Properties of Near Field Dwarf Galaxies Revealed by their 'Resolved' Stellar Populations

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Definition of "Nearby Galaxies"

Any galaxies with

$$D < 11 \text{ Mpc}$$

$$V_{LG} < 600 \text{ km s}^{-1}$$

($z \sim 0.002$)

where V_{LG} is radial velocity with respect to the Local Group centroid, and can be expressed as $V_{LG} = H_0 D$

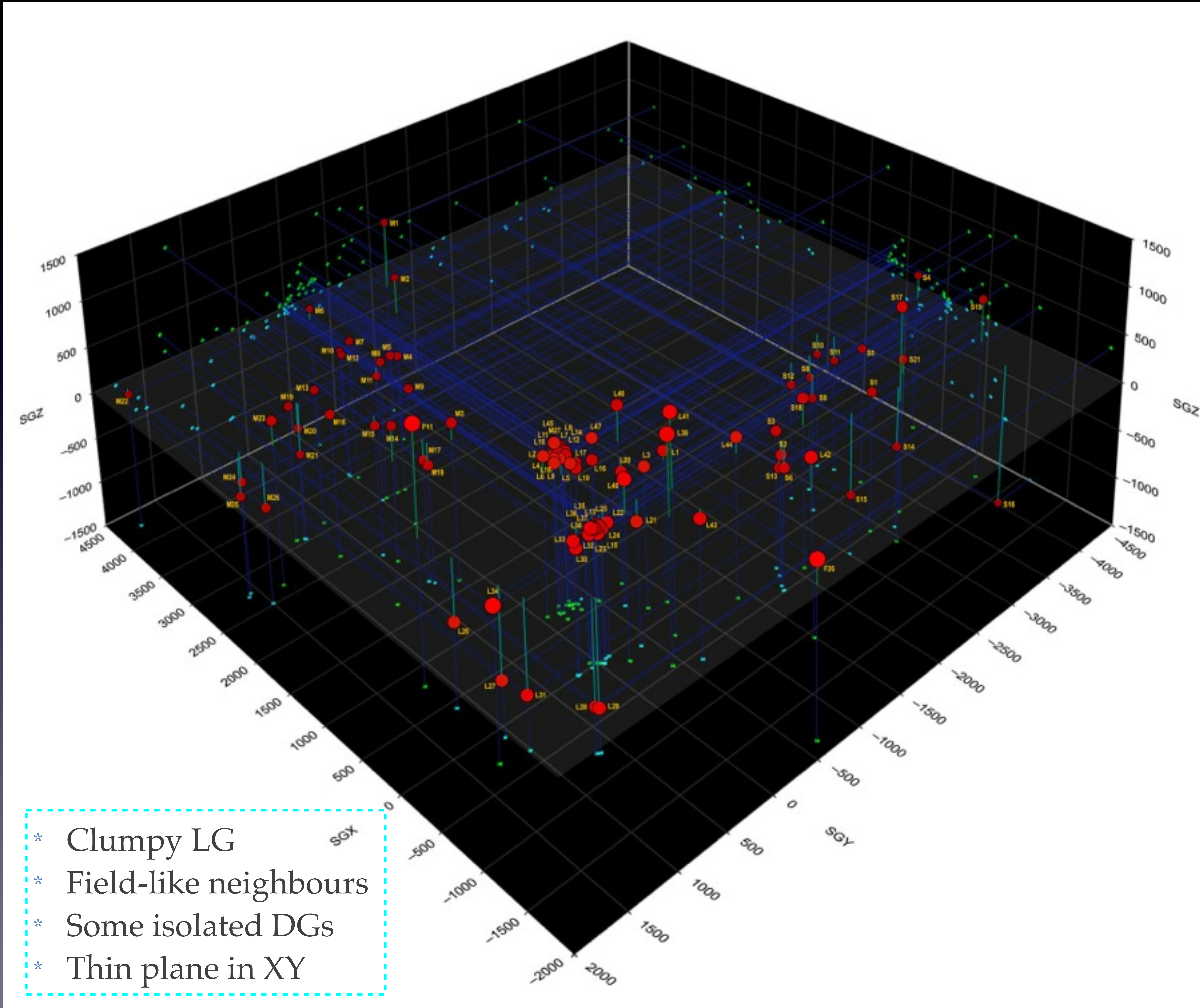
According to the latest compilation of the nearby galaxies collected by Karachentsev et al. (2013, AJ, 145, 101),

we now have a total of 869 galaxies within these category

Definition of "Dwarf Galaxies"

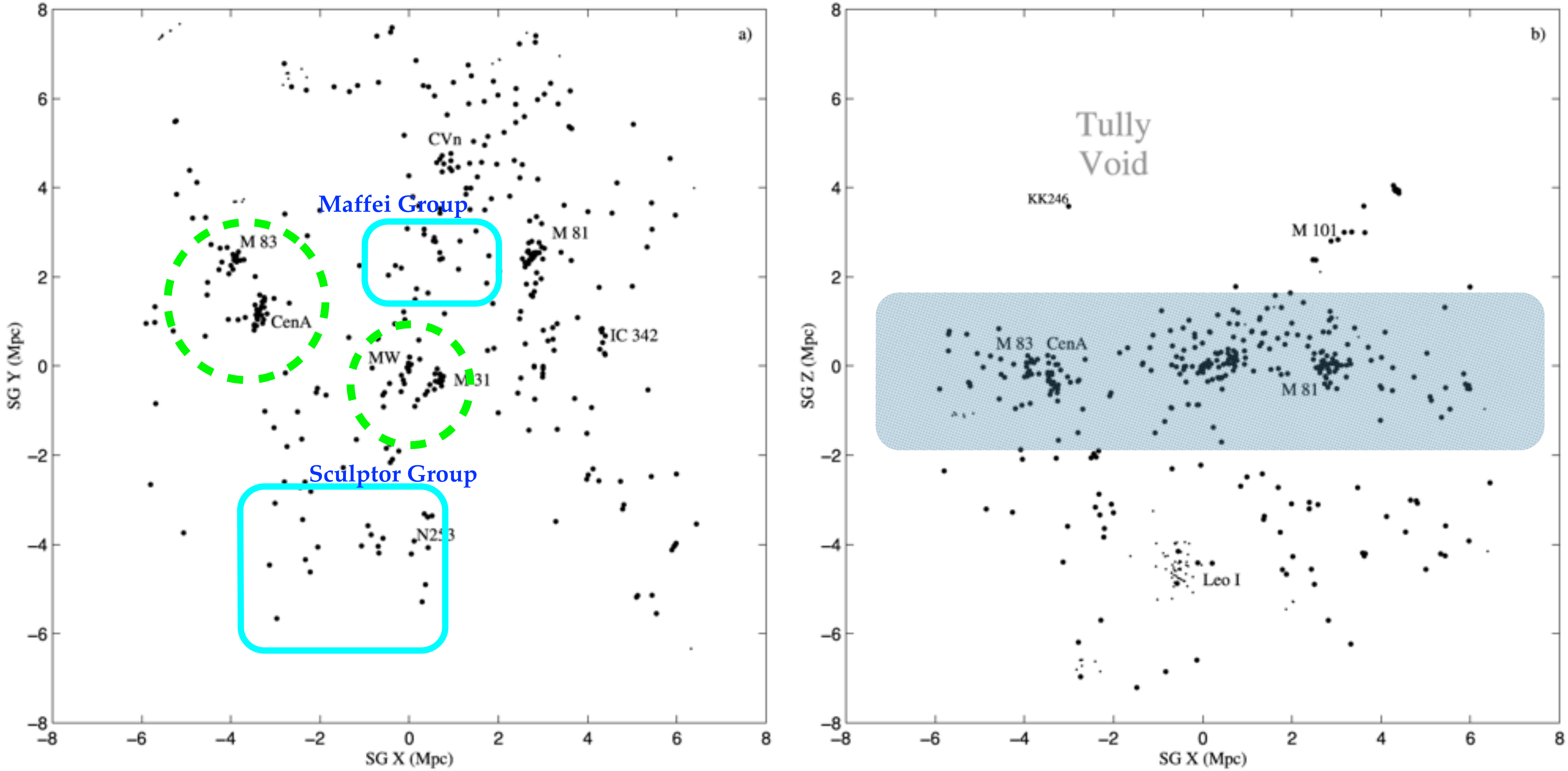
Categorised primarily by size & luminosity (mass)

Canonical dwarfs	$M_V < -8$ mag, $r_h > 100$ pc
Ultra-faint dwarfs	$M_V > -6$ mag, $r_h < 100$ pc
Hybrid/Mutant objects	$M_V \simeq$ as faint as uFd, but with GGC size (i.e. $r_h \simeq 30$ pc)



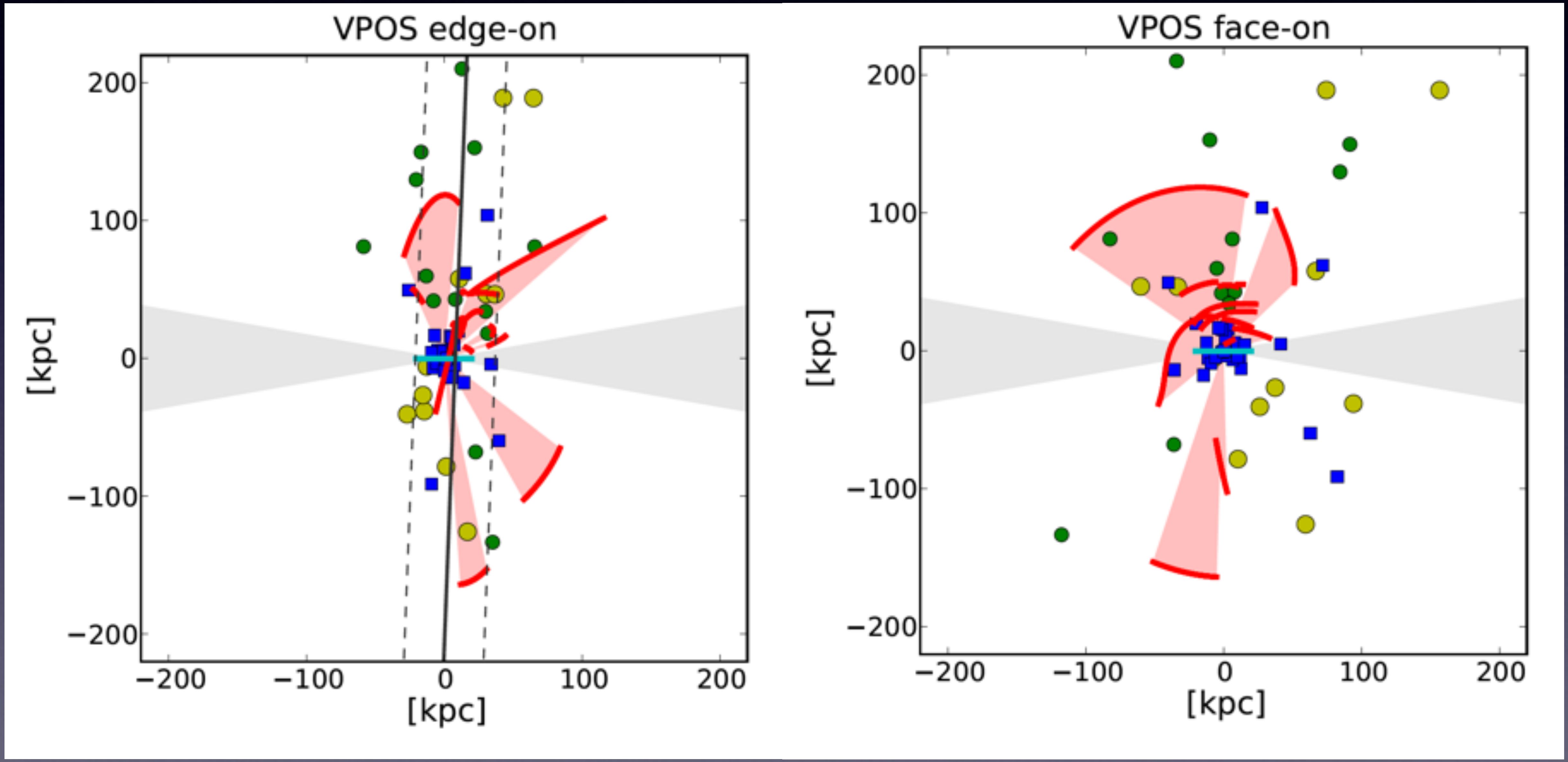
* Clumpy LG
* Field-like neighbours
* Some isolated DGs
* Thin plane in XY

* **M83 & Cen A**(NGC 5128) Groups appear to be a similar cousin to **MW-M31** pair
* Thin layer structure in SXY plane continues in larger scale!



Karachentsev et al. (2013)

Two giant spirals of the Local Group, MW & Andromeda shows characteristic thin disk structures of satellites.



Karachentsev et al. 2004, AJ, 127, 2031

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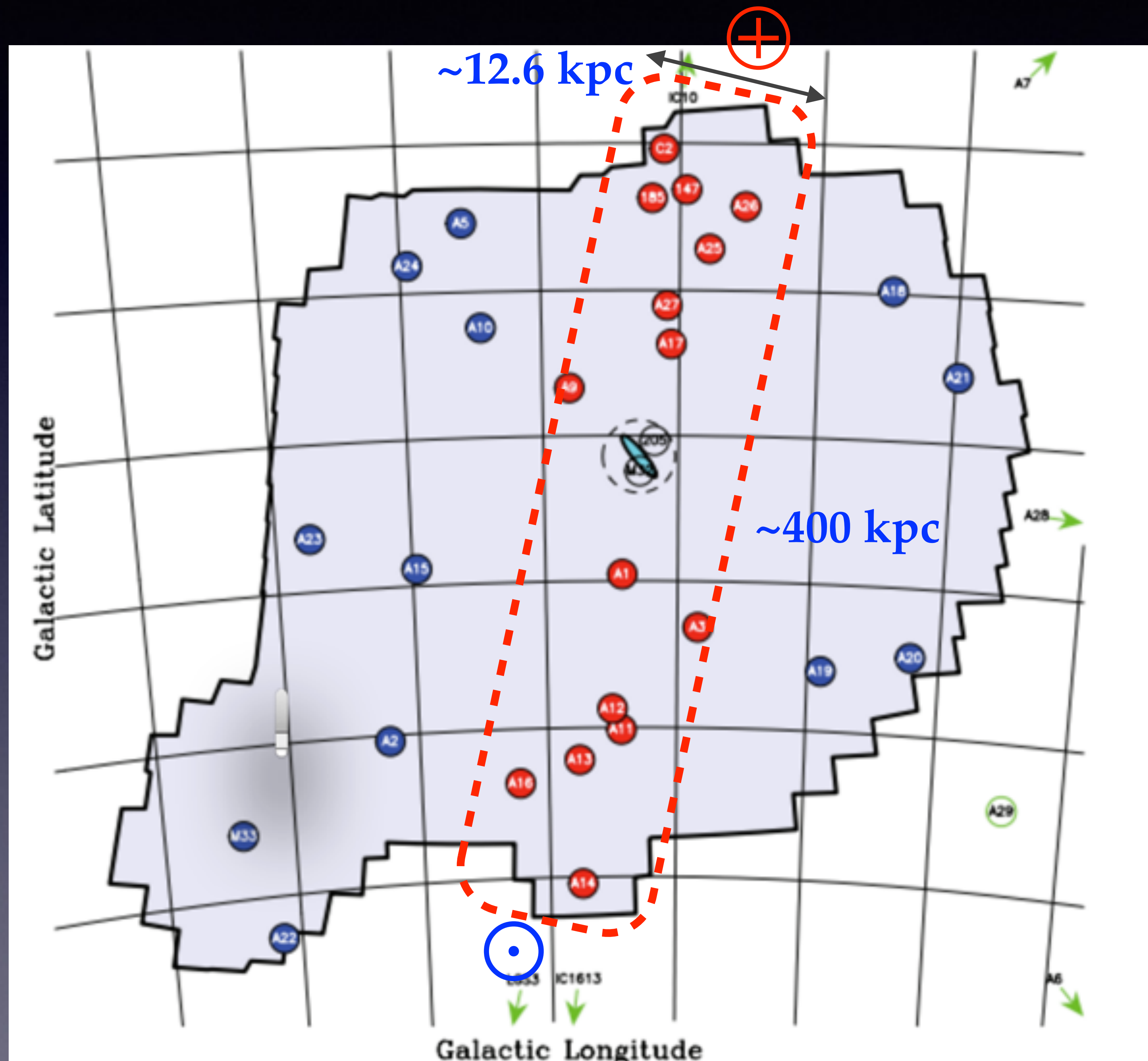


Ibata et al. 2013, Nature, 493, 62

What can we learn from resolved stellar populations?

