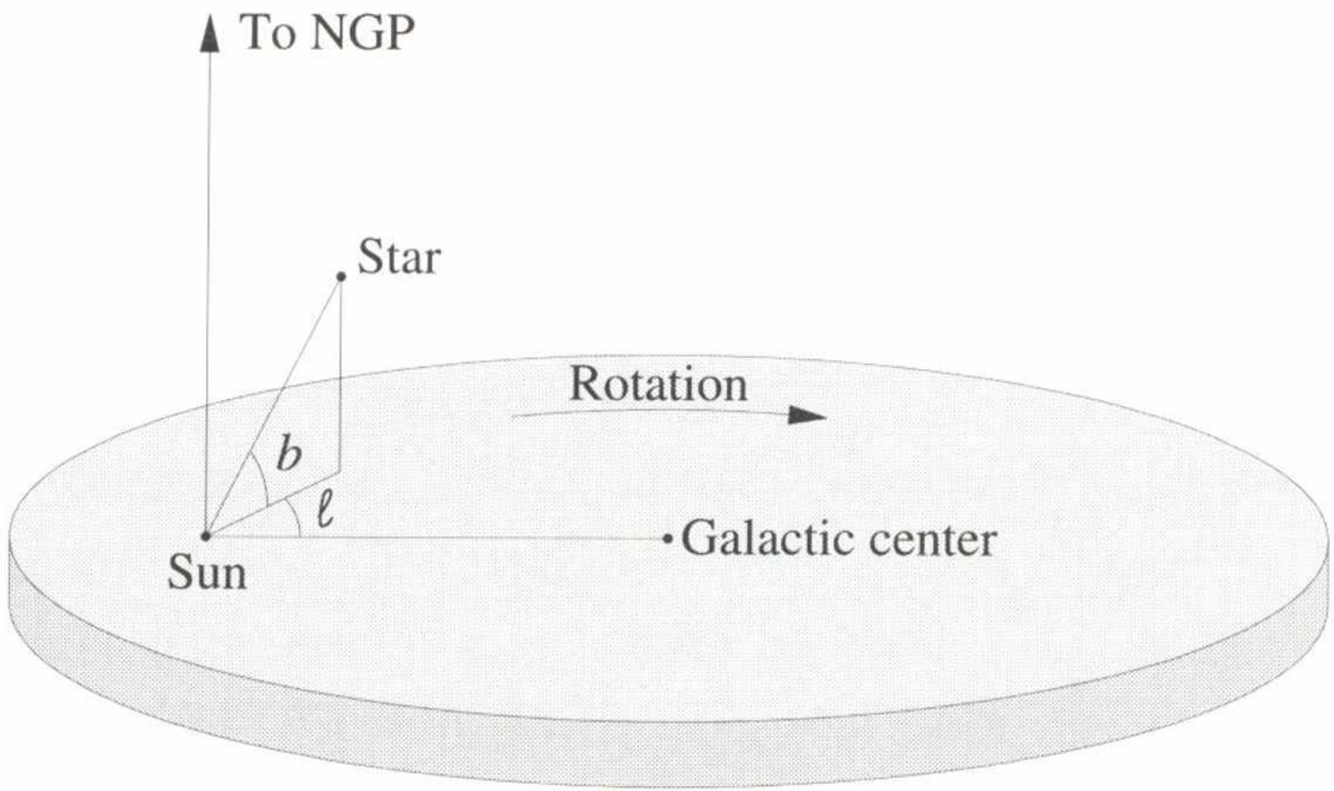
Gilmore & Reid 1983 (MN 202 1025)

Bensby & Feltzing 2010 (IAUS 265, 300)

3. Structure of the Milky Way Galaxy

Galactic Coordinate System

- Sun-centered (태양 중심)
- Galactic longitude (은경), ℓ : 0° to 360°
- Galactic latitude (은위), b : -90° to +90°



An Introduction to Modern Astrophysics (2nd edition) Bradley W. Carroll & Dale A. Ostlie (1996) p. 937

3. Structure of the Milky Way Galaxy

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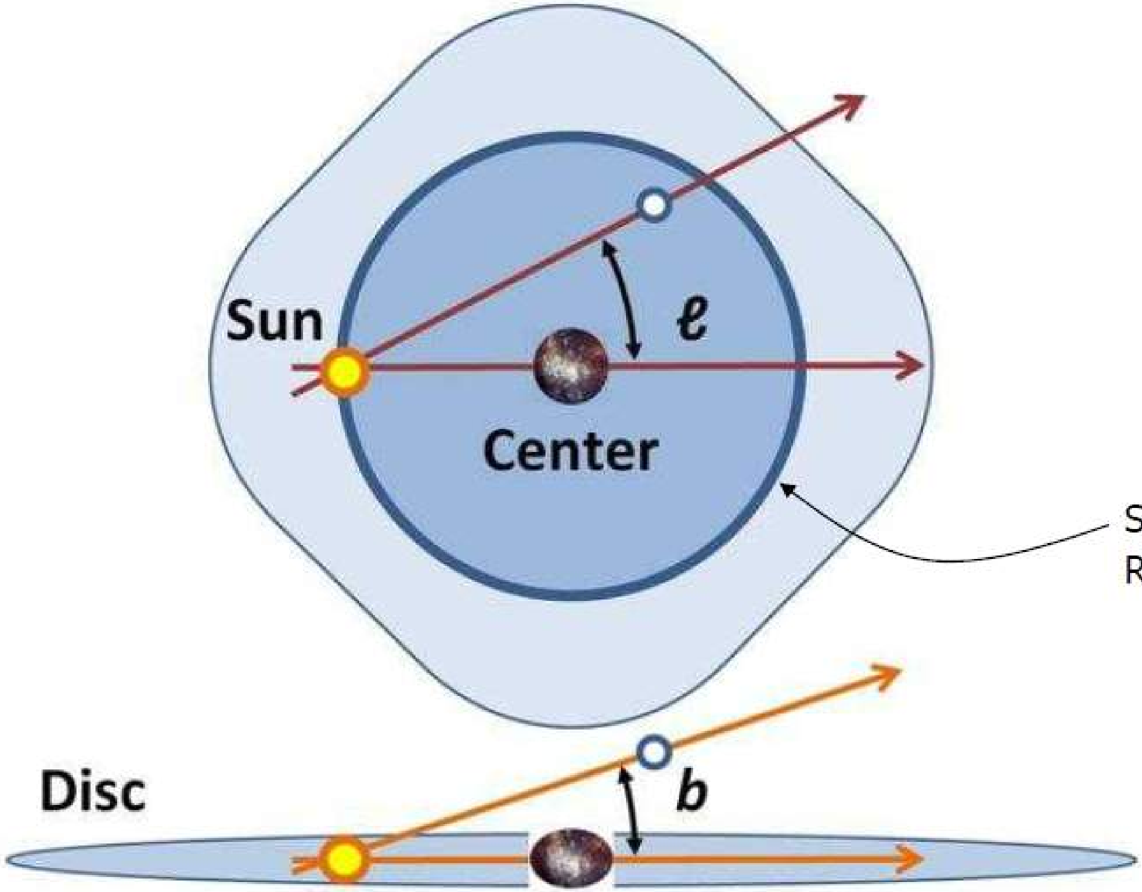


Solar circle (태양 공전 궤도)
R_0= (8.0 - 8.5) ± 1.0 kpc

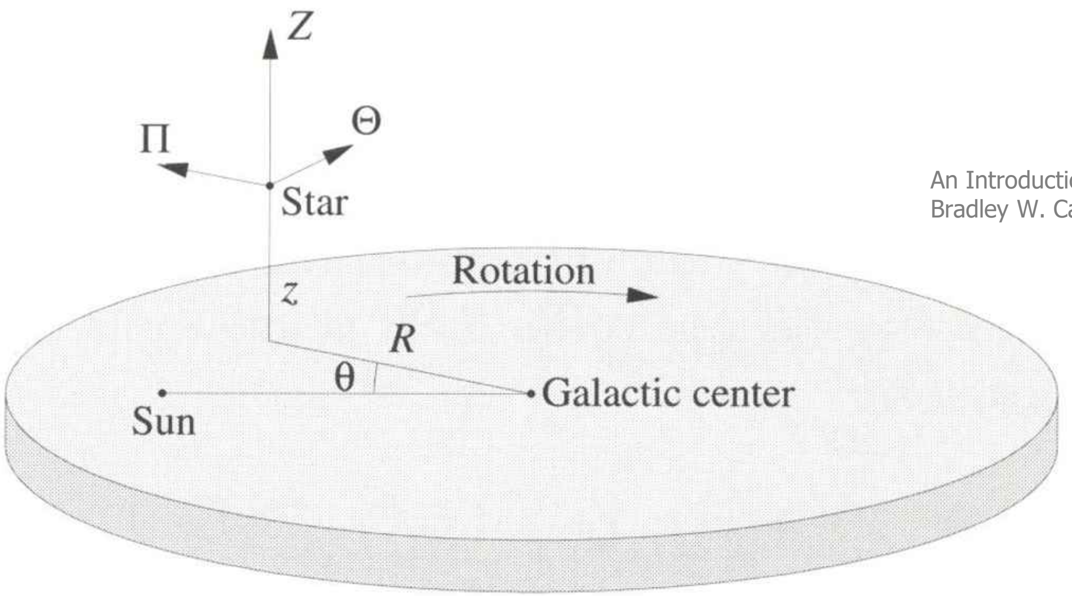
$(m\text{-}M)_0$ =14.52 to 14.65
→ M_V

Galactic_coordinates.JPG
https://en.wikipedia.org/wiki/Galactic_coordinate_system

3. Structure of the Milky Way Galaxy

Solar motion

- Cylindrical Coordinate System → (Π, Θ, Z)
- Velocity components : u, v, w



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

- Orbital speed at R_0 : $\Theta_0(R_0)$ = 220 km/s
- Solar motion : ~16.5 km/s toward ℓ =53°, b=25° (a point in the constellation of Hercules)

향점 solar apex : the point toward which the Sun is approaching

배점 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 km/s, $R_\odot$ = 8.5 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 :

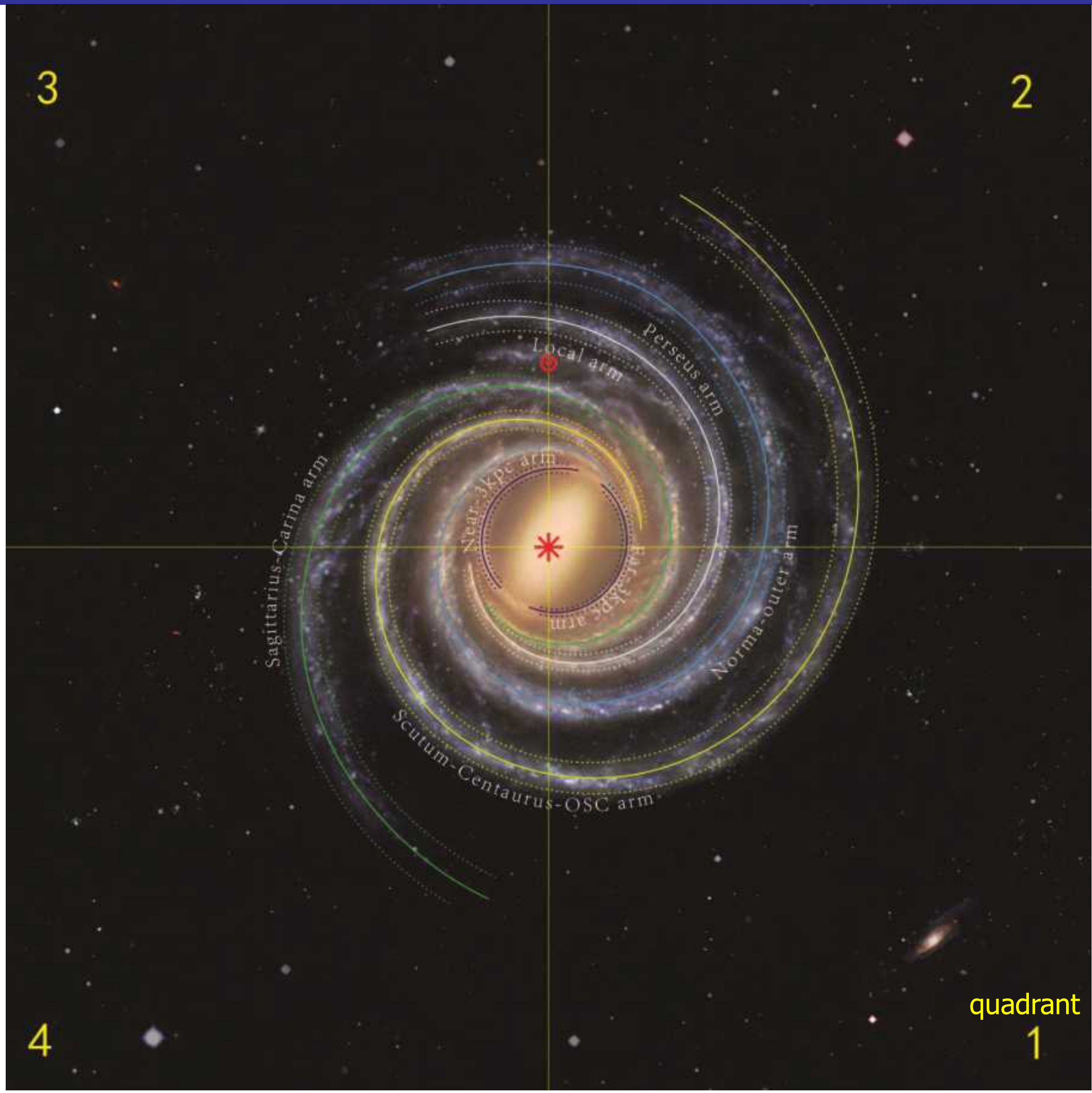
$$M_G = \frac{v_\odot^2 R_\odot}{G} = 1.9\times10^{44}\ \mathrm{g} \approx 10^{11}\ M_\odot$$

- Assuming an average stellar mass ~1 $M_\odot$

→ the Galaxy within the solar orbit = 10^{11} stars

2. Shape of the Milky Way Galaxy

4 major spiral arms

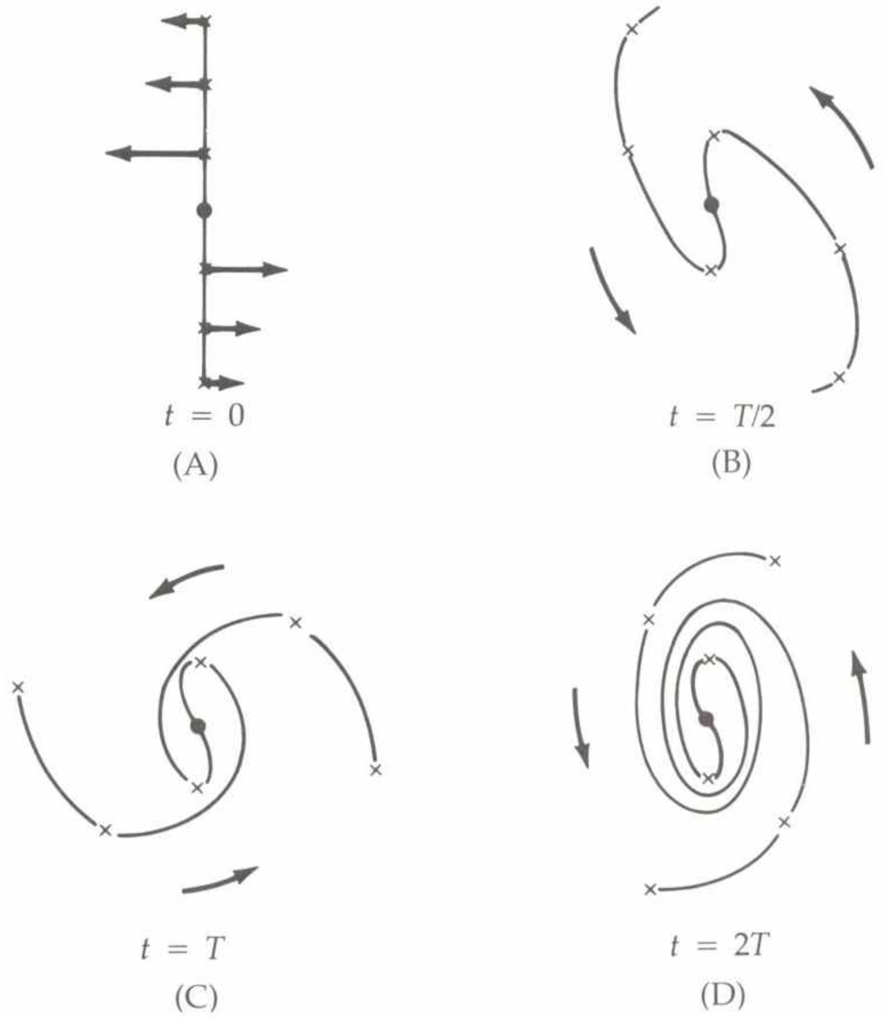


R_0 = 8.15 kpc

(Outer Scutum Centaurus)

Shen & Zheng 2020 RAA 20, 159

4. Spiral Arms of the MWG



- Spiral arms : believed to be produced by dynamical effects
- MW age ~ cosmic age (1.38×10^{10} yr)
- MW rotation period at the Sun's orbit

: 2.4×10^8 yr $\left(= \dfrac{2\pi R_\odot}{v_\odot}\right)$

→ Spiarl 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

Introductory Astronomy and Astrophysics (4th edition) Michael Zeilik & Stephen A. Gregory (1998) p. 279

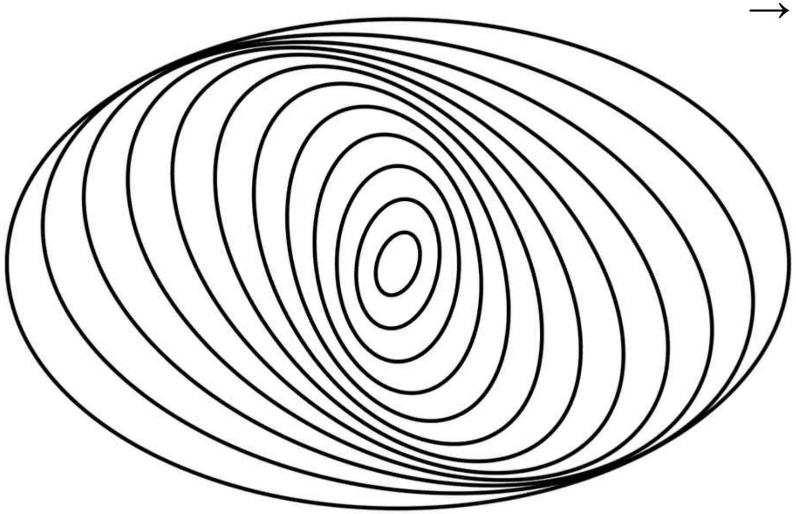
4. Spiral Arms – density wave

- MW rotation (spiral density wave)

