The ISLAndS Project II: The Lifetime Star Formation Histories of Six Andromeda dSphs

Skillman et al 2016

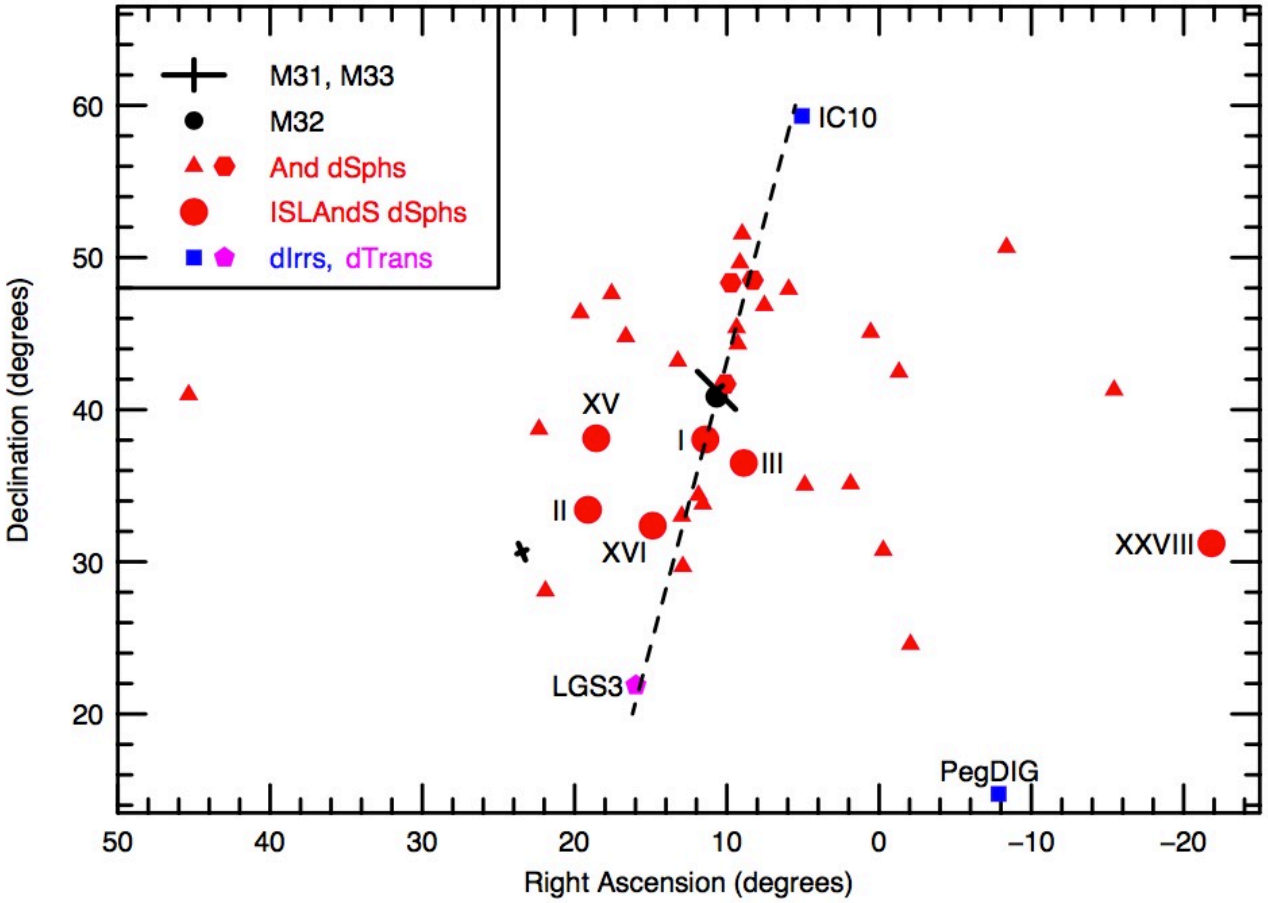
Initial Star formation and Lifetime of Andromeda Satellites

Introduction/Motivation

- Why dwarf galaxies of Local Group?
  - Galaxy formation and evolution
  - Close → stars, gas, dark matter
- Greatly influenced by environment
- Until recently, only had information on MW dSphs
  - Are they representative of dSphs in general?
- Goal: determine if evolution of M31 dSphs is significantly different from that of MW dSphs

Introduction/Motivation

- Why would the two dSphs groups be different?
  - M31 and MW have different properties
    - M31 more massive (although might have similar halo mass)
    - M31 has luminous and compact GCs at large radii, while MW does not
    - M31 has larger extended GCs
- What about their satellites?
  - M31 has more luminous dSphs (M_V = -14.6, -14.8, -16.5 vs MW satellites M_V = -13.4, -13.5)
  - M31 dSphs have redder HB morphologies
  - M31 dSphs parameter space regions have no analogue in MW systems


M31, M33
M32
And dSphs
ISLAndS dSphs
dIrrs, dTrans
IC10
XV
I
III
II
XVI
XXVIII
LGS3
PegDIG
Declination (degrees)
Right Ascension (degrees)
60
50
40
30
20
50
40
30
20
10
0
−10
−20

