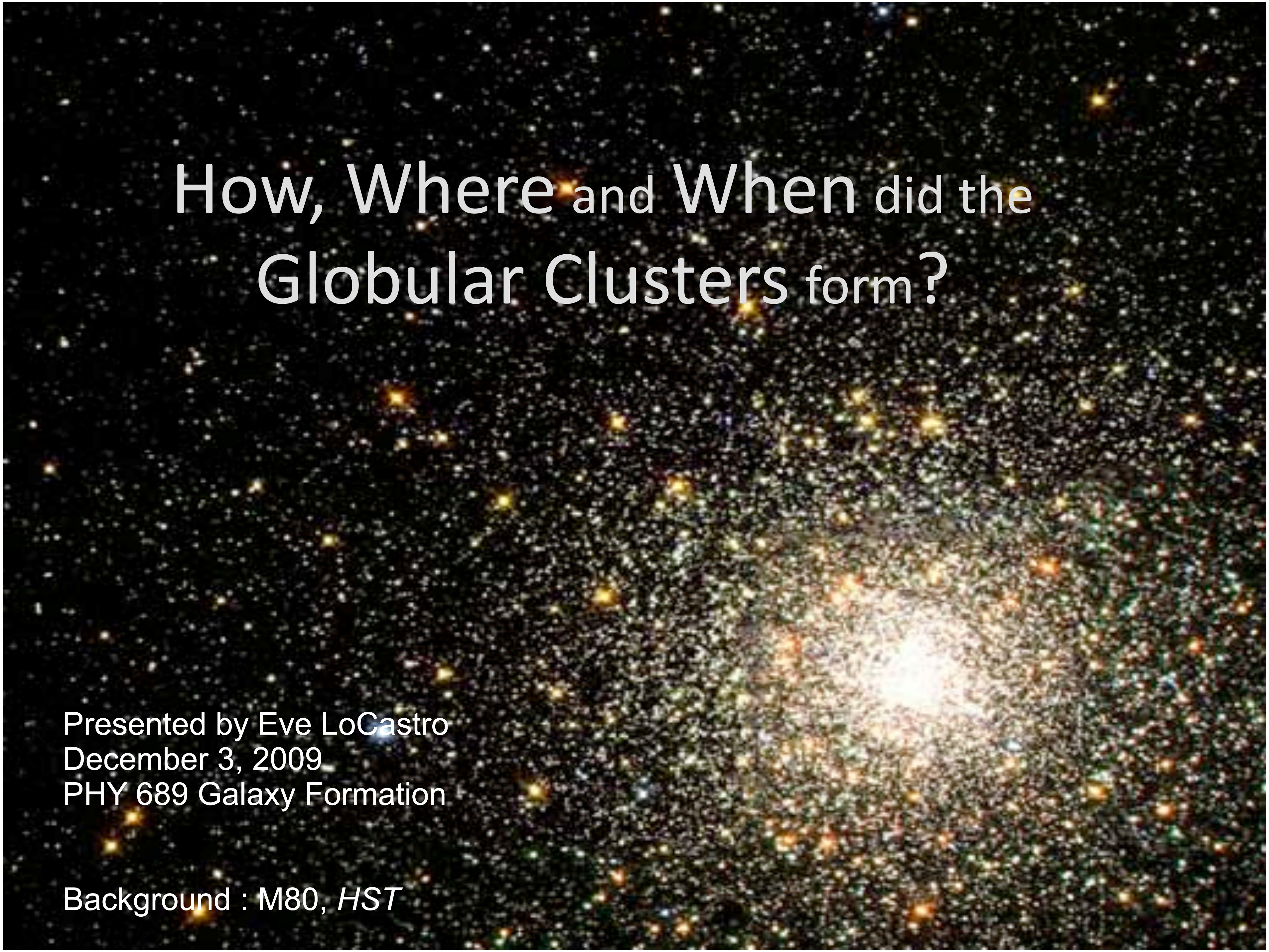
How, Where and When did the Globular Clusters form?



