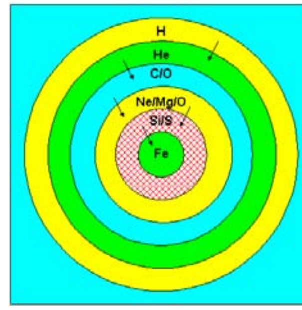
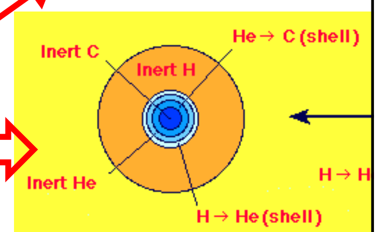
Summary: Nuclear burning in stars

Reaction	Min. Temp.
4 $^{1}H \rightarrow {}^{4}He$	10^{7} ° K
3 $^{4}He \rightarrow {}^{12}C$	2×10^{8}
$^{12}C + {}^{4}He \rightarrow {}^{16}O$, Ne, Na, Mg	8×10^{8}
Ne → O, Mg	1.5×10^{9}
O → Mg, S	2×10^{9}
Si → Fe peak	3×10^{9}



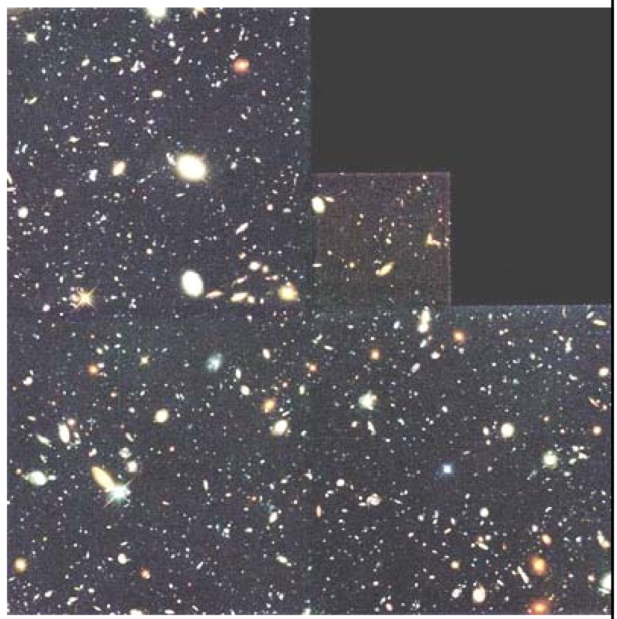
Evolution through nuclear burning.	
$M_{initial} > 3M_{\odot}$	Nuclear burning all the way to iron.
$M_{initial} < 3M_{\odot}$	Nuclear burning shuts off after He-flash.



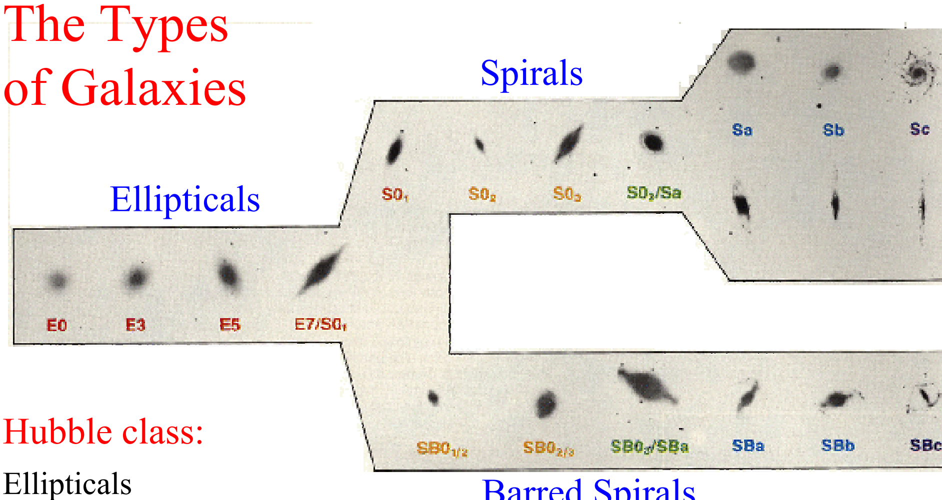
Galaxies

The Hubble Deep Field

- Tiny area of sky.
  - 1/12 angular size of full moon.
- Faintest objects ever measured.
- 10 days' exposure with Hubble Space Telescope.
- Only 20 stars.
- Remaining 5000 objects are galaxies.