Today's Keywords

Star Formation History
Chemical Enrichment History

SFH & CEH provide a direct & intuitive understanding on the galaxy formation and evolution

Definition of "Star Formation History"

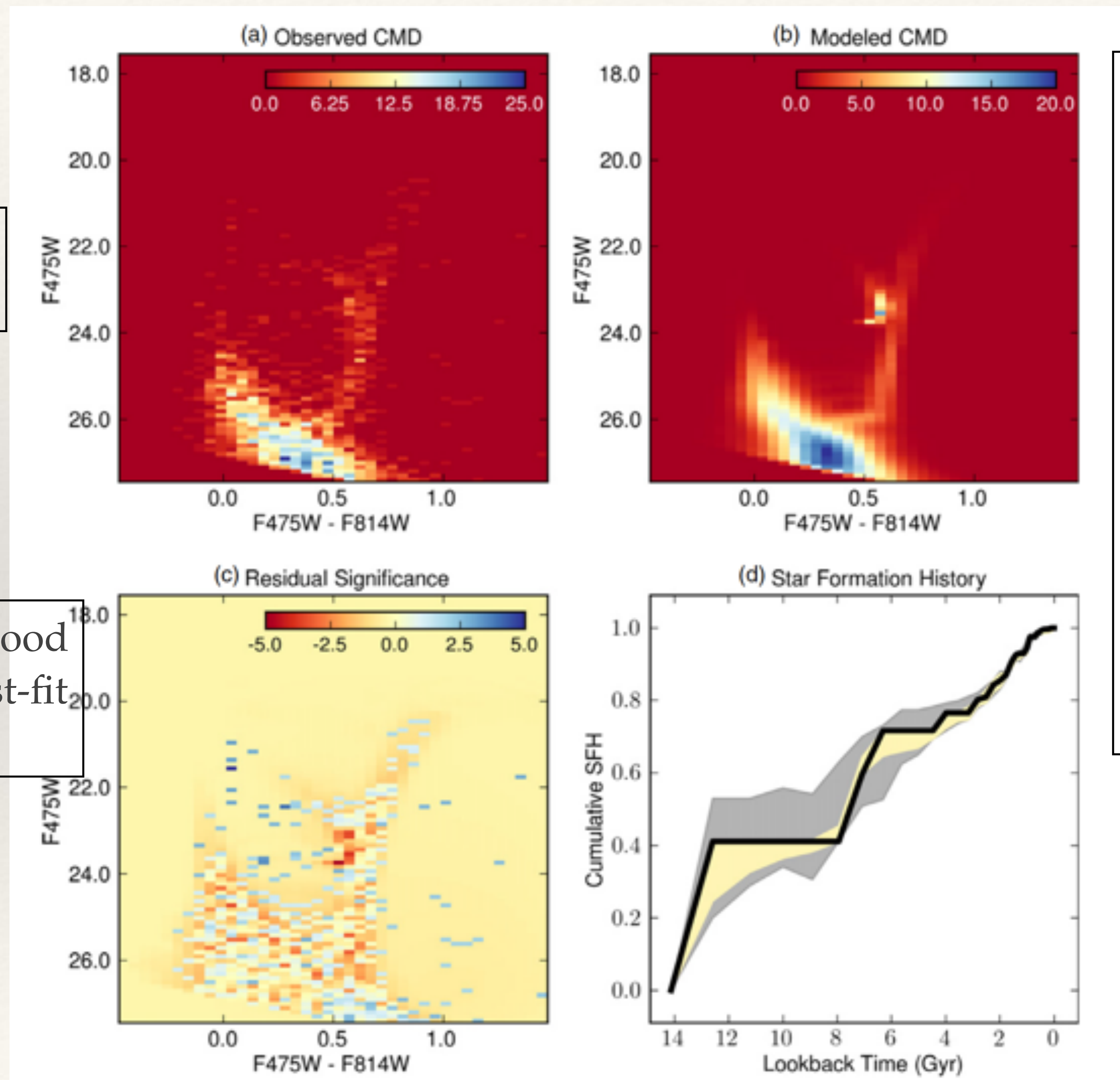
Star-formation rate as a function of lookback time and metallicity

How we can obtain SFH of a galaxy?

By directly comparing stellar evolution models and the temperature-luminosity distributions (e.g. color-magnitude diagram) of individual stars

Quick Summary of SFH Analysis

1. Deep & high quality observed CMD



2. Construct synthetic CMDs of simple stellar populations

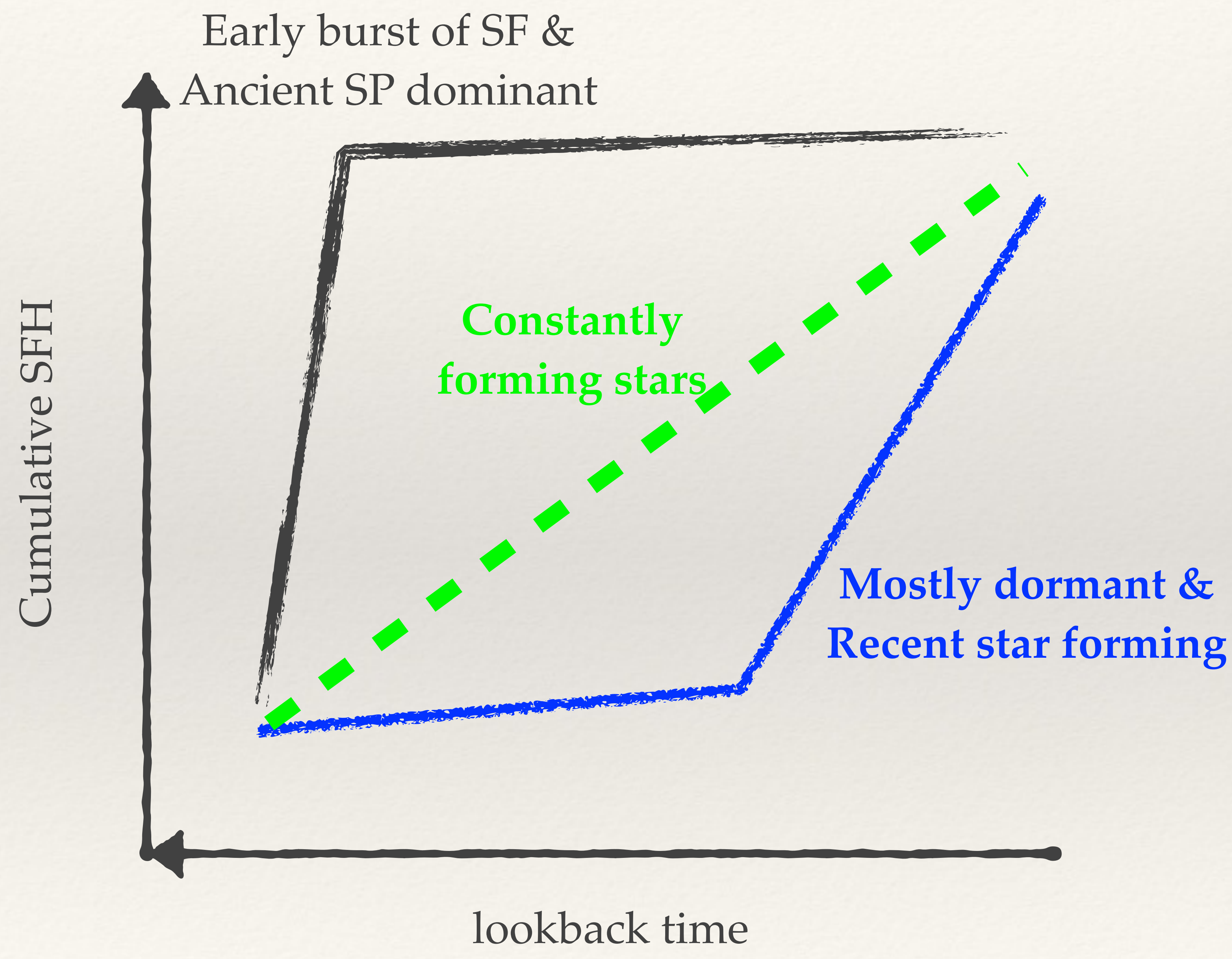
3. Produce linear combinations of the synthetic CMDs to form composite Model CMD with a complex SFH

4. Add photometric error to form simulated Model CMD

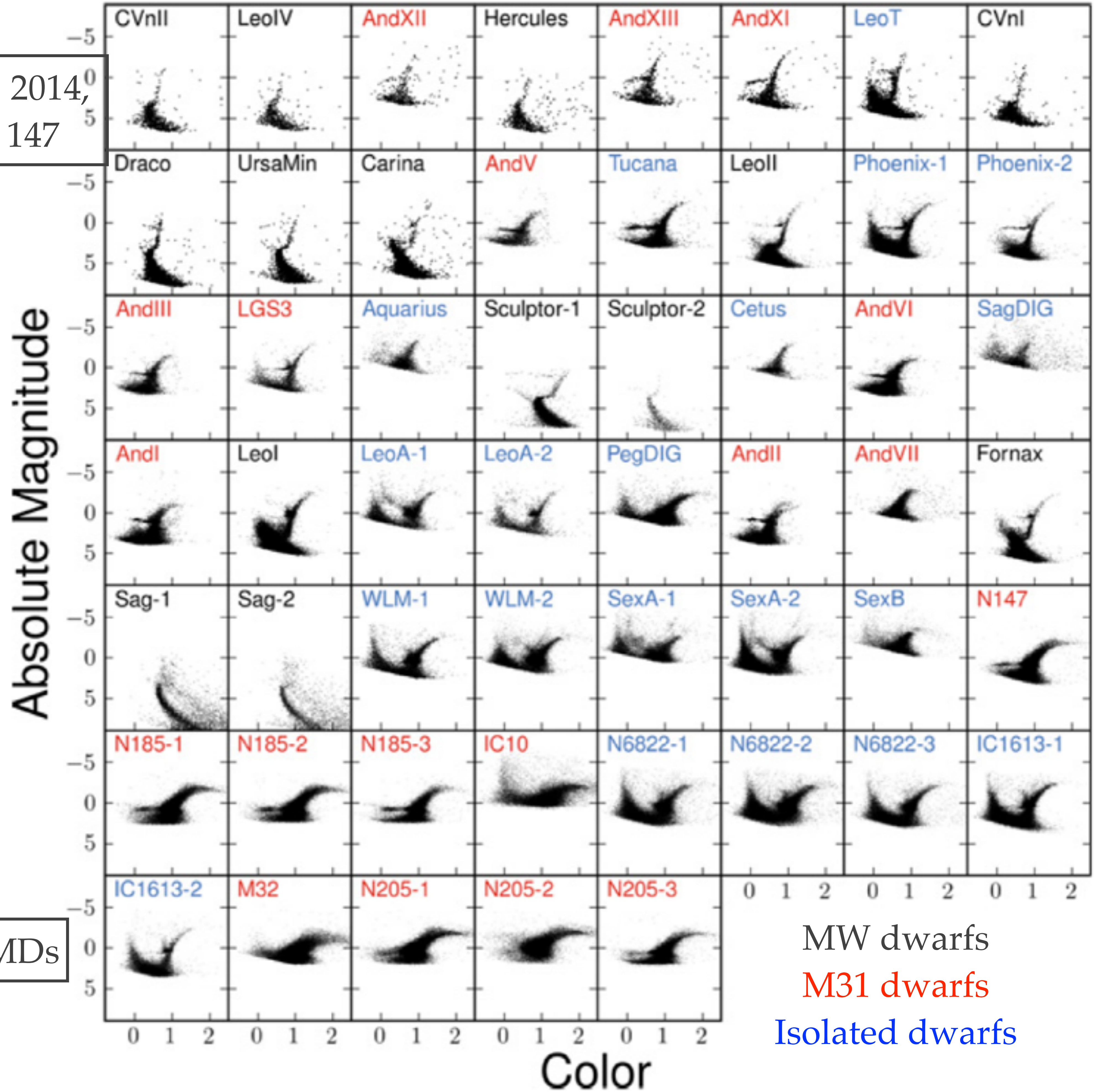
5. Run Maximum-likelihood routine to extract the best-fit Model CMD

Weisz et al. 2014, ApJ, 789, 147

How to Read SFH diagram?

