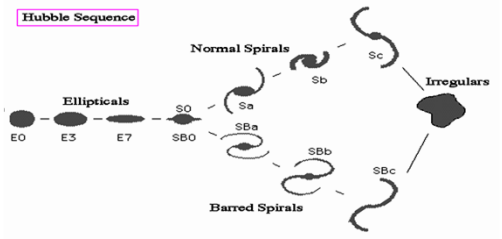
Slide by Chris Conselice

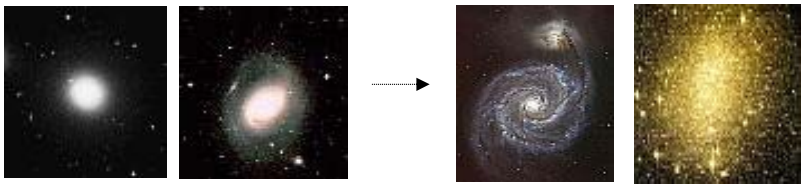
Hubble Types

98% of all nearby bright galaxies can be placed into a Hubble type



Hubble types are the $z = 0$ final state of bright galaxy evolution

Ellipticals have old stellar populations, spirals have both old and young components while irregulars are dominated by young stars

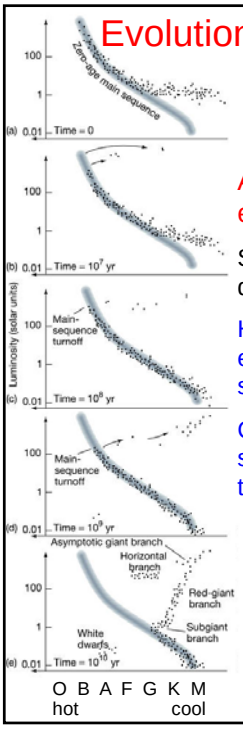


Old stars

Young stars

A significant amount of star formation must have occurred in the past for Es, but some young stars clearly exist in spirals

Evolution of galaxy spectrum over cosmic time.



AST 208 lab exercise (?)

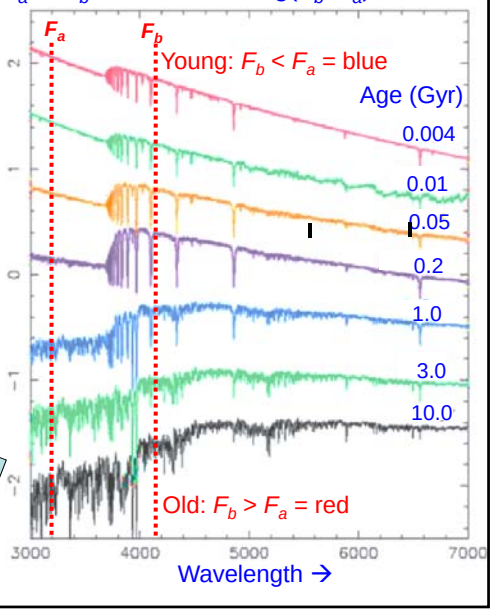
Star cluster age dating.

Hot, massive stars evolve off main sequence rapidly.

Cool, low mass stars take a long time.

From AST 208: Magnitudes…

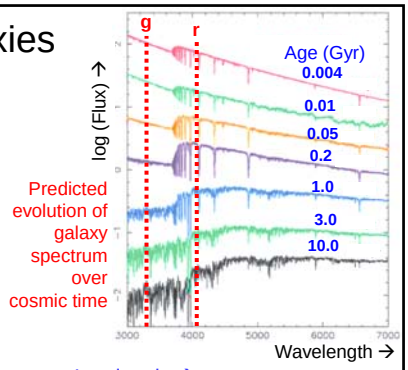
$m_a - m_b = a - b = 2.5 \log(F_b / F_a)$



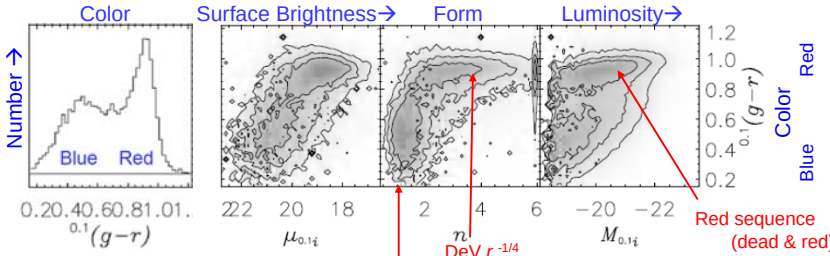
Combined spectrum of whole galaxy

A large sample of nearby galaxies

- SDSS (Sloan Digital Sky Survey)
  - 10^6 targets, mostly galaxies,
    - selected for spectroscopy
  - 10^4 deg^2 of sky
  - $m_r < 17.8$ mag
- 115,000 SDSS galaxies:



Predicted evolution of galaxy spectrum over cosmic time



Red sequence (dead & red)

Largest galaxies ended star formation long ago. *Why*????