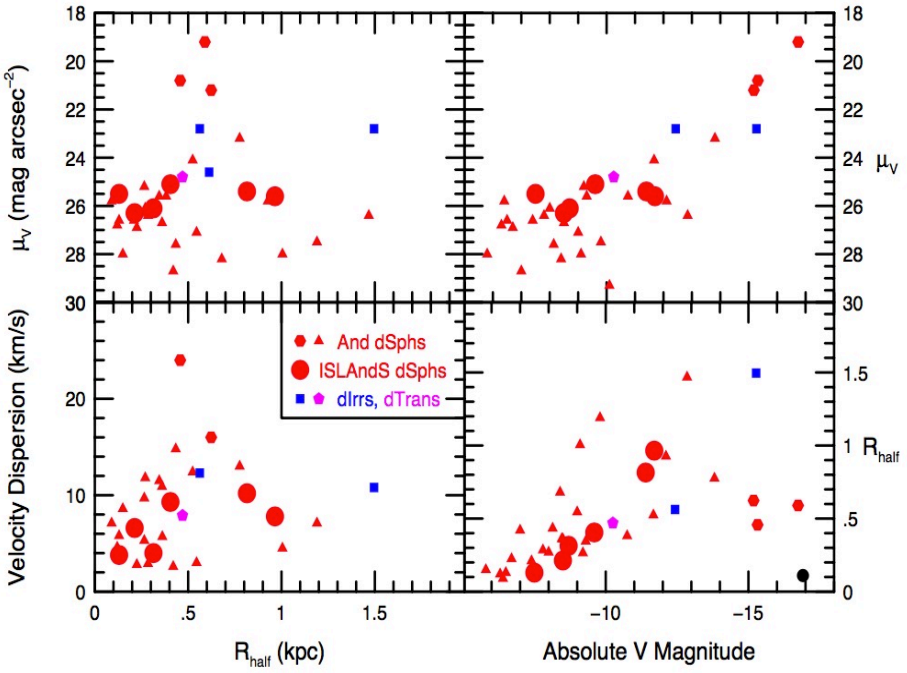
Sample Properties

TABLE 1
SUMMARY OF THE ISLANDS SAMPLE AND OBSERVATIONS

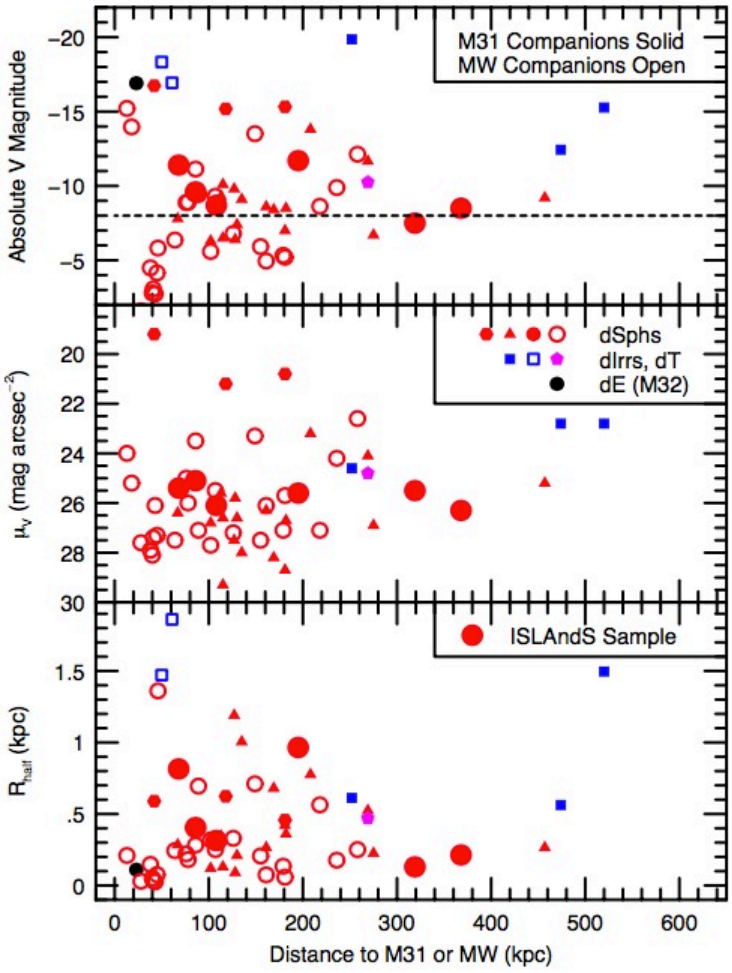
Galaxy (1)	HST ID (2)	F475W (sec) (3)	F814W (sec) (4)	$(m-M)_0$ (mag) (5)	E(B-V) (mag) (6)	M_V (mag) (7)	$R_{1/2}$ (pc) (8)	D_{M31} (kpc) (9)	$V_{c,1/2}$ km s^{-1} (10)	$V_{c,1/2}$ km s^{-1} (11)
And I	13739	19,833	15,709	24.47	0.047	−11.4	815	68	16.1 ± 4.4	18 ± 4
And II	13028	22,472	17,796	24.12	0.063	−11.7	965	195	12.3 ± 2.6	···
And III	13739	28,996	22,968	24.36	0.050	−9.6	405	86	14.7 ± 3.7	16 ± 2
And XV	13739	22,443	17,773	24.66	0.041	−8.7	314	108	$6.3\ ^{+3.4}_{-3.3}$	7 ± 3
And XVI	13028	19,833	15,709	23.60	0.066	−7.5	130	319	$8.8\ ^{+3.2}_{-2.7}$	7 ± 6
And XXVIII	13739	26,360	20,880	24.35	0.080	−8.5	270	368	$10.4\ ^{+7.7}_{-5.8}$	8 ± 3

NOTE. — Column 1—Galaxy name. Column 2—HST observing program. Columns 3 and 4—Integration time in the F475W and F814W filters with the ACS instrument. Column 5—Distances derived in this paper (on the TRGB scale of Rizzi et al. 2007, see text). Column 6—Galactic absorption from the dust maps of Schlegel et al. (1998) with the recalibration from Schlafly & Finkbeiner (2011). Column 7—Absolute V luminosity calculated from distances derived in this paper and apparent magnitudes from Martin et al. (in prep.) and McConnachie (2012) (And XXVIII). Column 8, 9—Half-light radius and distance from M31 from Martin et al. (in prep.) and McConnachie (2012) (And XXVIII), and And XV corrected to our distance. Column 10, 11— Circular velocity measured at the half light radius following Walker et al. (2009) from Collins et al. (2014) and Tollerud et al. (2014).

