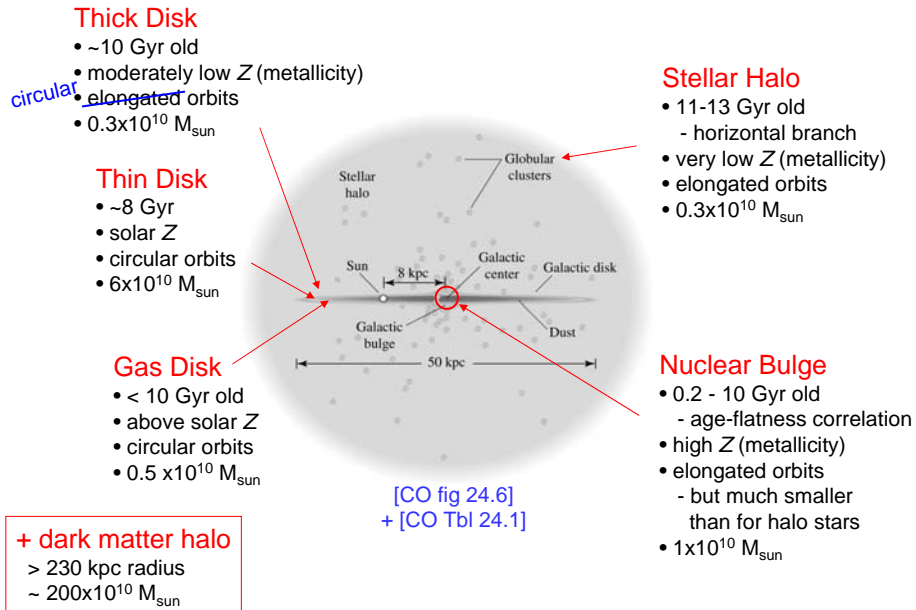
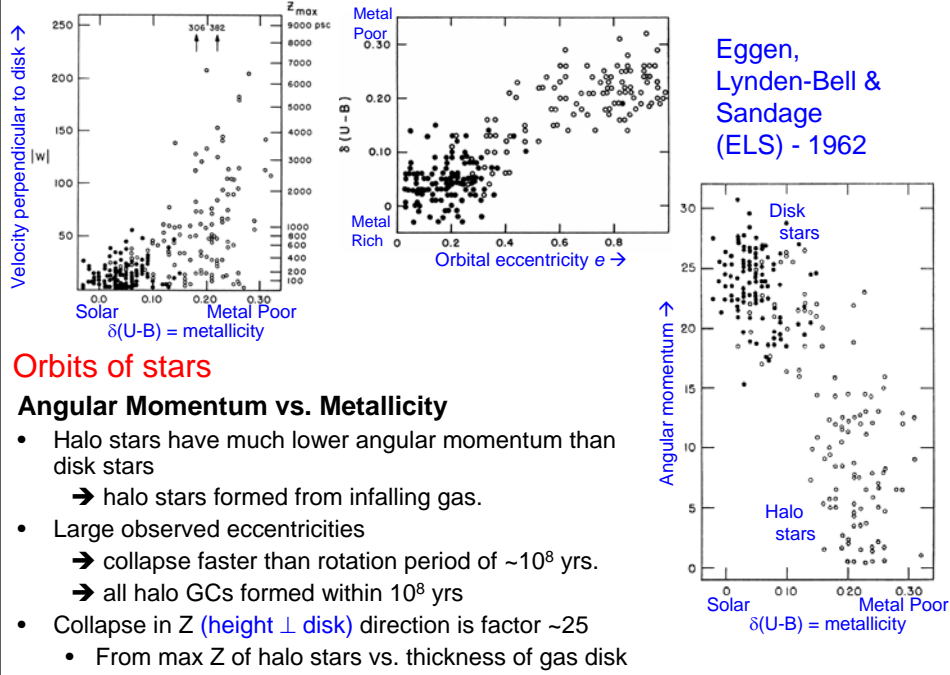


