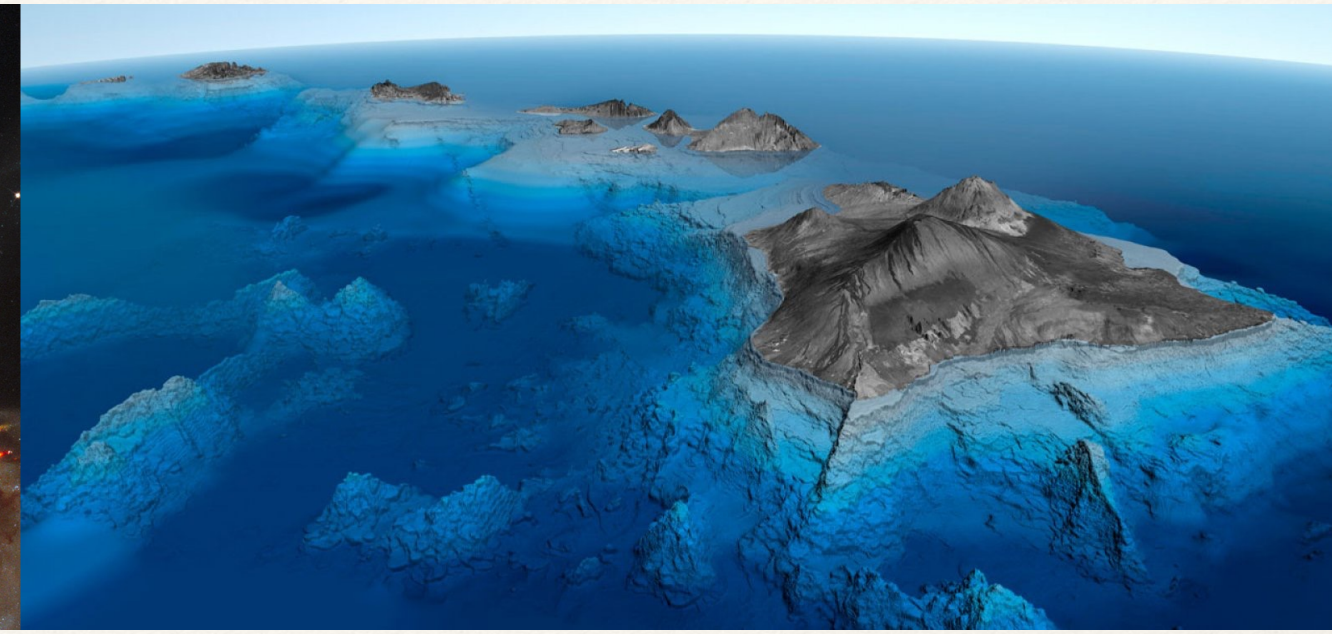


Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Outline for Today

- Building Blocks - Stars and Stellar Populations:
  - Star Formation Histories (SFH) of resolved stellar populations
    - Hess diagrams
    - Initial mass functions
    - Results for nearby galaxies

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

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

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

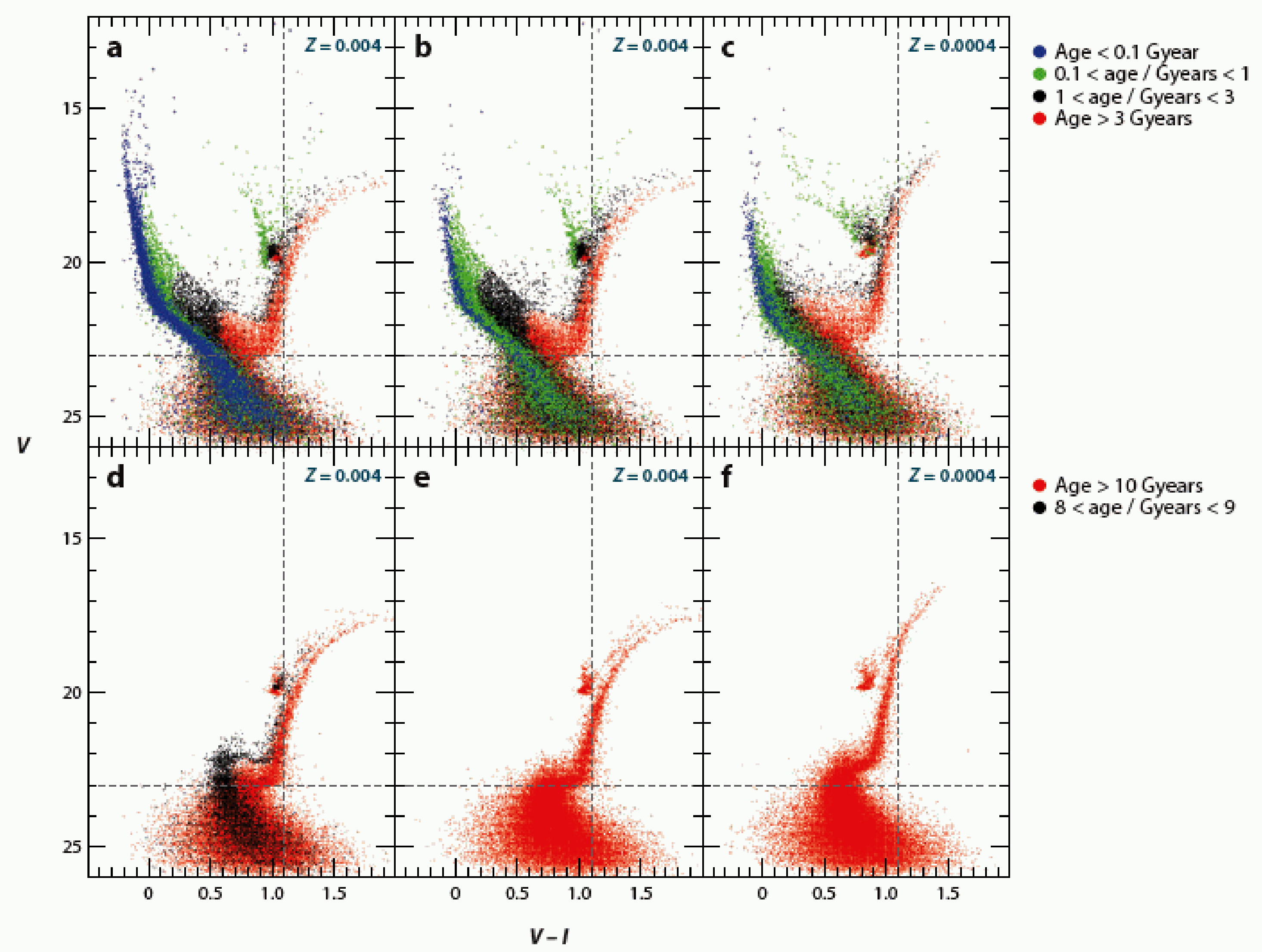
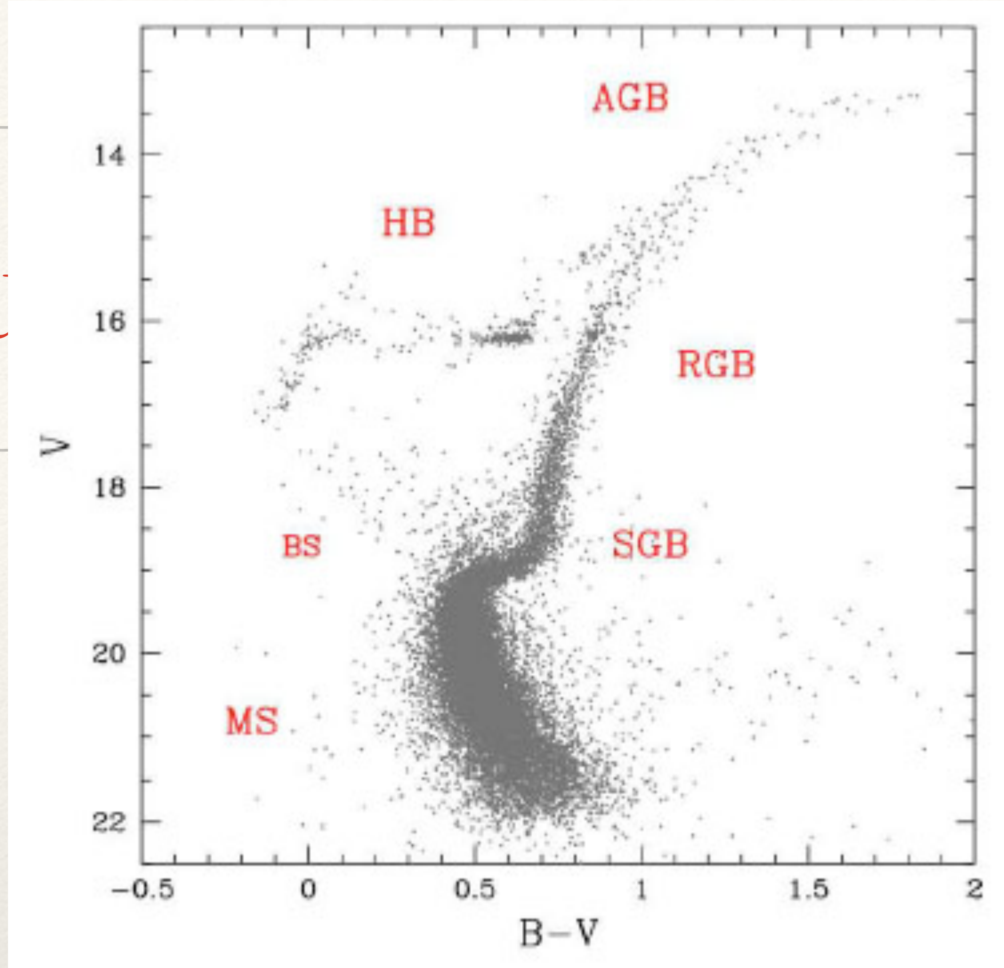


Figure 2

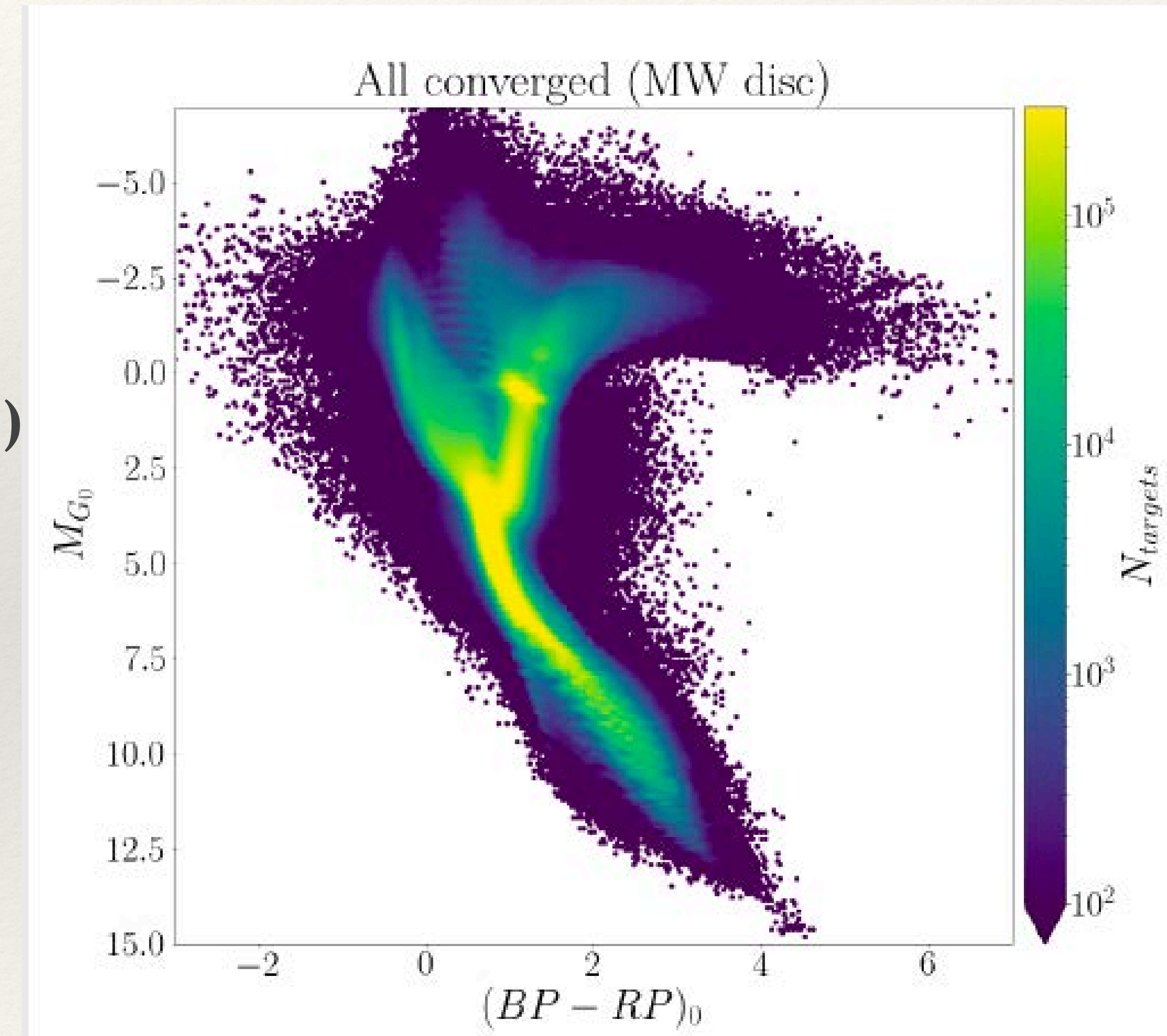
The effect on the color-magnitude diagram (CMD) of different star-formation histories (SFHs) for a hypothetical galaxy. All CMDs contain 50,000 stars, assume Salpeter's initial mass function, and are based on the Padova stellar evolution models (Fagotto et al. 1994a,b). A constant metallicity is assumed, and the value is indicated in the top-right corner of each panel. In all panels, the colors correspond to different stellar ages. The color codes for the top and bottom CMDs are shown in each row. The dotted lines are drawn to help visualize the differences between the various cases. (*b*) The star-formation rate (SFR) is constant from 13 Gyears ago to the present. (*a*) The effect of concentrating recent SFRs into the past 20 Myears. (*c*) The same SFH as in *b*, but with a ten-times lower metallicity. (*e*) An old burst of star formation with a constant SFR from 13 to 10 Gyears ago. (*d*) Two old bursts, one with a constant SFR from 13 to 10 Gyears ago and the other from 9 to 8 Gyears ago, where only 10% of the stars were born in the younger burst. (*f*) The same old SFH as in *e*, but with a ten-times lower metallicity.