Sample Properties

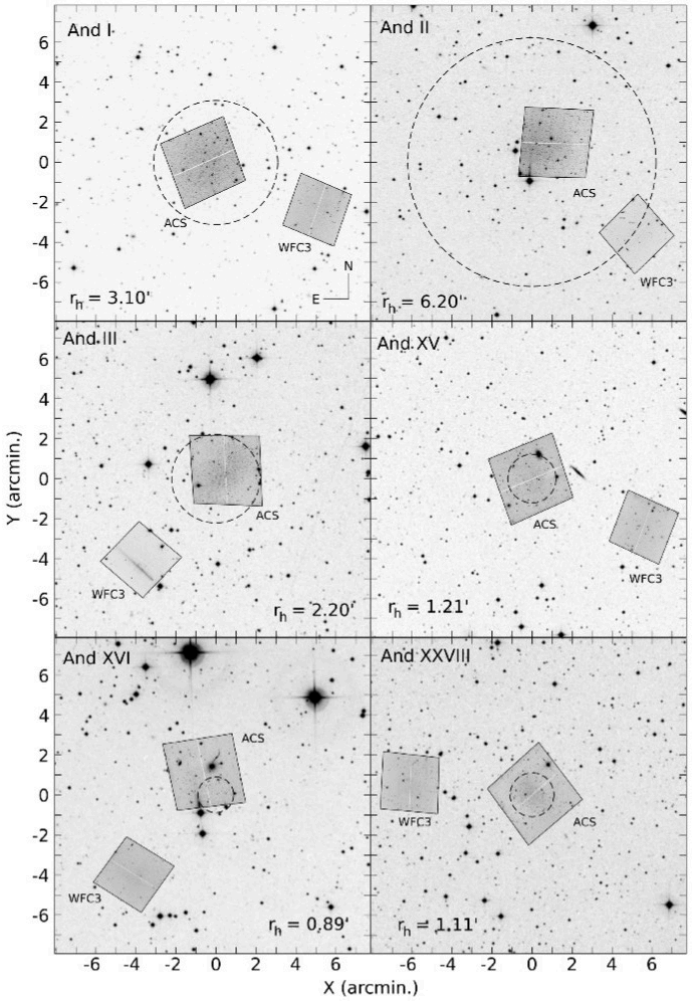


- 6 M31 dSphs
  - $M_V \lesssim -7$ to compare to MW counterparts
- Large spread in distances from M31
  - Stellar content – distance from galaxy correlation [van den Bergh 1994b]
    - Close – old SP
    - Distant – intermediate age SP



Sample Properties

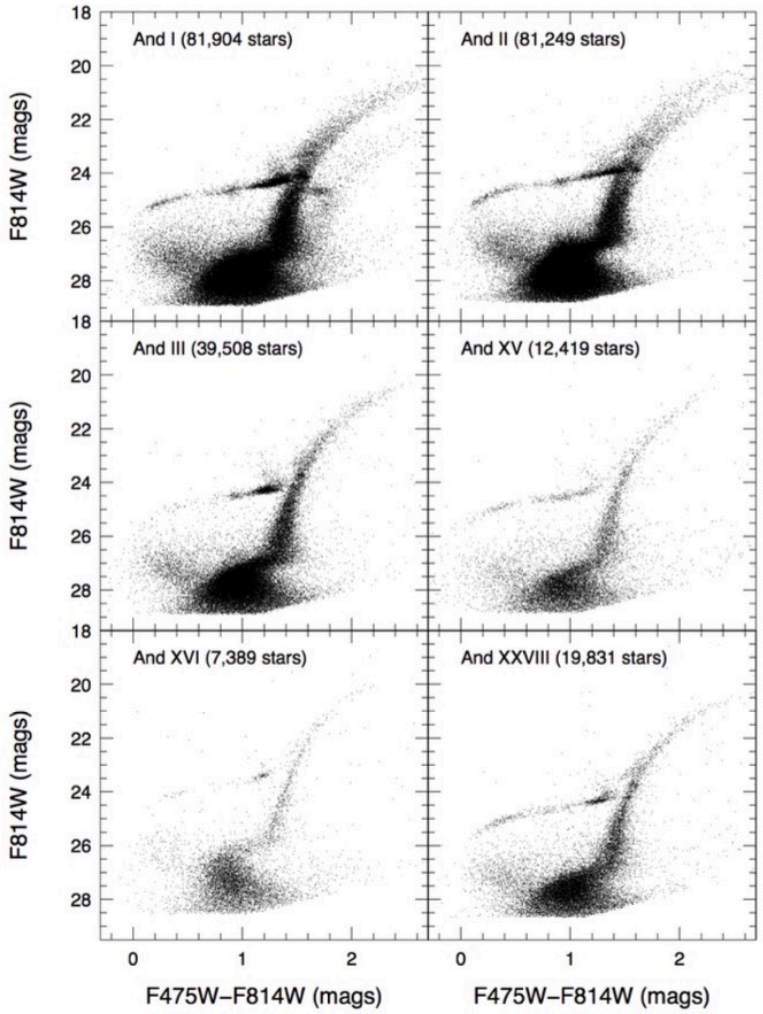
- Similar ranges in luminosity and radial distance from host to MW satellites



