Star Formation Histories of Local Galaxies

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Acknowledgements

Some of the research presented herein is my own done with…

postdoctoral researcher Brian Marsteller (UCI),
my former graduate students Tammy Bosler, and my colleagues
Andrew Cole (U. Tasmania),
Jay Gallagher (U. Wisconsin-Madison),
James Bullock (UCI), Peter Stetson & James Hesser (HIA/DAO)

And much of the research has been done by other groups, too.

If you are interested in this topic, a good way to learn more is to read this recent review paper: **Star-Formation Histories, Abundances, and Kinematics of Dwarf Galaxies in the Local Group,** Tolstoy, Hill & Tosi (2009, ARAA)

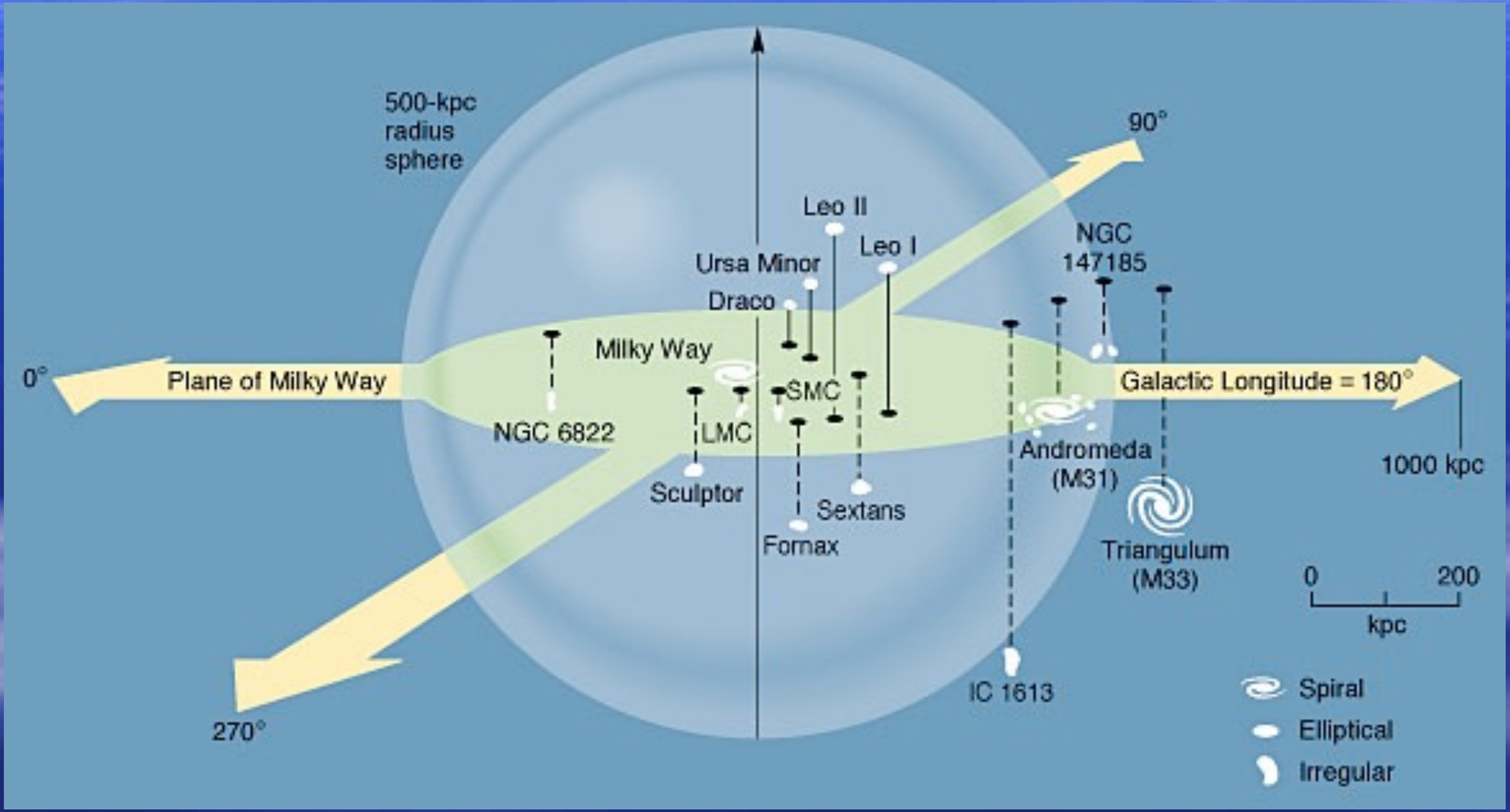
…All These Facilities Are Needed

Happy 50th Year!

Outline

1. Local Group Galaxies
2. Using Color-Magnitude Diagrams to Derive Star Formation Histories of Galaxies
   a) Stellar Evolution/CMDs
   b) Techniques for Deriving SFHs
   c) Examples: Carina & Leo I dSph, SMC/LMC, M31
4. Chemical Abundances
5. Implications for Galaxy Formation
   a) Despite having very small velocity dispersions (~15 to 20 km/s), most dSphs have formed stars over many Gyr. Some only ran out of gas in the past 1 Gyr.
   b) Despite actively forming stars over most of the Hubble time, the stars in dwarfs have nearly a constant metallicity. The galaxies enrich quickly to an [Fe/H] that correlates well with the galaxy's total luminosity. This implies dwarfs (dSphs & dIrrs) must accrete fresh gas over time and have metal-enriched winds.

The Inner Regions of the Local Group*



* Sphere around M Way with r <1 Mpc

Local Group as a Laboratory

Contains galaxies covering a very wide range mass, luminosity and gas:star ratios

– Milky Way/M31	$L_V \approx 2 \text{ x } 10^{10} L_{V\odot}$
– LMC	$L_V \approx 2 \text{ x } 10^{9} L_{V\odot}$
– Fornax dSph	$L_V \approx 2 \text{ x } 10^{7} L_{V\odot}$
– Carina dSph	$L_V \approx 3 \text{ x } 10^{5} L_{V\odot}$
– Ultra Faint dSphs	$L_V \approx 3 \text{ x } 10^{3} L_{V\odot}$

M31
M32
NGC 205

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Leo I
dSph

Hierarchical Formation of Galaxies

ΛCDM N-body simulation (dark matter only)
of the evolution of a Milky Way type galaxy

from

Bullock & Johnston (2005)

Hierarchical Formation of Galaxies

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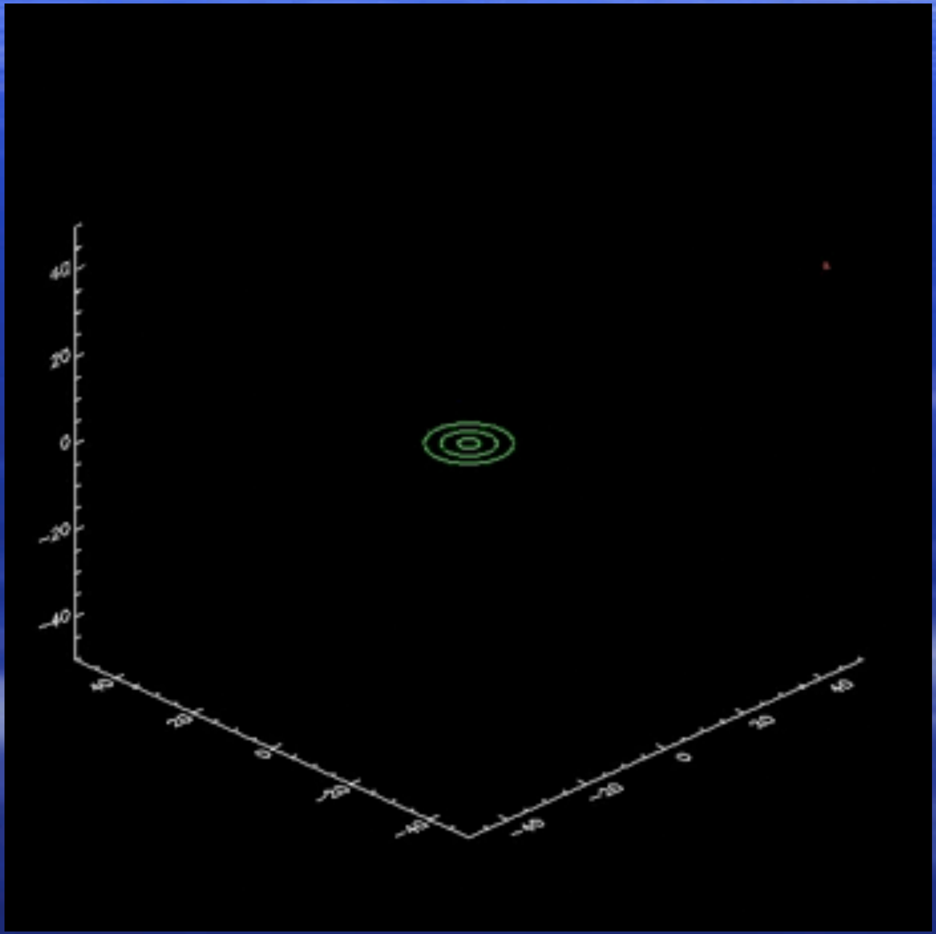


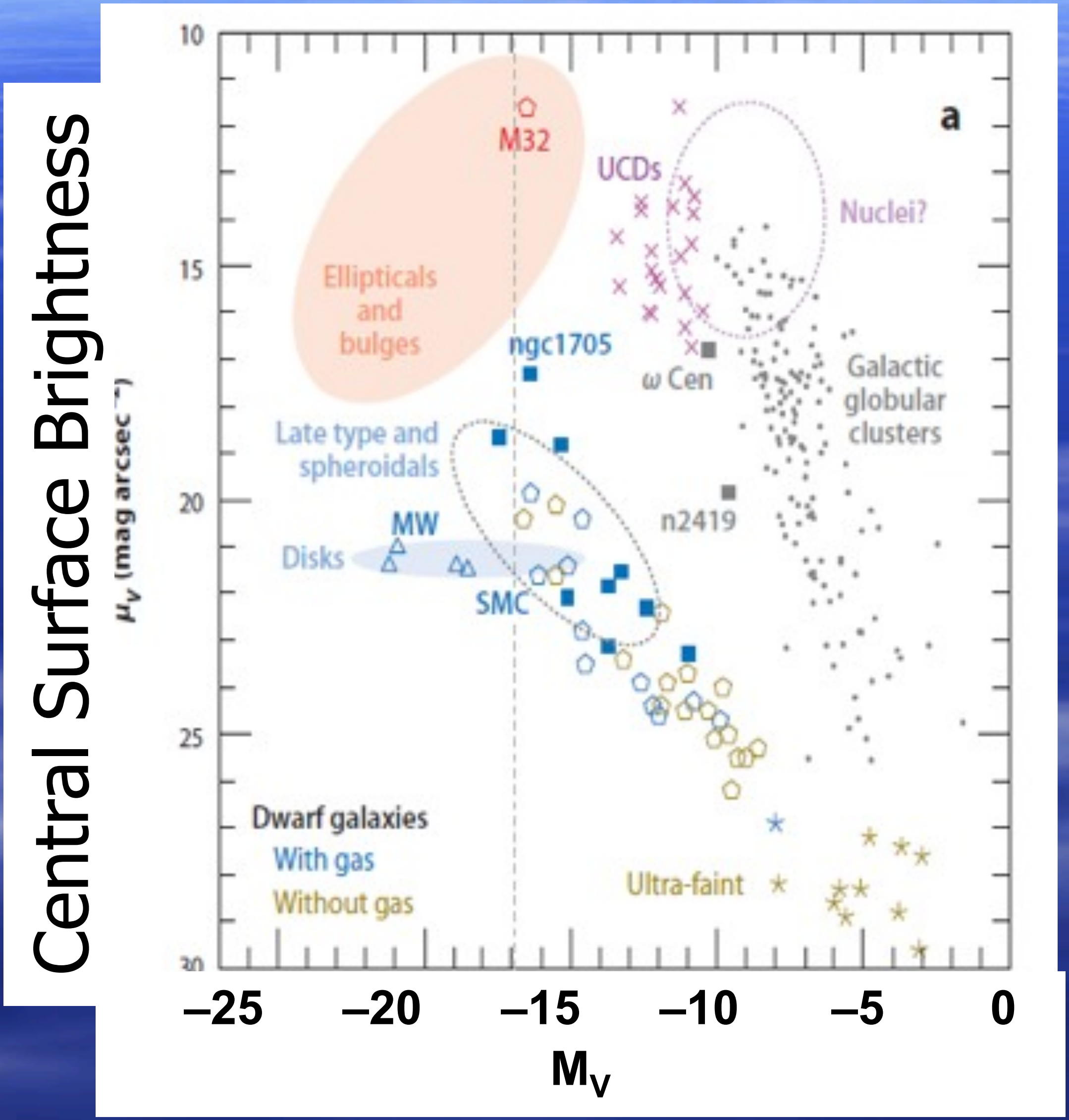
Stellar Populations of Galaxies

Collisions of proto-galactic fragments early in the evolution of a galaxy causes dissipation of energy & funneling of gas into the center, which may create bursts of star formation & form a galactic bulge

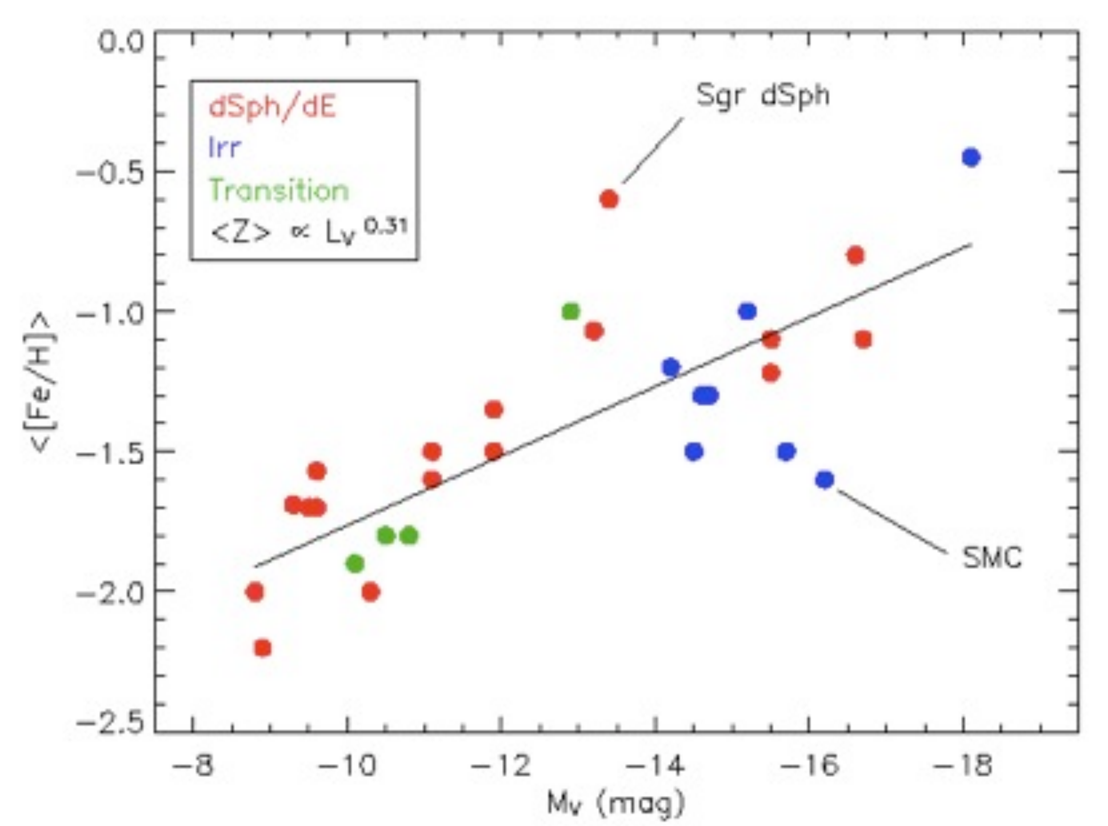
Stellar halos maybe be created from early merging of the proto-galactic fragments and later from cannibalization of dwarf galaxy satellites

Dwarf galaxies, being the simplest systems, should be excellent laboratories in which we can determine the important physics (inflow, outlfow, etc.) of galaxy evolution

Differences Between Galaxy Types and Star Clusters



Tolstoy, Hill & Tosi 2009



- Dekel & Silk (1986) using a simple analytical model predicted outflows dominate evoln if v < 100 km/s → $Z \propto L^{0.4}$, but at least one of their key assumptions is very wrong. More work is needed.
- Scaling Relationships tell us that star formation is probably not controlled mostly by environment, but by the physics of star/galaxy formation itself.

Galaxy Formation

Galaxy Formation

Star Formation

(Gas → Stars)

Galaxy Formation

Star Formation

(Gas → Stars)

Galaxy Formation

Star Formation

(Gas → Stars)

Evolution of Mass
(DM + Gas)
of Galaxies:

Infall of DM + Gas &
Gas Outflow in
Galactic Winds

Galaxy Formation

Star Formation

(Gas → Stars)

↕

Evolution of Mass
(DM + Gas)
of Galaxies:

Infall of DM + Gas &
Gas Outflow in
Galactic Winds

Galaxy Formation

Star Formation

(Gas → Stars)

← CMDs

↕

Evolution of Mass
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← CMDs

Evolution of Mass
(DM + Gas)
of Galaxies:

Infall of DM + Gas &
Gas Outflow in
Galactic Winds

← Chemical
Abundances
of
Stars

Stellar Evolution in the HR Diagram

- Massive Stars evolve and change T_{eff} at fixed L → Supergiants
- Low Mass Stars evolve and change in both T_{eff} and L → Red Giant/AGB stars
- τ_{MS} = 10 Gyr x $(M/M_\odot)^{-2.5}$

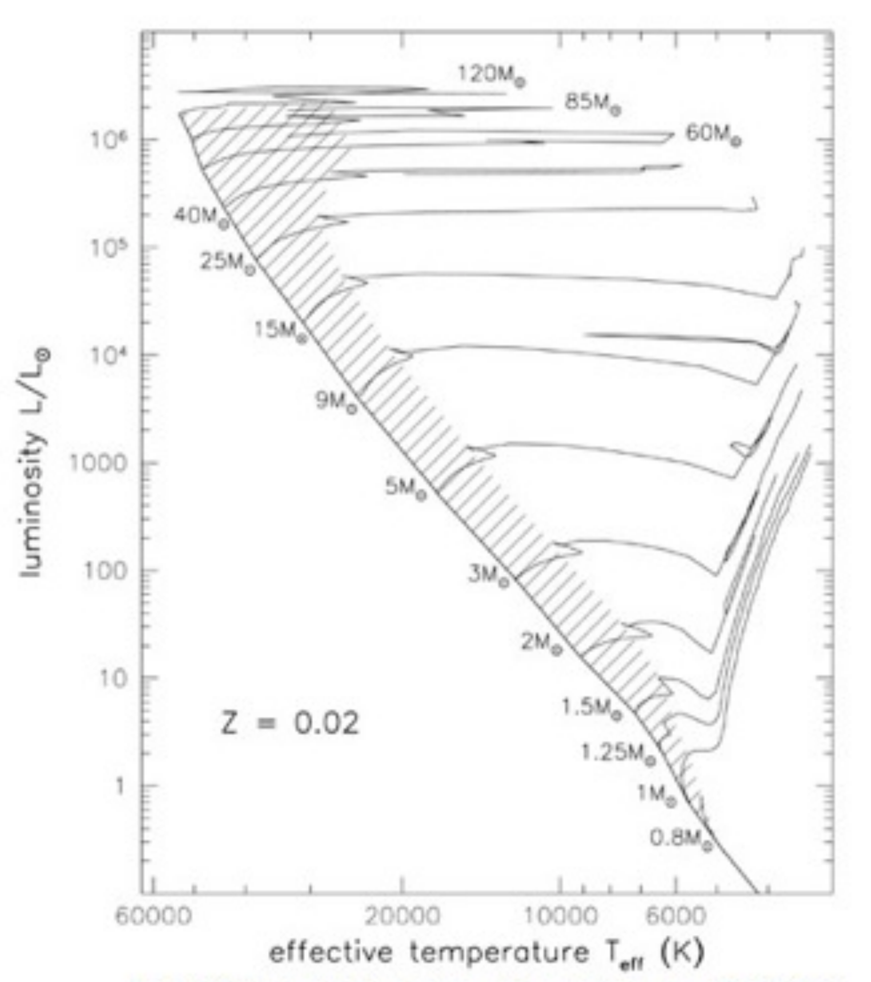


Fig 1.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Main Sequence Lifetimes

- Main sequence lifetimes:
  - $M = 10\ M_\odot$, $\tau_{MS} = 32$ million yr
  - $M = 0.5\ M_\odot$, $\tau_{MS} = 56$ Gyr > age of the Universe!

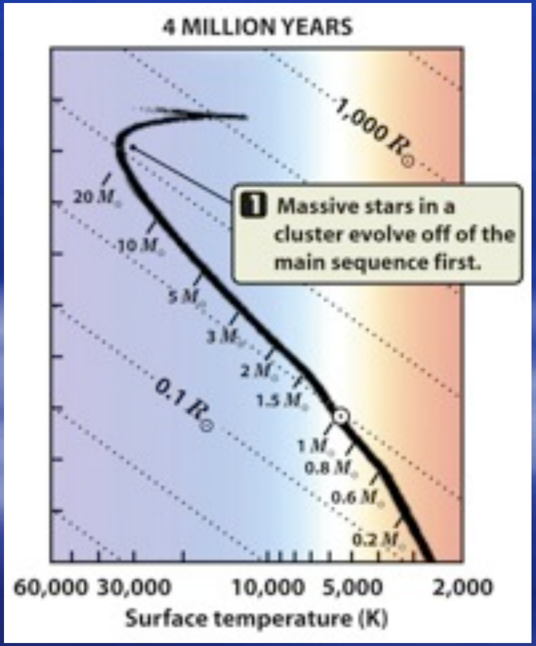
- All low mass stars with $M < 0.8\ M_\odot$ that ever formed in a galaxy are still there
- Measuring the # stars at different parts of the HR Diagram can tell you a galaxy's star formation history

- *Hess Diagram*: diagram showing the density of stars in bins of color & magnitude in an HR Diagram

Star Clusters

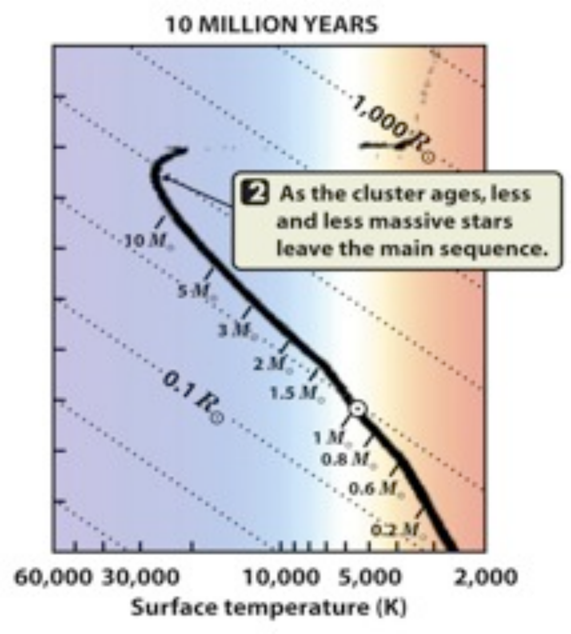
As the cluster ages, the main-sequence turnoff degreases in mass, becoming redder and fainter.

Shape of the CMD tells you the age, distance and chemical abundance of the cluster.



