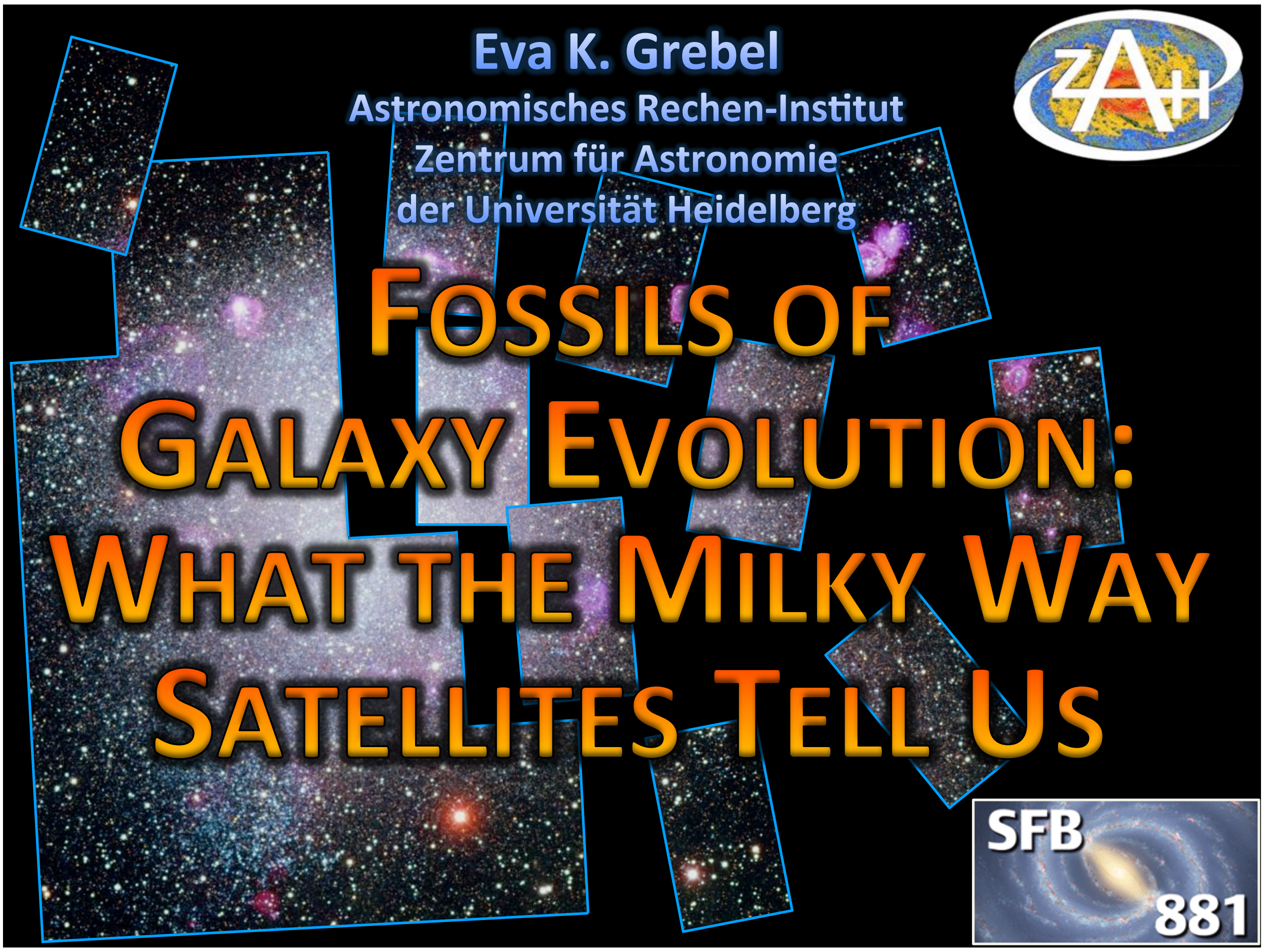

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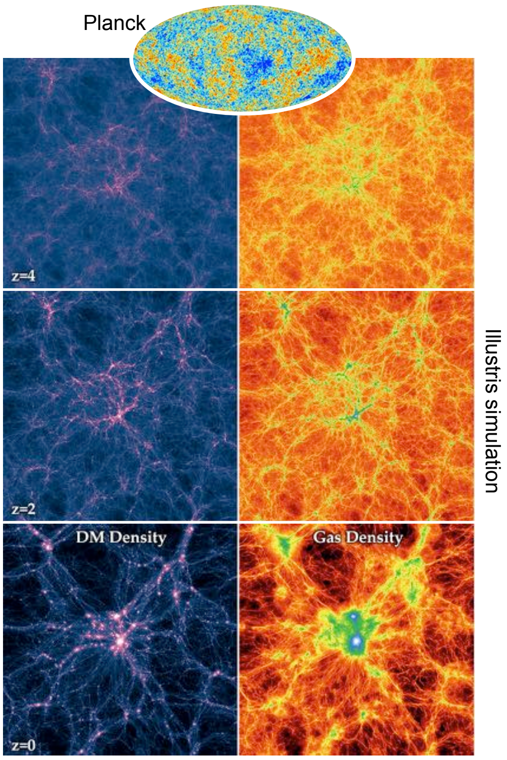
FOSSILS OF GALAXY EVOLUTION: WHAT THE MILKY WAY SATELLITES TELL US

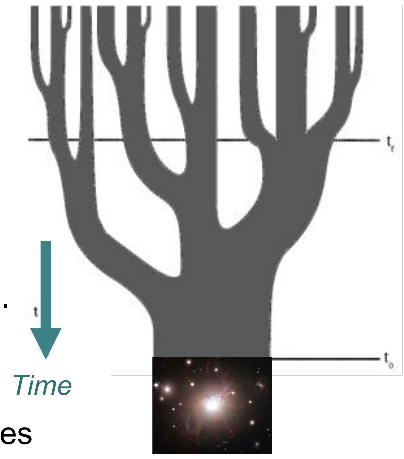
1. INTRODUCTION

Hierarchical Structure Formation



Fundamental scenario:
Large structures form through numerous mergers of smaller ones.

“Merger Tree”



- ☐ Larger structures form through successive mergers of smaller structures.
- ☐ If baryons are involved: Observable signatures of past merger events may be retained.

→ Dwarf galaxies as building blocks of massive galaxies.

Potentially traceable; esp. in galactic halos.

- ☐ Surviving dwarfs: Fossils of galaxy formation and evolution.