Bu rs and Stellar Populations



Maraston 2003

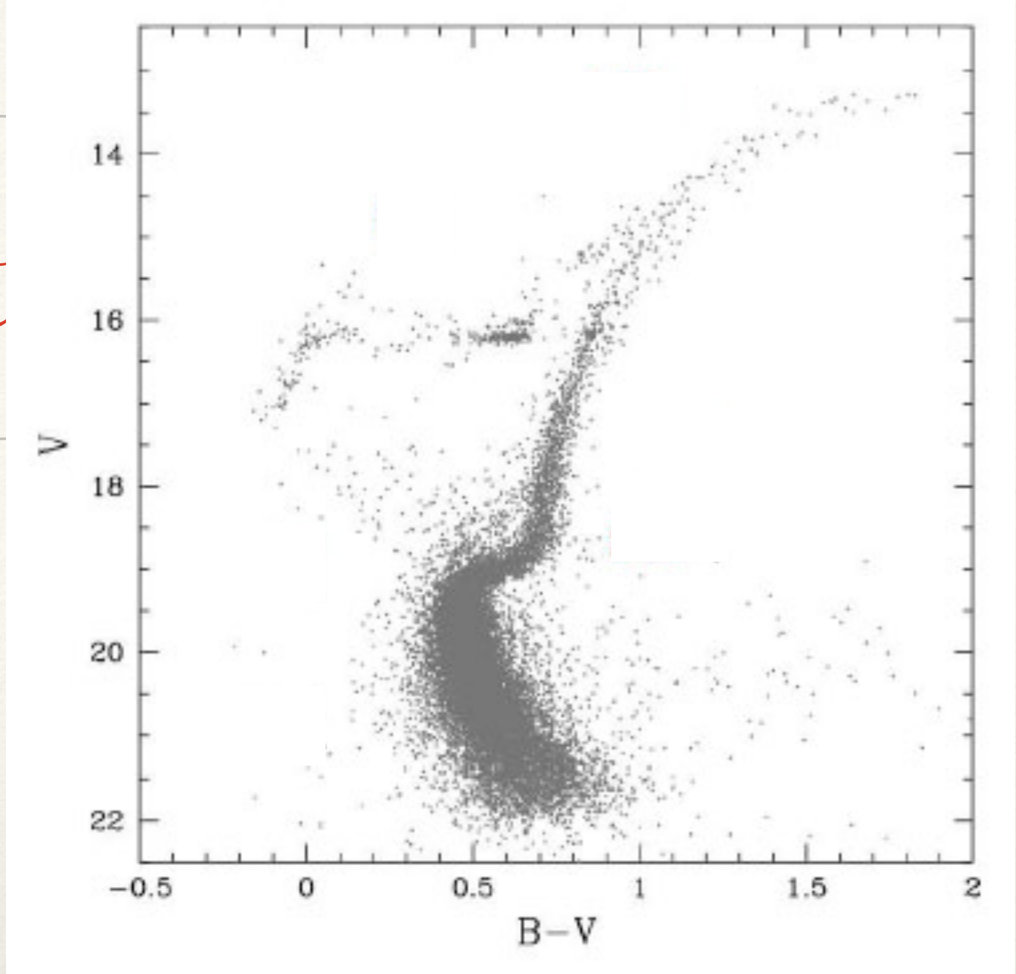
- **Color-Magnitude Diagram (CMD)** — shows individual stars at each location
- **Hess Diagram** — a CMD that shows relative number of stars at each location
  - To distentagle multiple populations, we need to consider numbers of stars!



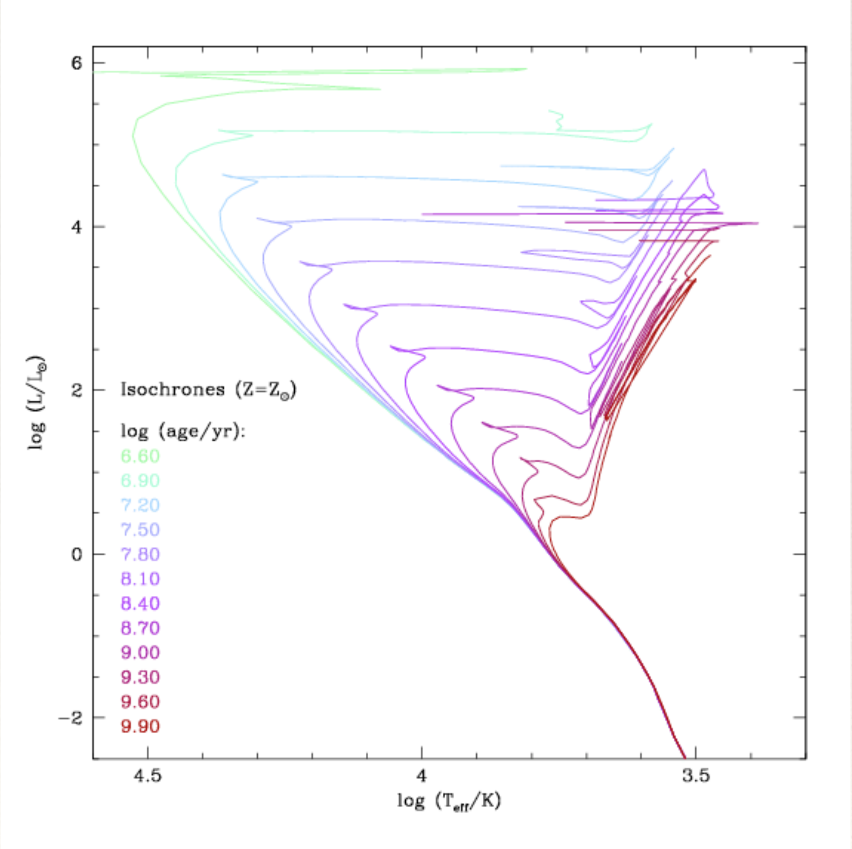
MW (Anders et al 2022)

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!



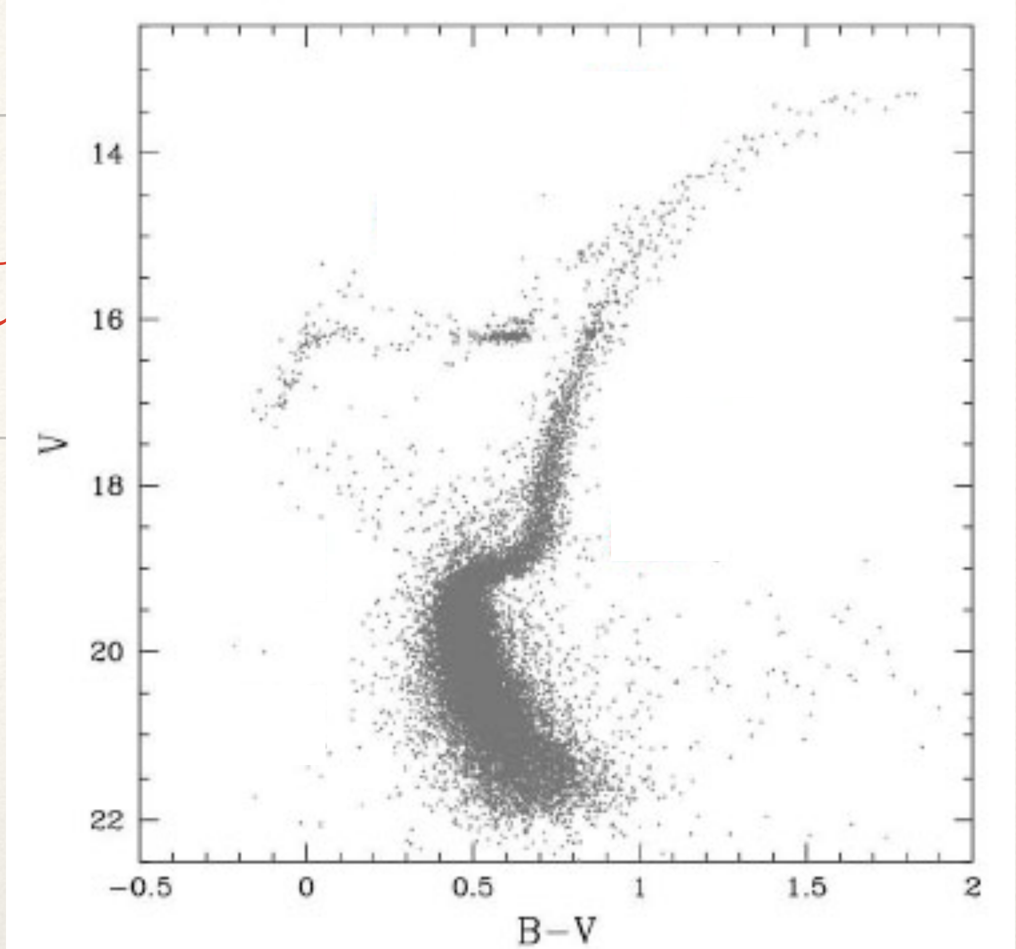
Maraston 2003



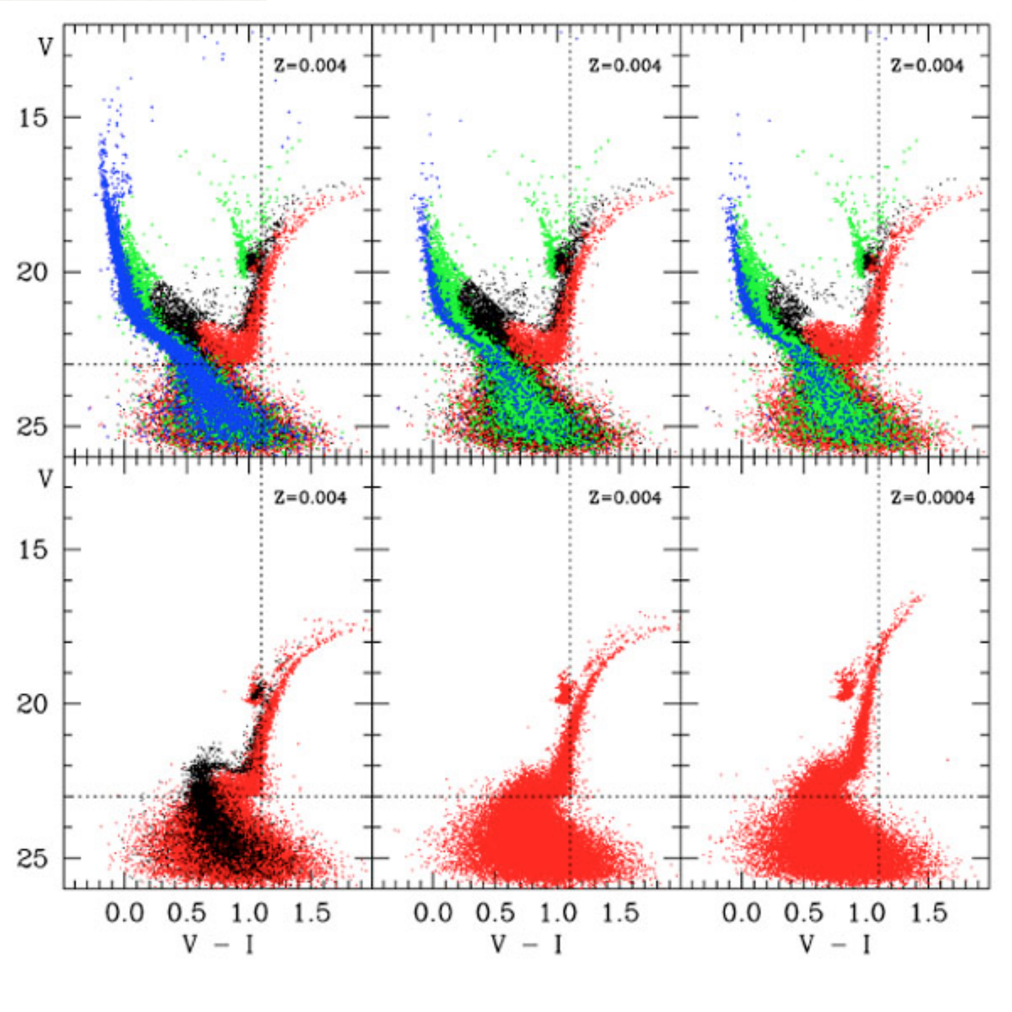
da Cunha 2008

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



Cignoni & Tosi 2010

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
- How does the mass change along an isochrone?