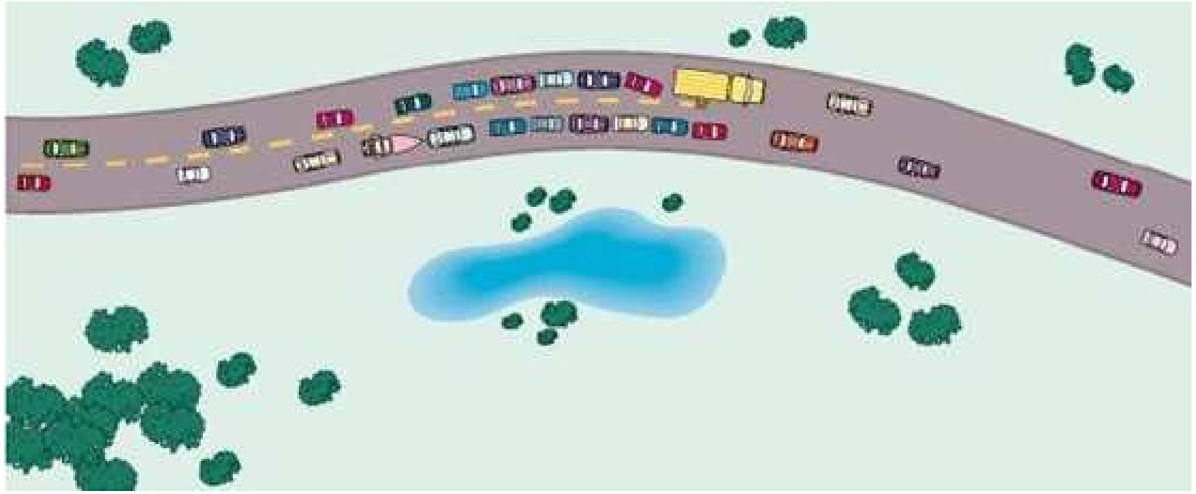
→ dust and gas are compressed

→ 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

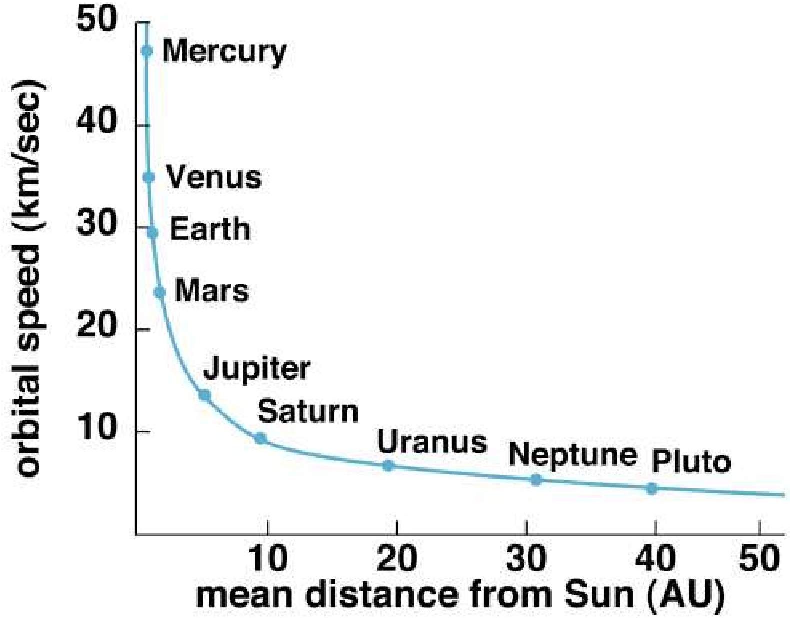


http://frigg.physastro.mnsu.edu/~eskridge/astr101/week12.html

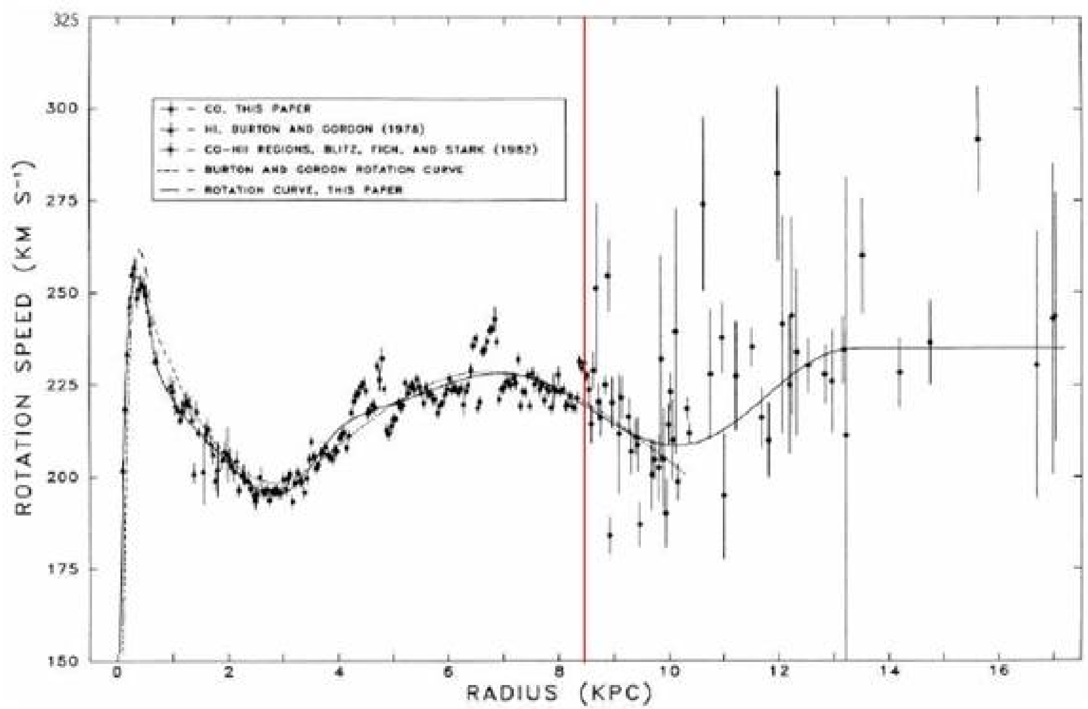
5. MWG rotation curve

- Ordinary matter (planets, stars, gas) → Keplerian rotation

- Using R_0= 8.5 kpc and Θ_0 = 220 km s^{-1}
- Observed Galactic rotation curve :
  - Near the Galactic center → rigid-body rotation
  - Outer region → roughly constant speed



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

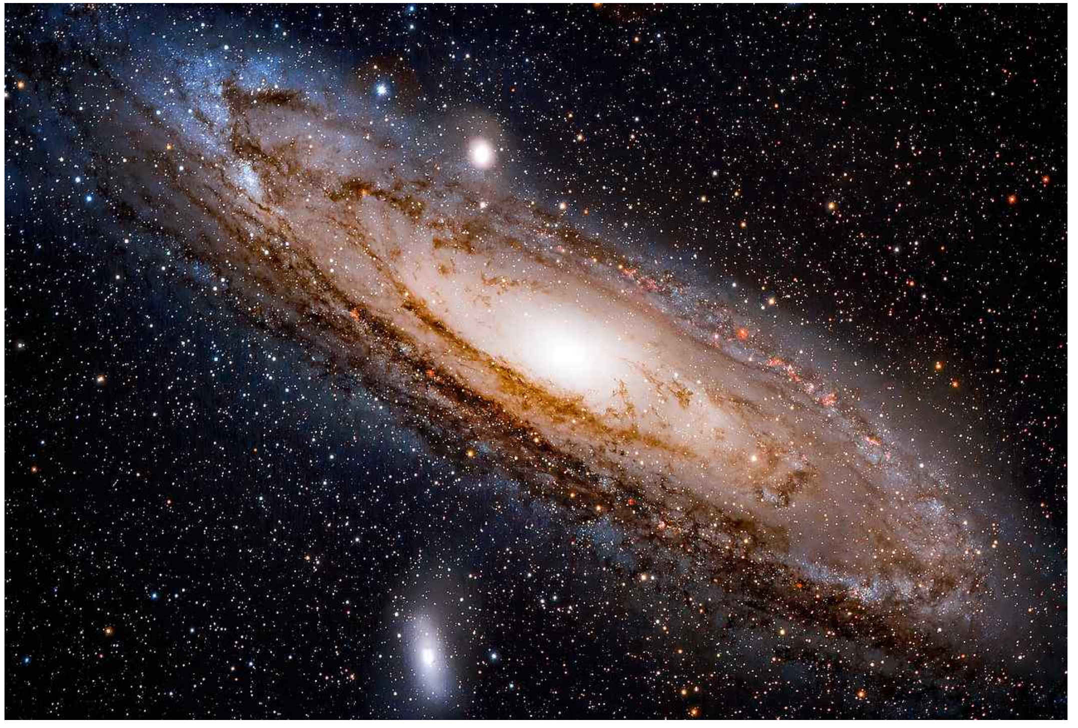
- Stellar 'populations'
  : families of stars with similar metal abundances and/or ages

https://en.wikipedia.org/wiki/Walter_Baade

- Walter Baade : World War II in 1940's at Mount Wilson 2.5m telescope

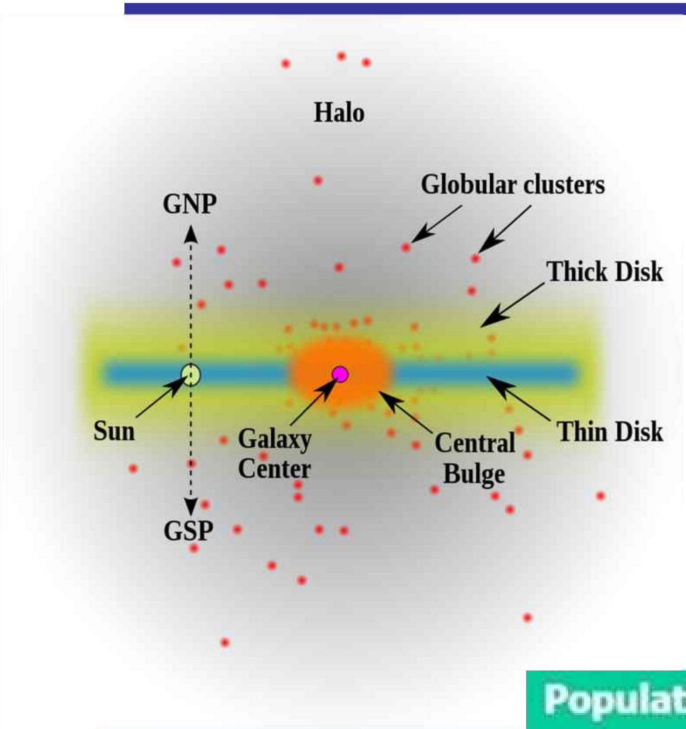
→ MW GCs, M31 (Andromeda Galaxy), Galactic bulge [Baade's window], halo stars, etc.

→ 1944 : populations I and II



https://en.wikipedia.org/wiki/Andromeda_Galaxy

6. Stellar Populations



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)

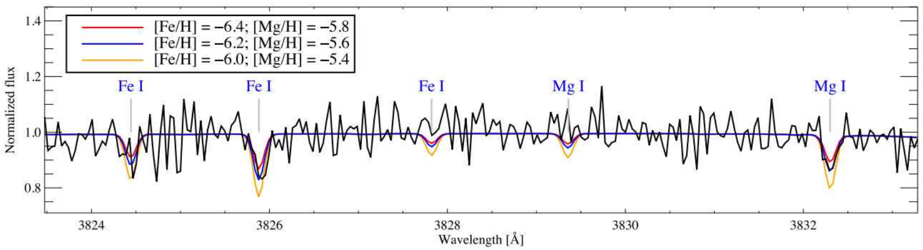
6. Stellar Populations

- 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!

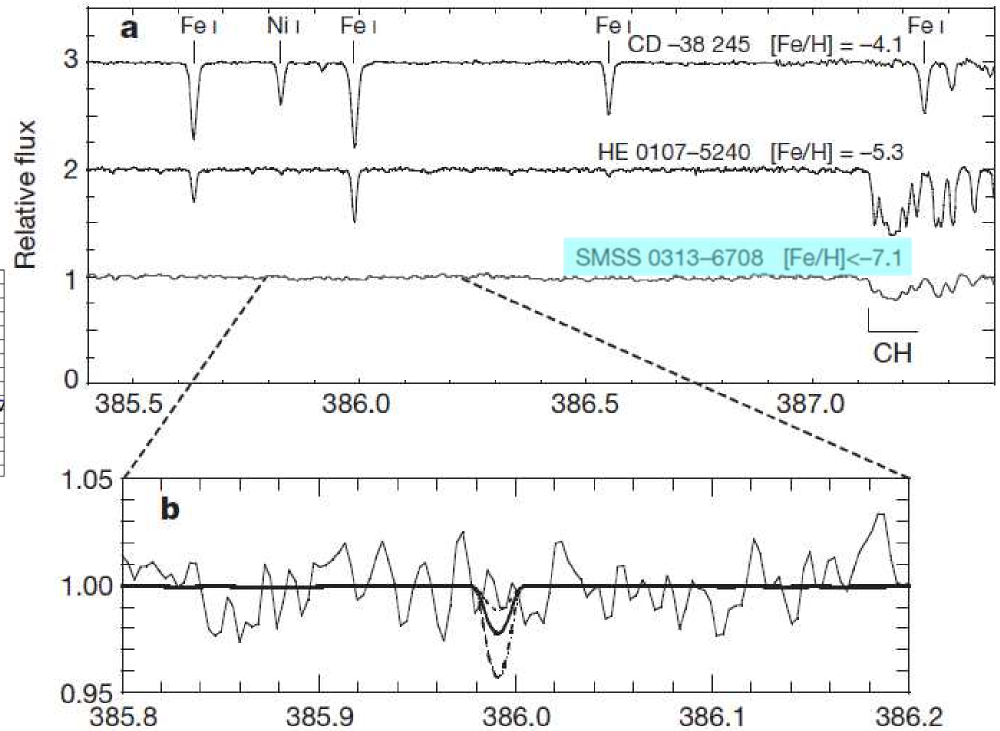
The most metal-poor halo stars :

SMSS J160540.18−144323.1, [Fe/H] = -6.2 ± 0.2



Nordlander+19 (MN 488 L109)

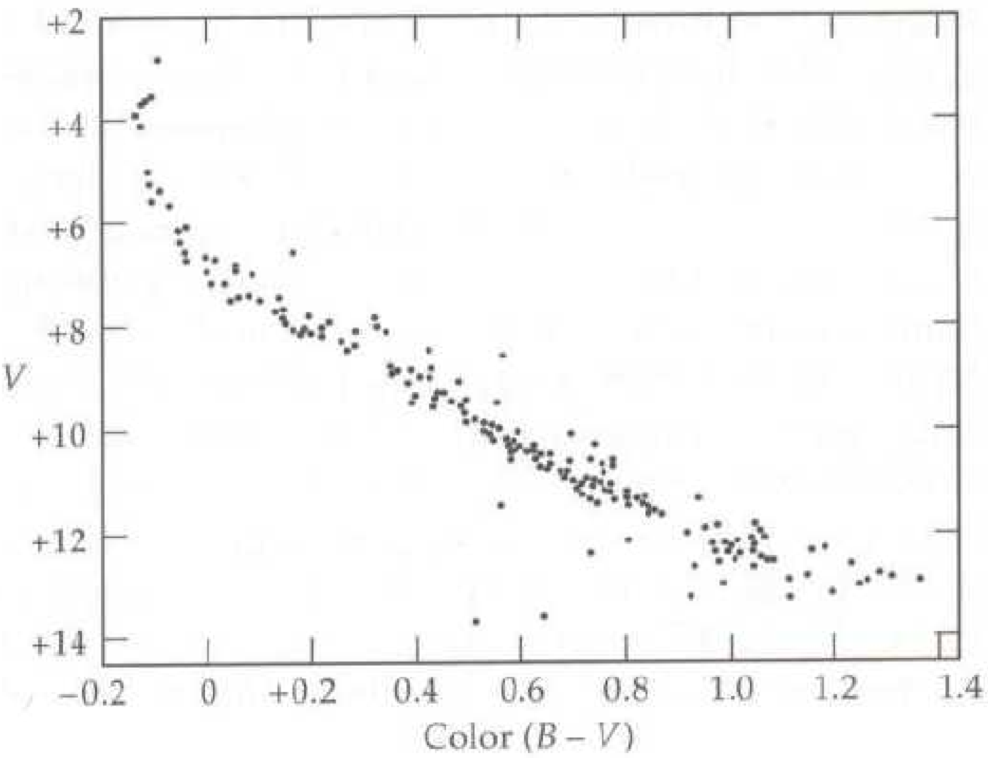
SMSS J031300.362670839.3, [Fe/H] < -7.1



Keller+14 Nature 506 463

6. Stellar Populations – Star Clusters

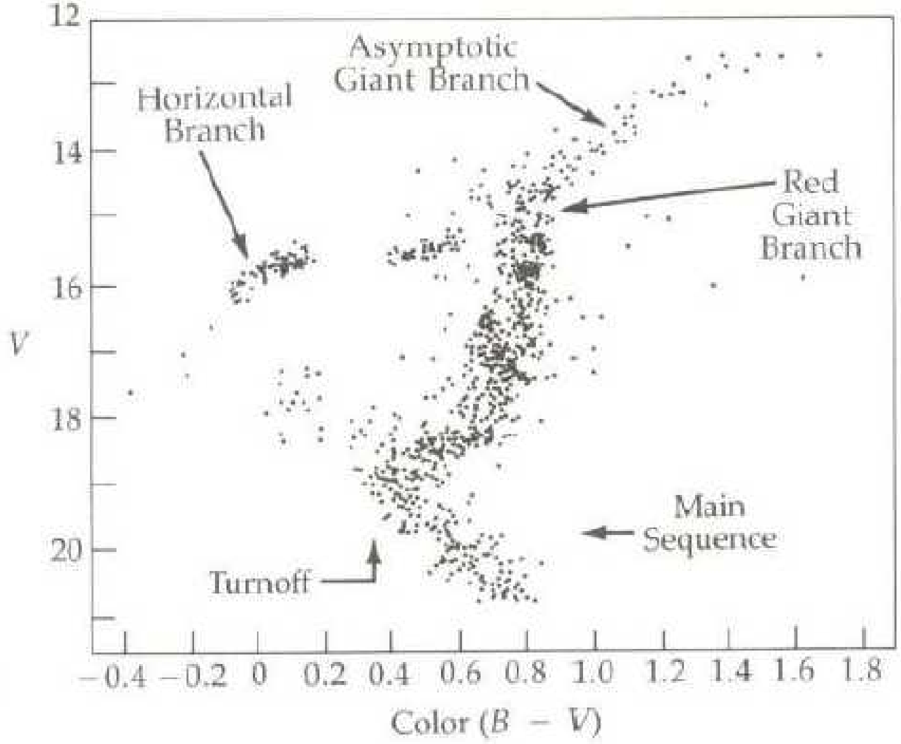
Open cluster (OC)