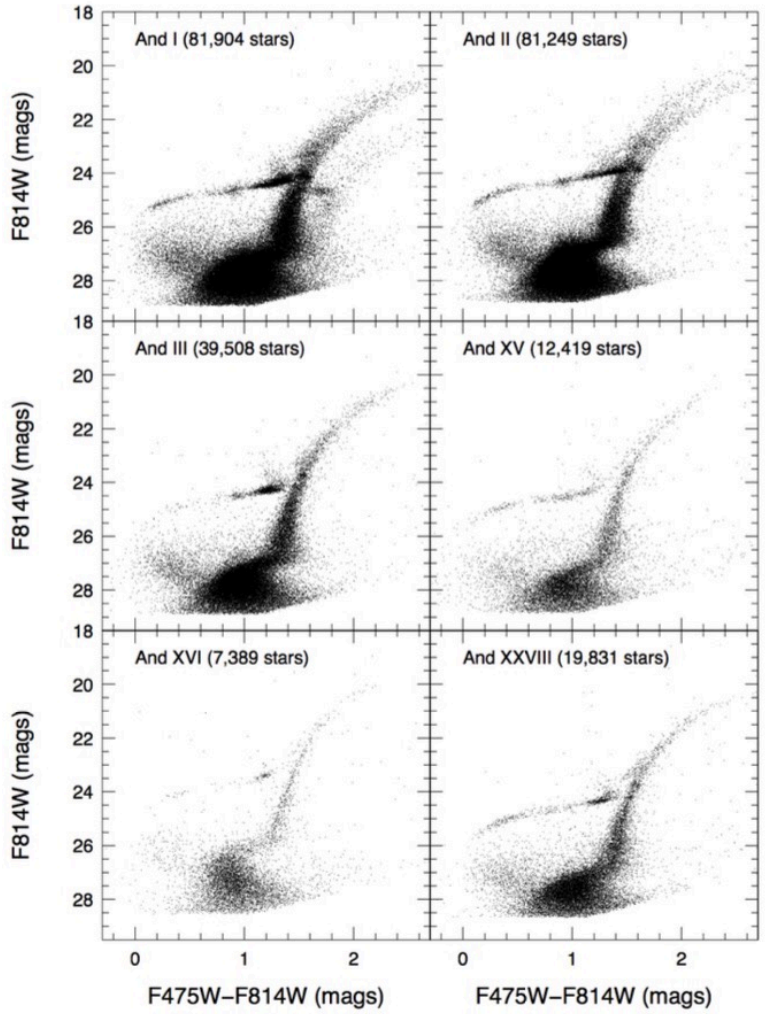
Observations/Data

- And I, And II
  - ACS covers part of galaxy within half-light radius
  - WFC3 has many member stars
- And III
  - WFC3 has some member stars, but not enough for SFH
- And XV, XVI, XXVIII
  - ACS covers most of galaxy half-light radius
  - WFC3 minimal member stars

ACS CMD

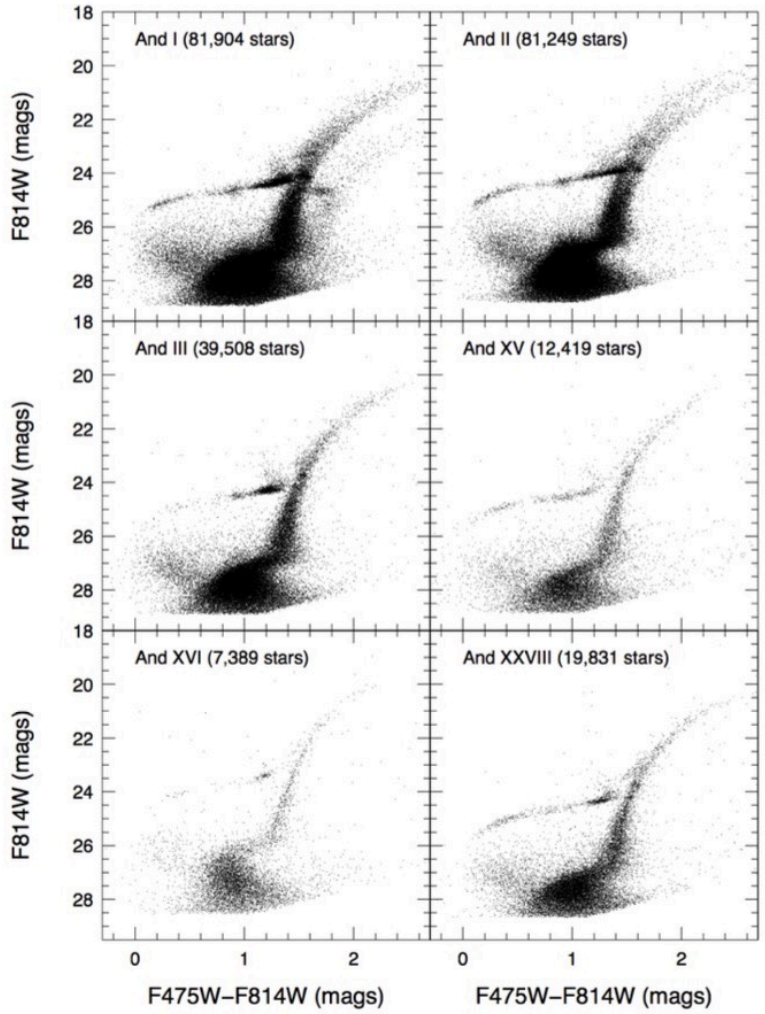


- Photometry below oldest main-sequence turn-offs
- All galaxies have blue horizontal branch stars
- All have complex horizontal branch morphologies
  - Metallicity or age range
  - Extends from blue to red side
  - Clump at color ~ 0.9 is RR Lyrae
  - And I, II, XXVIII have both red and blue in equal proportions
  - And III, XVI have more red
  - And I, II red HB merge with (wide) RGB → wide metallicity range



ACS CMD

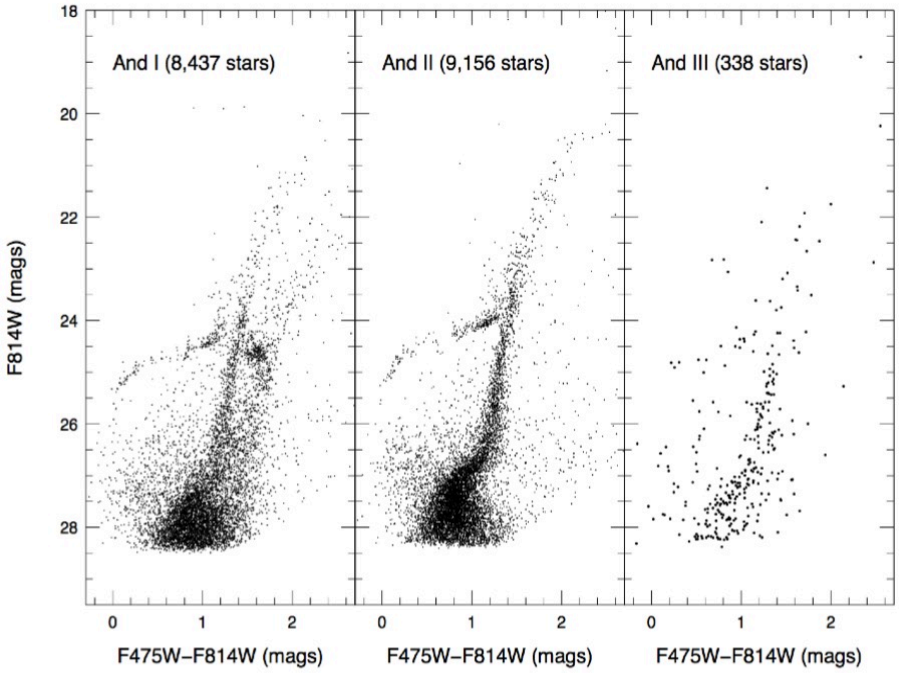
- All galaxies have blue plume below HB and above oMSTO
  - Associated with “blue straggler” population
  - MS with age down to ~ 2 Gyr
  - Altered evolution of coalescing primordial binary stars
- All galaxies show upward extension to red clump
  - Reflection of blue stragglers
- All galaxies lack multiple sequences in subgiant branch (multiple generations of star formation)