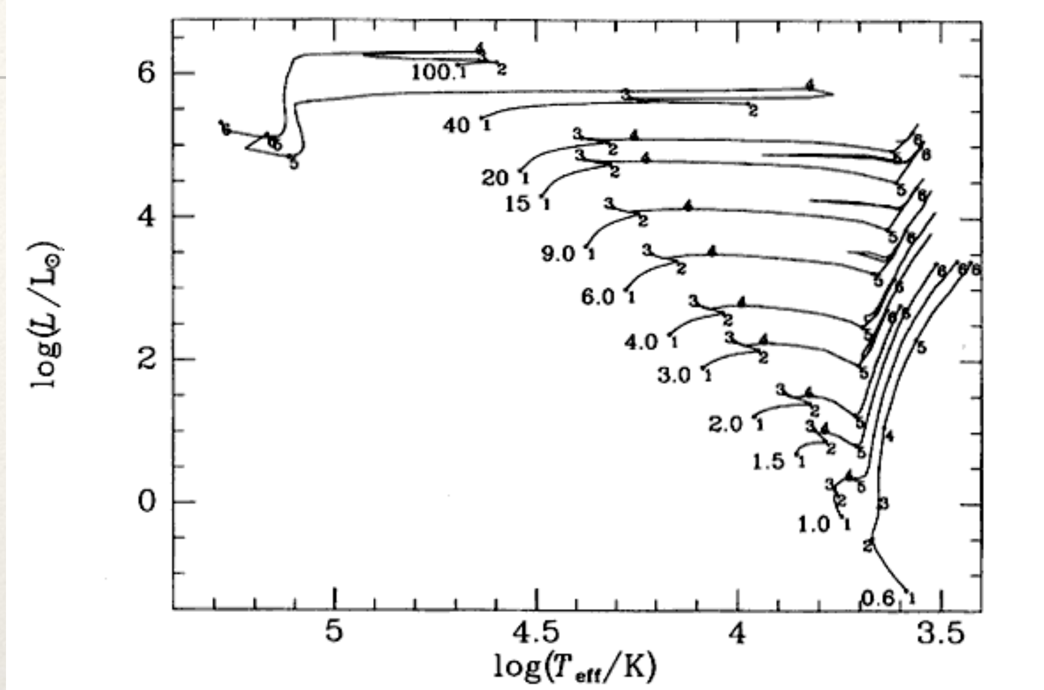
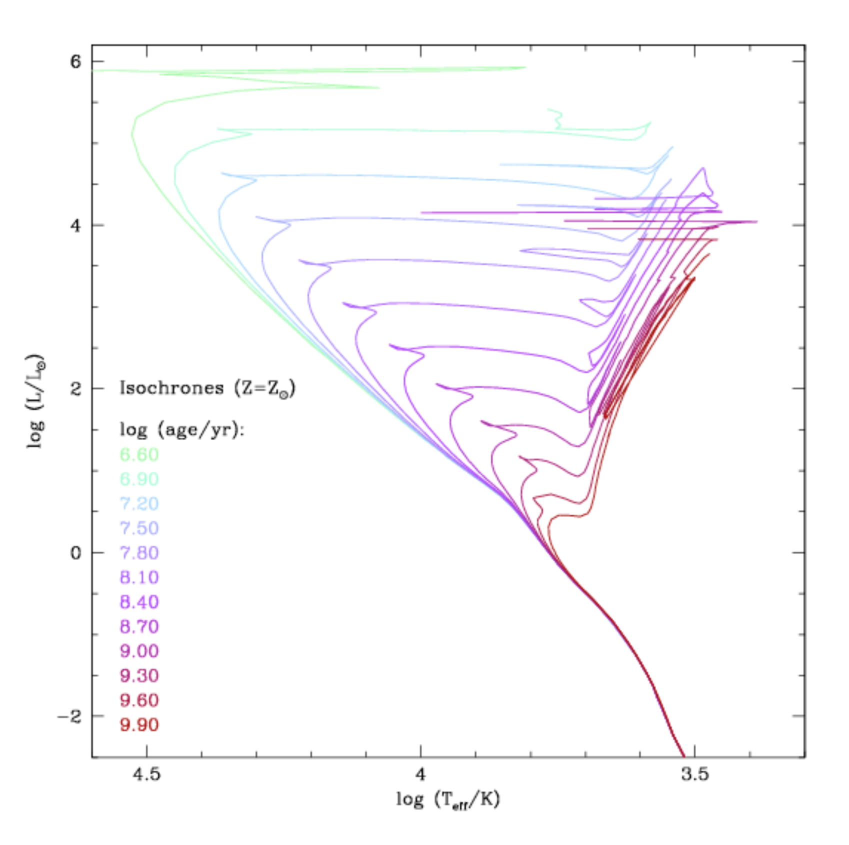


Figure 5.2 Evolutionary tracks for solar-metallicity stars $(Y, Z) = (0.28, 0.02)$ with initial masses from $0.6\,\mathcal{M}_\odot$ to $100\,\mathcal{M}_\odot$. On
Table 5.2 gives the time it takes a s
1. To avoid confusion tracks for $\mathcal{M}$
for the further tracks of these stars.
published in Bressan *et al.* (1993)]

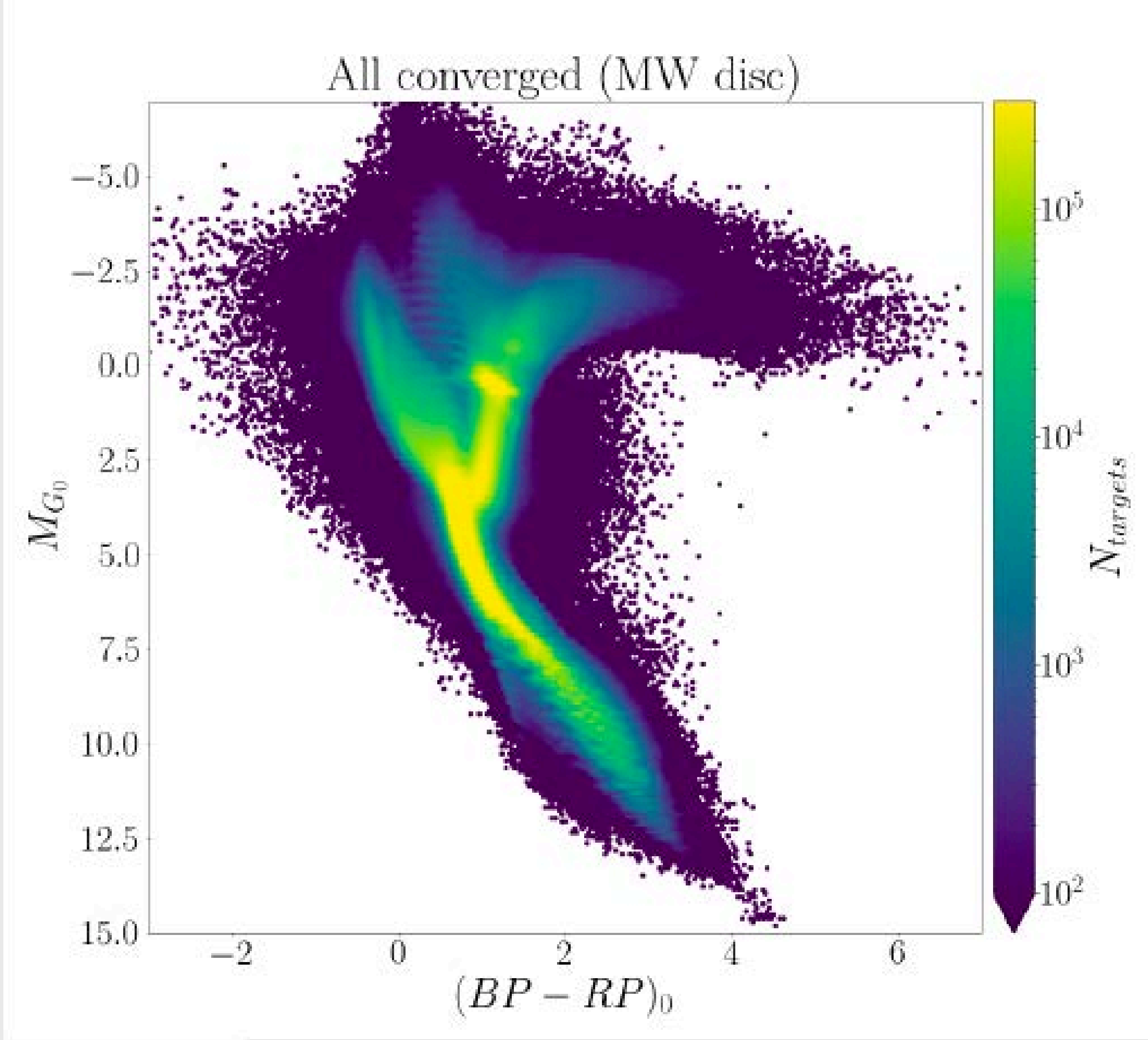
Bressan et al. 1993



da Cunha 2008

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)



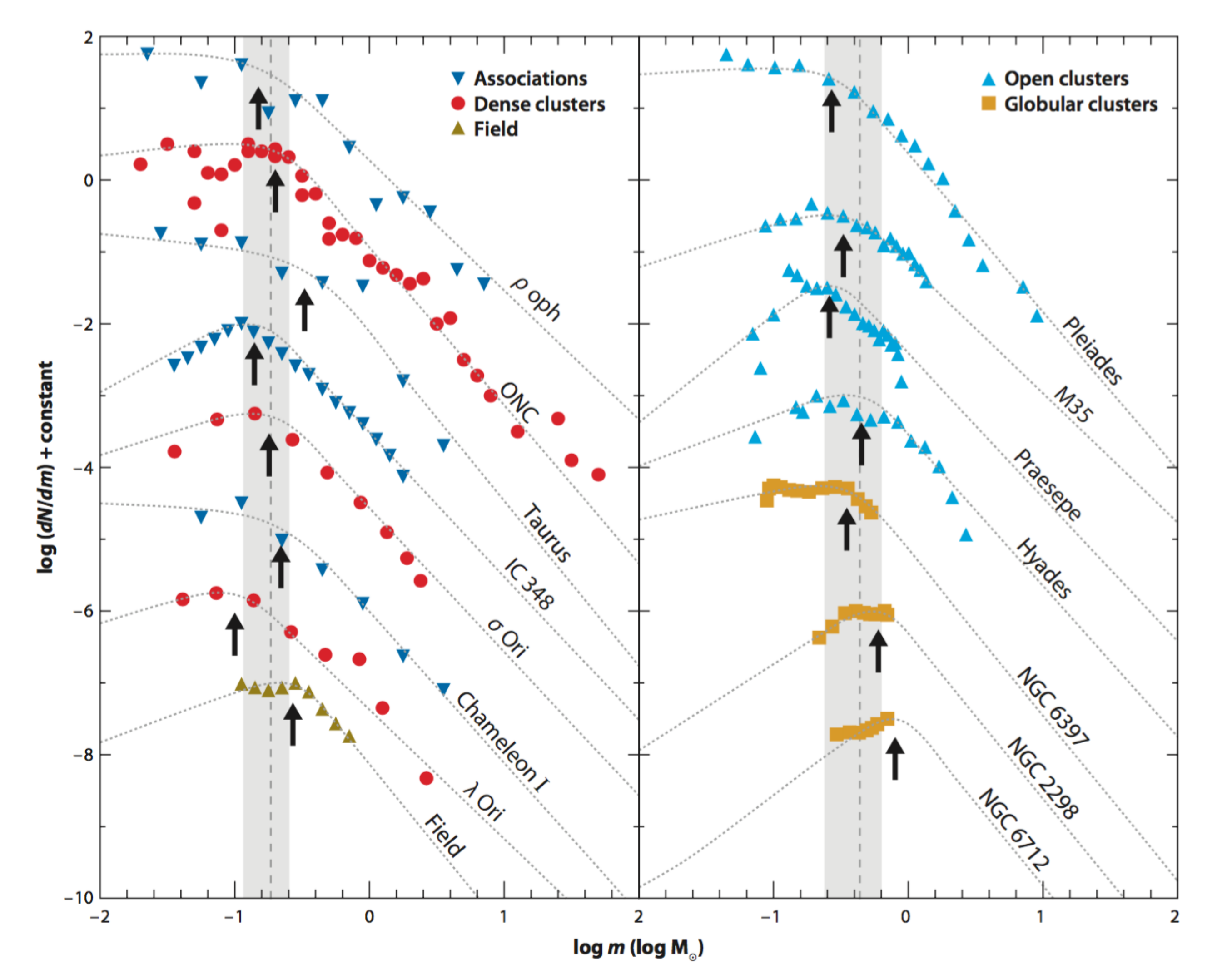
MW (Anders et al 2022)