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PHY 689 Galaxy Formation

Background : M80, *HST*

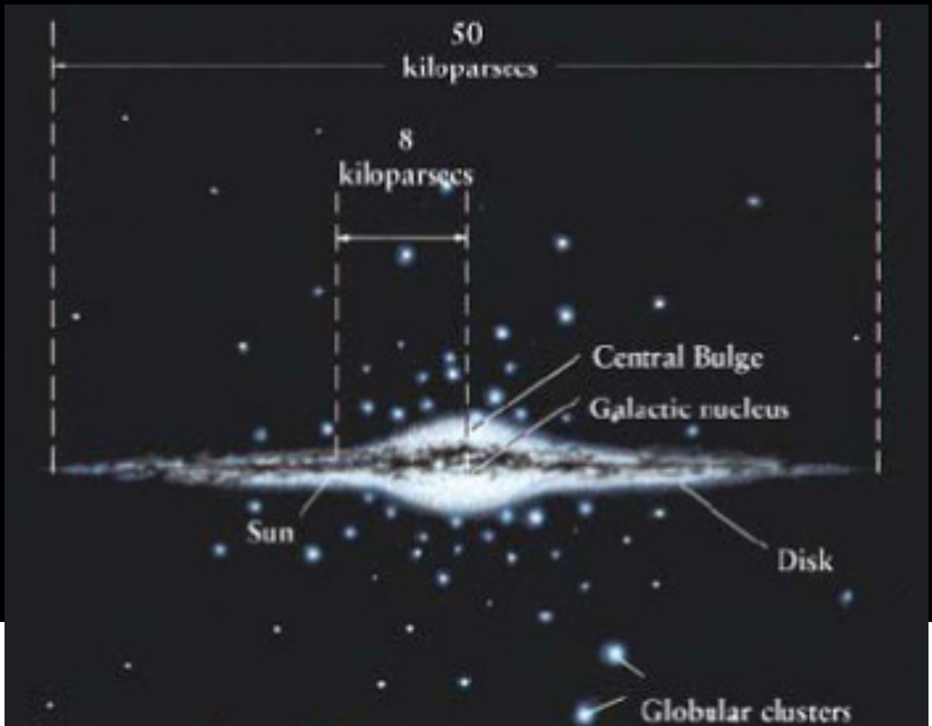
What are the Globular Clusters?

- *Dense:* tightly-packed stellar systems containing ~10^5 stars, with little or no dark matter
- *Ancient:* Amongst the oldest-known objects in the universe, with ages on order of 10-13 Gyr
- *Ubiquitous:* Clusters are found in orbit around every breed of galaxy in varying numbers, from cD to dE

Local Snapshot

Around our local Milky Way:

- 150-200 globular clusters are in orbit around the Galaxy's center
- Most are found within 8-10 kpc radius of Galactic center
- Two differing species of clusters observed, with orbits differently oriented to disk plane



(Credit not available)

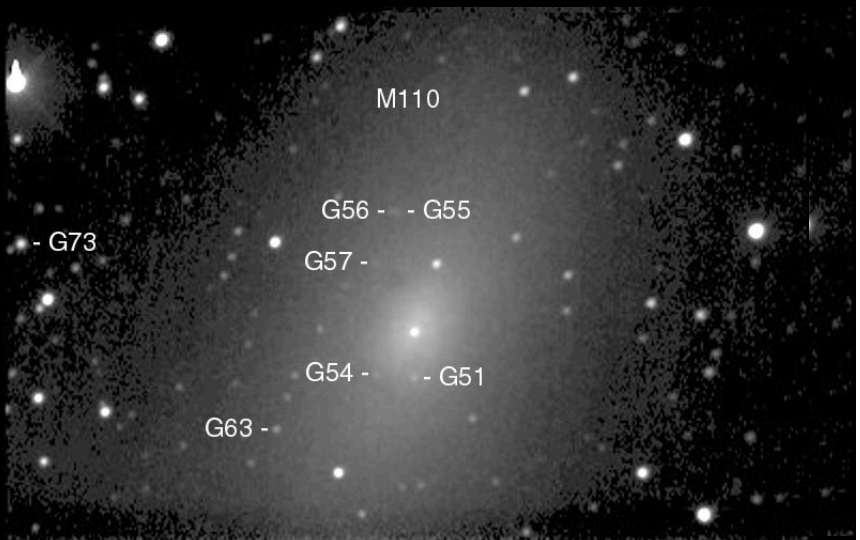
Clusters in External Galaxies

M87, *Virgo*, credit:: Anglo-Australian Observatory,

Universally old globular clusters are found surrounding all types of galaxies in varying numbers

- Virgo cD galaxy (left)contains on order 4000 clusters

- Dwarf-Elliptical companion to Andromeda (below)has a number of clusters distinctly identified with it