ACS CMD

- And I contaminated by Andromeda's Giant Stellar Stream (behind it, redder and fainter)
- And II has bifurcated RGB
  - Two distinct populations with different metallicities
- And XVI has few stars
  - Distance thought to be larger than it is
  - Luminosity is smaller than originally thought

WFC3 CMD



- And XV, XVI, XXVIII no detectable population
- And I similar to ACS, but less stars
- And II
  - Only older, metal poor RGB
  - Younger, more metal rich towards the center
- And III few stars

Distances

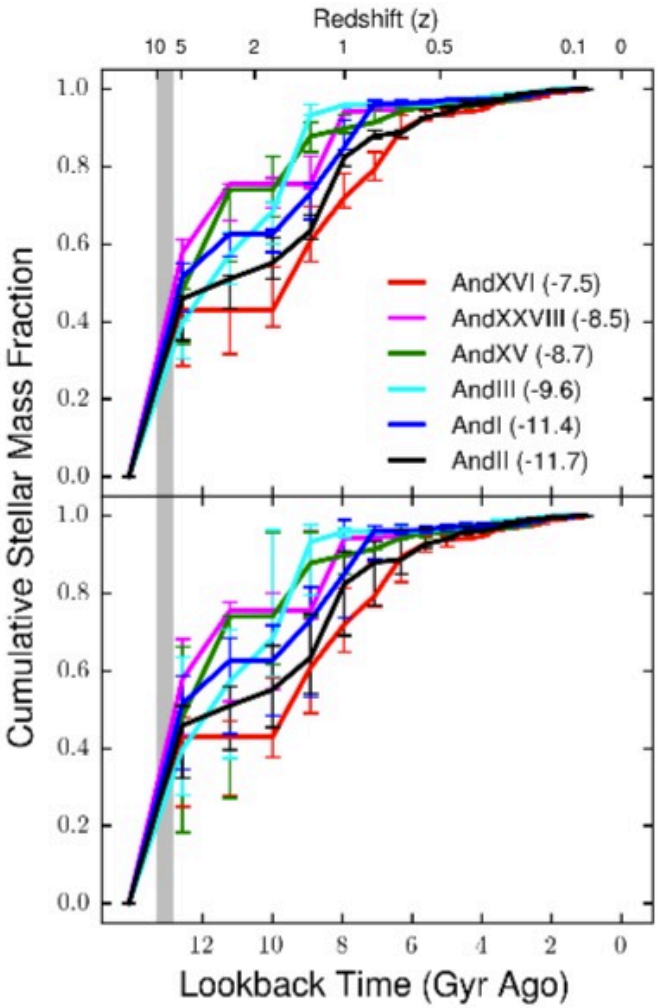
TABLE 3
SUMMARY OF THE ISLANDS SAMPLE DISTANCES AND INTRINSIC PROPERTIES

Galaxy (1)	TRGB F814W (2)	A_I (mag) (3)	$(m-M)_0$ (mag) (4)	$m_{V,0}$ (mag) (5)	M_V (mag) (6)	$M_{tot,1/2}$ ($M_\odot$) (7)
And I	20.50 ± 0.01	0.080	24.47	13.1 ± 0.1	-11.4	3.2×10^7
And II	20.16 ± 0.01	0.092	24.12	12.4 ± 0.1	-11.7	3.4×10^7
And III	20.39 ± 0.02	0.084	24.36	14.8 ± 0.1	-9.6	2.0×10^7
And XV	20.68 ± 0.08	0.070	24.66	16.0 ± 0.1	-8.7	2.9×10^6
And XVI	...	...	23.60	16.1 ± 0.1	-7.5	2.5×10^6
And XXVIII	...	...	24.35	15.9 ± 0.5	-8.5	6.8×10^7

NOTE. — Column 1—Galaxy name. Column 2—TRGB measured from HST observations. Column 3—I-band Galactic absorption from Schlafly & Finkbeiner (2011). Column 4—Distance modulus from columns 1 and 2. For And XV and And XVIII, distances were derived from the best solutions from MATCH. Column 5—Extinction corrected V-band apparent magnitude from Martin et al. (in prep.). Column 6—Absolute V-band magnitude. Column 7—Total mass within the half-light radius (from Table 1) and the stellar velocity dispersions (latest values from Table 2) and using the mass estimator from Walker et al. (2009).

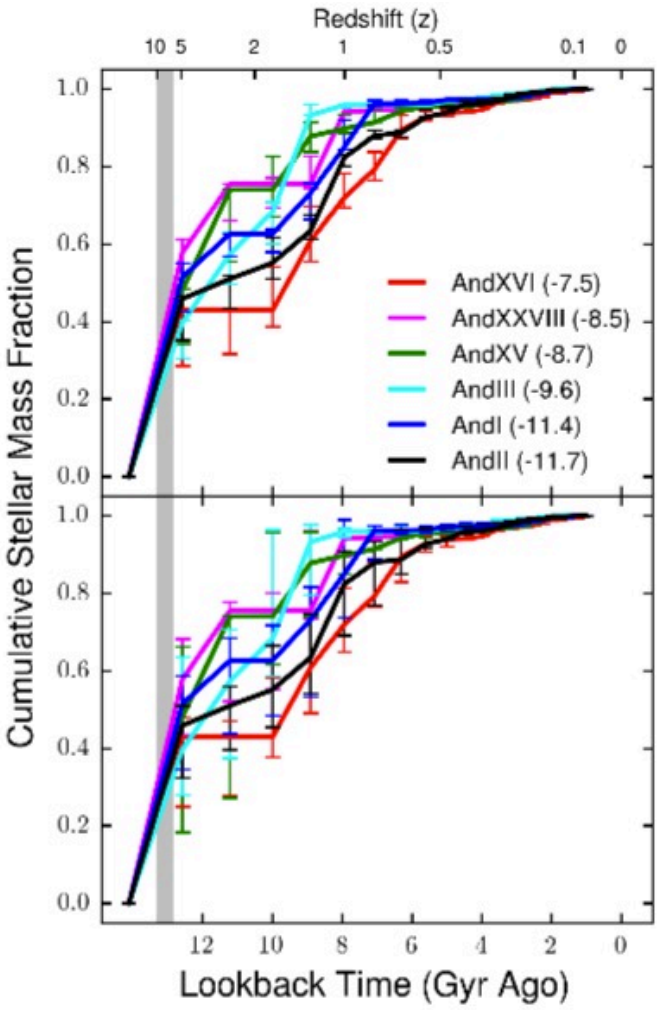
- Get distance from tip of the RGB
- Assume $M_I^{TRGB} = -4.05$ of ACS F814W
- Relatively good agreement with previous values