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:

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

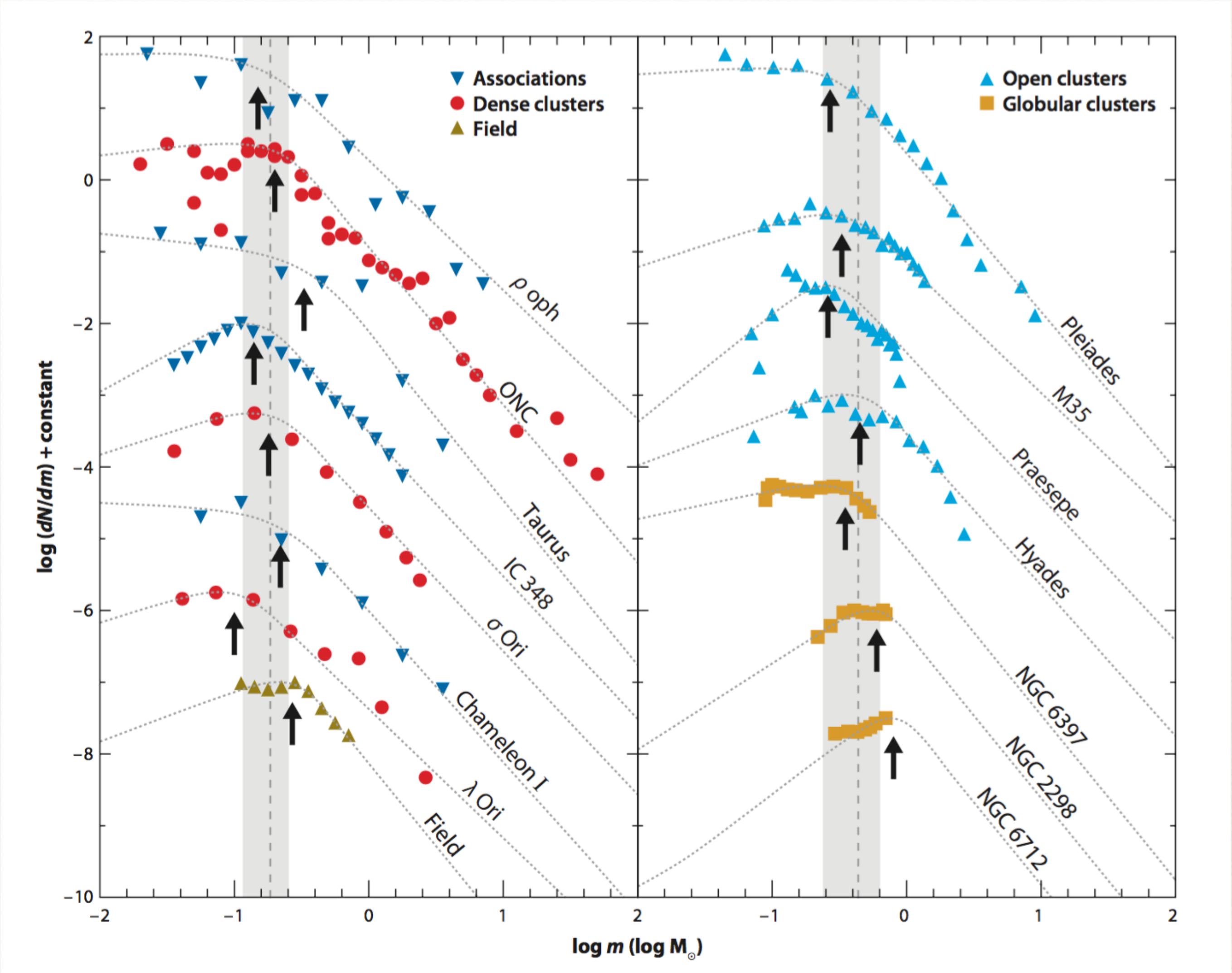
$$dN/d\log M \propto M^{\Gamma} \propto M^{\alpha+1}$$



Bastian et al. 2010

Thought Questions

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



Bastian et al. 2010

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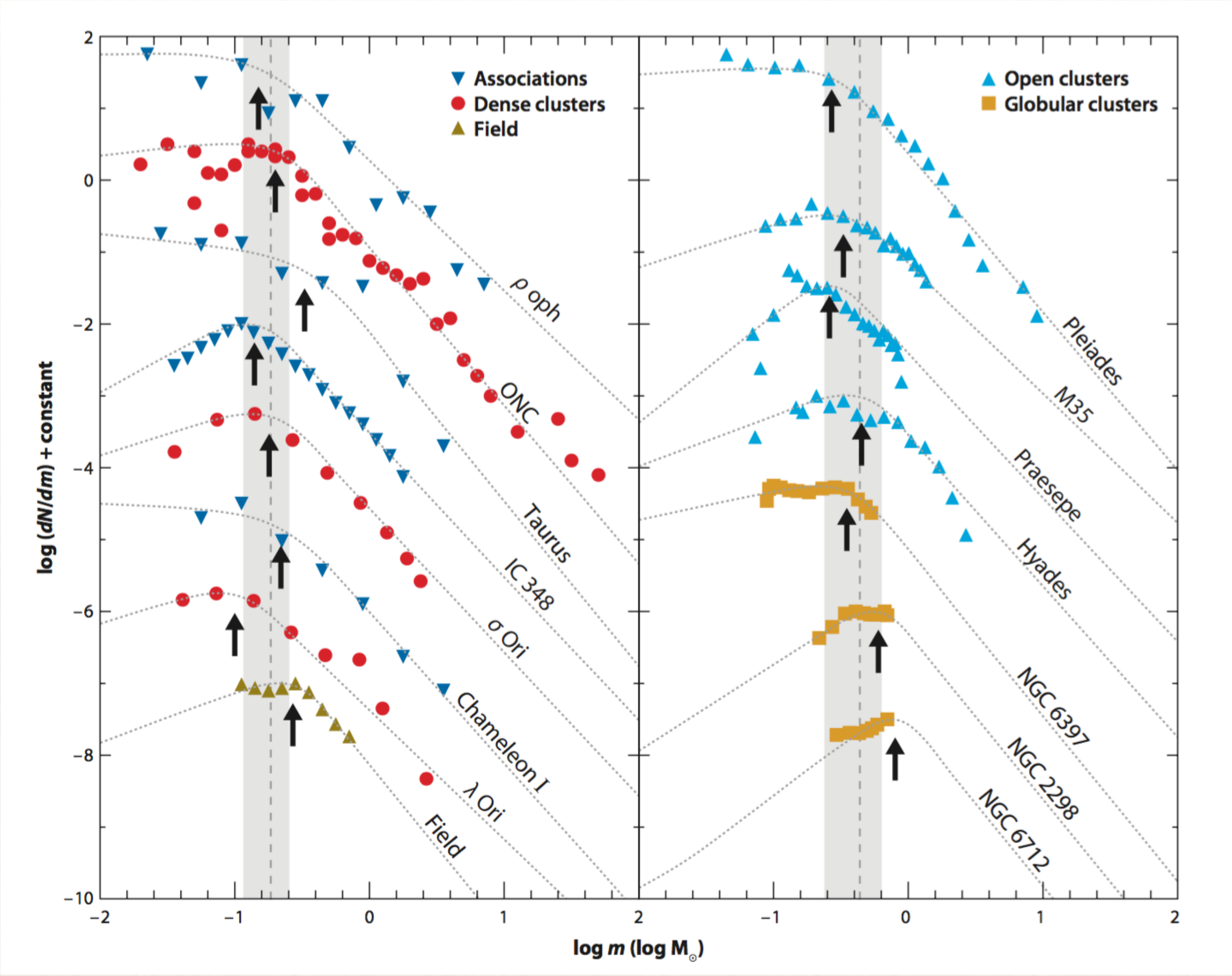
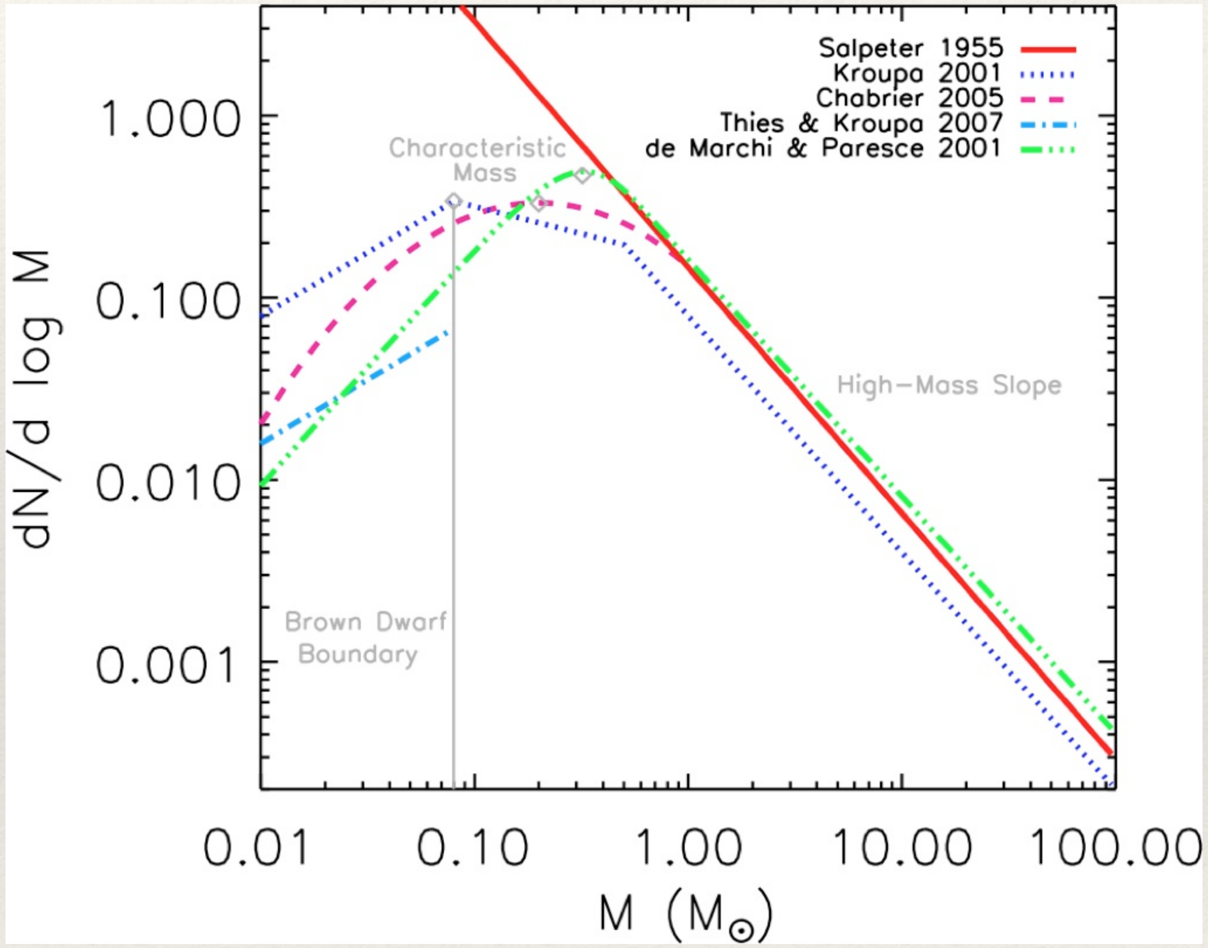


Bastian et al. 2010

Difficult to determine!

