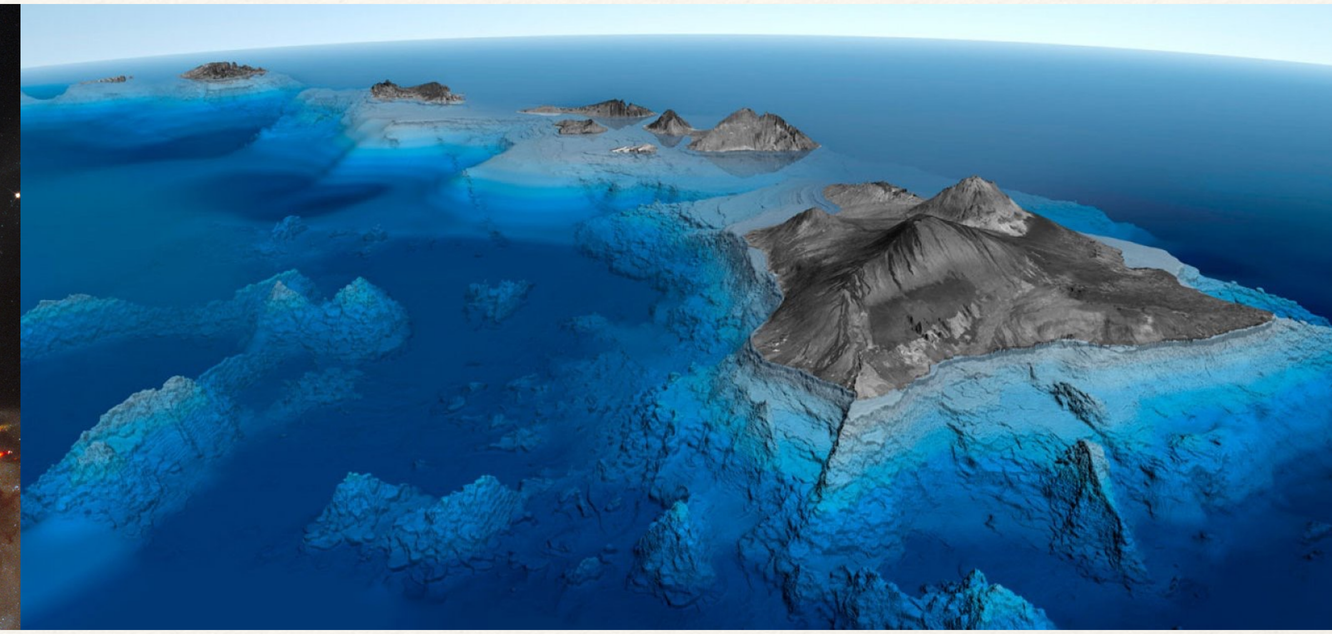


Getting to know the "island universes" out there.

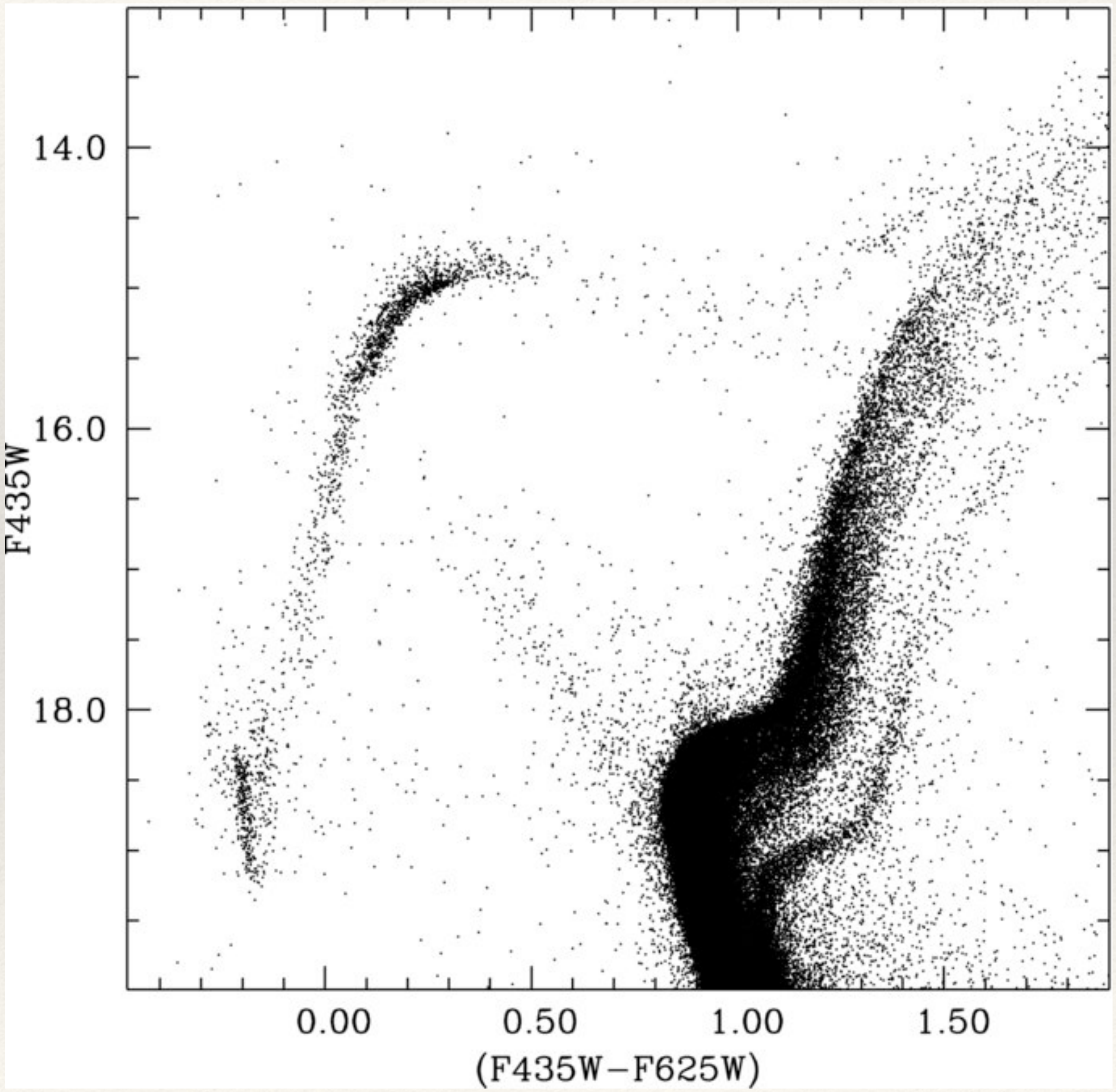
Galaxies I

ASTR 555
Dr. Moire Prescott

Warm-up

- **Write for 2 minutes on the following:**
  - Consider the Red Giant Branch in ω Centauri. What educated guesses can you make regarding stellar population age, metallicity, total stellar mass?
  - Locate the Blue Stragglers on this HR diagram — why are they there, and how much longer do you think they will stay there?

ω Centauri (Cassisi 2009)



Warm-up

Mucciarelli+2014 - https://arxiv.org/pdf/1410.2275.pdf

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  - Consider the Red Giant Branch in ω Centauri. What educated guesses can you make regarding stellar population age, metallicity, total stellar mass?
  - Locate the Blue Stragglers on this HR diagram — why are they there, and how much longer do you think they will stay there?

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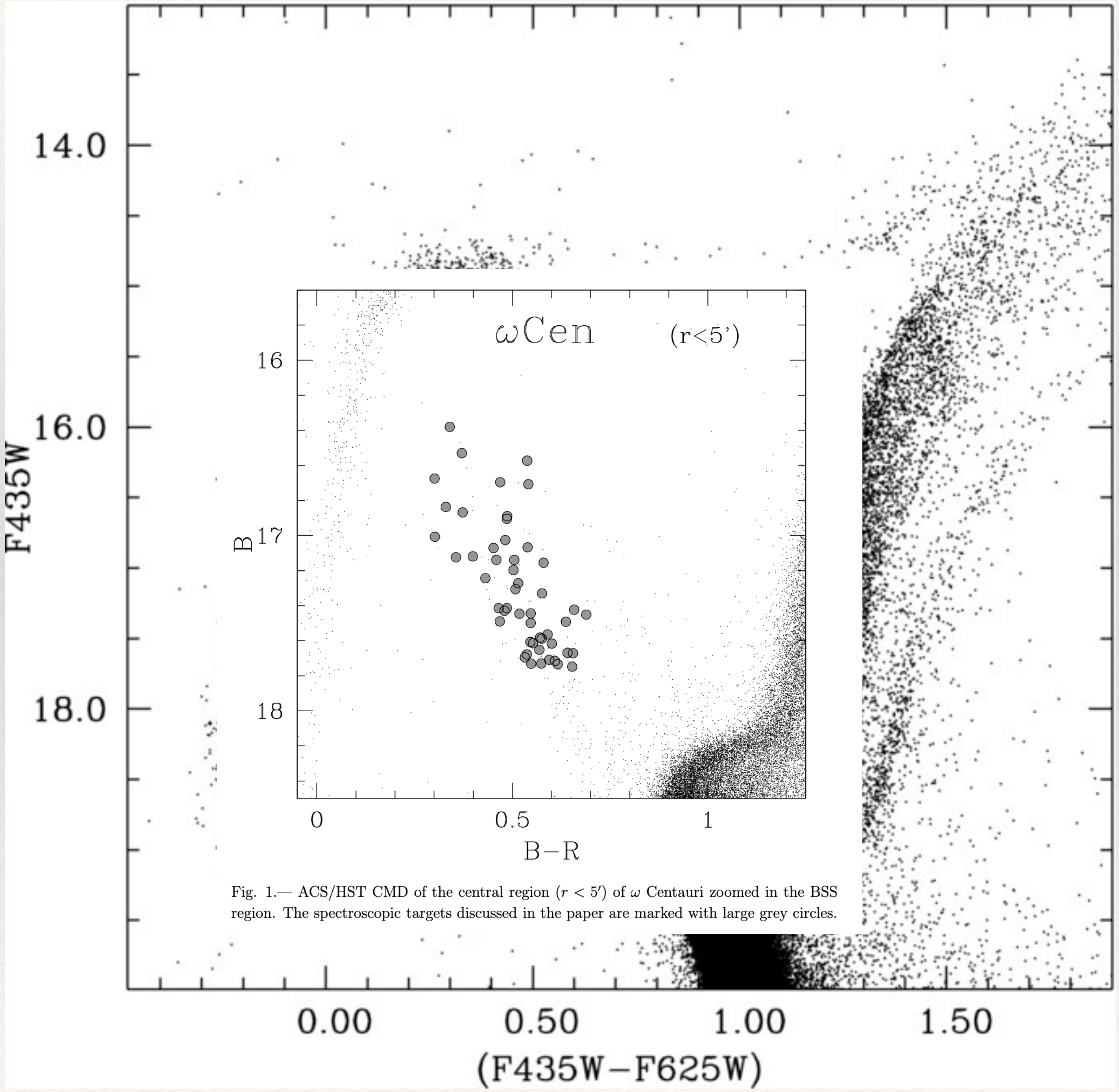
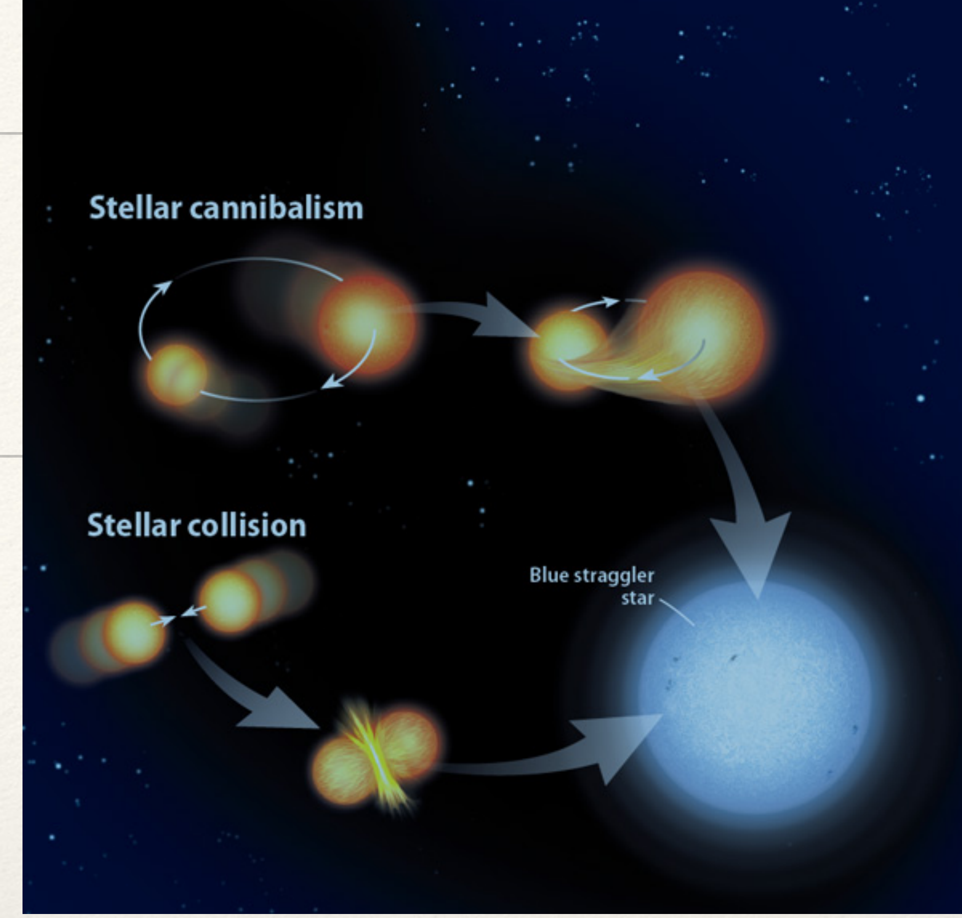
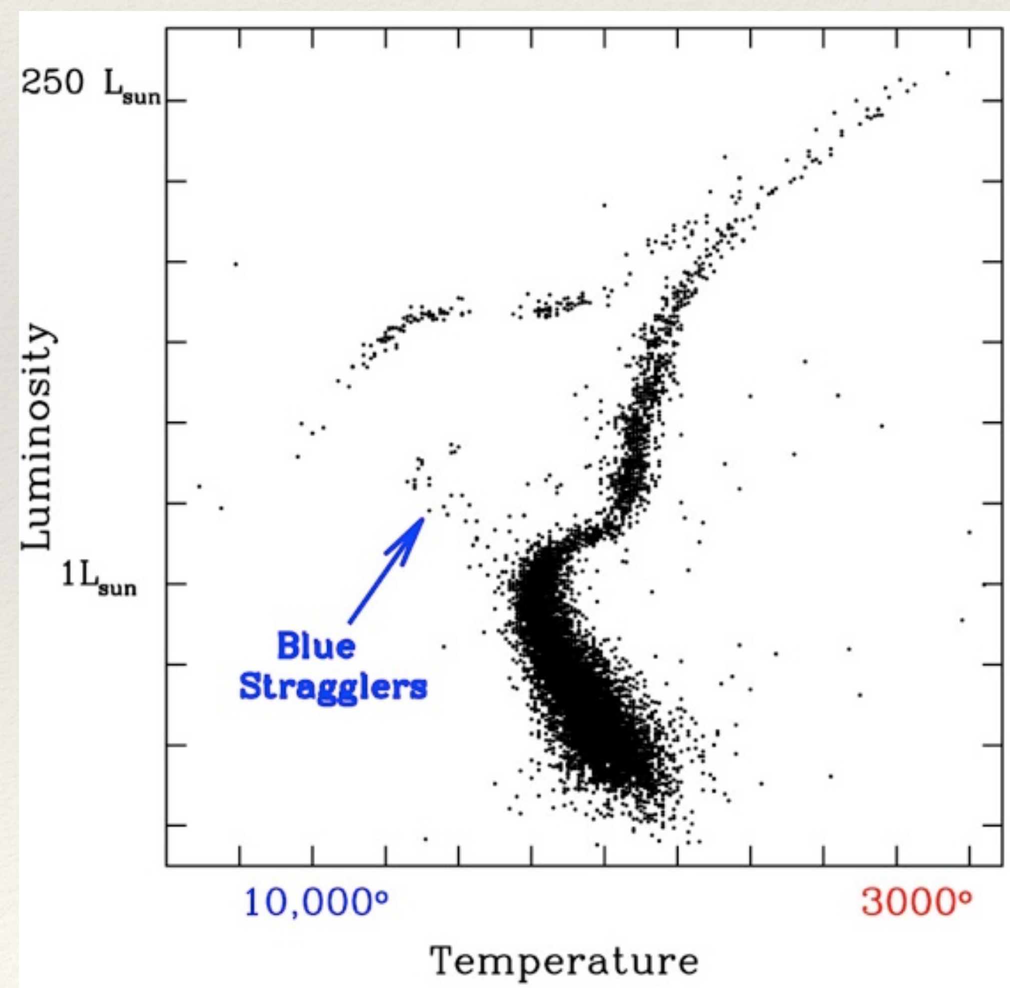