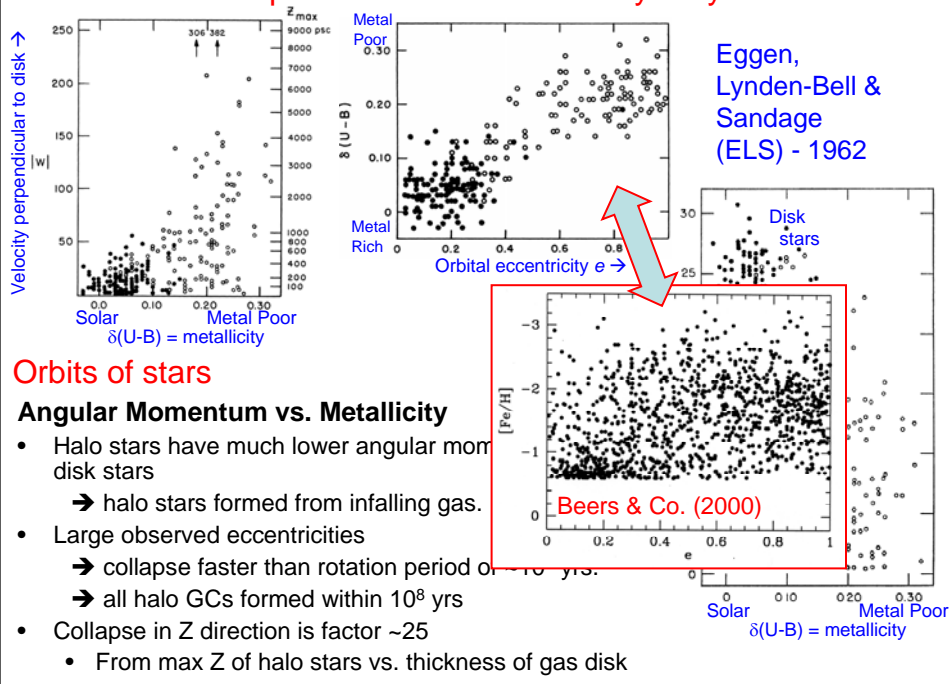
Formation of the Milky Way



Top-Down Formation of Milky Way



Top-Down Formation of Milky Way



Orbits of stars

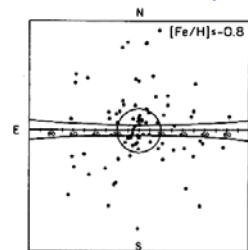
Angular Momentum vs. Metallicity

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

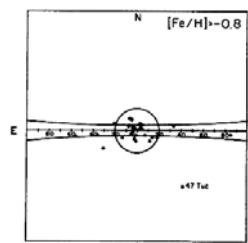
Earlier Problems for ELS Model

- Halo stars have angular momentum ~ 0
 - $\sim 1/2$ of all halo stars are in retrograde orbits
- Globular cluster age spread
 - 3 billion yr spread not consistent with freefall timescale $t_{ff} \sim 6 \times 10^8$ yrs.
- Range of globular cluster chemical abundances
 - Near galactic center \rightarrow metal rich, but (perhaps) older.
 - Outer halo \rightarrow 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



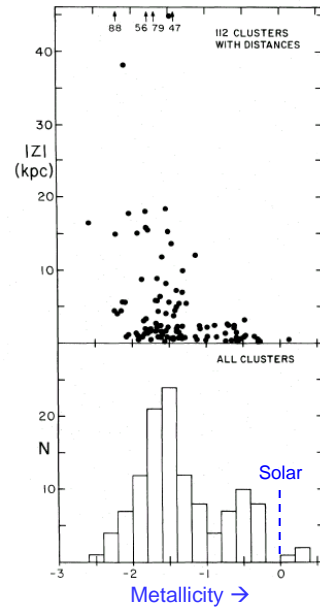
Metal poor



Metal rich

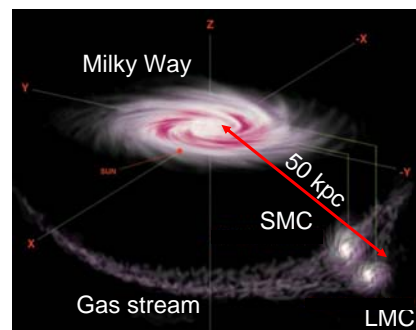
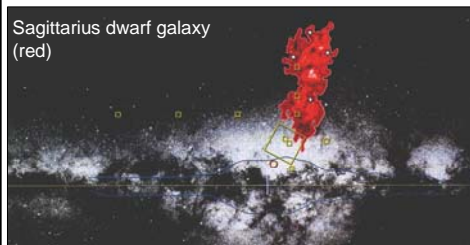
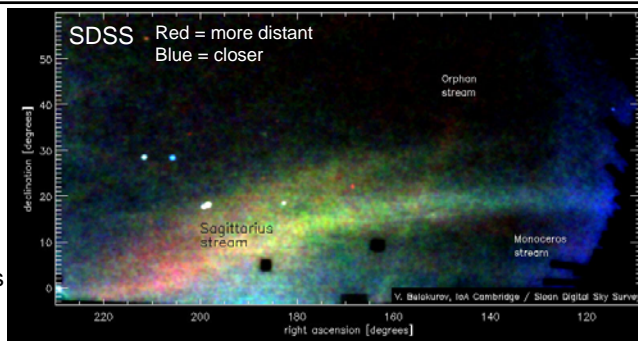
Bottom-up (Hierarchical Merger) Formation of Milky Way

- Searle & Zinn (1978)
 - Large range in metal abundances of globular clusters in outer halo → **mergers**.
- MW assembled from $\sim 10^8 M_{\text{sun}}$ 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
 - Λ CDM cosmology says so!
 - Small galaxies currently merging with MW
 - Halo has two major components
 - Distinct metallicities and kinematics (Carollo, Beers et al. 2007)
- Favoring top-down
 - Disk clearly formed from gas, not from stars pre-formed in smaller sub-units.
 - Λ CDM 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.

Final Exam

- 3 PM Monday, Dec. 14, in BPS 1420.
- Trying for a bit less than 2x length of Midterm 2.
- Will be about the things I've talked about in class.
- $\geq 50\%$ on part after Midterm 2.
- Study guide on course website.