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

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

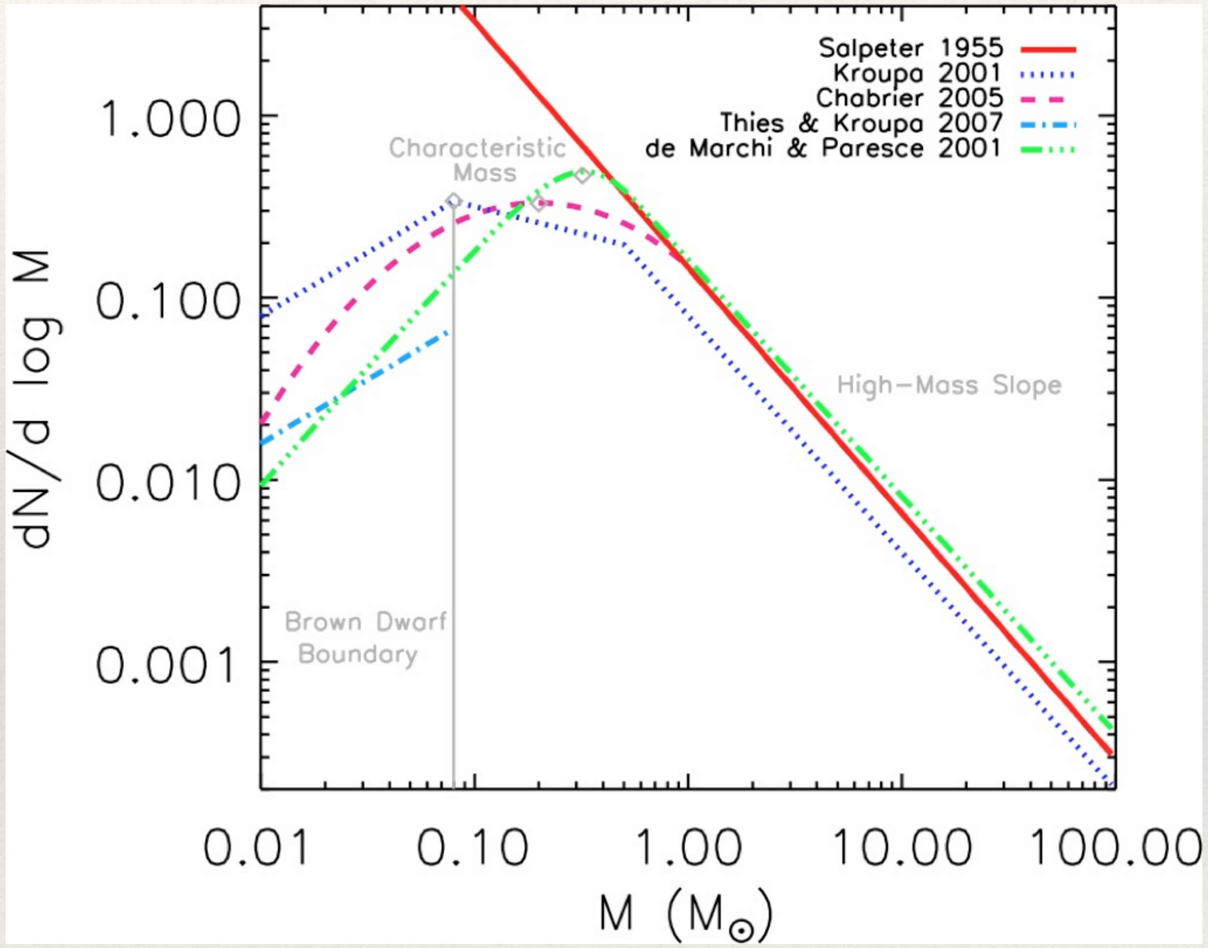
$$dN/dM \propto M^{-2.35}$$

  - 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

- Is the IMF universal/constant, e.g with time and location?
  - Generally 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 may not be 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:
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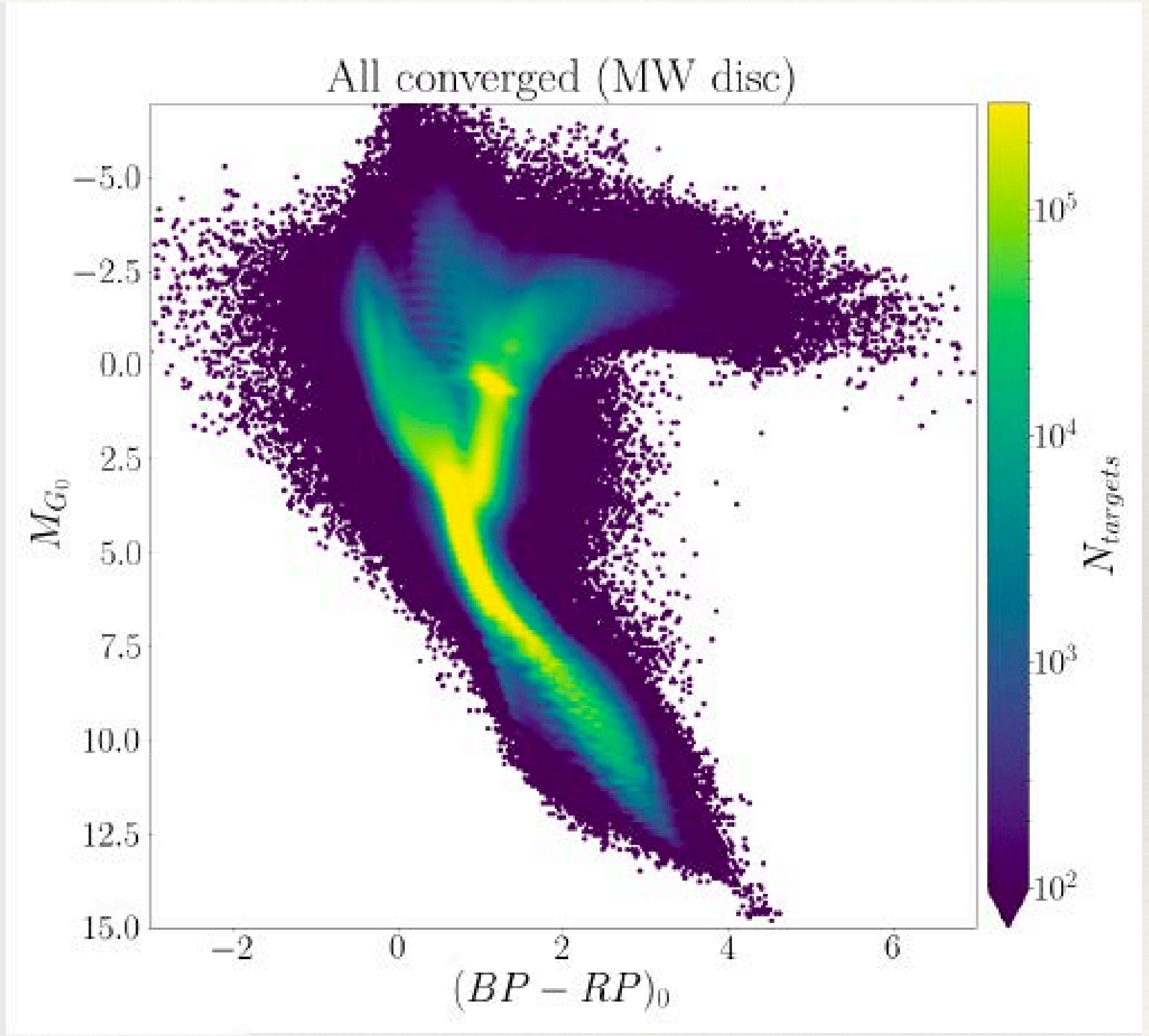
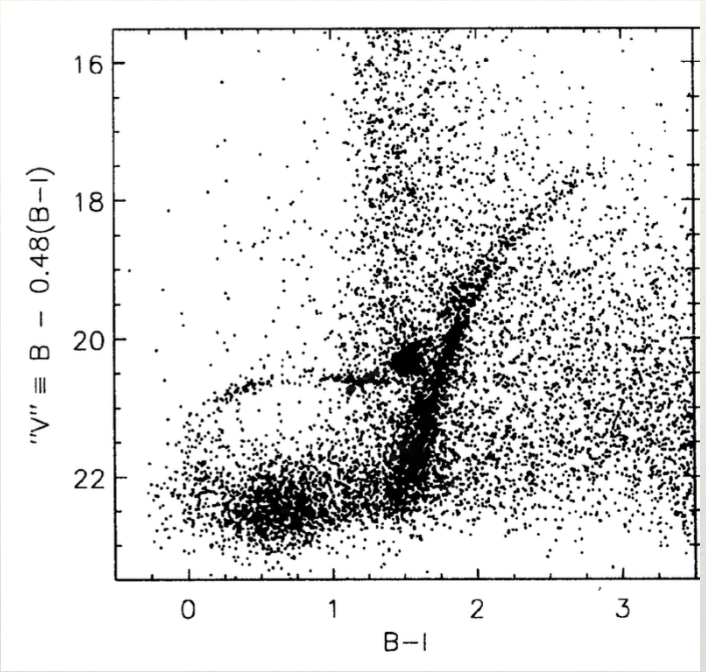


MW (Anders et al 2022)

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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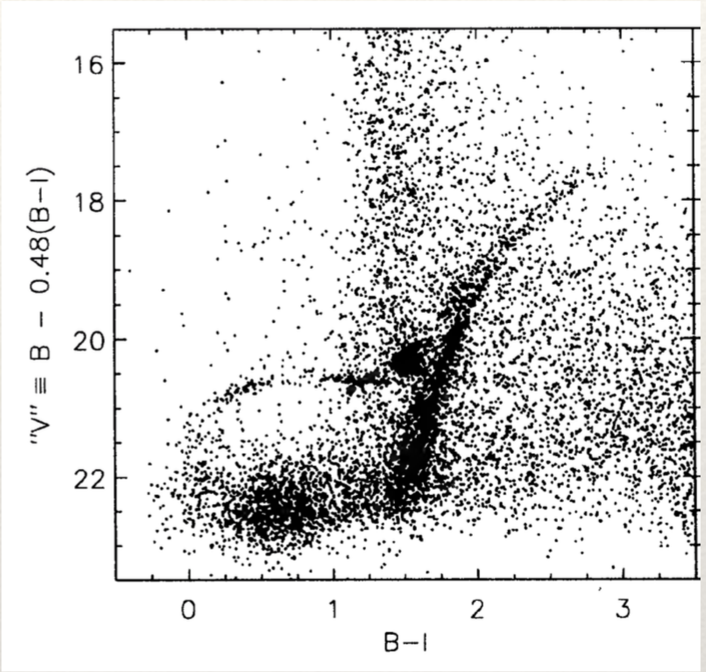