Building Blocks - Stars and … s



Credit: Astronomy Magazine



Cosmic-Lab Project

- **Blue Stragglers —**
  - stars “rejuvenated” due to mergers or binary interactions
  - Example:
    - two 0.8 Msun stars collide after 10 Gyr on MS
    - merger product has MS lifetime = 0.45 Gyr

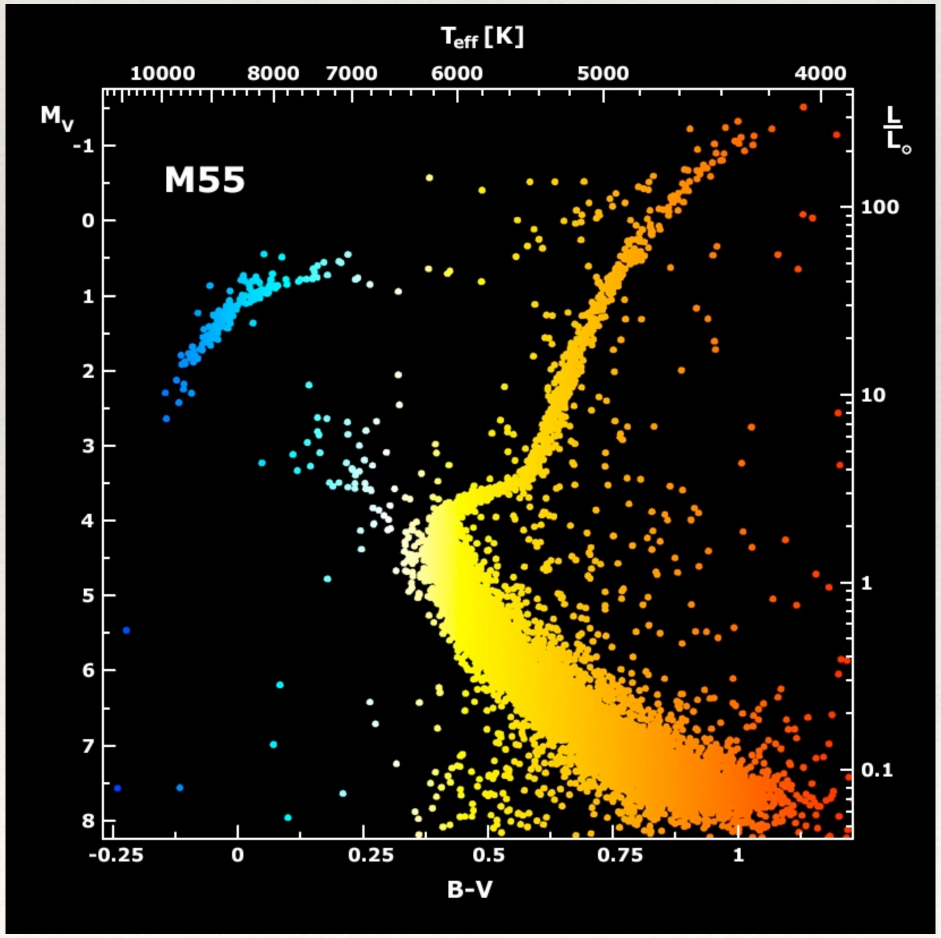
Outline for Today

- Building Blocks - Stars and Stellar Populations:
    - Initial Mass Functions (IMF)
    - Star Formation Histories (SFH)
        - Resolved Populations

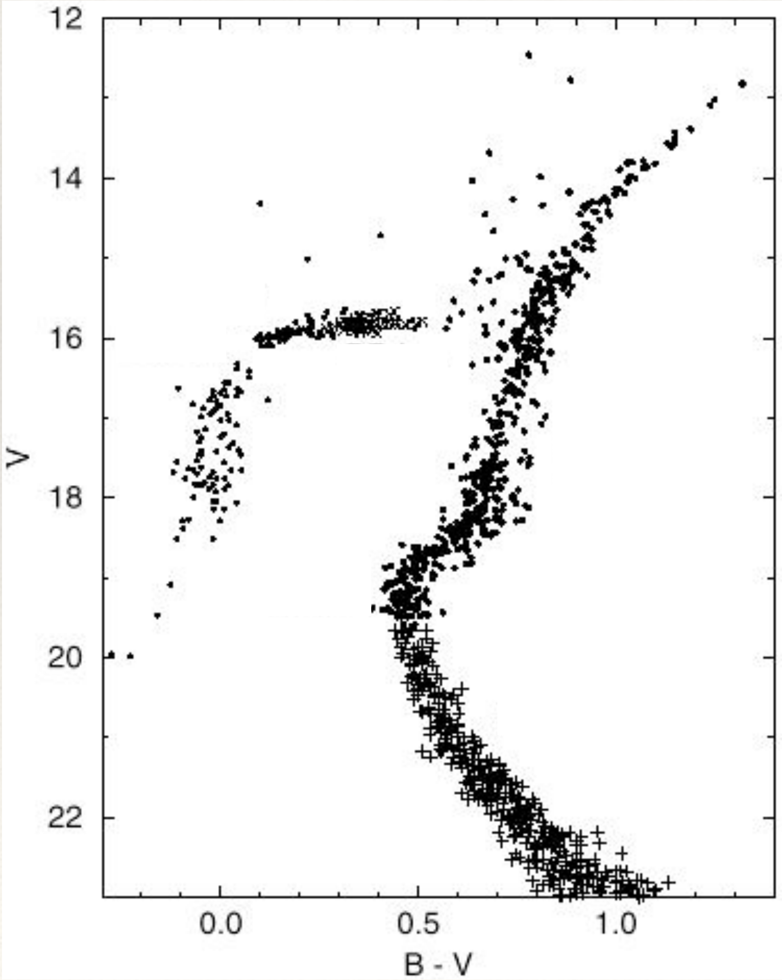
M31, Southwest arm, NGC 206 (Credit: Robert Gendler)

Building Blocks - Stars and Stellar Populations

- Galactic globular clusters:
  - cornerstone of understanding stellar evolution historically
  - in principle all stars same age and same metallicity

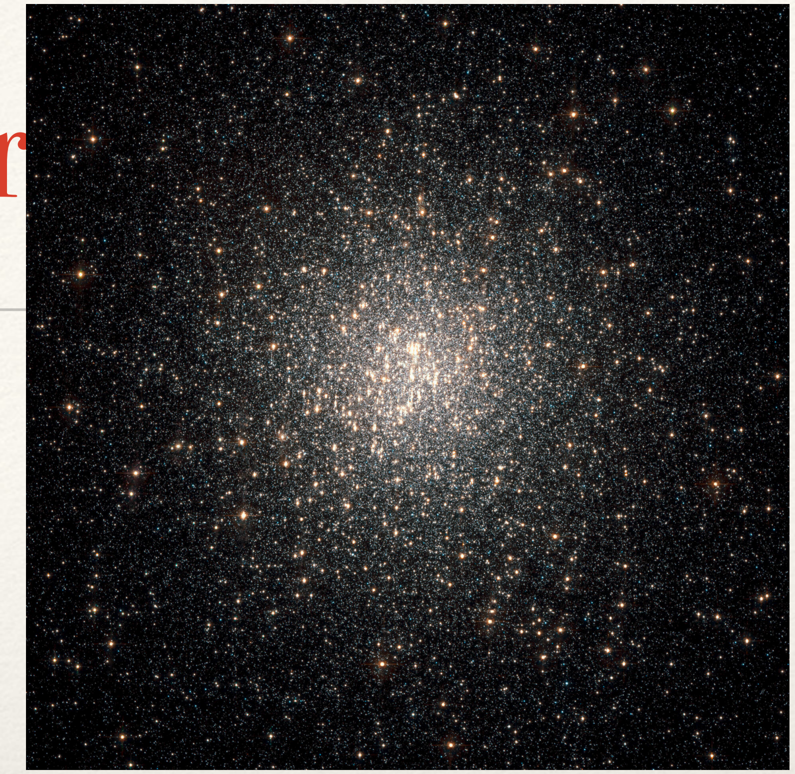


B.J. Mochejska, J. Kaluzny (CAMK), 1m Swope Telescope



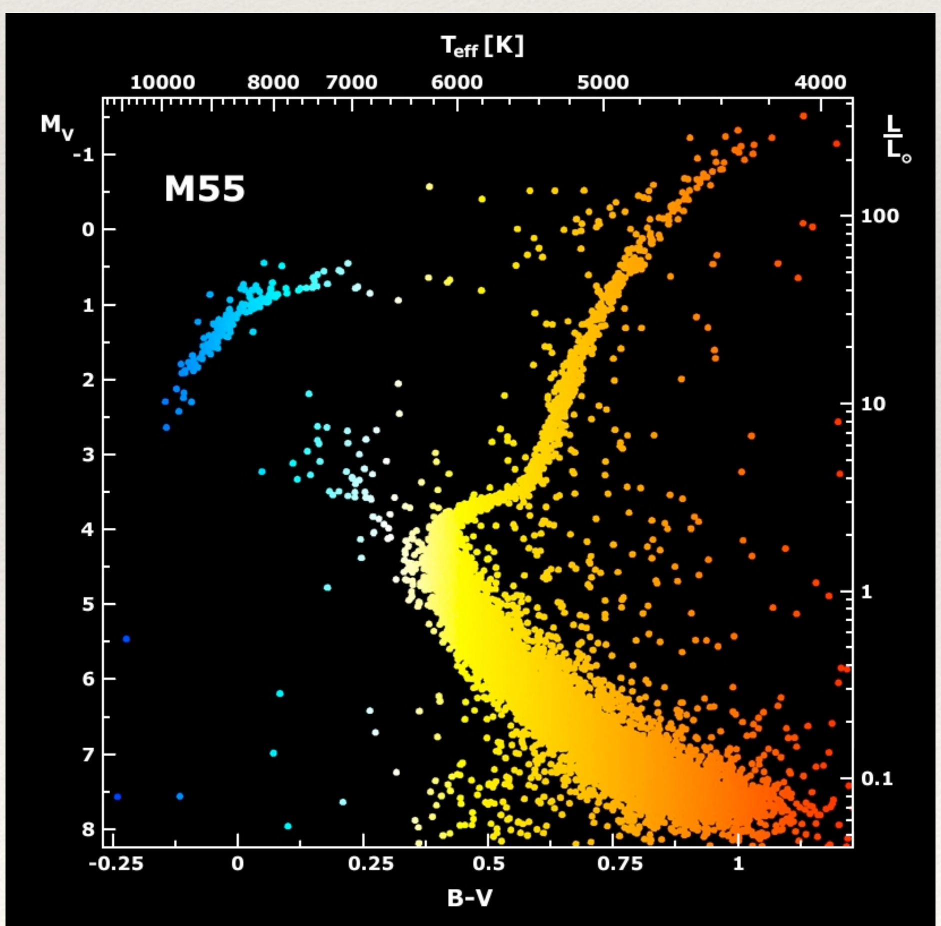
M15 (Krauss 2000)

Credit: NASA, ESA, G. Piotto (University of Padua) and A. Sarajedini (University of Florida)



Building Blocks - Stars and Stellar

- Globular clusters are in principle a "simple stellar population" (SSP)
  - Some exceptions! — multiple components, abundance variations



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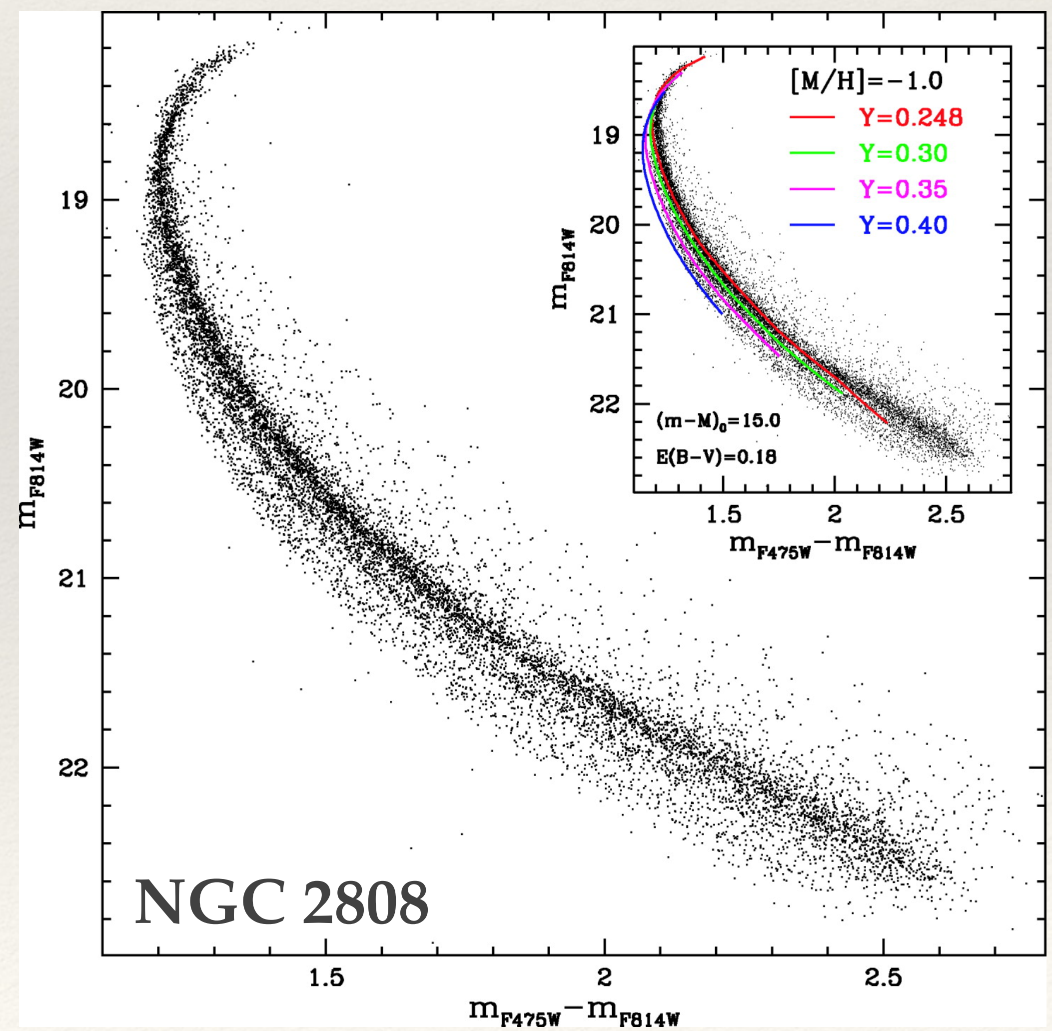