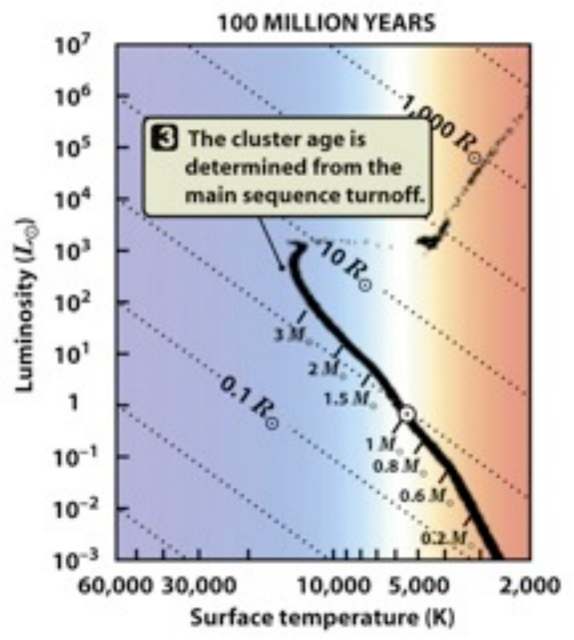
4 MILLION YEARS

1 Massive stars in a cluster evolve off of the main sequence first.



10 MILLION YEARS

2 As the cluster ages, less and less massive stars leave the main sequence.

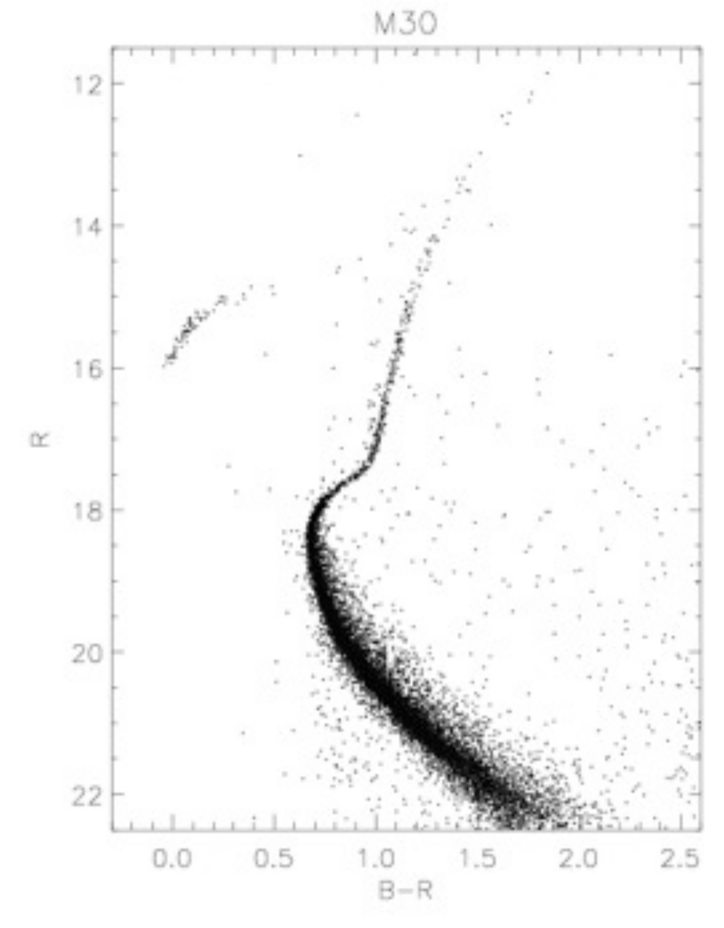


100 MILLION YEARS

3 The cluster age is determined from the main sequence turnoff.

Globular Cluster M30

Ground-based photometry taken with the CTIO 4m (Smecker-Hane, et al.)



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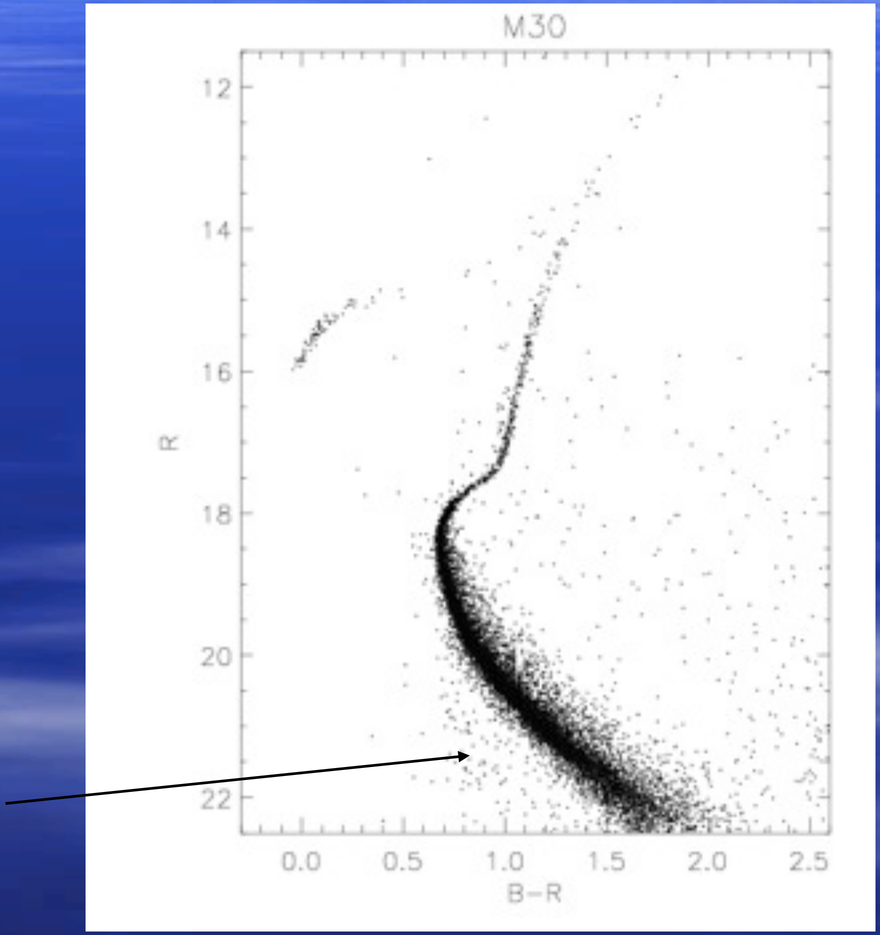

Main Sequence (unevolved stars)

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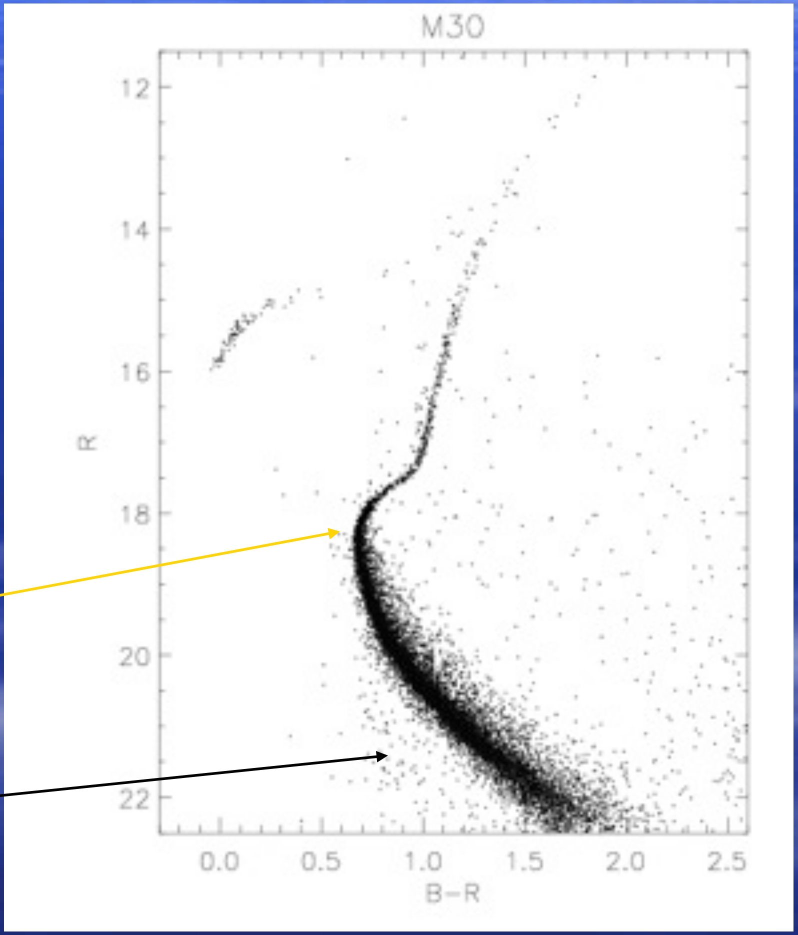
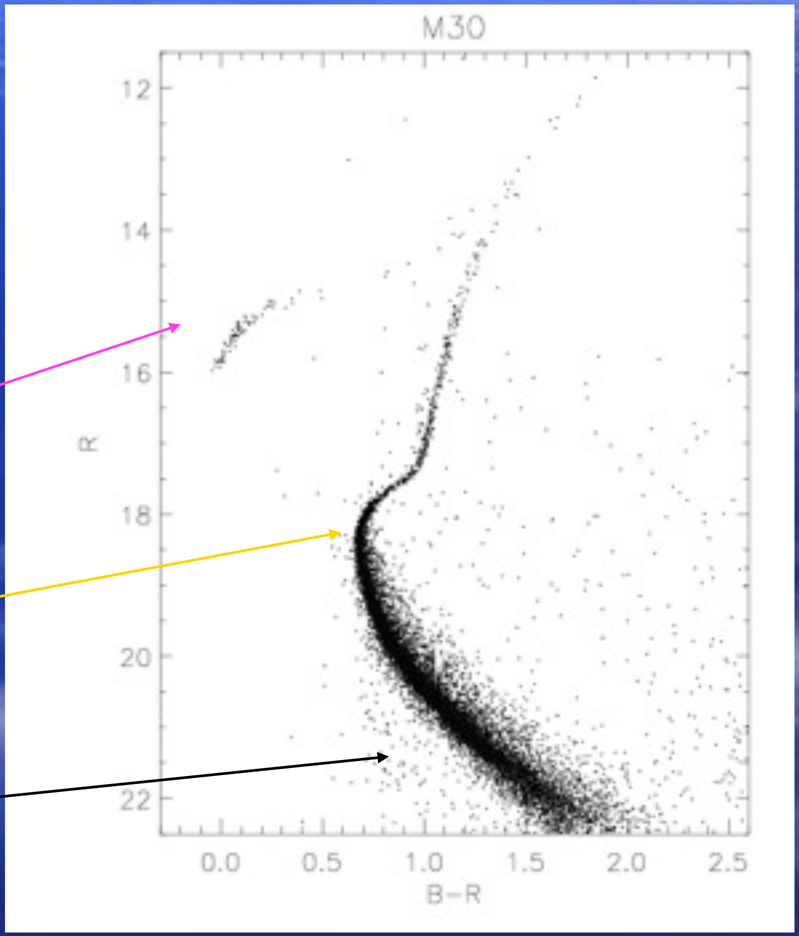


MSTO
(sensitive to age)

Main Sequence
(unevolved stars)

Globular Cluster M30

Ground-based photometry taken with the CTIO 4m (Smecker-Hane, et al.)



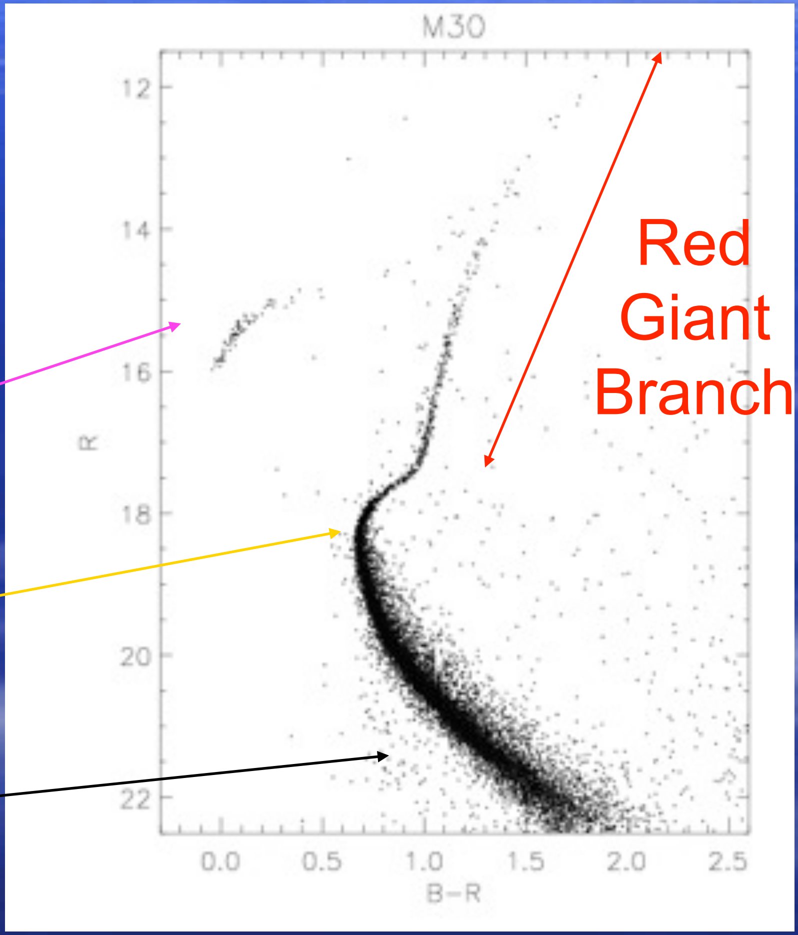
Horizontal Branch Stars (core He burning)

MSTO (sensitive to age)

Main Sequence (unevolved stars)

Globular Cluster M30

Ground-based photometry taken with the CTIO 4m (Smecker-Hane, et al.)



Red Giant Branch

Horizontal Branch Stars (core He burning)

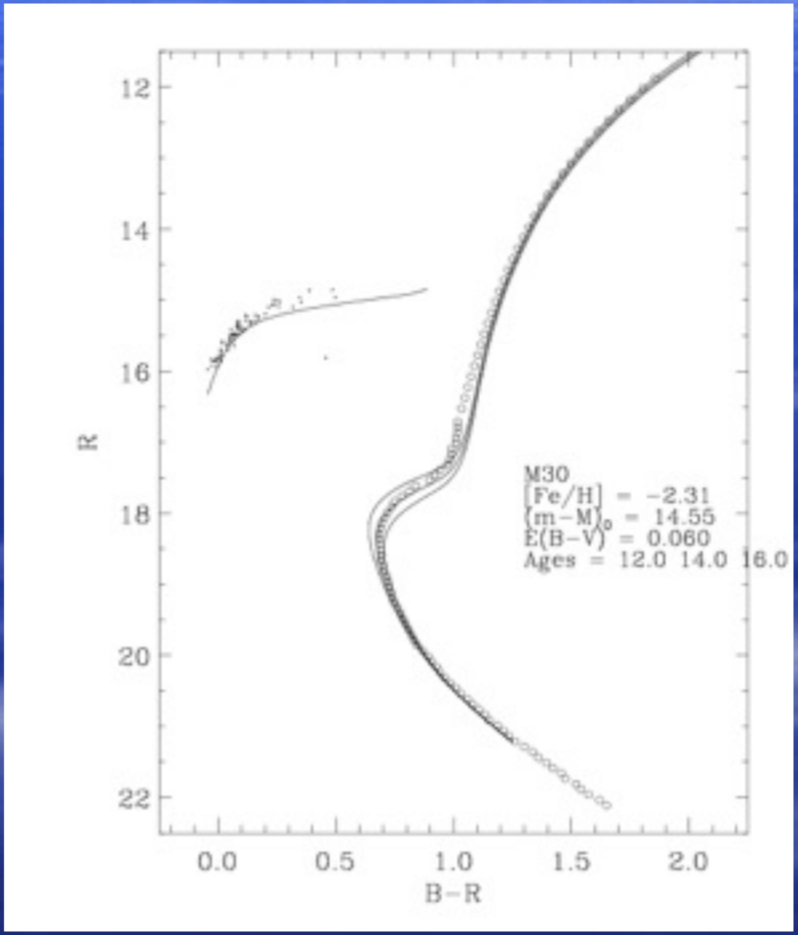
MSTO (sensitive to age)

Main Sequence (unevolved stars)

Globular Cluster M30

- Isochrones from Vandenberg et al. (1997)

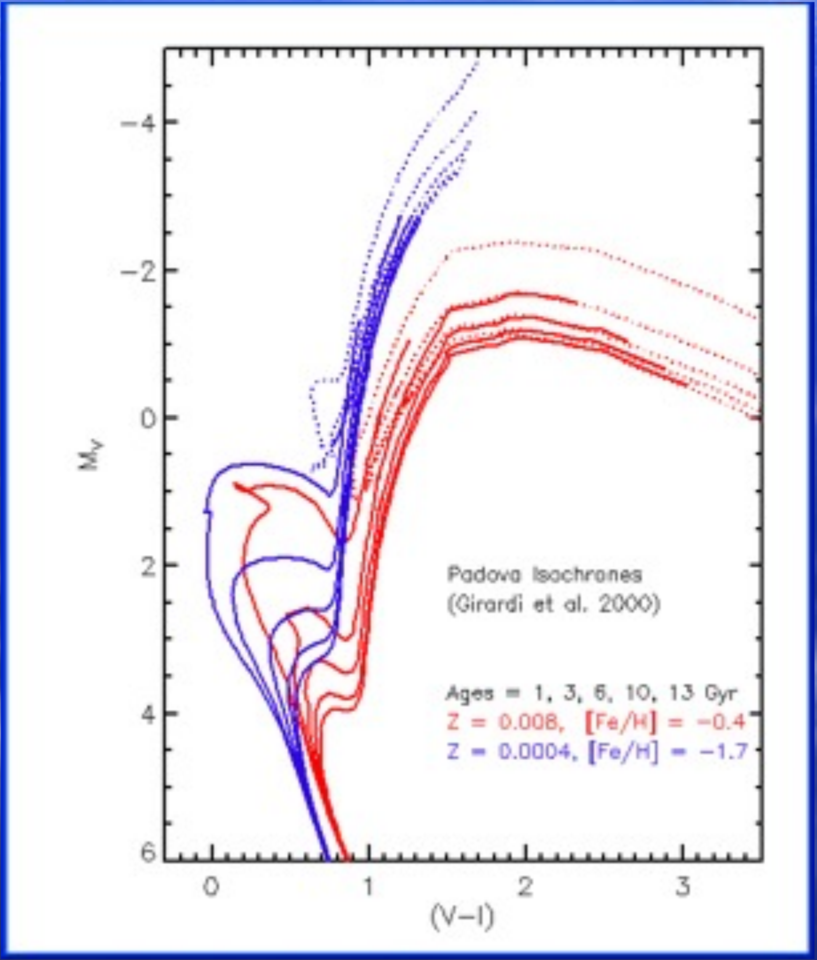
- Comparing the observed fiducial points to the theoretical isochrone allows you to determine the cluster’s reddening, distance, & age (chemical composition)



Stellar Evolutionary Models

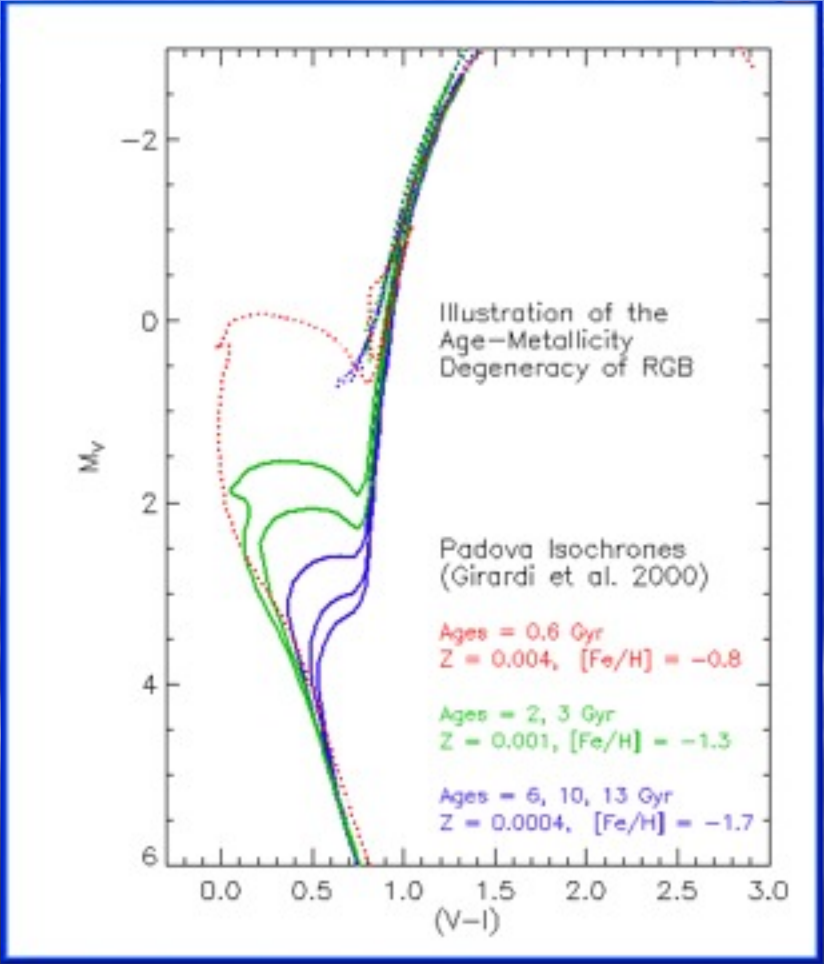
- Padova Isochrones (Girardi et al. 2000)

- An Illustration of How Metallicity and Age affect an Isochrone



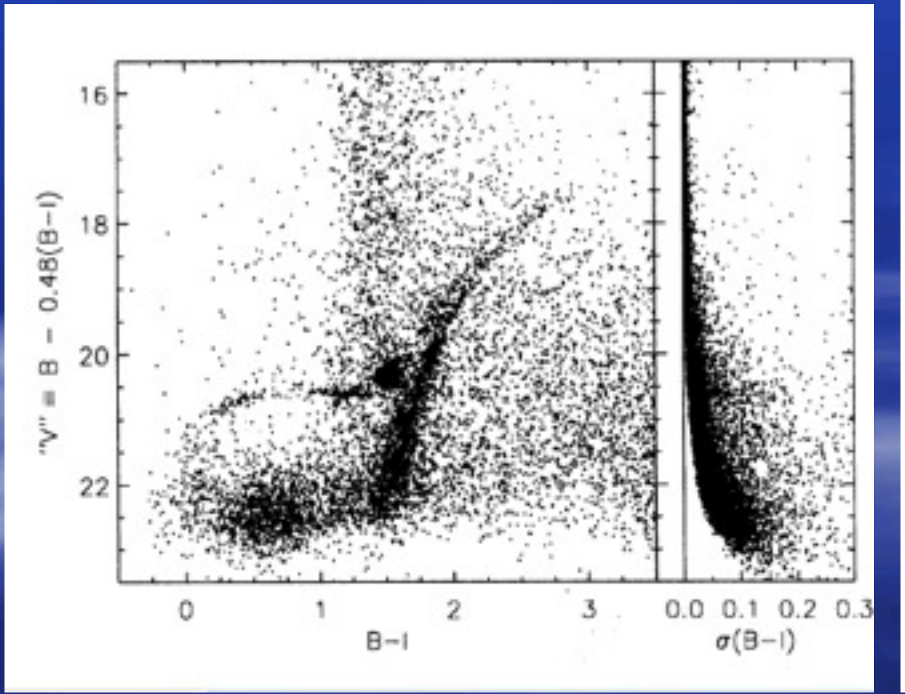
Stellar Evolutionary Models

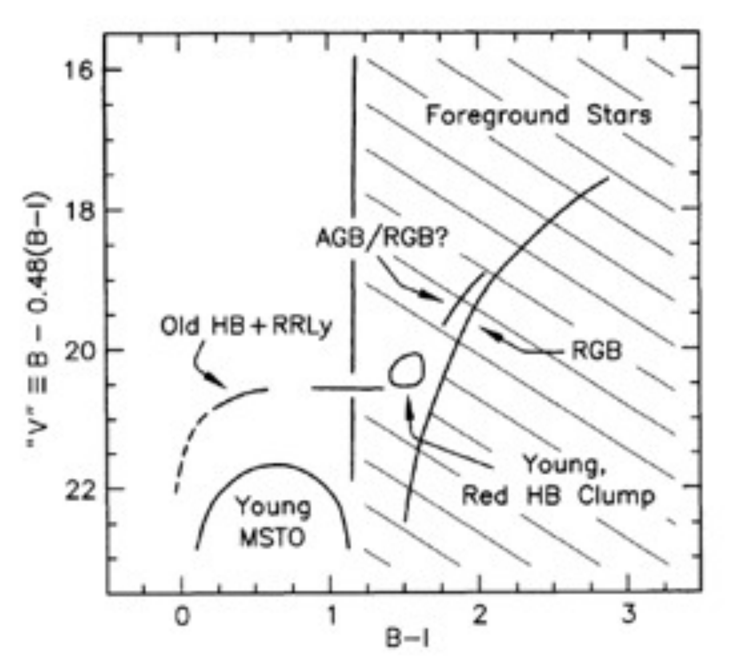
- Padova Isochrones (Girardi et al. 2000)
- An Illustration of the Age-Metallicity Degeneracy of the Red Giant Branch