M45 (Pleiades)

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

Globular cluster (GC)



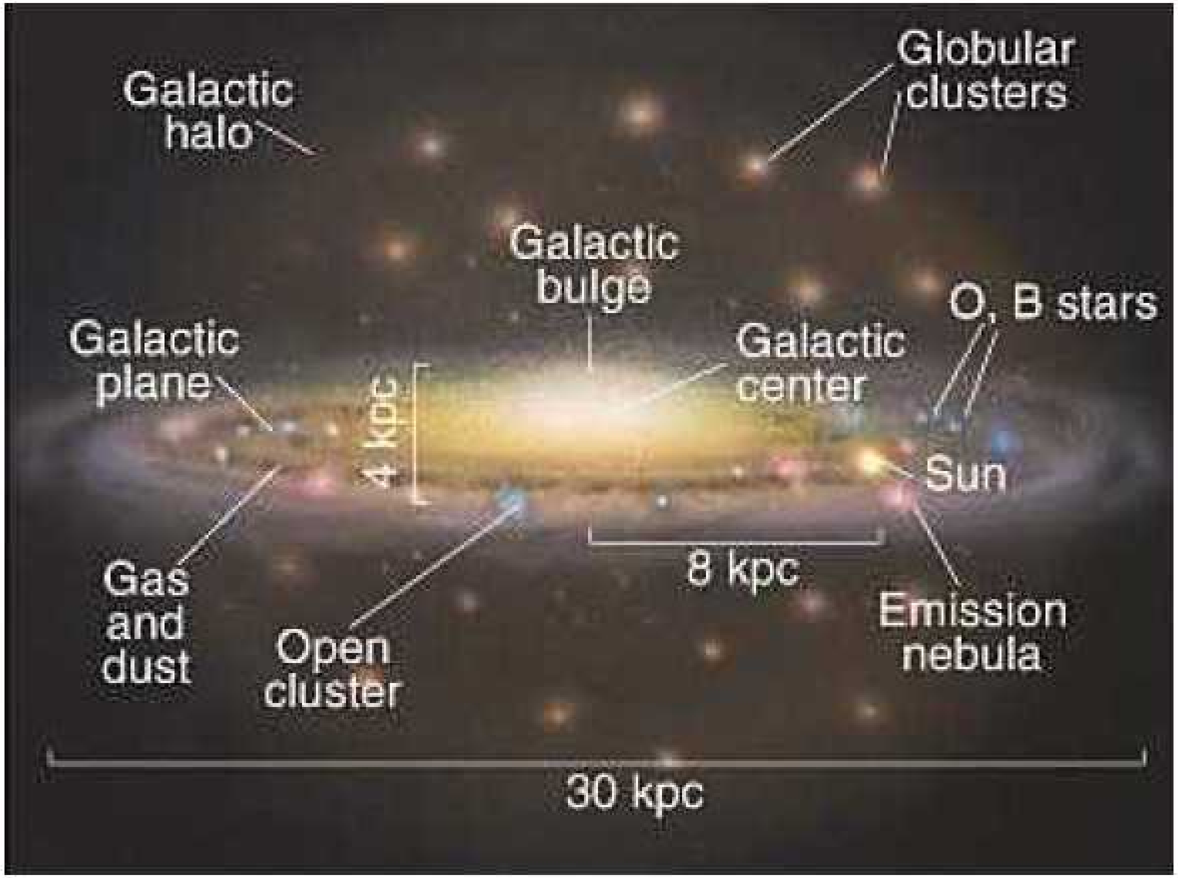
M3 (NGC 5272)

- MS : B-V≈0.4 (turnoff) → B-V=0.8
- Heavily populated giant branch
- High-luminosity branch running toward the left (**HB, AGB**)
- Stellar spectra → very low metal abundance (Z≤0.001) : population II

6. Stellar Populations – Star Clusters

Distribution in the Galaxy

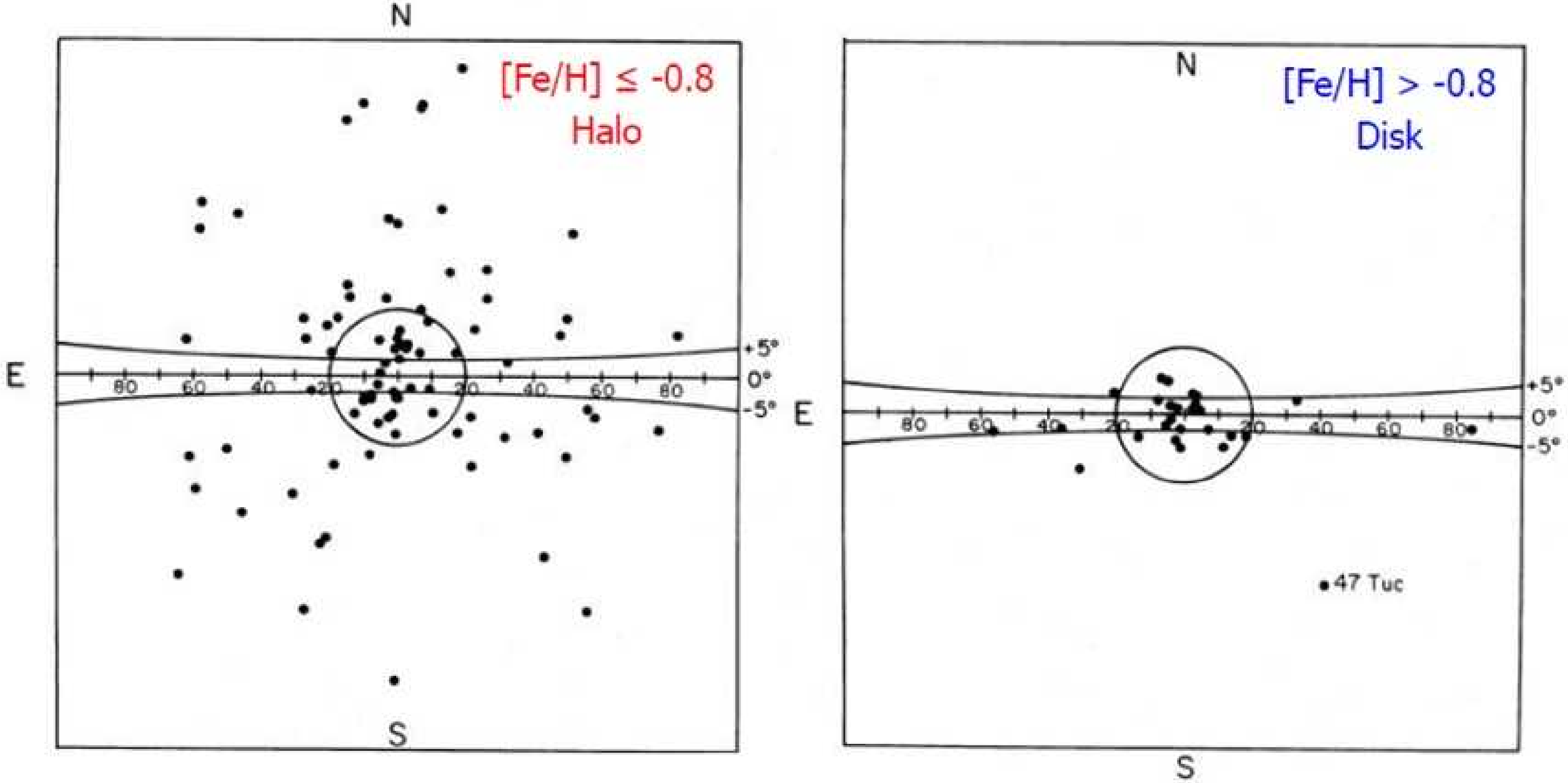
- Open clusters – disk
- Globular clusters – the whole galaxy (halo, bulge/disk)



http://www2.astro.psu.edu/users/caryl/a10/lec13_2d.html

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)

	Halo GCs	Disk GCs	Disk stars
[Fe/H]	-1.5	-0.5	0.0
$V_{rotation}$ [km/s]	45	185	220
$V_{dispersion}$ [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, Extremely metal-poor stars (subdwarfs), RR Lyrae stars (P>0.4d), Pop II Cepheids	High-velocity stars (Z>30 km/s), Long period variables (P<250 d)	PNe, Novae, Bright red giants, Galactic bulge, Weak-line stars, RR Lyrae stars (P<0.4d)	Sun, A-type stars, Strong-line stars, Me dwarfs, Giants, Older OCs	Gas, dust, O and B stars, supergiants, T Tauri stars, Young OCs, Classical Cepheids, H II regions
Mean age (Gyr)	≥10	≈10	3-10	0.1-10	<0.1
Distance from the Galactic plane (pc)	2000	700	400	160	120
Z 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 홍승수 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

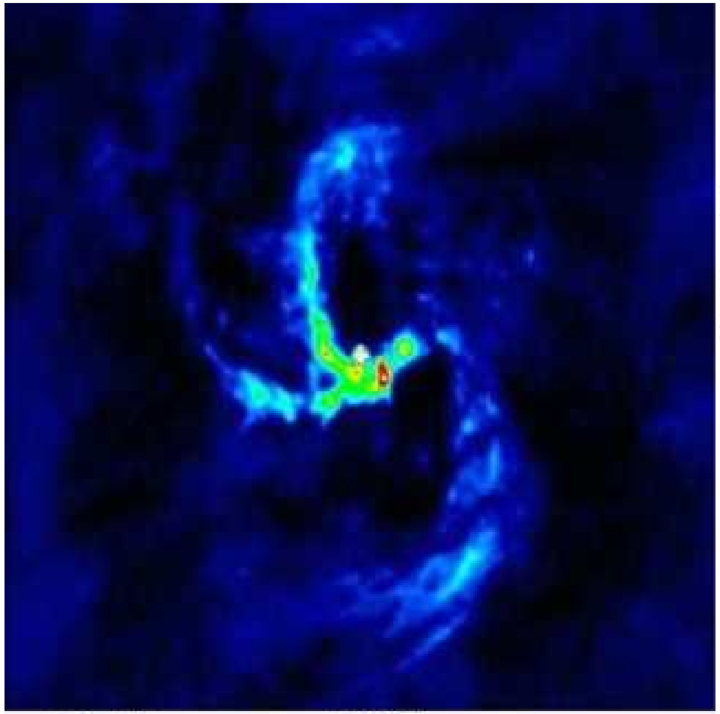
- H I 21-cm observation → 3 kpc expanding arm

  A gas cloud moving toward us at ~50 km/s

- Continuous radio emission → an intense radio source, "Sagittarius A"

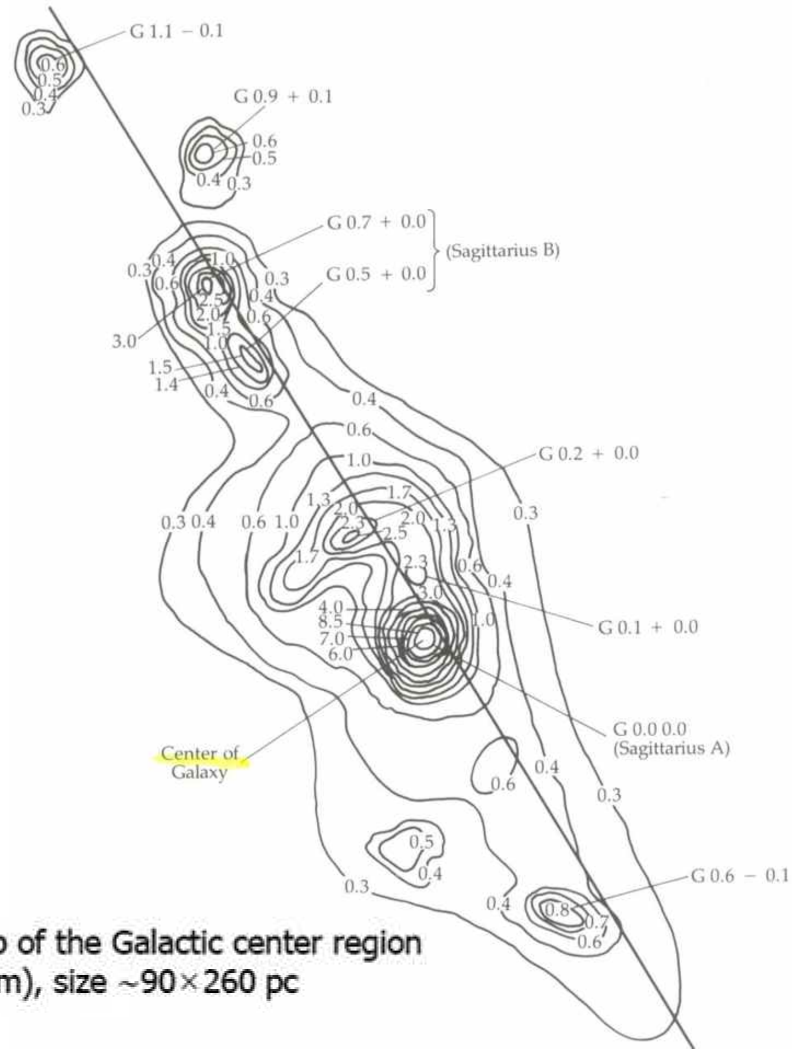
  → nonthermal point-like source (D < 0.1″), "Sgr A*"

- Gas motions → suggest high concentration of mass at the center, also a compact radio source (D<140 AU)→ Supermassive BH, M~10^6 $M_\odot$



http://images.nrao.edu/407

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

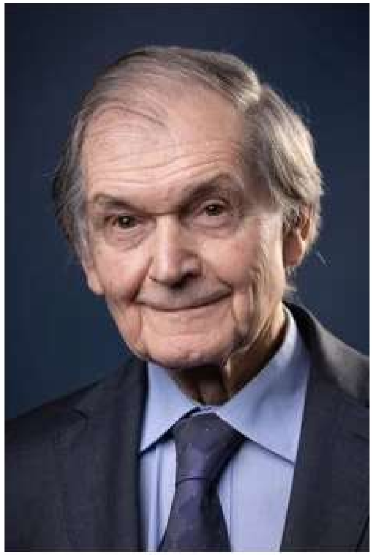


Radio map of the Galactic center region (λ=3.75 cm), size ~90×260 pc

Introductory Astronomy and Astrophysics (4th edition) Michael Zeilik & Stephen A. Gregory (1998) p. 401

7. Galactic center - Nucleus

Nobel Prize in Physics 2020



© Nobel Prize Outreach. Photo: Fergus Kennedy

Roger Penrose

Prize share: 1/2

© Nobel Prize Outreach. Photo: Bernhard Ludewig

Reinhard Genzel

Prize share: 1/4

© Nobel Prize Outreach. Photo: Stefan Bladh.

Andrea Ghez

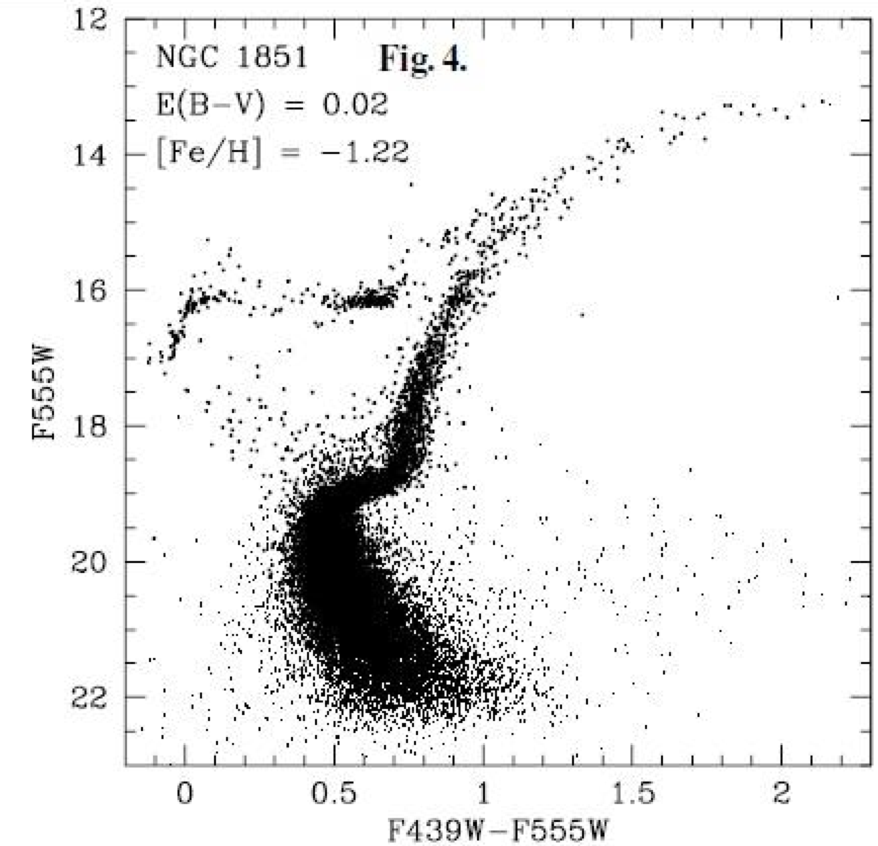
Prize share: 1/4

The Nobel Prize in Physics 2020 was divided, one half awarded to Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity", the other half jointly to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy"

https://www.nobelprize.org/prizes/physics/2020/summary/

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

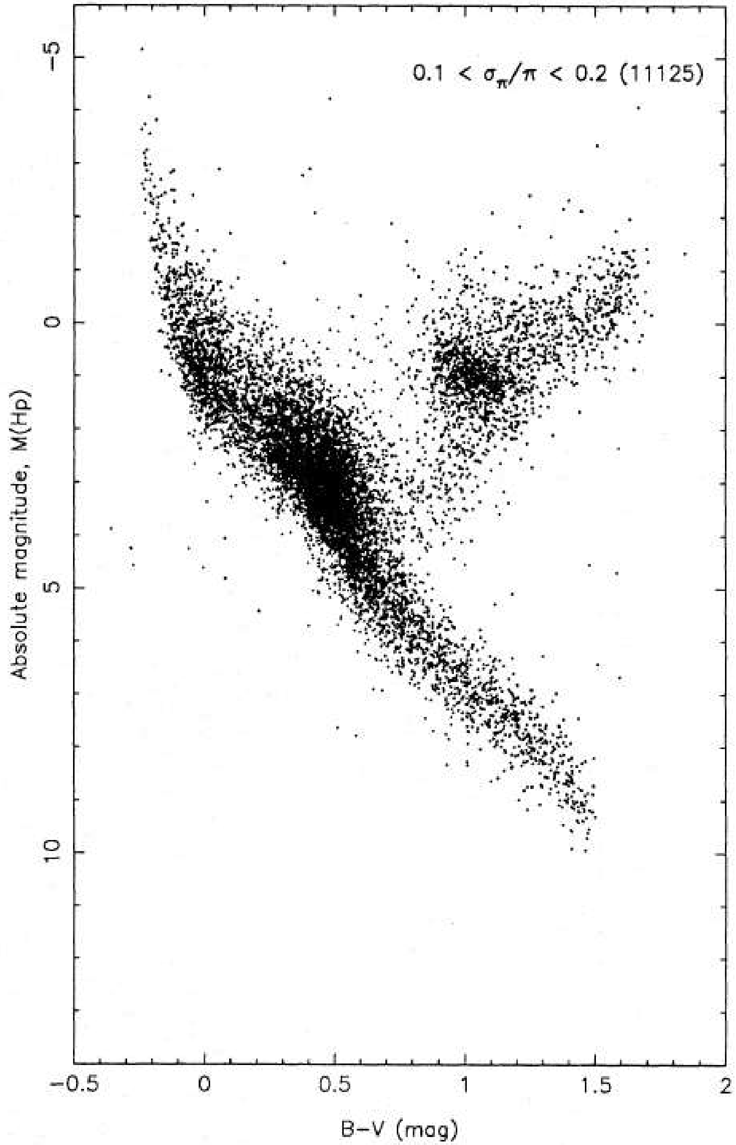


Piotto et al. (2002, A&A, 391, 945)