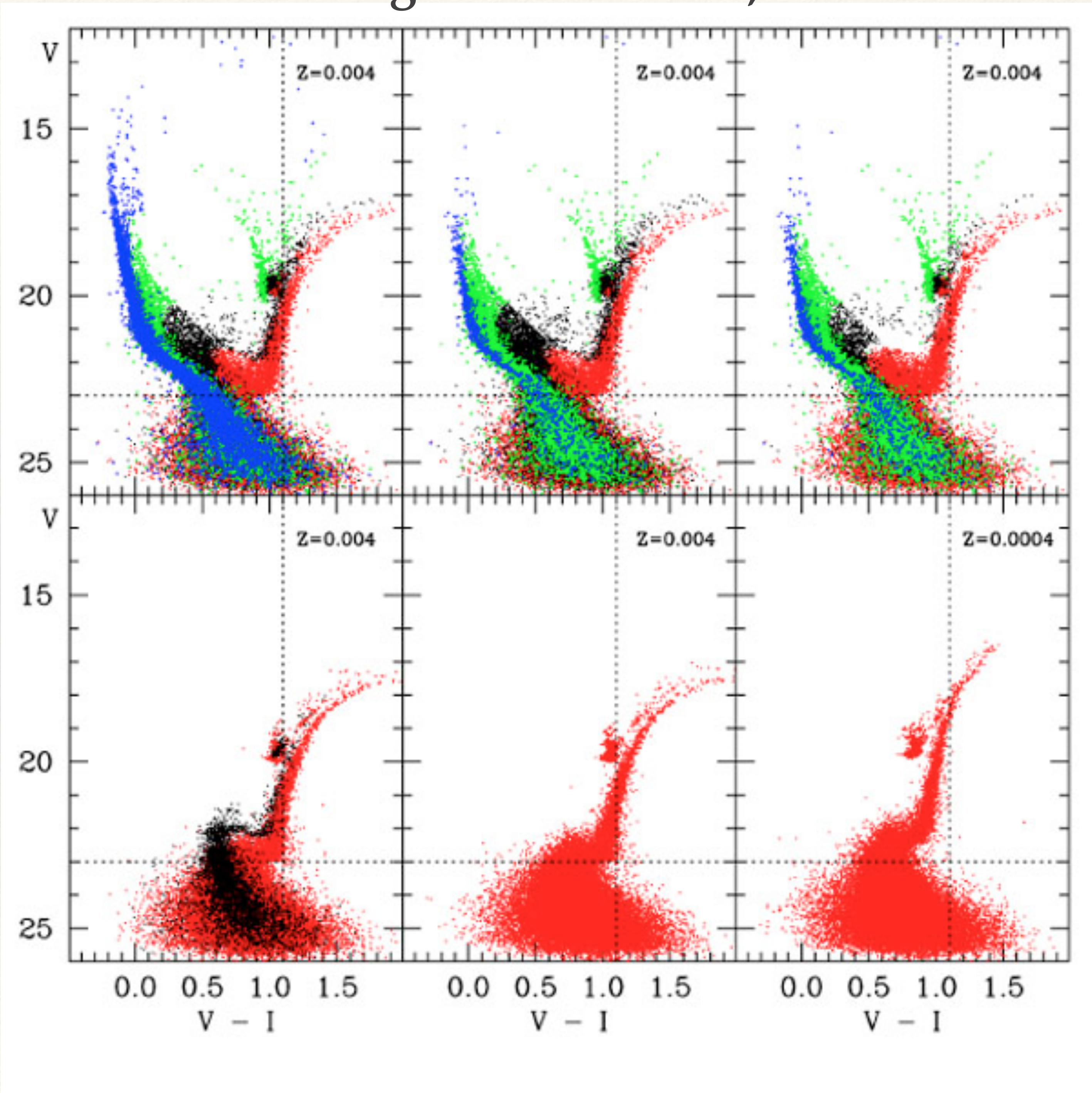
Piotto+2007 — https://iopscience.iop.org/article/10.1086/518503/fulltext/

Building Blocks - Stars and Stellar Populations

- Goal: use resolved stellar populations in galaxies to derive **Star Formation History (SFH)**
- = number of stars (or stellar mass) as a function of age, metallicity, and mass

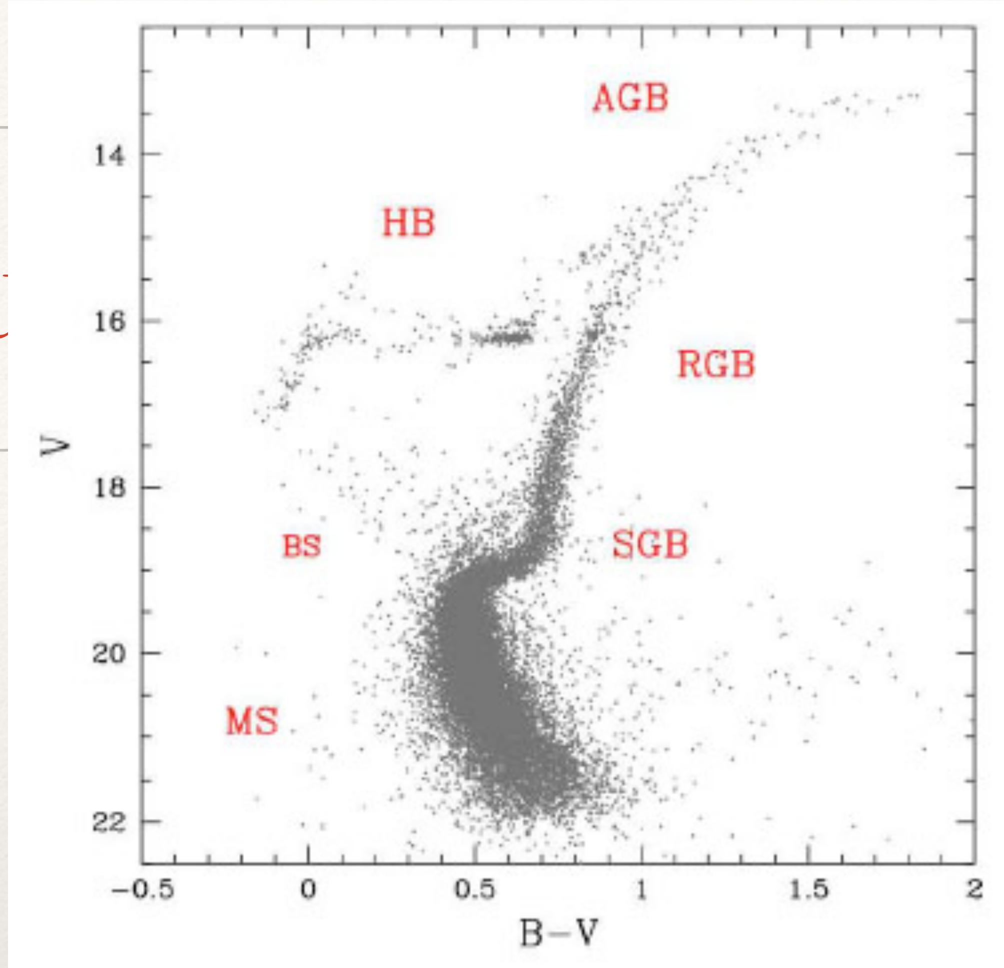
$$SFH(t, Z, M)$$

Simulated galaxies with 50,000 stars



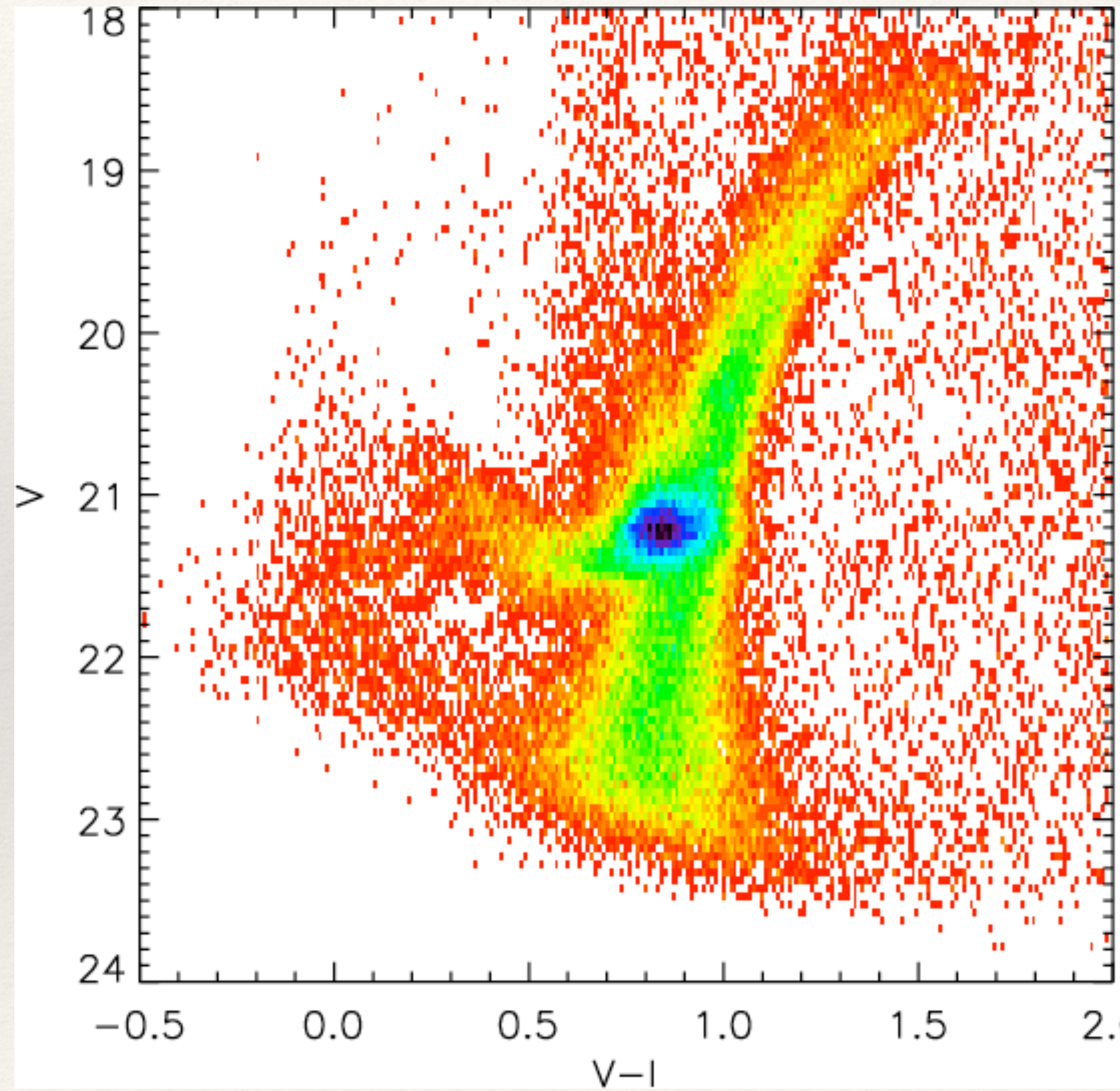
Cignoni & Tosi 2010

Bu rs and Stellar Populations



Maraston 2003

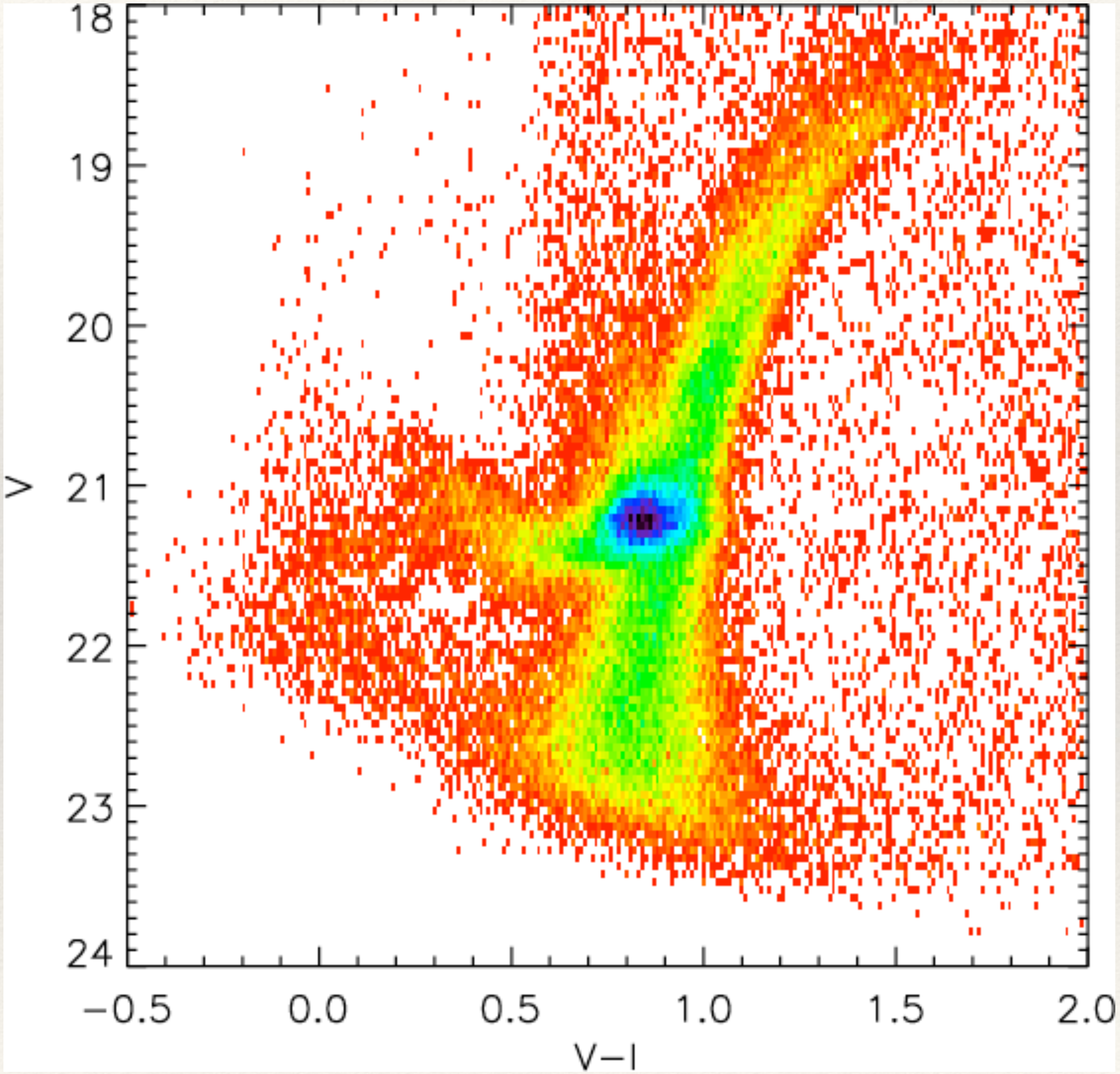
- **Color-Magnitude Diagram (CMD)** — shows individual stars at each location
- **Hess Diagram** — a CMD that shows relative number of stars at each location