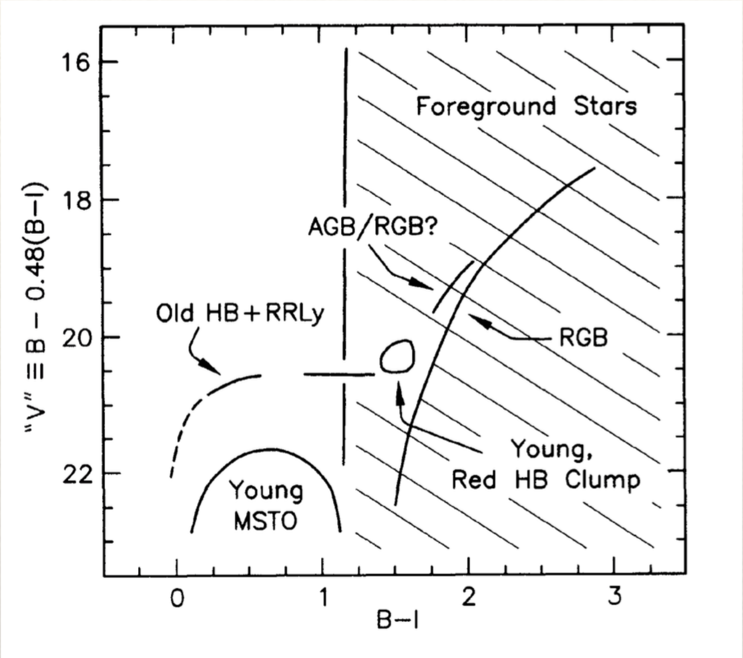

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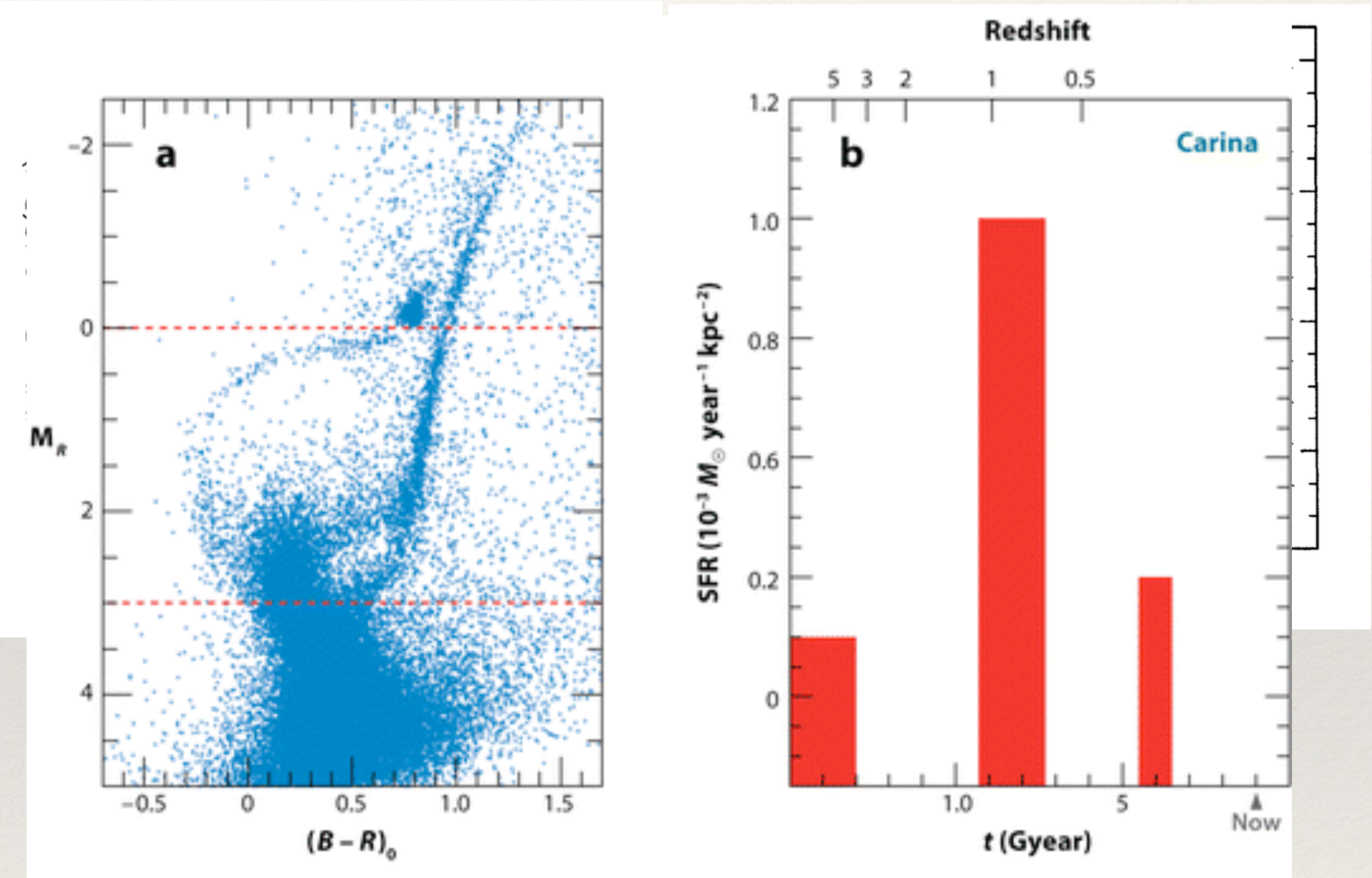
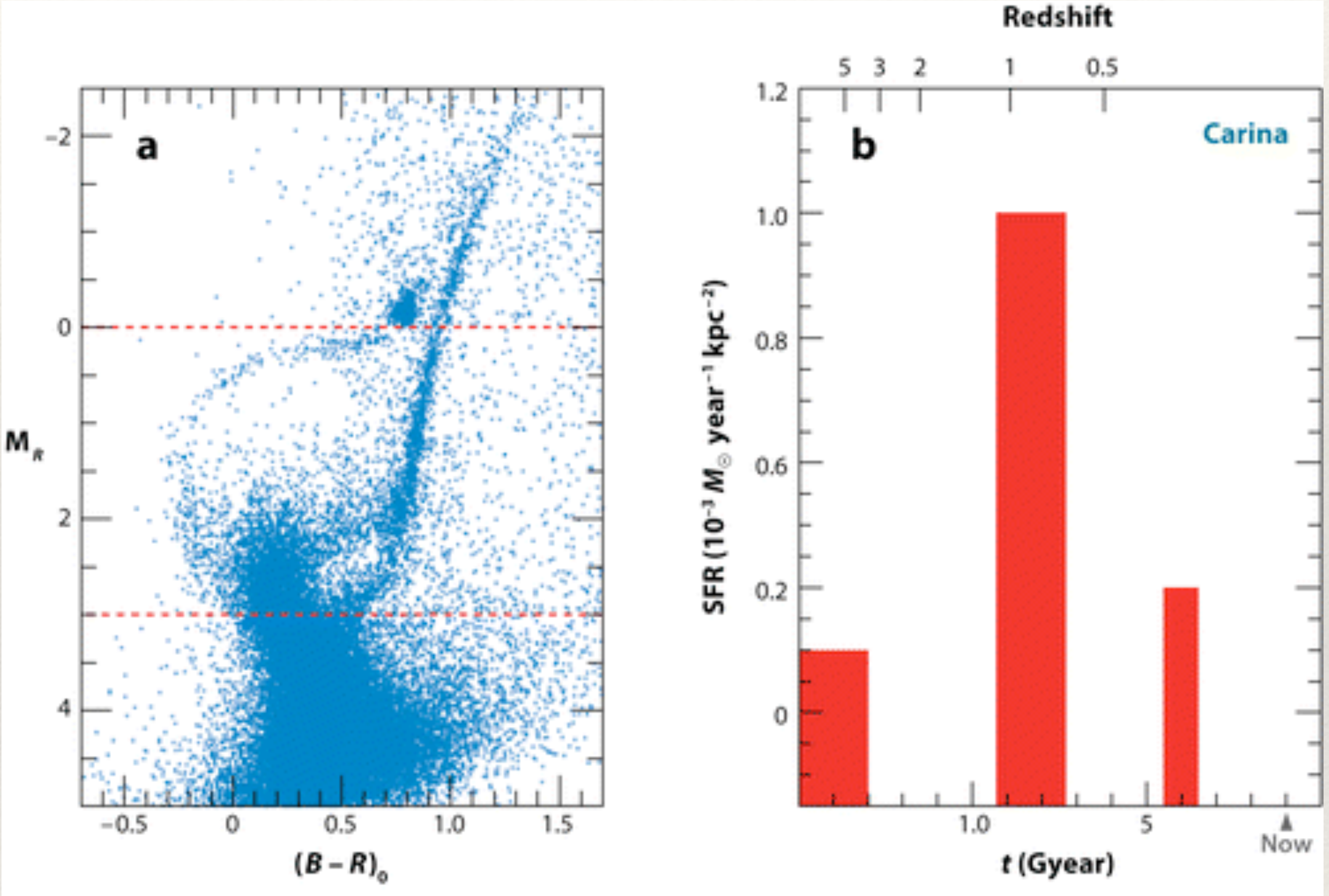


Tolstoy E, et al. 2009.
Annu. Rev. Astron. Astrophys. 47:371–425

Stars and Stellar Populations

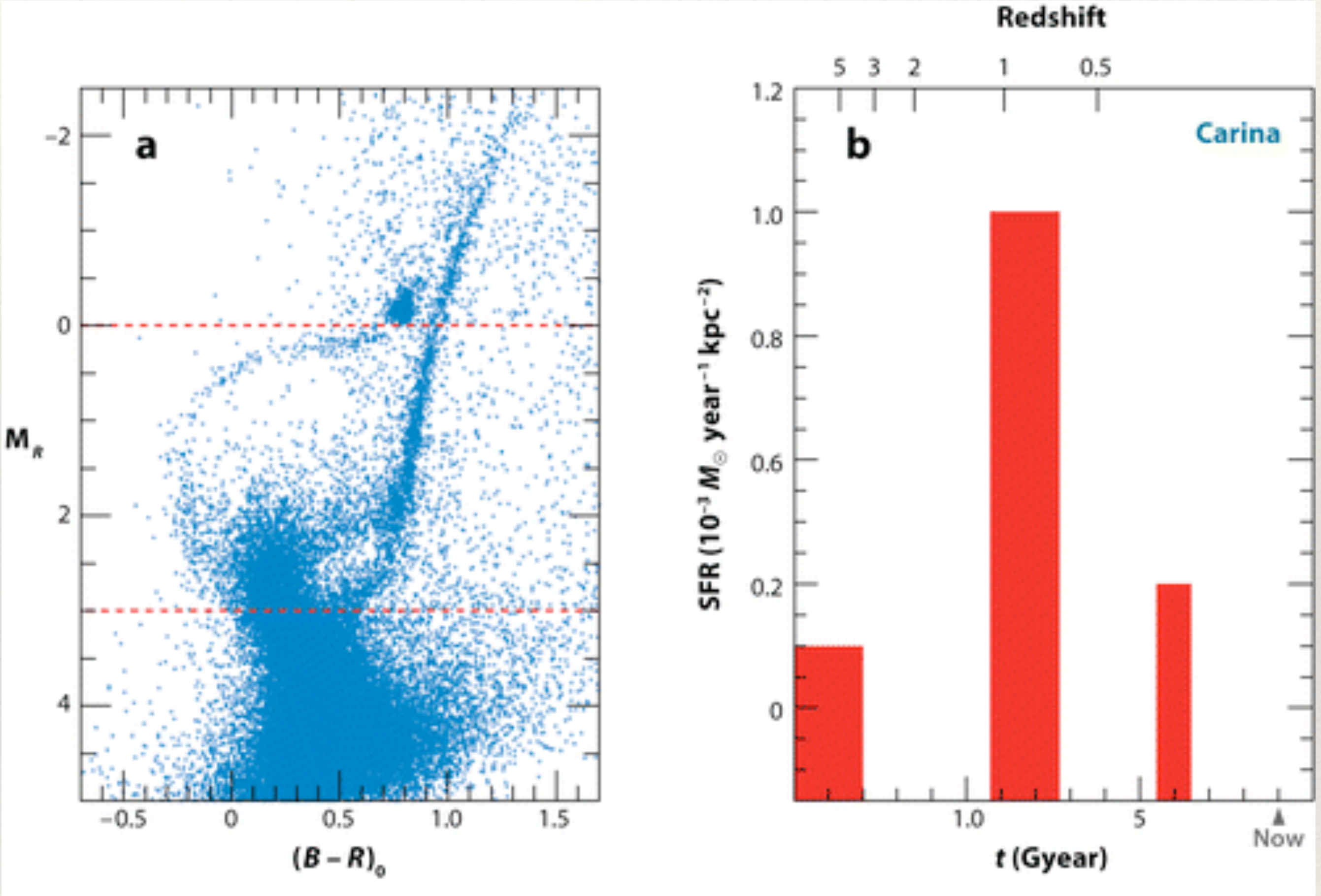
- To make a CMD, we need to resolve individual stars:
  - MW neighbors — resolved down to oldest Main Sequence Turnoff
  - M31 and neighbors — requires large investment of telescope time
  - Outside of Local Group — getting to the Main Sequence Turnoff is very difficult



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

Stars and Stellar Populations

- Results for Local Group dwarf galaxies:
  - Carina dSph —shows striking evidence of episodic star formation, **but it is exceptional!**
  - Others show a range of star formation histories, but significantly less burst



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.