Blanton et al. 2005, ApJ, 629, 143

Exponential r^{-1} Disks (spirals)

DeV $r^{-1/4}$ (ellipticals)

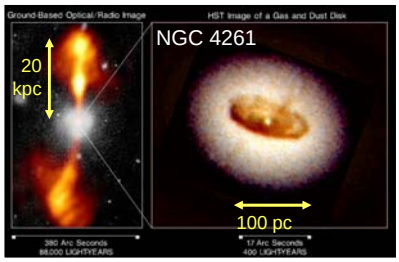
Shutting down galaxy growth

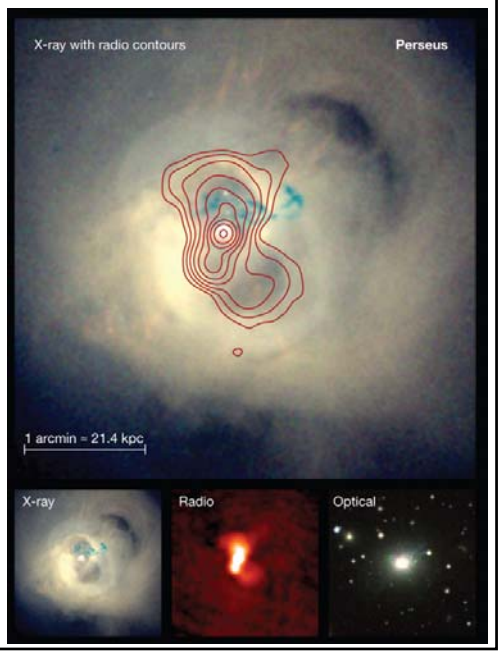
AGN feedback
- radiation pressure

Eddington limit.
Radiation pressure = gravity:

$$\frac{L_{Edd}}{4\pi r^2} m\sigma = \frac{GmM_{BH}}{4\pi r^2}$$

- radio jets heat gas, stop infall
- on both galaxy & cluster scales.





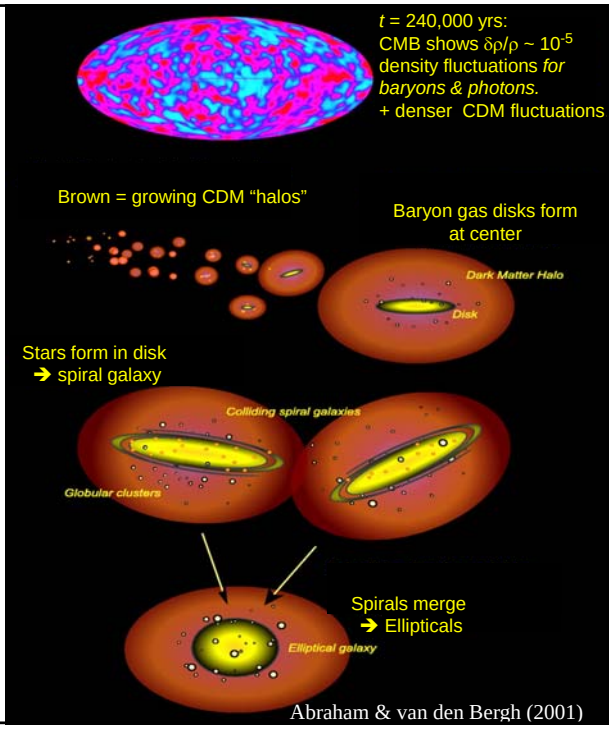
Basic idea behind galaxy formation - objects start small and grow by merging.

We see:

- Smaller galaxies back when t ~ 1-7 Gyr. (with caveats)
- Increase in space density of large galaxies since t ~ 7 Gyr = 1/2 current age. (with caveats)
- Lower Spiral/Elliptical ratio in cluster centers.
- Mergers.

But…

- Not enough very low-mass galaxies at current time ➔ SN winds??
- Many E galaxies ended star formation by t ~ 7 Gyr ➔ AGN feedback.