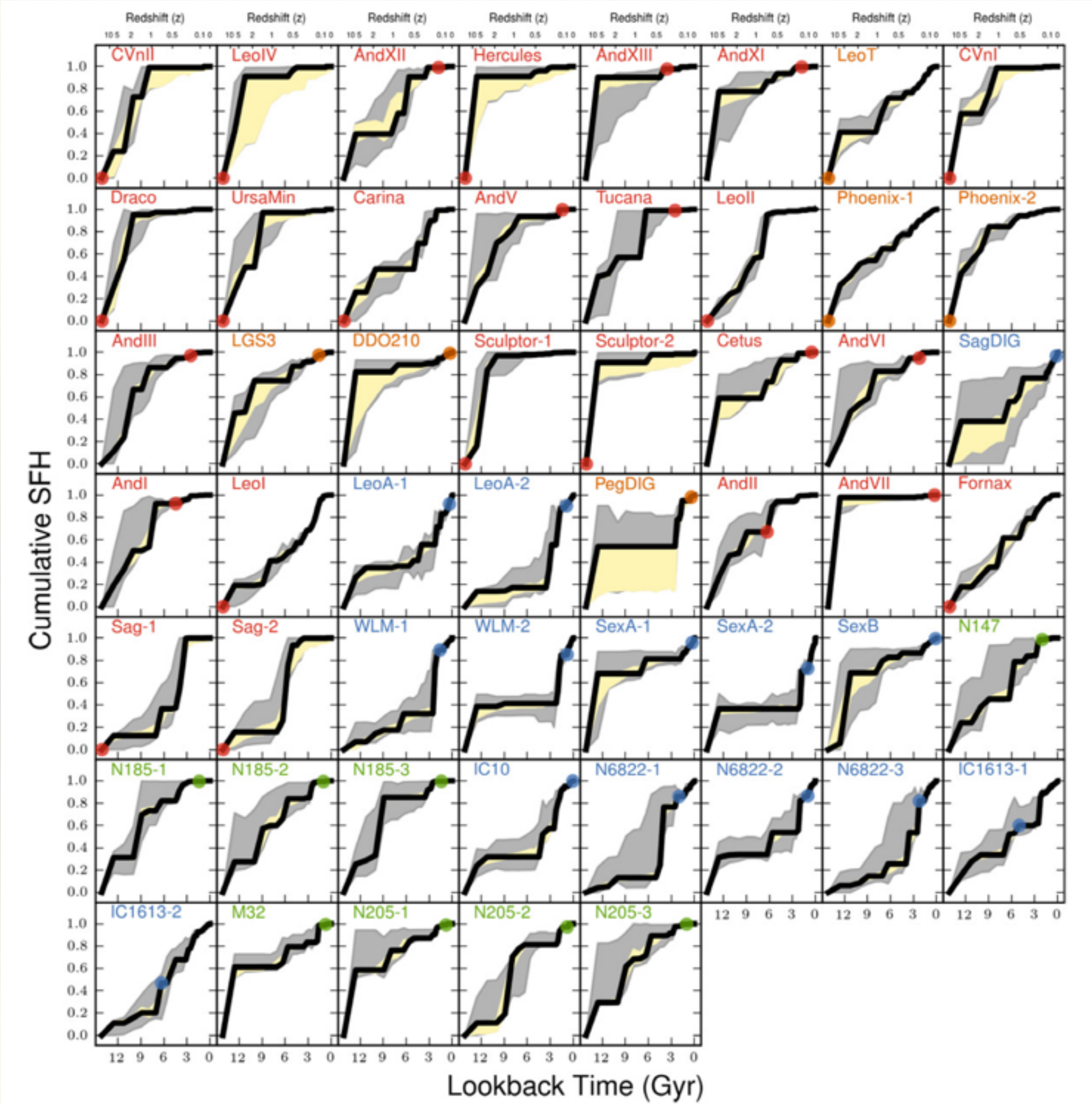


Weisz et al. 2014, ApJ, 789, 147

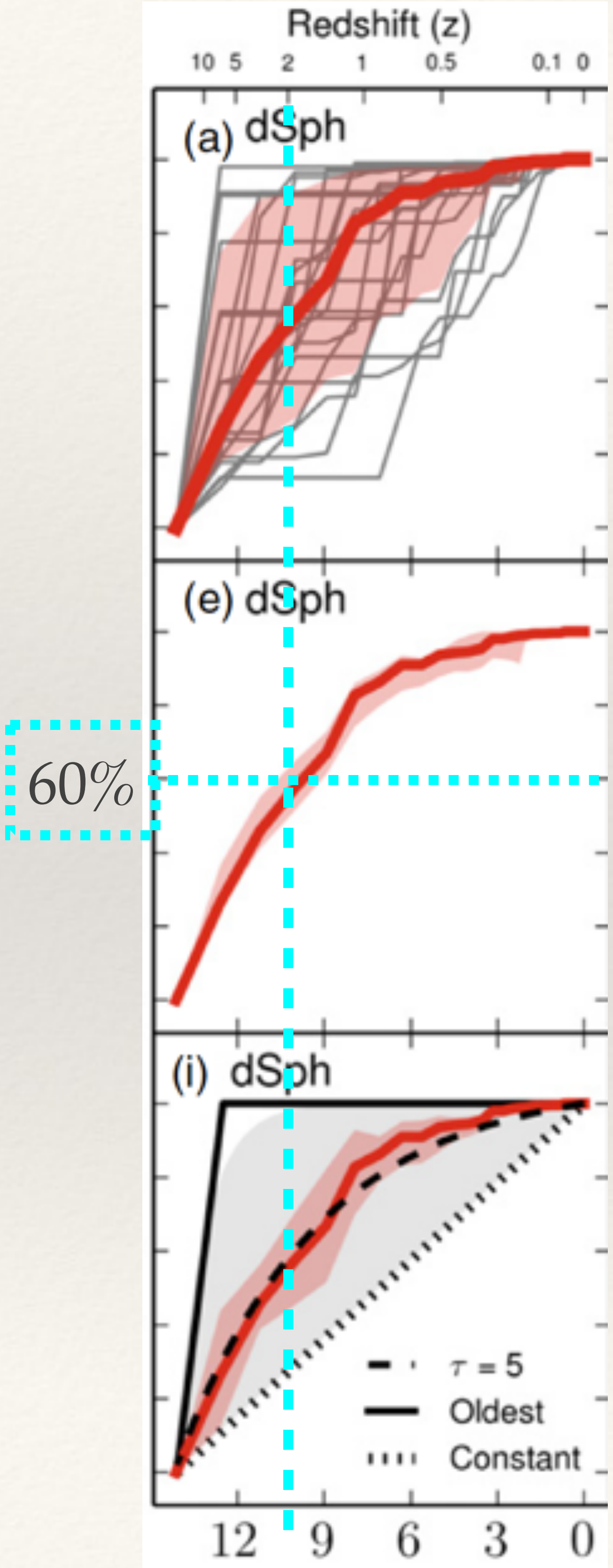


WFPC2 CMDs

dSph
dIrr
dTran
dE



Lessons from the comparison (1)

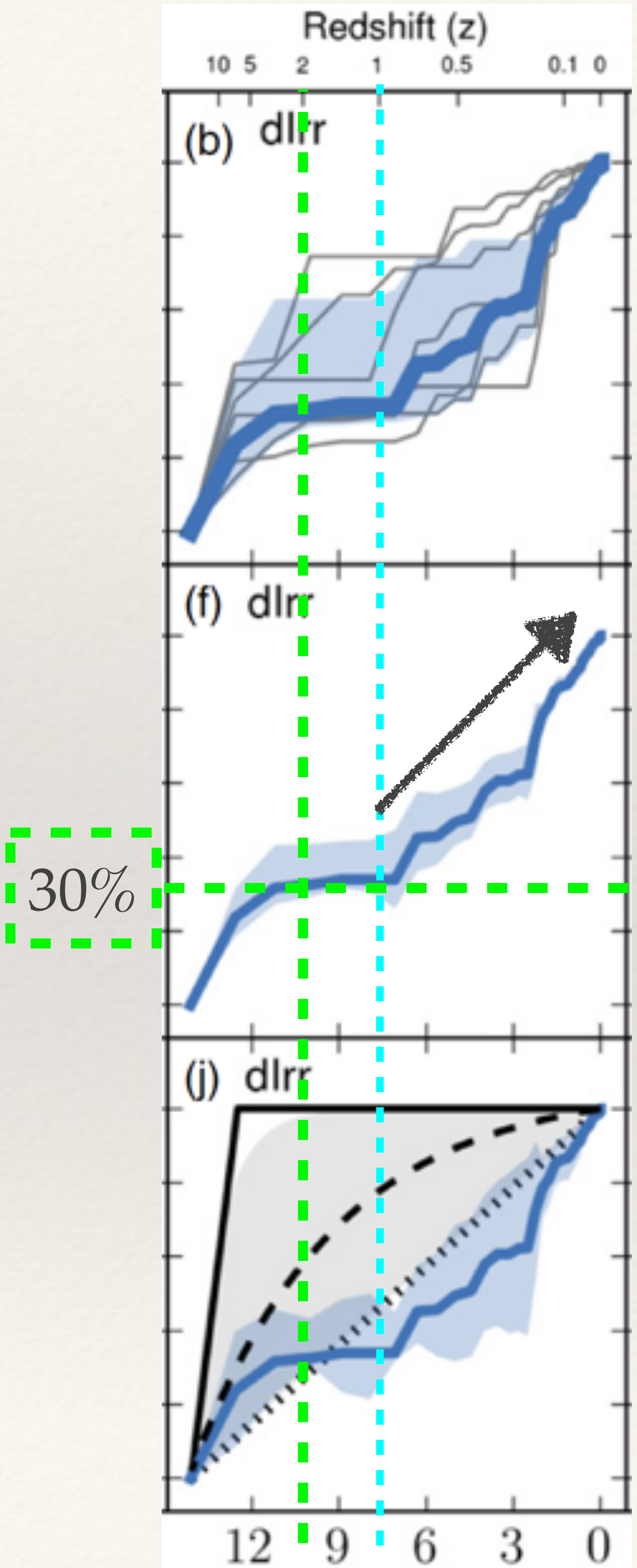


1. dSphs are predominantly old systems. In average, they have formed the vast majority of their stars prior to z~2 (10 Gyr ago)

2. However individual galaxies show significant scatter, ranging from purely old to those with constant lifetime SFHs

3. Overall SFH trend well matched with "exponentially decreasing model"

Lessons from the comparison (2)



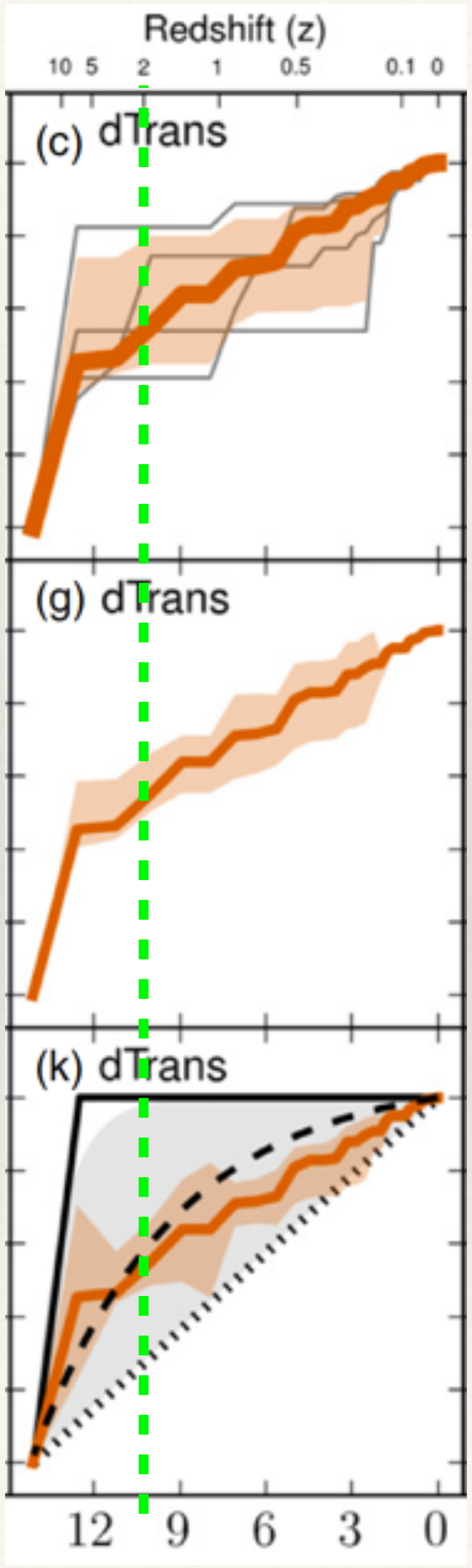
1. On average dIrrs formed ~30% of their stellar mass prior to z~2, and show an increasing SFR toward the present, beginning around z~1 (7.6 Gyr ago)

2. There are few predominantly old dIrrs

3. Show only modest scatter relative to the average

4. Nearby dIrrs may provide a template for how low mass galaxies evolve without significant environmental influence

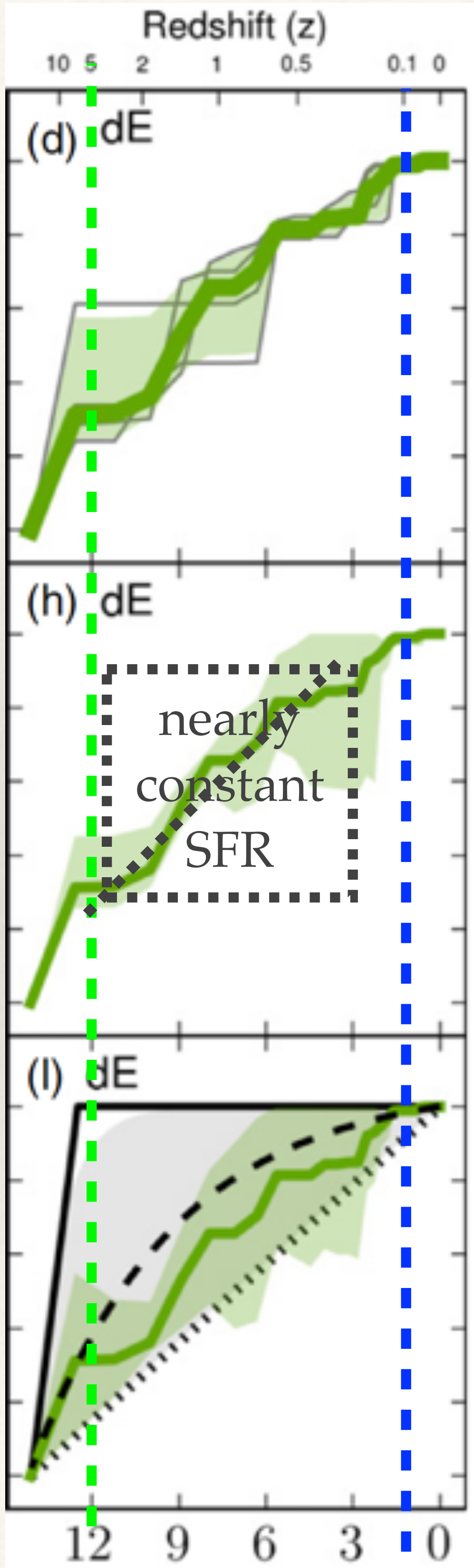
Lessons from the comparison (3)



1. dTrans appear to have formed ~45% of their stellar mass prior to z ~ 2, and have experienced nearly constant SFRs since that time

2. dTrans with predominantly old SFHs (e.g. DDO210) tend to have lower present-day gas fractions, while those with higher gas fraction have had more constant SFRs

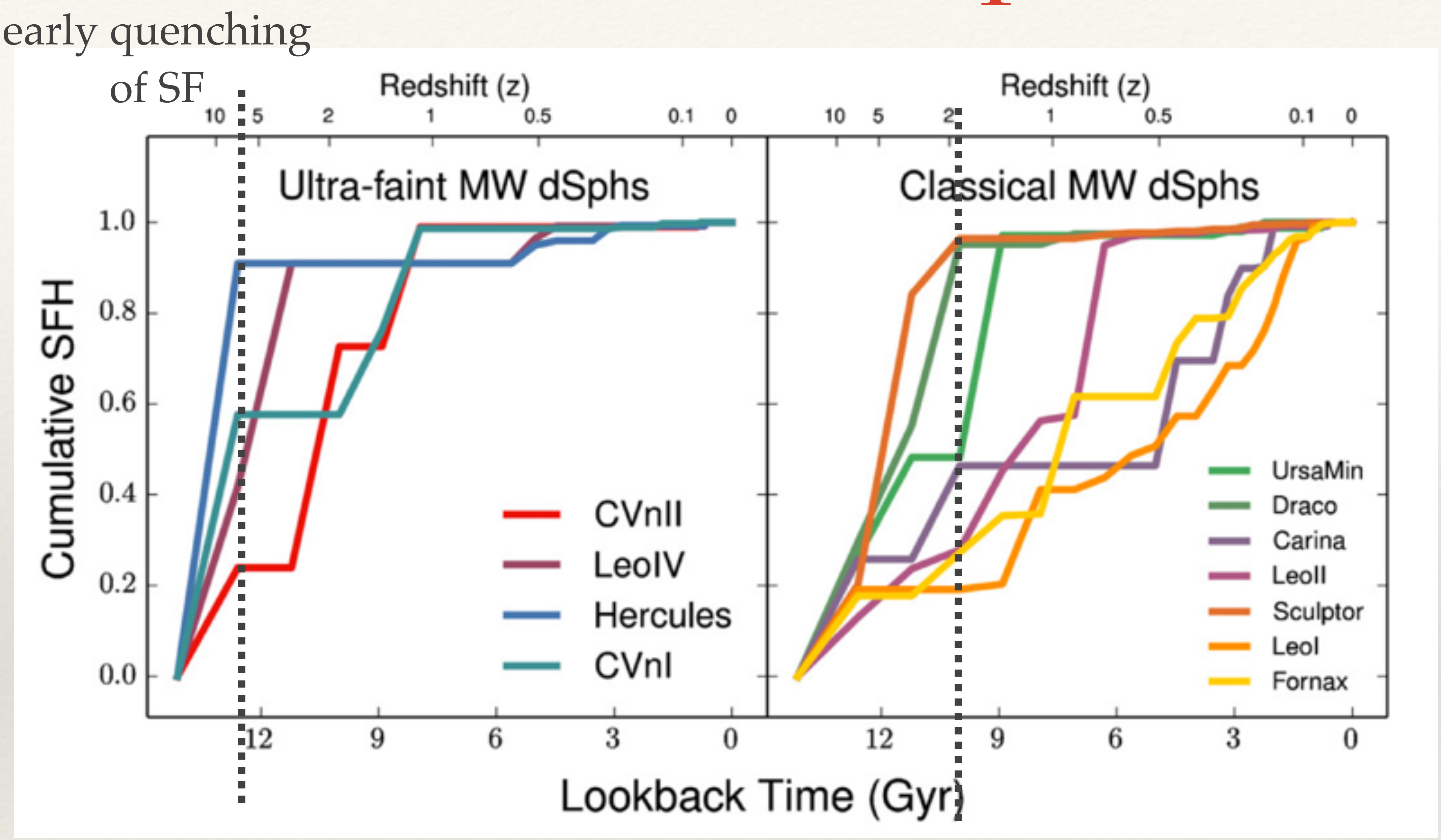
Lessons from the comparison (4)