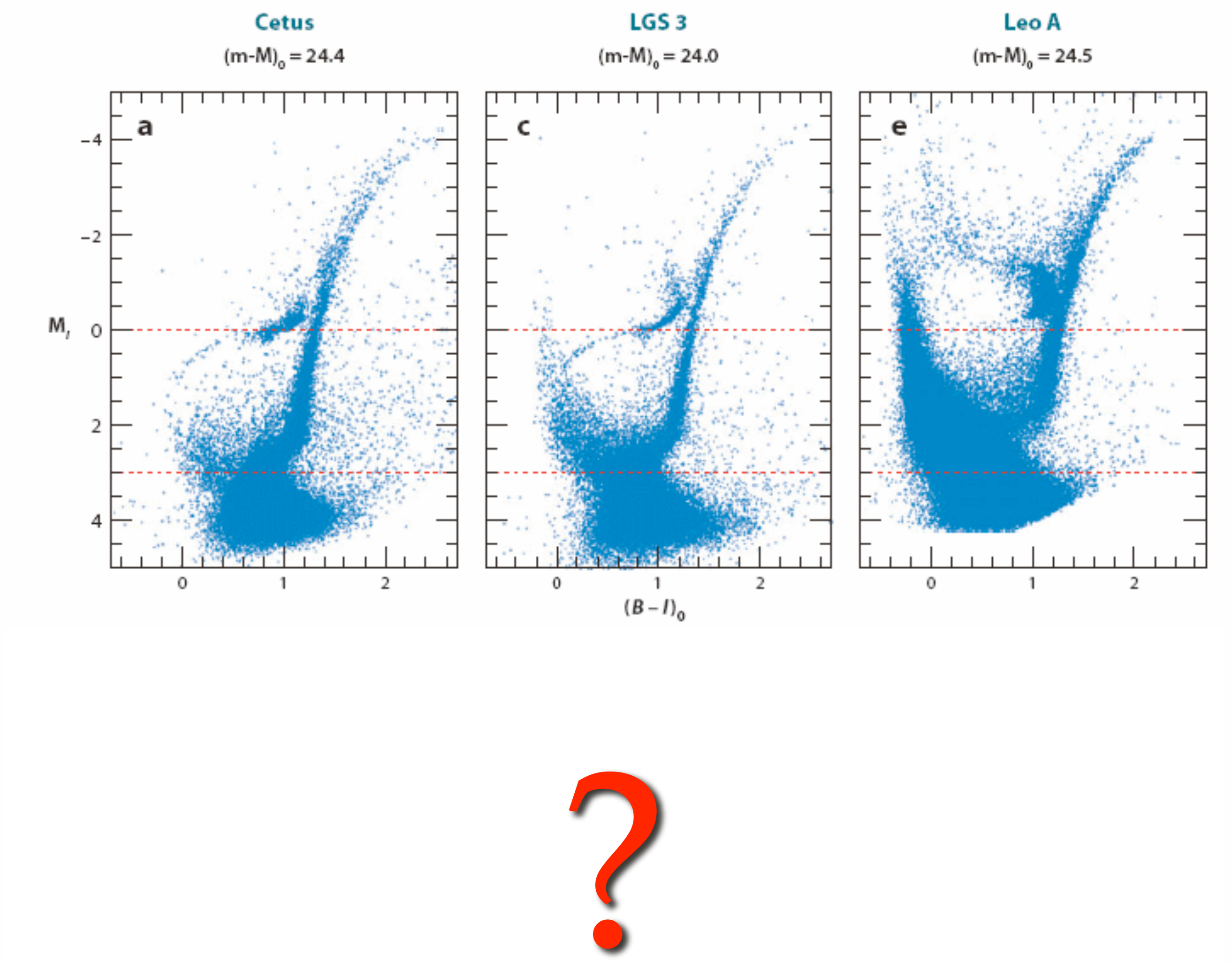


Figure 5

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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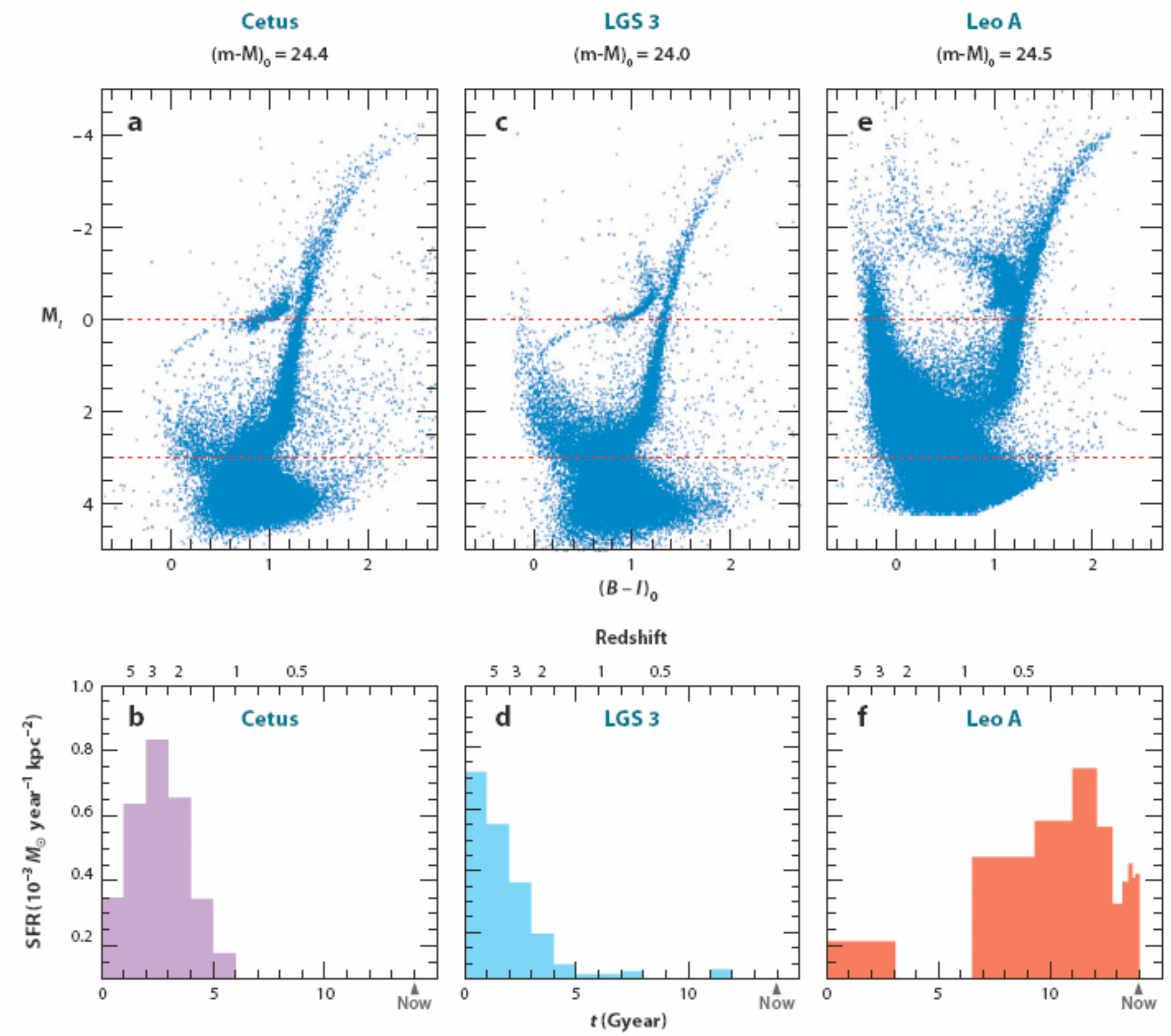

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Stars and Stellar Popu

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

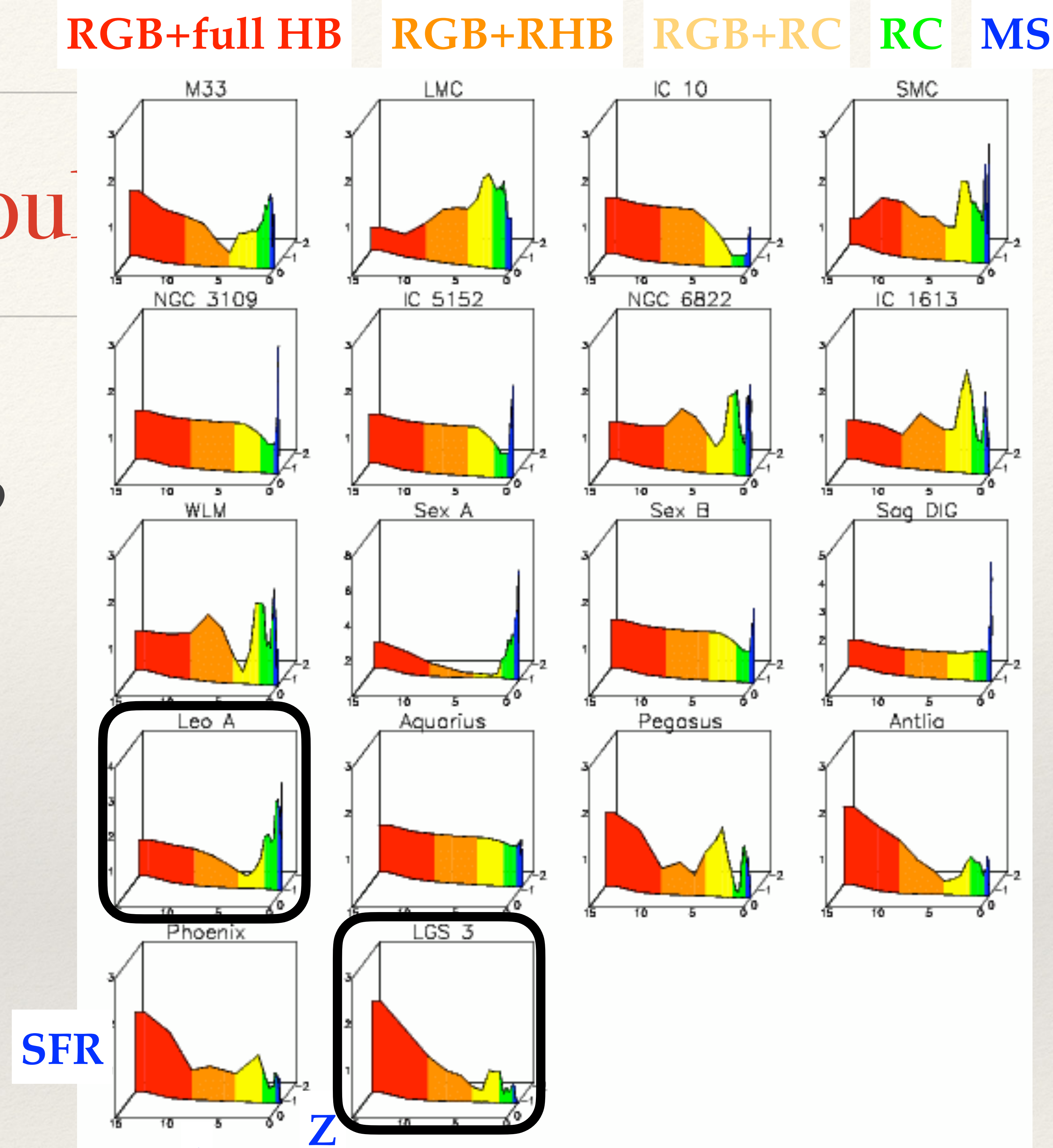
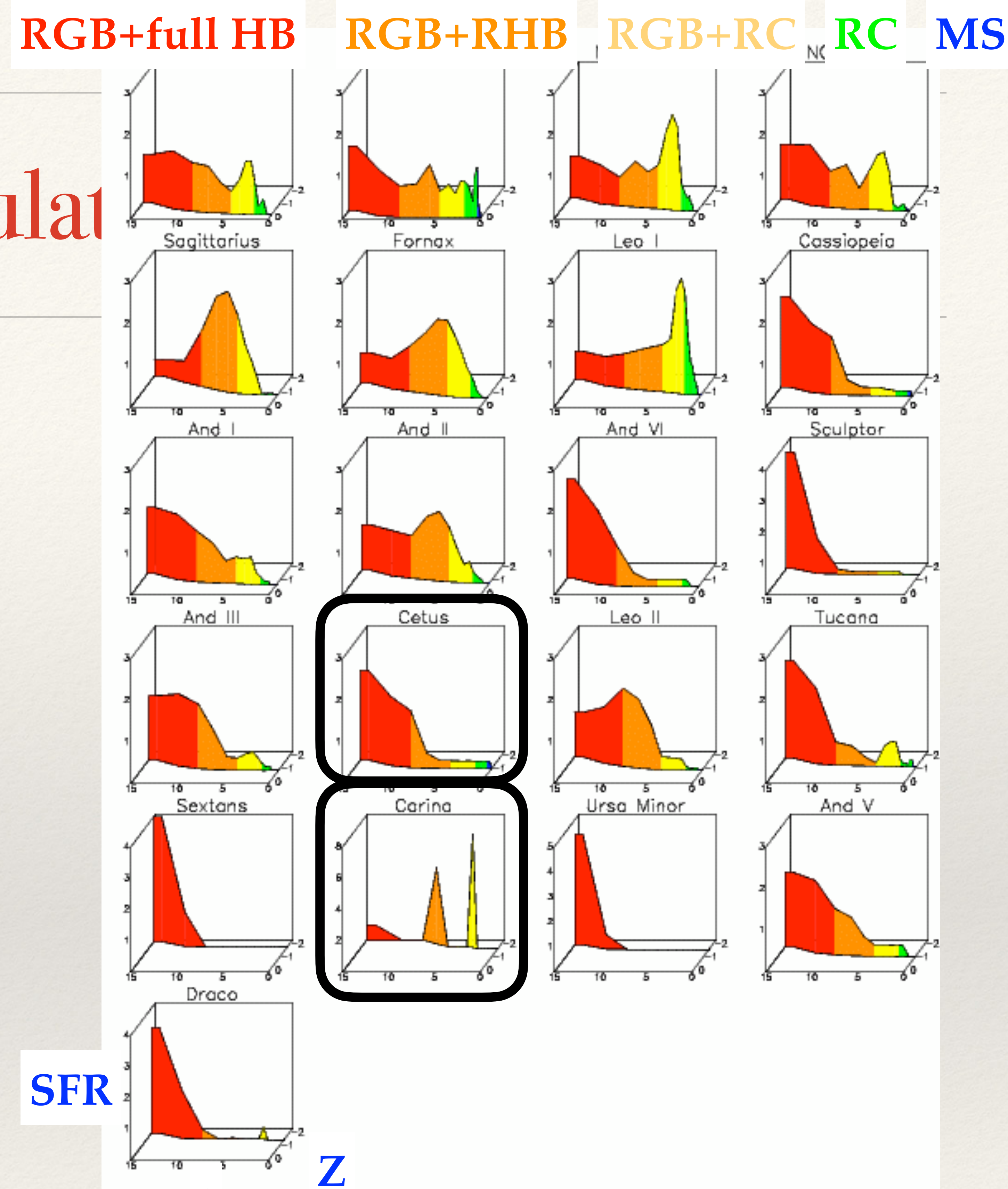