The Types of Galaxies

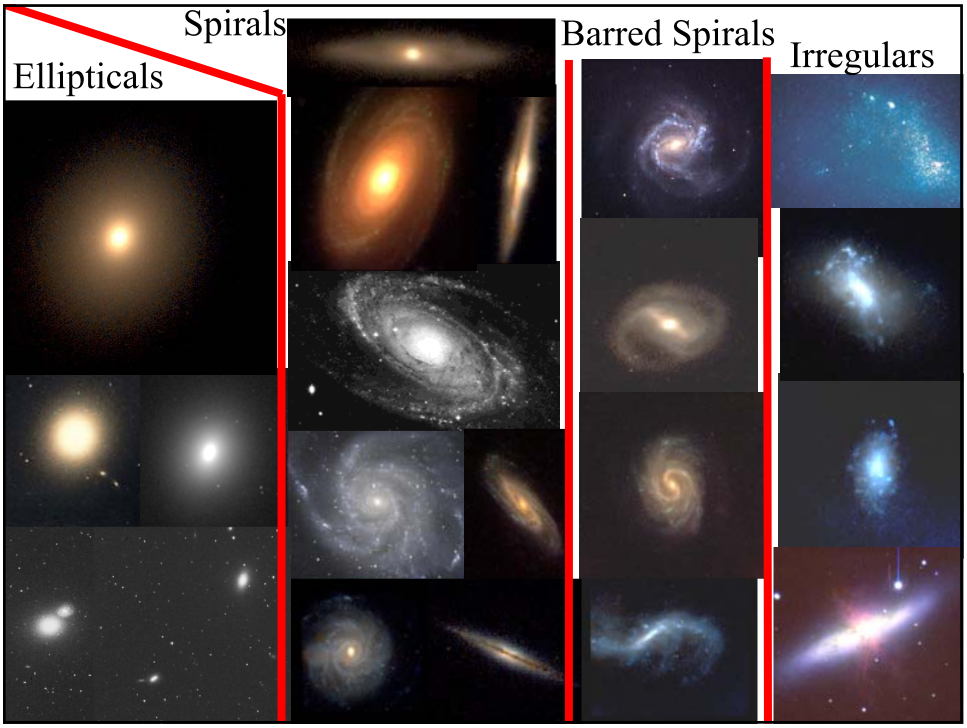


Hubble class:

Ellipticals
- E0 = round ➔ E7 = elongated

Spirals (Sa➔Sc, SBa➔SBc):
- Central concentration
- Tightness of arms
- Smoothness of arms

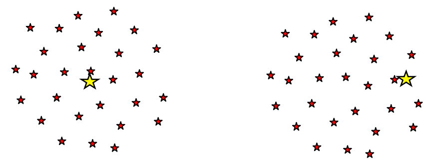
Irregulars

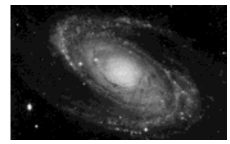


What kind of galaxy do we live in?

- The Milky Way
  - Obviously a disk
  - But where are we located within that disk?

Mapping our Galaxy, up until ~1920





What about "spiral nebulae"?

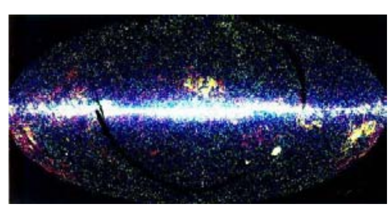
False detection of proper motion.

Counting stars ➔ Sun near center of small universe.