Fornax (Battaglia et al. 2006)

Building Blocks - Stars and Stellar Populations

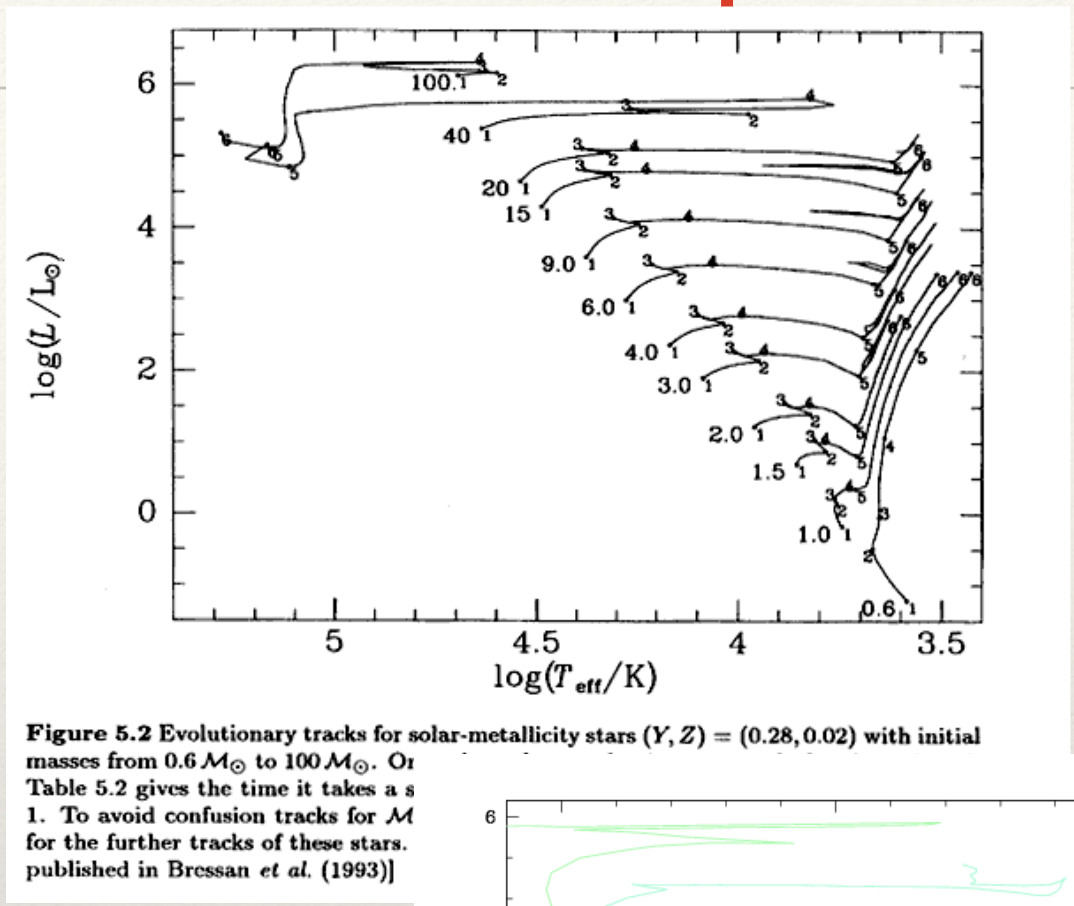
- For a **simple stellar population (SSP)**, relative number of stars at each stage determined by:
  - evolutionary timescale/lifetime at each stage
  - initial mass function (IMF)



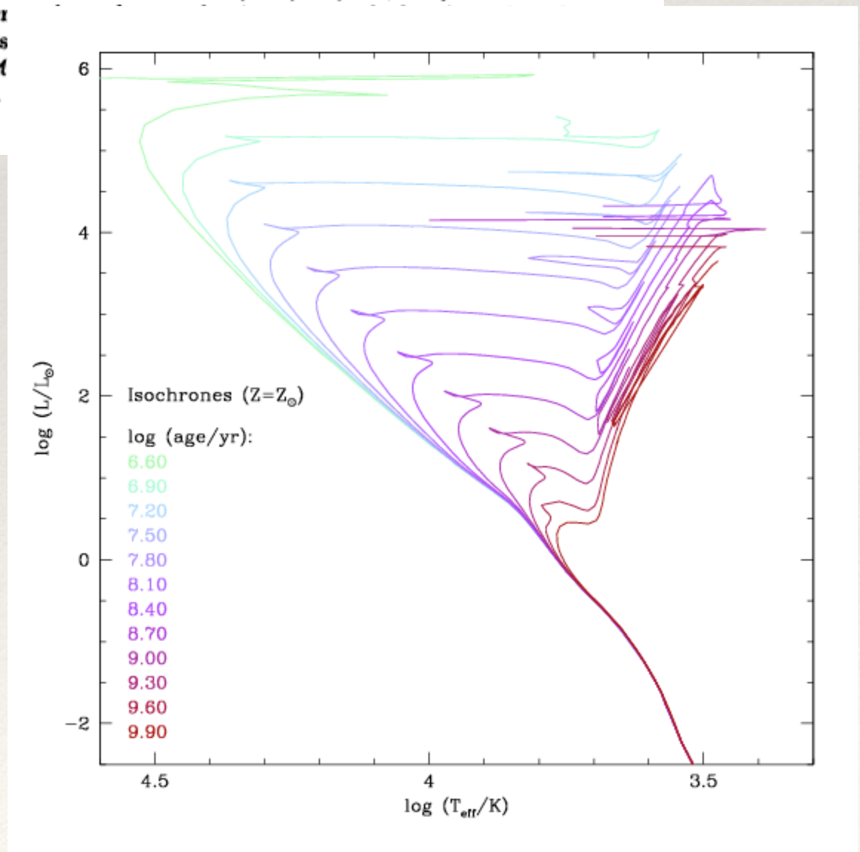
Fornax (Battaglia et al. 2006)

Building Blocks - Stars and Stellar Populations

- **Evolutionary Track** — shows path of a star through a CMD over time
- **Isochrone** — shows location of a stellar population in a CMD at a given time



Bressan et al. 1993



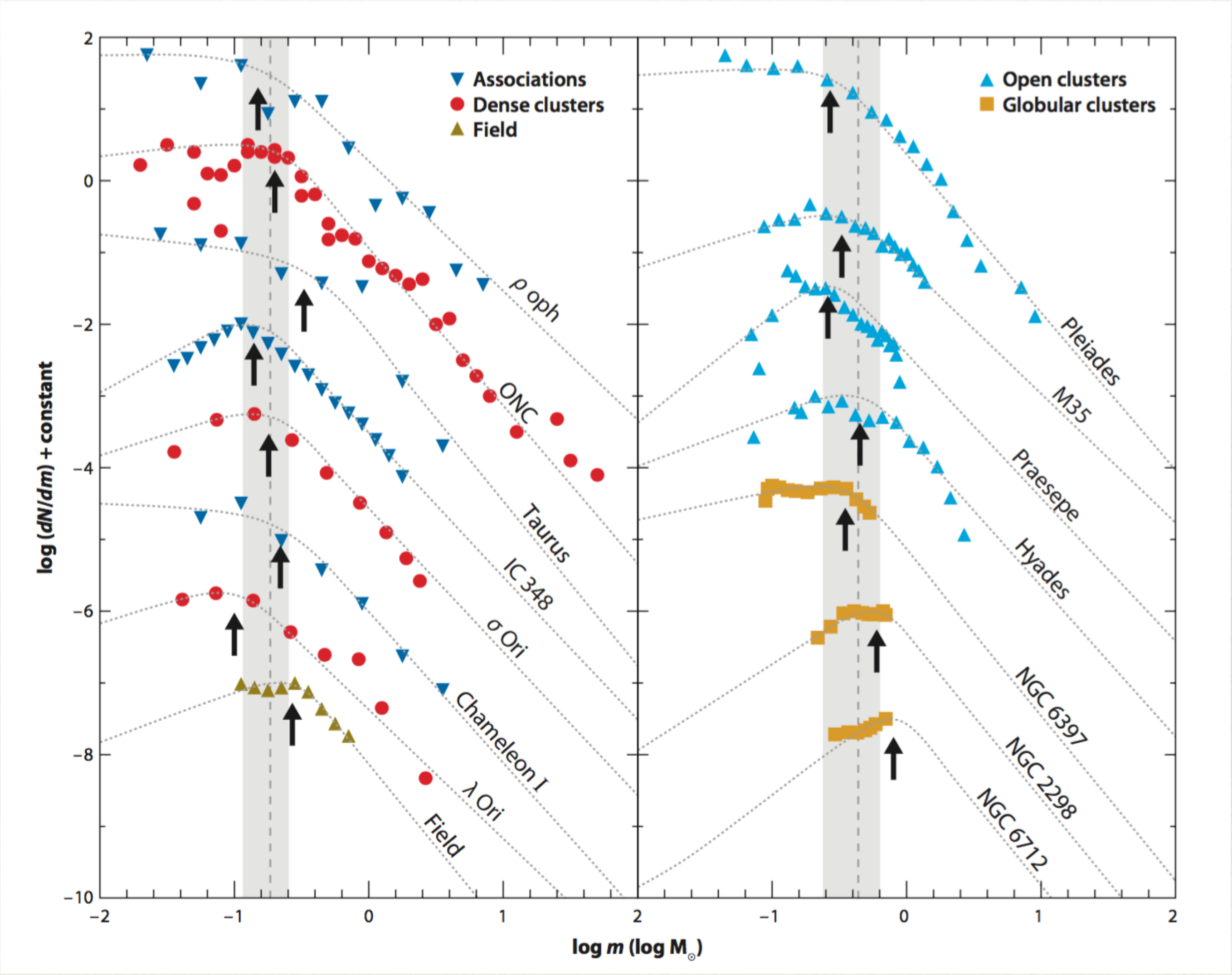
da Cunha 2008

Building Blocks - Stars and Stellar Populations

- **Initial Mass Function (IMF)**
  - dN / dM — number of stars formed initially per unit mass
  - Typically parameterized as a power law:

$$dN/dM \propto M^{\alpha}$$

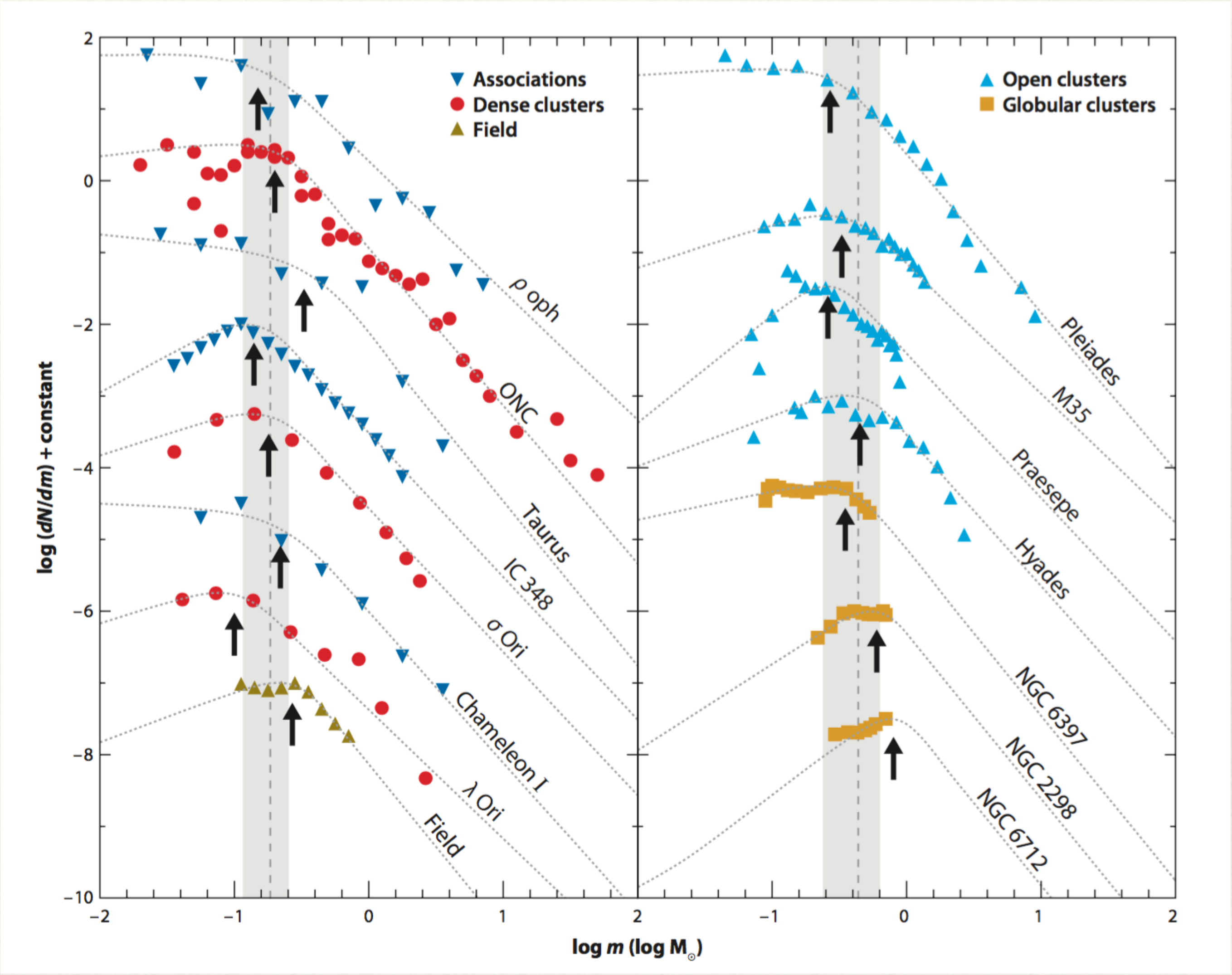
$$dN/d\log M \propto M^{\Gamma} \propto M^{\alpha+1}$$



Bastian et al. 2010

Thought Questions

- How would you go about measuring the IMF?
- What might make this difficult?