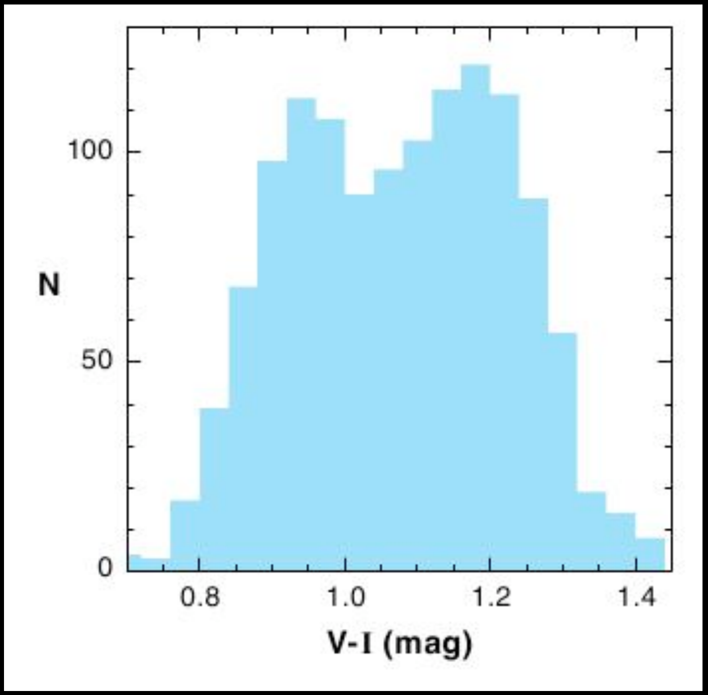


M110 dwarf elliptical and GC companions, credit: Ferguson Obs

Bi-Modal Color Distribution

- Like the Milky Way, nearly every galaxy studied has been shown to have two distinct subpopulations of GCs, Red and Blue

- Well-known degeneracy between age and metallicity; must examine spectra in addition to optical colors to determine ages



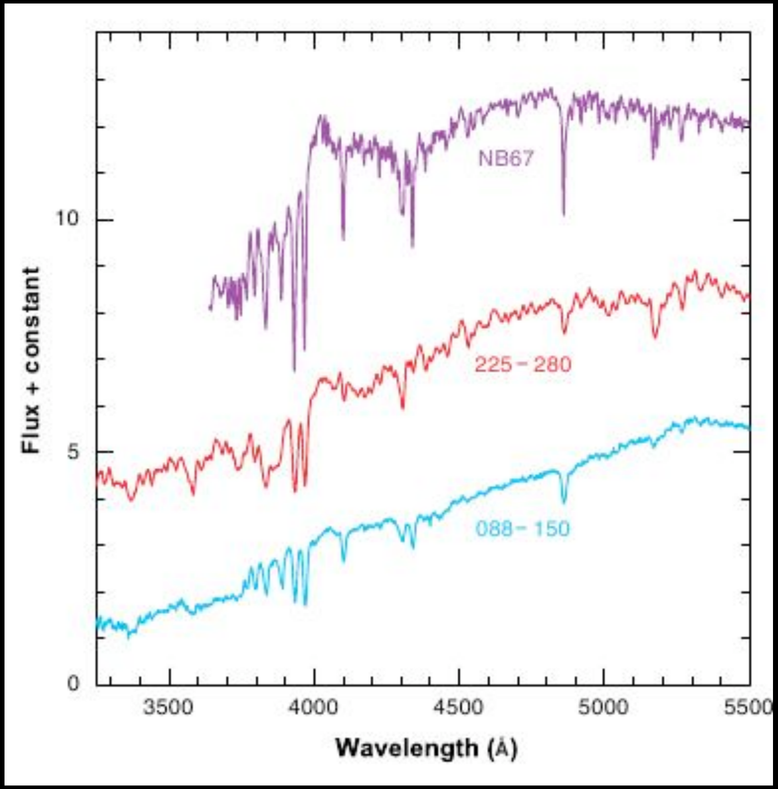
Bi-Modality in Virgo (M87)
Credit: Brodie and Strader 2006, Fig 1.

Dual Formation Channels

Blue population is older and metal-poor, with ages on order of ~13 Gyrs

Red population has greater metallicity and is *younger* on the order of several Gyr

Populations of clusters with different compositions indicates at least two major star-forming epochs in histories of galaxies



Representative fluxed spectra of M31 GCs. Credit: Brodie and Strader 2006, Fig 6.

Dual Formation Channels

- The oldest blue clusters may have formed prior to or concurrently with early galaxies
  - Agreement with the estimated ages and low metallicity
- Questions arise: why did clusters stop forming, and then resume forming at some later date?
  - Search continues for consistent mechanisms that would cause increased star formation in galaxies

Metal-Poor Clusters

- Also called *halo* clusters, the orbits of blue clusters in the Milky Way are distributed around Galactic center at all angles

- Properties of this cluster variety seem fairly constrained across all types of galaxies; i.e. color, low metallicity and similar age estimates

- Mass function resembles a power law at the high-mass end (proportional to $M^{-1.7}$ to $M^{-2.0}$)

Posited Origins

Metal-poor blue GCs must form at very high redshift, z~10-15; presumably in low mass dark-matter halos

Several mechanisms have been posited to account for metal-poor GC formation in the early universe:

- Jeans mass collapse; thermal shock, instability, re-ionization

It is difficult to correctly identify the causation mechanisms due to the homogeneity of blue GCs