1. dEs typically have an initial burst of SF prior to 12 Gyr ago (z~5), followed by nearly constant SFR

2. All dEs show declining SFHs starting at z~0.1 (2 Gyr ago)

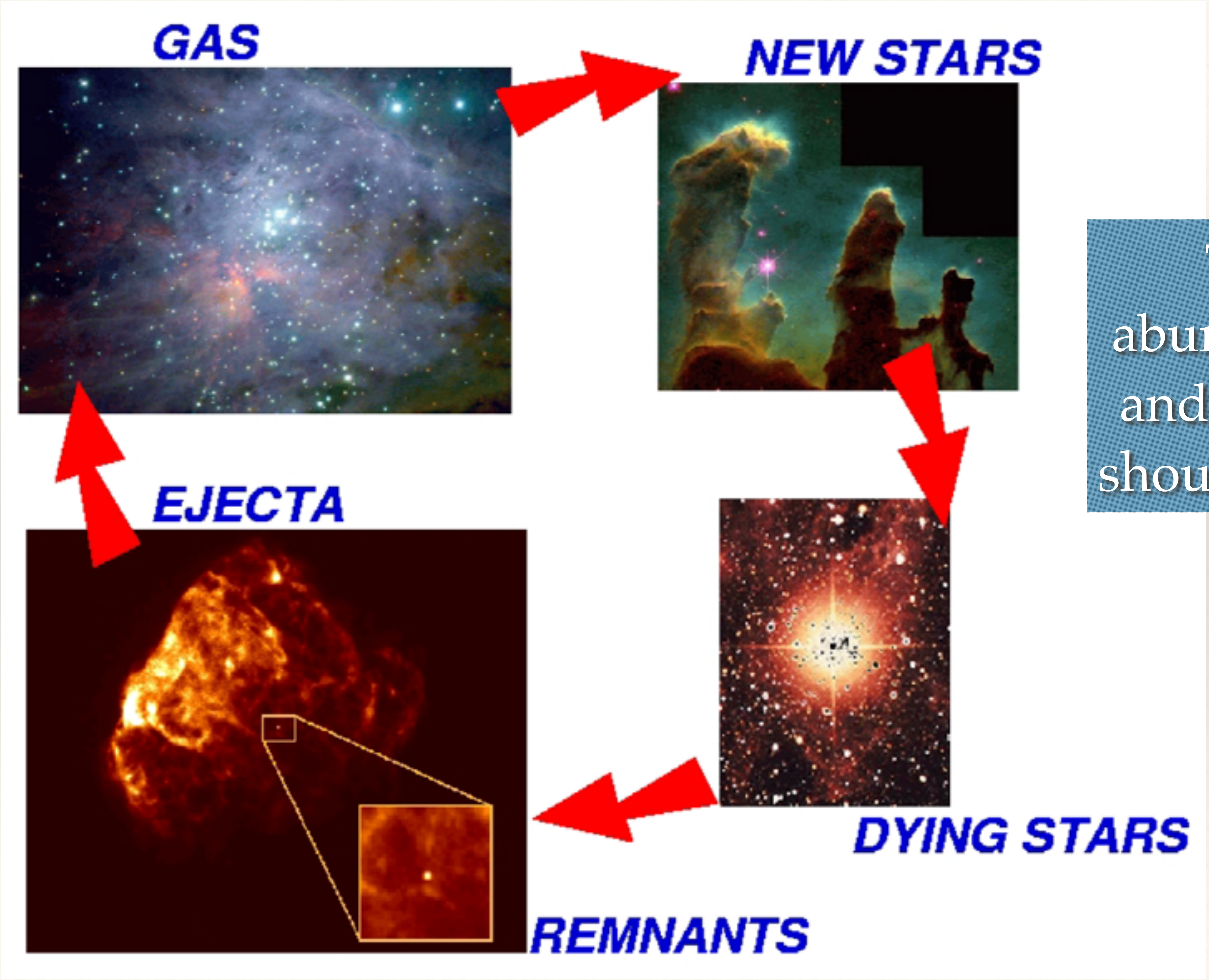
Lessons from the comparison (5)



1. SFs in the least luminous uFds have been quenched at earlier times than the most luminous dSphs
2. In general, more luminous dwarfs have extended SFHs, however deviations from this relationship suggest that environmental effects of individual galaxies might be as important as their mass

SFH of a galaxy is one of key factors determining the path of its chemical evolution because the number of stars formed (i.e. SFR) with a given initial mass function controls the rate of chemical enrichment

Simple Concept of Chemical Evolution



The chemical abundance of the gas and stars in a galaxy should evolve in time!

M_{gas} ↓

$M_{\star}$ ↑

M_h ↑

$\propto$ SFR

One key observable features that the SFH of a galaxy left behind is the metallicity distribution function (MDF) of its stars

Metallicity Distribution of the Stars

Simple Analytical Model

Equation of Gas phase Chemical Evolution

$$z(t) = z(0) - y * \ln[M_{gas}(t)/M_{gas}(0)]$$

$$M_{gas}(t) = M_{gas}(0) * e^{-[z(t)-z(0)]/y}$$

**where z mass fraction of heavy element (i.e. metallicity)

y chemical yield (i.e. "productivity" of elements)

M_{gas} gas mass

Equation of Stellar Mass with metallicity less than z(t)

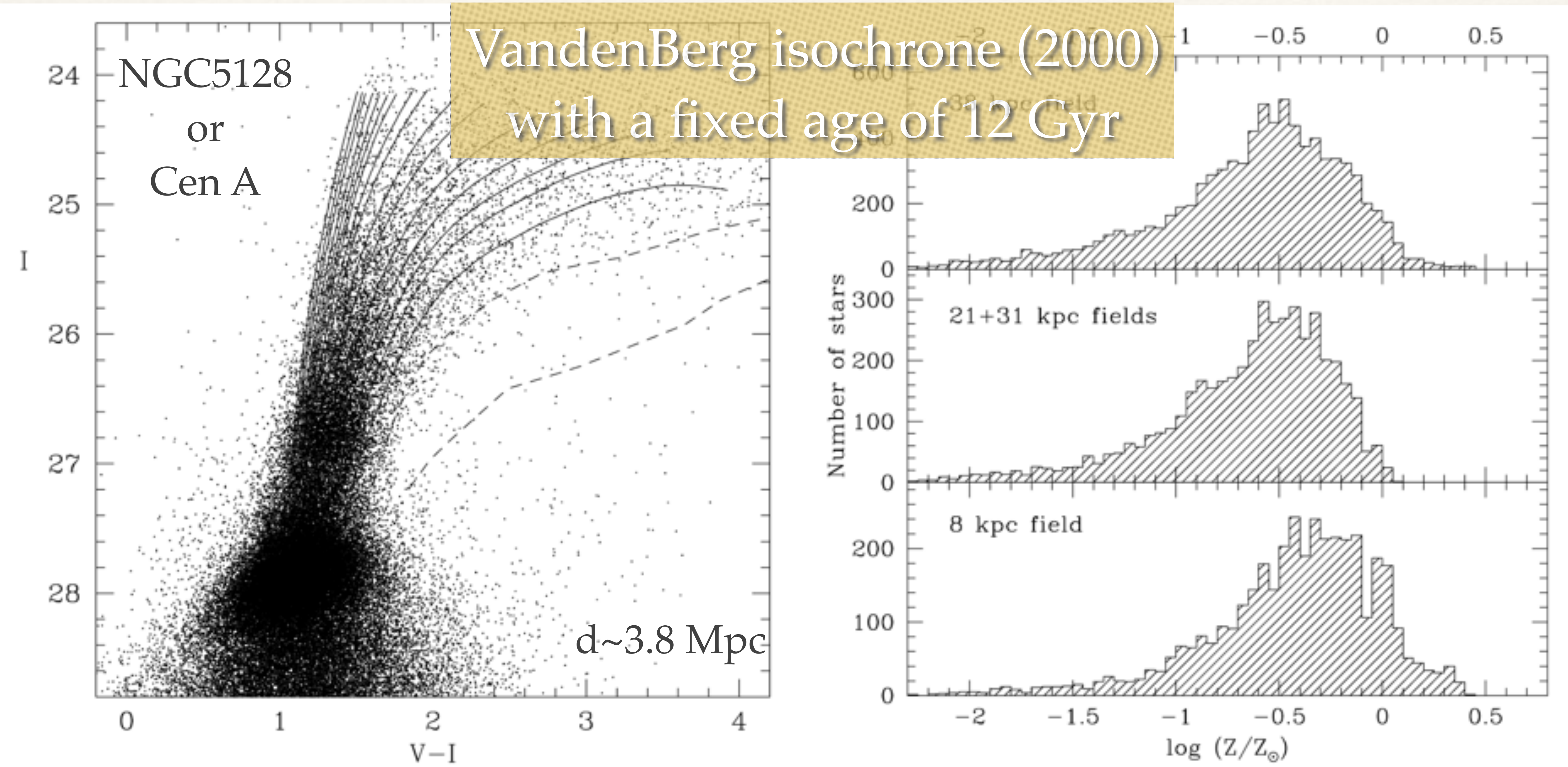
$$M_{\star}[<z(t)] \equiv M_{\star}(t) = M_{gas}(0) - M_{gas}(t)$$

$$dM_{\star}(z) \propto e^{-[z(t)-z(0)]/y} dz$$

Metallicity Distribution of RRLs

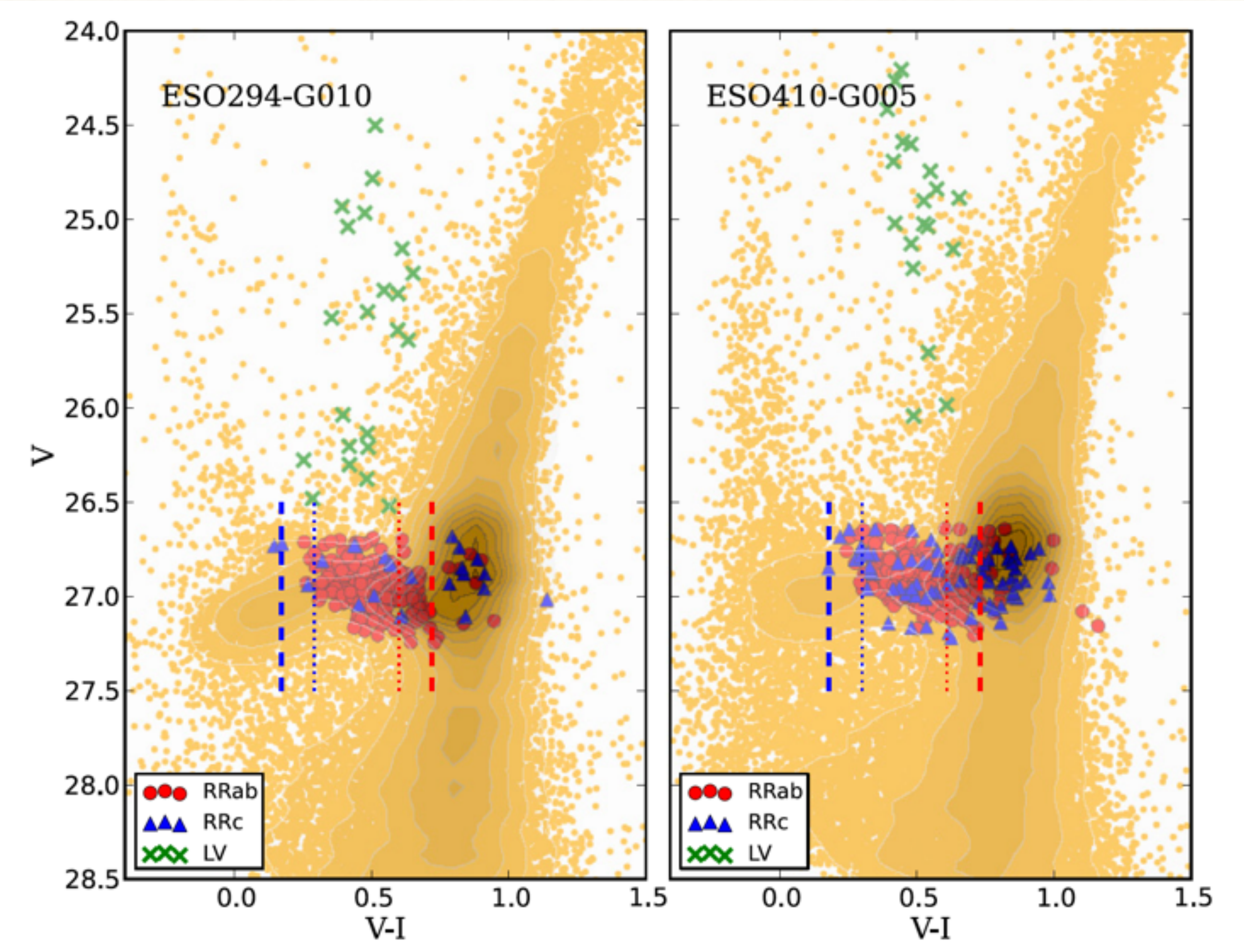
Why RRLs? Why not RGBs?