The Carina dSph Galaxy

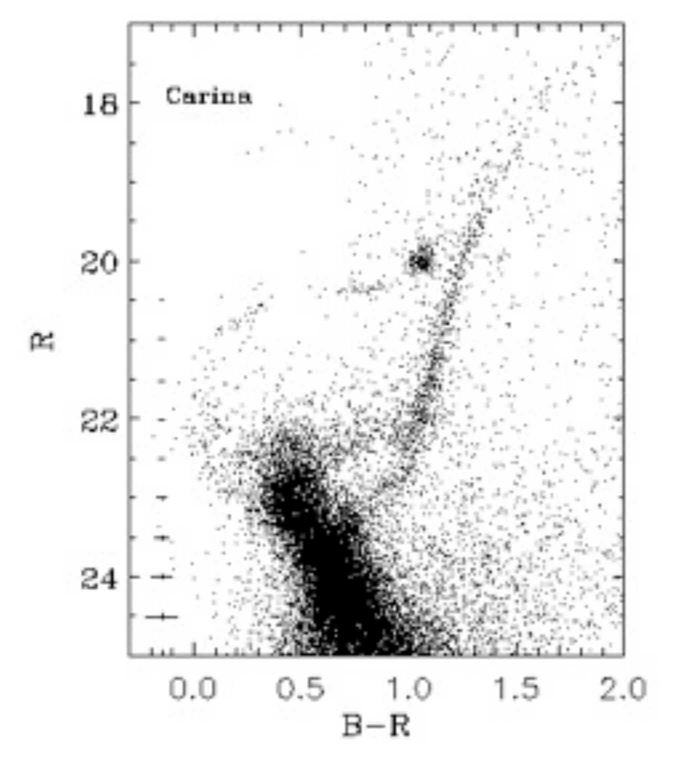
- Initial work by Mighell (1990) suggested a complex SFH
- Results from the CTIO 1.5 m Telescope over a wide field (Smecker-Hane, et al. 1994)

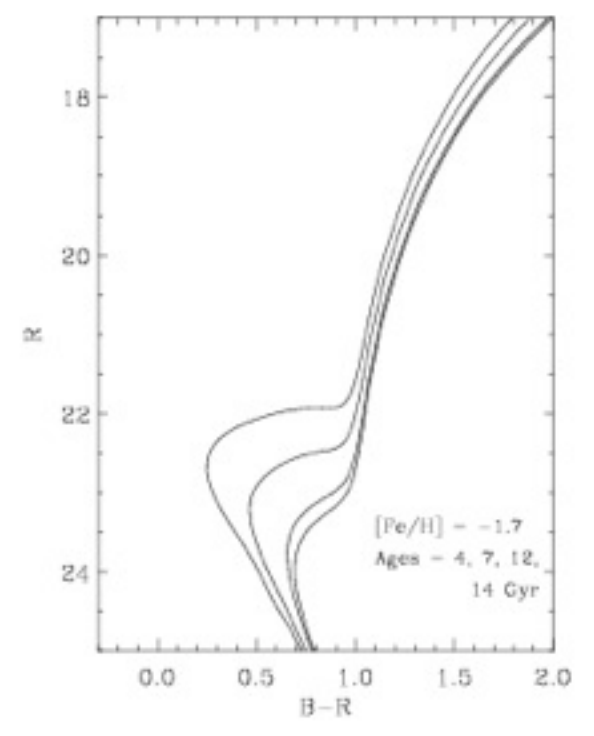




The Carina dSph Galaxy

Deeper Photometry from the CTIO 4 m Telescope (Smecker-Hane, et al 1996; see also Mighell 1990, Hurley-Keller et al. 1996)





What are the Differences Between Dwarf Spheroidal & Dwarf Irregular Galaxies?

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Leo I
Dwarf Spheroidal galaxy
(dSph)

Dwarf Irregular Galaxy Leo A

Suprime-Cam (B, R, z')
August 5, 2004

Subaru Telescope, National Astronomical Observatory of Japan
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Leo A
Dwarf Irregular Galaxy
(dIrr)

What are the Differences Between Dwarf Spheroidals & Dwarf Irregulars?

Leo I dSph:

- $M_V = -11.7$
- Devoid of neutral gas, $M_{HI} < 10^3 M_{\text{¤}}$
- No star formation in last ~0.5 Gyr, but Gallart et al. (1999) & Dolphin (2002) suggested a majority young stellar pop
- Stars: [Fe/H] ≈ -1.4
- Dark Matter (stellar velocity dispersion)

Leo A dIrr:

- $M_V = -11.9$
- Plenty of neutral gas, $M_{HI} = 2 \times 10^7 M_{\text{¤}}$
- Current star formation & HII regions $\Psi(t_{now}) \approx 10^{-4} M_{\text{¤}}/yr$
- Stars: [Fe/H] ≈ -1.4
- Dark Matter (HI)

Measuring the Star Formation History (SFH) of a Galaxy

- By modeling the Hess Diagram, the density of stars in the HR Diagram (T_{eff}-L plane) or its observational equivalent, the Color-Magnitude Diagram (CMD) we can derive a galaxy's SFH
- Major complications:
  - Degeneracy of age and chemical abundance
  - Uncertainties exist in stellar evolution models and the transformation to the observational plane
- Other minor complications:
  - Distance along the line-of-sight to the galaxy, differential reddening, photometric binaries, etc.

Where Do We Get the Data?

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- Hubble Space Telescope is needed to get accurate CMDs for galaxies > 100 kpc, because you need to do high precision photometry on faint stars and sometimes in very crowded regions

Where Do We Get the Data?

- Hubble Space Telescope is needed to get accurate CMDs for galaxies > 100 kpc, because you need to do high precision photometry on faint stars and sometimes in very crowded regions

- Major complications:
  - Its difficult to get time on HST!
  - Observing strategy (which filters to use, which texp, how many fields) is based on the efficiency and FOV of the camera

Analysis of CMDs to derive SFHs

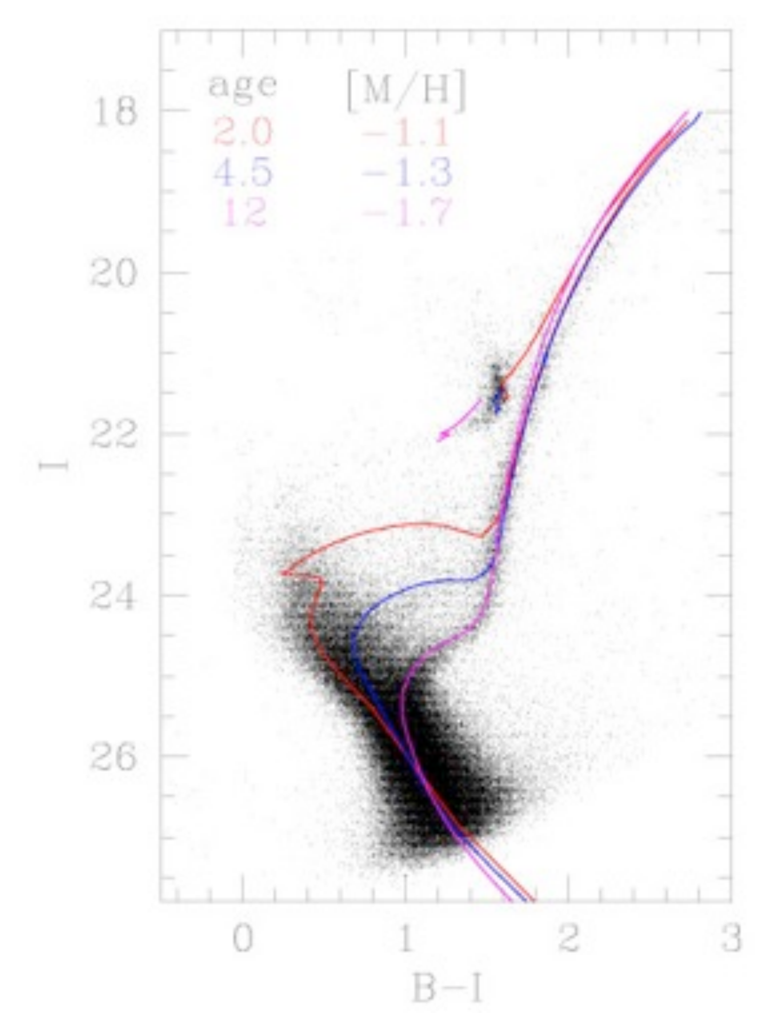
- Gallart, Apparicio, Bertelli, Vallenari and collaborators
  - Use wide boxes in the CMD
  - Match Hess diagram using Chi-Squared analysis
  - Less sensitive to errors in stellar evoln models
- Hernandez, Gilmore, & Valls-Gabaud (2000) and Dolphin (2002)
  - Use small bins in the CMD
  - Match Hess diagram using Maximum Likelihood Analysis
  - More sensitive to errors in stellar evoln models, but more stringent limits on the solution

Analysis of CMDs to derive SFHs

- Hernandez, Gilmore, & Valls-Gabaud (2000) and Dolphin (2002) , etc.
  - Solve for both chemical evolution, Z(t), and SFR(t)
- LCID Collaboration deriving SFHs for numerous dwarf galaxies and other groups working on individual dwarfs

SFH of the Leo I dSph Derived From the CMD

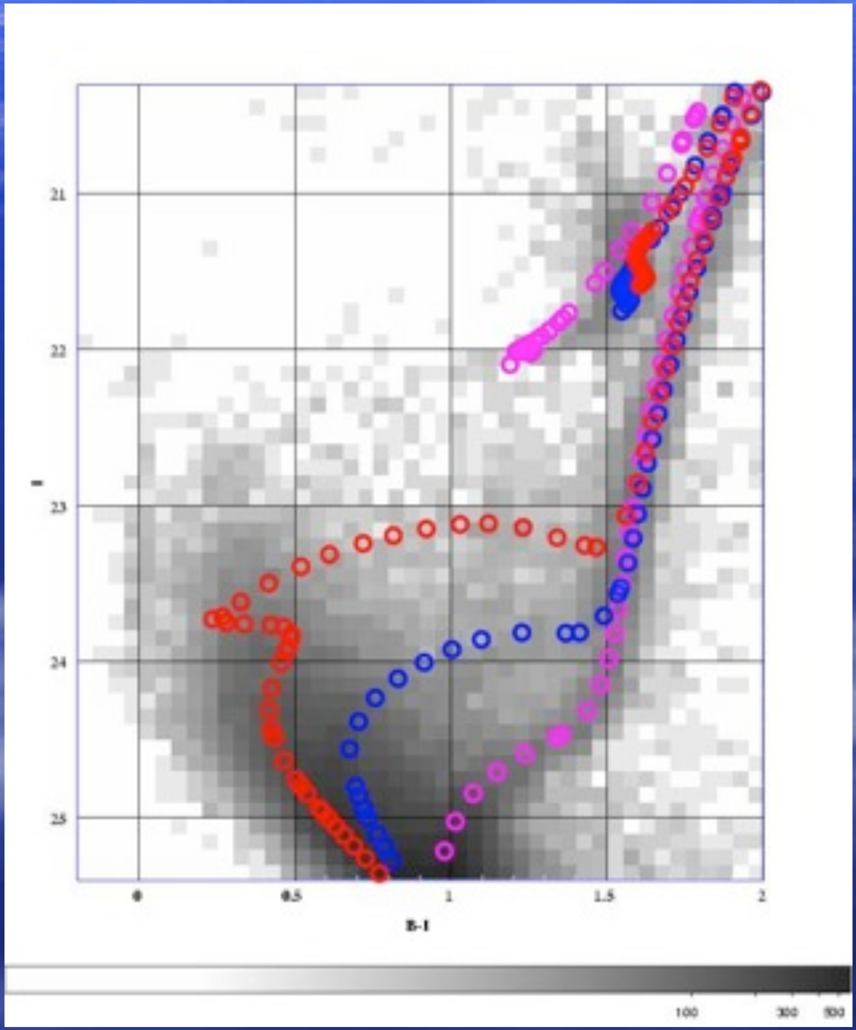
Smecker-Hane, Cole, Marsteller et al. (2010)



The Observed CMD overplotted with selected isochrones (Marigo et al. 2008) with different ages (in Gyr) & metallicities

SFH of the Leo I dSph Derived From the CMD

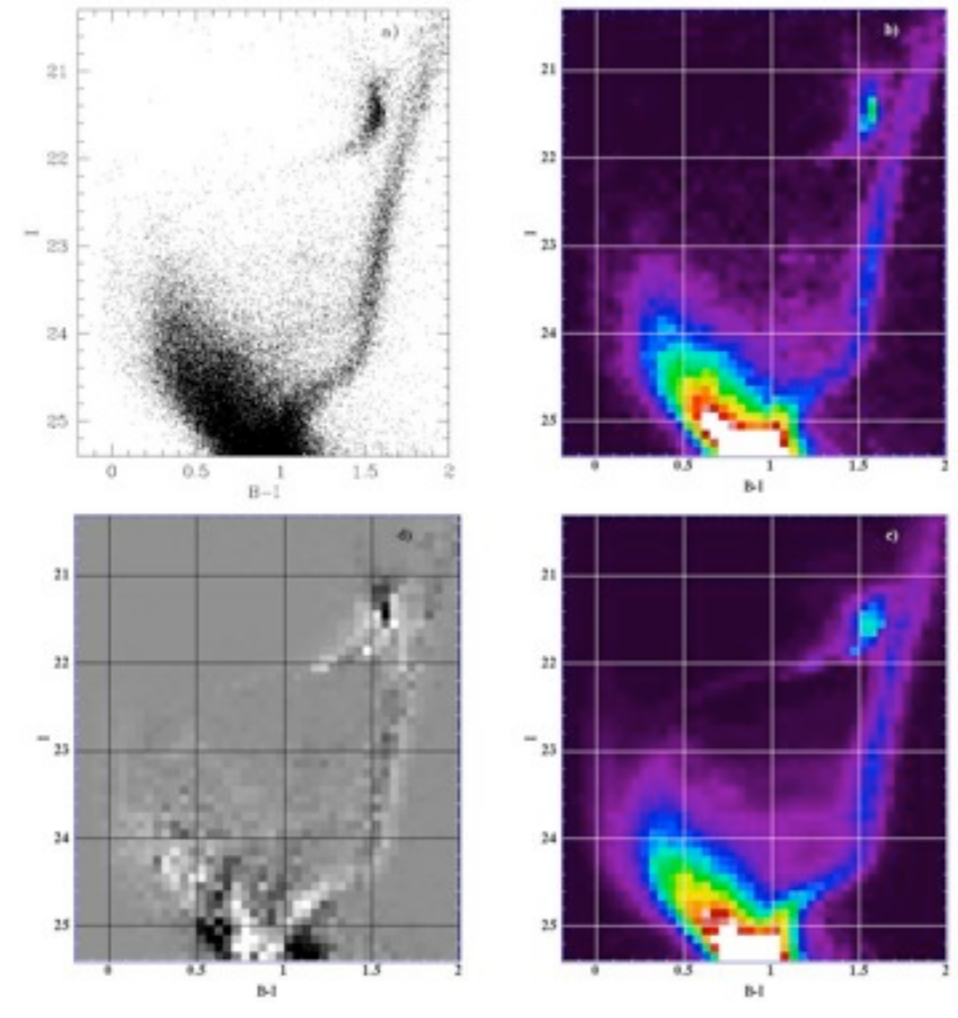
Smecker-Hane, et al. (2010)



- The Observed CMD overplotted with selected Padova isochrones (Marigo et al. 2008) with different ages & metallicities (same as in previous slide)

SFH of the Leo I dSph Derived From the CMD

Smecker-Hane, et al. (2010)



a) Observed CMD

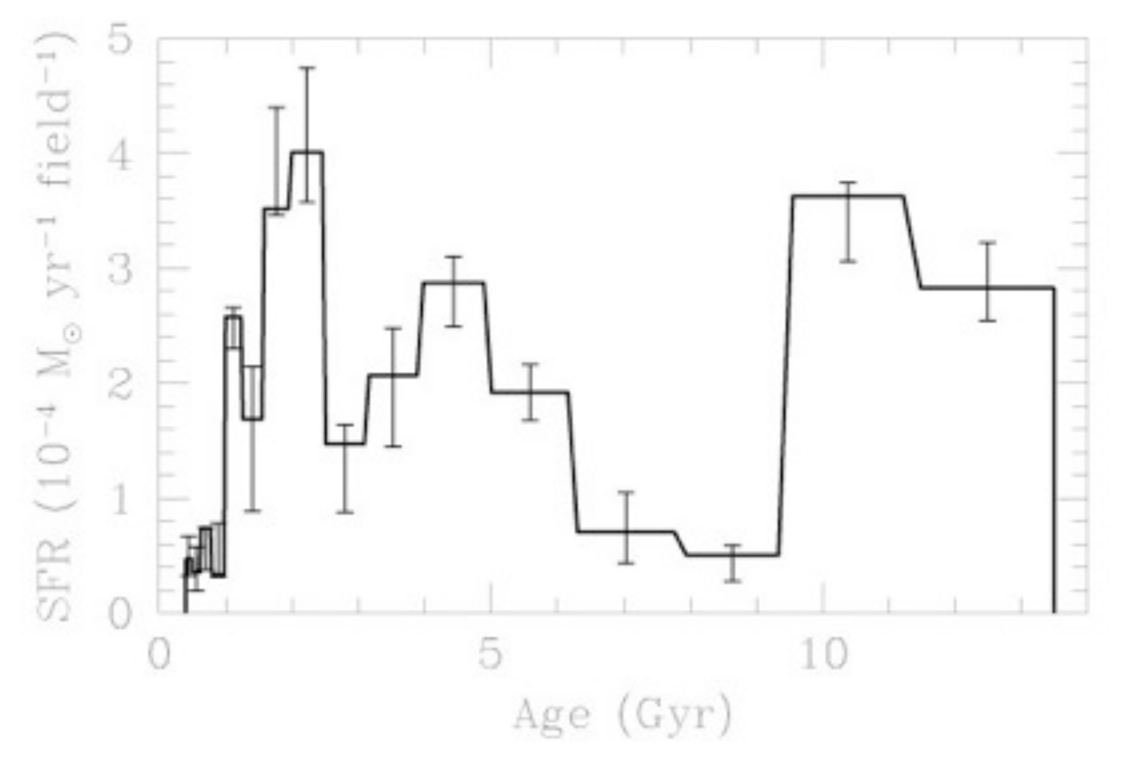
b) Hess Diagram of Observed CMD

c) Hess Diagram of Best Fit Model's CMD

d) Hess Diagram of Residuals

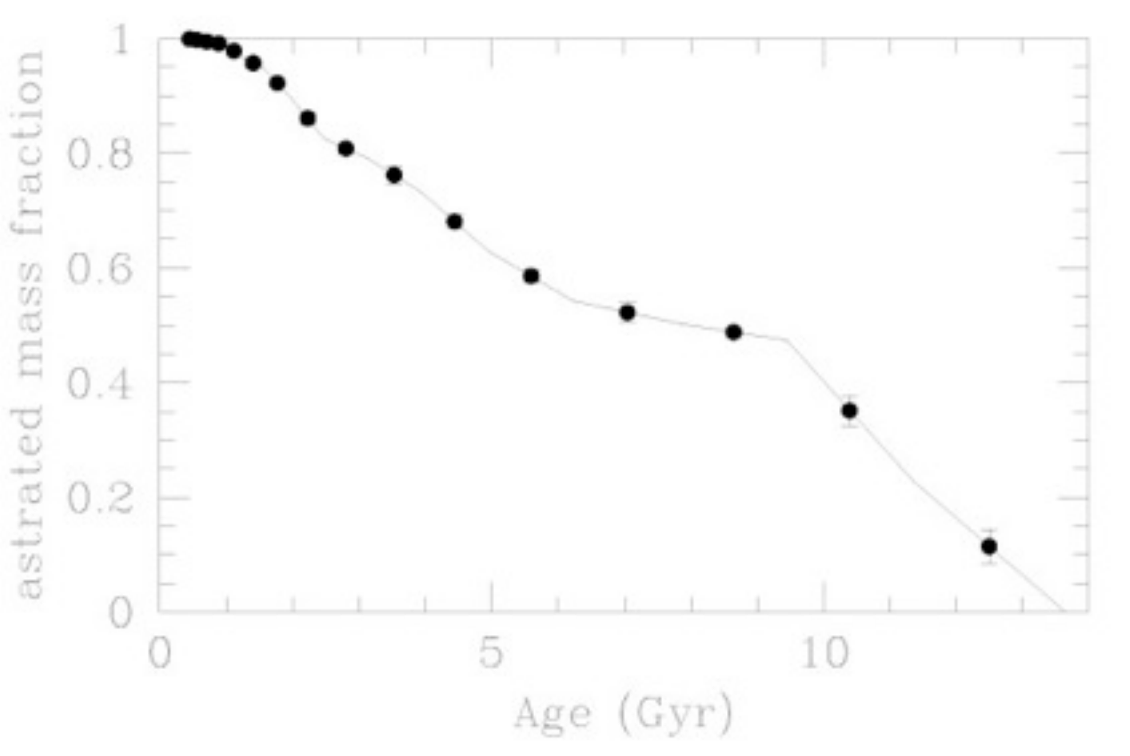
SFH of the Leo I dSph Derived From the CMD

Smecker-Hane, et al. (2010)



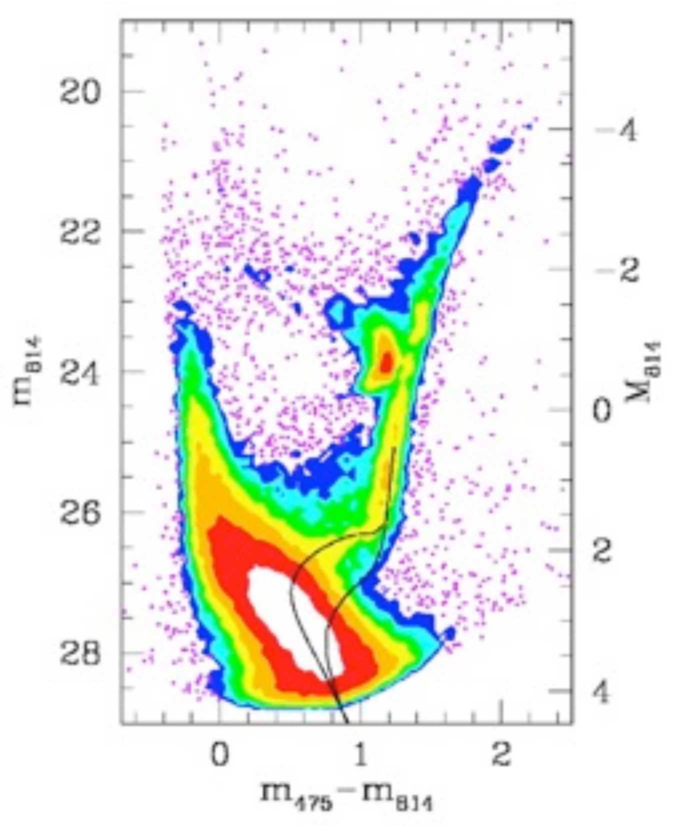
SFH of the Leo I dSph Derived From the CMD