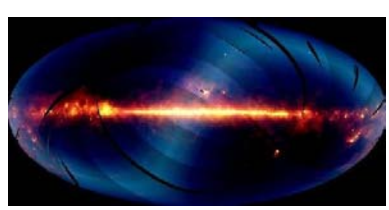
The Milky Way

- Optical view

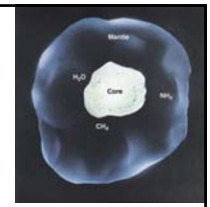
- Infrared view in light of stars

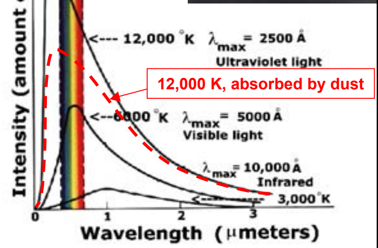


- Infrared view in light of glowing dust



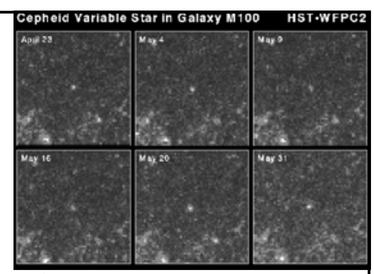
Need to correct for absorption by dust



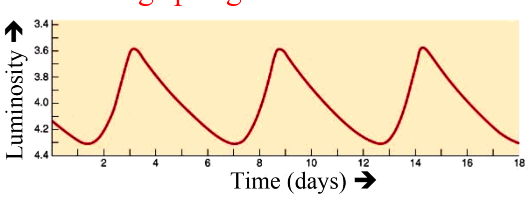


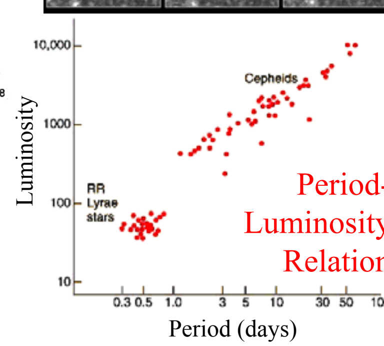
- $F = L/4\pi r^2$
- But absorption also affects F
  - Absorption, or larger r ?
- Dust absorbs more in blue than in red.
- Changes shape of black body curve
- Measurements at 3 wavelengths let you detect that change in shape.
- ➔ amount of absorption at each wavelength.

Pulsating Variable Stars



- These stars regularly expand & contract.
- Like a big spring.





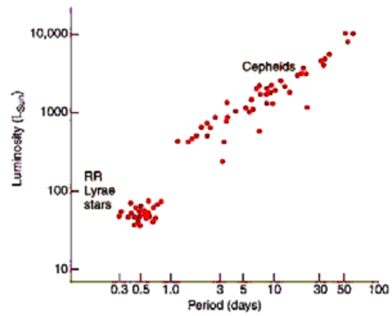
Period-Luminosity Relation

Change in size ➔
- change in temperature
- change in luminosity

Use $F = L/(4\pi r^2)$ to find r

Measuring distances inside the Galaxy

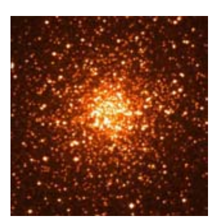
- Parallax: to 300 pc
- Pulsating variables (Cepheids, RR Lyraes)



Star clusters in the Milky Way

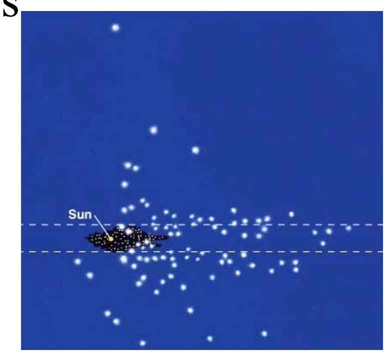

Open Clusters: found in disk of Galaxy.
Just a few hundred stars per cluster.
Some recently-formed, some middle-aged.





Globular Clusters: ~ 150, *not* confined to disk.
Typically 100,00 stars. All are very old.