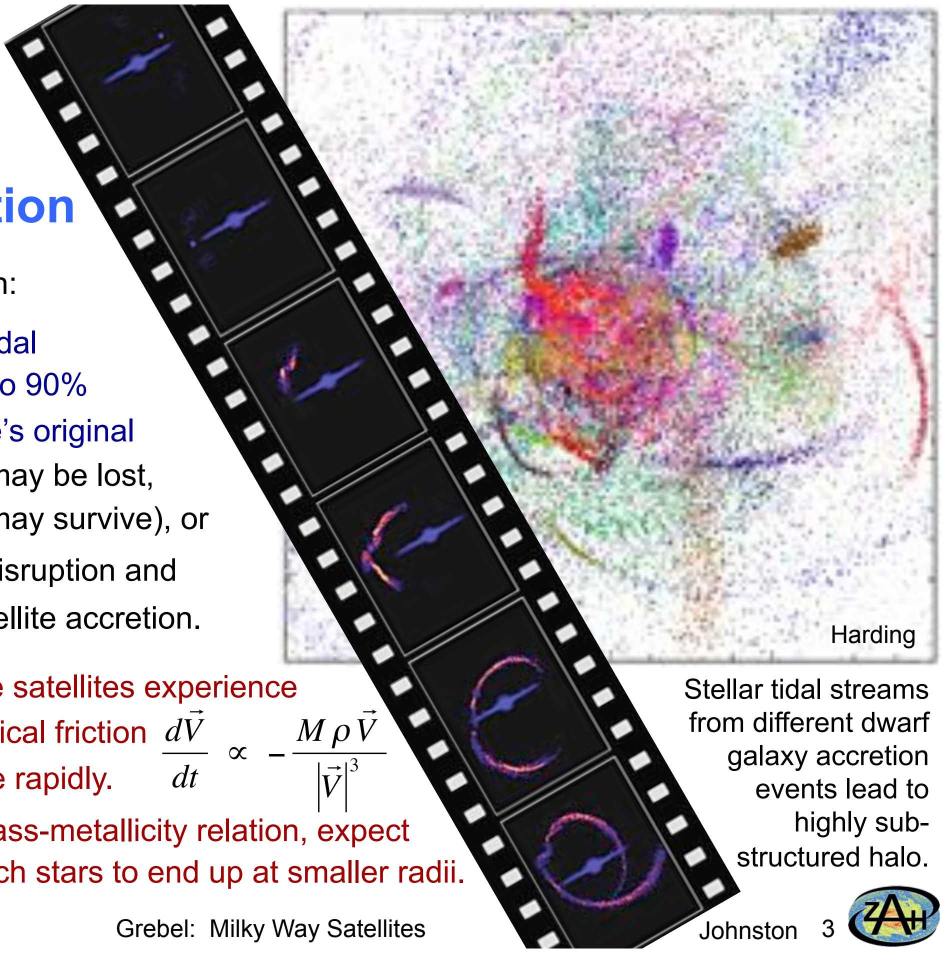
Satellite Disruption and Accretion

Satellite disruption:

- ☐ may lead to tidal stripping (up to 90% of the satellite’s original stellar mass may be lost, but remnant may survive), or
- ☐ to complete disruption and ultimately satellite accretion.

- ☐ More massive satellites experience higher dynamical friction $\frac{d\vec{V}}{dt} \propto -\frac{M\,\rho\,\vec{V}}{|\vec{V}|^3}$ and sink more rapidly.

→ Due to the mass-metallicity relation, expect more metal-rich stars to end up at smaller radii.



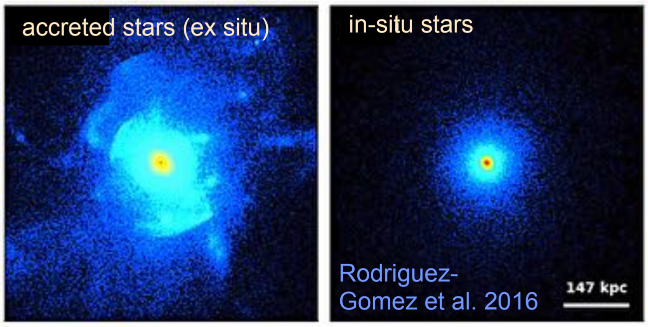
Harding

Stellar tidal streams from different dwarf galaxy accretion events lead to highly sub-structured halo.

Johnston

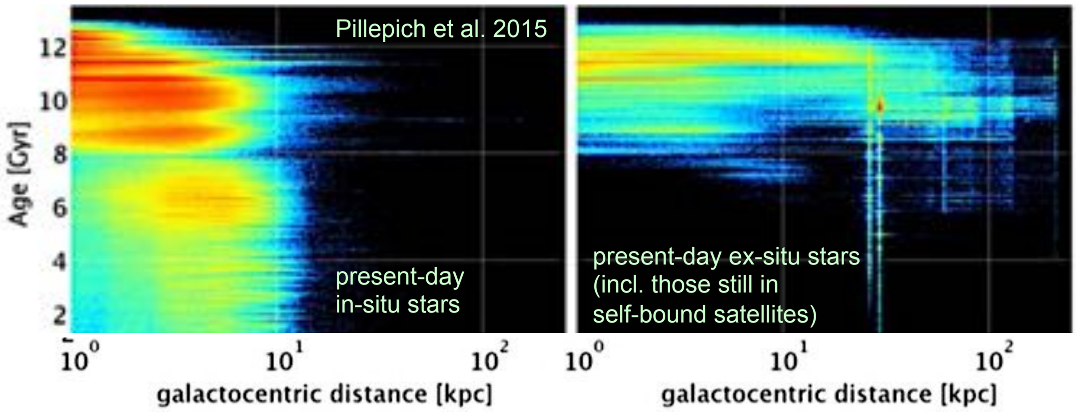
De Lucia & Helmi 2008; Cooper et al. 2010

Stellar Halo Origins



Rodriguez-Gomez et al. 2016

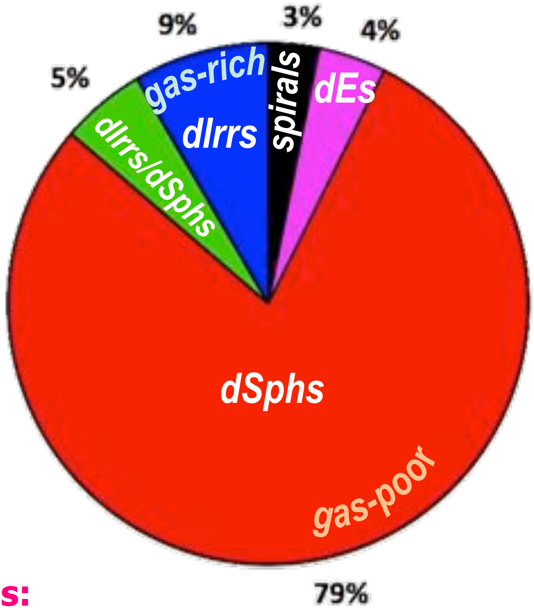
- Stellar halos composed in part of accreted stars and in part of stars formed in situ.
- Halos grow from “from inside out”.
- Wide variety of satellite accretion histories from smooth growth to discrete events.
- ≤ 5 luminous satellites (10^8 – 10^9 $M_\odot$) are the main contributors to stellar halos. Merged > 9 Gyr ago (inner halo). Satellite accretion *mainly* between $1 < z < 3$.



Pillepich et al. 2015

2. THE SURVIVORS: PRESENT-DAY DWARF GALAXIES

The Galaxy Content of the Local Group



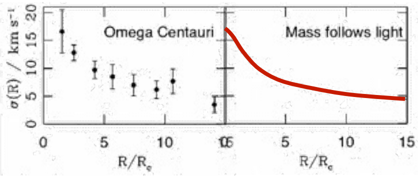
Certain or probable members:
≥ 91 galaxies within R_0 ~ 1 Mpc.

- 3 spiral galaxies (~ 95% mass).
- ≥ 88 dwarf and satellite galaxies (typically, $M_V \geq -18$).
- Some satellites have own satellites...

Gas-deficient, late-type dwarf galaxies:
dwarf elliptical (**dEs: 3; 1 cE**) & dwarf spheroidal galaxies (**dSphs: ≥ 75**)

Gas-rich, early-type dwarf galaxies:
dwarf irregular galaxies (**dIrrs: 8**), transition types (**dIrrs/dSphs: 5**)

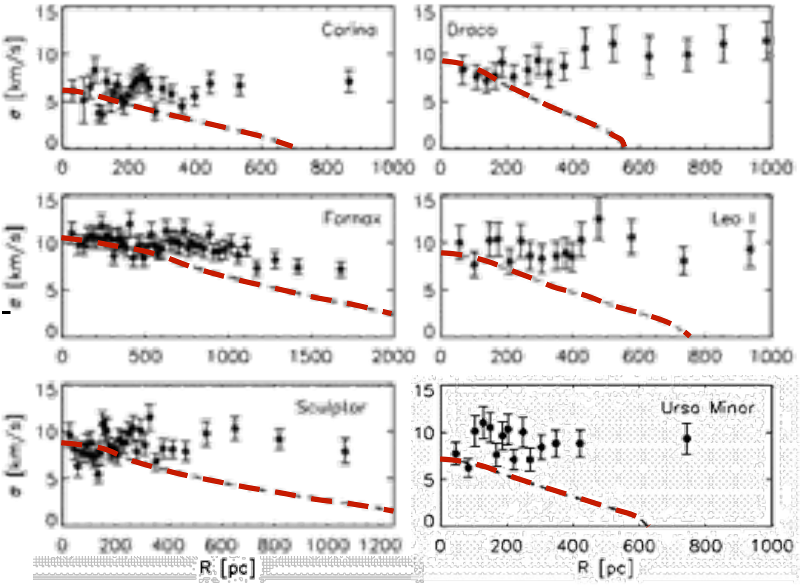
Radial Velocity Dispersion Profiles



☐ *If mass follows light:* Globular-cluster-like velocity dispersion profile; highest mass concentration in the center, then monotonic fall-off.