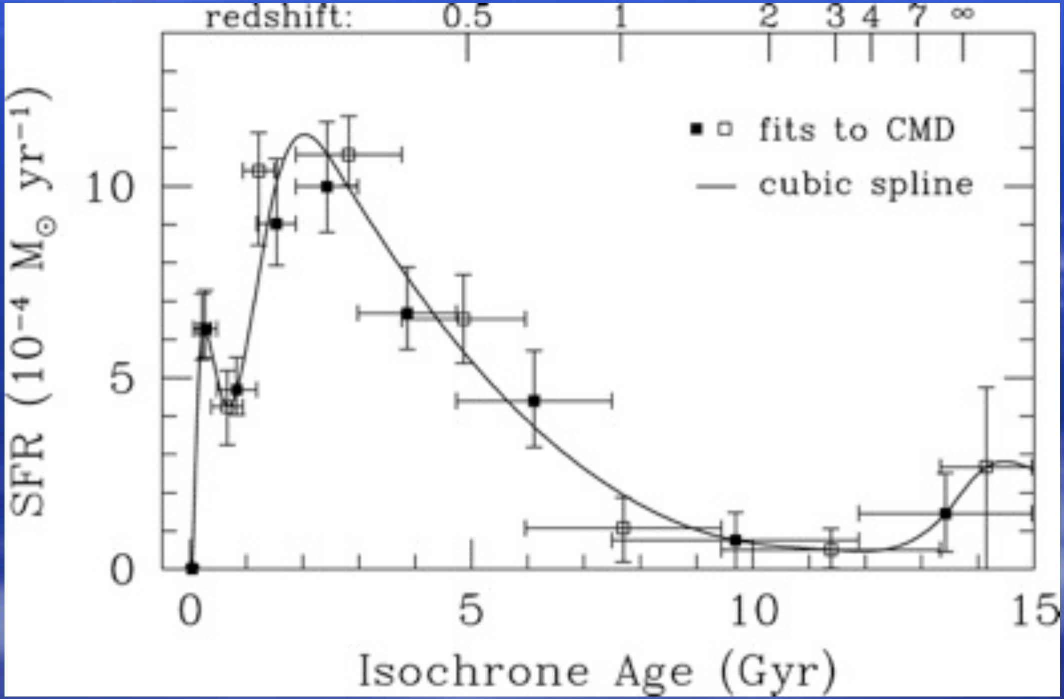
Smecker-Hane, et al. (2009)



50% of the
stars that
formed
now have ages
< 10 Gyr &
were formed in
the first 4 Gyr
after the
Big Bang

Leo A – Dwarf Irregular Galaxy (Cole, et al. 2007)





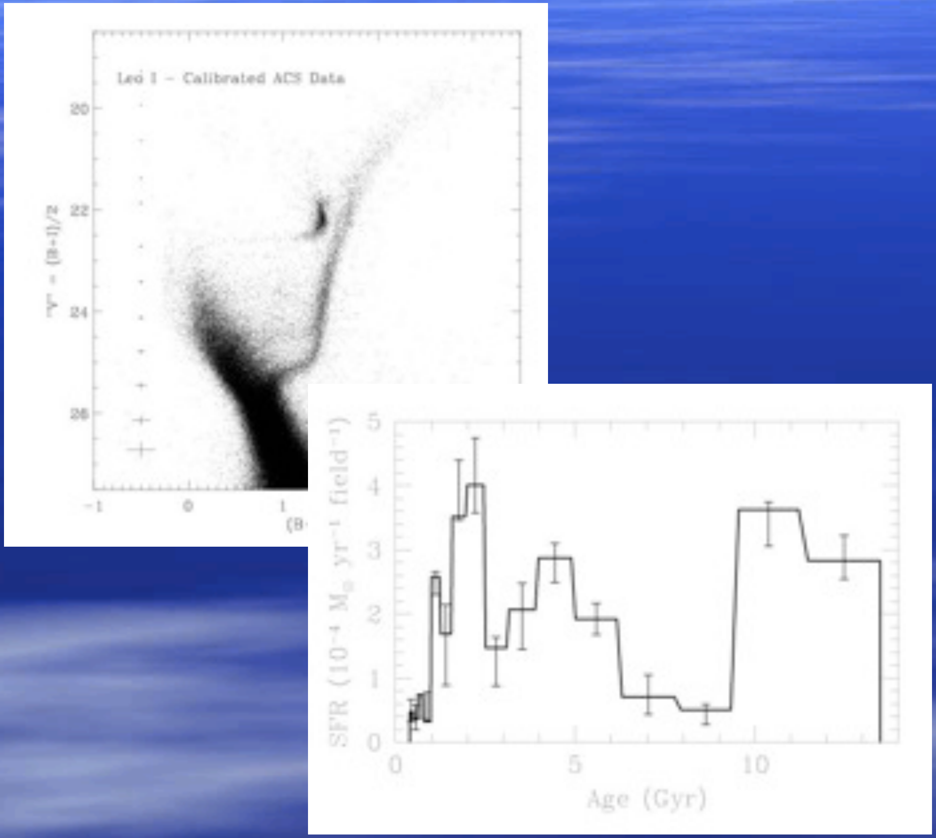
Isochrones

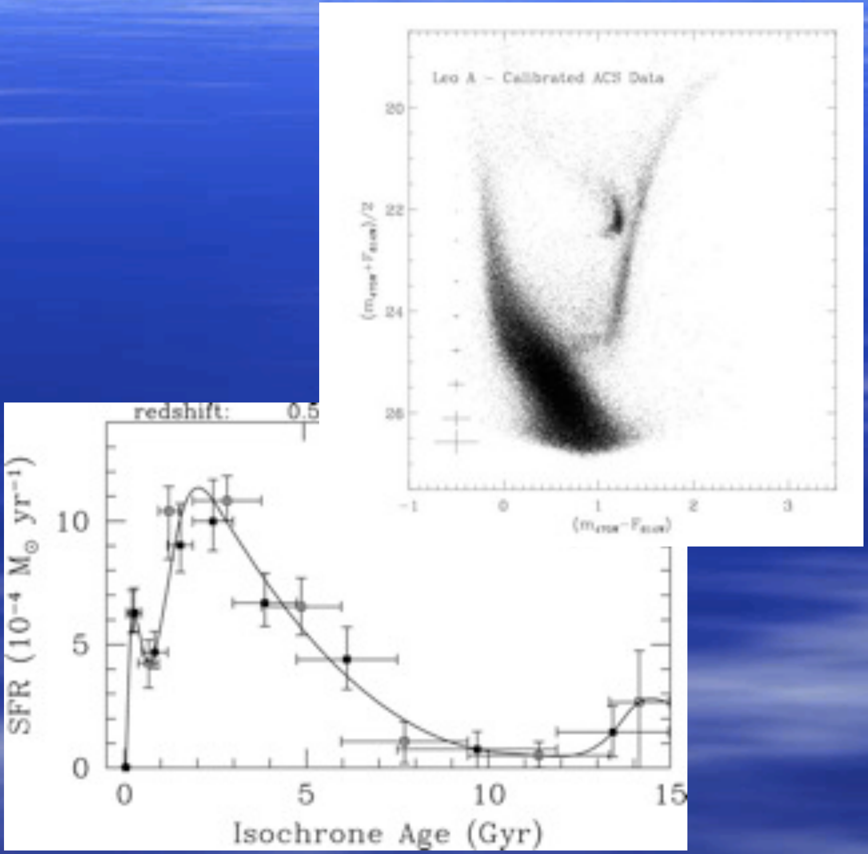
Age = 5 & 14 Gyr

Comparing the Leo I dSph & Leo A dIrr

Leo A dIrr (Smecker-Hane et al. 2010)

Leo A dIrr (Cole et al. 2007)





Different SFHs for Leo I dSph & Leo A dwarf irregular! Leo I started with big burst of SF, but Leo A started slowly. However both started forming stars ~14 Gyr ago.

Results of SFHs of Dwarf Galaxies

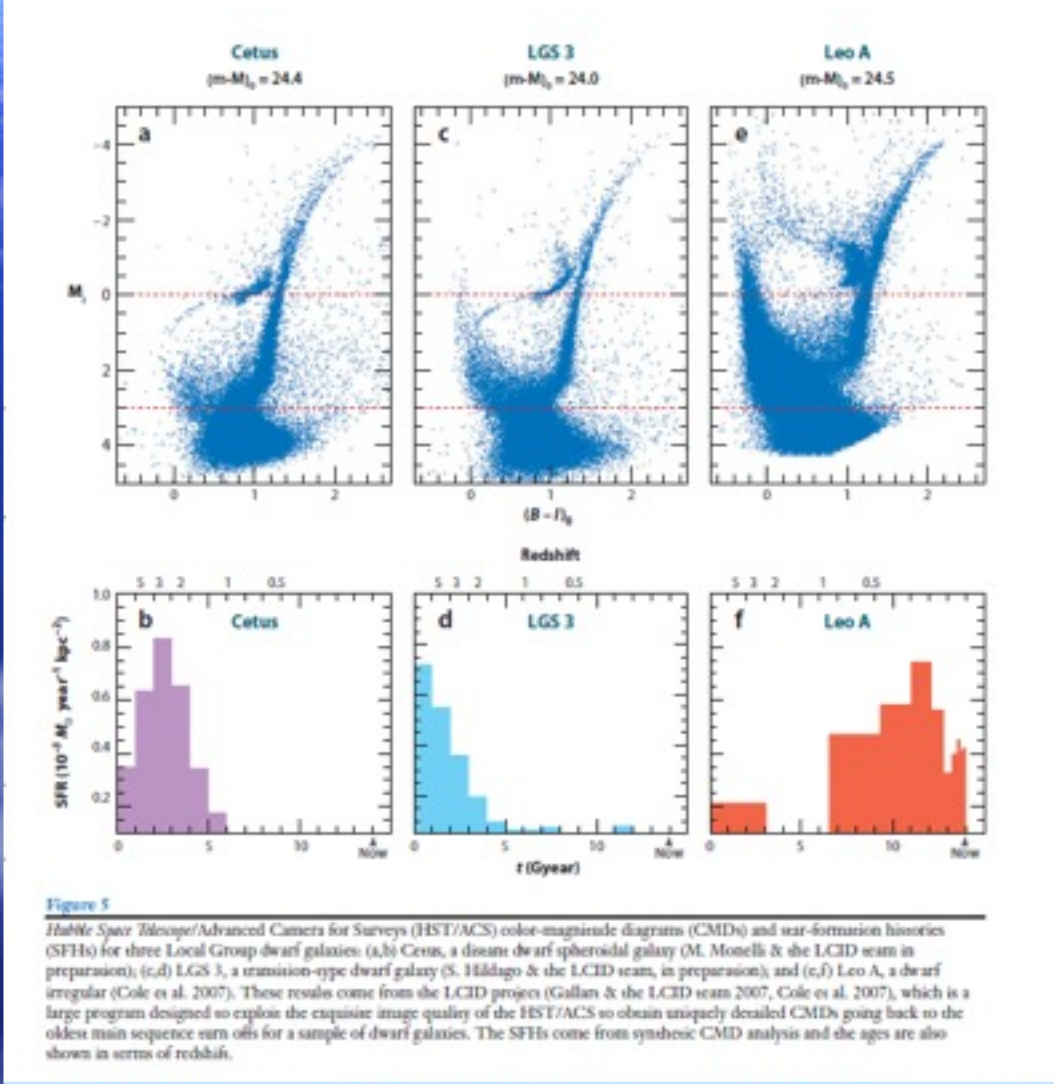


Figure 5

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. Hidalgo & 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.

Results from the LCID Collaboration

Tolstoy, Hill & Tosi 2009

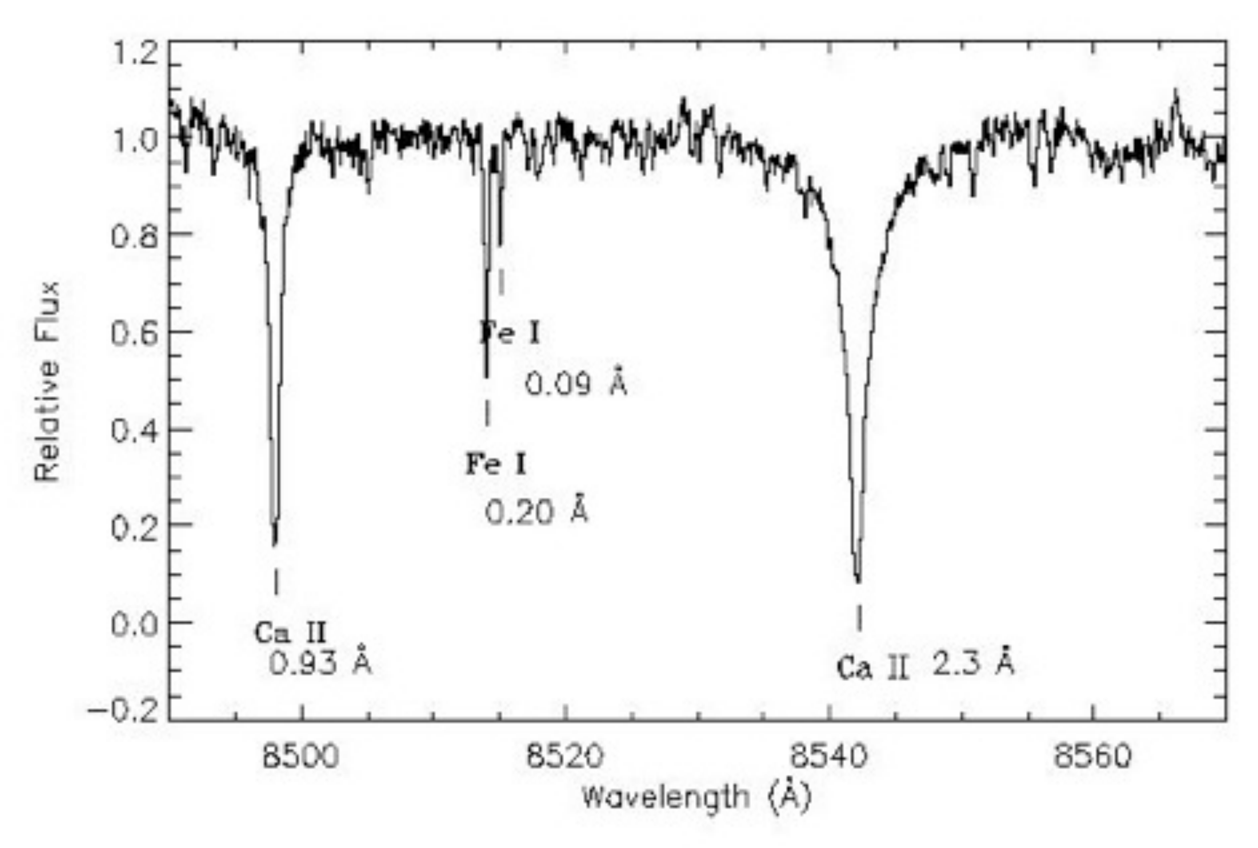
This Raises Some Questions

- All galaxies examined so far began forming stars at about the same time, ~14 Gyr ago, with no sign of pause due to reionization (12.6 Gyr, $z \approx 6$), but each has a seemingly unique star formation history extending over many Gyr. Why? Differences in DM halo masses, differences in continued infall, tidal forces, stripping?

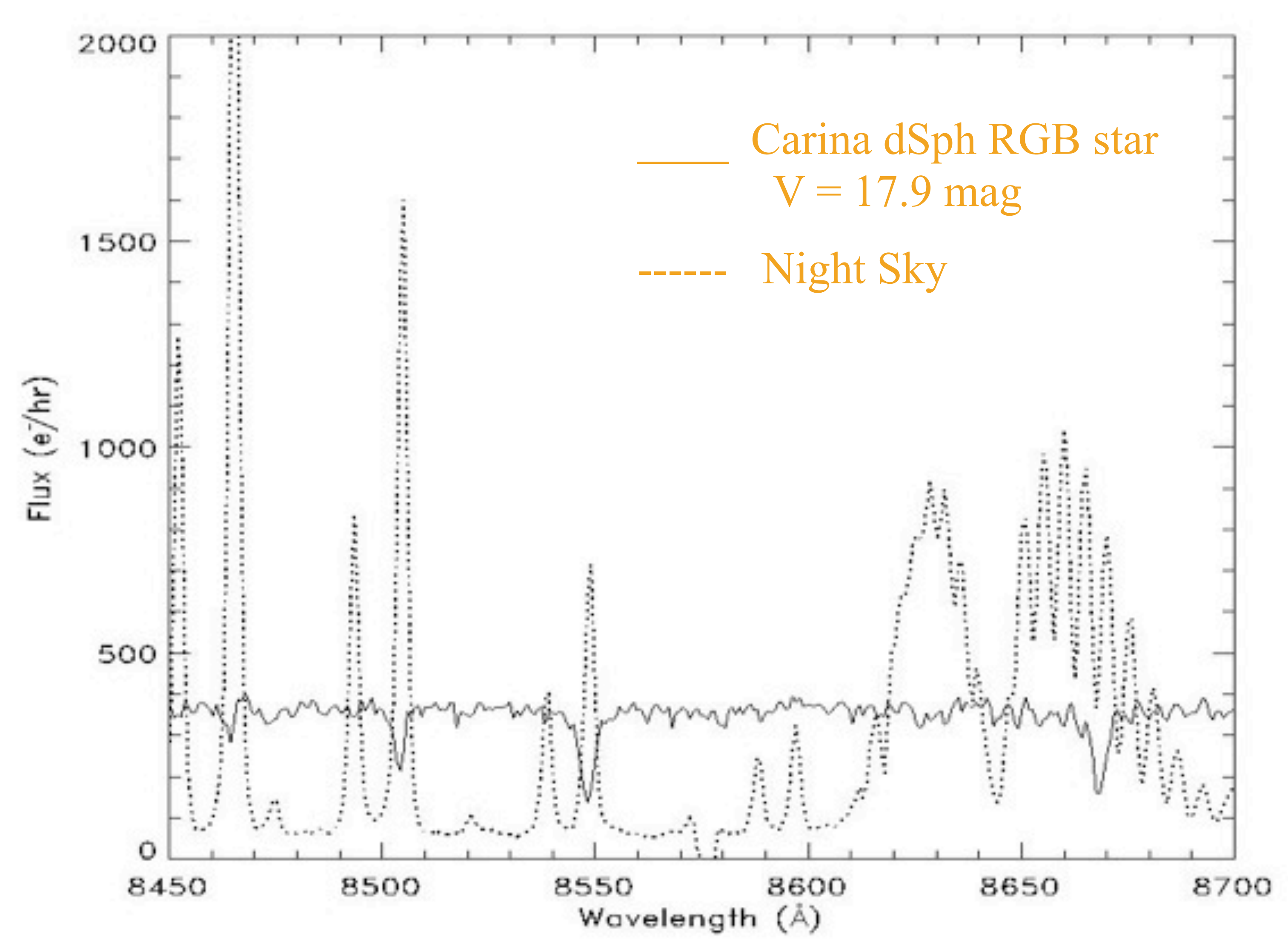
- Do the SFHs derived match those predicted by ΛCMD? Lets compare with simulations.

- What can we do to further constrain the rate of inflow of pristine gas and outflow of metal-enriched winds? Measure chemical abundances for individual red giant stars in the dSphs. Also, determine abundances for numerous elements that are created on different timescales.

The Calcium Triplet as an Abundance Indicator



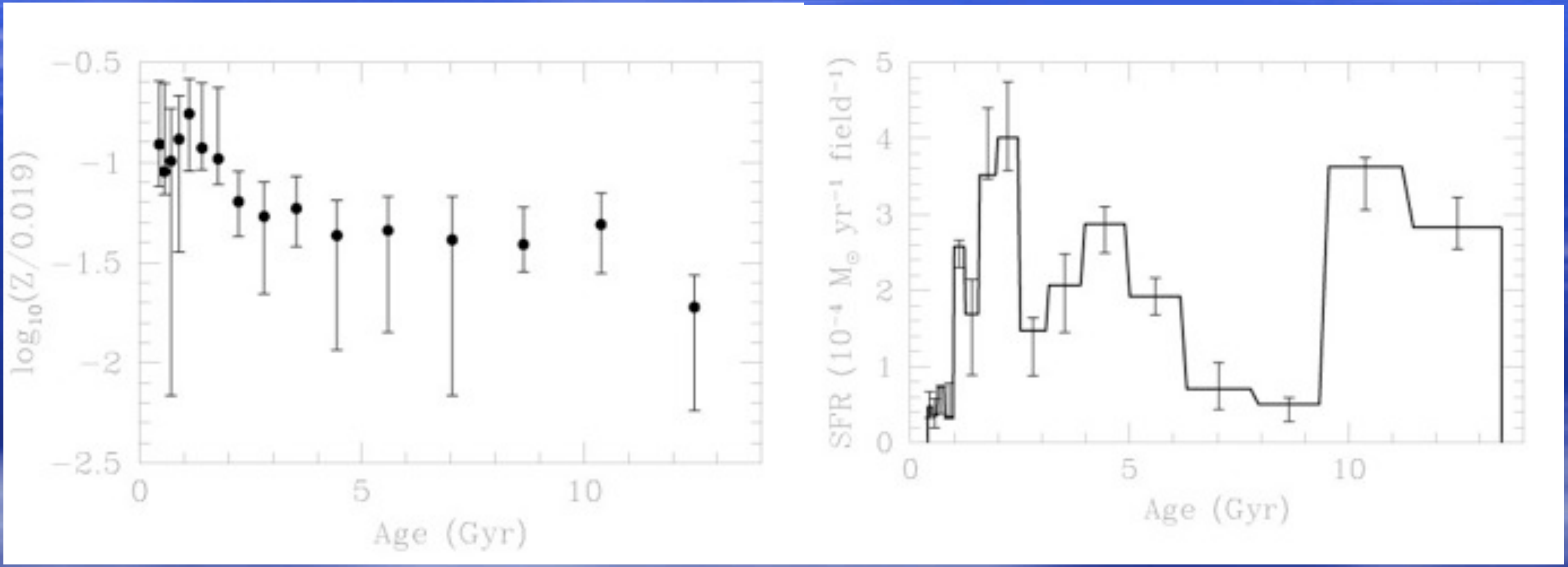
A High–Dispersion Echelle Spectrum of an RGB star near two of the CaT lines (T. Bosler, Ph. D. thesis)



2000
1500
1000
500
0
Flux (e⁻/hr)
8450
8500
8550
8600
8650
8700
Wavelength (Å)
____ Carina dSph RGB star
V = 17.9 mag
------ Night Sky

Age – Metallicity Relationship in the Leo I dSph Derived From the CMD

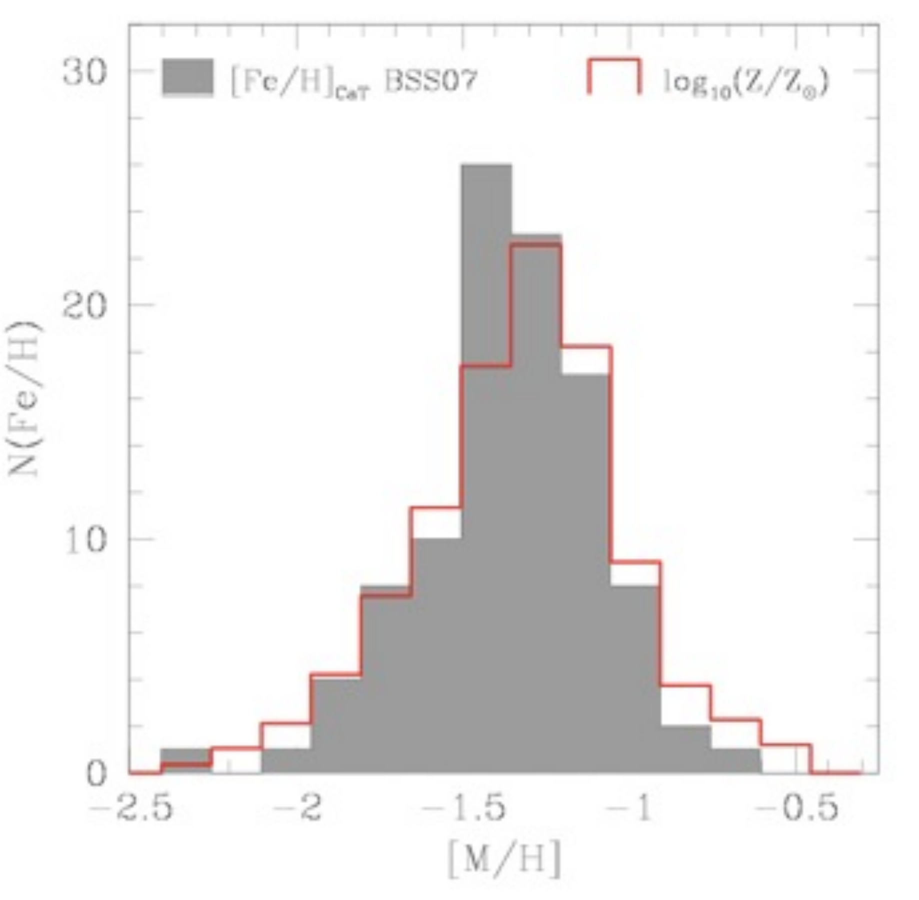
Smecker-Hane, et al. (2010)



Comparing such data to analytical models of chemical evolution suggest that in order to get such a flat age-metallicity relationship you need both inflow of fresh gas and outflow of metal-enriched winds (c.f., Lanfranchi, Matteucci & Cescutti 2006)

Metallicity Distribution of Stars in Leo I dSph

Smecker-Hane, et al. (2010)



The results from spectroscopy of individual RGB stars and the new CMD analysis agree beautifully!