VandenBerg isochrone (2000) with a fixed age of 12 Gyr



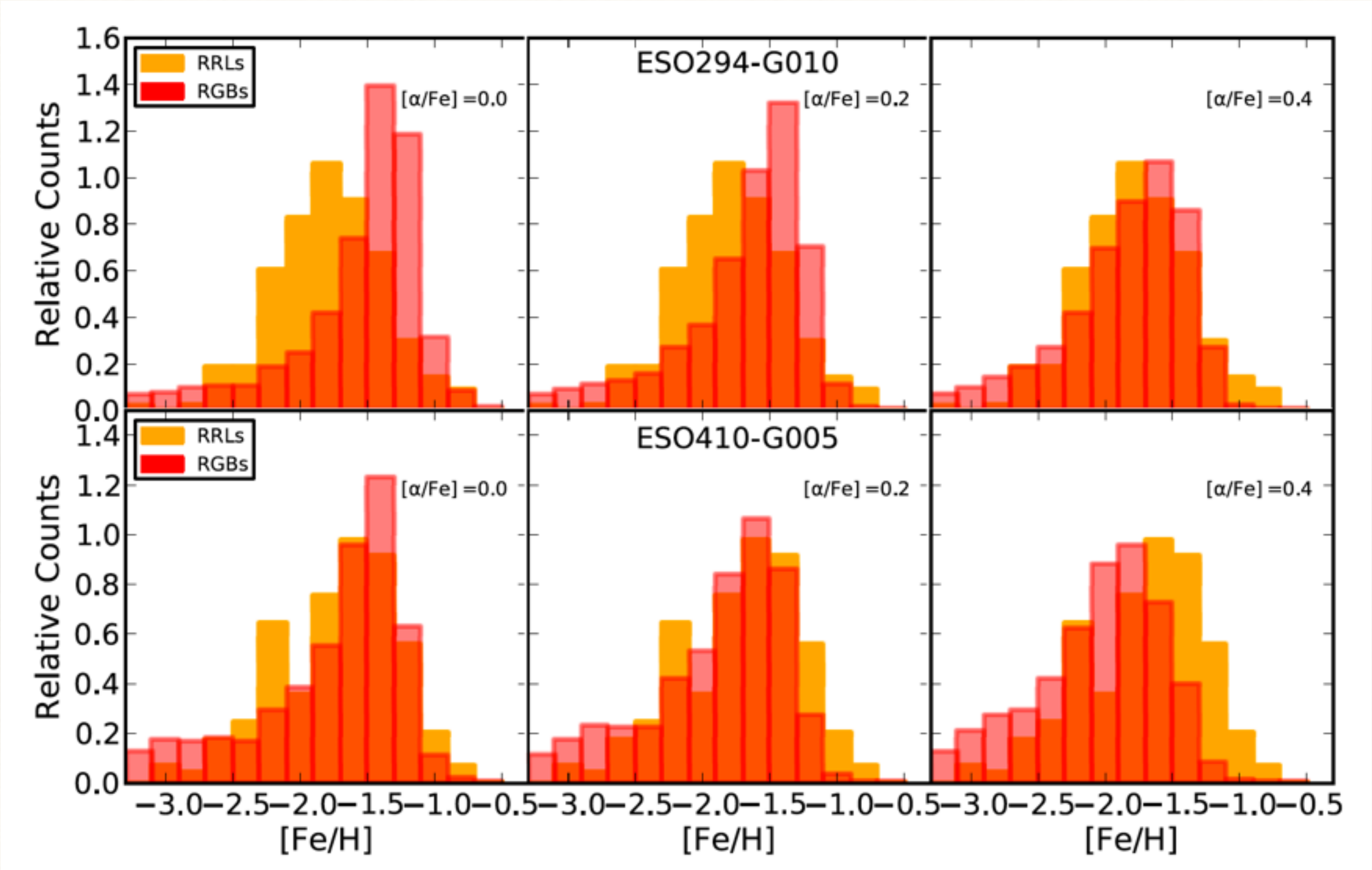
Rejkuba et al. 2005, ApJ, 631, 262

Color-Magnitude Diagrams from HST / ACS F606W,F814W



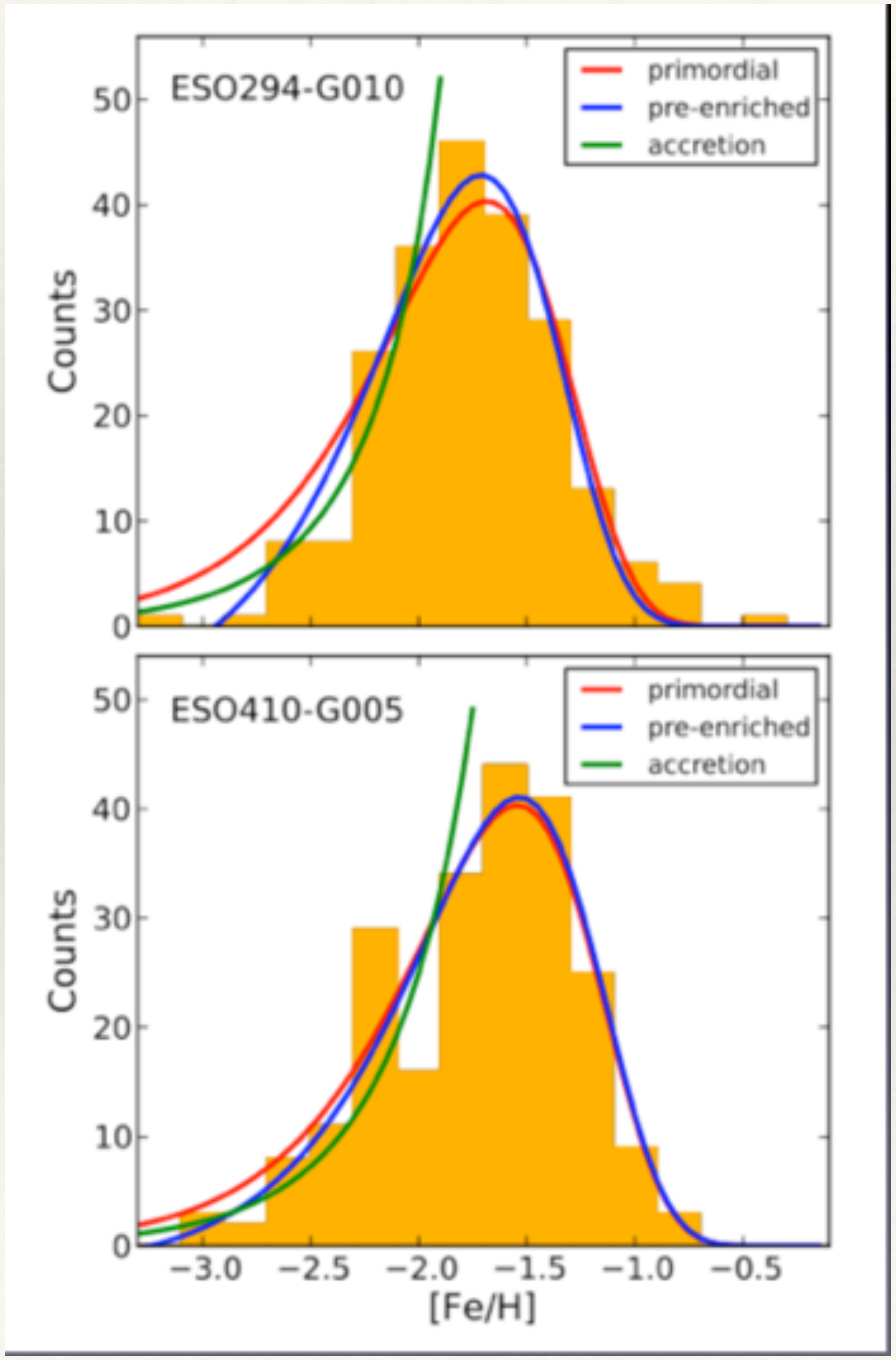
Yang et al. 2014, ApJ, 784, 76

RGB MDF is influenced by inclusion of young/intermediate age populations.
It also depends on the stellar evolution models and abundance of alpha elements!



Metallicity Distribution of RRLs

Simple Analytical Model of Chemical Evolution



Closed-box models : primordial & pre-enriched

$$\frac{dn}{d[M/H]} \sim \frac{Z - Z_0}{y} e^{-(Z-Z_0)/y}.$$

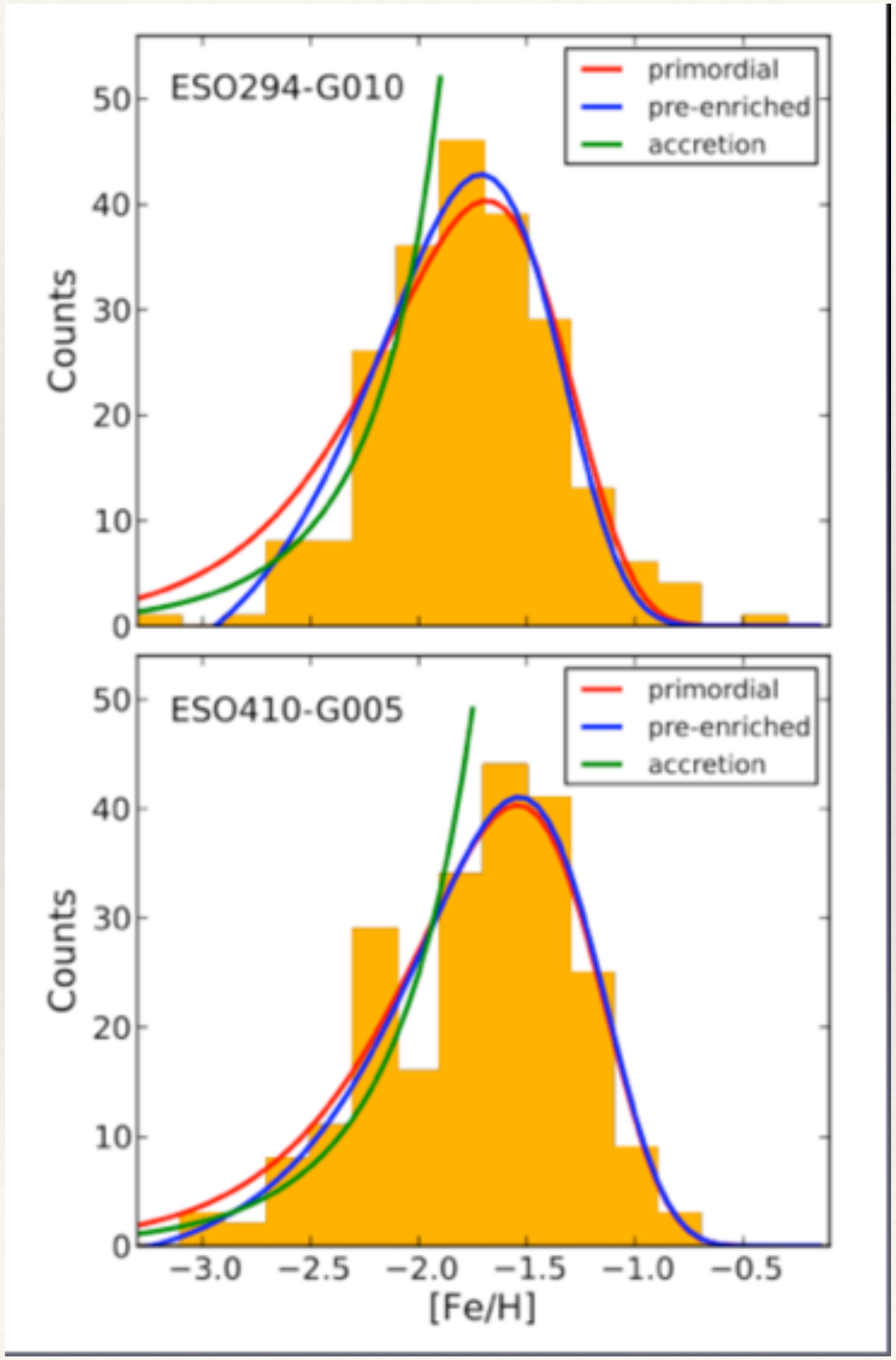
Simple accretion model

$$\frac{dn}{d[M/H]} \sim M_g \frac{Z}{y - Z}.$$

Best-fit solutions for "pre-enriched" model

	y	Z_0	$[M/H]_0$
ESO294	0.00064	0.00004	-2.7 dex
ESO410	0.00097	0.00002	-3.0 dex

Early Chemical Enrichment of the Sculptor dTrans

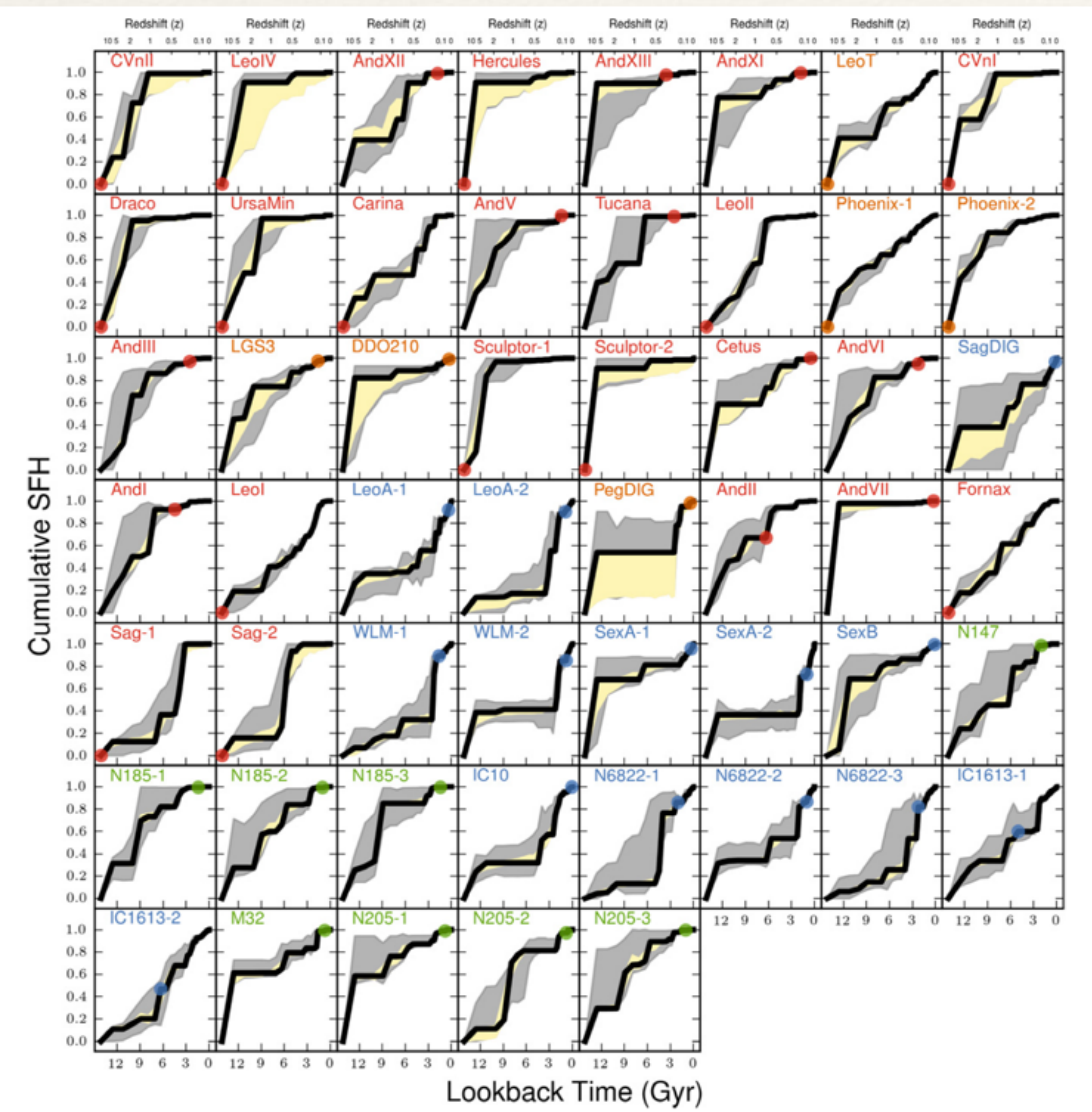


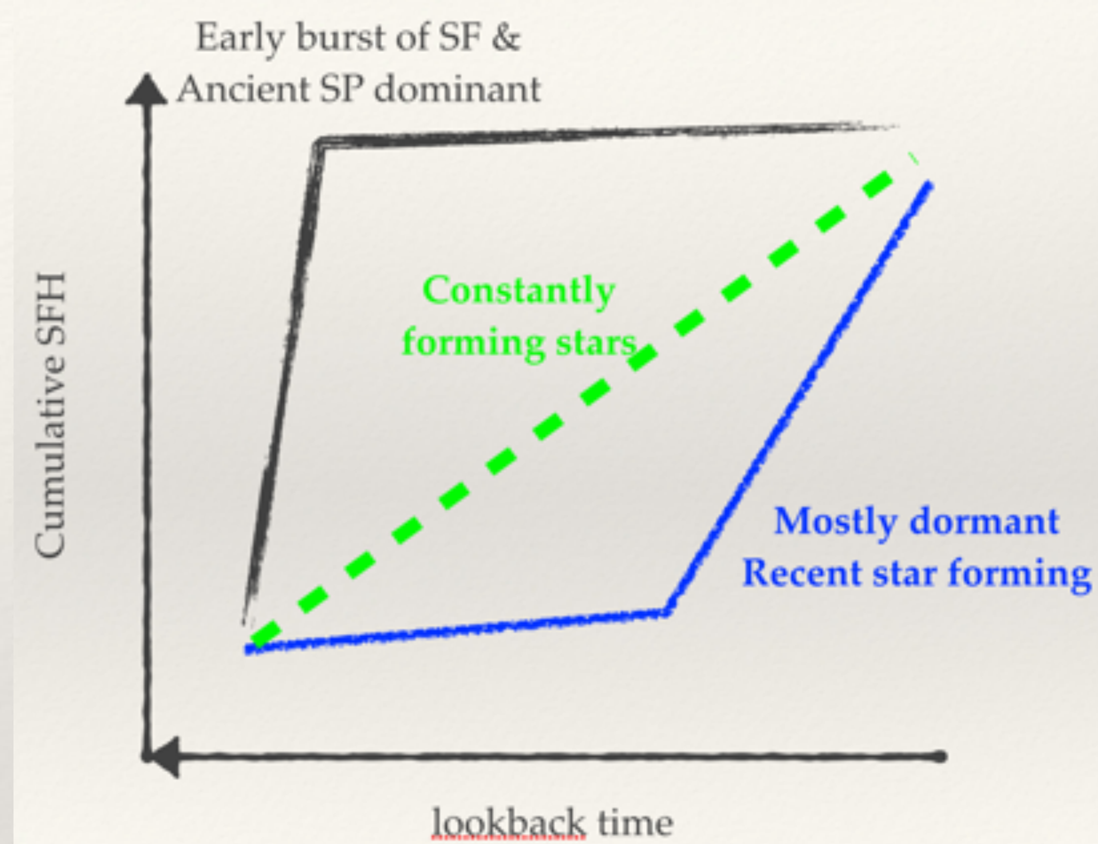
- All three simple models appear to describe the RRL MDFs fairly well