SFHs of M31 dSphs

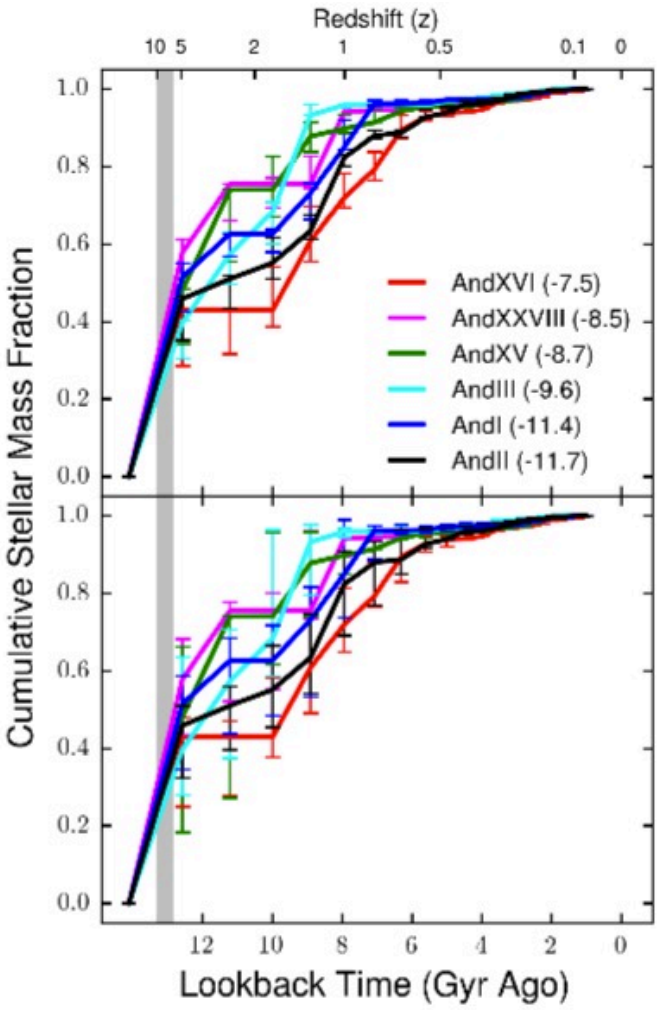


- In terms of cumulative mass fractions
- Why?
  - SFR are sensitive to time binning
  - Compare at arbitrary value of CSMF
  - Lacks info about absolute masses

SFHs of M31 dSphs



- No correlation between mean age and present day luminosity
  - And III, XV, XXVIII similary SFHs, but different luminosities, distances
- All 6 galaxies
  - Start star formation early
  - 50% stars by 9 Gyr
  - Stop ~ 6 Gyr



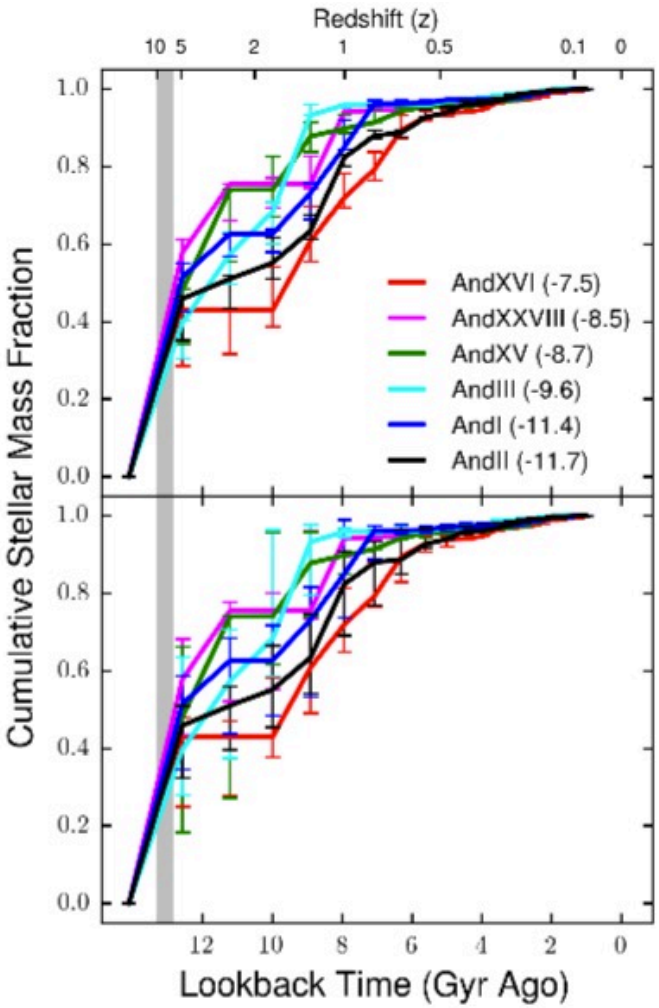
SFHs of M31 dSphs

- And XV, XXVIII oldest mean populations
  - Not consistent with single age population
  - Didn't form all stars before reionization
- And XVI most extended star formation
- Very late quenching time is absent (e.g. Carina, Fornax, Leo I for MW)

Quenching

- Quenching time definition is vague
  - Blue stragglers → 2-3 Gyr population accounting for 2-3% stellar mass
  - Quenching time as SFR = 0 definition misleading
- Typically set as a time when star formation is almost complete
- This paper: 90% of the stars have formed
  - Not affected by blue stragglers