☐ But in dSphs: Radial velocity dispersion profiles as function of galactocentric radius: ~ ***flat***.

☐ Dashed line: Slope expected if mass follows light (King 1966 models); normalized to central dispersions.



Walker 2013

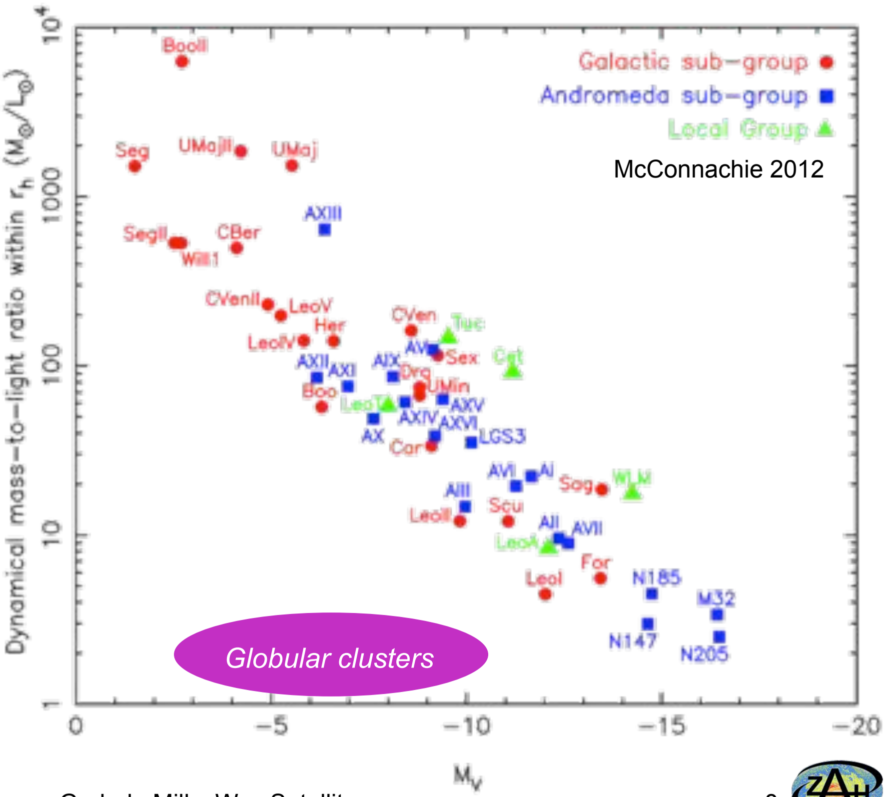
☐ High velocity dispersions at large radii (in contrast to King models): dominant and extended DM halos.

Dynamical M/L ratios increase with decreasing luminosity

Faintest dSphs are the most dark-matter-dominated ones (of all galaxy types!).

Discontinuity in dynamical M/L_V between dSphs and globular clusters seems to mark a boundary between objects with dark matter and without.

e.g., Walker 2013



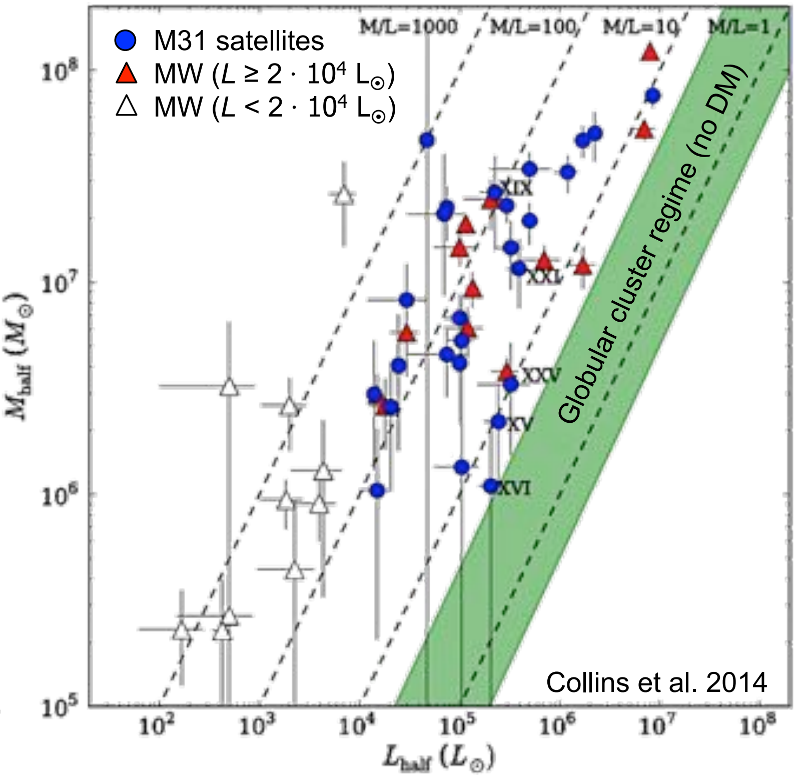
McConnachie 2012

DM Content

Mass within $r_{1/2}$ vs. $L_{1/2}$:

- ☐ Considerable scatter, no longer a universal mass profile (Adén,..., Grebel, et al. 2009; Collins et al. 2014).
- ☐ High M/L at low L
- ☐ Satellites in low M/L regime may have suffered considerable tidal stripping

  (as in cosmological DM + baryon simulations of, e.g., Brooks & Zolotov 2014).



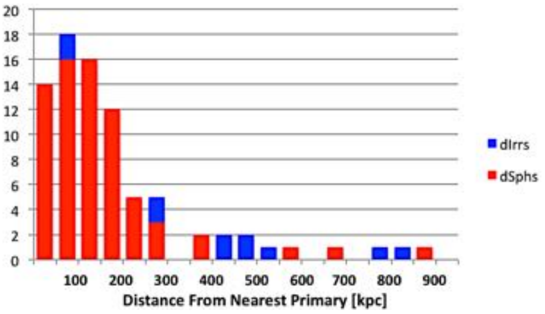
Collins et al. 2014

Not necessarily disruption, but mass loss.

➙ Expect corresponding stellar contributions to MW / M31 (outer) halo.

Present-day Dwarfs

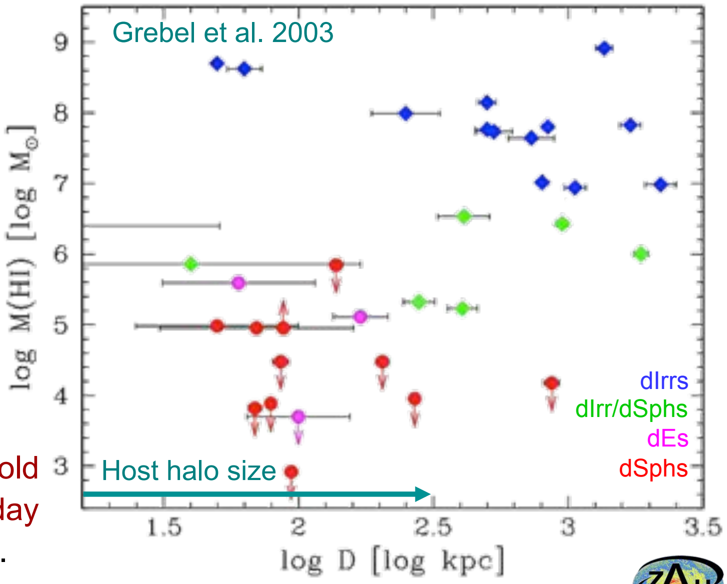
Morphology-density relation



≠ dwarfs at time of dominant accretion!