Mapping our Galaxy with globular clusters

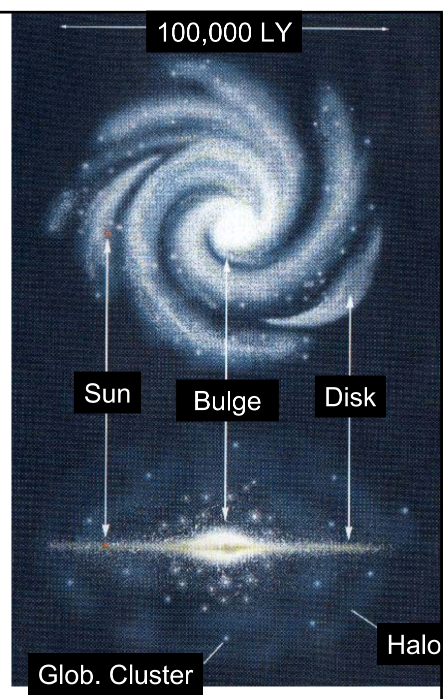


- Globular Clusters offer key breakthrough (in ~1920).
  - Distances from pulsating variables.
  - Spherical distribution in space
    ➔ line of sight is not in dusty disk of Galaxy

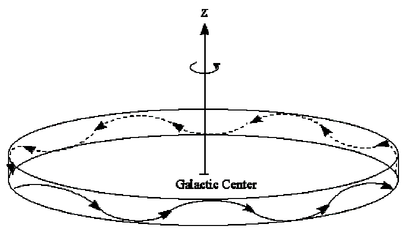
  - Result: Sun very far away from center.

Our Galaxy (The Milky Way)

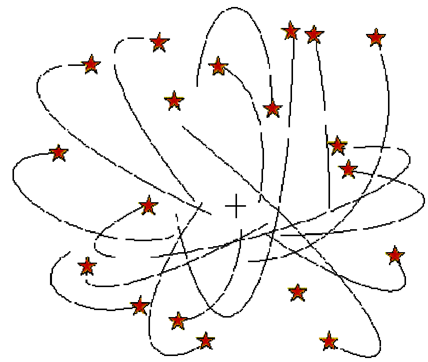
- 100,000 LY diameter
- Sun is 30,000 LY from center
- Gas, large fraction of stars in thin disk
  - ~1000 LY thick
  - Spiral structure
- Spherical halo
  - ~150 globular clusters
  - But most halo light is from spherical distribution of stars
- Nuclear bulge



Orbits in the Galaxy

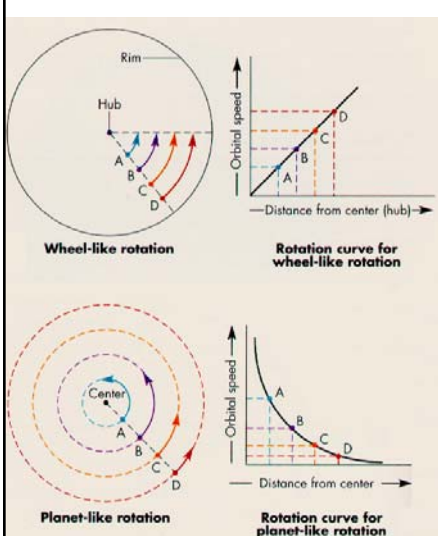


Stars, gas in disk

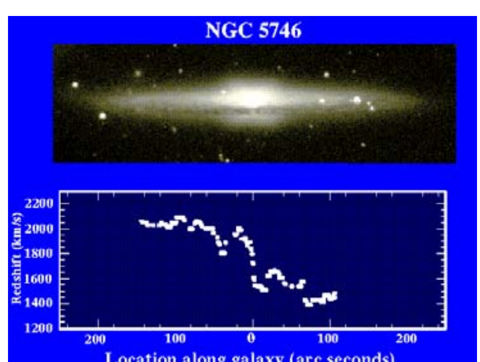


Stars in halo & nuclear bulge

The masses of galaxies

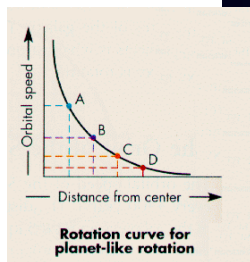


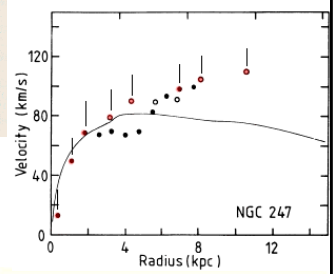
- $P^2 (M_1 + M_2) = a^3$
- Velocity = $(2\pi a)/P \propto \sqrt{1/a}$
- Measure Doppler shift of absorption lines & emission lines at different points in galaxy.