Quenching



- No evidence of synchronized quenching
- And III earlier than ~ 9 Gyr
- And XV, XXVIII ~ 8 Gyr
- And I ~ 7.5 Gyr

Quenching by reionization

- Understanding comes from MW satellites
- Early picture: low-mass galaxies permanently quenched by reionization on short time scale
  - Not supported by SFH of Local Group dwarfs
- Recently: cosmic UV stops infall of fresh gas, but doesn’t remove already present cold gas
- Wheeler 2015 model: peak virial mass criterion below which model shows star formation to be entirely quenched by z ~ 2 (~ 10 Gyr ago)

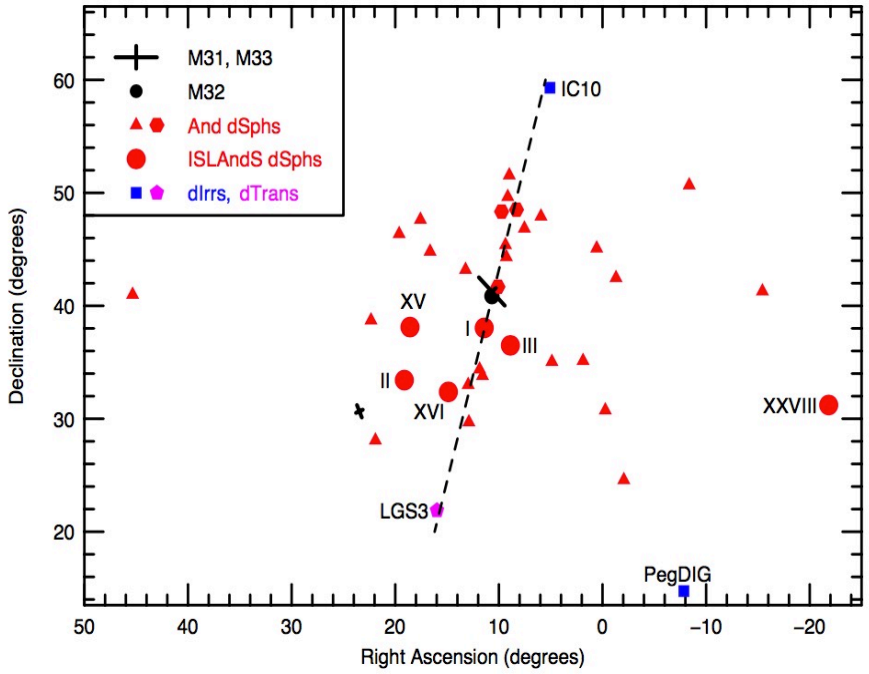
Quenching by reionization

- And XV, XVI – at the limit
  - And XV – marginally consistent
- And XVI – not consistent with quenching by reionization
  - SFR decreases after reionization
- And III
  - SFR increases after reionization

Thin plane/Non-thin plane

- Half of M31 satellites live in a planar structure with 400 kpc diameter, 14 kpc width
- Rotate in the same direction
- From velocity dispersion, mass, half-light radius, luminosity, metallicity, the two groups (on and off plane) are indistinguishable

Thin plane/Non-thin plane

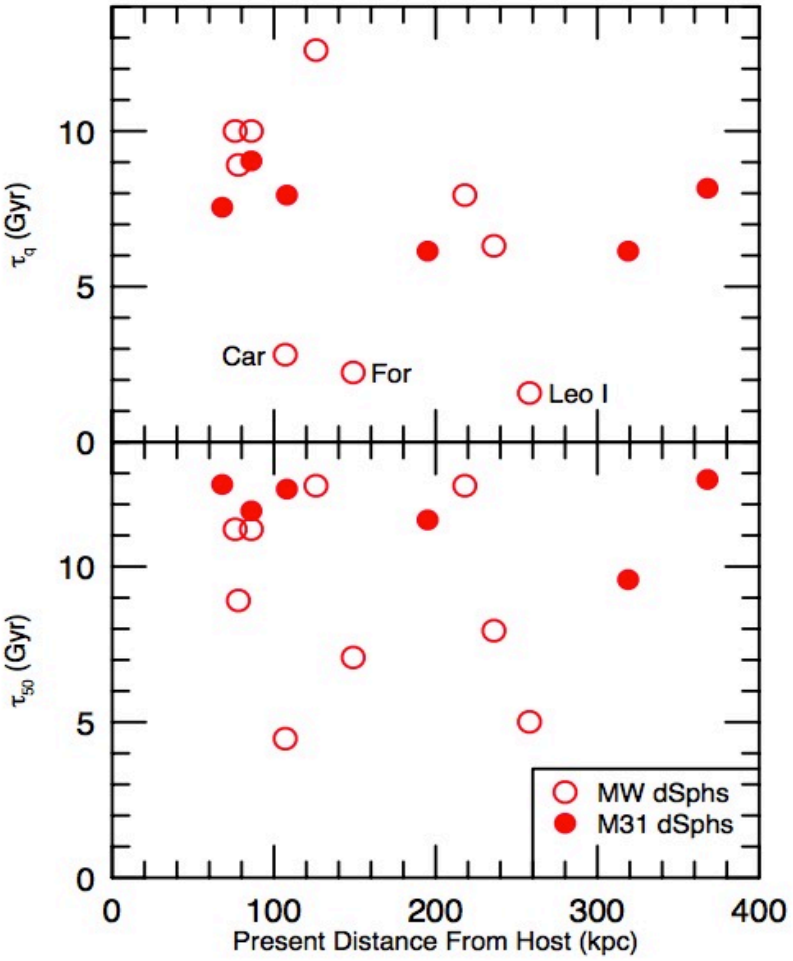


- And I, III, XVI in plane
- And II, XV, XXVIII off plane
- SFH comparison shows no difference
  - And II, XVI most extended SFH, different groups
  - And III, XV, XXVIII earliest truncation time, 1 in plane, 2 off plane