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Jeans Mass Collapse

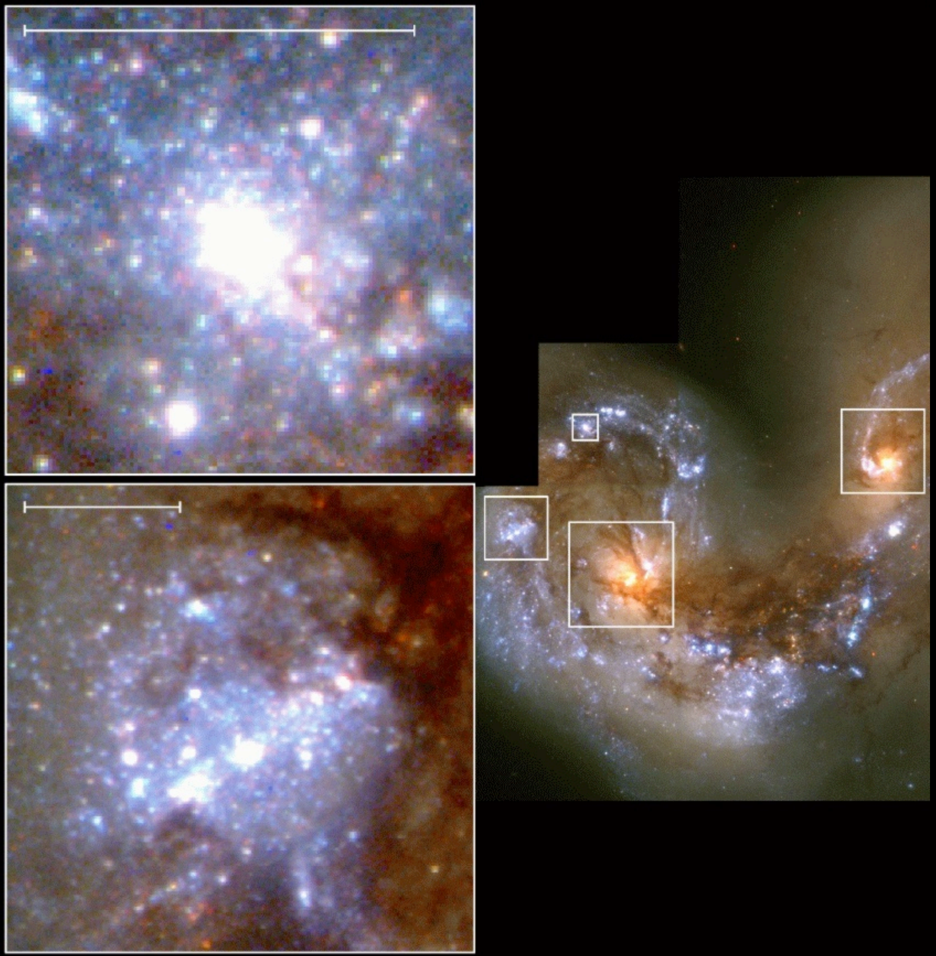
- Peebles (1984) argued for the collapse of gas massive (10^6 M_{solar}) gas clouds within ~10^8 M_{solar} halos to form the first stars
- The globular clusters might then be "stripped" out of the dark matter halo, but with stars remaining intact
- Adjusting the estimate for 2.8σ halos, gives reasonable estimates for the apparent mass fraction of metal-poor GCs in a variety of galaxies
- *Drawback:* the necessary baryonic collapse factor should produce clusters with more rotation than that observed

Re-ionization Fronts

- Cen (2001) proposed that *reionization* might be responsible for igniting the collapse into globular clusters
- During cosmological reionization at *z*~6-20, small halos with idle neutral gas awash by approaching front of ionization photons
- A self-gravitating baryonic system would form, the low-spin $M_{b\sim}10^{4-}10^{7}M_{solar}$ system would be compressed by a factor of about 100 in radius and continue collapsing to form a cluster
- *Pro:* Correct slope prediction of GC mass function
- *Con:*Has not been numerically modeled rigorously

Metal-Rich Cluster Origins

- Good reasons to believe GC formation should accompany major star-forming events
- Observations of young massive star clusters in many remnants of recent mergers



Young star cluster regions in Antennae galaxies, Credit: *HST,* NSSDC

Stellar Formation Tracers

- Expectation is that the characteristics of the metal-rich globular clusters should be identifiable with the field stars of the parent if they formed from a common star formation event
- Difficult to accomplish except in local galaxies where individual galaxy stars can be discerned

Constraints on Major Merger Model

Yet unclear whether the young massive star clusters will have properties consistent with those of old GC systems

- Correlation between number of globular clusters

References

- Forbes et al., 1997. "*On the Origin of Globular Clusters in elliptical and cD Galaxies,*" AJ, 113, 5, 1997.
- Cen, Renyue, 2001. "*Synchronized Formation of Subgalactic Systems at Cosmological Reionization: Origin of Halo Globular Clusters,*" ApJ, 560:592-598.
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