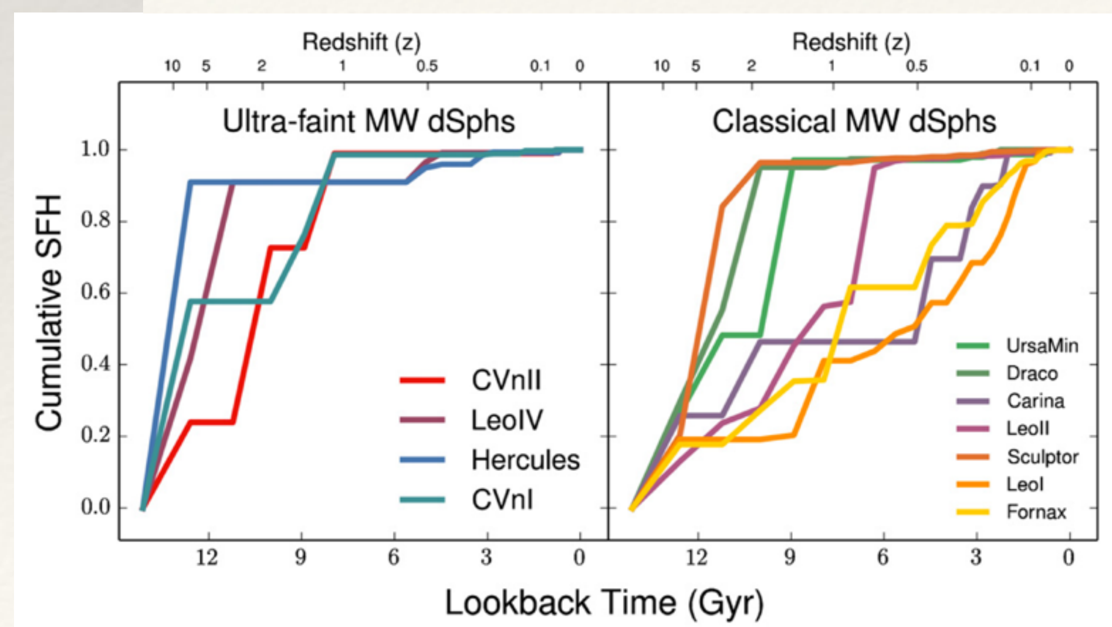
- Possible scenarios for the early enrichment process
  - "**Prompt initial enrichment**" : Preferential proto-galactic enrichment by high-mass stars (or Pop III stars?) during the very early phase of galaxy formation. The initial cosmic enrichment levels ($10^{-6} < Z_0 < 10^{-4}$) can be achieved by the end products of Pop III stars (Schneider et al. 2002)
  - "**Two-phase enrichment**" : The metal-poor tails of the MDFs formed first in a very early gas infall phase. Then the dTrans approached to a steady state ($z \longrightarrow y$), then they entered into a closed-box-like phase to form the remaining part of the MDFs. These phase transition should be completed within a very short period of time ($t < 1$ Gyr)

Take Home Messages

- **About SFHs of Nearby Dwarf Galaxies**







Take Home Messages

- **About SFHs of Nearby Dwarf Galaxies**
  - Individual galaxies show significant scatter, ranging from purely old to those with constant lifetime SFHs
  - More luminous dwarfs have extended SFHs, however deviations from this relationship suggest that environmental effects of individual galaxies might be as important as their mass
  - SFs in the least luminous uFds have been quenched at earlier times than the most luminous dSphs

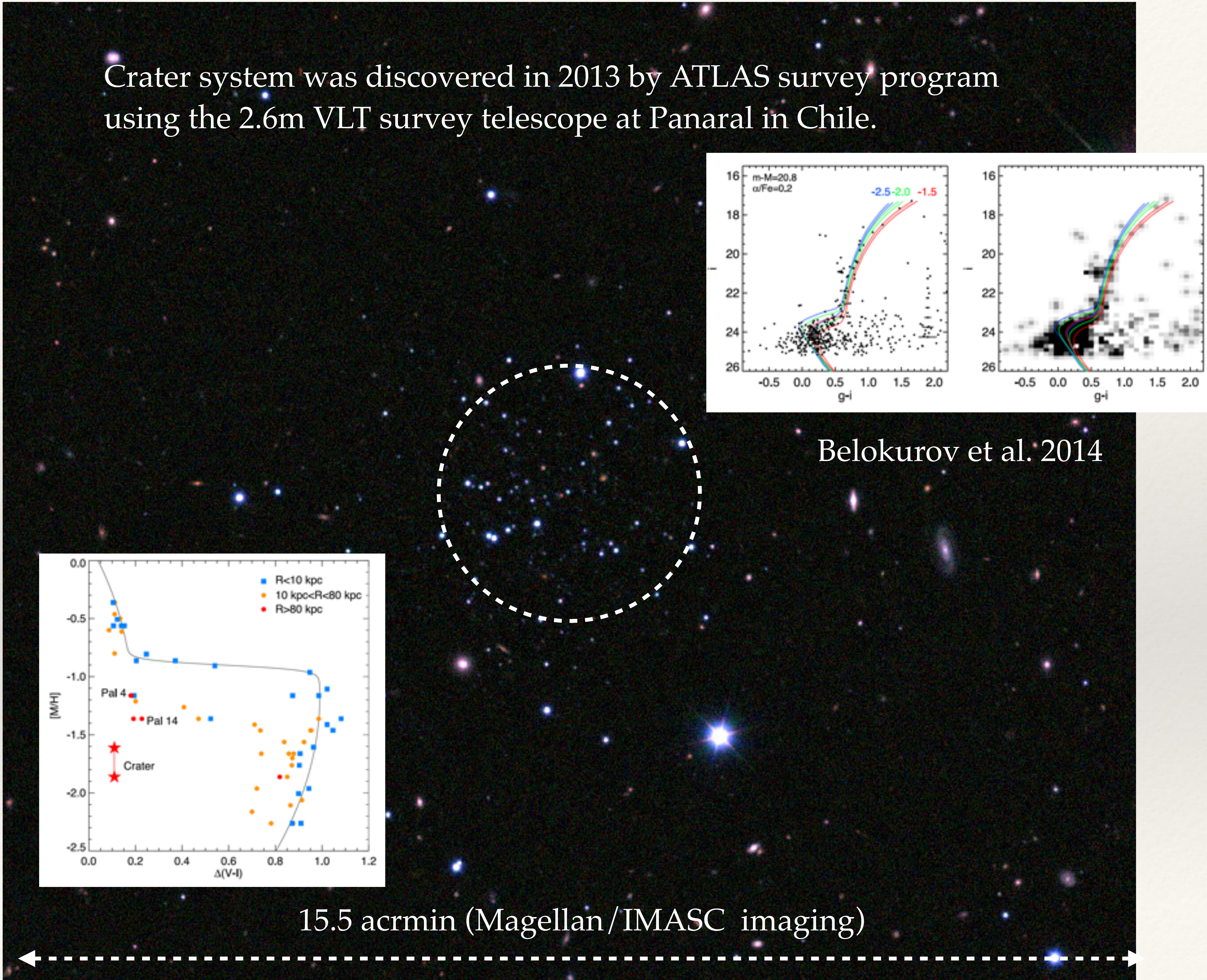
Take Home Messages

- **About Early Chemical Evolution of the Sculptor dTrans**
  - SFH of a galaxy is one of key factors determining the path of its chemical evolution
  - RRL MDF can be used as a useful analytical tool for investigating early chemical enrichment process of nearby dwarf galaxies

True Nature of a Mysterious Crater Stellar System

Yang et al. 2015 in prep

Crater system was discovered in 2013 by ATLAS survey program using the 2.6m VLT survey telescope at Panaral in Chile.

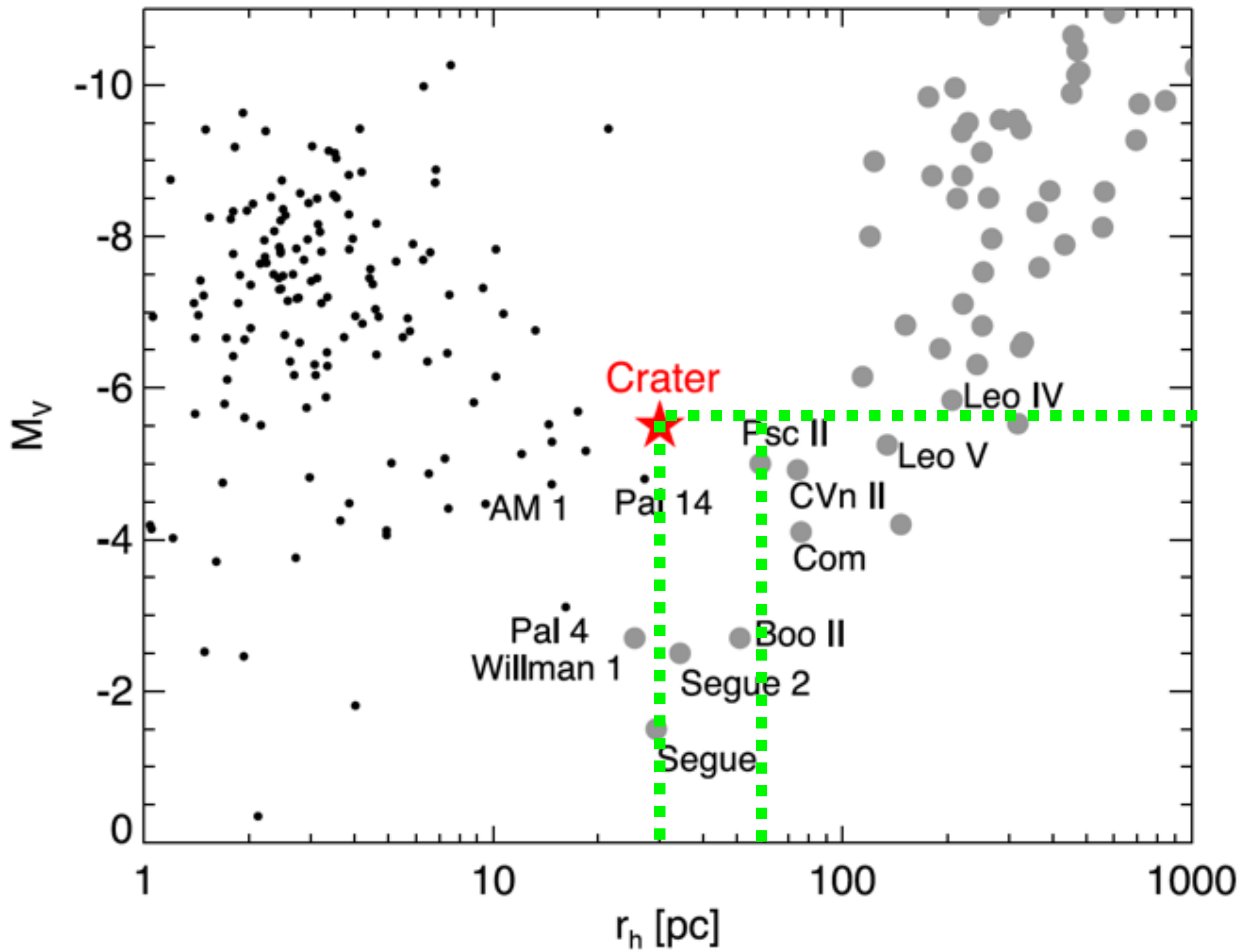


Belokurov et al. 2014

15.5 acrmin (Magellan/IMASC imaging)

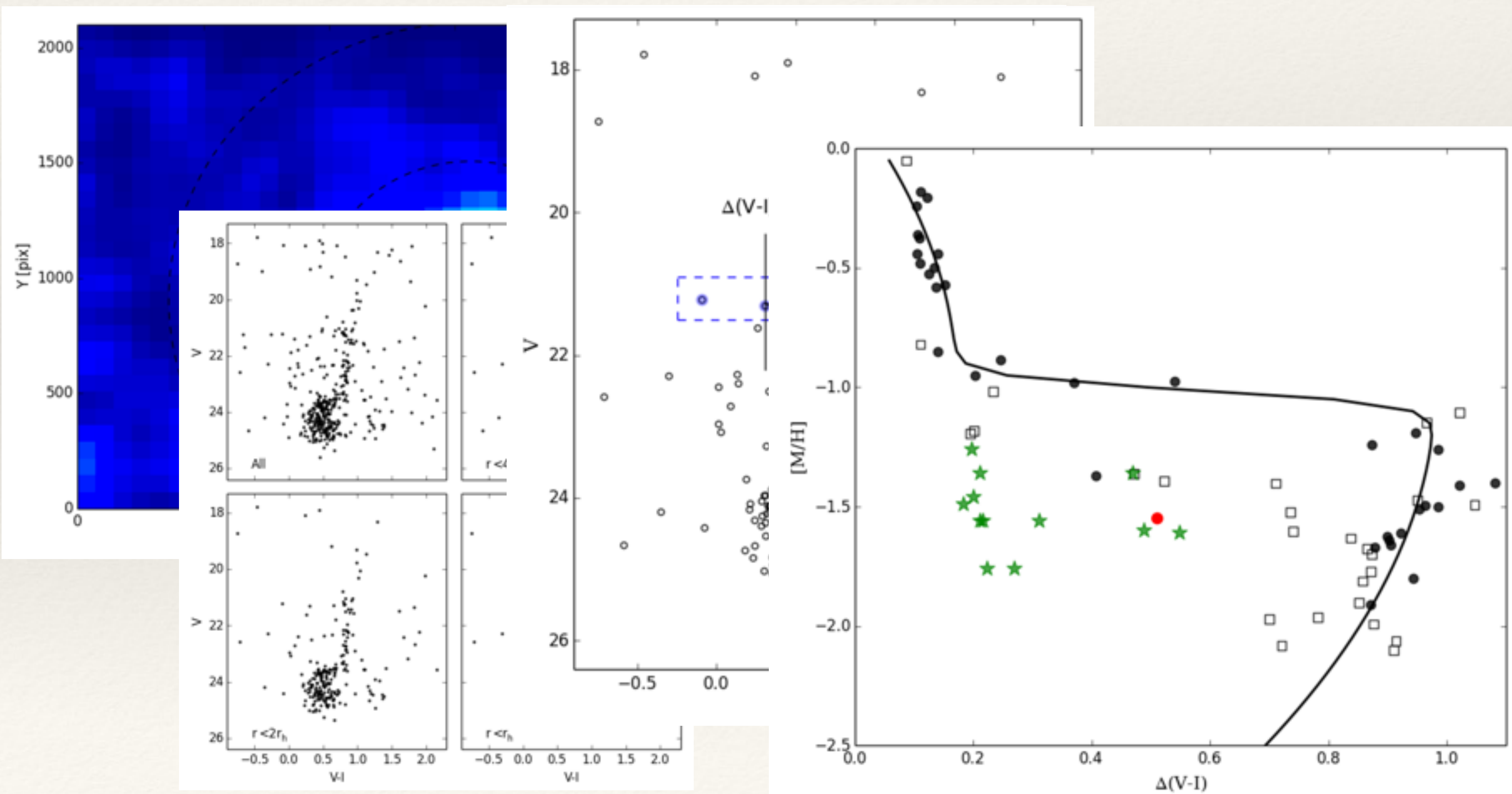
Crater seems to be too compact to be a dwarf galaxy

Belokurov et al. 2014, MNRAS,441, 2124



Magellan/IMACS VI Imaging of the Crater

The preliminary results of our analysis seem to reveal quite different nature of the Crater system

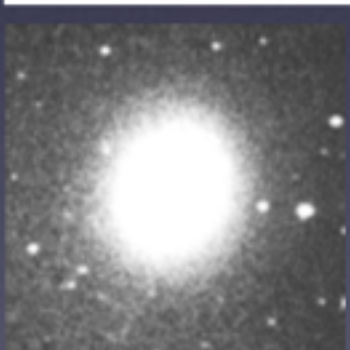


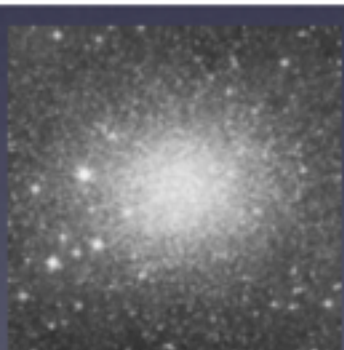
Please stay tuned for our upcoming results.