- ☐ Present-day dwarfs continued to evolve.
- ☐ Evolution governed by (1) intrinsic properties (mass, star formation, feedback, gas content), but also modified by

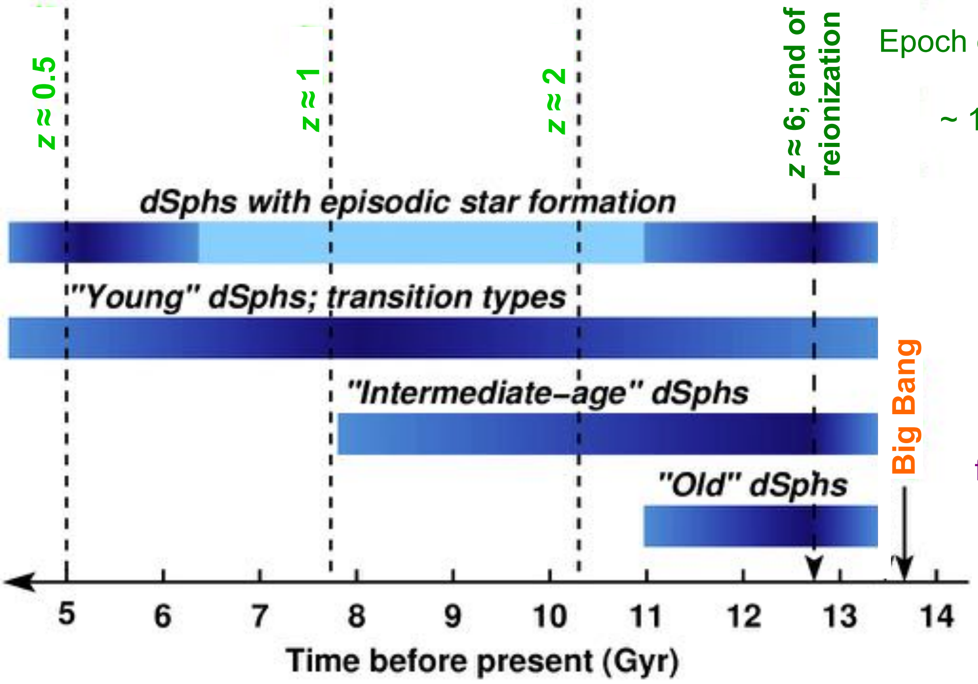
  (2) external influences (environment), including gas accretion, local and global re-ionization, ram pressure and tidal stripping.
- ☐ Most infall/accretion predicted at early times: → we focus on old stellar populations in present-day dwarfs, especially in satellites.


Grebel et al. 2003

Early Star Formation

In all dwarf galaxies studied *in detail* so far: Old populations ubiquitous.

Grebel & Gallagher 2004

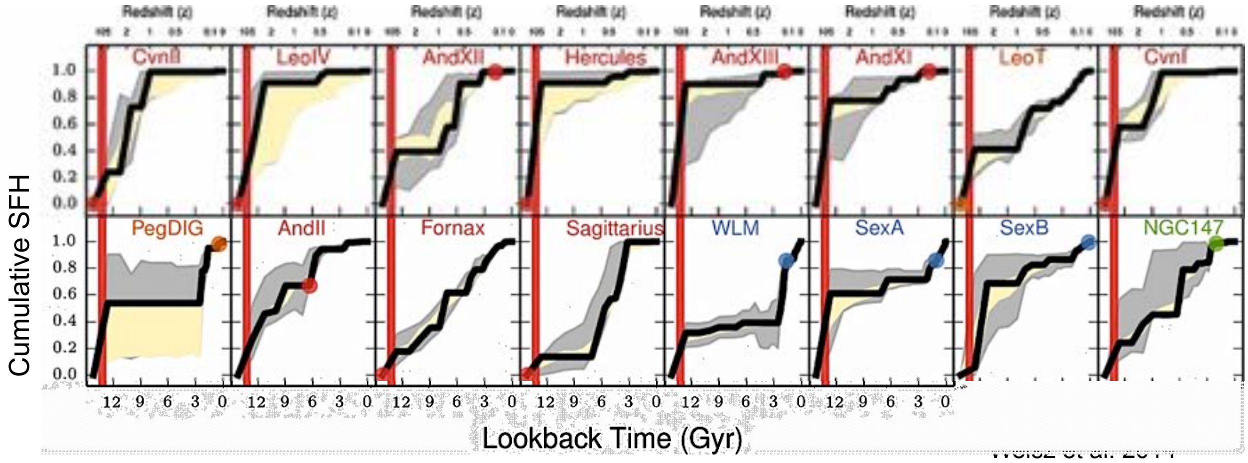


Epoch of re-ionization:
z ~ 6 – 14 or
~ 12.8 – 13.4 Gyr.

Not even ultra-faint dSphs are simple stellar populations.

Early Star Formation

Dwarfs generally continued to form stars after epoch of re-ionization.
Some formed most of their stars prior to/during re-ionization, but no evidence for *significant* re-ionization quenching. Grebel & Gallagher 2004; Weisz et al. 2014

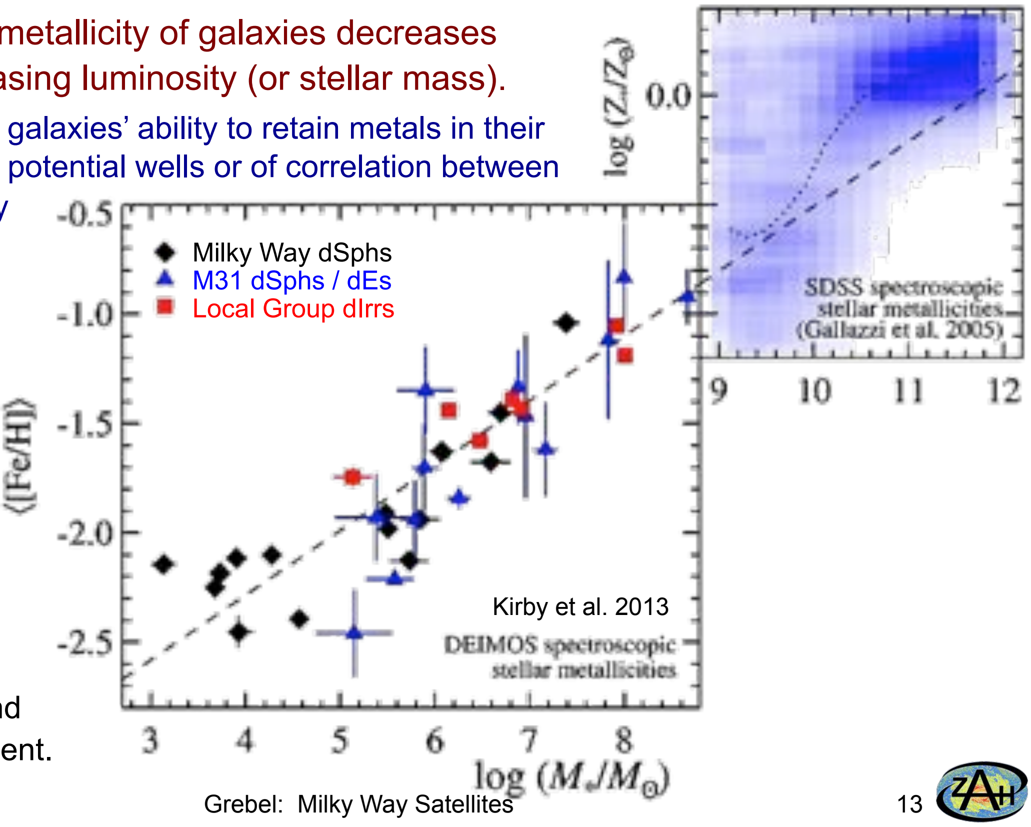


Dwarf satellites generally formed bulk of their stellar populations prior to $z = 1$.
Higher-mass galaxies formed larger fraction of their mass at later times ("upsizing").