Dark matter

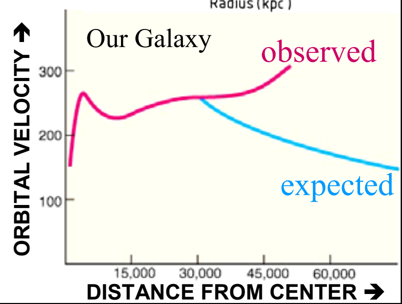
- We expected falling "Keplerian" curve out beyond outermost luminous matter.



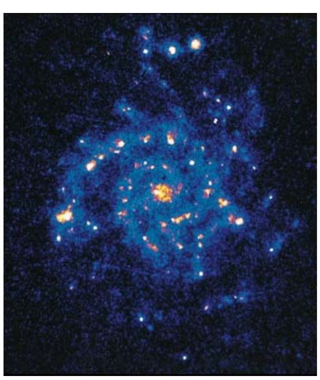


- But curves do not drop off
  - ➔ large amounts of additional "dark matter" in outer parts of spiral galaxies.

Components of our Galaxy	(10^{10} $M_{\odot}$)
Nuclear bulge	1
Disk	7
Halo	0.1
Dark matter	55



Spiral arms are delineated by young stars & HII regions

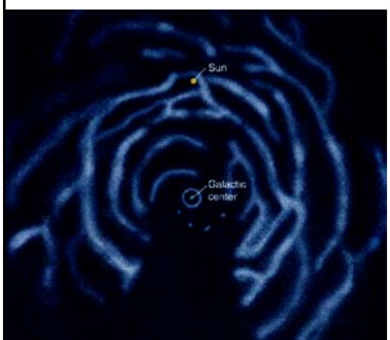


M74 in the ultraviolet

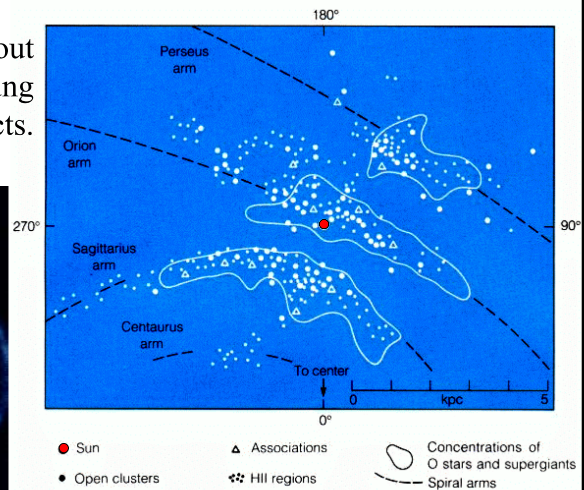
UV to red sequence in M81
(12 Million LY away)
The Spiral Arms

The spiral structure in the Milky Way

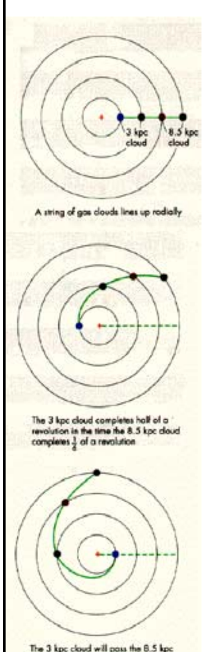
From mapping out positions of young objects.