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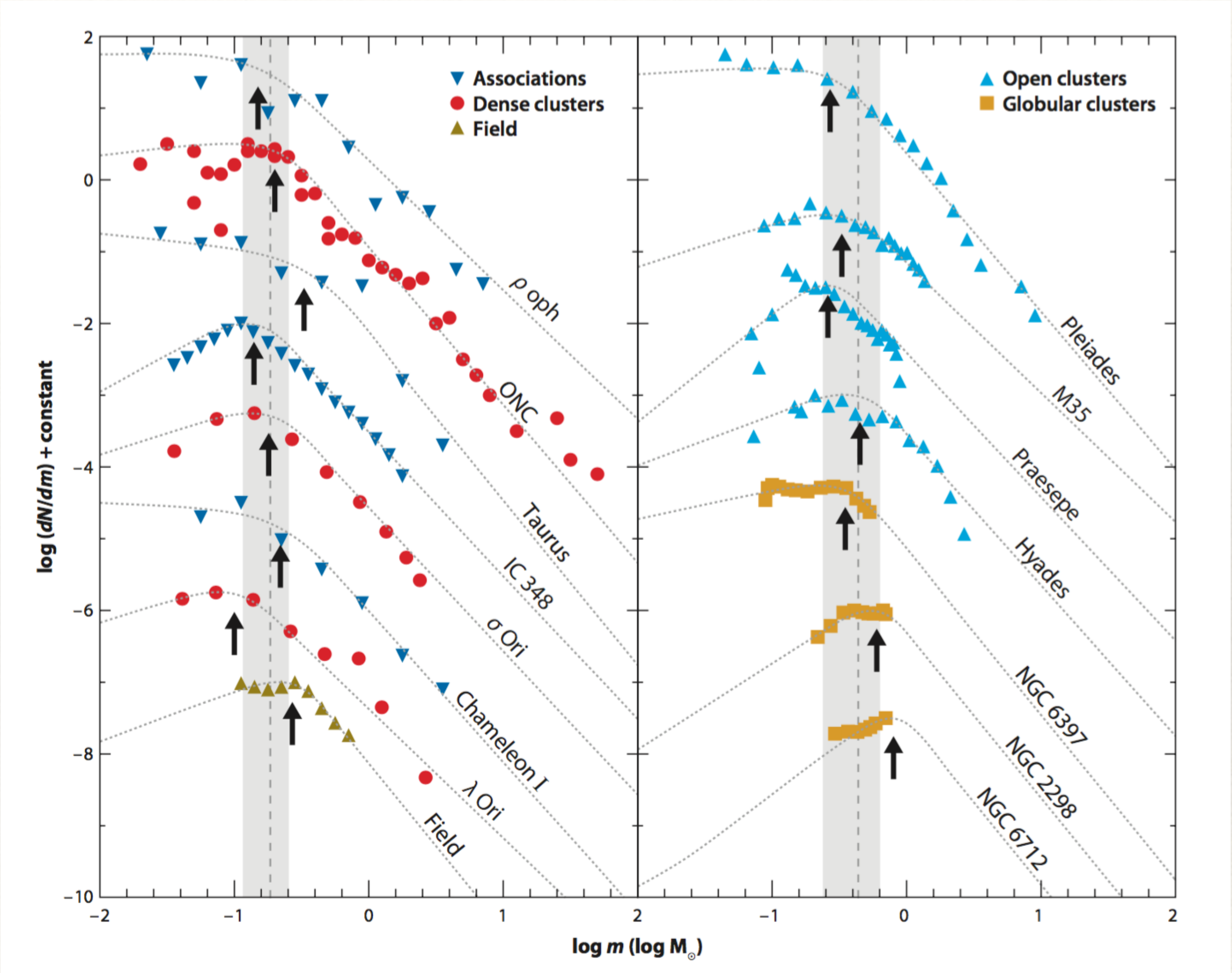


Bastian et al. 2010

Difficult to determine!

Building Blocks - Stars and Stellar Populations

- **Initial Mass Function (IMF)**
  - "Classical" Salpeter (1955):

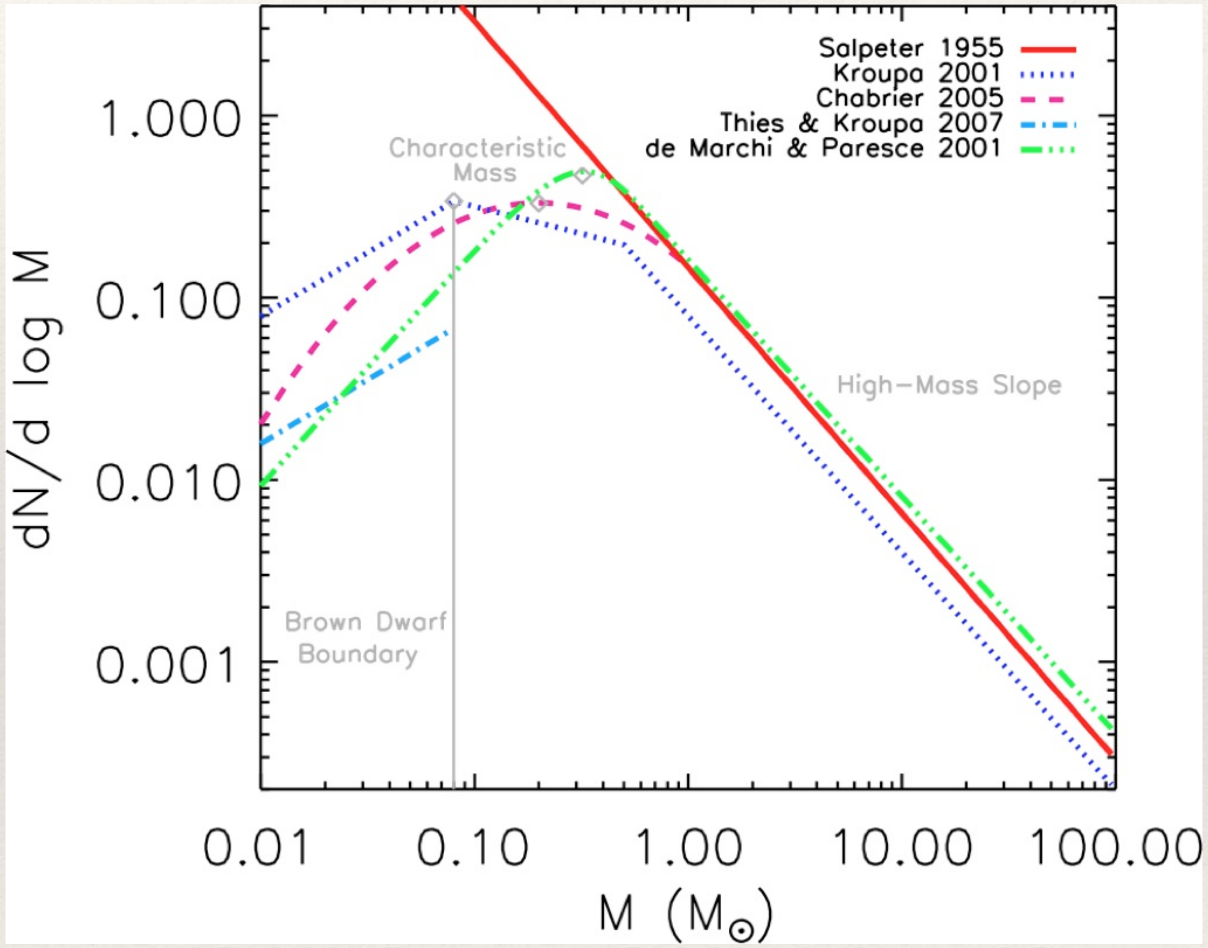
$$dN/dM \propto M^{-2.35}$$

  - Kroupa et al. (1993):

$$dN/dM \propto M^{-2.7} \text{ for } M > 1\ M_{sun}$$
$$dN/dM \propto M^{-2.2} \text{ for } 0.5 < M < 1\ M_{sun}$$
$$dN/dM \propto M^{-1.3} \text{ for } M < 0.5\ M_{sun}$$

  - Chabrier (2003):

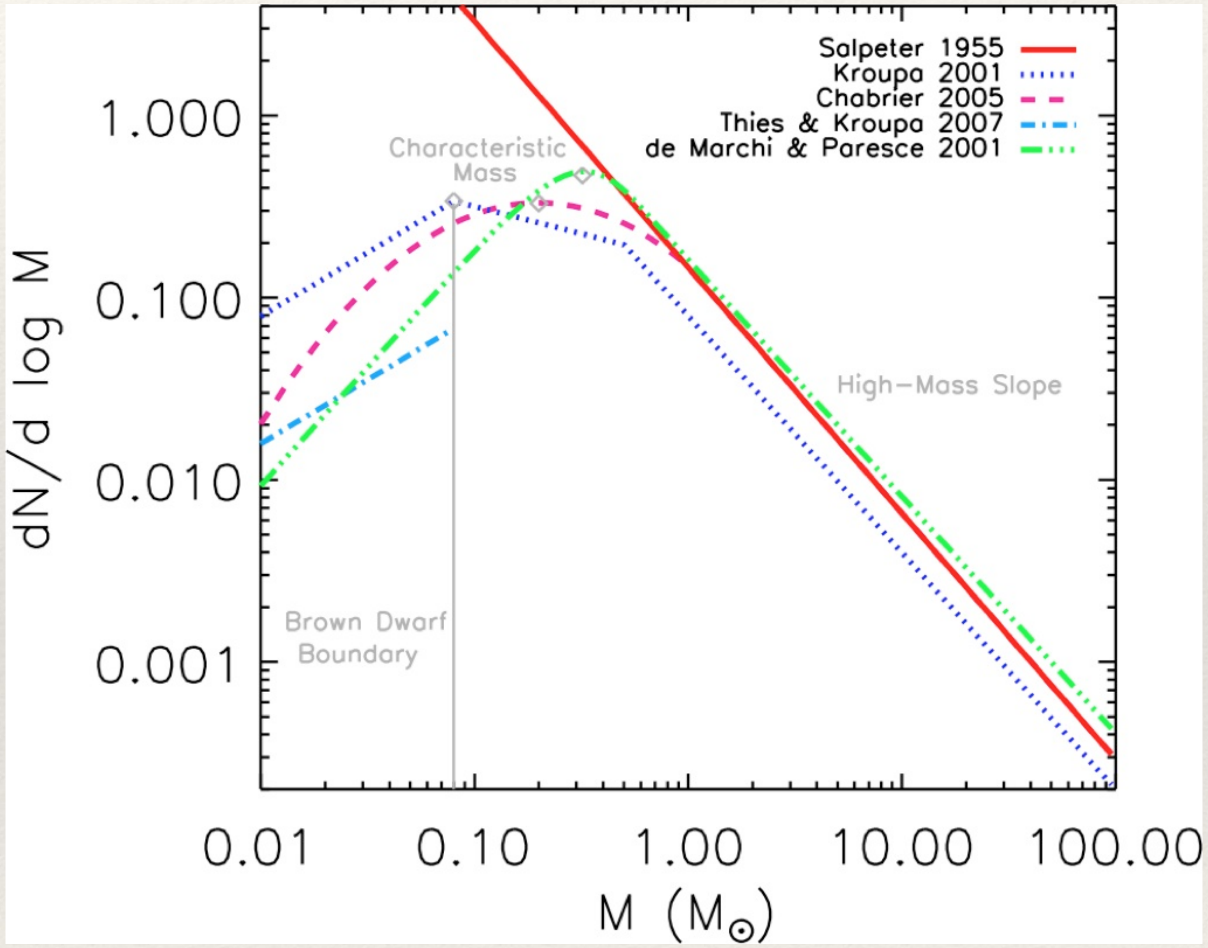
$$dN/dM \propto \exp(\log M - \log M_0)^2$$



Offner et al. 2014

Building Blocks - Stars and Stellar Populations

- **Initial Mass Function (IMF)**
  - No well-established theory for predicting IMF, yet IMF very important!
    - high-mass stars — nucleosynthesis, chemical evolution
    - low-mass stars — mass-to-light ratio normalization



Offner et al. 2014

Building Blocks - Stars and Stellar Populations

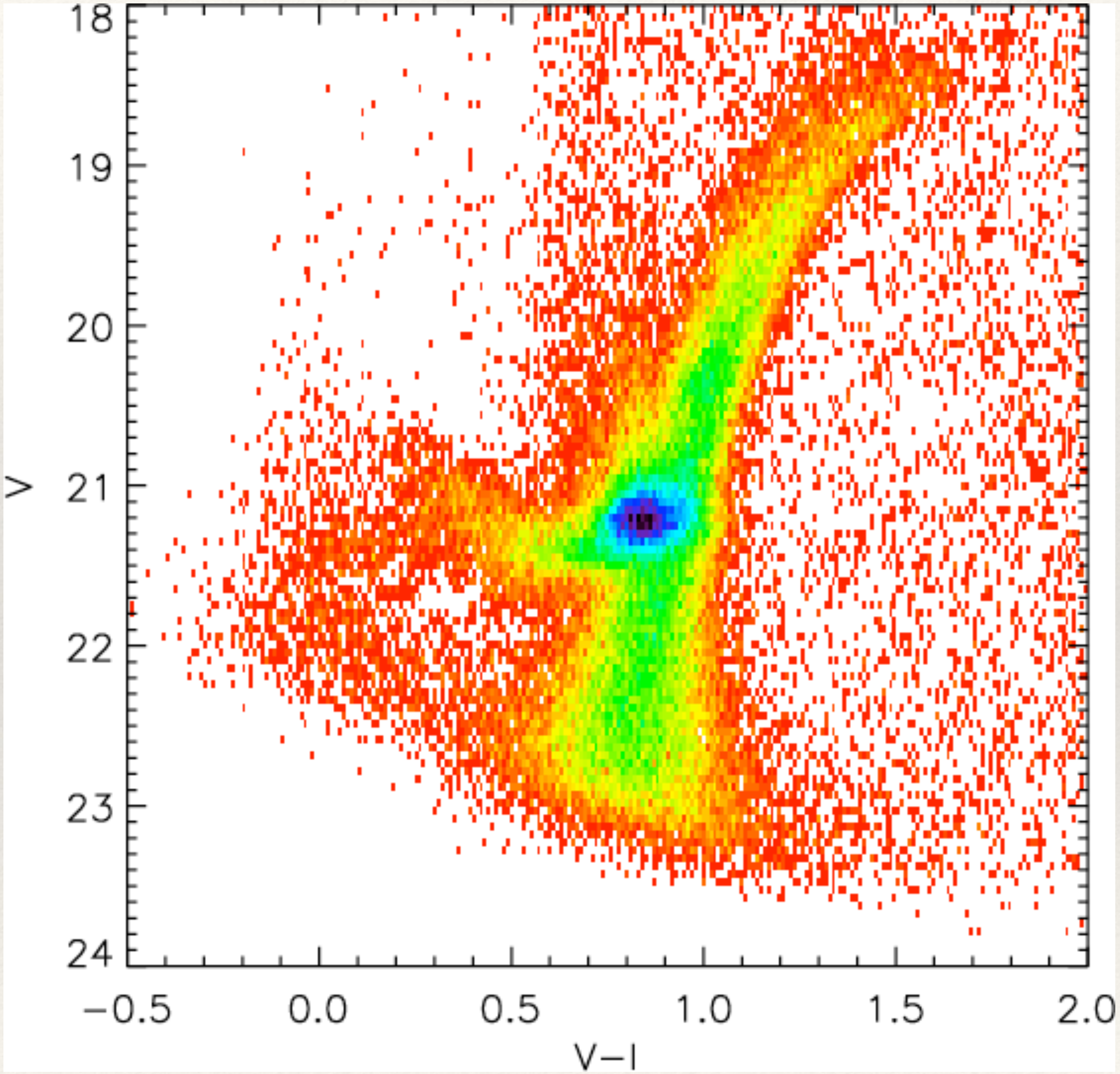
- Is the IMF universal/constant?
  - Early on, assumed universal — no strong evidence to the contrary from resolved studies (makes life easier!)
  - If IMF doesn't vary with t or Z, can separate out:

$$SFH(t, Z, M) = \xi(M)\psi(t, Z)$$

  - where $\xi(M)$ = IMF and $\psi(t,Z)$ = star formation rate
- Recent evidence that IMF not universal! (more later)