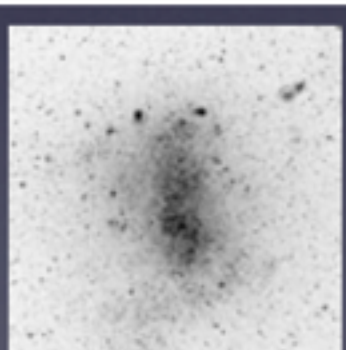
Thanks & Any Questions?

Summary of “LG Dwarf Galaxies”

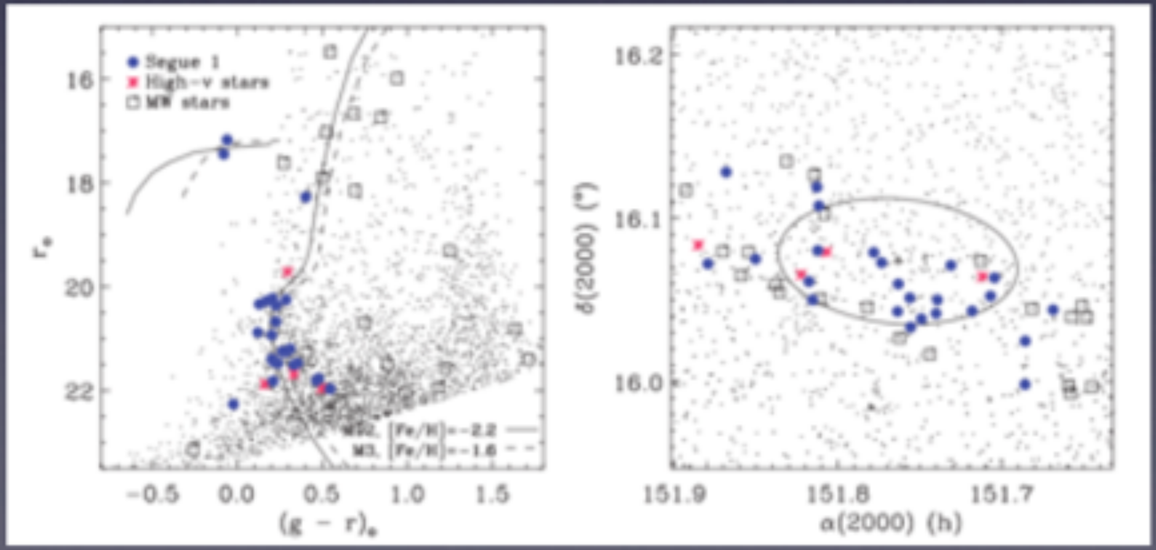
Type	M_{dyn}	M_B	$\langle[Fe/H]\rangle_{RGB}$	*M/L	SFH
dE dSph dIrr dTran uFd	$10^7 \sim 10^5$ $M_\odot$	-0.7 ~ -18 mag	-0.5 ~ -2.7 dex i.e. the most metal-poor systems	>100 i.e. the most dark matter dominated system	no two Local Group dwarfs have the same SFH


M32 dE


Sculptor dSph


NGC6822 dIrr


Phoenix dTran



Segue I uFd

Nearby Dwarf Galaxies in the Near-field Environment

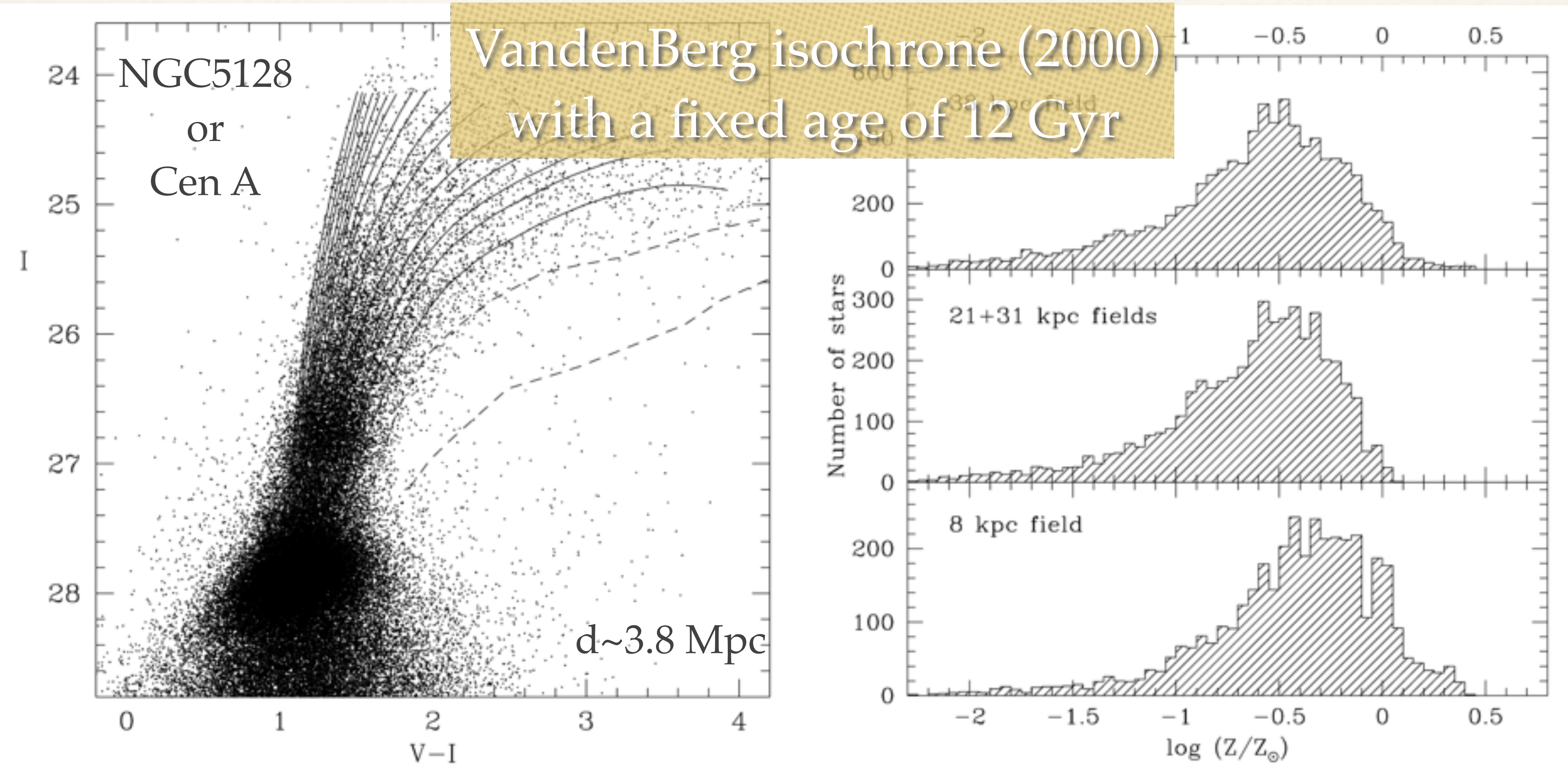
- **Gas-poor dSph/dEs** appear to be located more closer to their giant hosts while gas-rich dIrr / dTrans tend to be isolated

- The overall properties of nearby dwarf galaxies seem to be consistent with their counterparts in distant universe

Metallicity Distribution of RRLs

Why RRLs? Why not RGBs?

VandenBerg isochrone (2000) with a fixed age of 12 Gyr

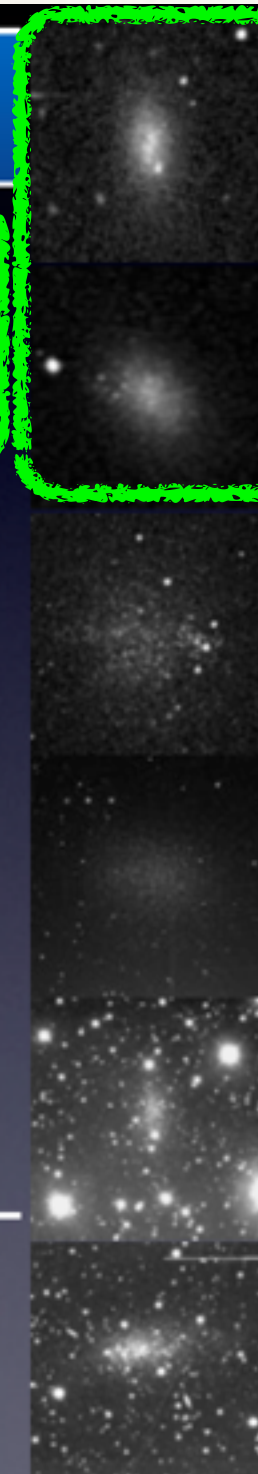


Rejkuba et al. 2005, ApJ, 631, 262

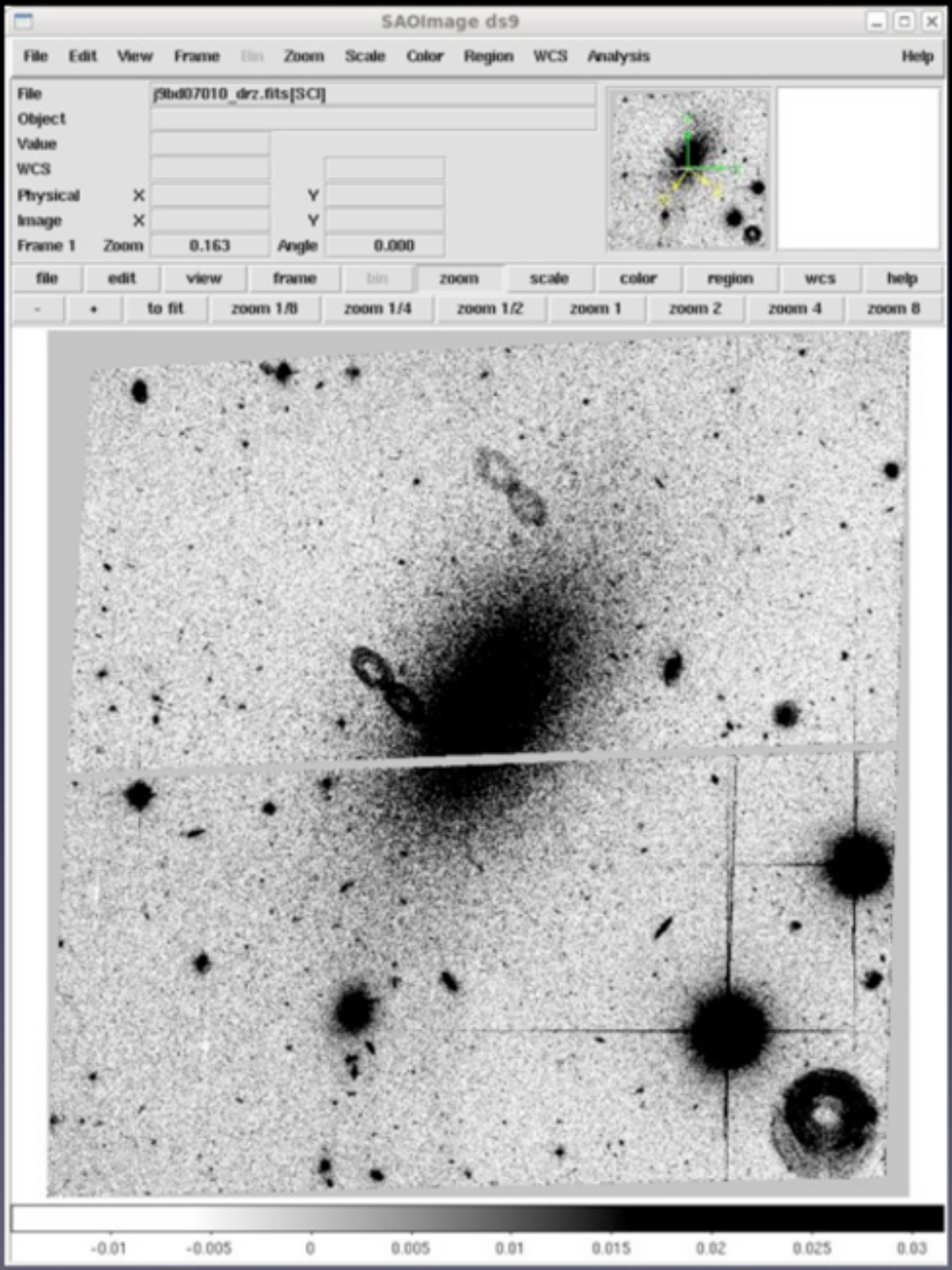
dTrans in the Sculptor Group

Target	Mv	<[Fe/H]>	$(m-M)_0$	Type	MD
ESO294-G010	-11.11	-1.77*	26.38*	dIrr/dSph	NGC 55
ESO410-G005	-11.42	-1.64*	26.30*	dIrr/dSph	NGC 55
Phoenix	-9.8	-1.9	23.04	dIrr/dSph	MW
Leo I	-11.9	-1.4	22.40	dIrr/dSph	MW
LGS3	-9.8	-1.7	24.08	dIrr/dSph	M31
DDO210	-10.9	-1.9	24.89	dIrr/dSph	M31