The Metallicity – Mass Relation

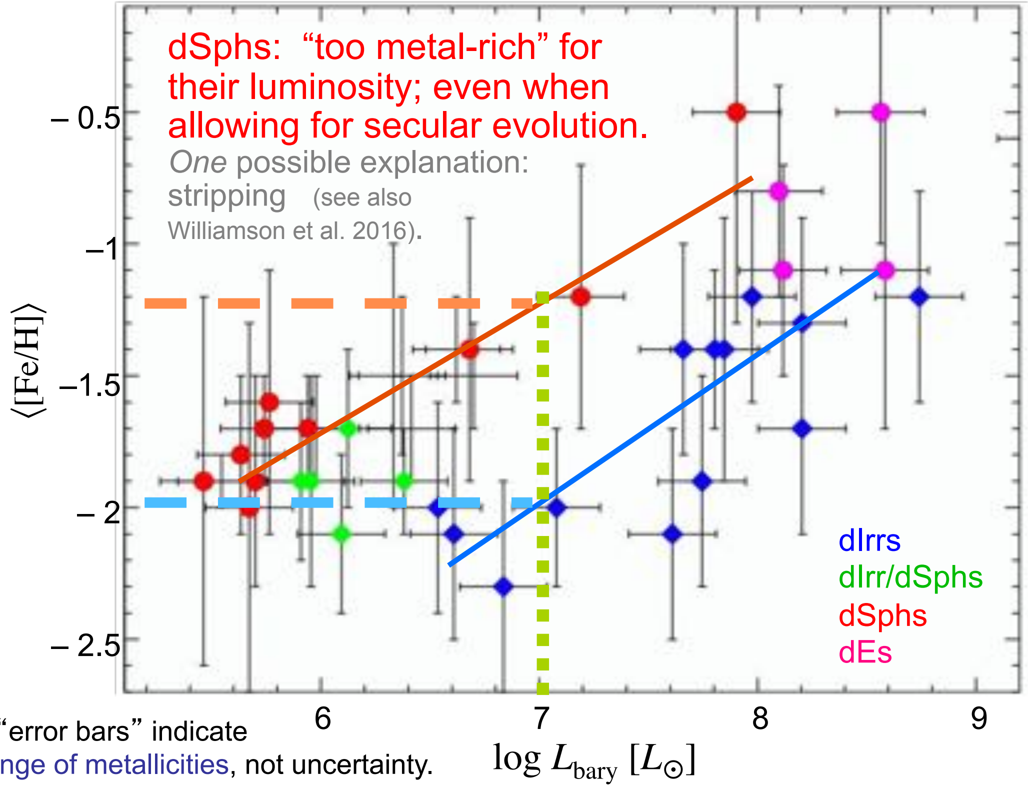
The mean metallicity of galaxies decreases with decreasing luminosity (or stellar mass).

Signature of galaxies' ability to retain metals in their gravitational potential wells or of correlation between SF efficiency and stellar mass.



Present-day luminosity (or stellar mass) correlates tightly with system properties during star formation and self-enrichment.

Metallicity-Luminosity relation for the same (old) populations



dSphs: “too metal-rich” for their luminosity; even when allowing for secular evolution.

One possible explanation: stripping (see also Williamson et al. 2016).

Grebel, Gallagher, & Harbeck 2003, AJ, 125, 1926

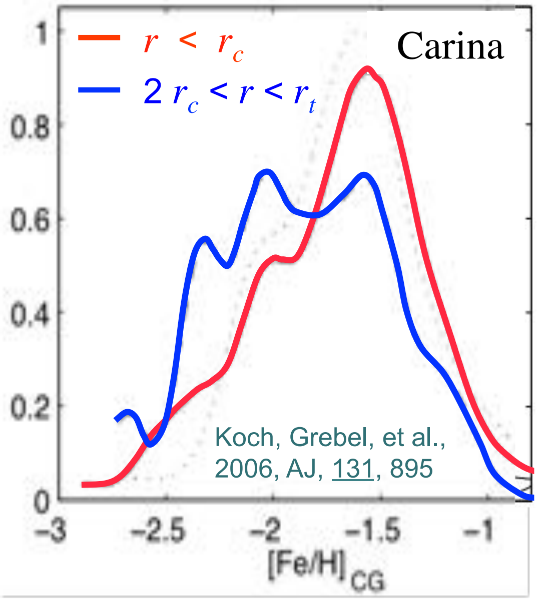
Here: “error bars” indicate true range of metallicities, not uncertainty.

Metallicity Gradients (Population Gradients) in Dwarfs

Younger and/or more metal-rich stars: more centrally concentrated

(Harbeck, Grebel et al. 2001, AJ, 122, 3092)

and kinematically colder.



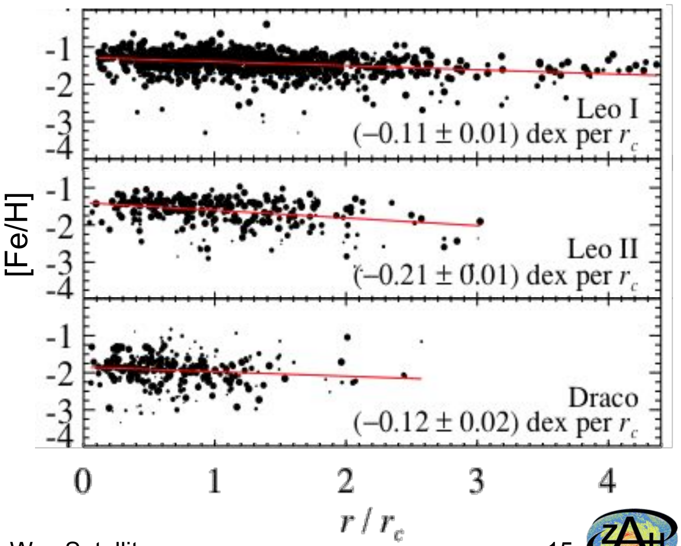
Koch, Grebel, et al., 2006, AJ, 131, 895

Radial abundance gradients in disks of spirals and Irrs/dIrrs:

e.g., Pilyugin, Grebel, et al. 2014, AJ, 147,131; 2014, AJ, 148, 134; 2015, MNRAS, 450, 3254