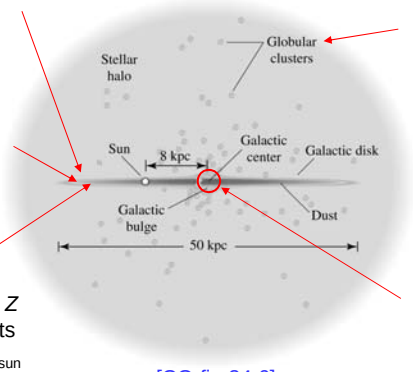
Formation of the Milky Way [CO 26.2]

Thick Disk
- ~10 Gyr old
- moderately low Z (metallicity)
- circular orbits
- 0.3x10^{10} M_{sun}

Thin Disk
- ~8 Gyr
- solar Z
- circular orbits
- 6x10^{10} M_{sun}

Gas Disk
- very young
- above solar Z
- circular orbits
- 0.5 x10^{10} M_{sun}

+ dark matter halo
> 230 kpc radius
~ 200x10^{10} M_{sun}

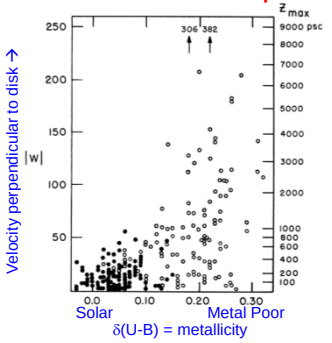


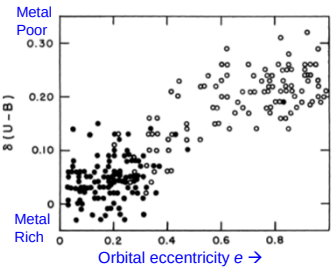
[CO fig 24.6]
+ [CO Tbl 24.1]

Stellar Halo
- 11-13 Gyr old
  - horizontal branch
- very low Z (metallicity)
- elongated orbits
- 0.3x10^{10} M_{sun}

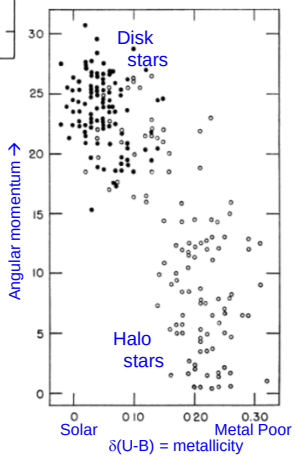
Nuclear Bulge
- 0.2 - 10 Gyr old
  - age-flatness correlation
- high Z (metallicity)
- elongated orbits
  - but much smaller than for halo stars
- 1x10^{10} M_{sun}

Top-Down Formation of Milky Way





Eggen, Lynden-Bell & Sandage (ELS) - 1962



Orbits of stars

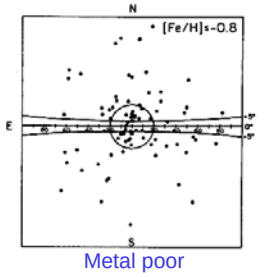
Angular Momentum vs. Metallicity

- Halo stars have much lower angular momentum than disk stars
  - ➔ halo stars formed from infalling gas.
- Large observed eccentricities
  - ➔ collapse faster than rotation period of ~10^8 yrs.
  - ➔ all halo GCs formed within 10^8 yrs
- Collapse in Z (height ⊥ disk) direction is factor ~25
  - From max Z of halo stars vs. thickness of gas disk

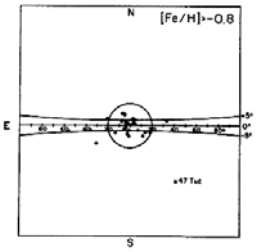
Problems for ELS Model

- Halo stars have angular momentum ~ 0
  - ~ ½ of all halo stars are in retrograde orbits
- Globular cluster age spread
  - 2 billion yr spread not consistent with freefall timescale t_{ff} ~ 2x10^8 yrs.
- Range of globular cluster chemical abundances
  - Near galactic center ➔ metal rich, but (perhaps) older.
  - Outer halo ➔ wider range in metallicity, but on average younger.
- Multi-component disk with different ages.
- Chemical abundances in disk not consistent with closed-box chemical evolution.