Building Blocks - Stars and Stellar Populations

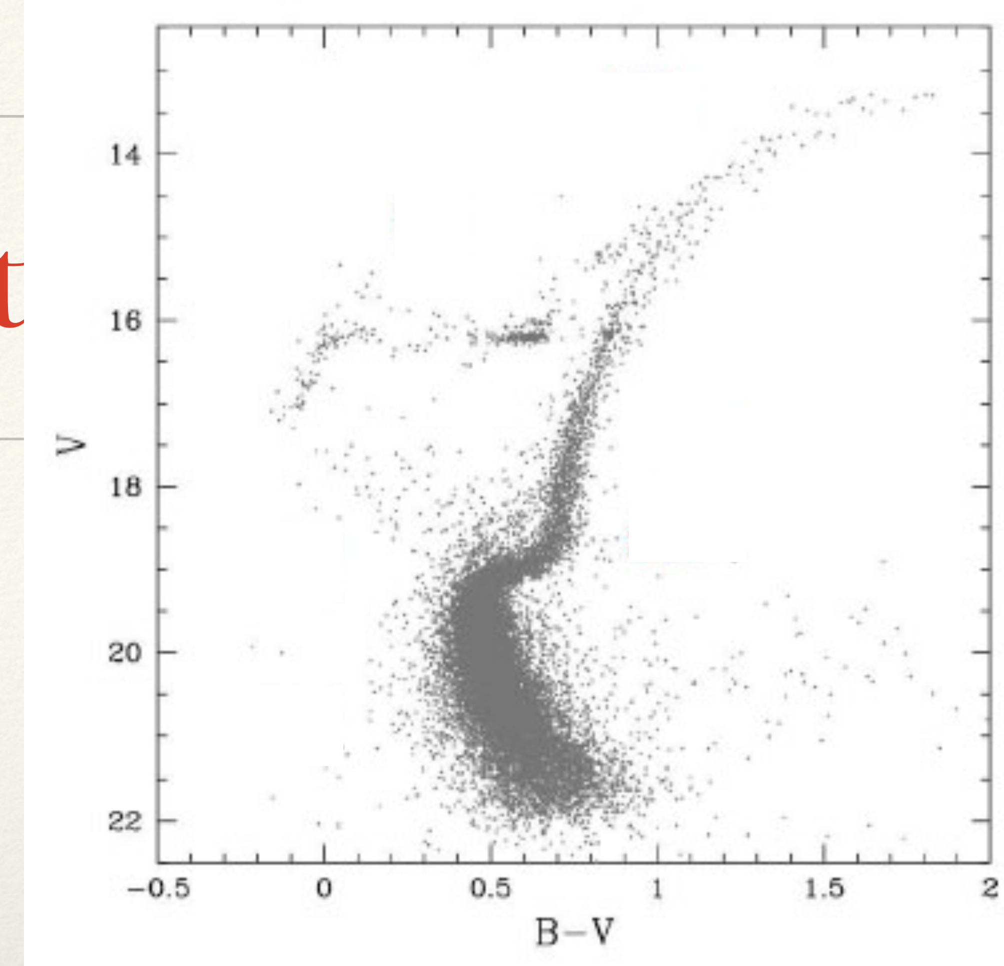
- Goal: use resolved stellar populations in galaxies to derive **Star Formation History (SFH)**
- For a **simple stellar population (SSP)**, relative number of stars at each stage determined by:
  - evolutionary timescale / lifetime at each stage
  - initial mass function (IMF)



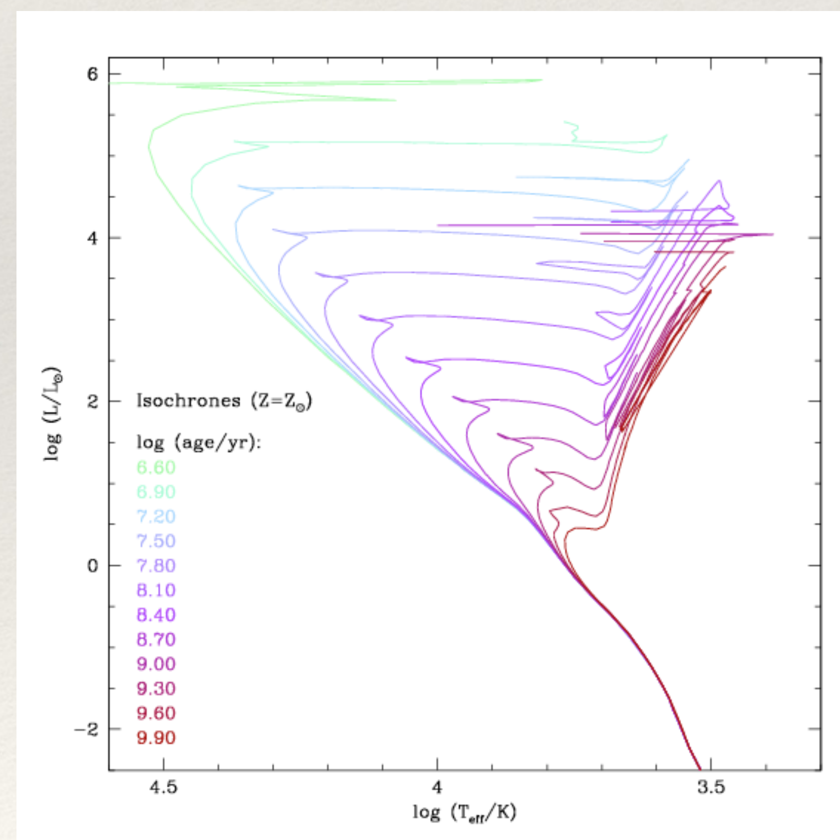
Fornax (Battaglia et al. 2006)

Building Blocks - Stars and St

- SFH Methods:
  - **Isochrone fitting**:
    - can work well for SSPs (e.g., some star clusters)
    - in general, galaxies are not SSPs!
  - **Synthetic CMD fitting:**
    - fit Hess diagrams of resolved stellar populations with combinations of SSPs to derive constraints



Maraston 2003



da Cunha 2008

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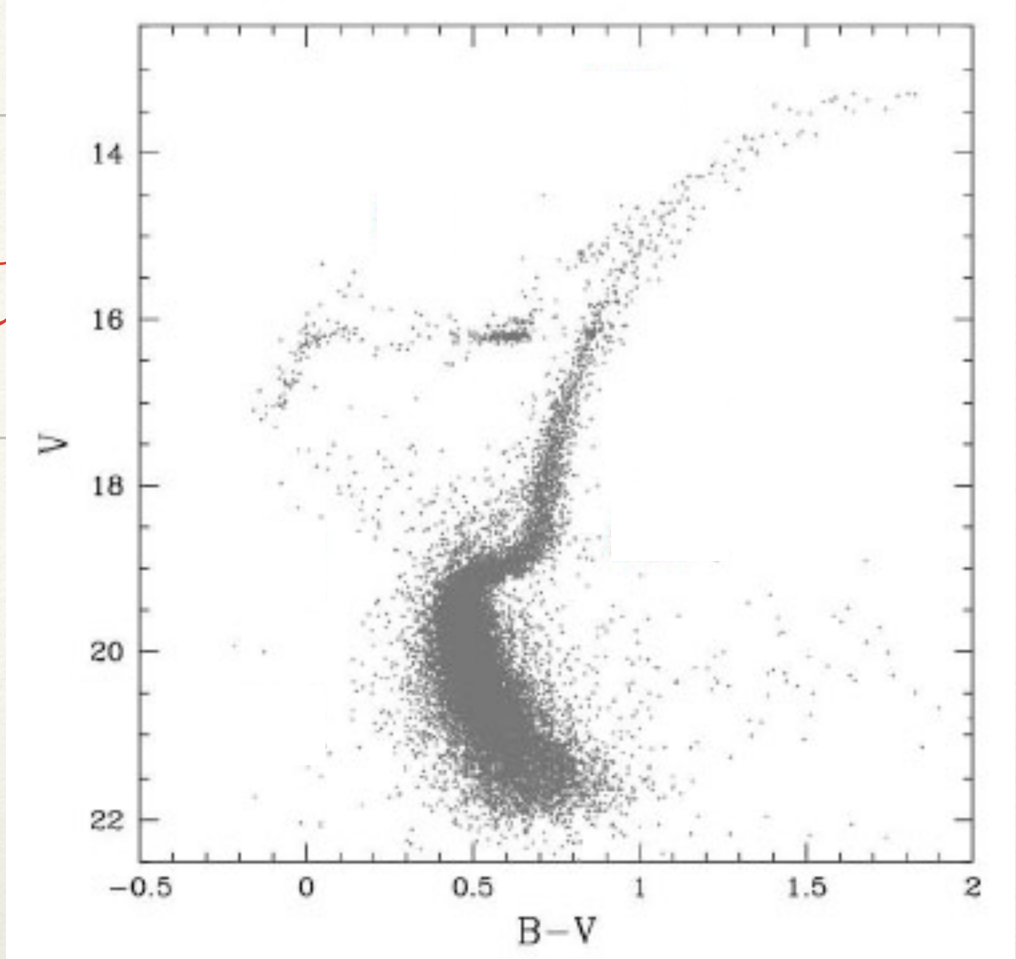
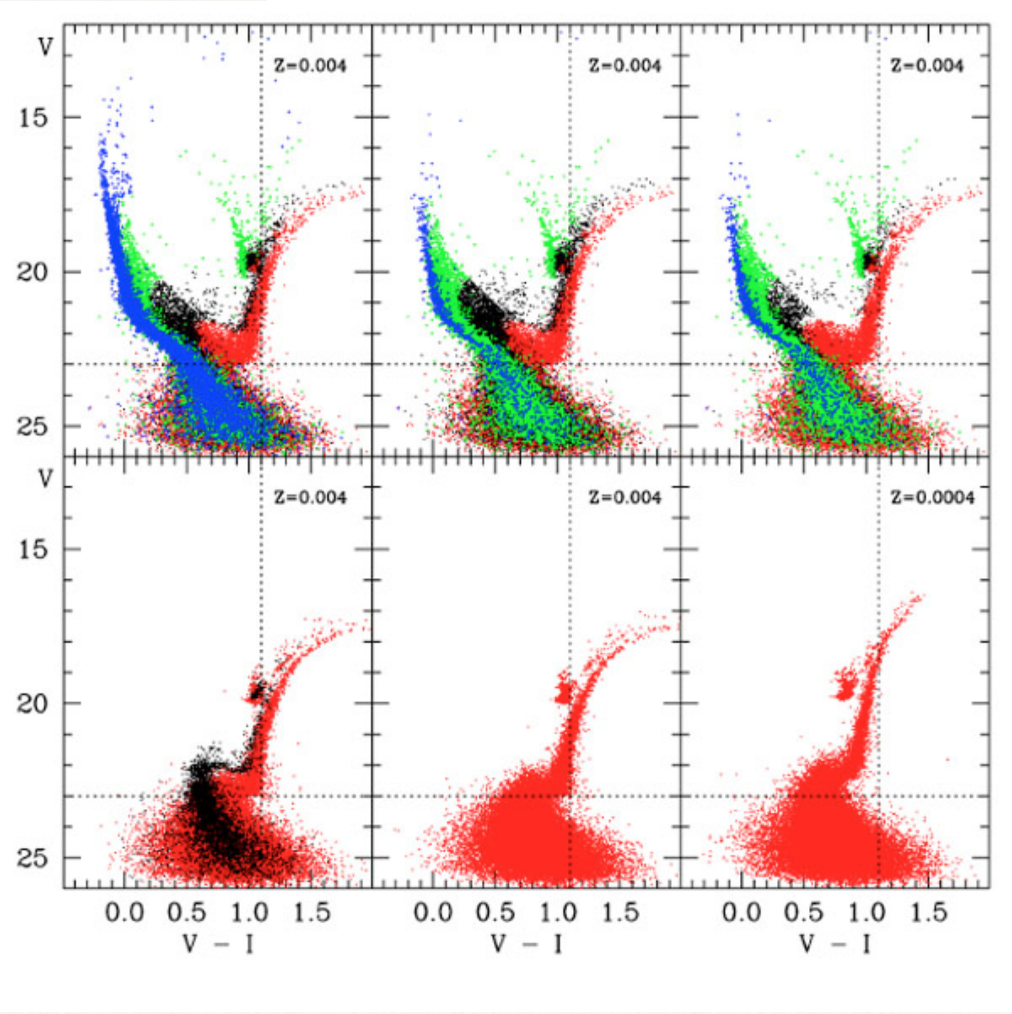


Maraston 2003

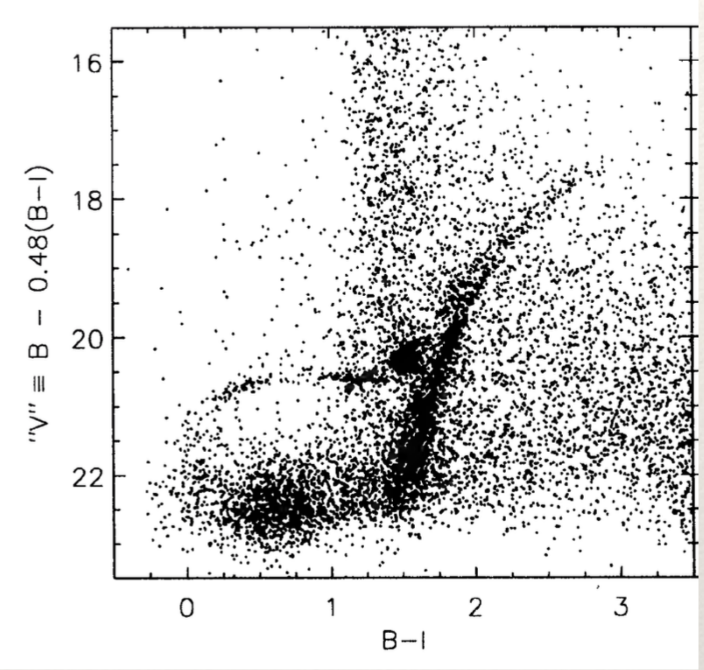


Cignoni & Tosi 2010

Thought Question

- Consider this CMD for Carina (local dSph):
  - What CMD features can you identify?
  - What could make these data challenging to interpret?
  - How many stellar populations are there in Carina?