M31 – MW Satellites Comparison

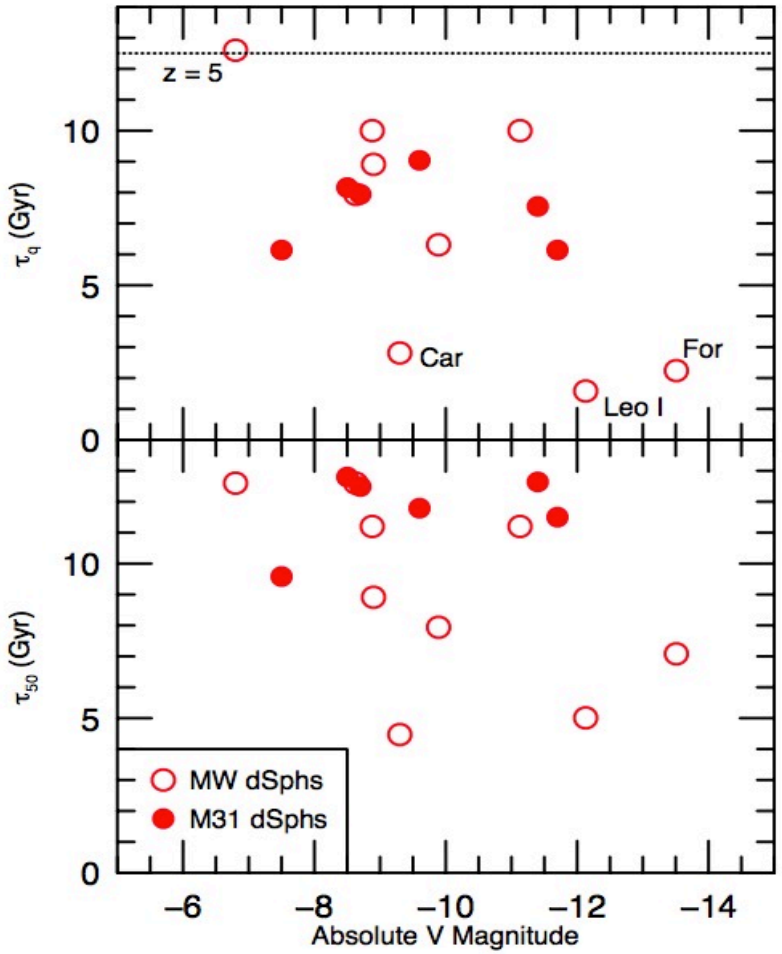
- Key quantities to compare
  - 50% formation time
    - Roughly separate between quick and steady build up
  - 90% formation time
    - Good approximation of quenching time
    - Not affected by blue stragglers
- Diagnostic plots
  - Versus distance from host
  - Versus luminosity
  - Direct comparison
- Small number statistics!

Trends with distance



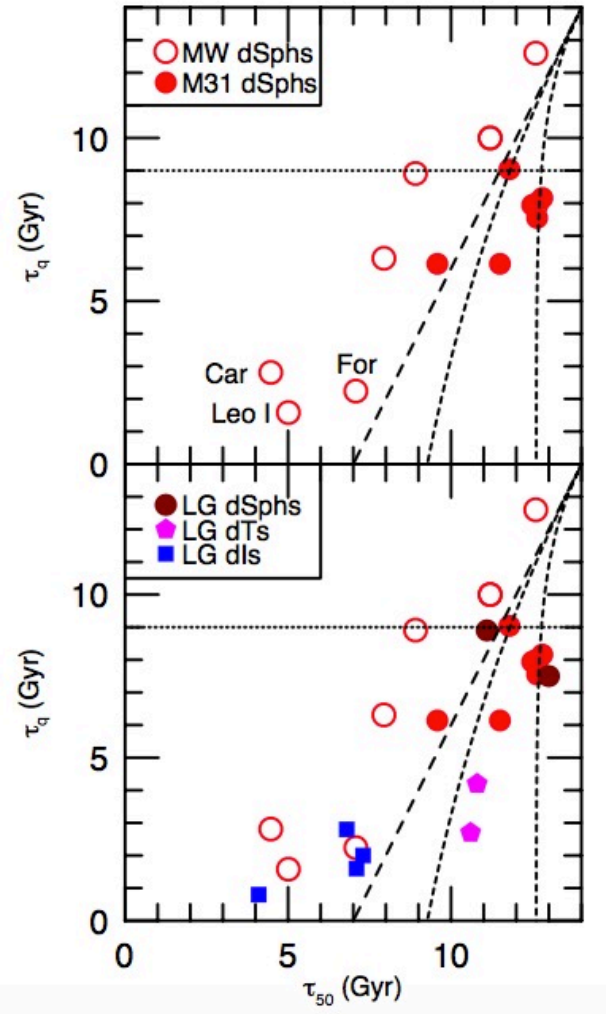
- MW dSphs: weak trend in τ_q with large scatter
- And dSphs: weak trend in τ_q with less scatter
- Lack of And galaxies showing late τ_q ($\leq$ 5 Gyr)
- MW dSphs: no trend with distance
- And dSphs: mild trend for decreasing τ_{50}
- All And galaxies have formed 50% stars before 9 Gyr lookback time

Trends with Luminosity



- Only lowest luminosity MW satellite shows quenching by reionization
- MW dSphs: stronger trend than with distance (more luminous – later quenching times)
- M31 dSphs: little evidence for a trend
- MW dSphs: higher luminosities – later star formation
- M31 dSphs: no trend
- M31 satellites produce 50% stars much faster than MW satellites, but have comparable quenching times
  - Evidence M31 dSphs evolution more uniform that MW dSphs evolution

$\tau_{50} - \tau_q$ comparison



- General trend: relatively constant start formation, followed by quenching
- MW dSphs: constant SF
- M31 dSphs: range of τ models
- "slow" vs. "fast"
  - Some MW dSphs are "fast" (quenched by 9 Gyr)
  - Most M31 dSphs are "slow"
- No late quenching M31 dSphs
- dI overlap late quenching MW dSphs
- Suggests late quenching MW dSphs a few Gyr ago are the same as present day dIs
  - Morphology ≠ long term evolution

Conclusions

- 6 dSphs show varied SFHs not correlated with luminosity or distance
- Broad range of quenching times, but all earlier than ~ 6 Gyr ago
- No evidence of complete quenching by reionization
- No differences between on and off plane dSphs
- primary difference between M31 and MW satellites
  - No very late quenching ($\tau_q \lesssim 3$ Gyr) for M31 dSphs
- Secondary difference
  - M31 dSphs consistent with τ models, MW consistent with nearly constant star formation