Large and Small Magellanic Clouds

The SMC

HST survey of star clusters and field stars in the Small Magellanic Cloud done by a large collaboration: Gallagher, Grebel, Nota, Tosi, Sabbi, Glatt, etc.

Goals:

- Accurately measure the ages (±0.5 Gyr) and distances of star clusters in the SMC
- Use the star clusters to trace the evolution of the metallicity over time in this dwarf galaxy
- Use the field stars to derive the star formation and metal enrichment history
- Identify how cluster formation compares to the star formation

NGC 121: the SMC's Only Globular Cluster

Glatt, et al. (2008)

5 isochrones displayed at 0.5 Gyr intervals

Age = 10.5 ± 0.5 Gyr

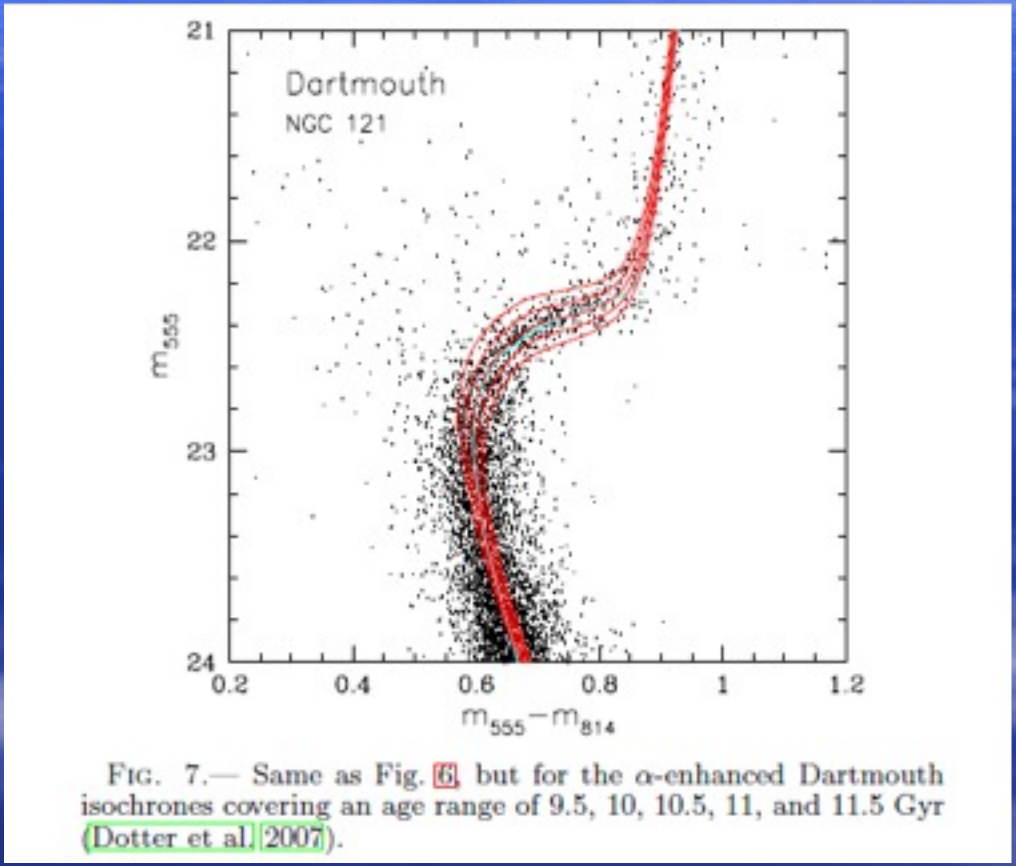


FIG. 7.— Same as Fig. 6, but for the α-enhanced Dartmouth isochrones covering an age range of 9.5, 10, 10.5, 11, and 11.5 Gyr (Dotter et al. 2007).

SMC Star Clusters

- NGC 121 has an age of 10.5 Gyr and [Fe/H] = –1.46 ("intermediate" metallicity)
- NGC 121 is the only globular cluster in the SMC, and is its oldest star cluster

- SMC's current star formation rate is higher than similar galaxies (interaction LMC/SMC)

- Is the SMC a "young" galaxy? … SMC Field Stars say "No."

The Stellar Populations of the SMC

6 SMC “Field Star” Areas in Gallagher et al.

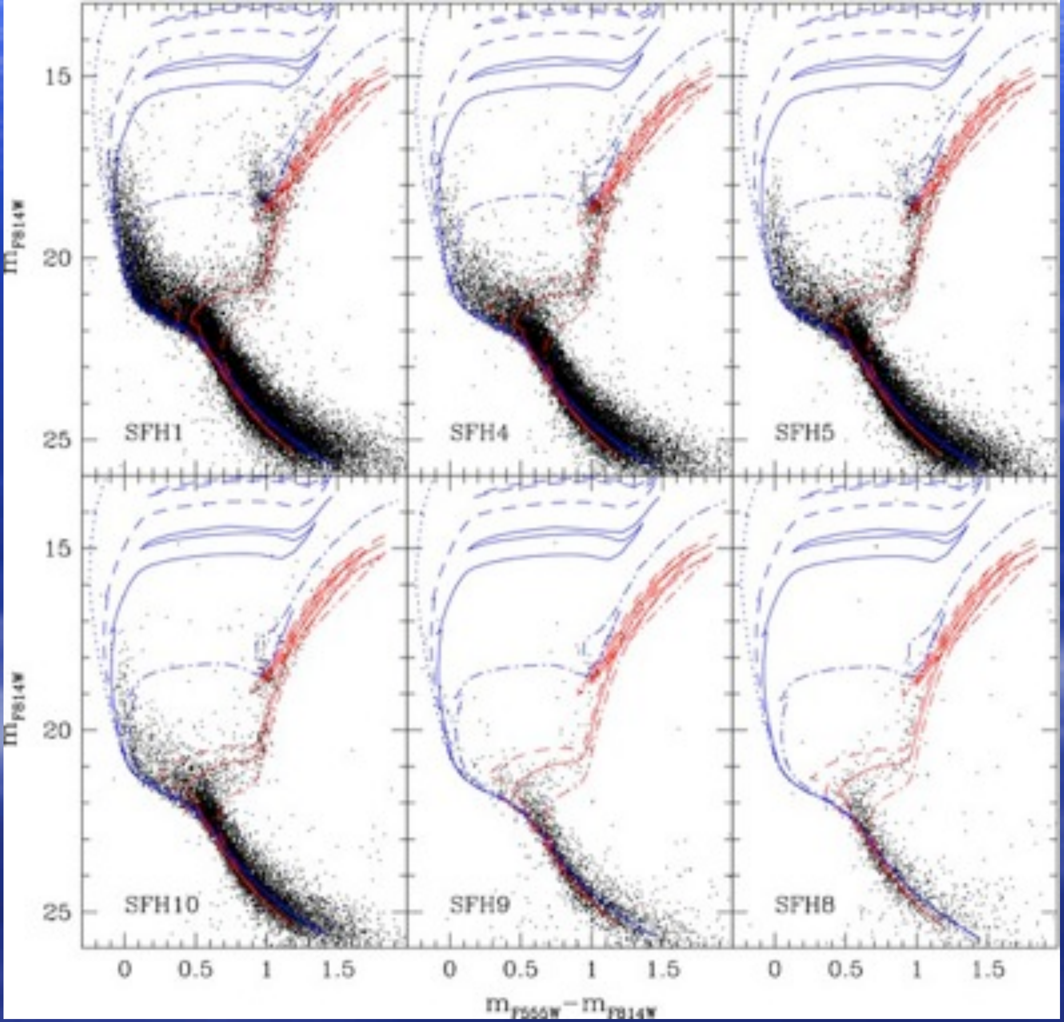
The Stellar Populations of the SMC

Field Stars in
6 SMC Locations

(Sabbi, et al. 2009)

Z = 0.004
Ages = 50, 100, & 500 Myr

Z = 0.001
Ages = 3, 5, & 12 Gyr



The Stellar Populations of the SMC

Full analysis of the CMDs is not complete yet, but simply from comparing the CMDs to isochrones, we find that the SMC does have 10-12 Gyr old stars. Just not that many. Thus the SMC had a slow start to its formation… which maybe a reason so few globular clusters formed in it.

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doi:10.1088/0004-637X/703/1/721

STAR FORMATION HISTORY OF THE SMALL MAGELLANIC CLOUD: SIX *HUBBLE SPACE TELESCOPE*/ADVANCED CAMERA FOR SURVEY FIELDS*

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ABSTRACT

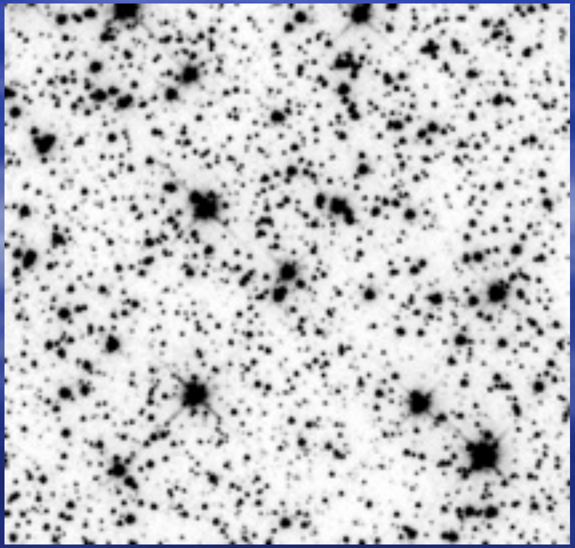
We observed six fields of the Small Magellanic Cloud (SMC) with the Advanced Camera for Survey on board the *Hubble Space Telescope* in the F555W and F814W filters. These fields sample regions characterized by very different star and gas densities, and, possibly, by different evolutionary histories. We find that the SMC was already forming stars ~12 Gyr ago, even if the lack of a clear horizontal branch suggests that in the first few billion years the star formation activity was low. Within the uncertainties of our two-band photometry, we find evidence of a radial variation in chemical enrichment, with the SMC outskirts characterized by lower metallicity than the central zones. From our color-magnitude diagrams, we also infer that the SMC formed stars over a long interval of time until ~2–3 Gyr ago. After a period of modest activity, star formation increased again in the recent past, especially in the bar and the wing of the SMC, where we see an enhancement in the star-formation activity starting from ~500 Myr ago. The inhomogeneous distribution of stars younger than ~100 Myr indicates that recent star formation has mainly developed locally.

Large Magellanic Cloud

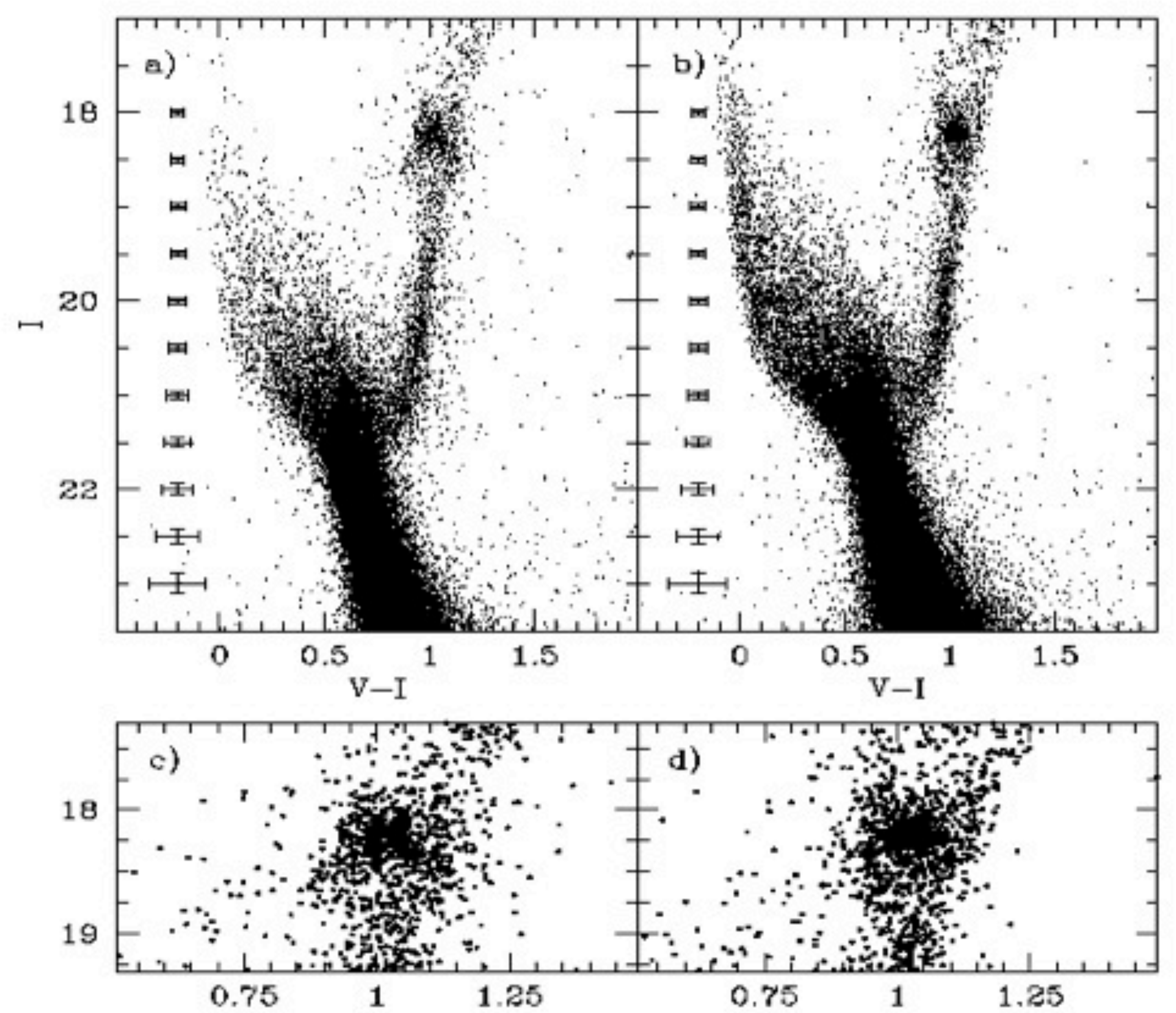
- Smecker-Hane, Cole, Gallagher & Stetson (2002) imaged star fields in the LMC with the WFPC2 on the Hubble Space Telescope (HST)

- Derived SFHs for the Bar and Disk 1 fields from the # stars as a function of magnitude on the main-sequence

- 5% of WFPC2 area shown at right; mean separation of stars with V ≤ 25 mag is ~ 6 pix = 0.6”



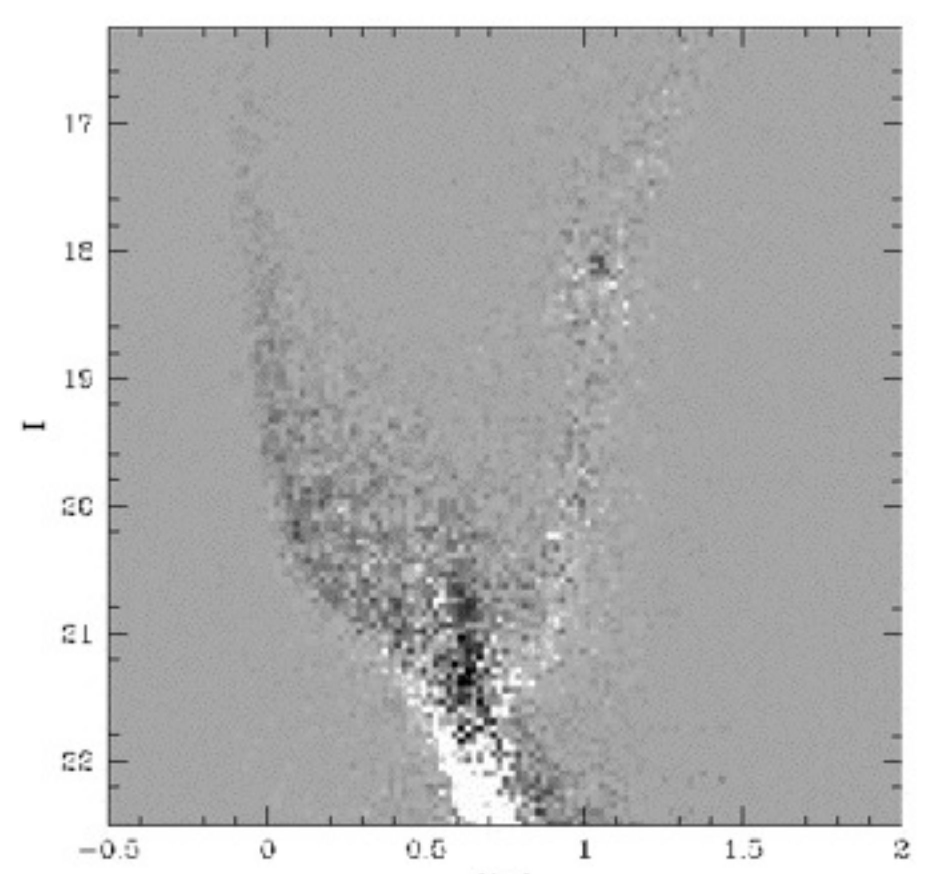
LMC Disk LMC Bar



LMC Field Stars

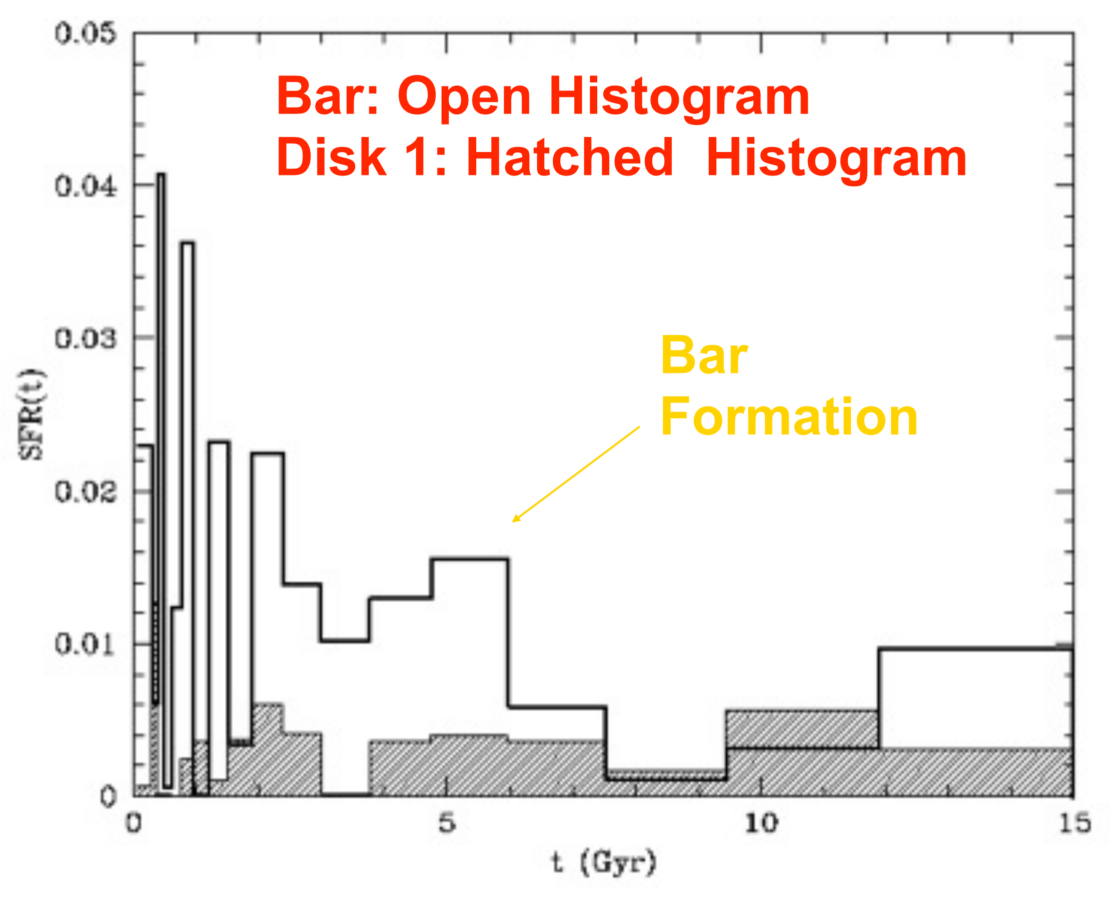
A Differential Hess Diagram

Black = Larger # stars in the Bar Field
White = Larger # stars in the Disk 1 Field



V– I

LMC Field Stars



LMC Global SFH & Chemical Evolution

Harris & Zaritsky (2009)

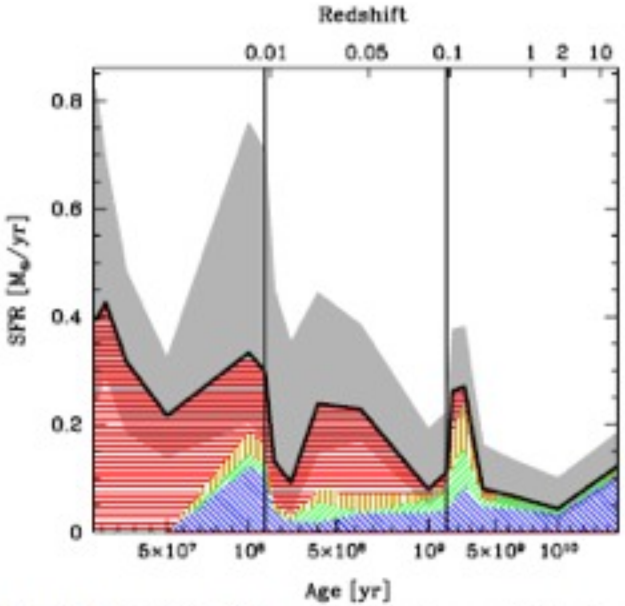


Figure 11. Total SFH of the LMC, computed by summing over all 1376 regions covering the MCPS survey region. The time axis is shown with a linear scale that is broken into three segments: the left panel covers ~100 Myr, the middle panel covers ~1 Gyr, and the right panel covers ~14 Gyr. The best-fit SFR as a function of age is shown with a thick black line; the uncertainty on the fit (including covariance between age bins) is shown as a gray shaded envelope. The distribution of metallicity at each age is shown by the mix of colors below the SFR line ($Z = 0.001$ in blue and downward sloping; $Z = 0.0025$ in green and upward sloping; $Z = 0.004$ in orange and vertical; $Z = 0.008$ in red and horizontal).

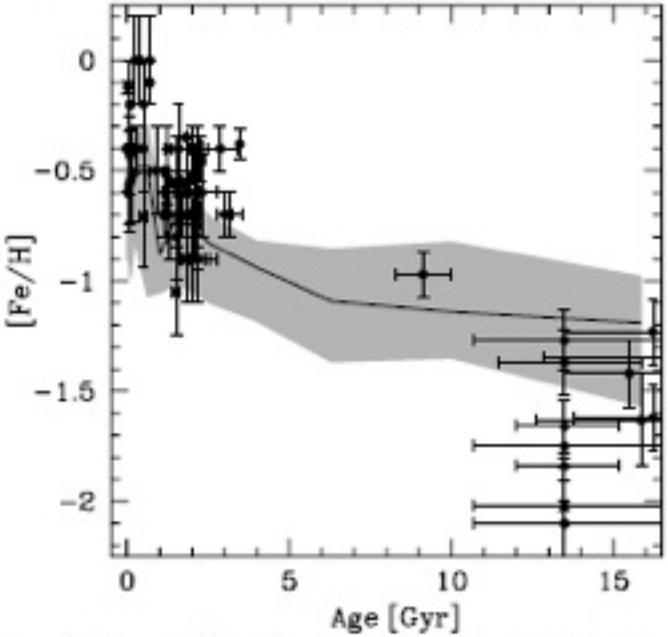


Figure 20. Age–metallicity relation for the LMC. The points with errorbars are 85 LMC star clusters which have age and metallicity measurements in the literature. The mean metallicity as a function of age derived from our SFH analysis is shown as a heavy line, and its statistical variance is shown as a gray envelope. Our analysis contains only a single value for ages older than 4 Gyr, because we anchored the old SFH to published results based on deep *HST* imaging.