Star Clusters are
“laboratory for stellar evolution”

Color-Magnitude Diagrams for Field Stars

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



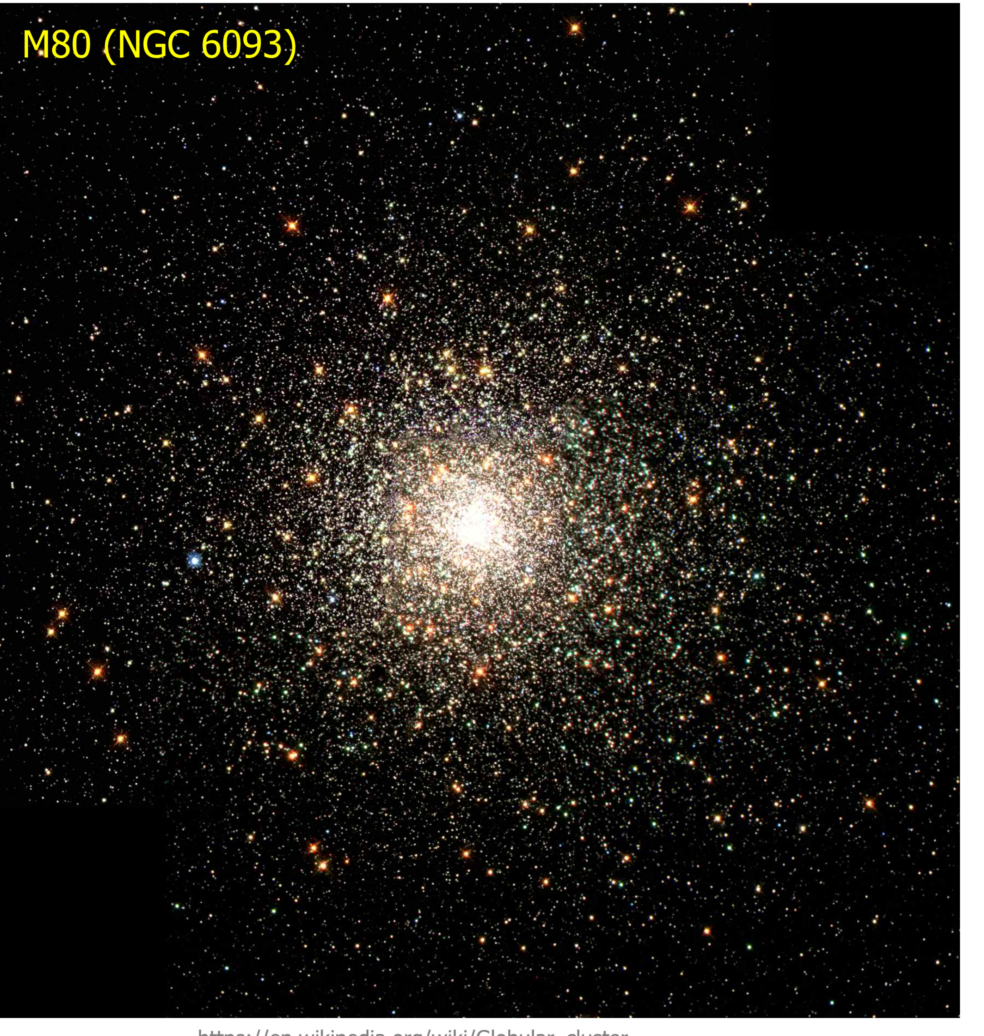
Perryman et al. (1995 A&A 304 69)

Star Clusters

Open Cluster (OC, Galactic Cluster, 산개성단)

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

Globular Cluster (GC, 구상성단)



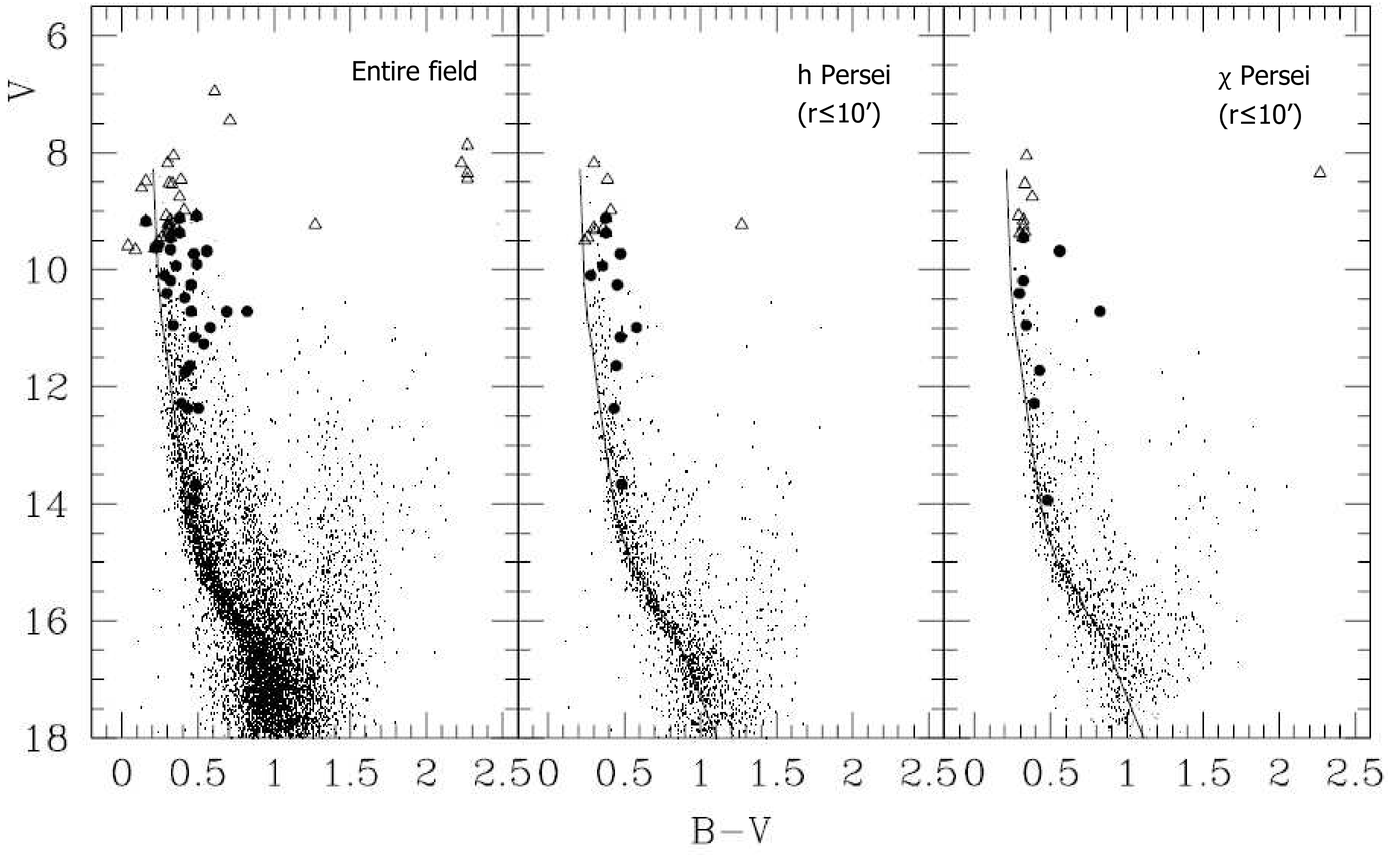
https://en.wikipedia.org/wiki/Globular_cluster

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

h and χ Persei Cluster (age ~1.26×10^7 yr)

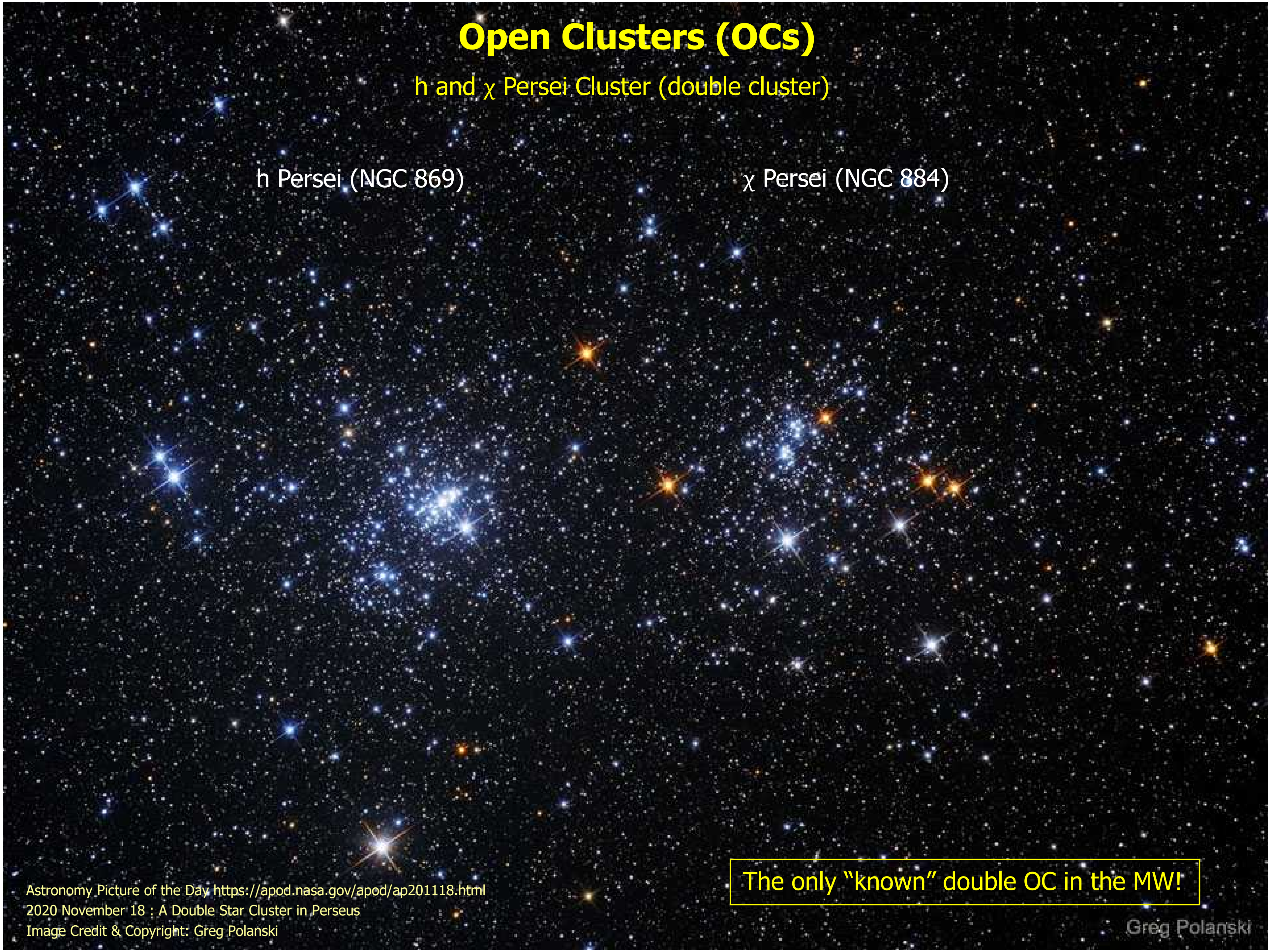
Thin line : ZAMS (Zero Age Main Sequence, 영년주계열)



Keller et al. (2001 AJ 122 248)

Open Clusters (OCs)

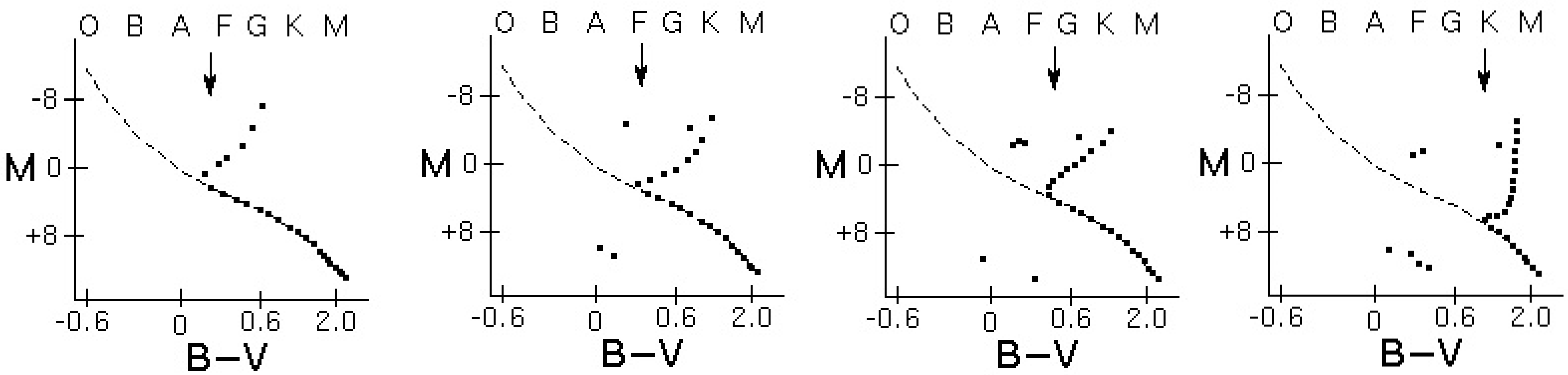
h and χ Persei Cluster (double cluster)



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!