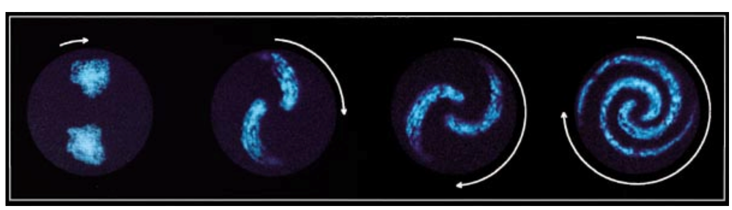


At radio wavelengths



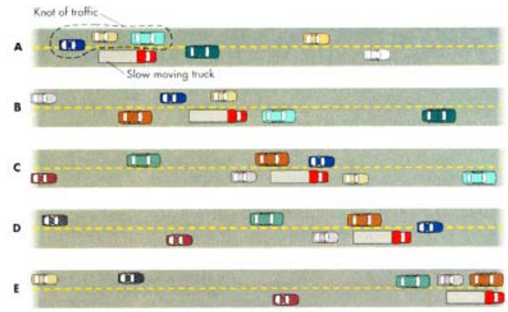
Formation of Spiral Arms





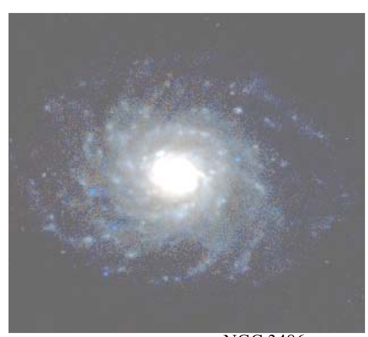
- *Differential Rotation*
  - $P^2 = a^3$ (Kepler's 3rd Law)
  - Gas, stars closer to center orbit in less time than those farther from center.
  - ➔ automatic stretching of any feature into a trailing spiral.
  - But arms should rapidly wind up and disappear

Spiral Arms & the Interstate Highway



- Density wave
  - Spiral arms have higher density than space between arms
  - Excess gravitational attraction slows down gas, stars when they pass through spiral arm in course of their orbits.
  - ➔ spiral arms are a traffic jam

Formation of Spiral Arms II



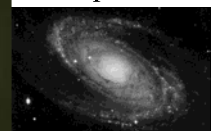
NGC 3486

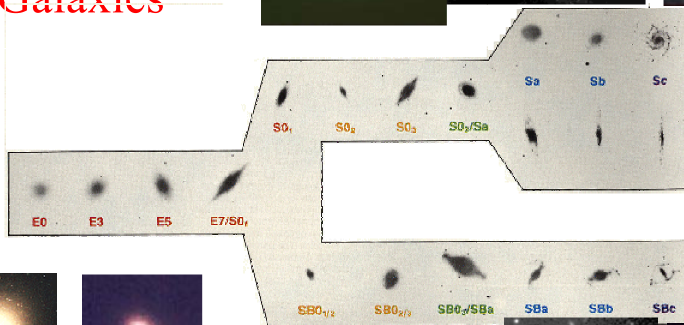
- Density waves most likely to occur in presence of external driving force
  - Example: Satellite galaxy in process of colliding with M51.

- "Flocculent" spirals may be due to different process (???)
  - Waves of star formation form linear structures.
  - Followed by winding up due to differential rotation.

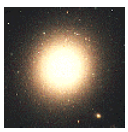
The Types of Galaxies

Spirals





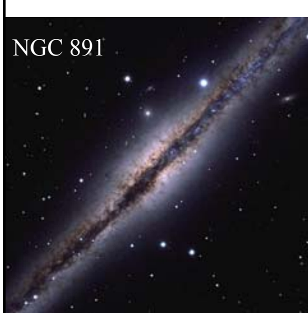
Also… Irregulars

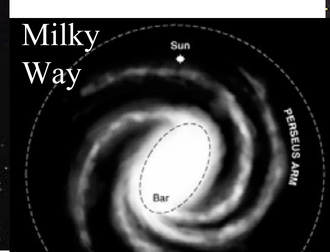


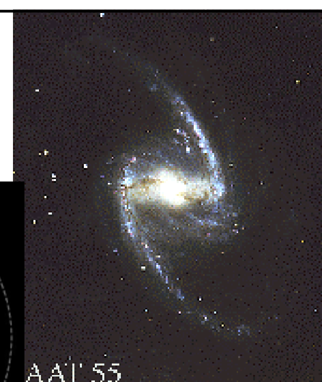
Ellipticals

Barred Spirals

Where's the nearest bar?





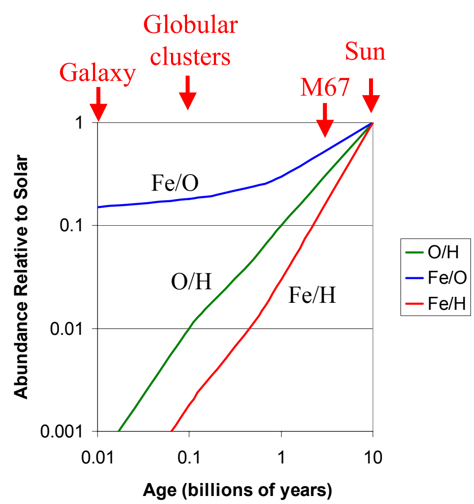


Probably in our Galaxy!