Shown here: Gradients in Galactic dSphs

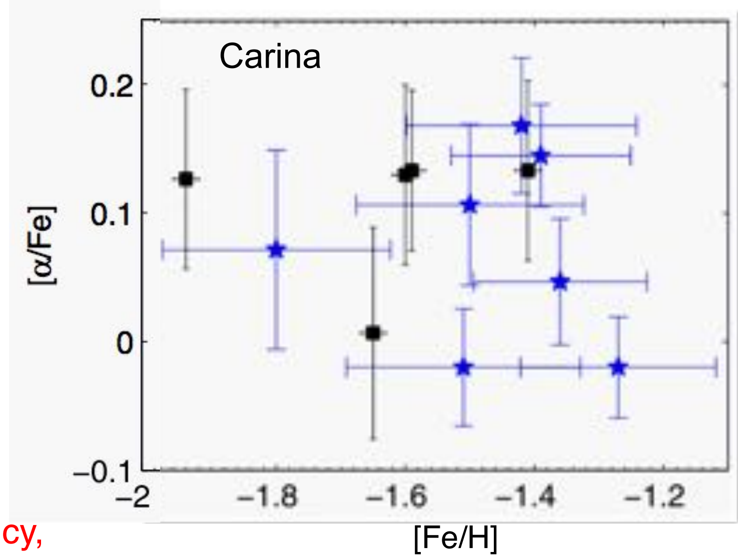
Kirby et al. 2011, ApJ, 272, 78



Element Abundance Inhomogeneities

- ❑ Considerable abundance spreads observed in dSph field stars:
  Up to > 1 dex even in dwarfs dominated by old populations
  (e.g., Shetrone et al. 2001, ApJ, 548, 592; Norris et al. 2008; ApJ, 689, L113)
- ❑ At a given age:
  scatter in abundances
  e.g., SMC (Glatt, Grebel, et al. 2008, AJ, 136, 1703),
  Sex B (Kniazev, Grebel, et al. 2005, AJ, 130, 1558).
- ❑ At a given metallicity:
  scatter in α abundance ratios (e.g., Koch, Grebel, et al. 2008, AJ, 135, 1580)

➜ Slow, stochastic SF,
low star formation efficiency,
dwarfs not well mixed



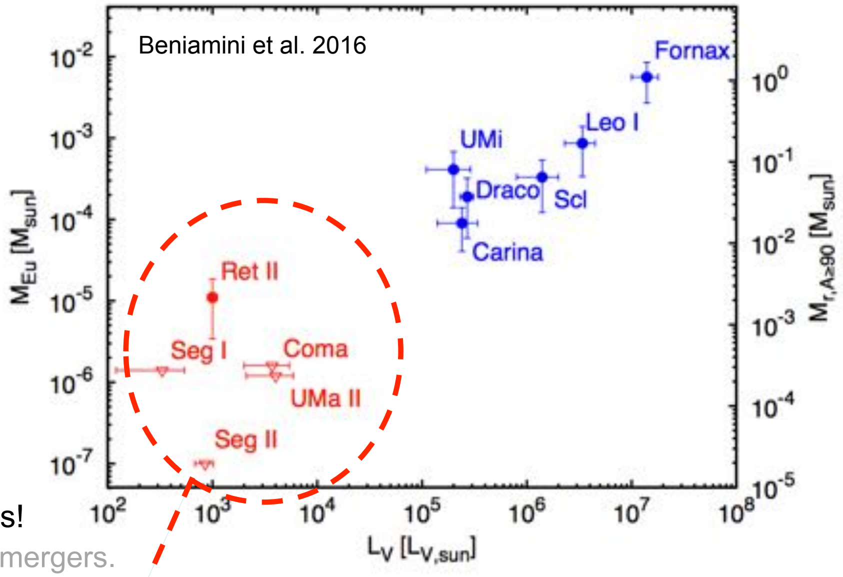
Koch, Grebel, et al. 2008, AJ, 135, 1580

Trends in Individual Element Abundance Ratios

- ❑ Eu mass in ultra-faint dSphs and
- ❑ large scatter in abundances of *r* - process elements (and derivatives, mass number A ≥ 90)

in metal-poor dSphs (and in metal-poor stars in MW):

Produced in rare events!
Possibly in neutron star mergers.

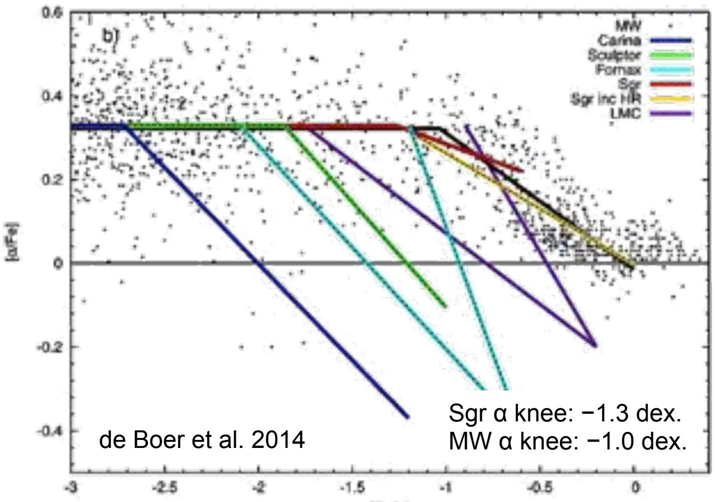


As with α elements, we see contributions from individual events.

Stochasticity begins to dominate

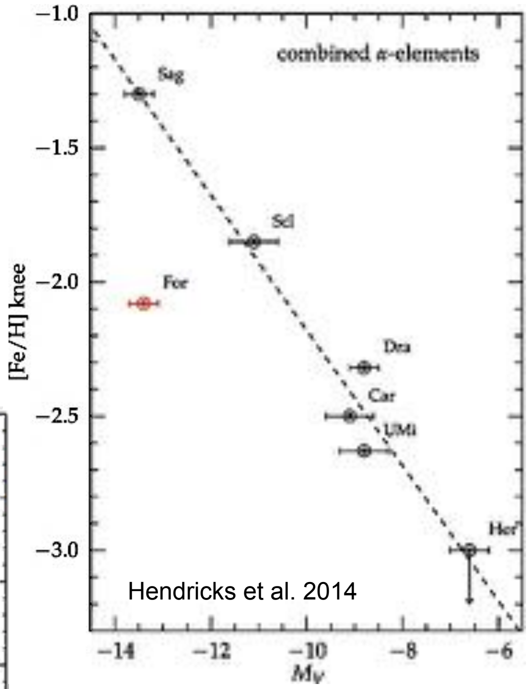
Trends in a “Significant Contributor” Event

Sgr dSph: Position of “α knee” shows that early accretion (before knee formed) of Sgr-like galaxies could have contributed metal-rich parts of inner MW halo.



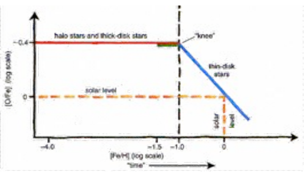
de Boer et al. 2014

Sgr α knee: −1.3 dex.
MW α knee: −1.0 dex.



Hendricks et al. 2014

Position of “α knee” correlates with dSph luminosity (or stellar mass).

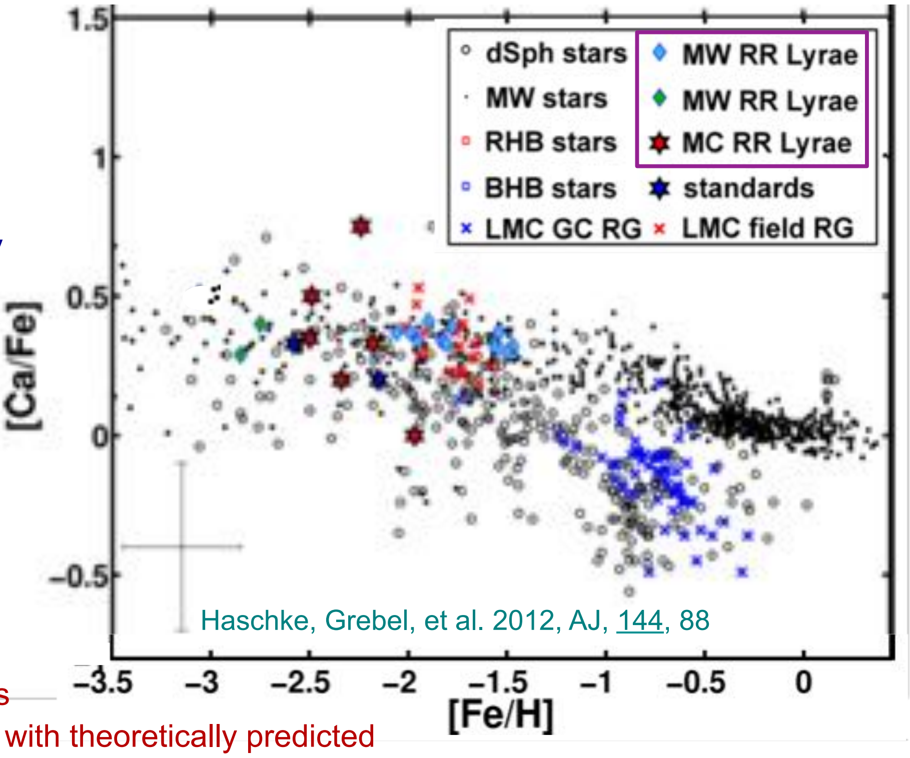


Trends in a “Significant Contributor” Equivalent (2)

Old stars in the Magellanic Clouds: Sparse. Hard to find. Traced best by using RR Lyrae and other HB stars as genuinely old populations.