Globular Cluster Distribution on sky



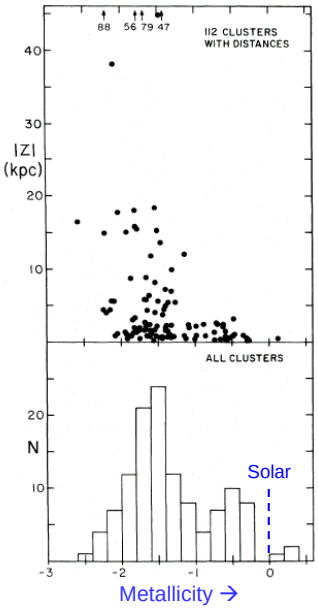
Metal poor



Metal rich

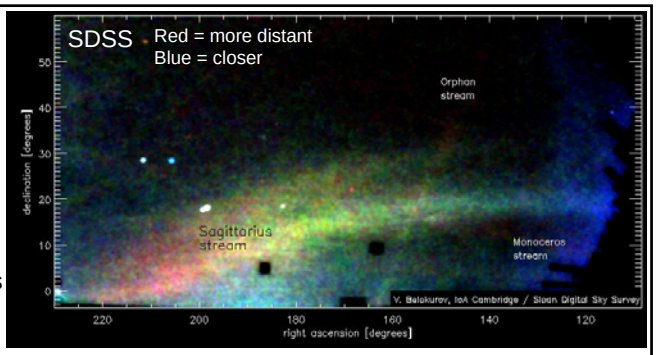
Bottom-up (Hierarchical Merger) Formation of Milky Way

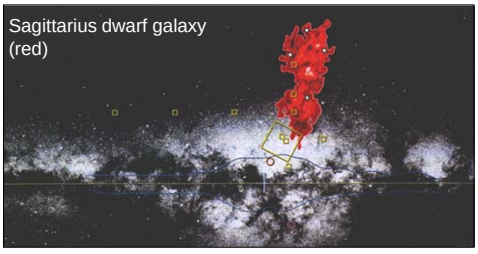
- Searle & Zinn (1978)
  - Large range in metal abundances of globular clusters in outer halo ➔ mergers.
- MW assembled from ~ 10^8 M_{sun} proto-galaxies.
  - Had already formed stars, evolved chemically.
  - Halo formed from different fragments than disk
    - so different angular momentum is OK.
- Dense bulge captured rest of halo.
- Remaining gas formed thick disk
  - Then collapse to thin disk

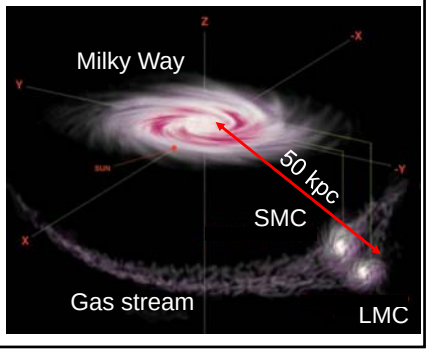


Milky Way Mergers

- Recent/current dwarf galaxy mergers
  - Sagittarius
  - Monoceros
  - Canis-Majoris
- Show up as star streams in halo.
- Magellanic clouds
  = merger in progress?
  - Magellanic stream (H^0 gas)
  - But recent result casts doubt







MW Formation: Bottom-Up or Top-Down?

- Favoring bottom-up
  - ΛCDM cosmology says so!
  - Small galaxies currently merging with MW
  - Halo has two major components
    - Distinct metallicities and kinematics (Carrollo, Beers et al. 2007)
- Favoring top-down
  - Disk clearly formed from gas, not from stars pre-formed in smaller sub-units.
  - ΛCDM predicts 100s of low mass DM halos still orbiting MW
    - Only 10-15 are seen.
- Top-down apologia
  - Thick disk may be stars stirred up from thin disk by accretion of dwarf galaxies.
  - Bulge stars may be formed from gas falling in from halo and disk.

The issue is still unclear…
May be a combination of both, or bottom-up may do it all.

AST 308 in one slide

Part 1: Galaxies Today

- Study is observationally based.
- Morphologies, etc were measured, not predicted.
- Most of general picture was worked out in 1920s, '30s.
- Theory is used to explain observations.
- *BUT…* Dark Matter was a big surprise in 1980's.

Part 2: Cosmology

- Theory worked out by 1920s, '30s.
- Big surprise #1 = Expanding Universe (1929).
- Nice confirmation: CMB (1964)
- Big surprise #2 = Dark Matter (1980s)
- Big surprise #3 = Dark Energy (1999)
  ➔ Dark Energy, Dark Matter dominate (ΛCDM universe).
- Now more like a physics experiment.
  - Realizing how to analyze CMB fluctuations!

Part 3: Galaxy Formation

- Early growth of fluctuations comes from theory.
  - Giant numerical simulations are key ingredients.
- But after $z \sim 7$, it is strongly based on observations.
- Do we really understand how galaxies form in a ΛCDM universe?

Or… how did galaxies *really* form?

- Bottom-up merging – generally confirmed, but not in all details..
- AGN feedback – throttles galaxy, cluster growth.

Final Exam

- 12:45 PM Tuesday, Dec. 13, in BPS 1420.
- 30% of grade.
- Will be about the things I've talked about in class.
- > 50% on part after Midterm 2.
- Study guide on course website.