The LMC

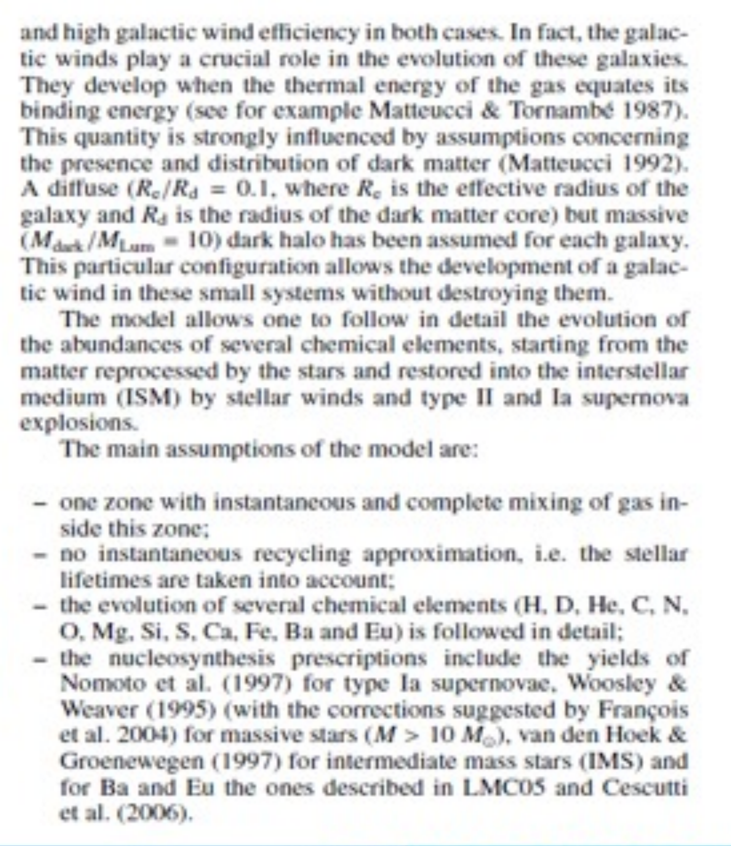
- SFR of the LMC Disk was nearly constant with time, not varying by more than a factor of 2 to 3 (Olsen 1999, Holtzman et al. 1999, Smecker-Hane et al. 2002, Harris & Zaritsky 2009)

- SFH of the LMC Bar is very different than the Disk
  - Initial formation of the bar ~ 4 to 6 Gyr ago, exact age depends on the assumed metallicity
  - SFR in last 1 to 2 Gyr also has been high in Bar

- The LMC, like the Leo I dSph, has a very flat age-metallicity relationship & highly-peaked metallicity distribution, implying continual gas accretion & outflow.

Chemical Evoln Modeling of dSphs

From Lanfranchi, Matteucci & Cescutti (2006), "*Detailed Evolution of Carina and Sagittarius dSph Galaxies*" …

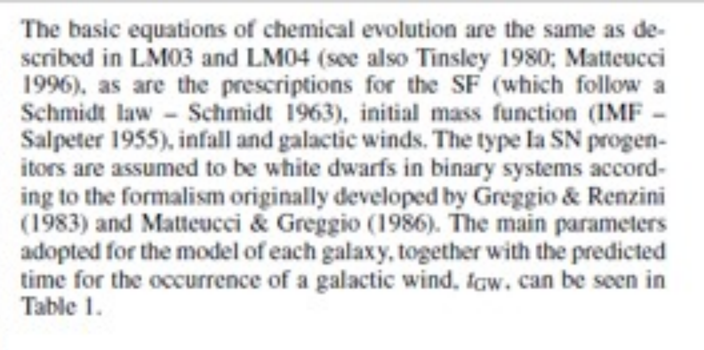


and high galactic wind efficiency in both cases. In fact, the galactic winds play a crucial role in the evolution of these galaxies. They develop when the thermal energy of the gas equates its binding energy (see for example Matteucci & Tornambè 1987). This quantity is strongly influenced by assumptions concerning the presence and distribution of dark matter (Matteucci 1992). A diffuse ($R_e/R_d = 0.1$, where R_e is the effective radius of the galaxy and R_d is the radius of the dark matter core) but massive ($M_{\rm dark}/M_{\rm Lum} = 10$) dark halo has been assumed for each galaxy. This particular configuration allows the development of a galactic wind in these small systems without destroying them.

The model allows one to follow in detail the evolution of the abundances of several chemical elements, starting from the matter reprocessed by the stars and restored into the interstellar medium (ISM) by stellar winds and type II and Ia supernova explosions.

The main assumptions of the model are:

- one zone with instantaneous and complete mixing of gas inside this zone;
- no instantaneous recycling approximation, i.e. the stellar lifetimes are taken into account;
- the evolution of several chemical elements (H, D, He, C, N, O, Mg, Si, S, Ca, Fe, Ba and Eu) is followed in detail;
- the nucleosynthesis prescriptions include the yields of Nomoto et al. (1997) for type Ia supernovae, Woosley & Weaver (1995) (with the corrections suggested by François et al. 2004) for massive stars ($M > 10\ M_\odot$), van den Hoek & Groenewegen (1997) for intermediate mass stars (IMS) and for Ba and Eu the ones described in LMC05 and Cescutti et al. (2006).

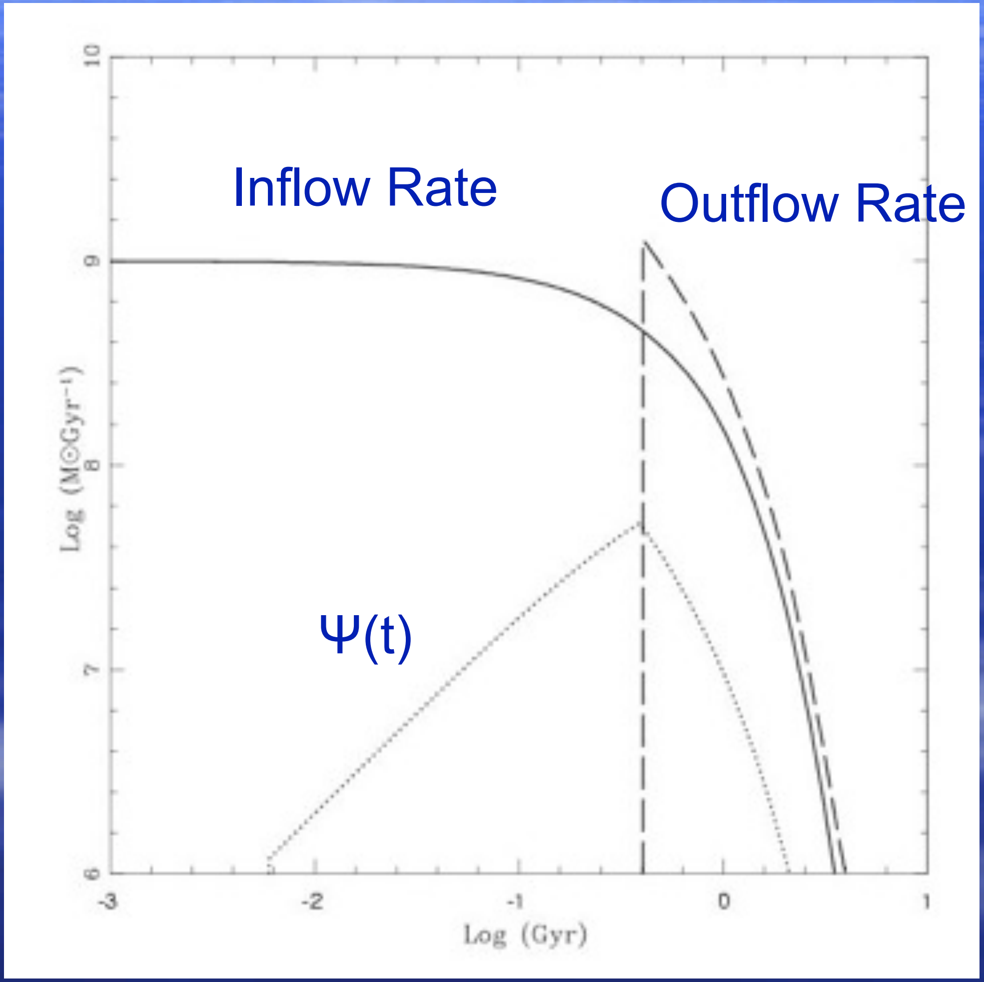


The basic equations of chemical evolution are the same as described in LM03 and LM04 (see also Tinsley 1980; Matteucci 1996), as are the prescriptions for the SF (which follow a Schmidt law – Schmidt 1963), initial mass function (IMF – Salpeter 1955), infall and galactic winds. The type Ia SN progenitors are assumed to be white dwarfs in binary systems according to the formalism originally developed by Greggio & Renzini (1983) and Matteucci & Greggio (1986). The main parameters adopted for the model of each galaxy, together with the predicted time for the occurrence of a galactic wind, $t_{\rm GW}$, can be seen in Table 1.

Chem Evoln Modeling of Ursa Minor dSph

Cescuti & Matteucci (2008, priv. comm.)

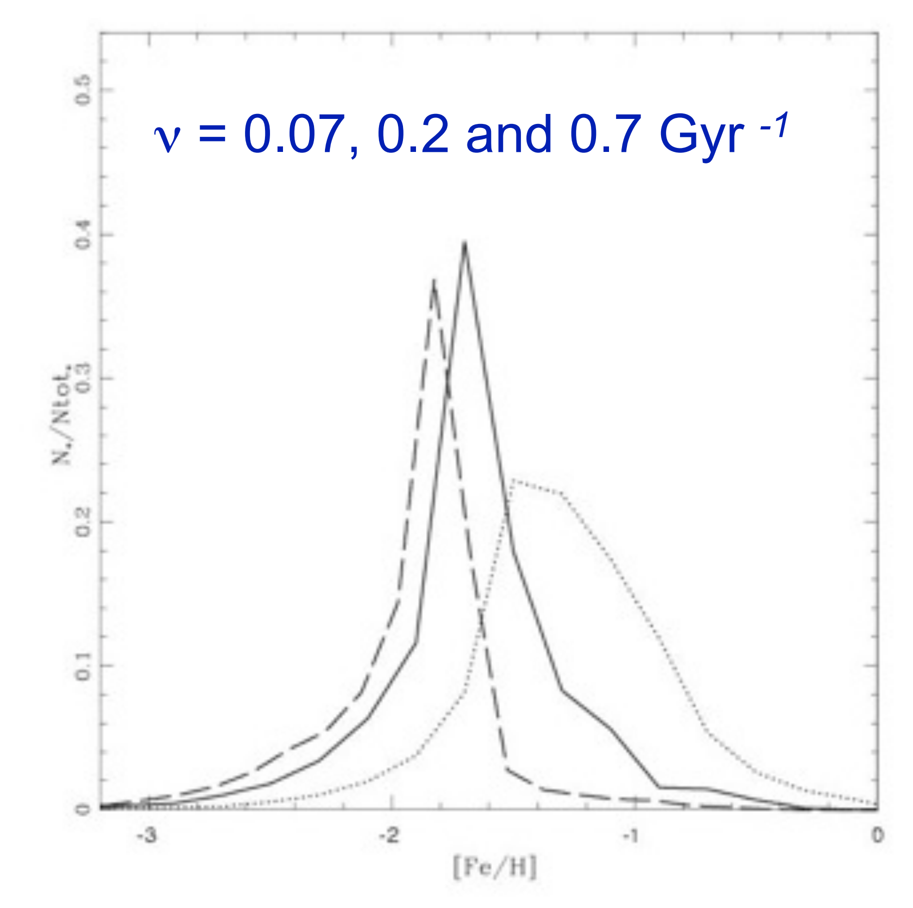
- *SF ends after ~ 4 Gyr*
- *Requires both inflow of pristine gas and outflow of metal-enriched winds*



Chem Evoln Modeling of Ursa Minor dSph

Chemical Evoln models from Cescuti & Matteucci (2008, priv. comm.)

- *Designed to re-produce the observed phot metallicity distribution*
- $\Psi(t) = \nu\, M_{gas}(t)$
- $M_{outflow}(t) = w\, \Psi(t)$
- Best Fit for $\nu = 0.2$ *Gyr* $^{-1}$ *and* $w = 10$



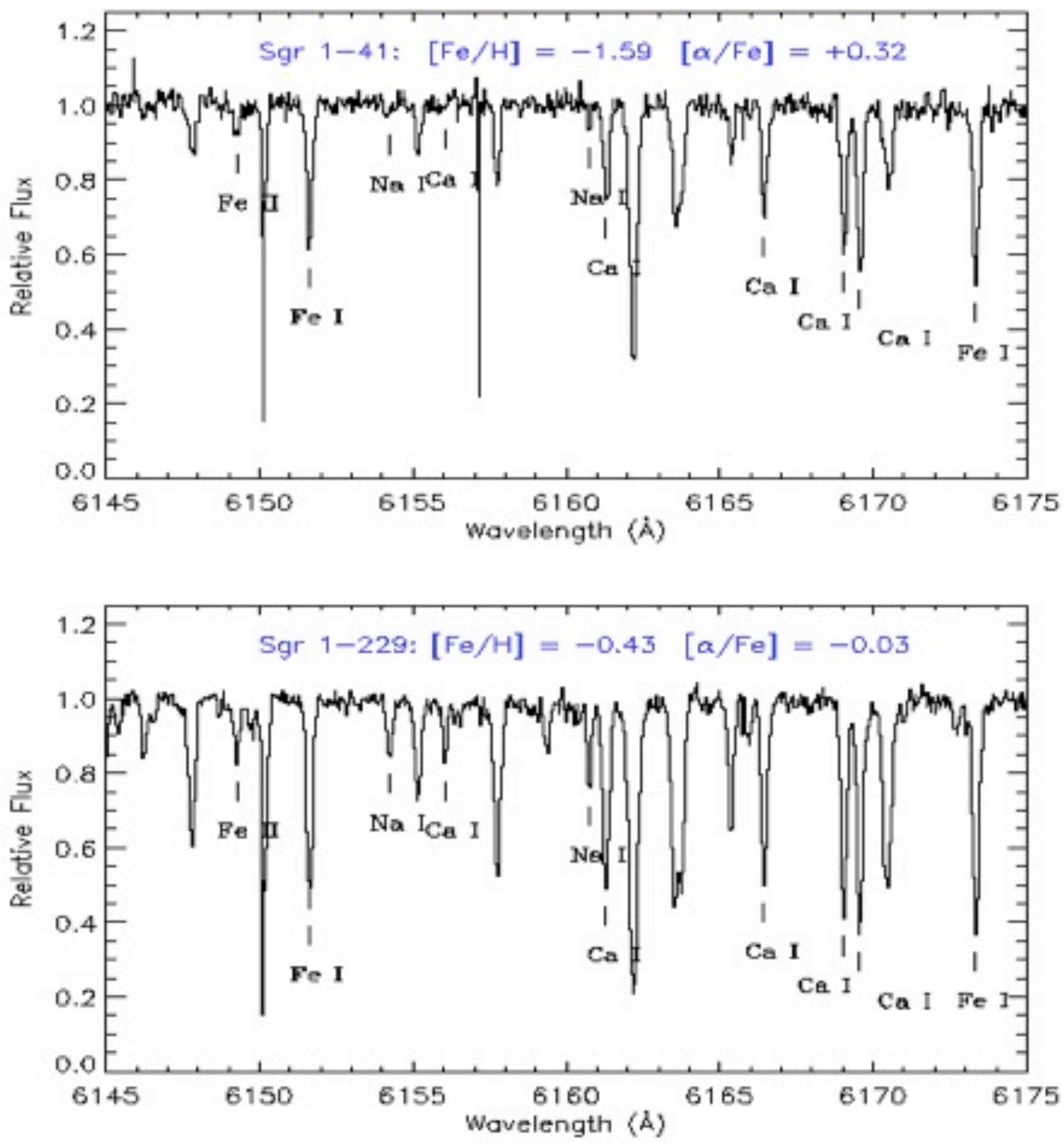
Chemical Evolution

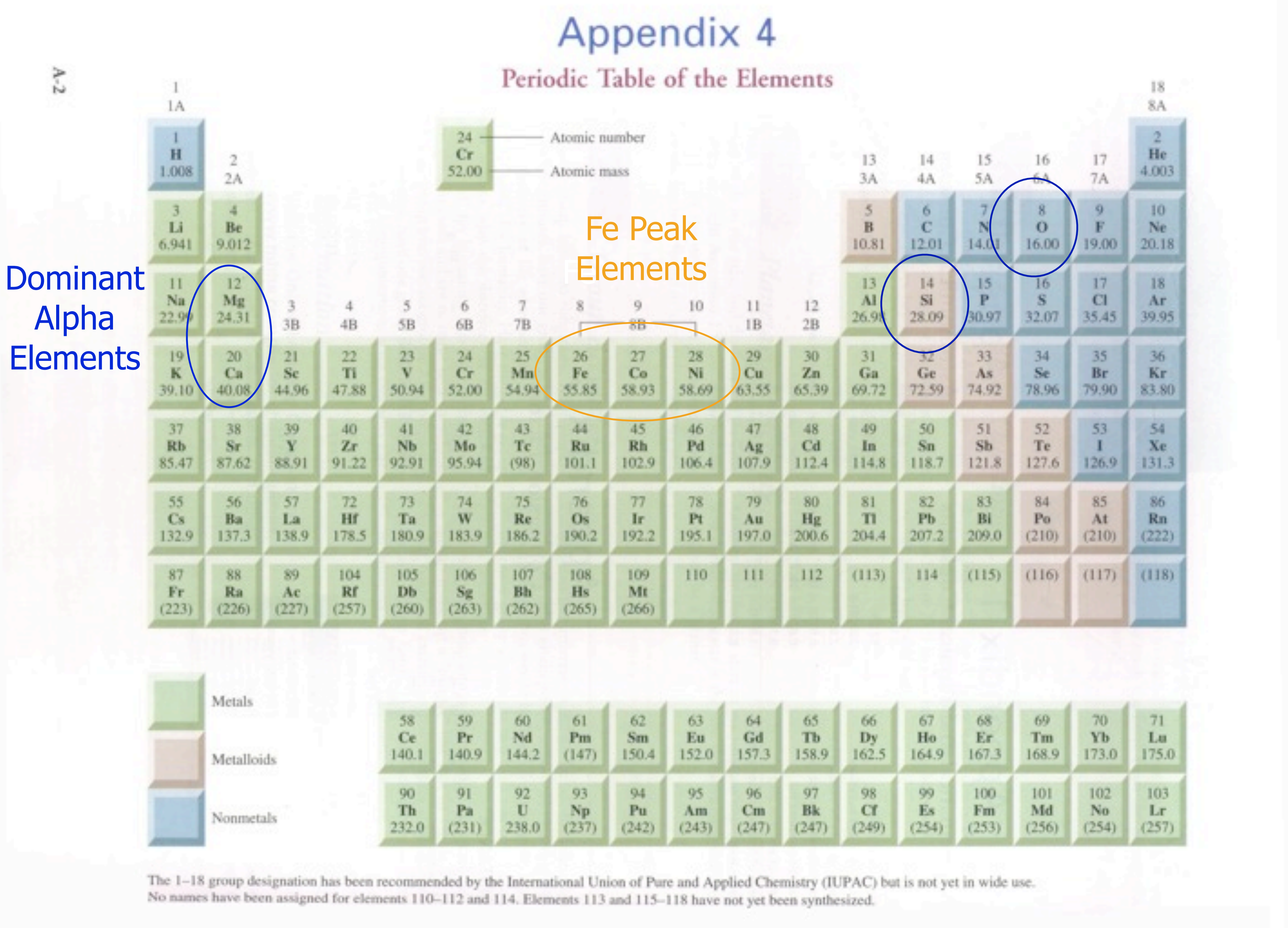
- A flat age-metallicity relationship (or very peaked metallicity distribution) often implies both inflow and outflow is needed, i.e, Leo I dSph, LMC, SMC.
- BUT … in order to solve the “Missing Satellite Problem” cosmologists assume most of the reservoir of gas that could accrete onto dwarfs over time is “boiled off” during reionization. If so, then where do dSphs accrete pristine gas to sustain their star formation over most of the Hubble time?

Another New Frontier in dSph Research: High Dispersion Spectroscopy

- Today large telescopes allow us to get high dispersion spectra of stars in Local Group galaxies
  - Keck 10m + HIRES (single star; multiple orders)
  - VLT + fiber-fed UVES (multiple stars; single order)
- What can you learn?
  - Numerous chemical abundances
  - Because different elements are produced on different timescales, element ratios in stars give you powerful constraints on inflow/outflow of gas from the galaxy
    - α elements (Type II SNe/explode quickly)
    - Fe-peak elements (Type Ia SNe/explode over long timescales)
    - s-process elements (AGB stars/medium? slow?)
    - r-process elements (SNe/quickly)

HIRES Spectra of 2 Sagittarius dSph Stars (Smecker-Hane & McWilliam 2005)





Appendix 4

Periodic Table of the Elements

Dominant Alpha Elements

Fe Peak Elements

24 Cr 52.00 — Atomic number: 24; Atomic mass: 52.00

1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1 H 1.008																	2 He 4.003
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (257)	105 Db (260)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110	111	112	(113)	114	(115)	(116)	(117)	(118)

58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (147)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
90 Th 232.0	91 Pa (231)	92 U 238.0	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (254)	103 Lr (257)

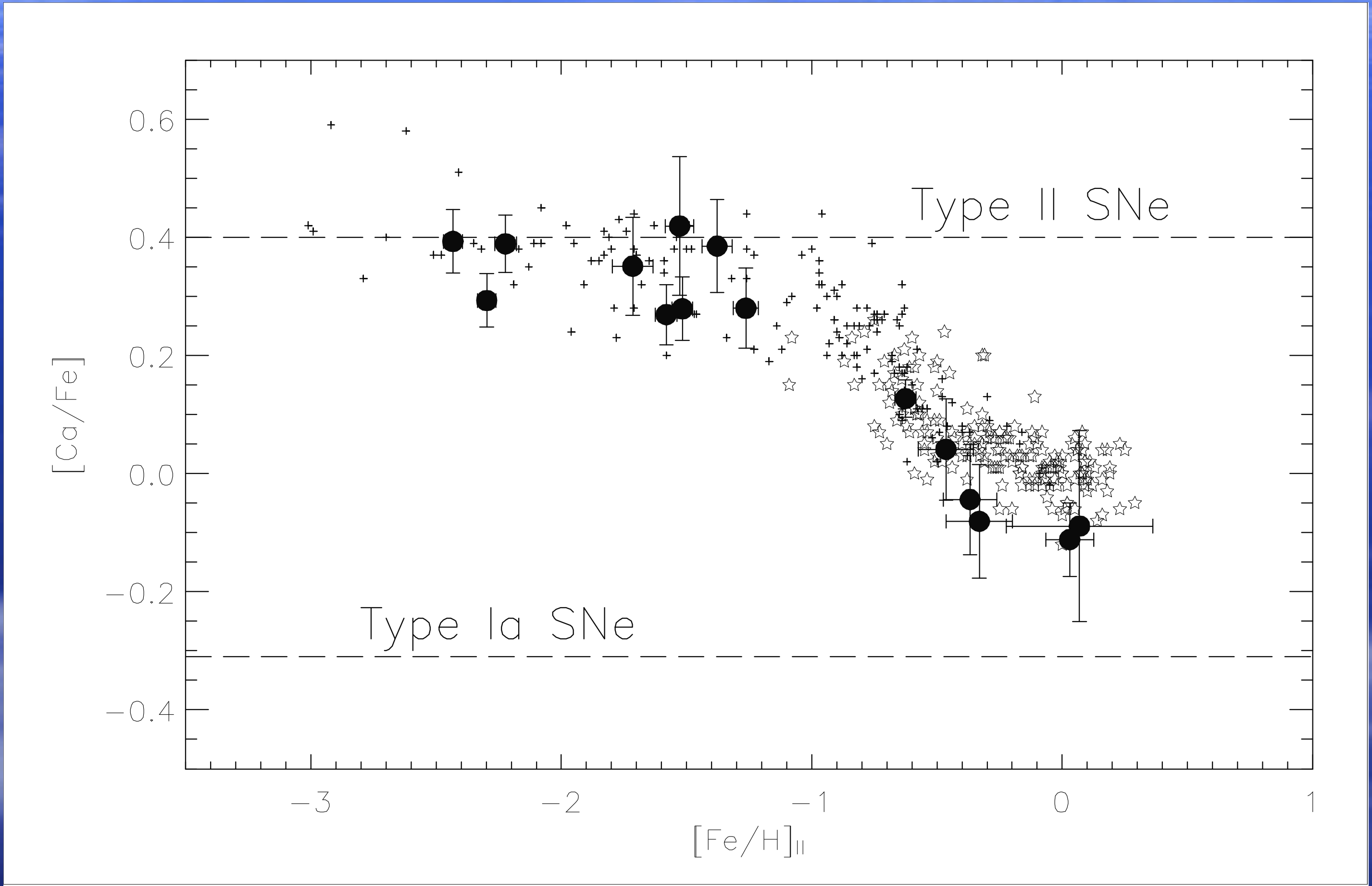
🟩 Metals

🟫 Metalloids

🟦 Nonmetals

The 1–18 group designation has been recommended by the International Union of Pure and Applied Chemistry (IUPAC) but is not yet in wide use. No names have been assigned for elements 110–112 and 114. Elements 113 and 115–118 have not yet been synthesized.