➙ Overall no metallicity gradients, but large spread. (Haschke et al. 2012)

Most metal-poor LMC star found so far: [Fe/H] = –2.67. $\langle[\alpha/\text{Fe}]\rangle_{\text{old}} = 0.36$.



Haschke, Grebel, et al. 2012, AJ, 144, 88

Individual abundances and trends consistent with theoretically predicted MW (inner) halo accretion.

Very Metal-Poor Stars

Given the low number of stars with [Fe/H] < –3.5 known in MW halo, ultrafaint dSphs are probably important source of such stars.

Now no longer lack of extremely metal-poor stars in dwarfs, but consistency or even “too many” compared to MW halo!

However: well-studied halo stars mainly part of *inner* MW halo.

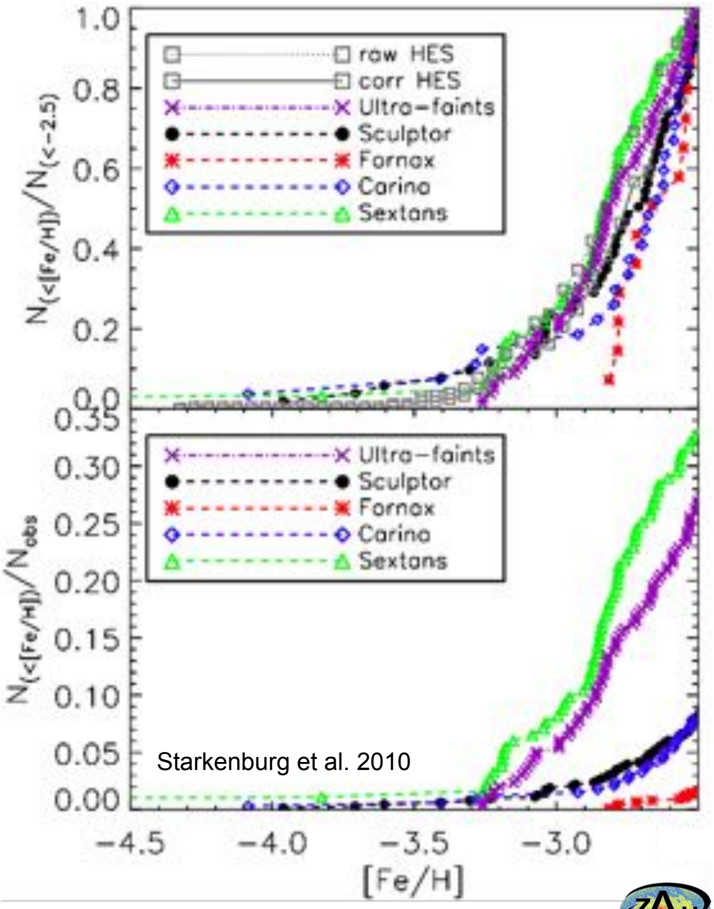
Inner halo:

Larger progenitor systems may mask contributions from smaller ones.

Outer halo:

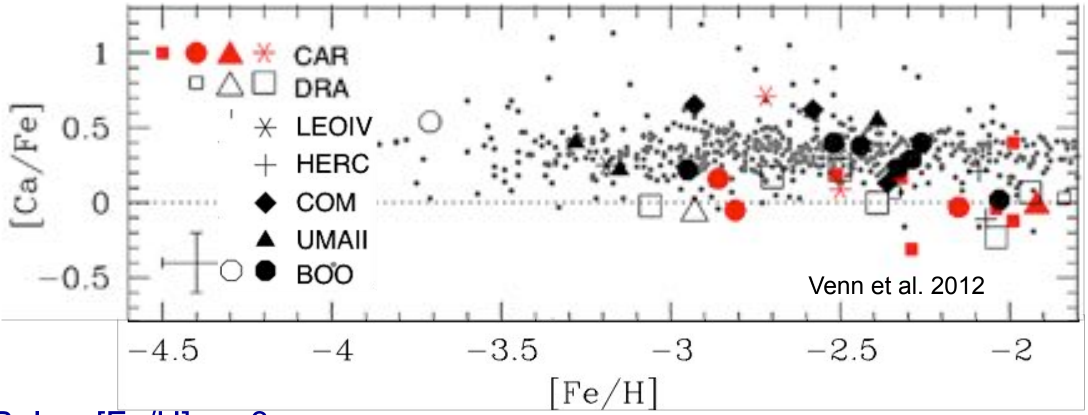
Likely small system accretion.

Lai et al. 2011; Carollo et al. 2012



Starkenburg et al. 2010

Trends in Individual Element Abundance Ratios



Venn et al. 2012

Below [Fe/H] = –3:

- ☐ α elements in low-mass and massive galaxies very similar.
- ☐ Iron peak, Al, Na follow trends seen in MW halo.

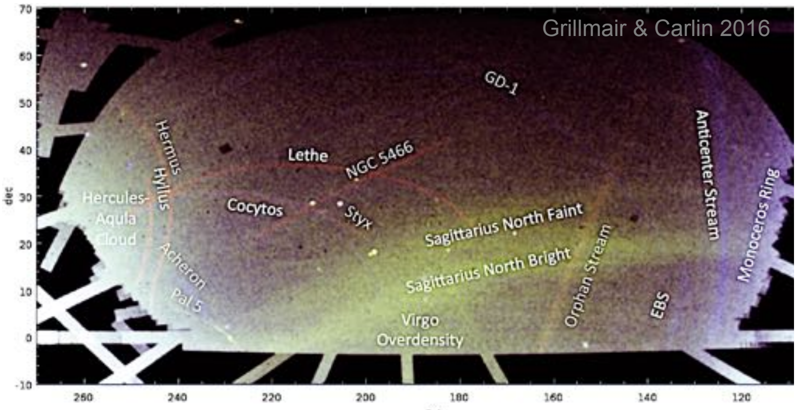
Below [Fe/H] = –3.5: Similarly low Ba, Sr (n-capture) contents.

Above –3.5: dSphs fainter than Dra similar, while more massive ones show increase in r-process abundances all the way to the solar level.