Infra-red light shows "Peanut-shaped" nuclear bulge

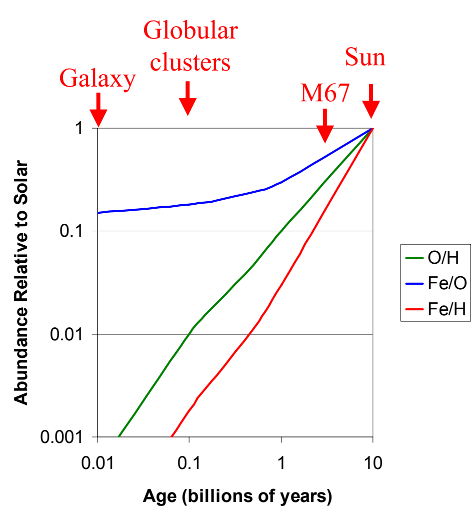
Chemical history of our galaxy

- *Chemical enrichment*
  - The buildup of the heavy elements through nucleosynthesis.
- Galaxy started with just H, He, Li
- H ➔ He ➔ C ➔ O burning has steadily built up carbon, oxygen.
- Elements like iron built up (somewhat) more recently.



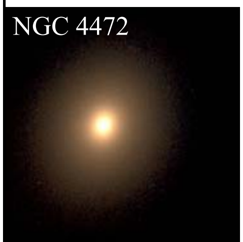
Stellar Populations

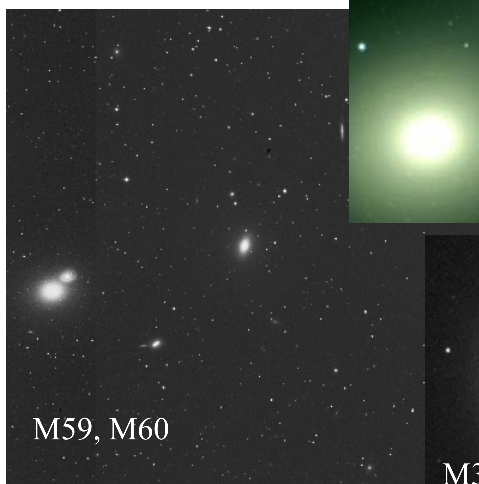
- Population I
  - Wide range of ages
  - More enriched
  - Circular orbits in disk
- Population II
  - Old
  - Very low heavy-element abundances
  - Elliptical orbits in halo
    - huge range of inclinations
- Nuclear Bulge
  - Abundances like Sun (enriched)
  - But elliptical orbits

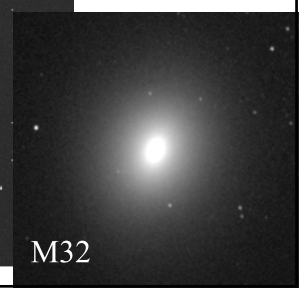


Elliptical Galaxies

No gas.
No dust.
No young stars.

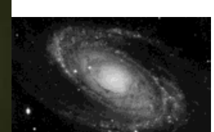


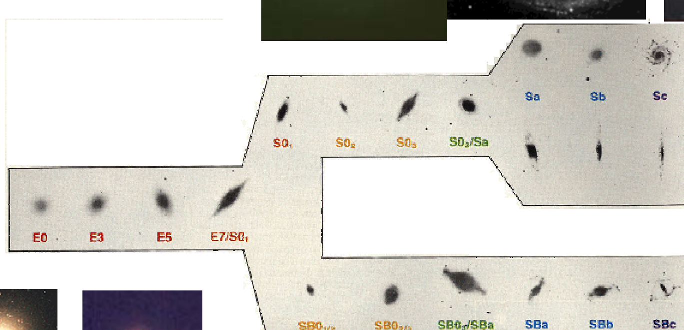




Efficiency of star formation

Spirals





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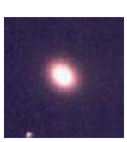

Ellipticals

Barred Spirals