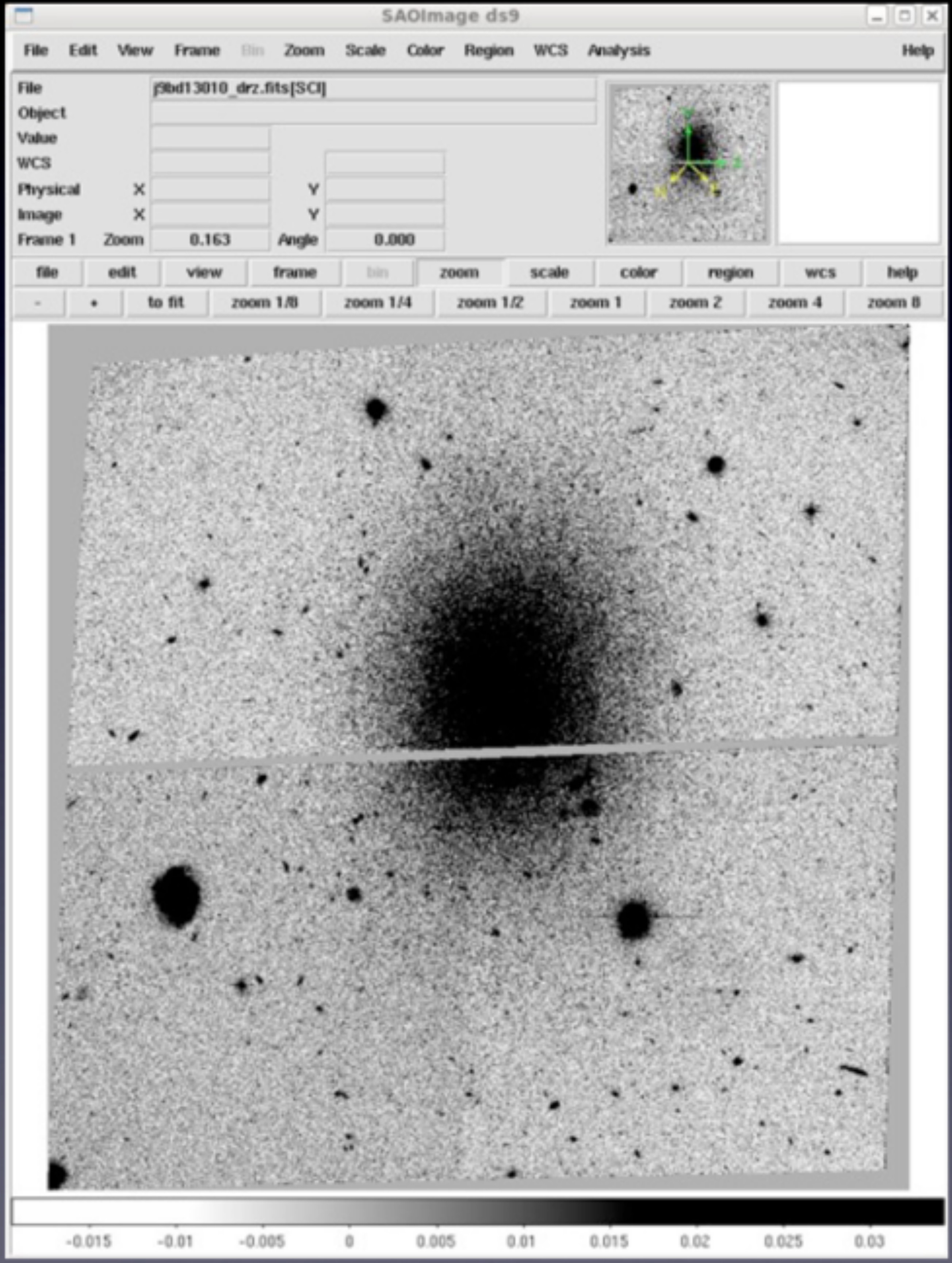
*Note : [Fe/H] values from previous studies refer "photometric metallicity" measured using RGBs, while the [Fe/H] values of ESO291 & ESO410 are derived via the P-Amp-[Fe/H] relation of Alcock et al. (2000).



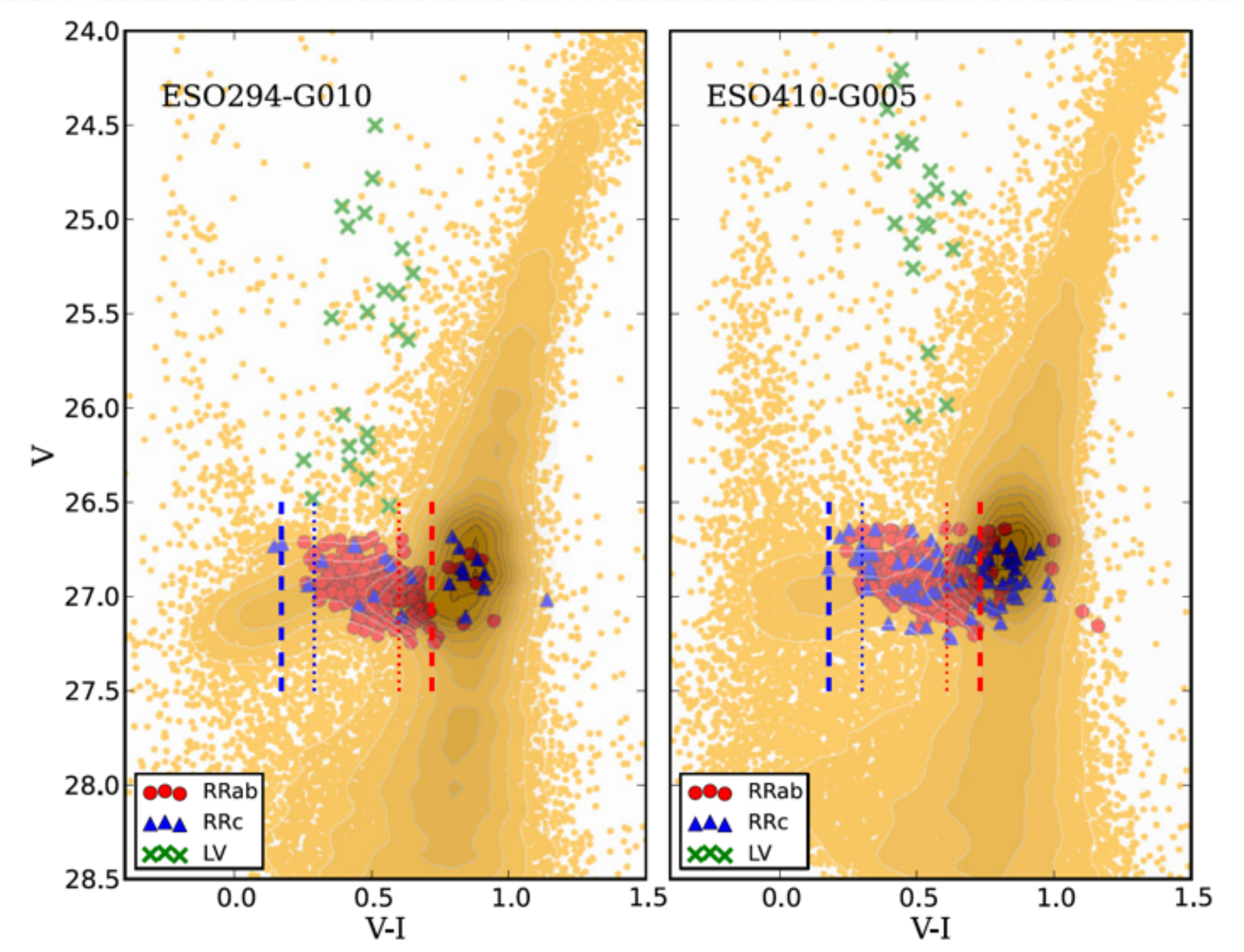
ESO294-G010

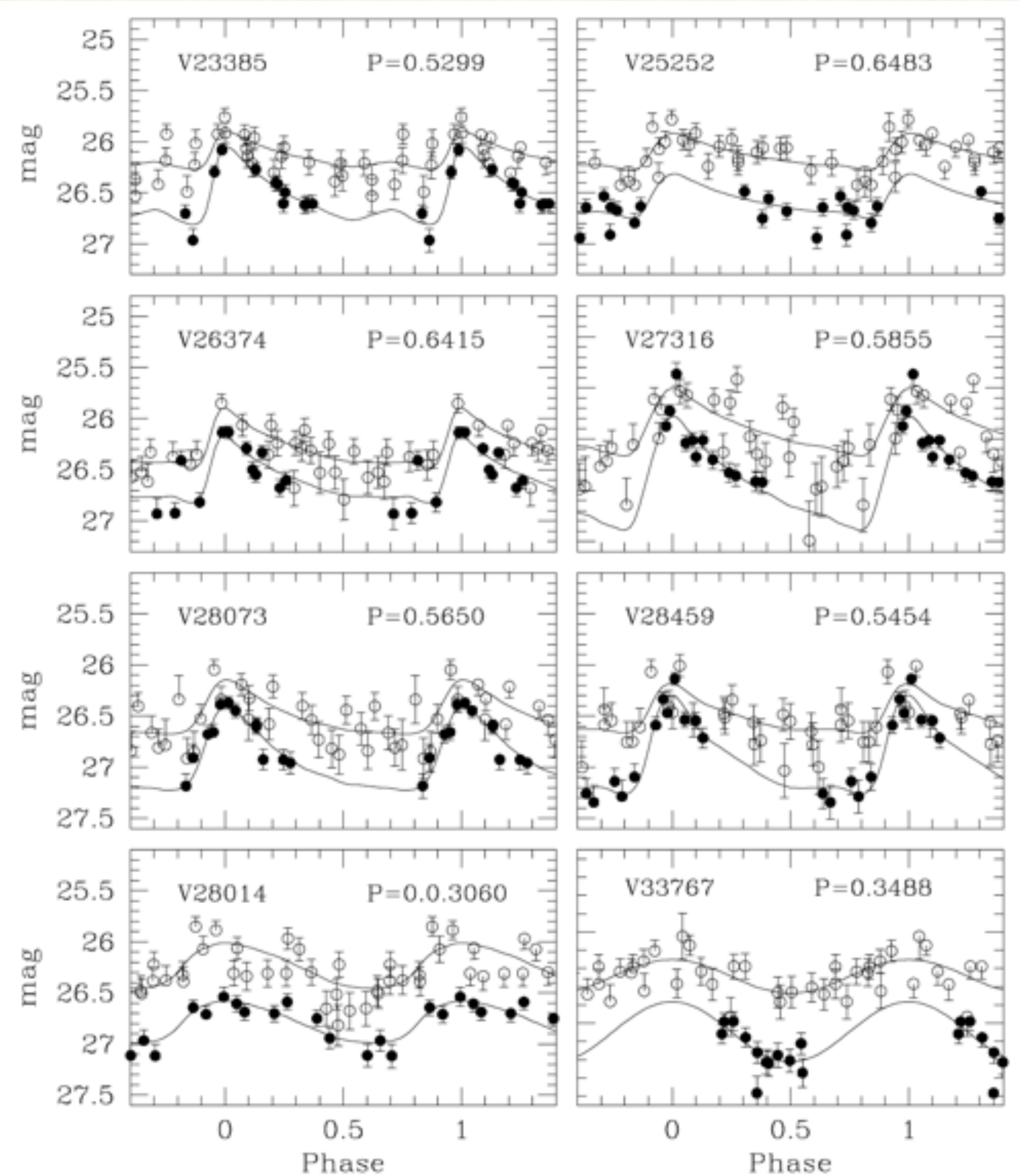


ESO410-G005



Color-Magnitude Diagrams from HST / ACS F606W,F814W




V23385
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V25252
P=0.6483
V26374
P=0.6415
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P=0.5855
V28073
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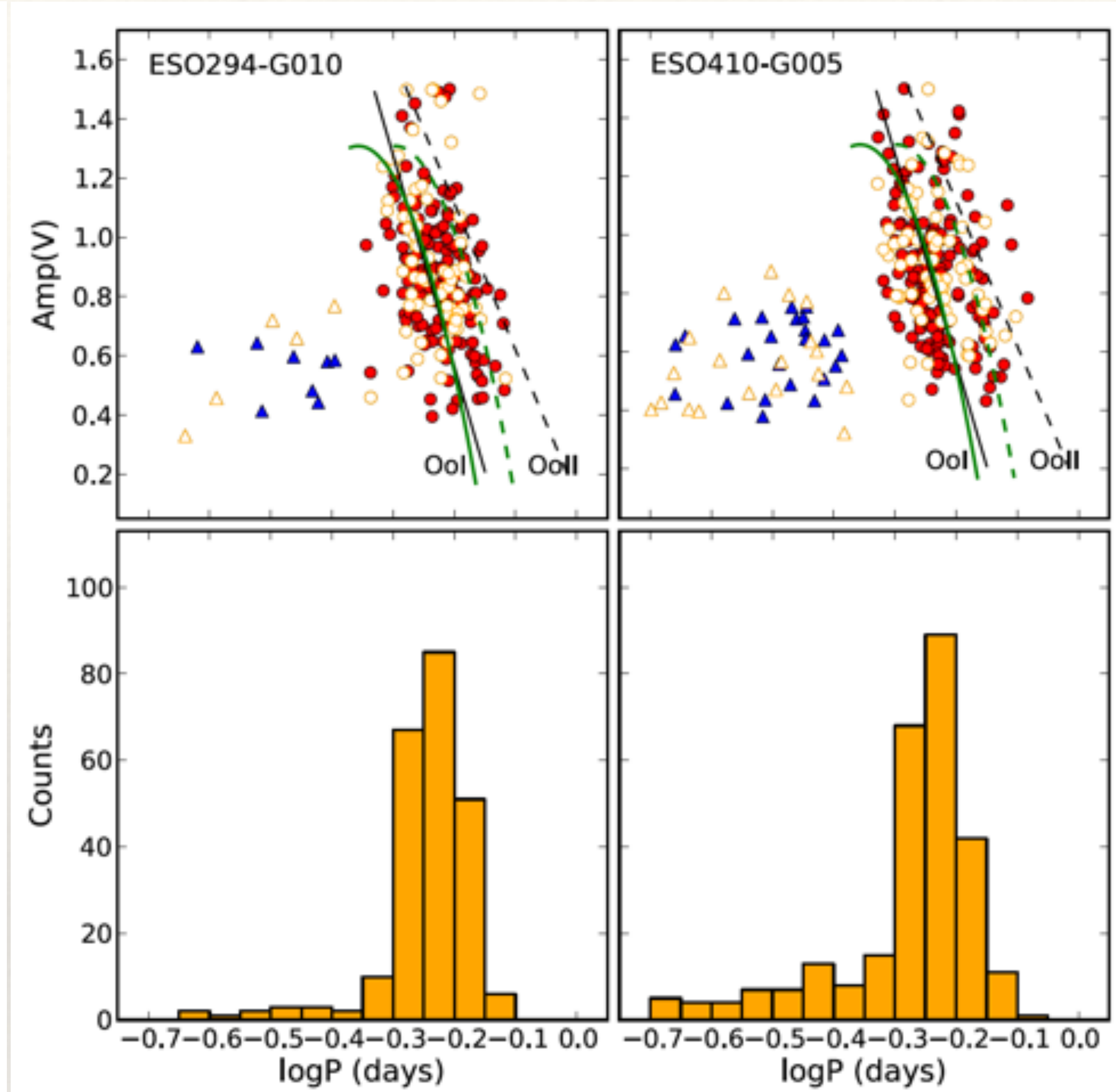
V28459
P=0.5454
V28014
P=0.0.3060
V33767
P=0.3488
mag
Phase


ESO294-G010
ESO410-G005
Amp(V)
OoI
OoII
Counts
logP (days)

Pop III star formation & Early Chemical Enrichment

The first generation of stars, formed out of pristine primordial gas, had a top heavy initial mass function, with a typical mass scale of order of ~100 M(sun) and most probably just one star per halo (e.g. see Abel et al. 2002; O'Shea & Norman 2007).

These stars started forming after about 30-40 million years from the big bang at redshift z~55-65 (Naoz et al. 2006; Trenti & Stiavelli 2007; see also Gao et al. 2005), and given their high mass, they live only a few million years ending with a pair-instability SN phase or a direct collapse to a black hole (Heger et al. 2003).

A halo with a mass of ~ 10^8 M(sun) can be enriched to a critical metallicity Zcrit > 10^-4 Z(sun) by the most massive pair-instability SN. More typical explosions may instead enrich significantly less gas (~ 10^6 M(sun)) although at a corresponding higher metallicity (Bromm et al. 2003; Kitayama & Yoshida 2005; Grief et al. 2007; Whalen et al. 2008).