Carina (dSph)



Smecker-Hane et al. 1994

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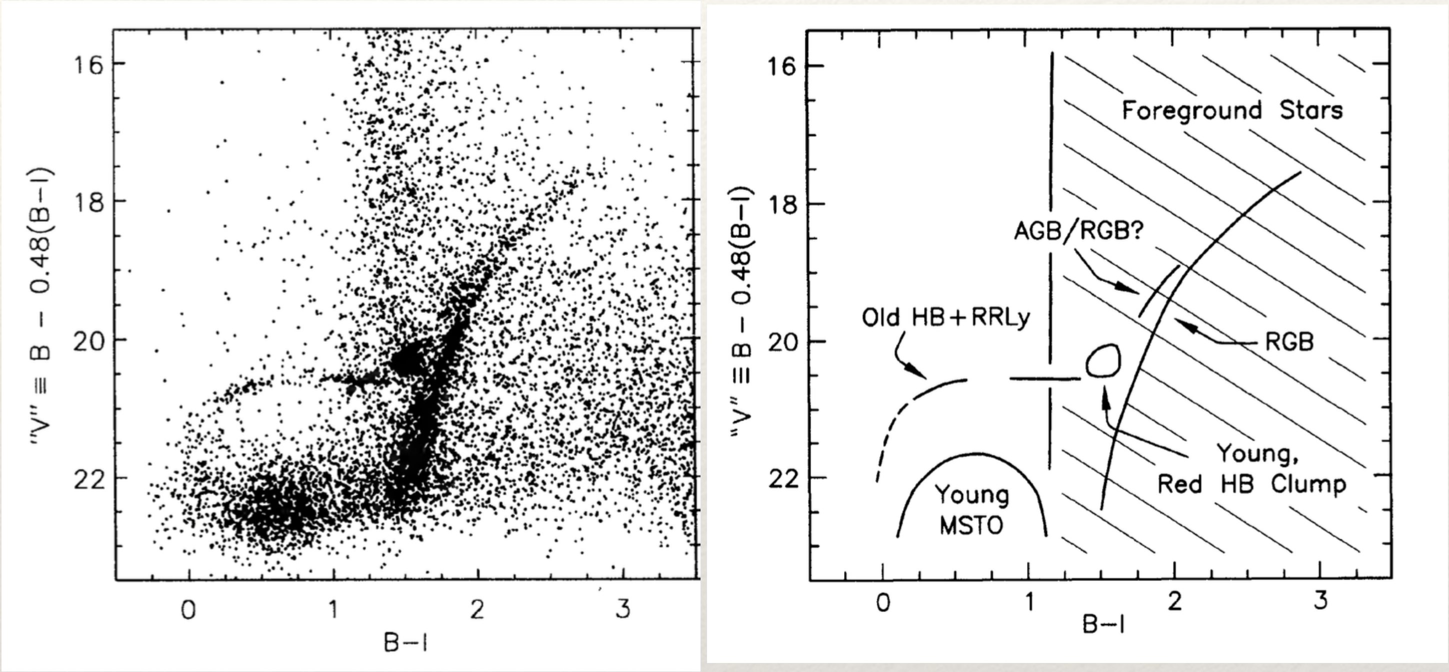

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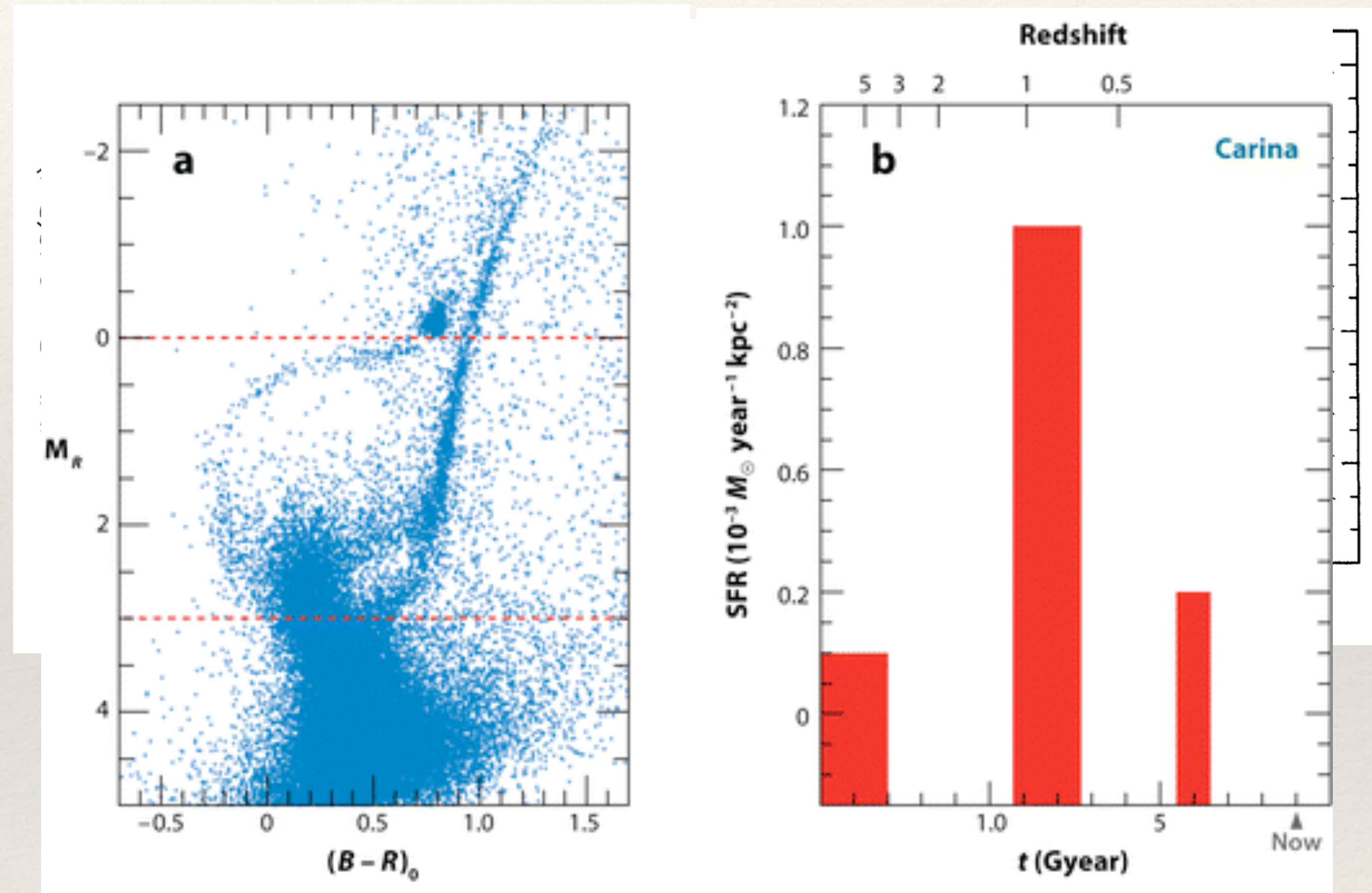
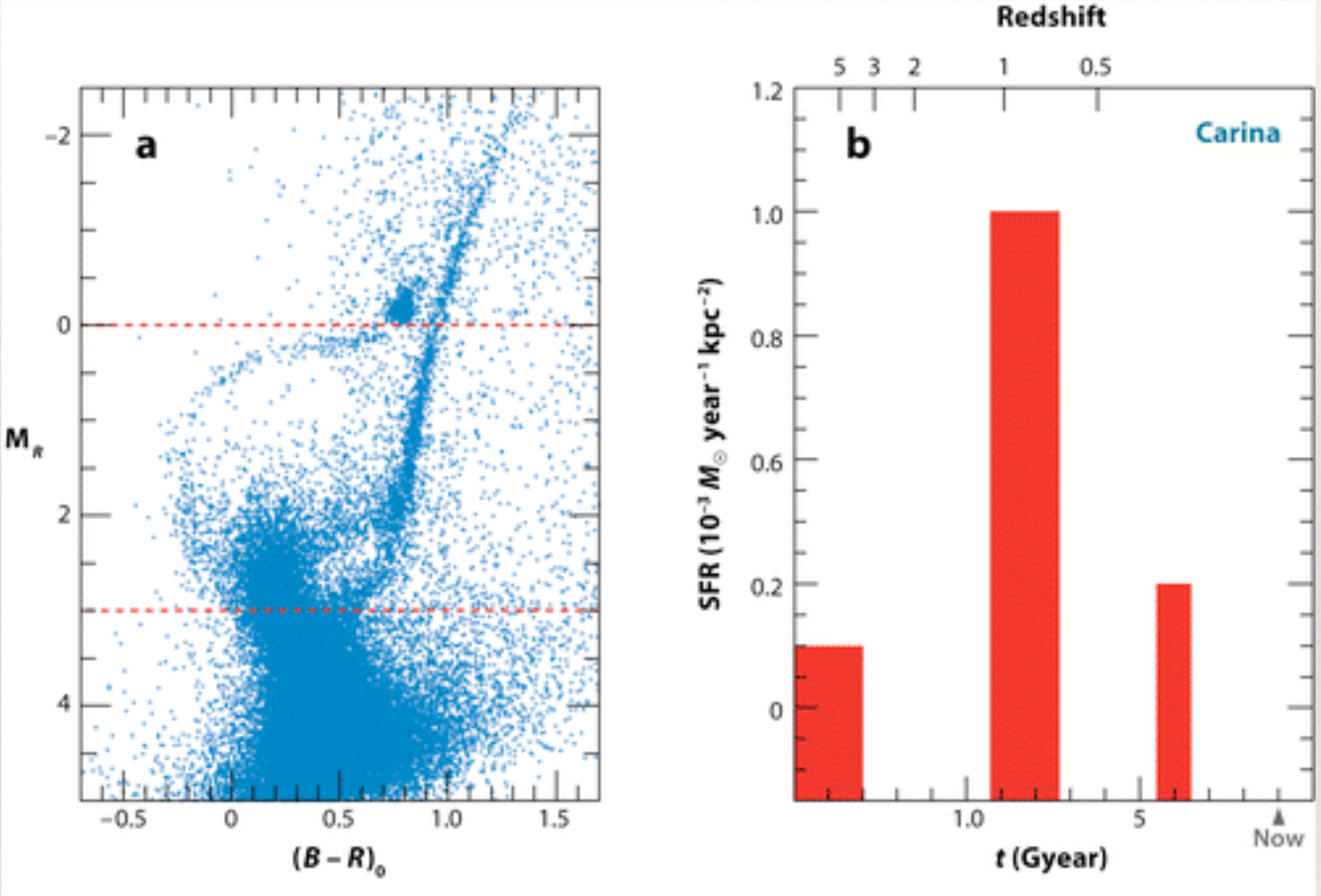


Tolstoy E, et al. 2009.
Annu. Rev. Astron. Astrophys. 47:371–425

Building Blocks - Stars and Stellar Populations

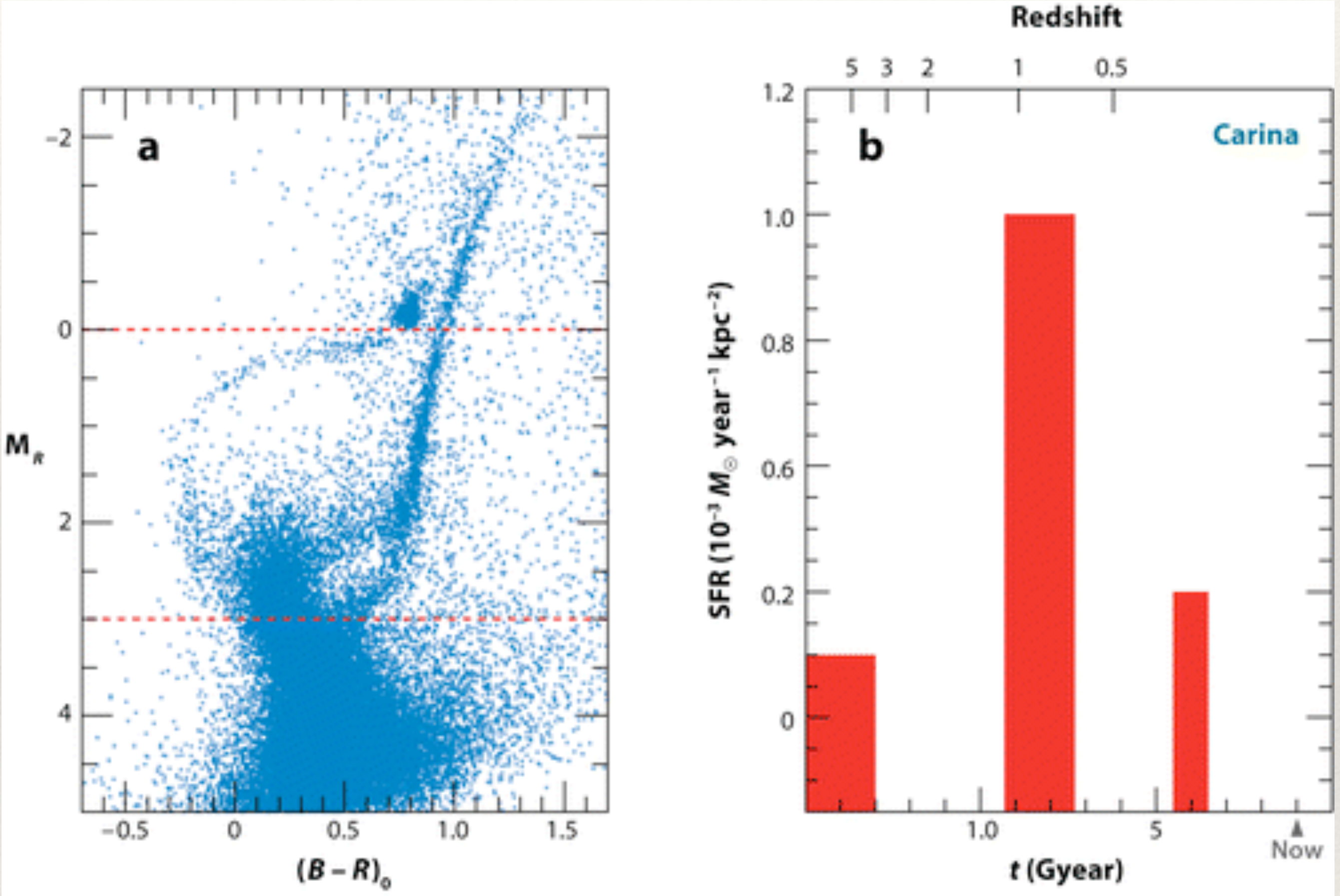
- To make a CMD, we need to resolve individual stars:
  - MW neighbors — resolved down to oldest Main Sequence Turnoff
  - M31 and neighbors — requires large investment of telescope time
  - Outside of Local Group — getting to the Main Sequence Turnoff is very difficult



Tolstoy E, et al. 2009.
Annu. Rev. Astron. Astrophys. 47:371–425

Building Blocks - Stars and Stellar Populations

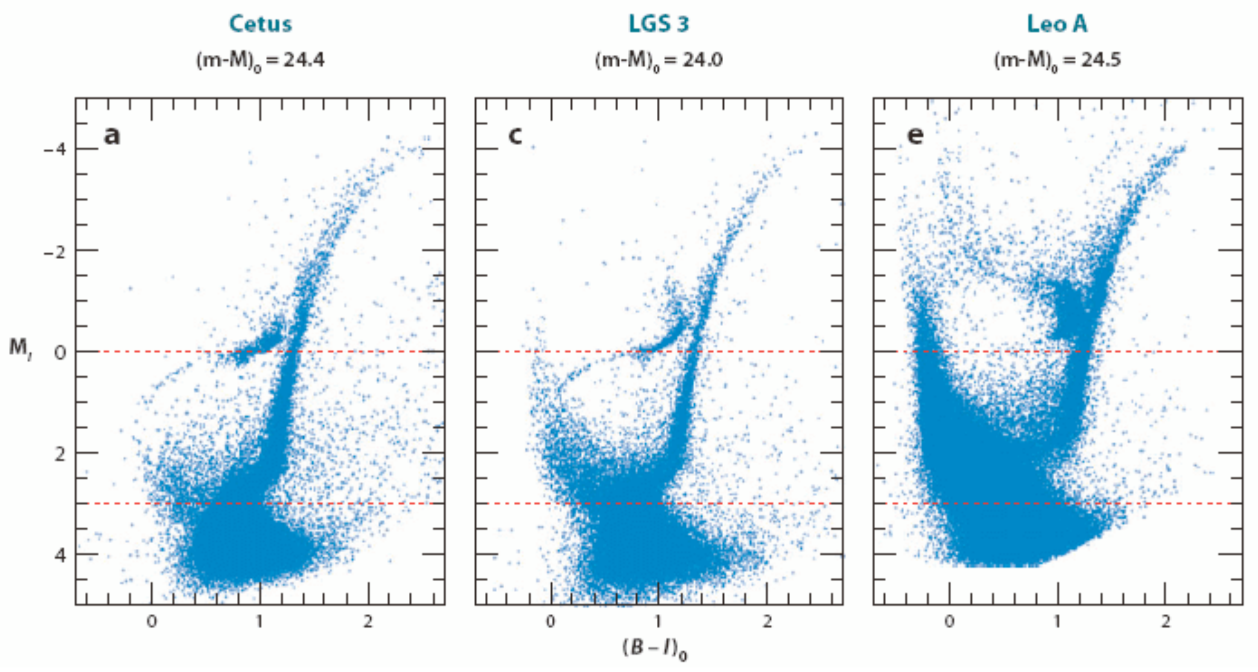
- Results for Local Group dwarf galaxies:
  - Carina dSph — shows striking evidence of episodic star formation
  - However, others show a range of star formation histories



Tolstoy E, et al. 2009.
Annu. Rev. Astron. Astrophys. 47:371–425

Thought Question

- What would you guess for the SFH of each of these Local Group dwarf galaxies?
- Make a sketch of SFR surface density vs. time.