Galactic Star Clusters vs Field Stars



Open and Globular Clusters: • Bosler (2004)

Field Stars: ☆ Edvardsson et al. (1993), + Fulbright (2000)

Supernovae Nucleosynthesis

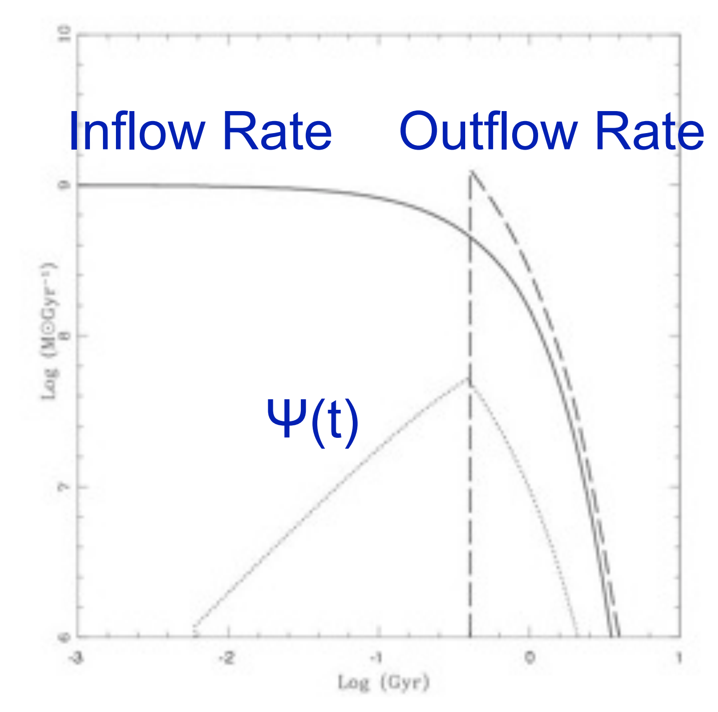
- **Type II SNe:**
  - Core collapse of a massive ($\geq 6\ M_{¤}$) star
  - Intermediate mass elements ejected **10^7 - few x 10^8 yr** after stars form
  - α elements: O, Mg, Si, S, Ca, Ti
  - Yields: **[α/Fe] = +0.35 [Na/Fe] = 0 [Al/Fe] = 0** (e.g., McWilliam 1997; Woosley,Timmes & Weaver 1993)

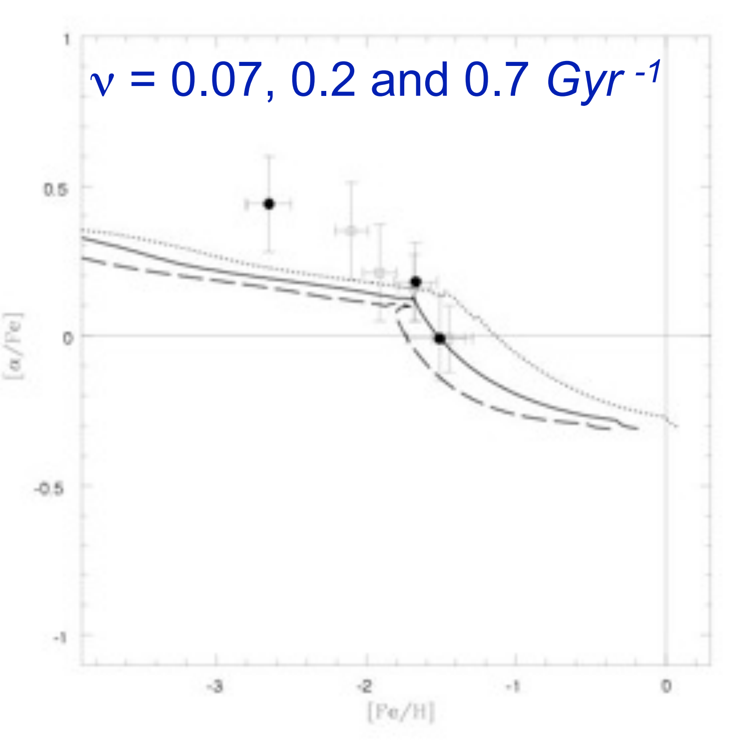
- **Type Ia SNe:**
  - Accretion induced collapse of a white dwarf ($M_{WD} > 1.4\ M_{¤}$)
  - Fe-peak elements ejected **≥ 0.1 Gyr – many Gyr** after stars form
  - Yields: **[α/Fe] = –0.36 [Na/Fe]= –4.0 [Al/Fe]= –1.8** (Thielemann, Nomoto & Yokoi 1986)

Chem Evoln Modeling of Ursa Minor dSph

Cescuti & Matteucci (2008, priv. comm.)

Assumptions: $\Psi(t) = \nu\, M_{gas}(t)$ & $M_{outflow}(t) = w\, \Psi(t)$



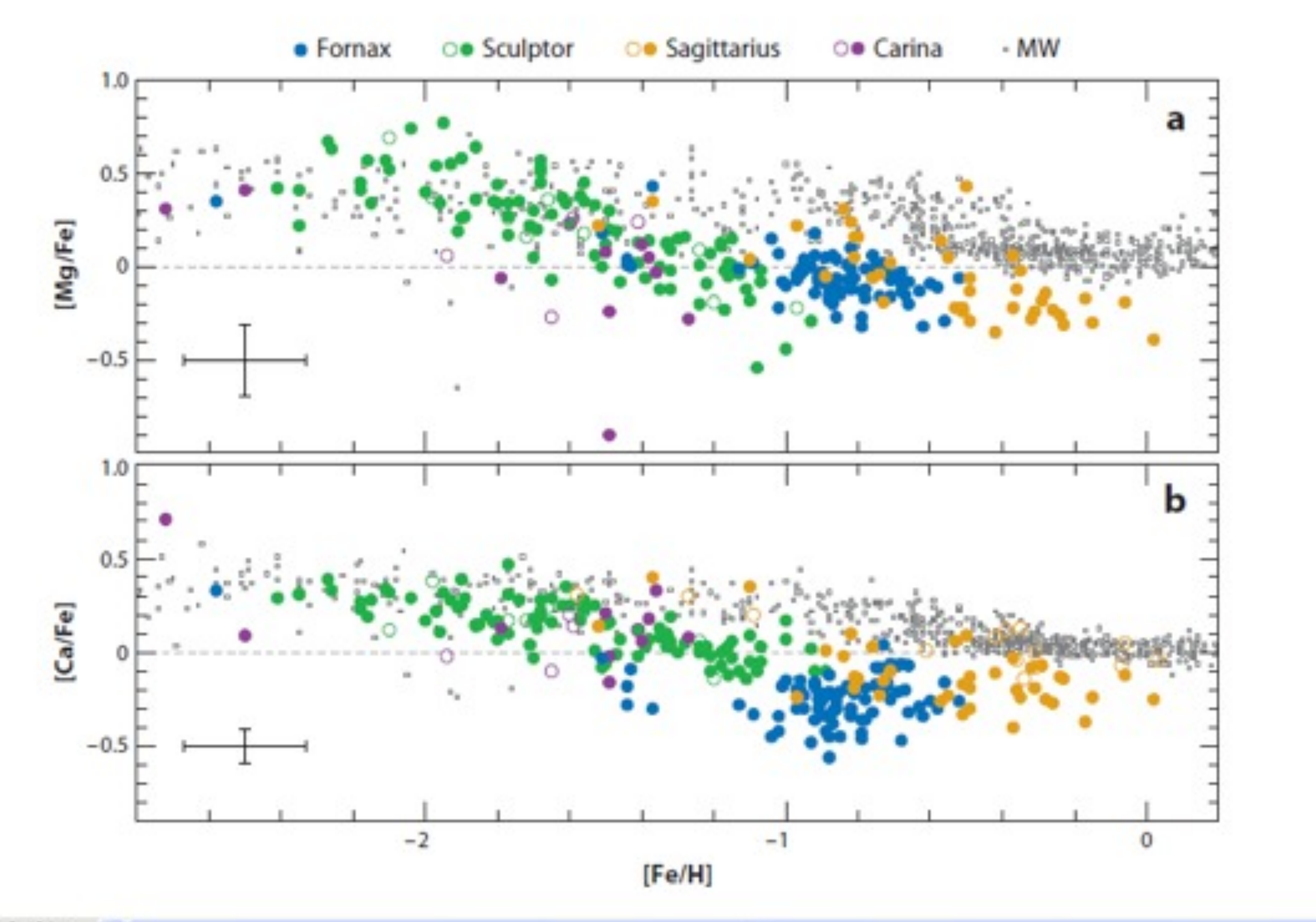


What about [α/Fe] in other dSphs & the Milky Way?

Tolstoy, Hill & Tosi (2009)

Trend w/ galaxy luminosity

Trend inside individual galaxies



M31: The Andromeda Galaxy

Brown et al. used HST to image numerous fields in M3 in a series of papers from 2003 – 2009

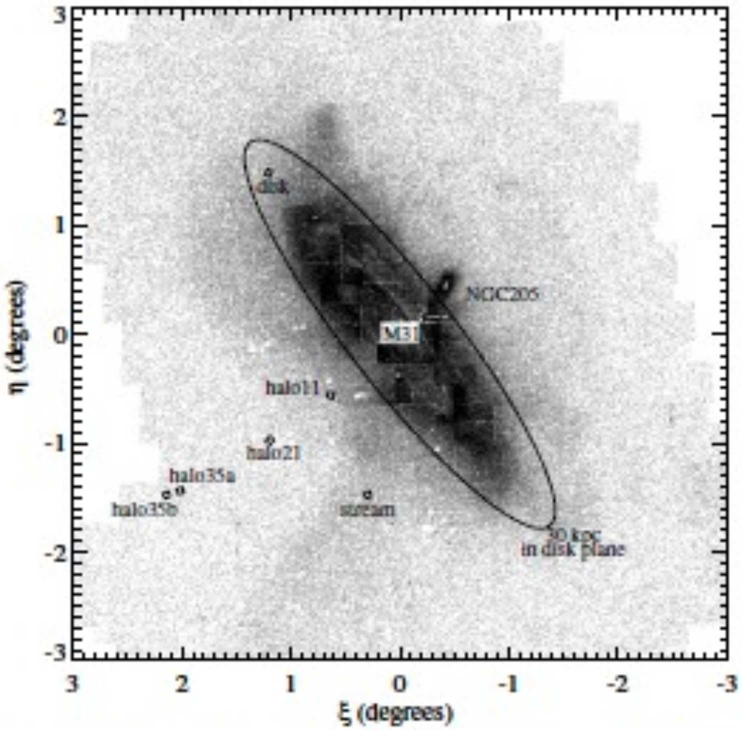


Figure 1. Stellar density in the Andromeda vicinity, from counts of RGB stars (Ferguson et al. 2002). Our six fields are indicated (labeled boxes). An ellipse marks the area within 30 kpc of the galactic center in the inclined disk plane (labeled). Later surveys that go wider and deeper (e.g., Ibata et al. 2007) show an even greater wealth of substructure in the system.

M31: The Andromeda Galaxy

Brown et al. (2008)

M31 “Halo” Results:

- The 11 kpc field is contaminated with stars from M31’s extended outer disk
- Halo of M31 @ 21 and 35 kpc is mostly old, but has an age spread and a wide range of metallicity

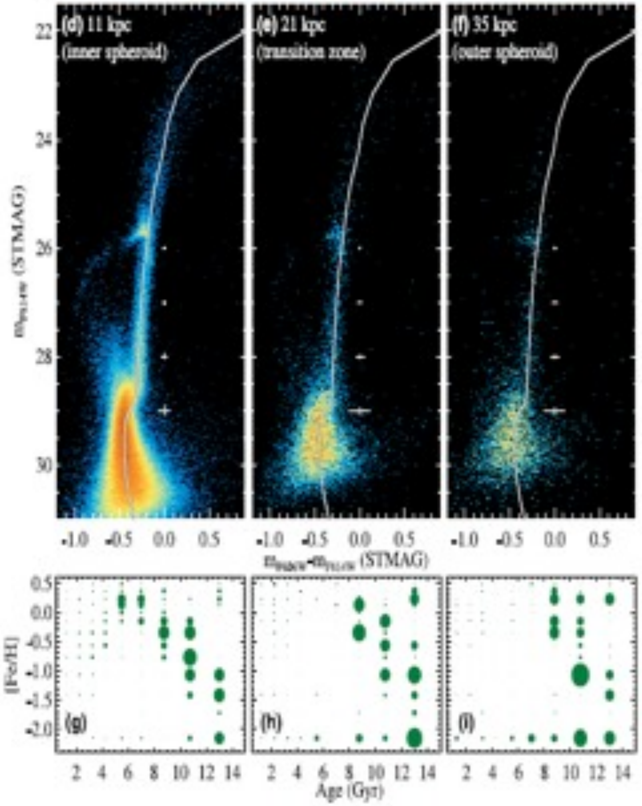


FIG. 2.—(a–c) Velocities for RGB stars within 9′ of our 11 kpc field, 14′ of our 21 kpc field, and 17′ of our 35 kpc fields (blue histograms); these samples are taken from survey regions that include and surround our ACS fields. The velocities in each region exhibit a broad distribution near the M31 systemic velocity (dotted line). To better demonstrate the broad (i.e., hot) distribution of velocities in the 35 kpc sample, we also show a data set (gray histogram) that includes a region ~30′ to the west of our 35 kpc field; Gilbert et al. (2007) find no significant cold component in this region. (d–f) CMDs for the populations at 11, 21, and 35 kpc. The ridgeline of 47 Tuc (white curve; Brown et al. 2005), shifted to the M31 distance of 770 kpc (Freedman & Madore 1990) with a reddening of $E(B-V) = 0.08$ mag (Schlegel et al. 1998), is shown for reference. (g–i) Best-fit star formation histories for the populations at 11, 21, and 35 kpc, from StarFish. The area of each filled circle is proportional to the number of stars at that age and metallicity. The populations in all three fields exhibit broad ranges of metallicity and age, but the population at 11 kpc includes far more stars younger than 8 Gyr (due at least in part to debris from the GSS).

Conclusions

1. Star Formation Histories
   SFHs derived from CMDs tell us how galaxies convert their gas into stars; SFHs vary widely in Local Group galaxies, but all began forming stars shortly after the Big Bang and many galaxies have only recently run out of gas

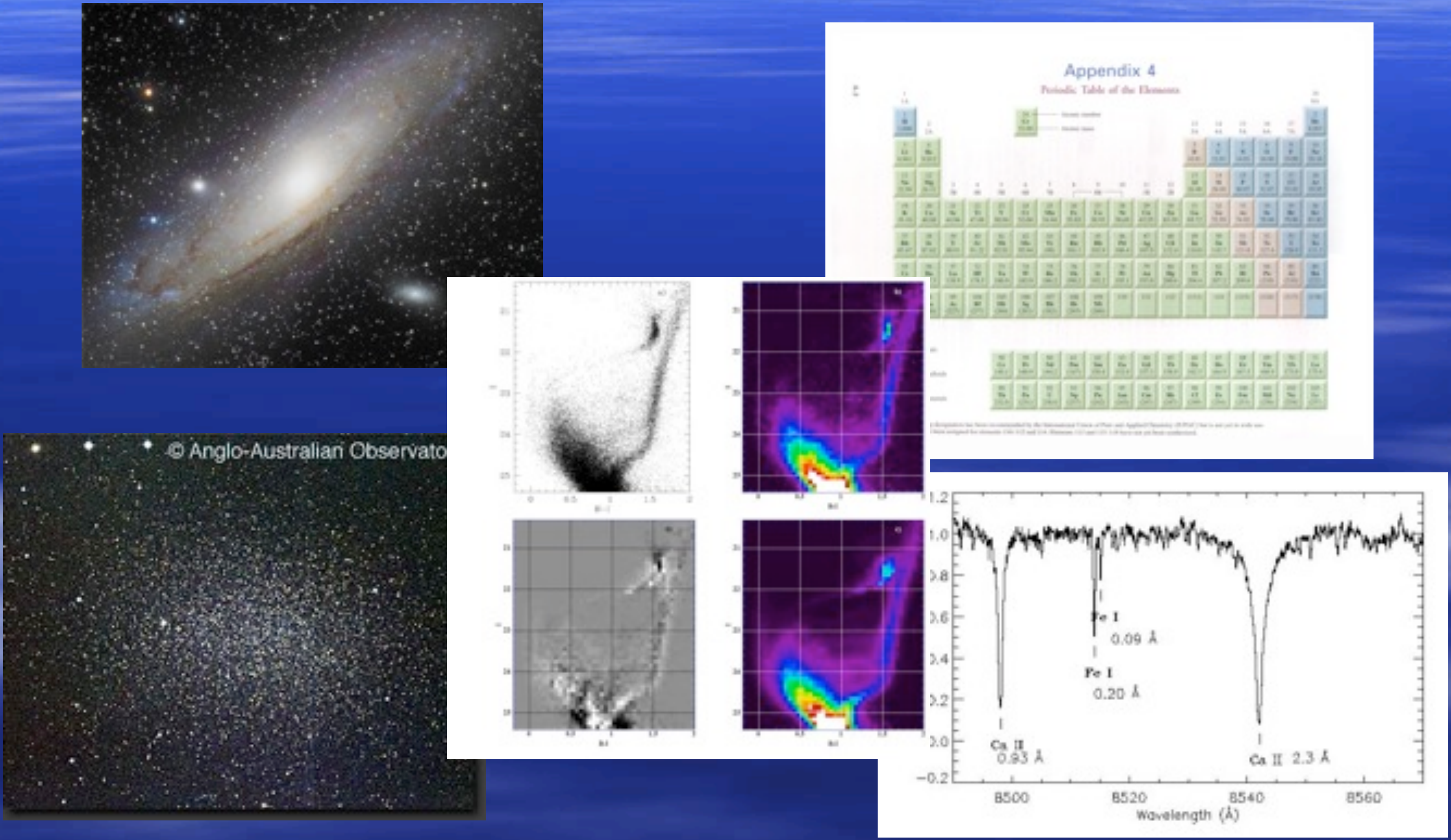
2. Chemical Abundance Distributions of Stars in dSphs

   CaT spectroscopy & CMD analysis can yield information on the metallicity distribution of stars; most galaxies seem to have flat age-metallicity relationships implying infall of pristine gas over long times and outflow of metal-enriched winds

3. Chemical Evolution of dSphs

   Measuring the evolution of numerous chemical elements with echelle spectroscopy can teach us much about the physics regulating galaxy evolution (inflow/outflow of gas)

Thanks for your Attention ... Any Questions?



Stellar Populations of Galaxies

Questions:

Do all galaxies have stellar halos?

What about a bulge-less spiral like M33?

Do the ages and metallicities of the stars in the halos match the predictions of sophisticated hierarchical galaxy formation simulations, and can they be tested over a range of galaxy luminosity?

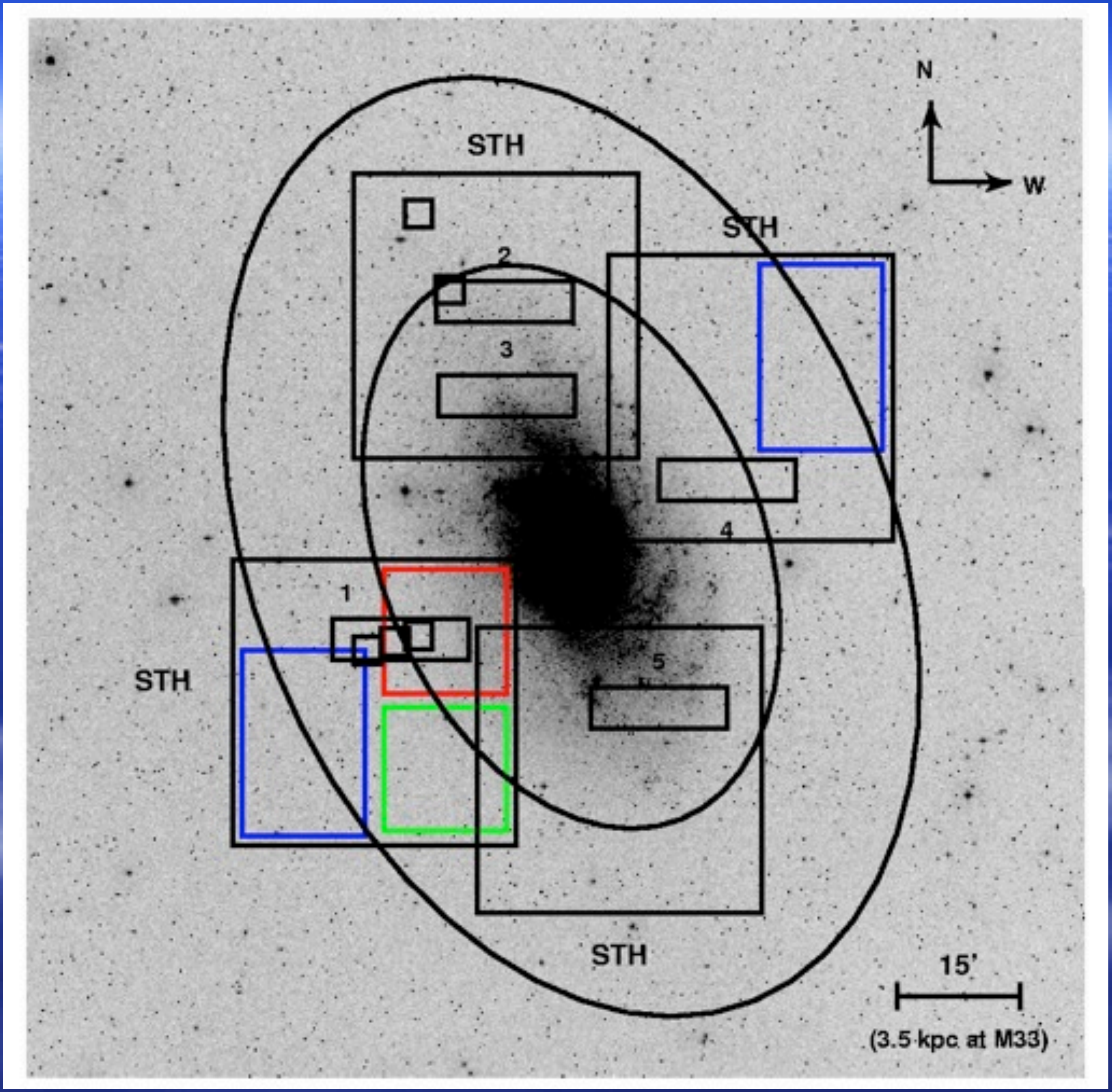
M33 Spectroscopic Survey

- With Michael Hood, Matt Teig, Annette Ferguson & Mike Irwin, and myself

- Spectra taken w/ Keck II 10-m telescope and the DEep Imaging Multi-Object Spectrograph (DEIMOS)

The areas studied in different parts of this project

DEIMOS spectrscopic fields are the long & narrow fields.