Figure 44. Star formation histories of irregular and transition-type galaxies. Colors correspond to the CMD features generated by each age. Red: RGB plus full HB. Orange: RGB plus red HB. Yellow: RGB plus red clump. Green: bright red clump. Blue: young MS and blue helium-burning stars. Ages are given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

Dolphin et al. 2005

Stars and Stellar Populat

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

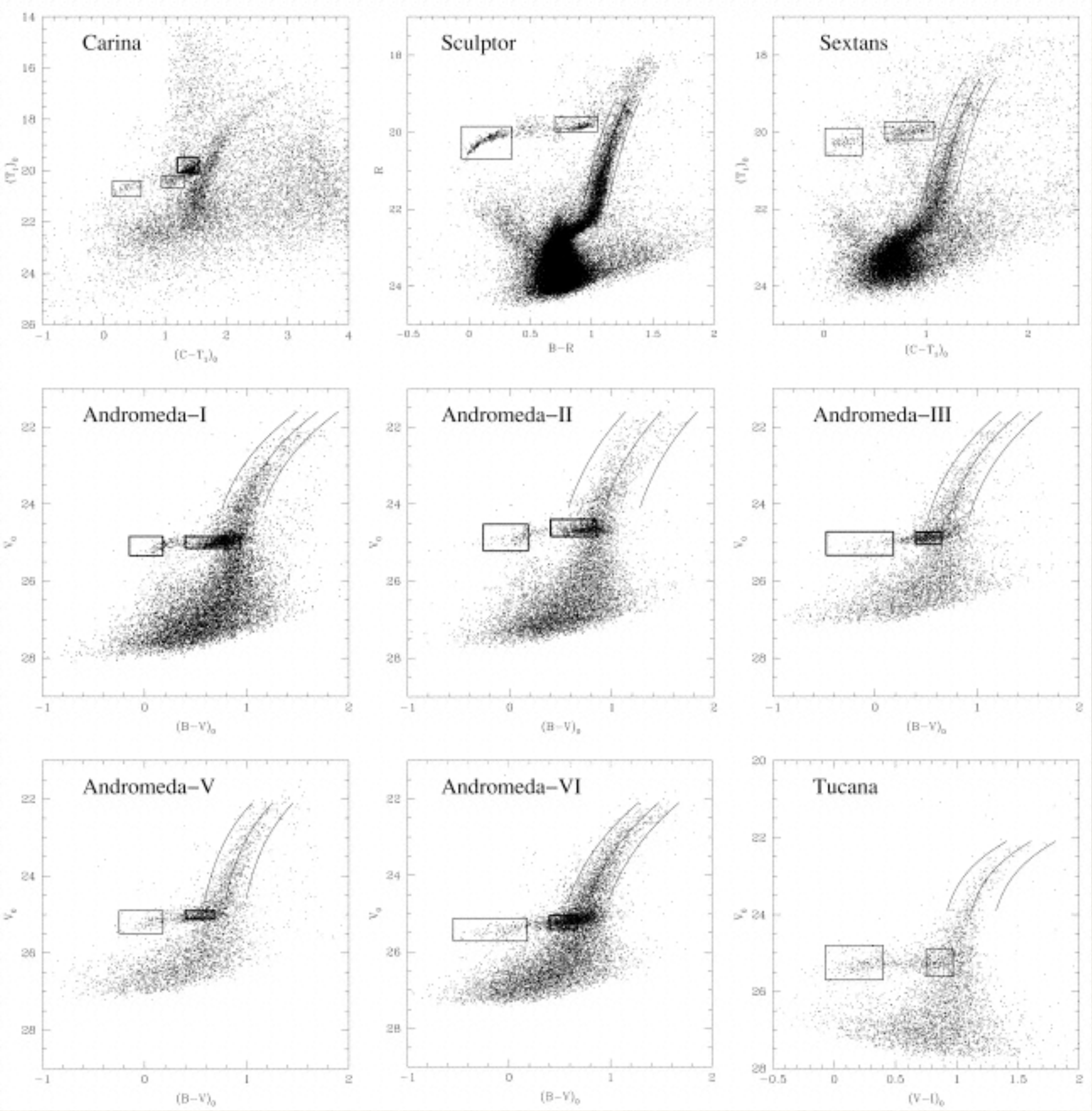


Fig… 43. Star formation histories of elliptical and spheroidal galaxies. Colo… correspond to the CMD features generated by each age. Red: RGB plus full HB. Orange: RGB plus red HB. Yellow: RGB plus red clump. Green: bright red clump. Blue: young MS and blue helium-burning stars. Ages are given in Gyr,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

Dolphin et al. 2005

Stars and Stellar Populations

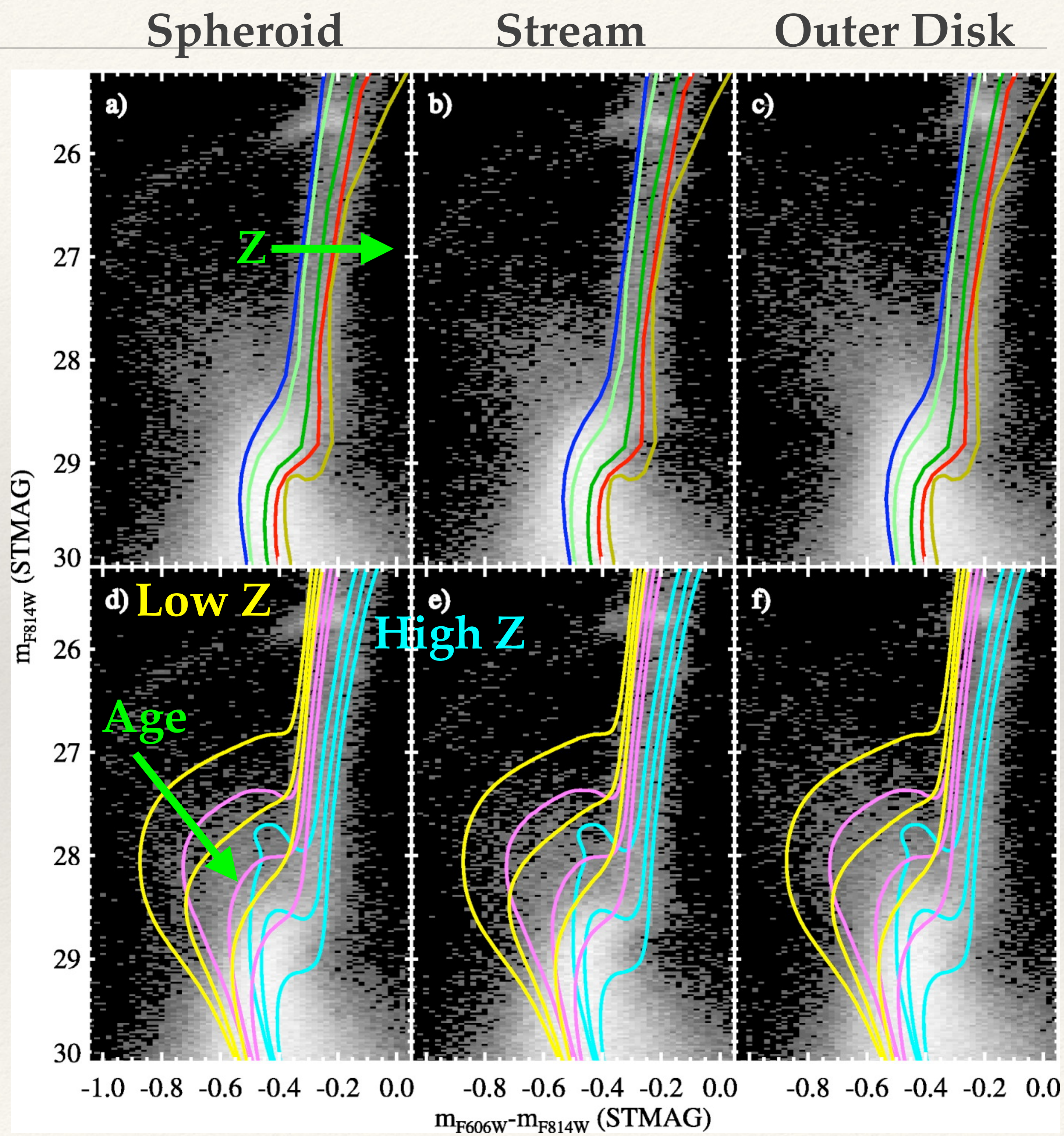
- Other results for Local Group dwarf galaxies:
  - Gradients from RGB/HB morphology
    - Higher metallicity, younger age population in centers of galaxies



Harbeck et al. 2001

Stars and Stellar Populations

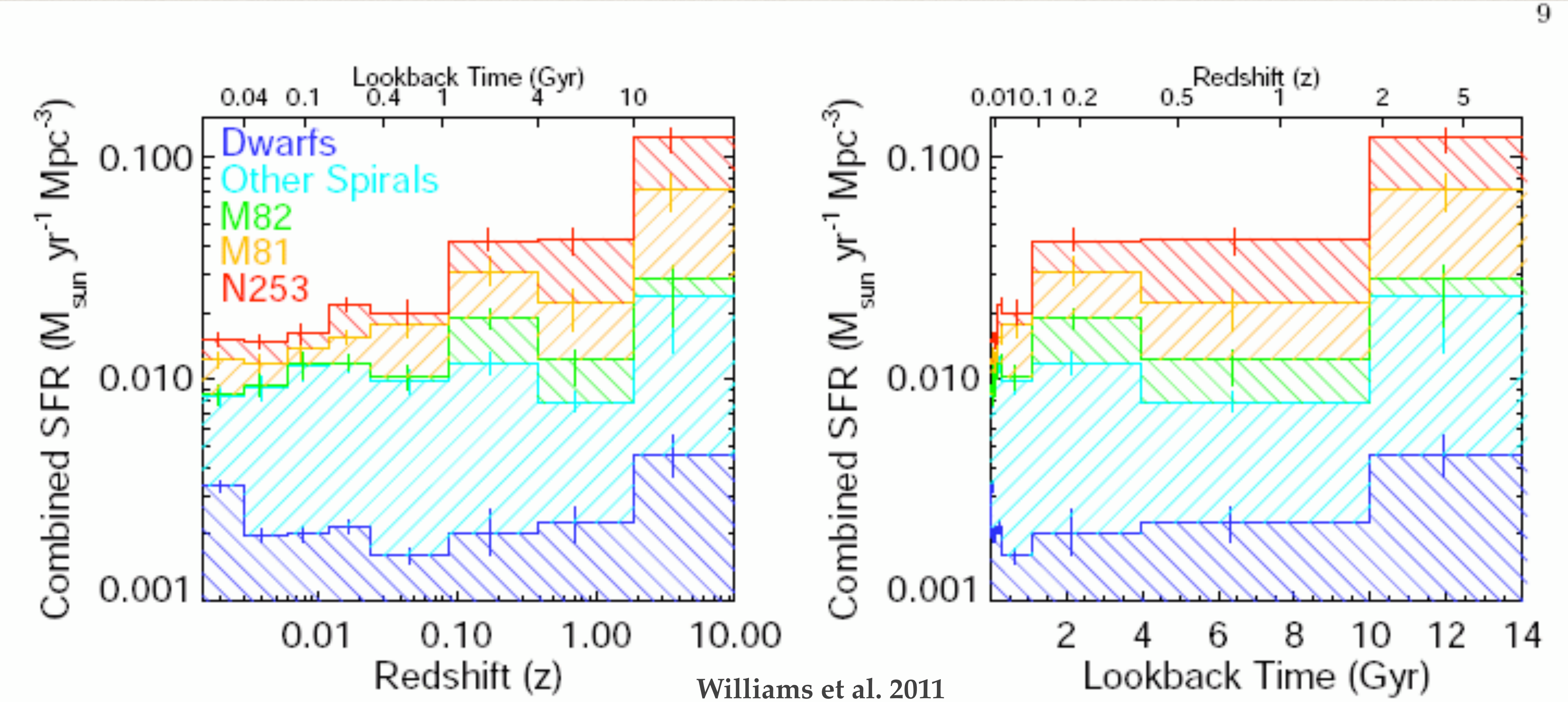
- Results for M31 halo:
  - 100+ orbits HST time!
  - Extended star formation history
  - An intermediate-old population
  - Different from Milky Way!



Brown et al. 2006

Stars and Stellar Populations

- Results on SFH of more distant galaxies based on advanced stages (HB/RC):
  - e.g., local volume star formation history



Williams et al. 2011

Stars and Stellar Populations

- General conclusions from Local Group SFH:
  - galaxies are not SSPs!
  - significant population of old stars in nearby galaxies— all galaxies have old stars
  - LG Irrs similar SFH to dSph at older ages, but dSph appear to have had their SF cut off, so differ largely by lacking in younger population
  - while SF is ongoing, it is ~smoothly varying (down to available time resolution) ; strong bursts (like Carina) the exception
  - galaxies have gradients in their stellar populations