?

Figure 5

Hubble Space Telescope/Advanced Camera for Surveys (HST/ACS) color-magnitude diagrams (CMDs) and star-formation histories (SFHs) for three Local Group dwarf galaxies: (a,b) Cetus, a distant dwarf spheroidal galaxy (M. Monelli & the LCID team in preparation); (c,d) LGS 3, a transition-type dwarf galaxy (S. Hildago & the LCID team, in preparation); and (e,f) Leo A, a dwarf irregular (Cole et al. 2007). These results come from the LCID project (Gallart & the LCID team 2007, Cole et al. 2007), which is a large program designed to exploit the exquisite image quality of the HST/ACS to obtain uniquely detailed CMDs going back to the oldest main sequence turn offs for a sample of dwarf galaxies. The SFHs come from synthetic CMD analysis and the ages are also shown in terms of redshift.

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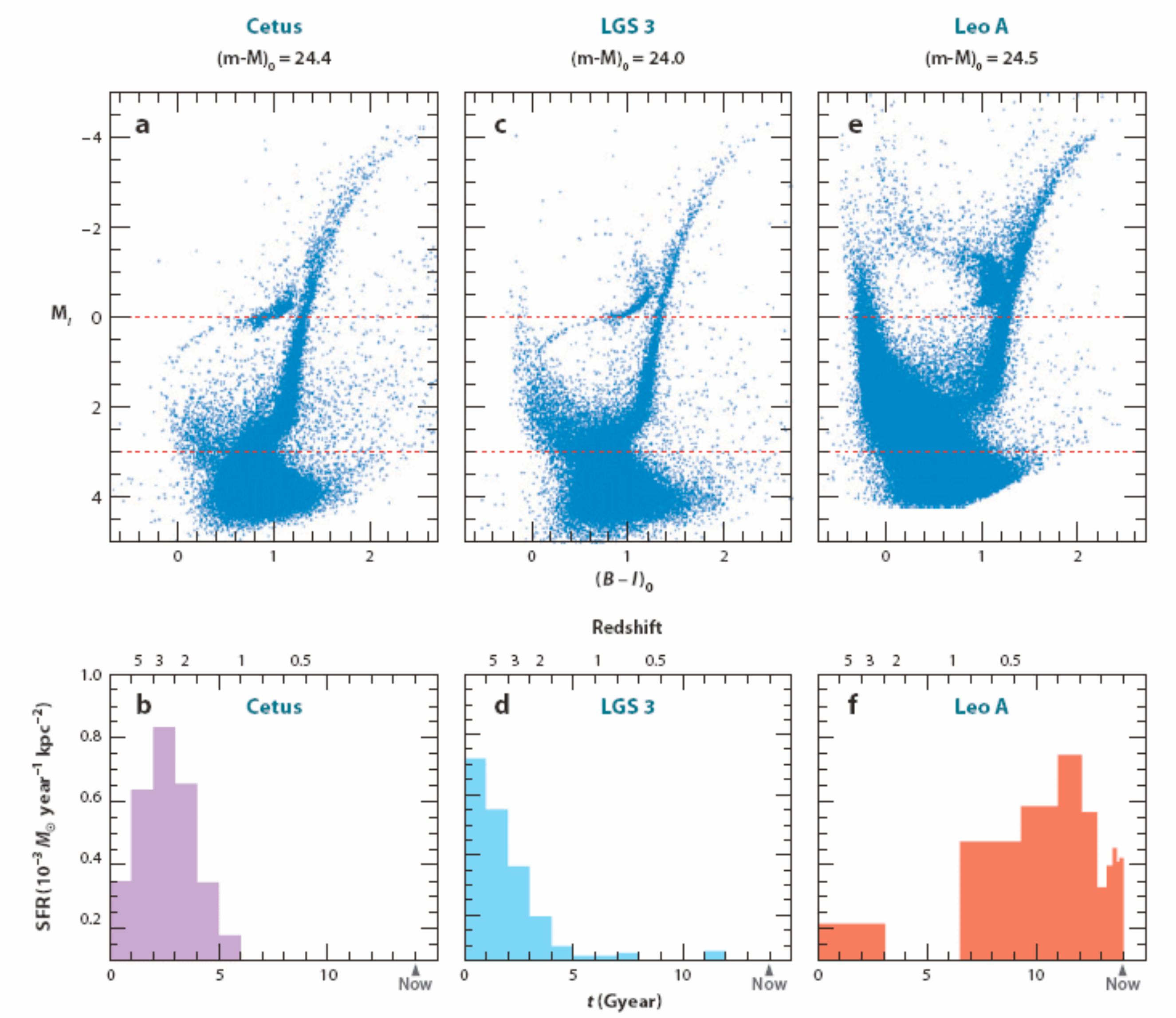

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Building Blocks - Stars

- Results for Local Group dwarf galaxies:
  - Local Group dIrrs — plotted in a “population box” (number of stars formed as function of age and metallicity)

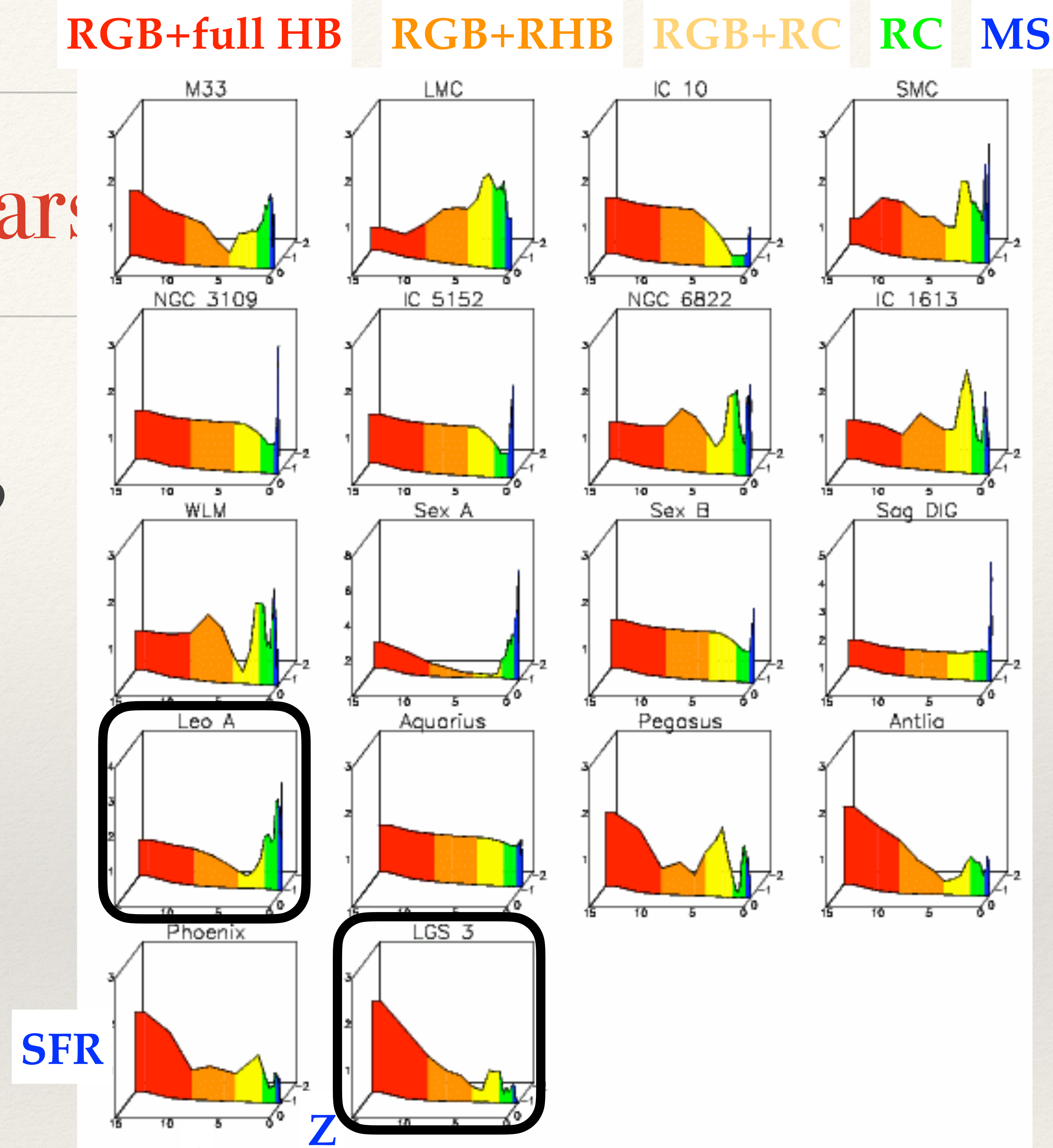

Fig. 44. Star formation histories of irregular and transition-type galaxies. Colors correspond to the CMD features generated by each age. Red: RGB plus full HB. Orange: RGB plus red HB. Yellow: RGB plus red clump. Green: bright red clump. Blue: young MS and blue helium-burning stars. Ages are given in Gyr, and star formation rates are normalized to the lifetime averages.

Dolphin et al. 2005

Building Blocks - Stars a

- Results for Local Group dwarf galaxies:
  - Local Group dSphs — similar to dIrrs but without recent star formation?

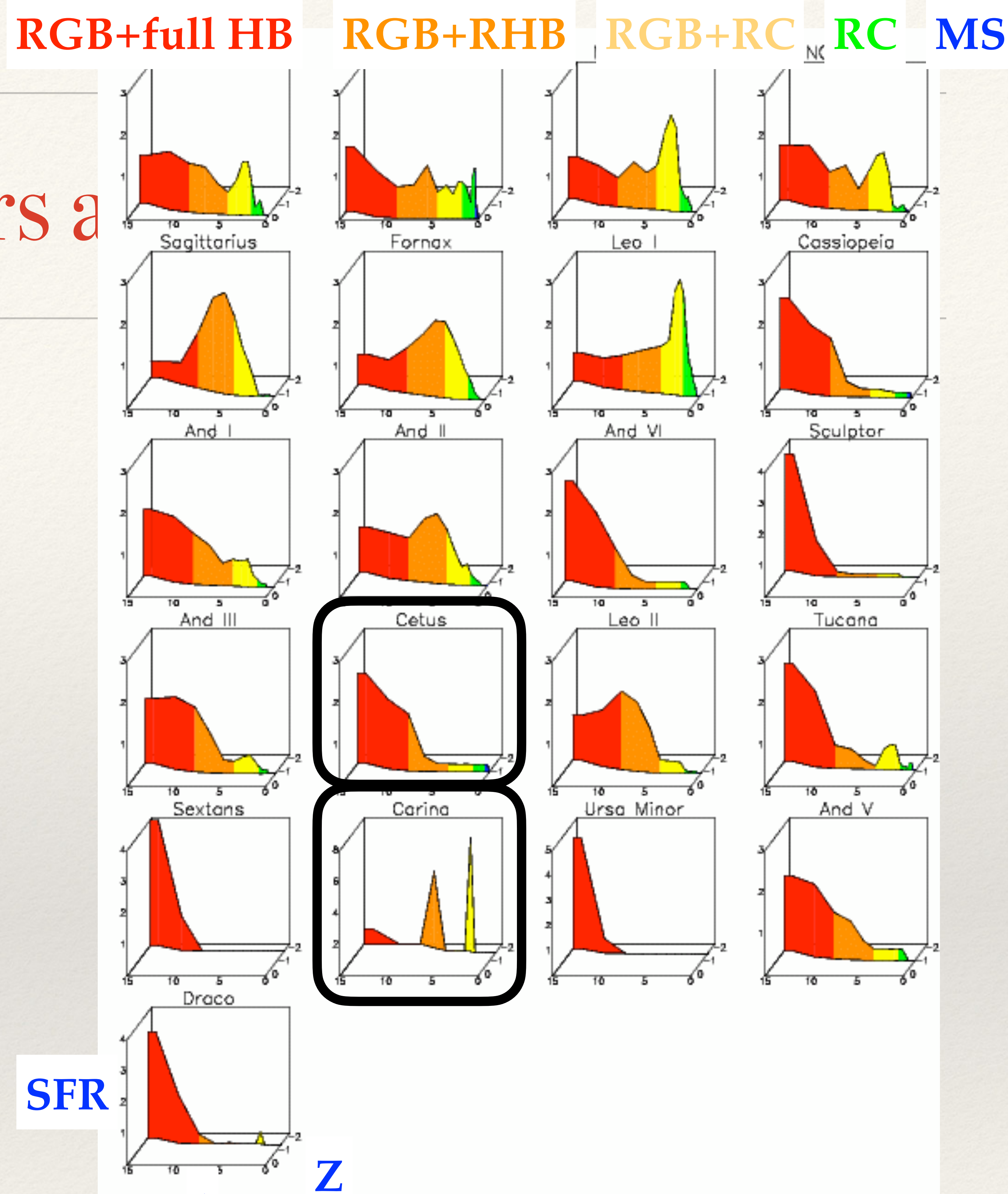

Figure 43. Star formation histories of elliptical and spheroidal galaxies. Colors correspond to the CMD features generated by each age. Red: RGB plus full HB. Orange: RGB plus red HB. Yellow: RGB plus red clump. Green: bright red clump. Blue: young MS and blue helium-burning stars. Ages are given in Gyr, and star formation rates are normalized to the lifetime averages.

Dolphin et al. 2005