M33 Spectroscopic Survey

- Dispersion = 0.47 Å/pix, Resolution = 1.8 Å
- Exposure time = 3 hrs
- Average S/N per pixel = 6   (3.5 to 15)
- Average Velocity Error = 9 km/s
- Field of View over which slits are placed is 16.3′ x 5.0′
- Multiplexing is key to getting to our eventual goal: observing ~ 400 M33 RGB stars

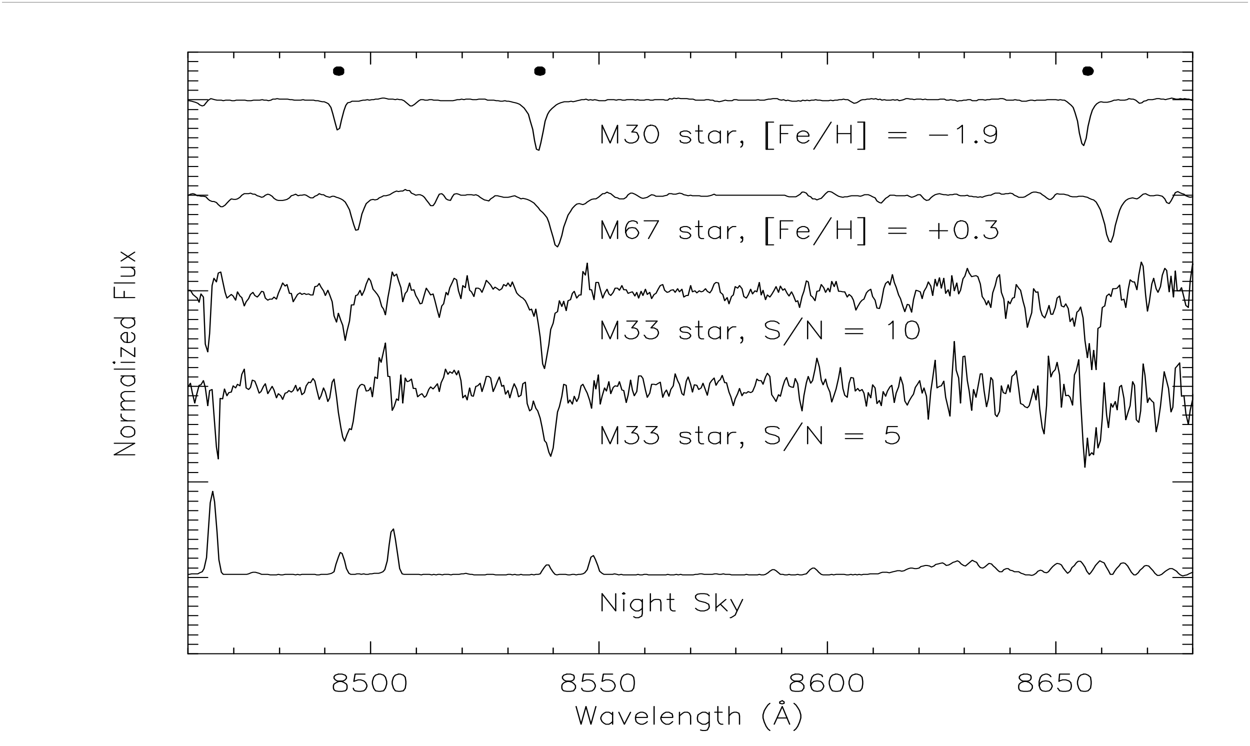
M33 Spectroscopic Survey

- Initial runs selected stars for spectroscopy based on Ferguson et al.'s photometric survey (Ferguson et al. 2006)
- Judge whether or not M33 or Milky Way stars after the fact using our DDO51 photometry
- Kinematic results presented here for 173 stars which are likely M33 members based on DDO51 photometry and relative densities of stars in the Hess diagrams of the "cleaned" MWay and M33 CMDs

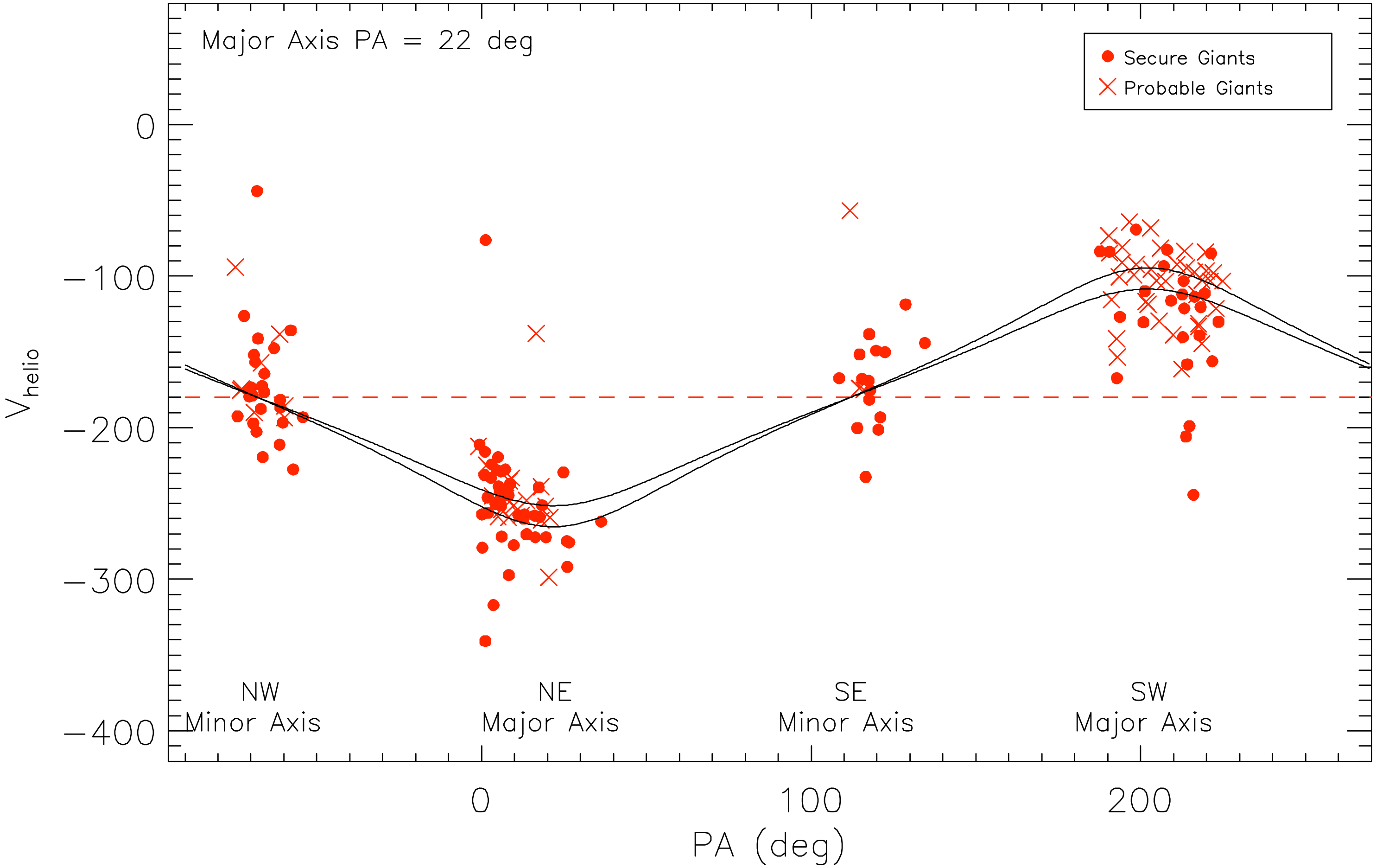
Spectra of the Calcium Lines

3 Calcium Absorption Lines:

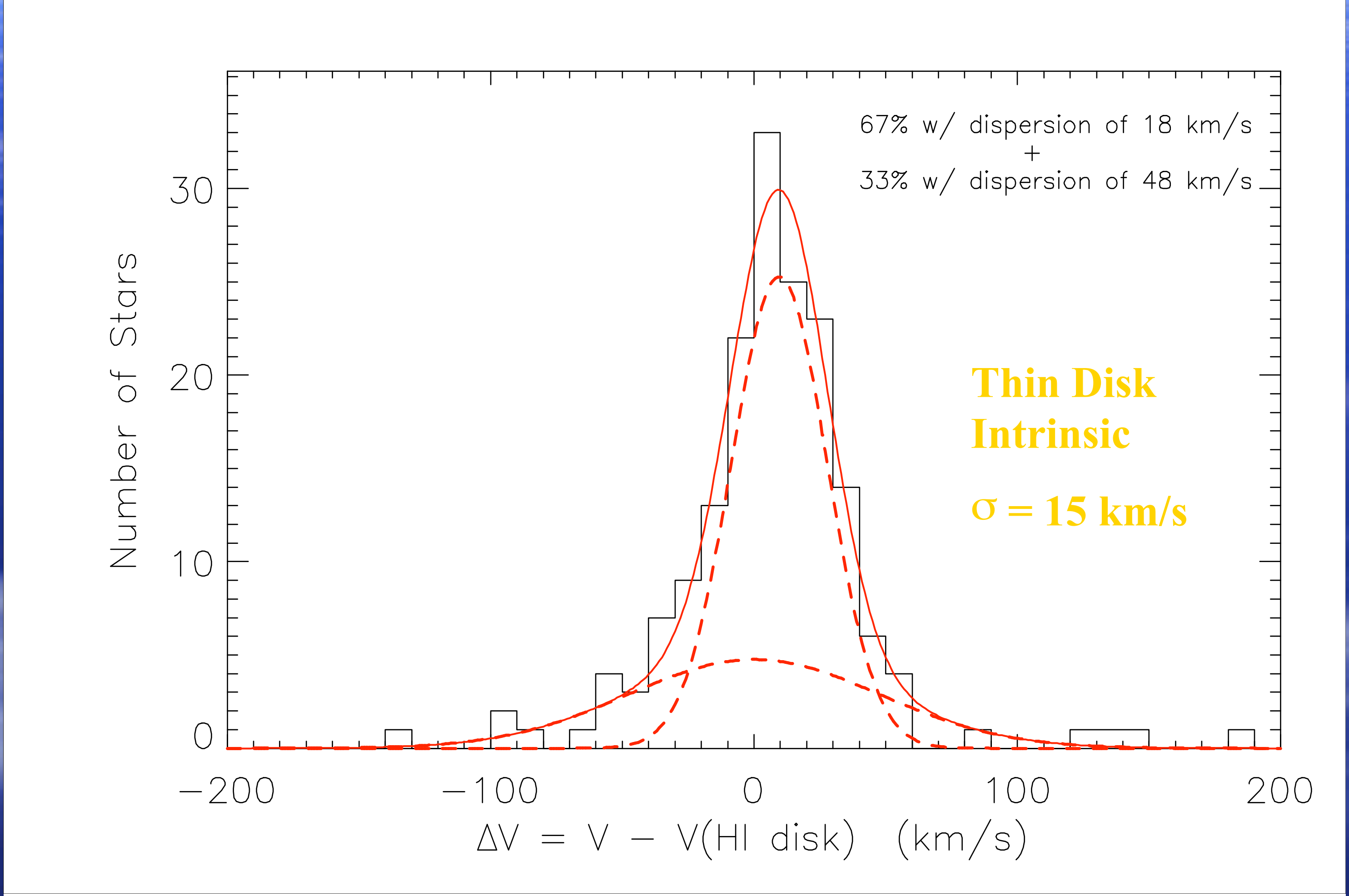
- Wavelength → star's velocity along the line of sight
- Depth → abundance of Calcium in the star (Ca/H)



Heliocentric Velocity vs Position Angle



M33 Velocity Results



Thin Disk Intrinsic

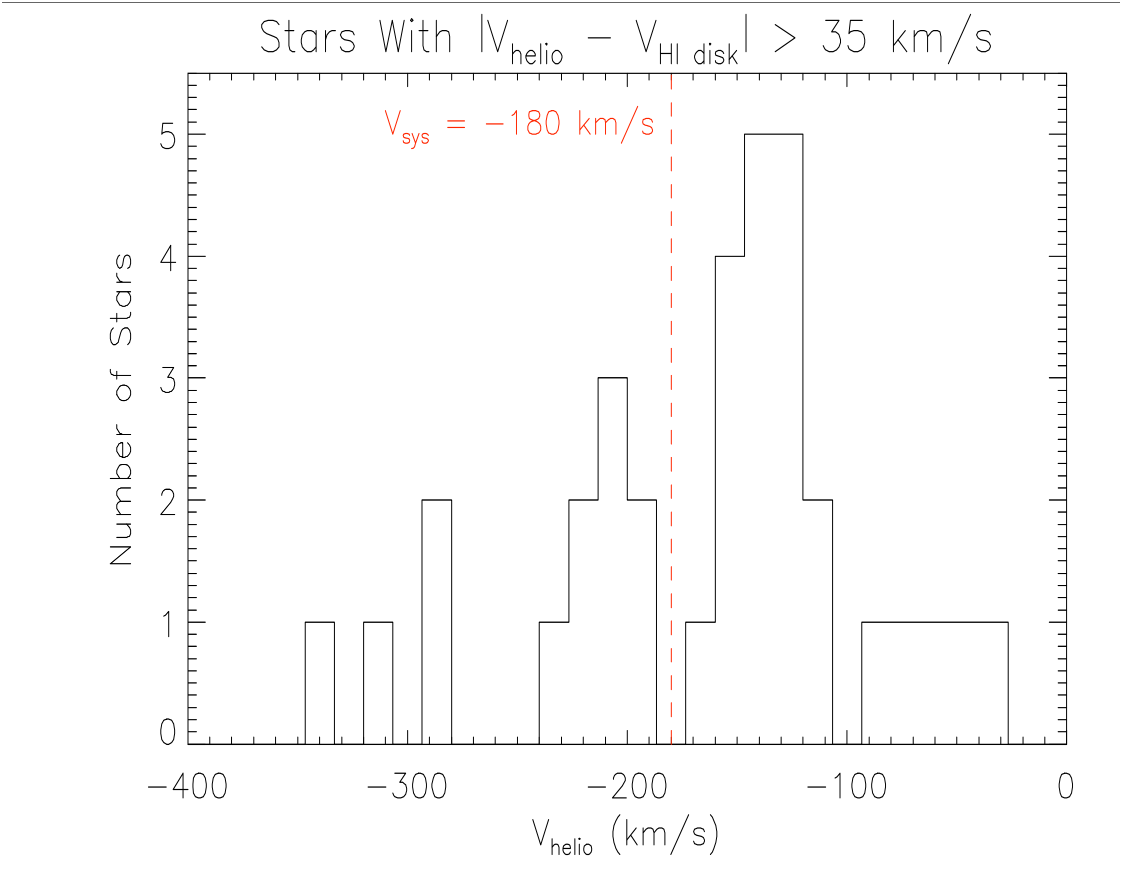
σ = 15 km/s

The Stellar Halo of M33

Omitting Rotating Disk Stars (|Δv | < 35 km/s), what is the intrinsic dispersion in heliocentric velocity?

N = 34 stars

Simple Calculation:
<Vhelio> = –170 km/s
RMS implies a Halo intrinsic σ = 72 km/s

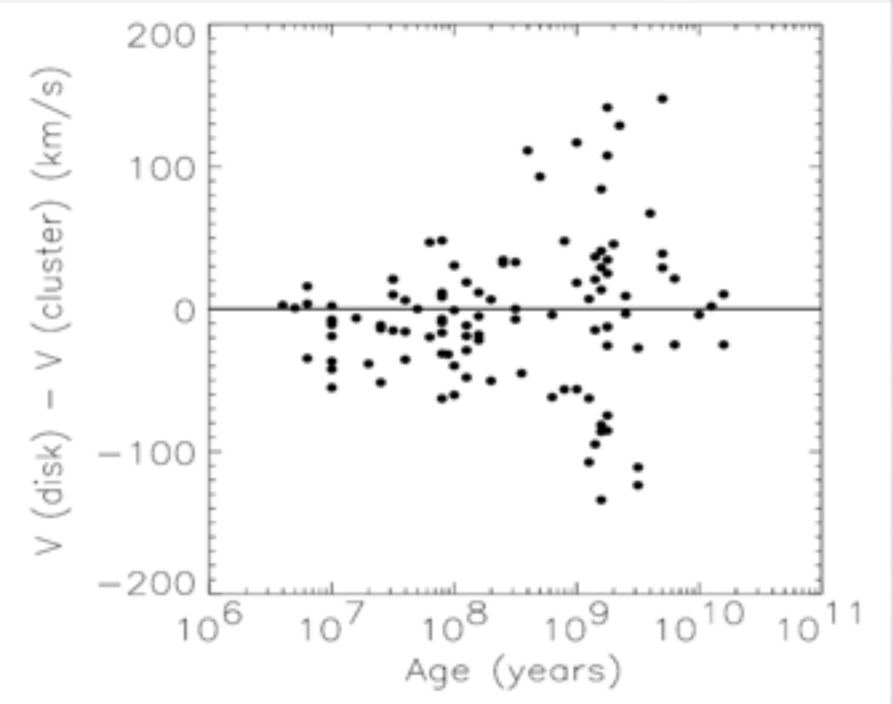


M33 Star Clusters

- M33 does have a population of star clusters that have much higher velocity dispersion than the HI disk (Chandar et al. 2002)

- Clusters w/
  age > 1 Gyr
  have σ = 68 km/s

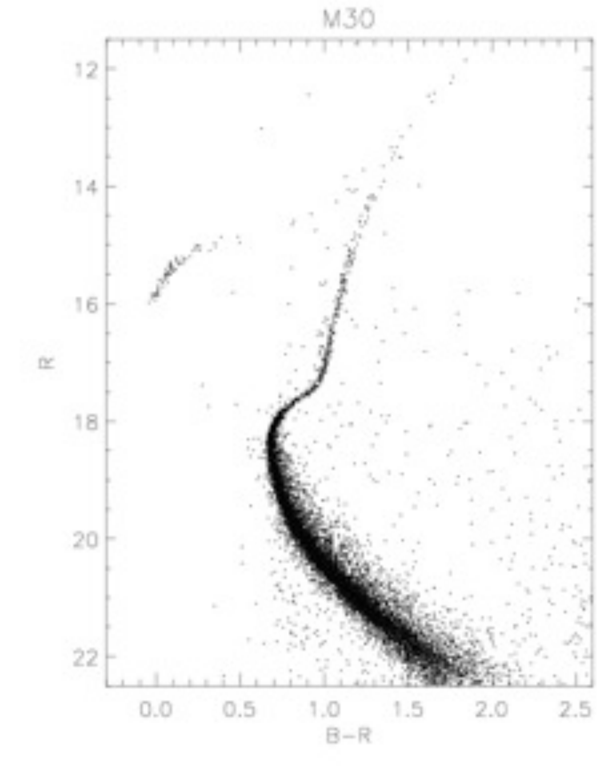
- However only 18
  clusters have
  kinematics that are
  inconsistent
  with disk rotation



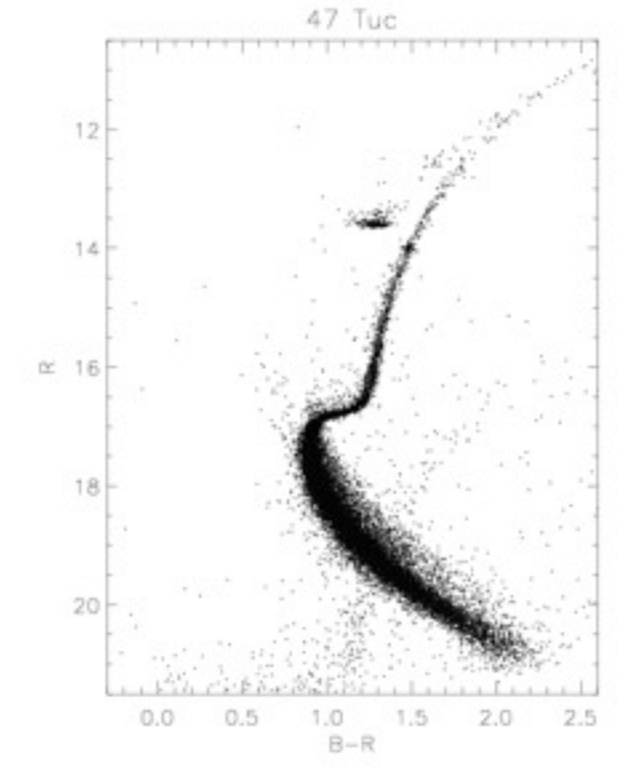
Globular Clusters

Two different clusters with about the same age, but very different chemical abundances (×25)

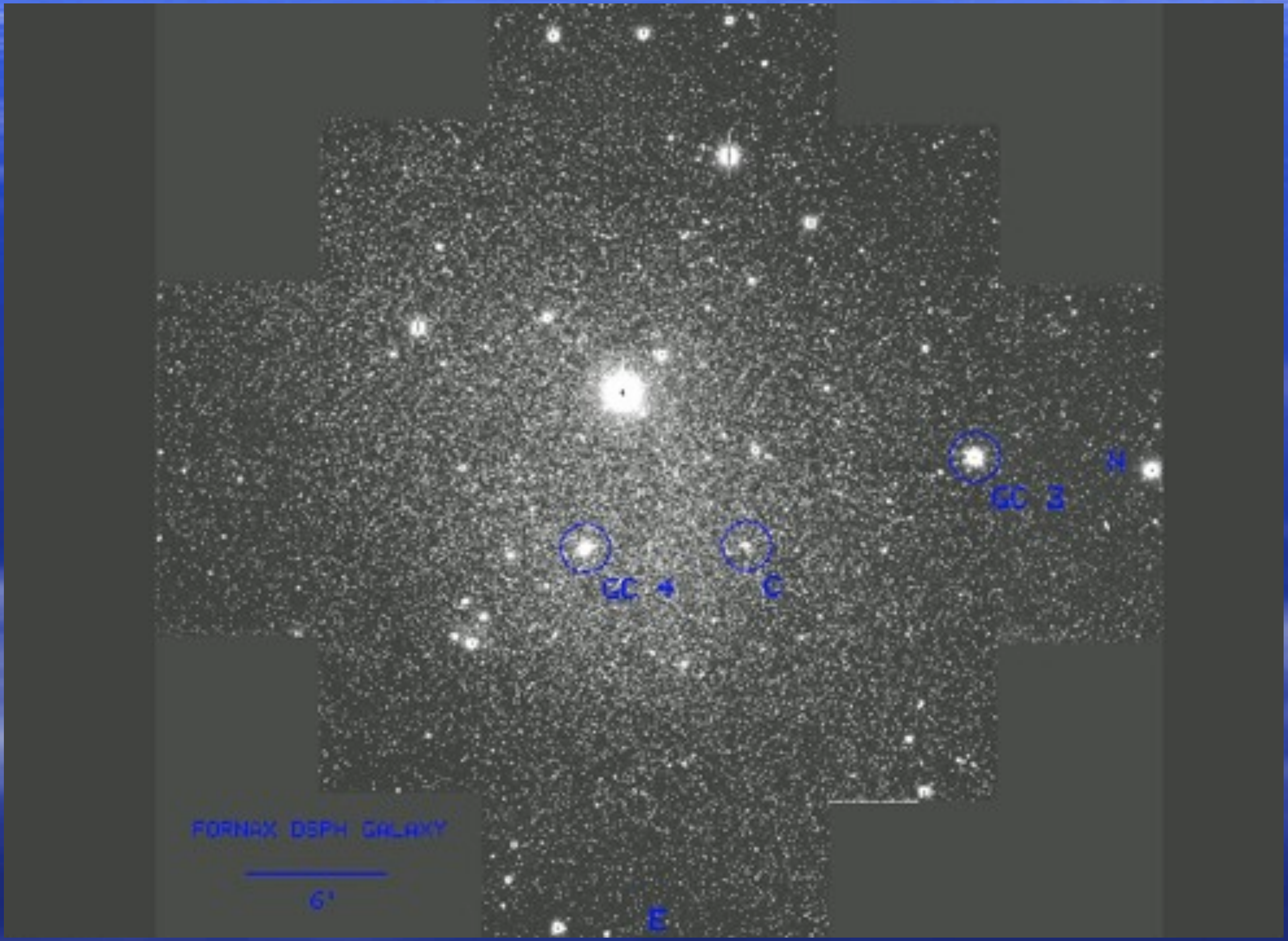
M30: [Fe/H] = –2.1



47Tuc: [Fe/H] = –0.7



The Fornax dSph Galaxy



The Fornax dSph Galaxy

Deeper Photometry from the CTIO 4 m Telescope (Smecker-Hane, et al)