Color-Magnitude Diagrams for Open Clusters (OCs)

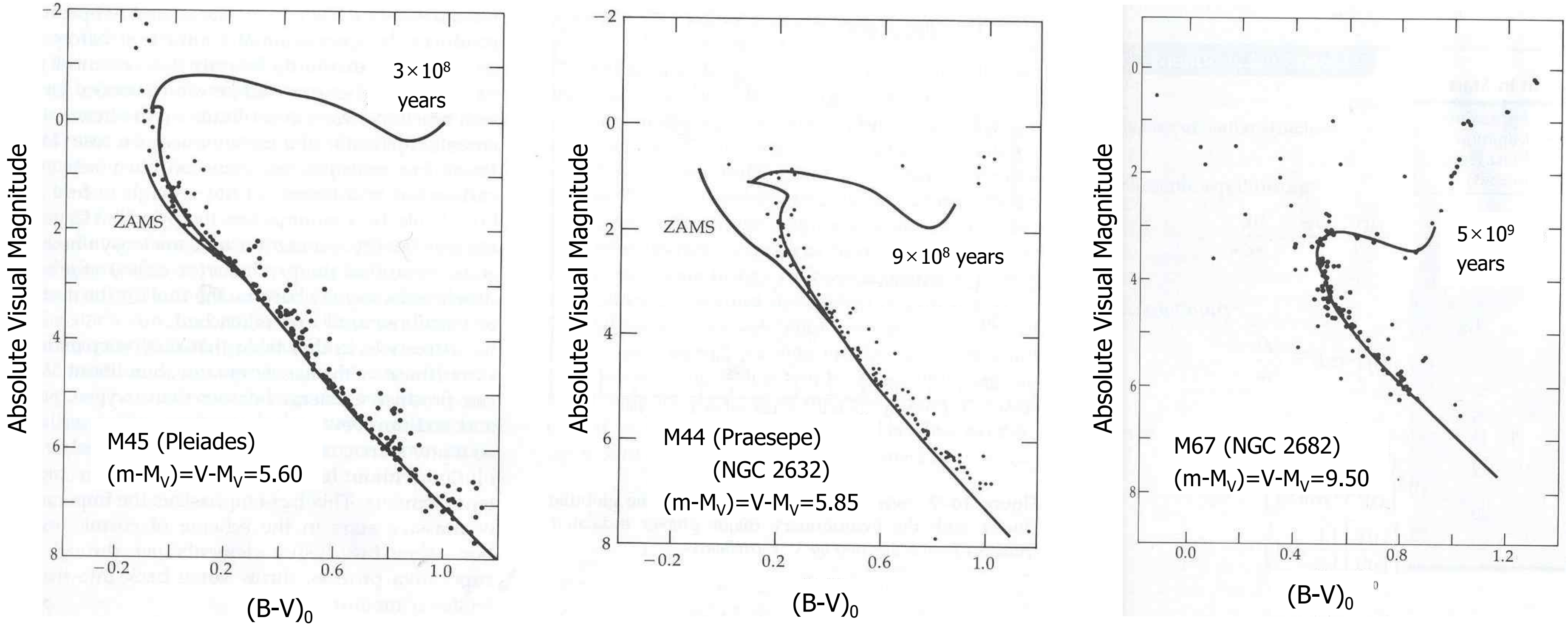


http://www.astronomynotes.com/evolutn/s9.htm

- 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)

Solid lines : theoretical isochrones (이론적인 등연령곡선)



- Observed turnoff points → approximate ages of the OCs (성단의 나이)
- $M_{V,0}$, $(B-V)_0$, $(V-M_V)_0$: extinction corrected

Introductory Astronomy and Astrophysics (4th edition)
Michael Zeilik & Stephen A. Gregory (1998), p. 327

Color-Magnitude Diagrams for Open Clusters (OCs)

MSTO for old OCs

•Blue turnoff (BTO)

•Red turnoff (RTO)

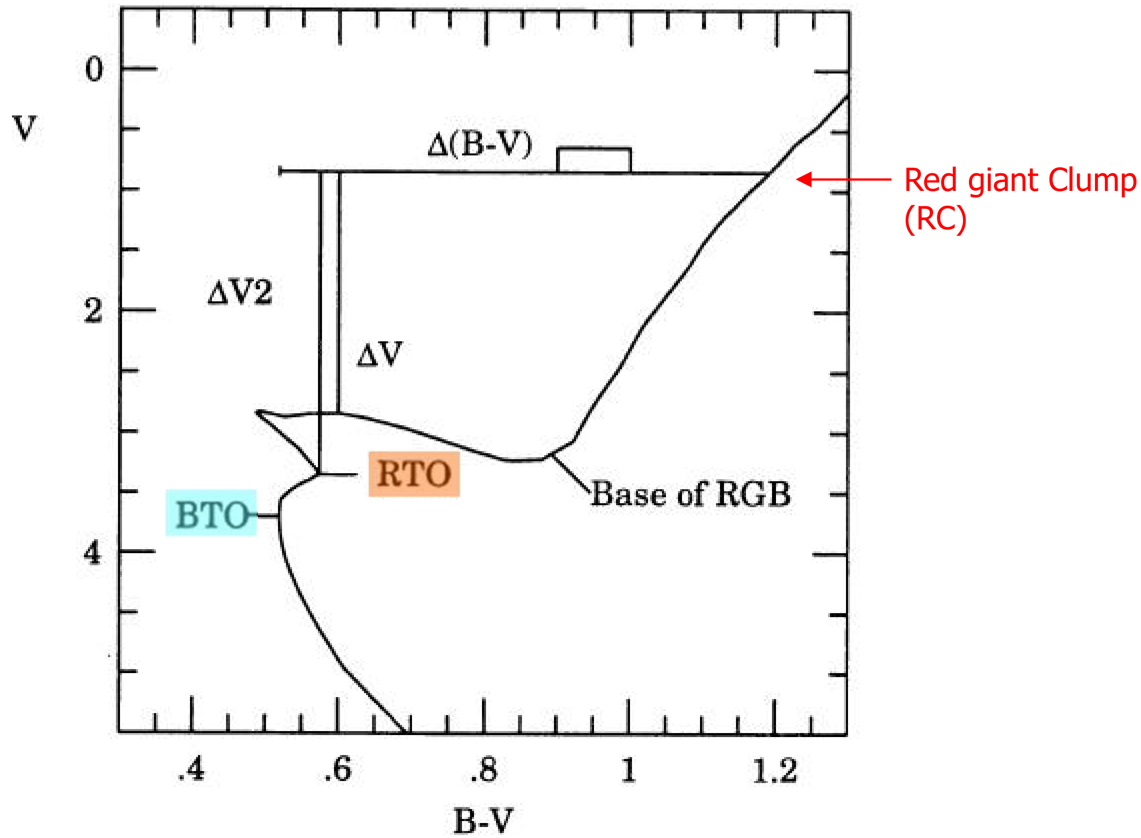
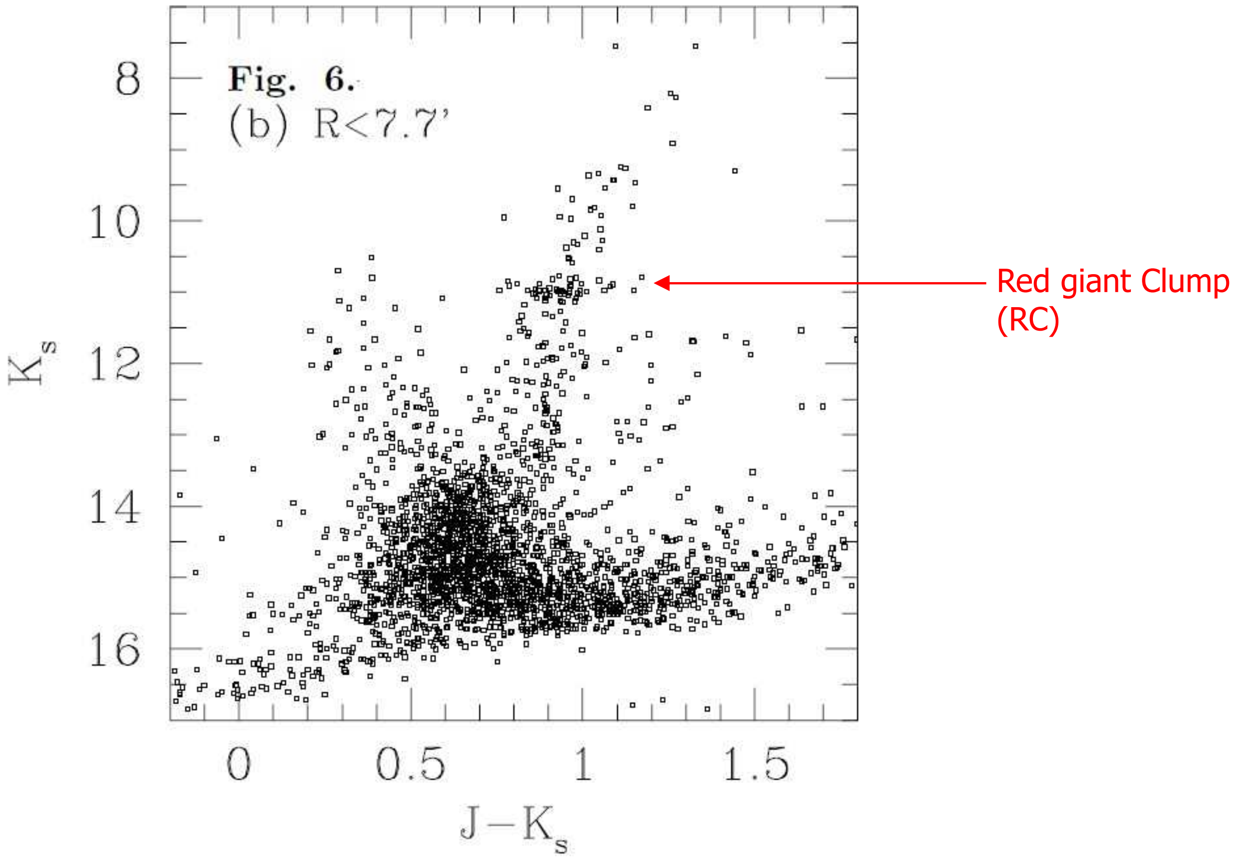


Fig. 2. Theoretical isochrone for stars of solar metallicity and age = 4Gyr (Meynet et al. 1993). Positions of the blue turnoff (BTO), the red turnoff (RTO) and the base of the red giant branch (RGB) are marked. The location of the red giant branch clump is marked with a rectangle

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

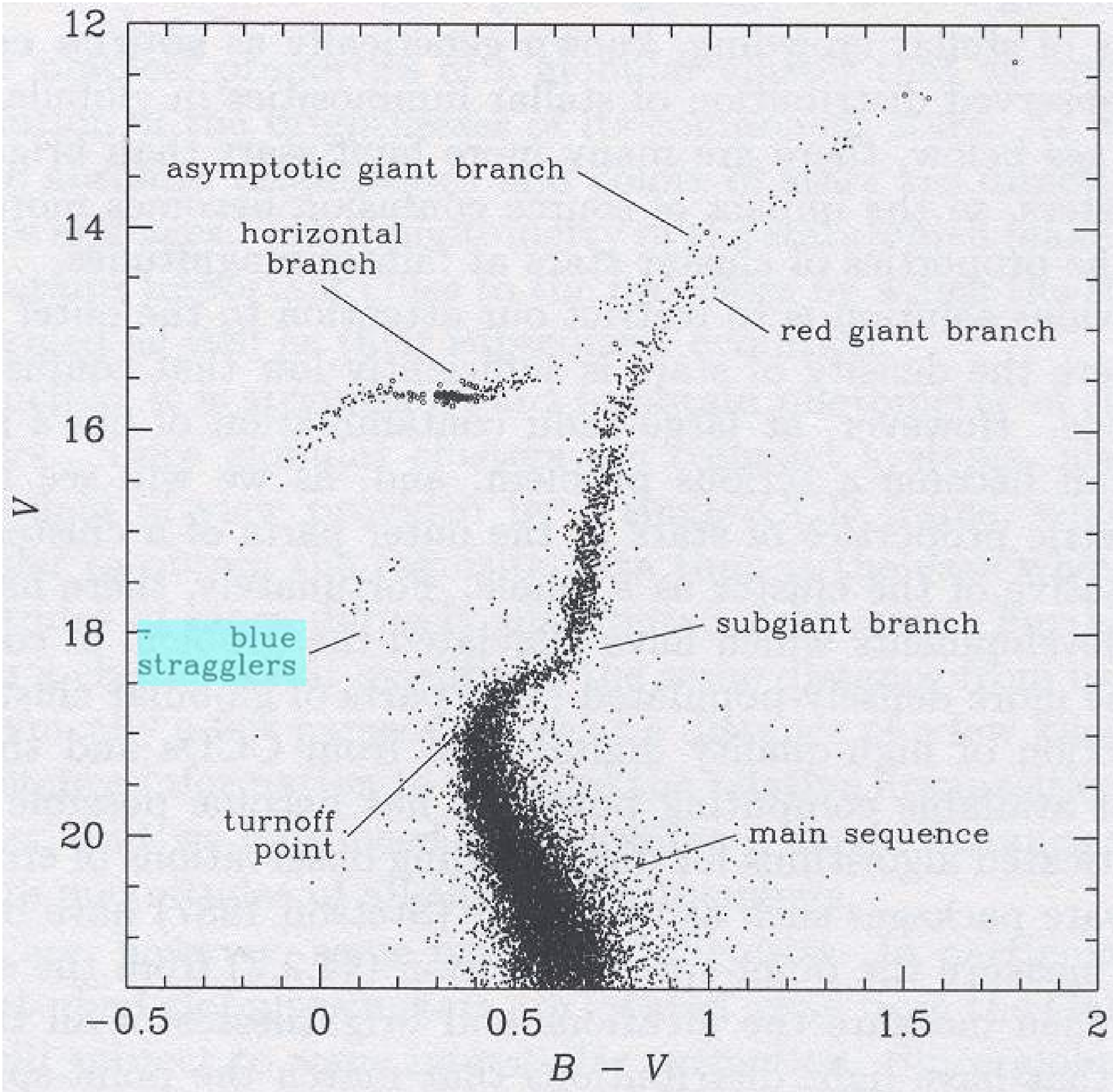


OC Trumpler 5

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

Blue stragglers (BSs, 청색낙오성)

Globular cluster (GC) M3 (NGC 5272)

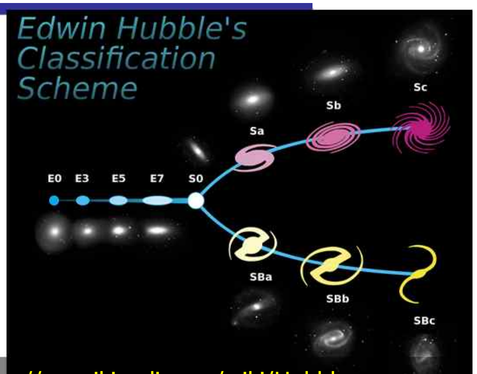


- Should have left the MS
- Probably
  - Mass exchange with a binary companion
  - Merger with a close companion
  - Internal chemical mixing that provided more H fuel to the core

Galactic Astronomy (James Binney and Michael Merrifield, 1998) p. 334

Stellar populations – Simple Stellar Population (SSP)

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



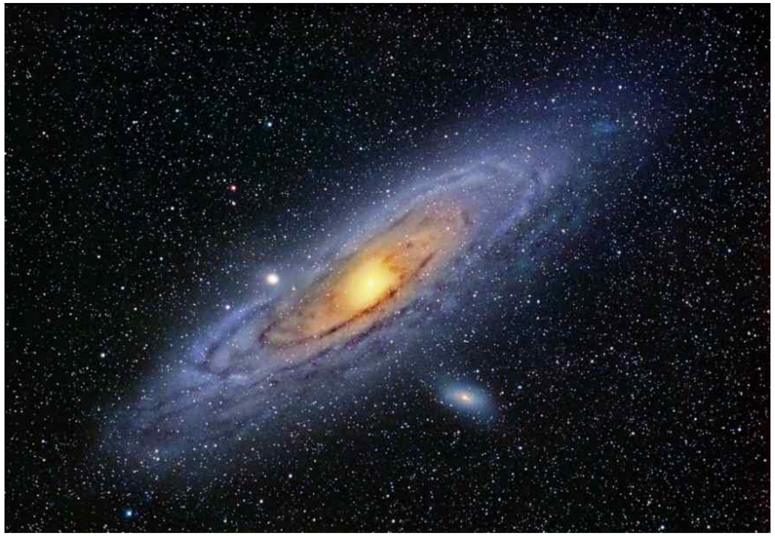
https://en.wikipedia.org/wiki/Hubble_sequence

Stellar populations – Multiple Stellar Populations

- galaxies
- Giant galaxies – elliptical galaxies (E), lenticular galaxies(S0) spiral galaxies (S : Milky Way Galaxy), irregular galaxies

$\underbrace{\text{elliptical galaxies (E), lenticular galaxies(S0)}}_{\text{Early-type galaxies}}$ $\underbrace{\text{spiral galaxies (S : Milky Way Galaxy), irregular galaxies}}_{\text{late-type galaxies}}$

- 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

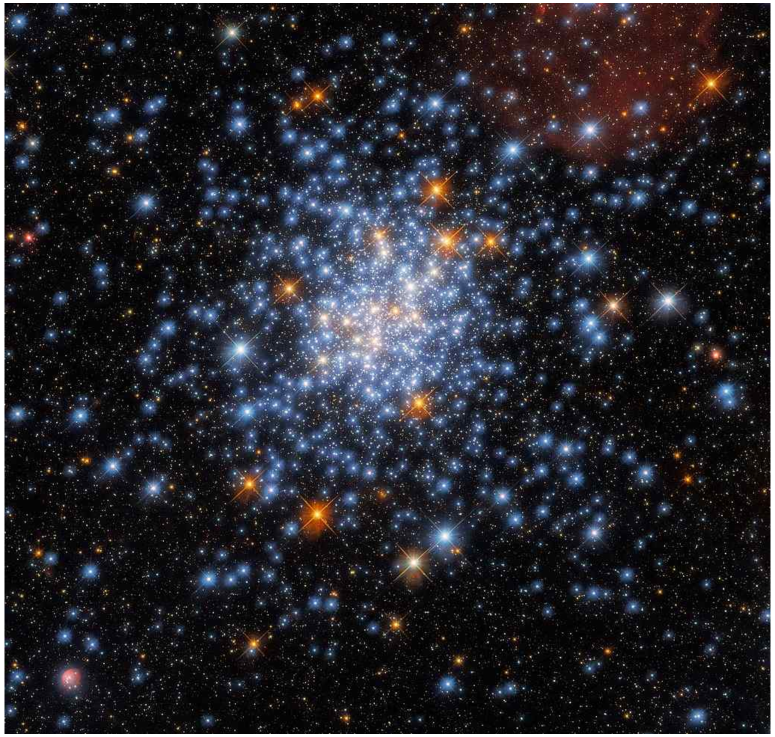
Fornax https://en.wikipedia.org/wiki/Dwarf_spheroidal_galaxy

(young) populous clusters

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

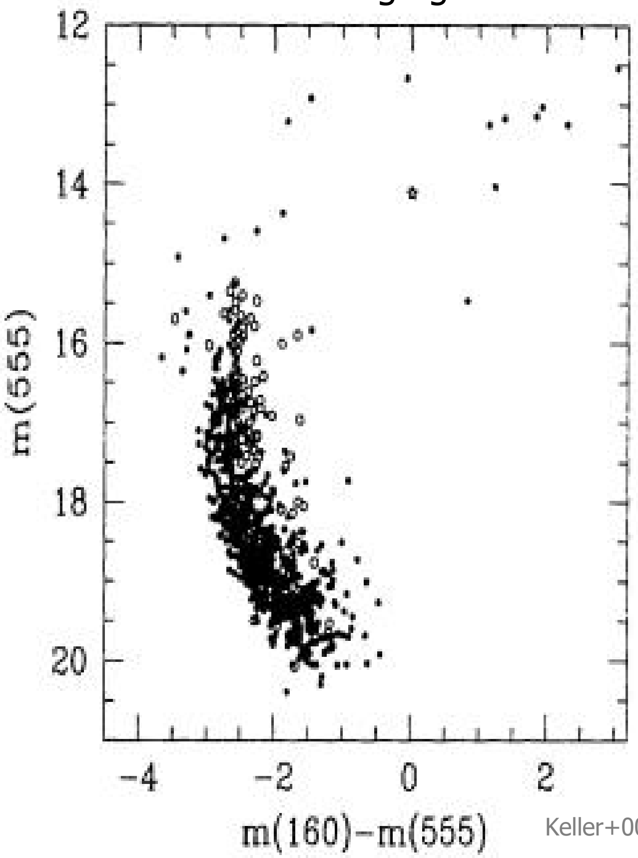
NGC 330 (SMC)

GC-like



https://en.wikipedia.org/wiki/NGC_330

Young age

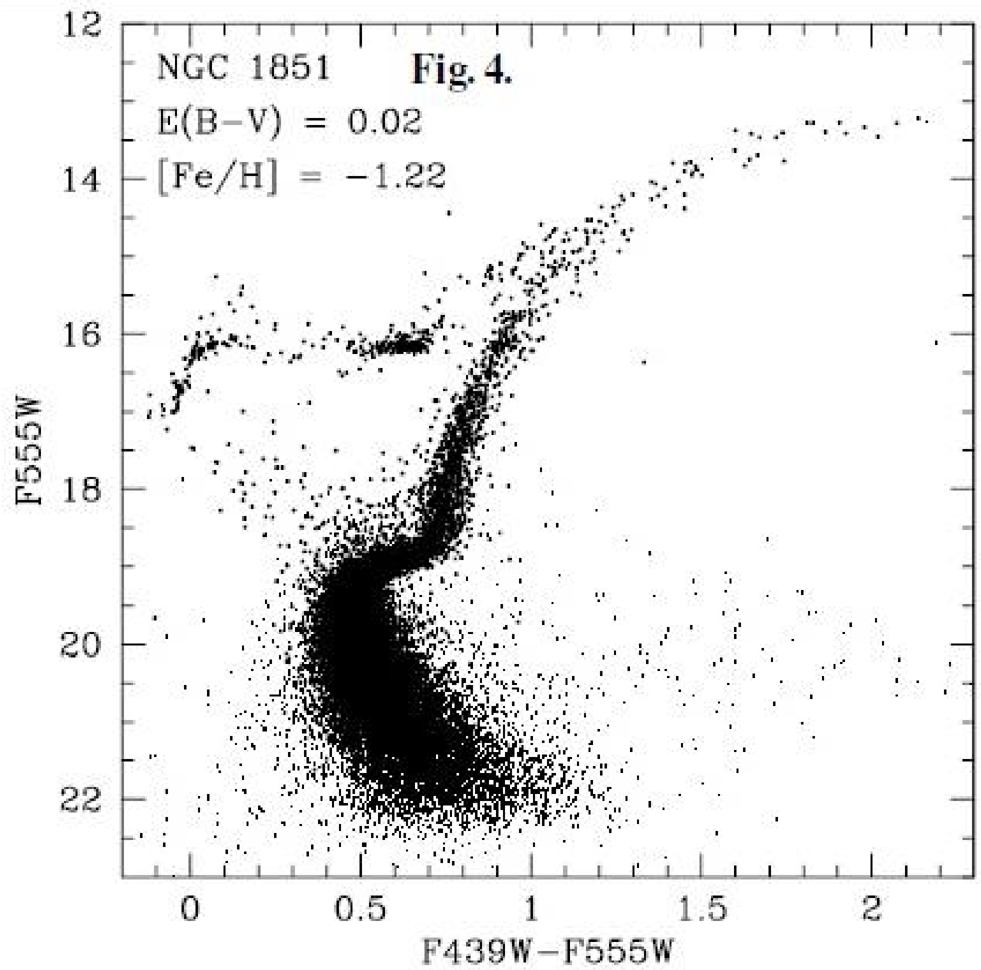


Keller+00 (ASPCS 211, 124)

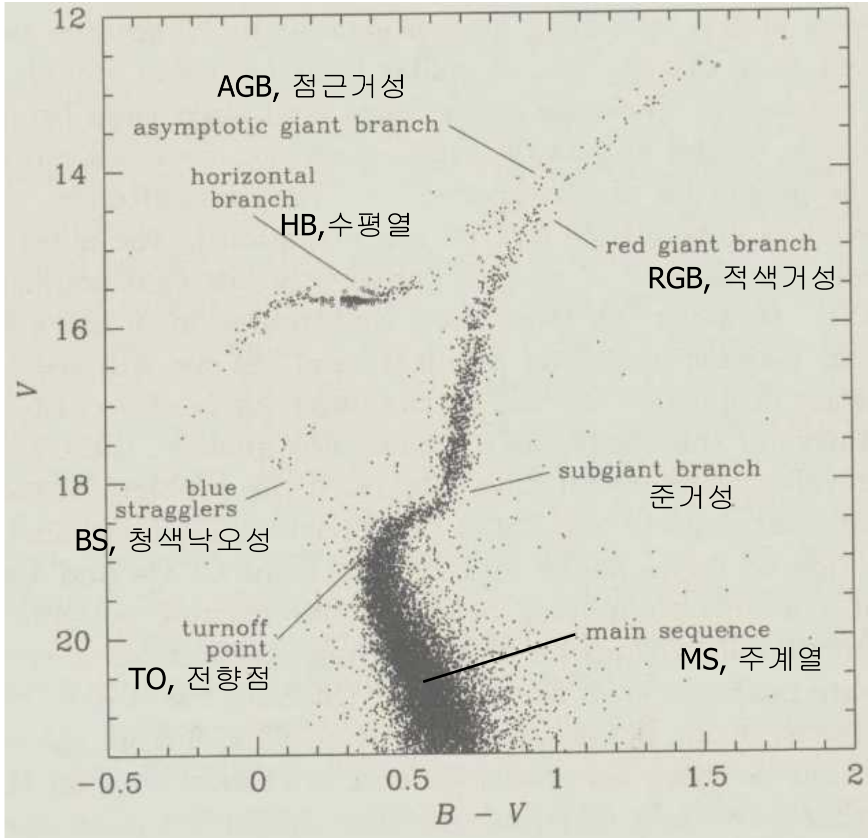
t=4×10^7 years

(Ying-Yi Song+ 21 MNRAS 504 4160)

Color-Magnitude Diagrams for globular clusters (GCs)



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

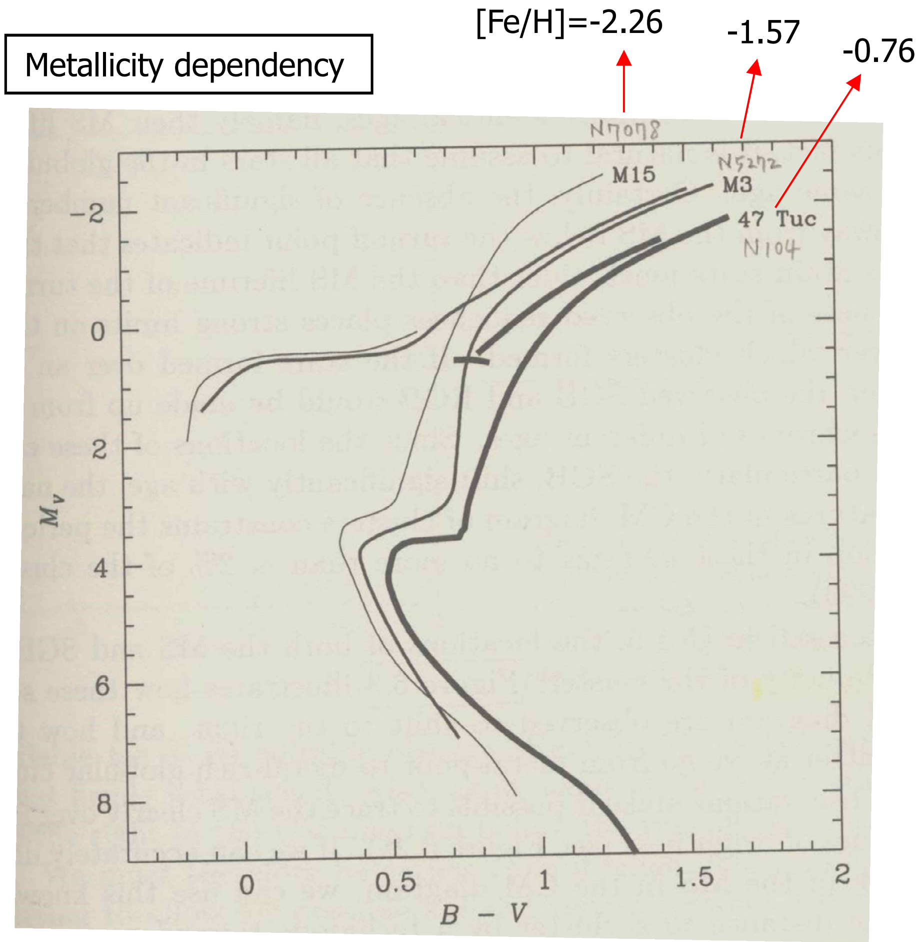


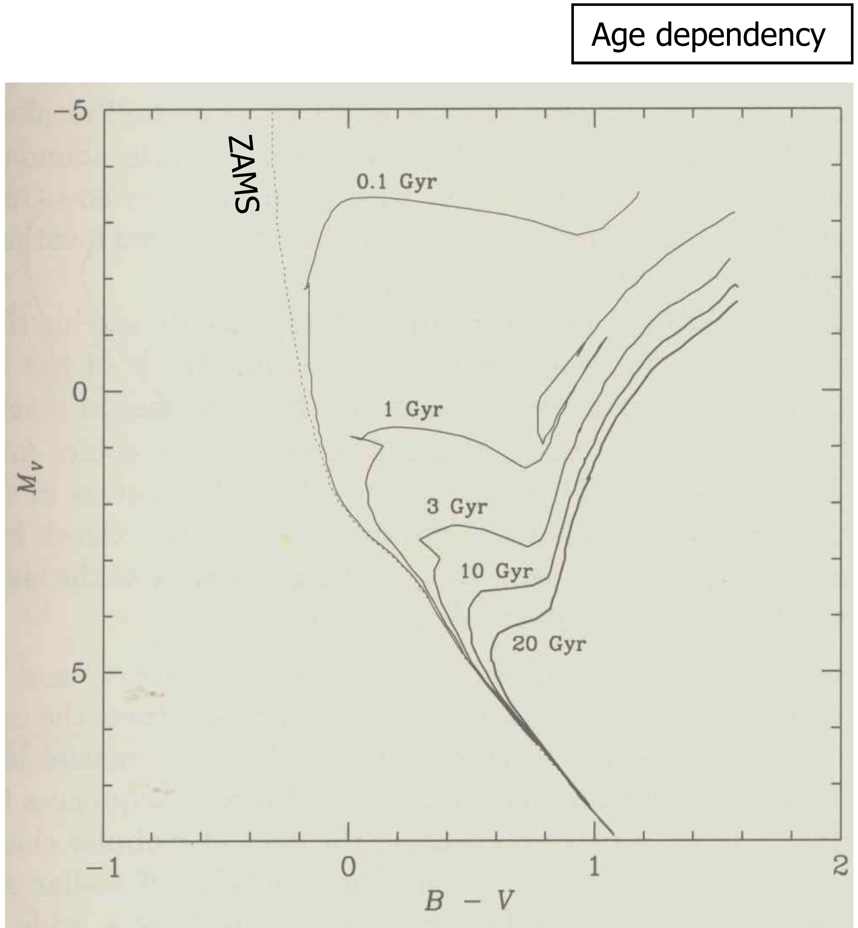
GC M3 (NGC 5272)
(variables=open circles)

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

Galactic Astronomy (J. Binney & M. Merrifield, 1998) p. 334

Globular Cluster (GC) – metallicities and ages





Bertelli + (1994, A&AS, 106, 275)

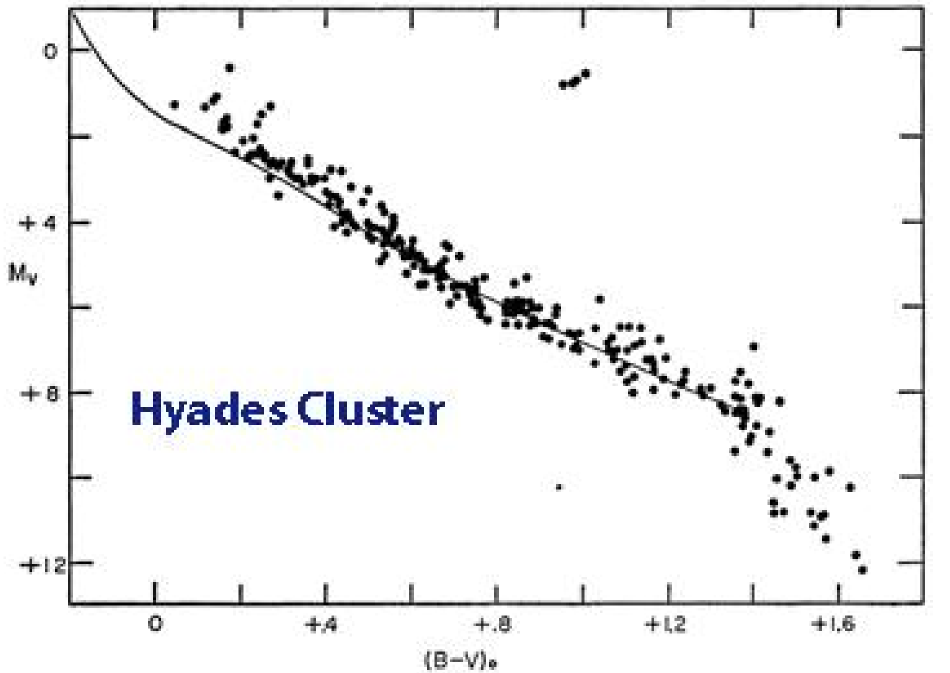
Padova isochrones, Z=0.004, Y=0.24

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

Galactic Astronomy (J. Binney & M. Merrifield, p. 335, 339)

Globular Cluster (GC) - introduction

산개성단
(散開星團,
open cluster)

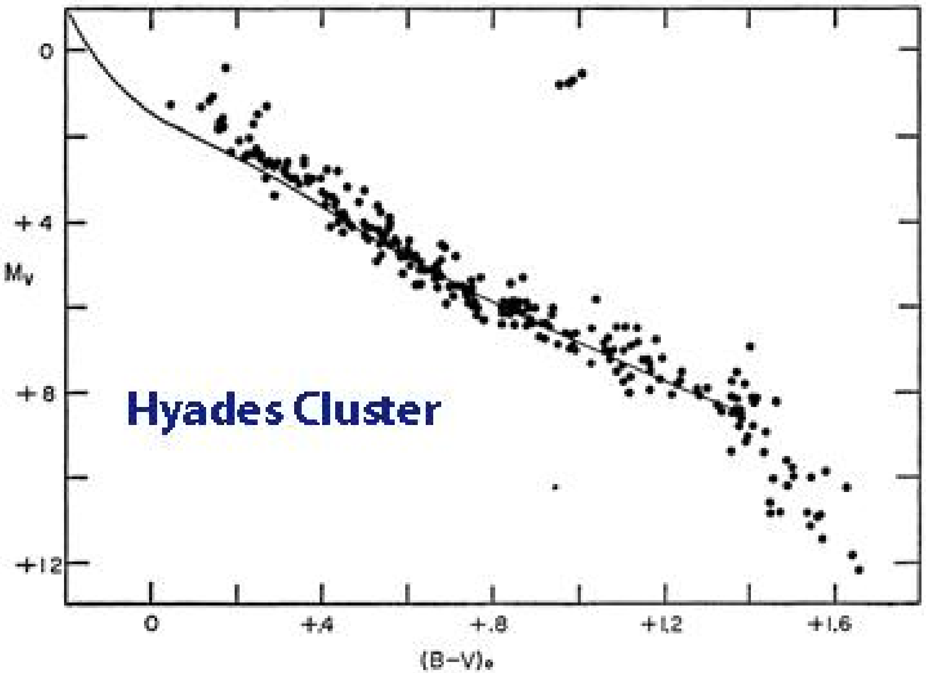


http://www.daviddarling.info/encyclopedia/H/Hyades.html

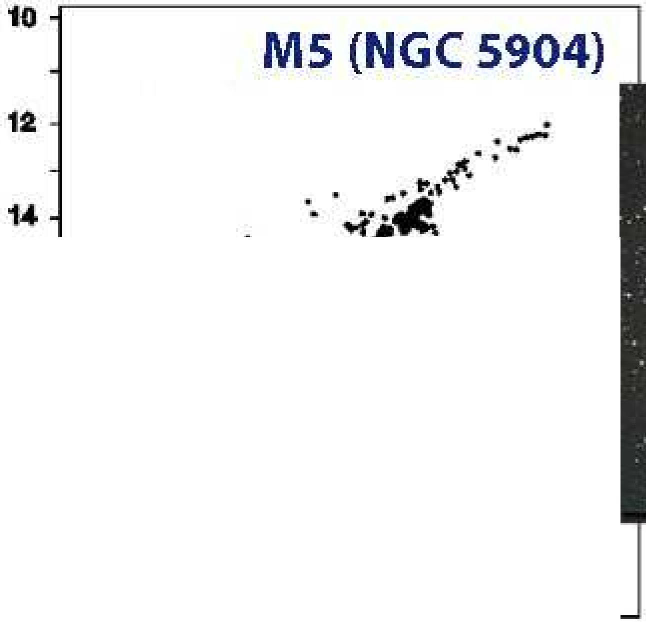
http://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_pleiadesact.html

Globular Cluster (GC) - introduction

산개성단
(散開星團,
open cluster)



구상성단(球狀星團,
globular cluster)

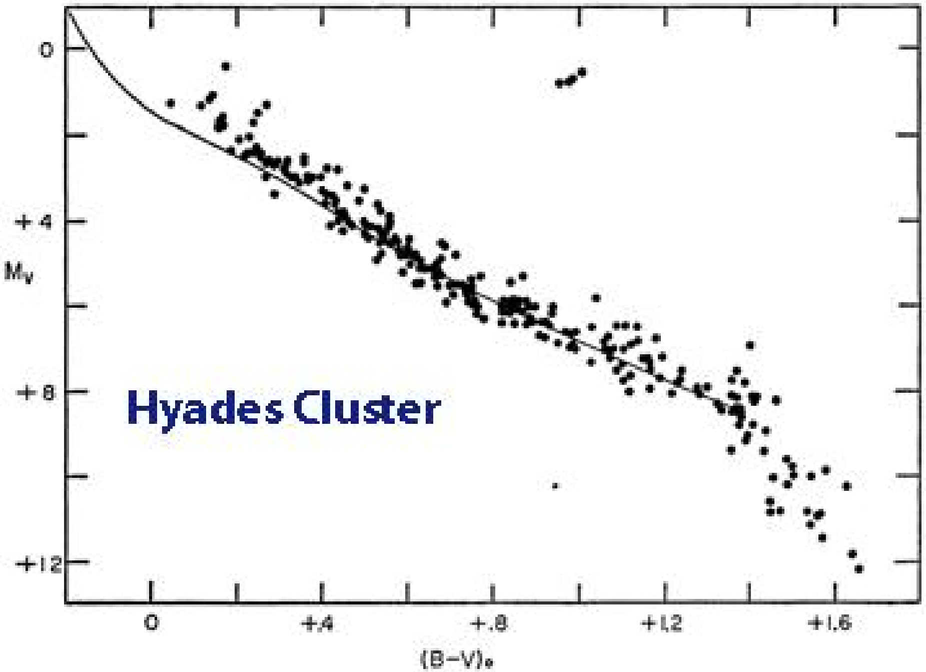


http://www.daviddarling.info/encyclopedia/H/Hyades.html

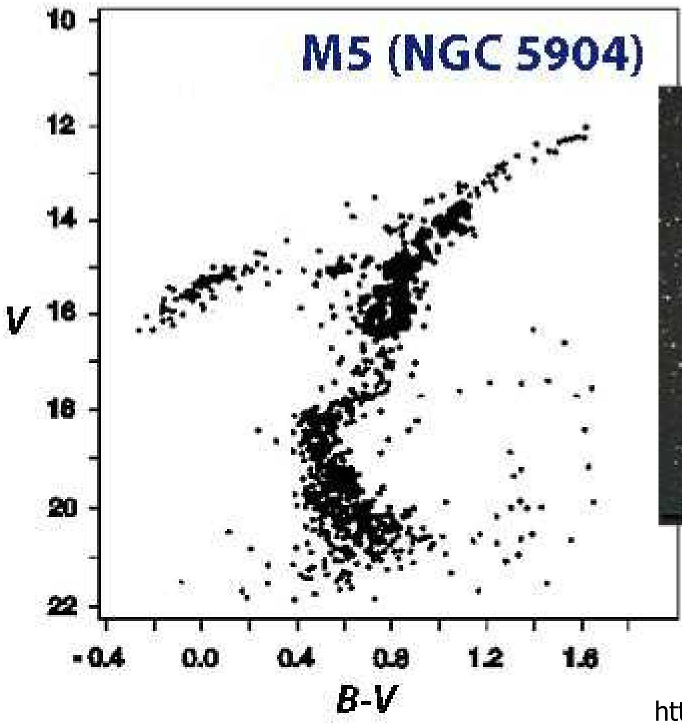
http://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_pleiadesact.html

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

http://www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_pleiadesact.html

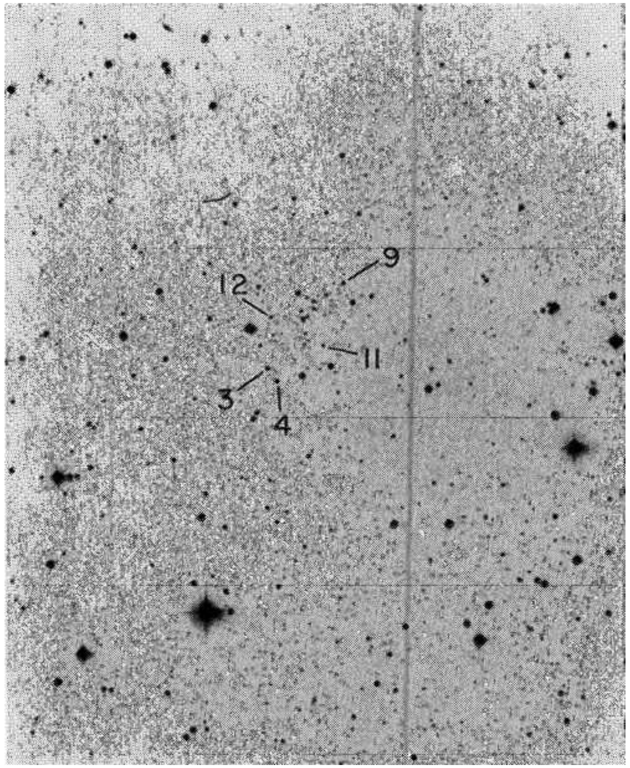
Globular Cluster (GC) - definition

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



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	$6\times10^5\ M_\odot$	$250\ M_\odot$
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 ~ 150
M31 : N ~ 245 (only confirmed GCs) ← Revised Bologna Catalogue V.5 (Aug 2012)
(http://www.bo.astro.it/M31/)
N ~ 2060 (all GCs and GC candidates)

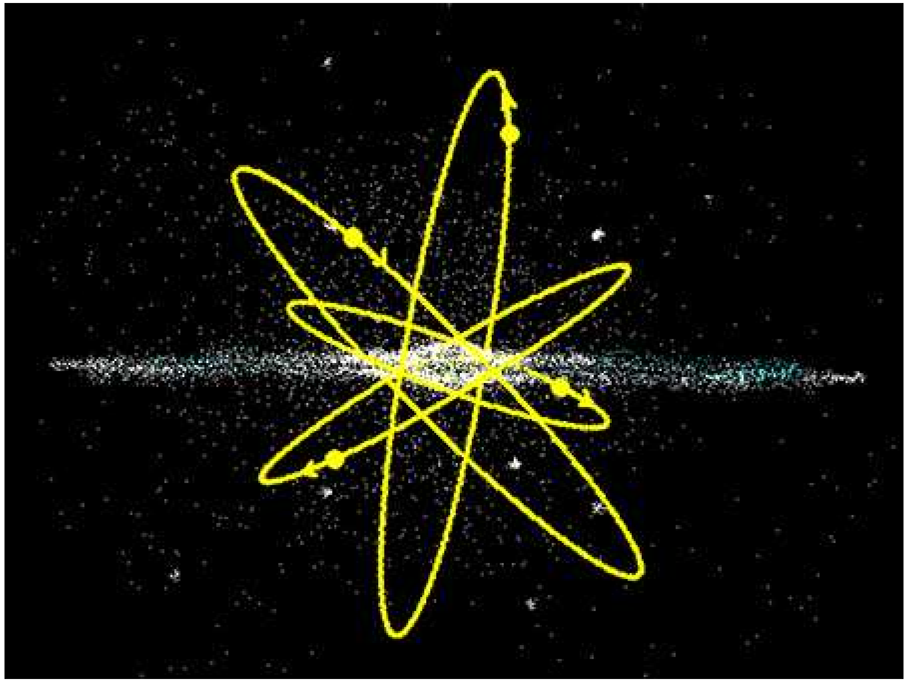
Galactic Astronomy (J. Binney & M. Merrifield, 1998) p. 386

GCs and OCs in the MW

GCs : high velocity dispersion, eccentric orbits

OCs

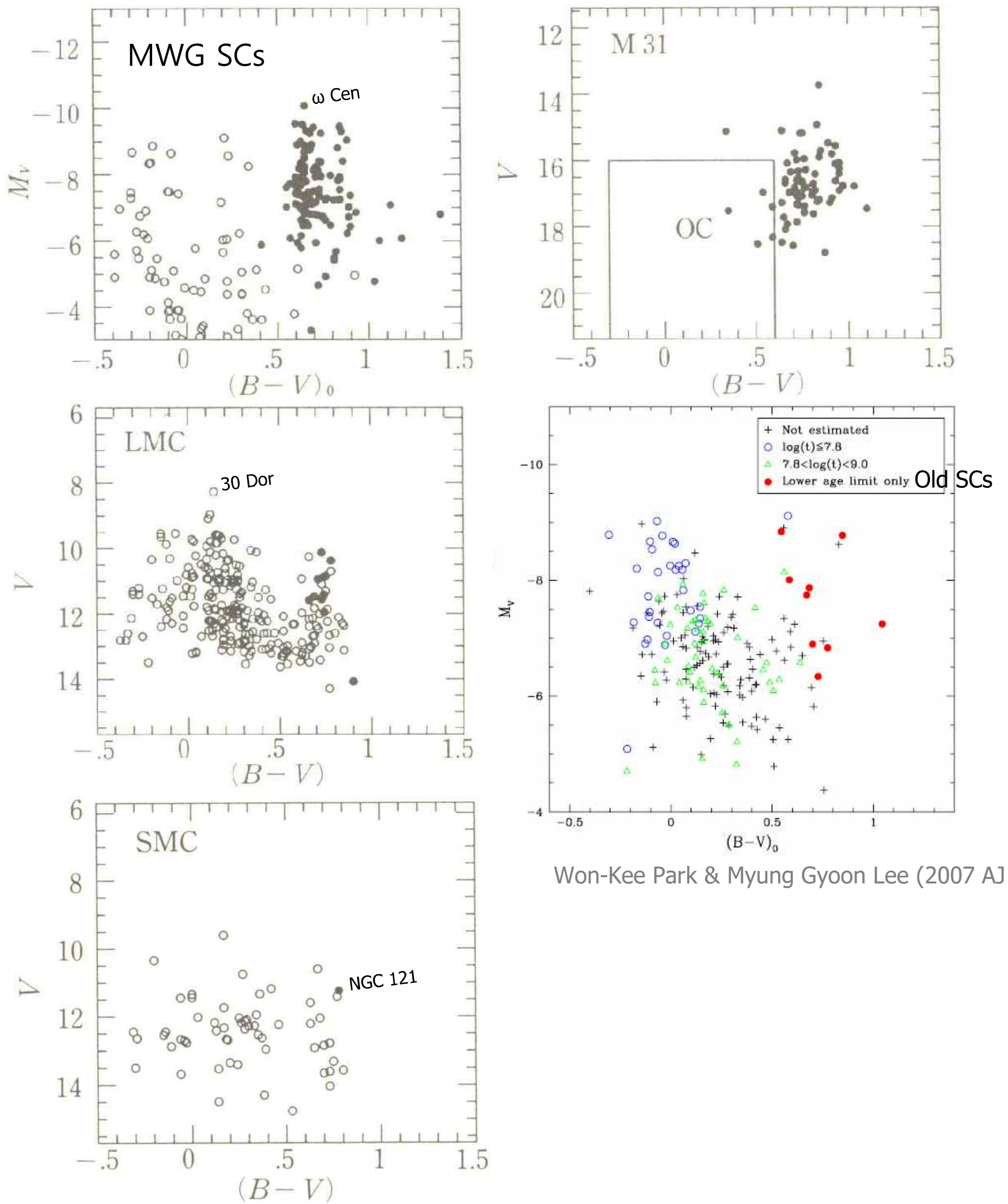
: circular rotation
in the disk



http://www.khadley.com/courses/Astronomy/ph_207/topics/milkyWay/

GCs and OCs in the MW

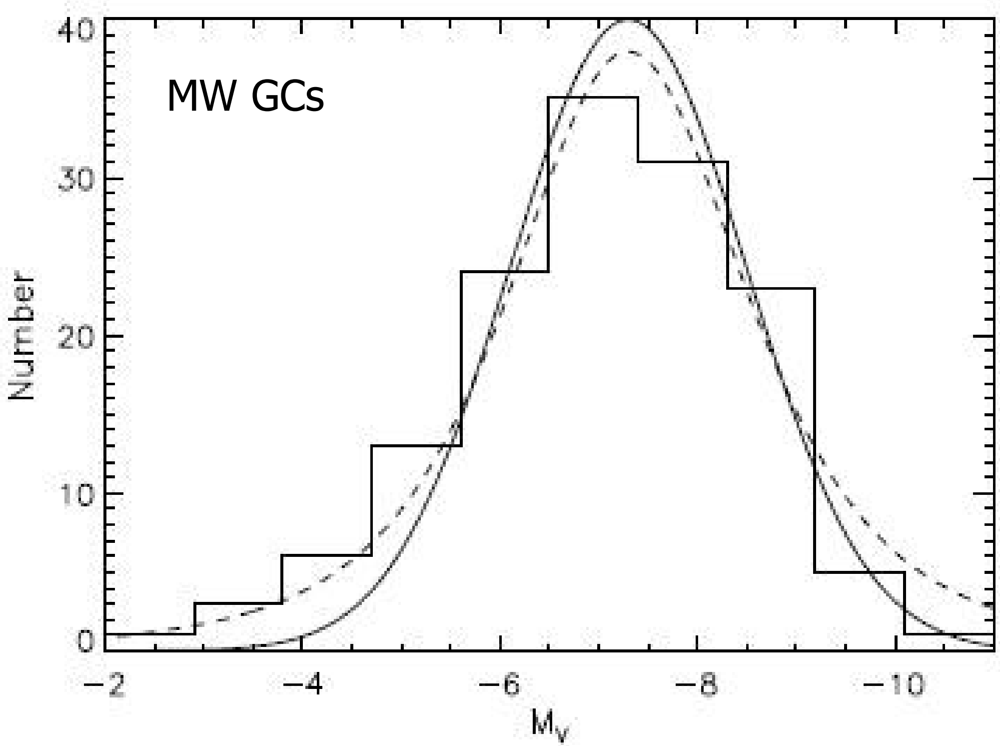
● : GCs
○ : young SCs



Won-Kee Park & Myung Gyoon Lee (2007 AJ 134 2168)

구형항성계의 진화(1997, 안홍배 오갑수 이명균 등, p. 51)

GC luminosity function (GCLF)

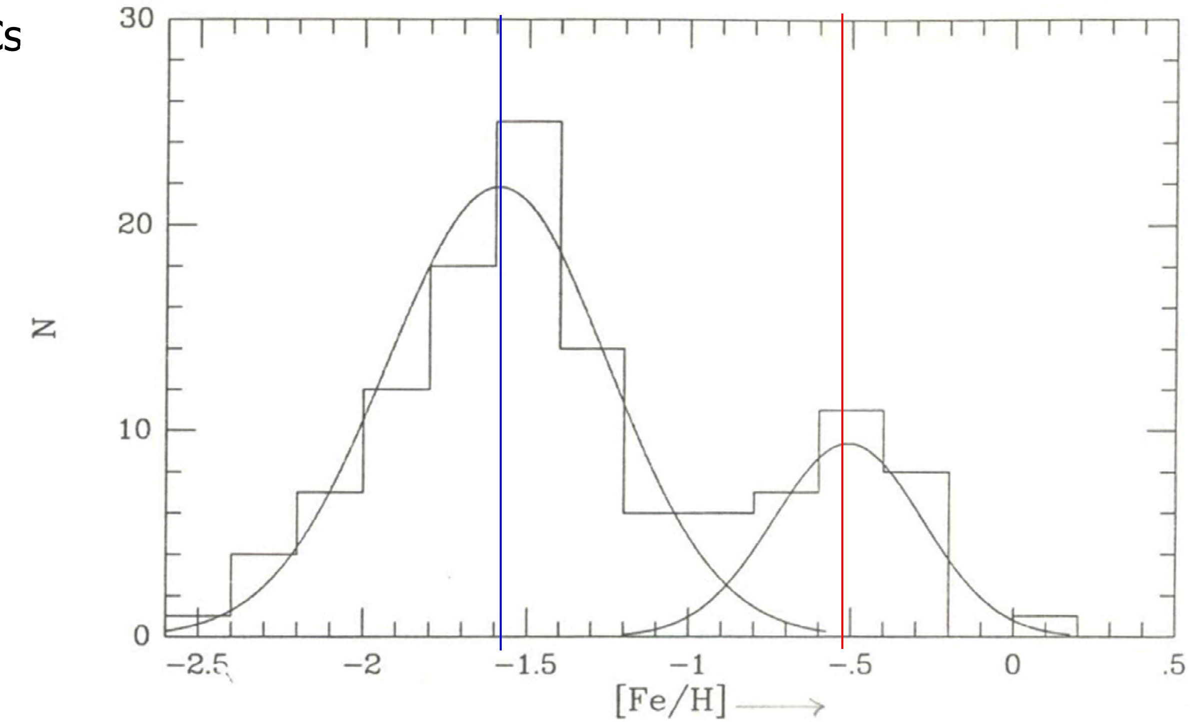


Rejkuba (2012, Ap&SS, 341, 195 – GCLF as distance indicator) – Fig. 3

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

Metallicity Distribution Function (MDF)

MW GCs



Metal-poor (MP) GCs
[Fe/H] = -1.6

Metal-rich (MR) GCs
[Fe/H] = -0.5

Different origins
(Formation mechanisms)

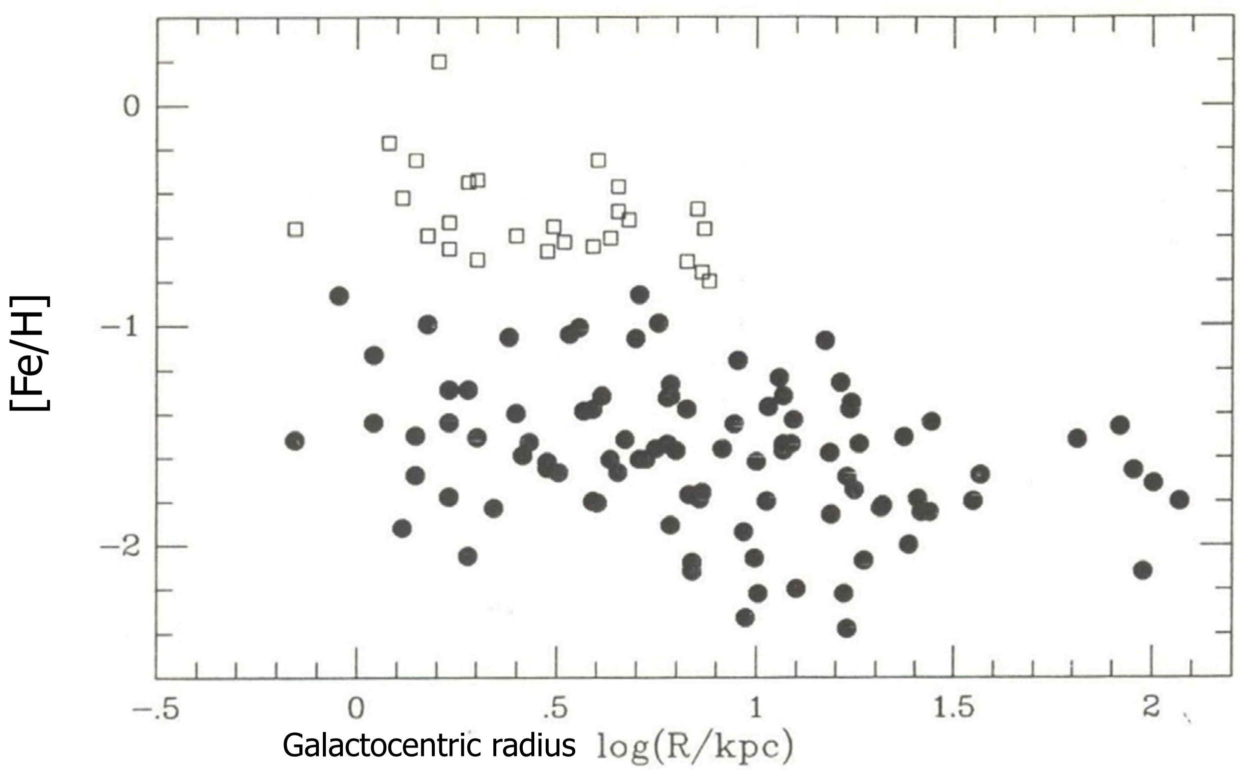
Globular Cluster Systems (1998, K. M. Ashman & S. E. Zepf, p. 37)

Radial metallicity distribution

MW GCs

□ : disk GCs

● : halo GCs



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

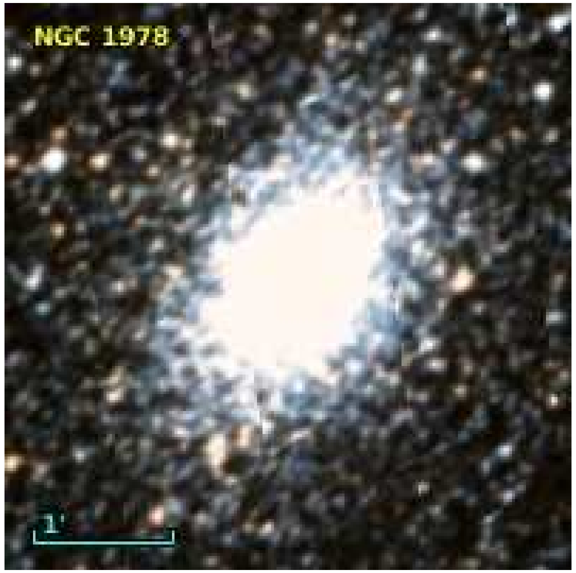
Globular Cluster Systems (1998, K. M. Ashman & S. E. Zepf, p. 40)

GCs : ellipticity (타원율)

ω Cen (Omega Centauri) = NGC 5139
ε=0.19, M_V = -10.1, slow rotation

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

NGC 1978 (LMC)
ε=0.33, M_V = -8.0, t = 2.5 Gyr



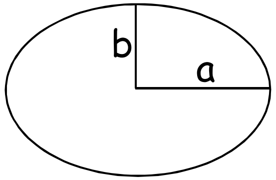
http://aladin.u-strasbg.fr/simbad-thumbnails/thumbnails23.html

NGC 121 (SMC)
ε=0.26, M_V = -7.7, t = 1.2 Gyr

HST
https://pl.wikipedia.org/wiki/NGC_121

G1 = Mayall II (M31)
ε=0.22, M_V = -11.0

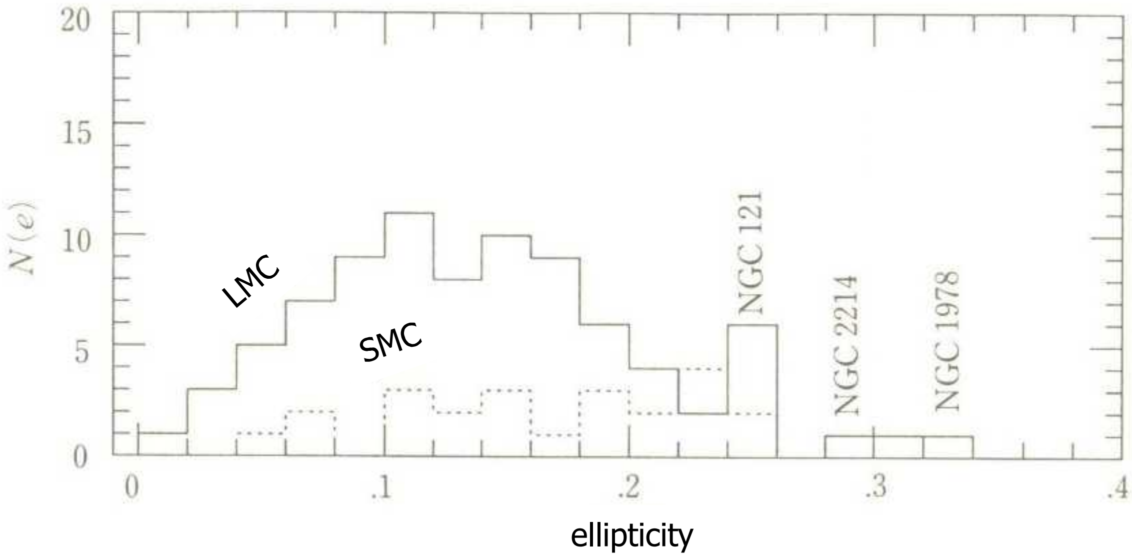
HST
https://en.wikipedia.org/wiki/Mayall_II

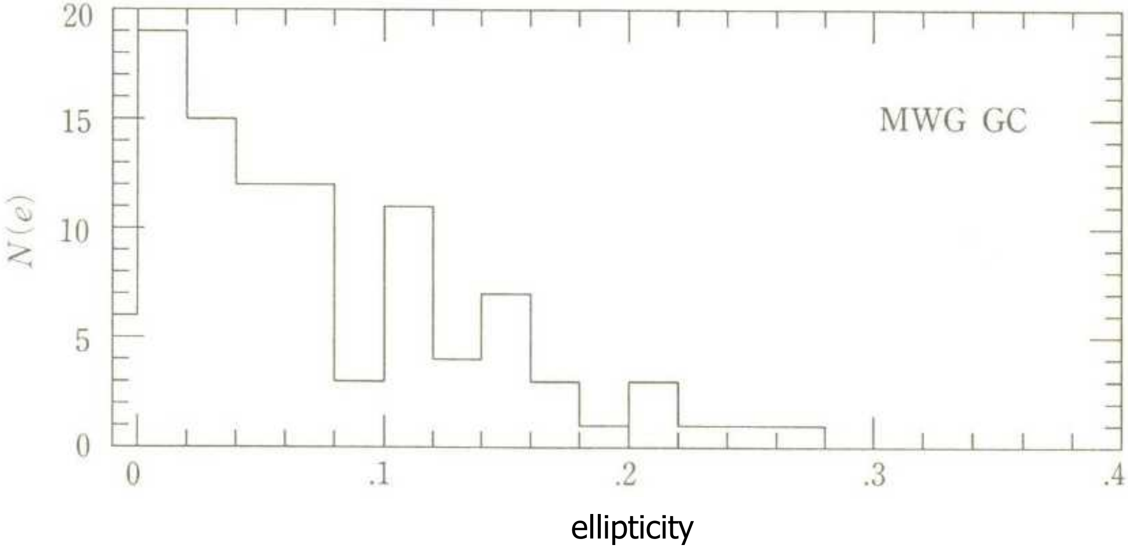


Ellipticity, $\varepsilon = \frac{a-b}{a}$

GCs : ellipticity (타원율)

- Brightest GCs in galaxies ~ large ellipticities
- MCs : larger ellipticities than MW
- Largest ε in MCs » largest ε in MWG

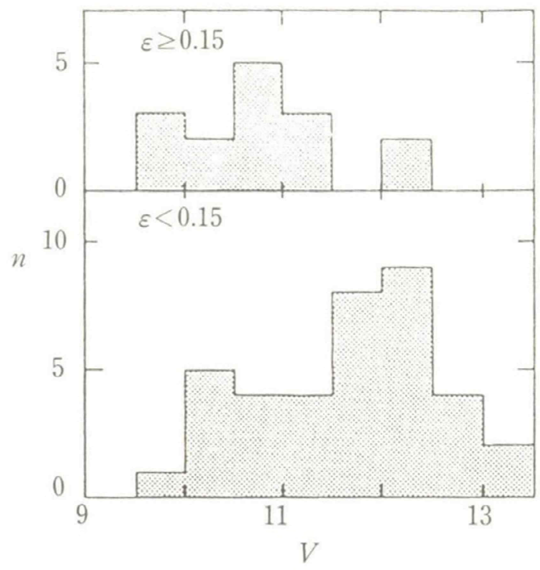




구형항성계의 진화(1997, 안홍배 오갑수 이명균 등, p. 67)

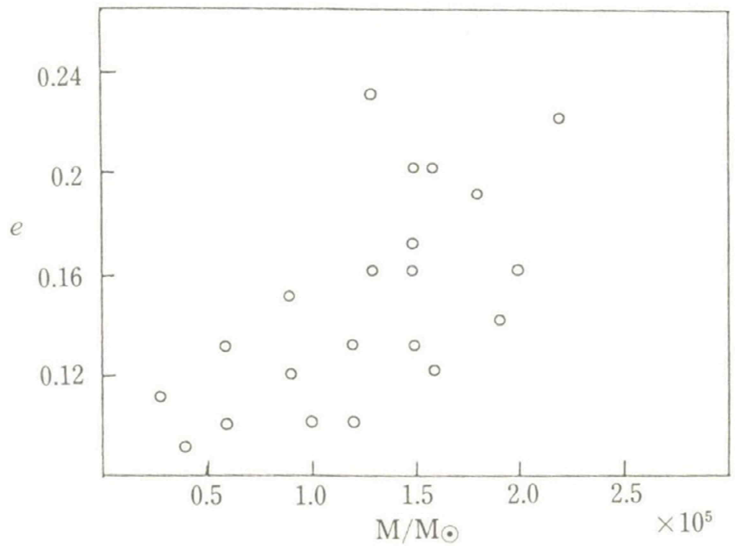
GCs : ellipticity (타원율)

Brighter GCs ~ larger ε



LMC SCs

massive GCs ~ larger ε

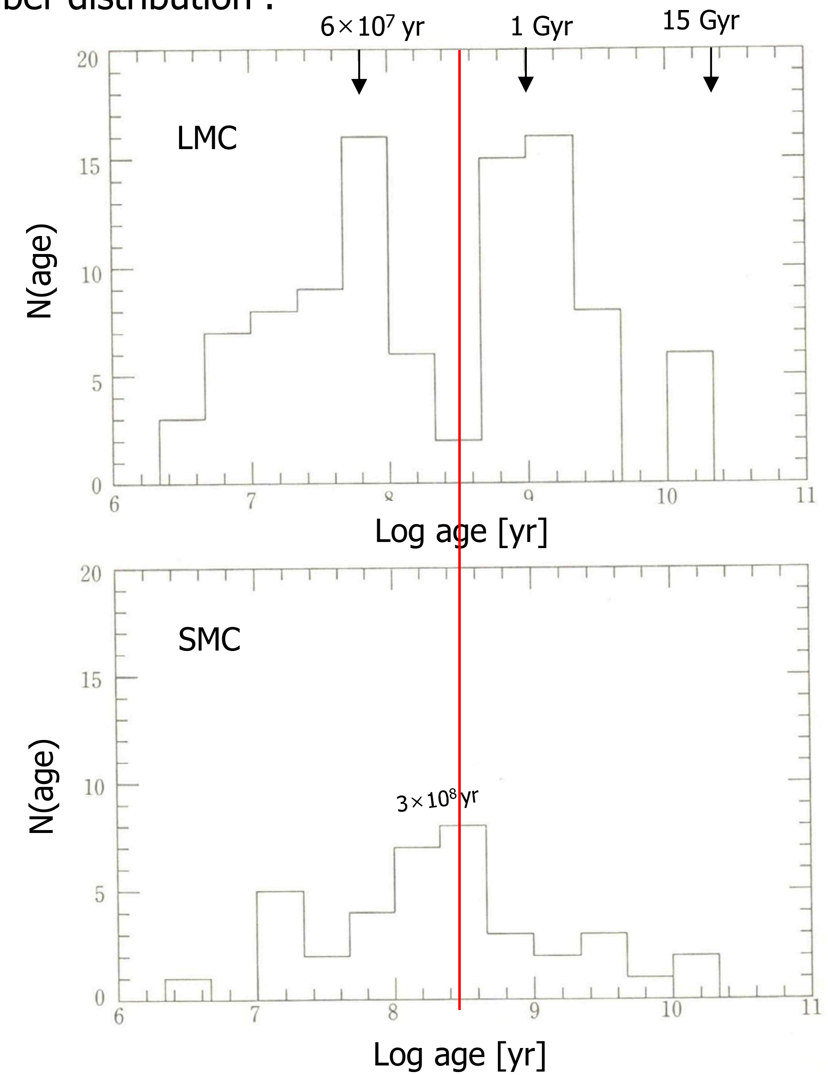


LMC SCs

구형항성계의 진화(1997, 안홍배 오갑수 이명균 등, p. 67)

GCs : age distribution

Number distribution :



LMC – 3 peaks (6×10^7 yr, 1, 15 Gyr)

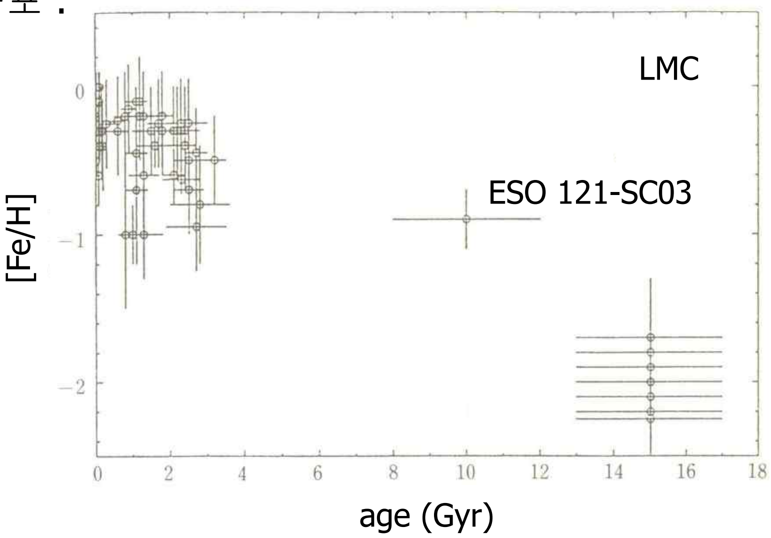
– 2 valleys

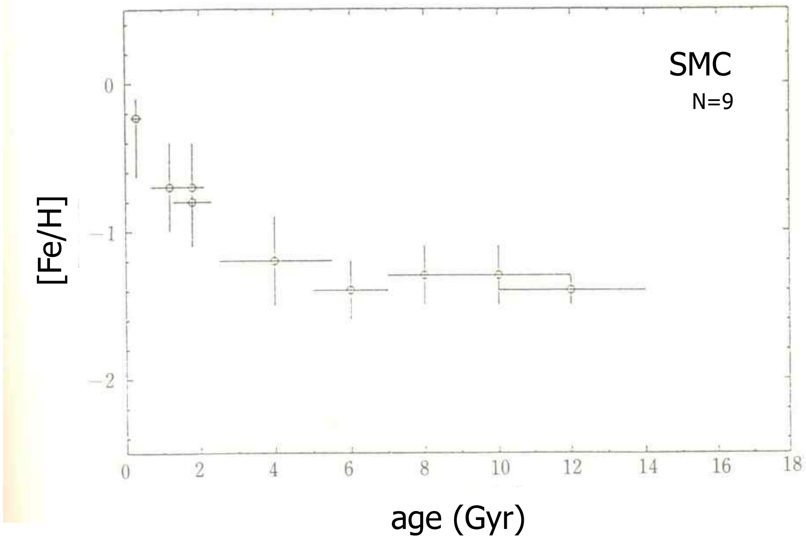
SMC – peak at 3×10^8 yr

구형항성계의 진화(1997, 안홍배 오갑수 이명균 등, p. 69)

GCs : age-metallicity

개수 분포 :



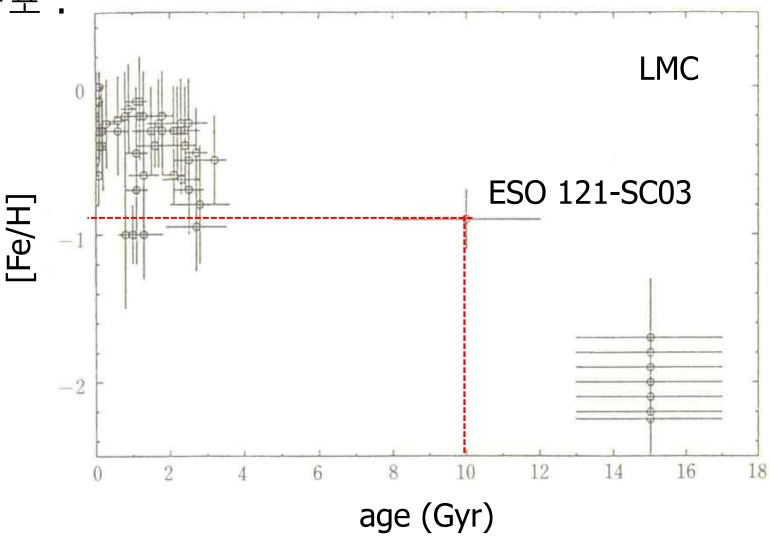


LMC – young SCs → -1.0 < [Fe/H] < 0.0
– old GCs → -2.3 < [Fe/H] < -1.6

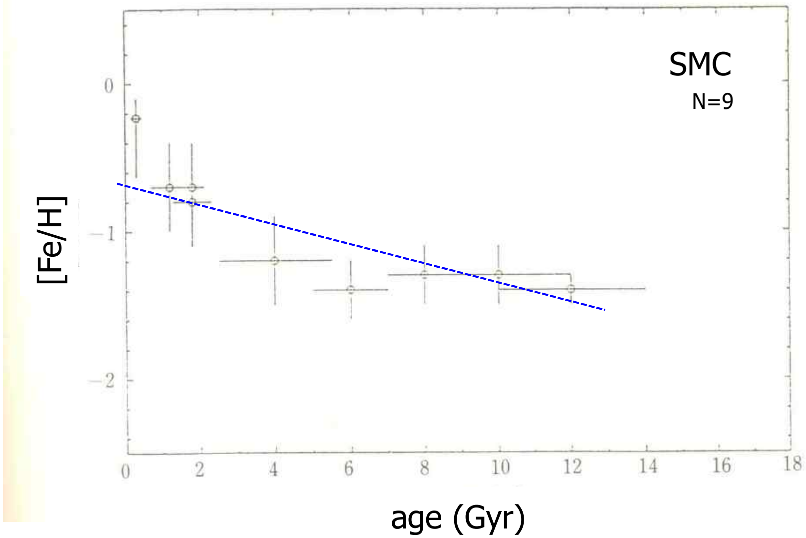
구형항성계의 진화(1997, 안홍배 오갑수 이명균 등, p. 69)

GCs : age-metallicity

개수 분포 :



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



→ correlation between age-metallicity

구형항성계의 진화(1997, 안홍배 오갑수 이명균 등, p. 69)

Summary

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 $\boxed{\text{mass}}$