Tafelmeyer et al. 2010

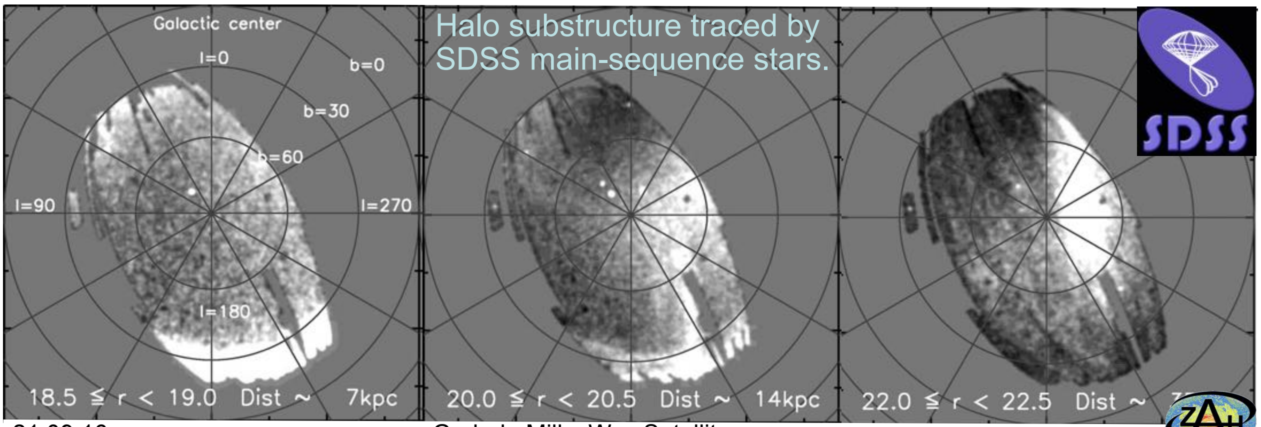
3. FOSSIL REMNANTS IN THE GALACTIC HALO

Stellar Halo (obs.)


Grillmair & Carlin 2016

Abundant substructure

- Features differ in age & metallicity. Debris?
- Stellar population constraints: No evidence for accretion of young/ very metal-rich stars from massive satellites.
- Lower-mass satellite progenitors and/or early accretion preferred.

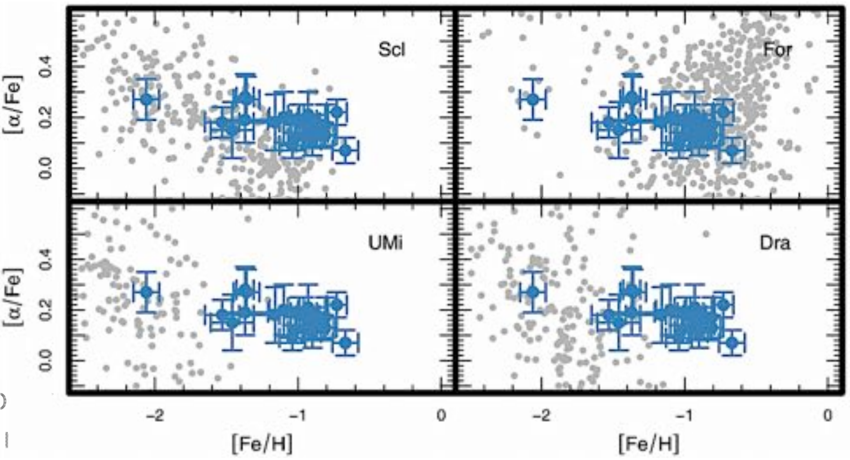

Halo substructure traced by SDSS main-sequence stars.

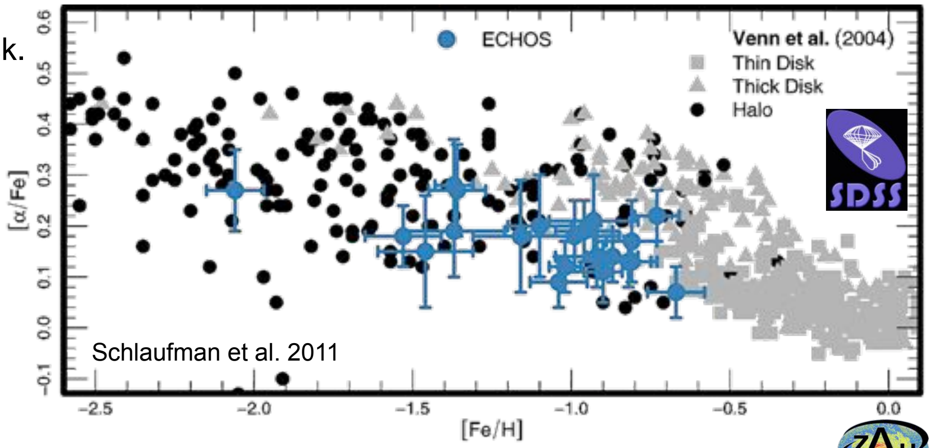
Bell et al. 2008

SDSS

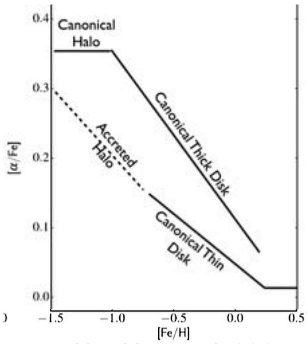
"Elements of Cold Halo Substructure"

- ECHOS plausibly associated w. dSph progenitor like Scl or Leo I.
- ECHOS: more metal-p than thick disk and more poor & α-enhanced than typical thin disk.





Schlaufman et al. 2011

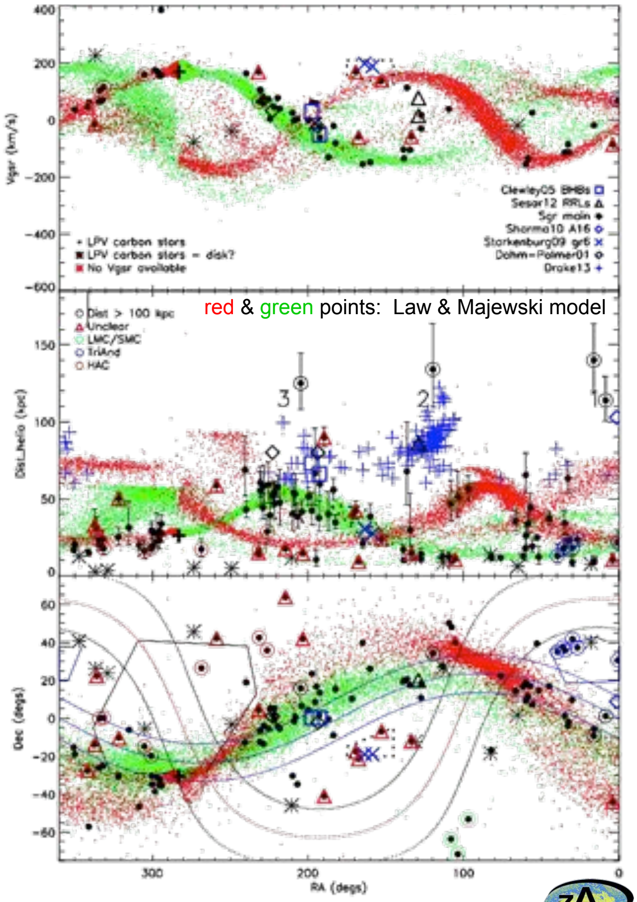


Hawkins et al. 2015

Intermediate-Age Populations in the Halo

Tracer: Carbon stars.

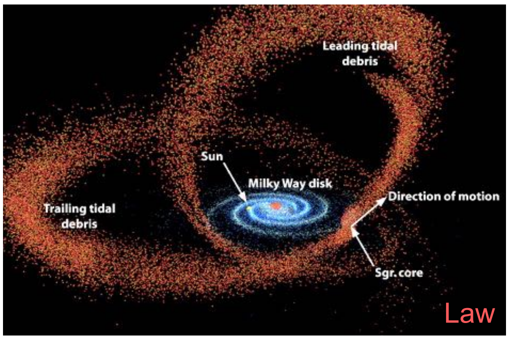
- ❑ Time domain surveys permit us to use light curves of long-period variables to infer distances.
- ❑ Most C stars associated with Sgr tidal arms, but also several other known (LMC, SMC, GAS, Tri-And-Per, Pisces, Gemini, SG6, etc.) *and new features*.
- ❑ Means to constrain accretion of intermediate-age populations, nature of progenitors, and times.

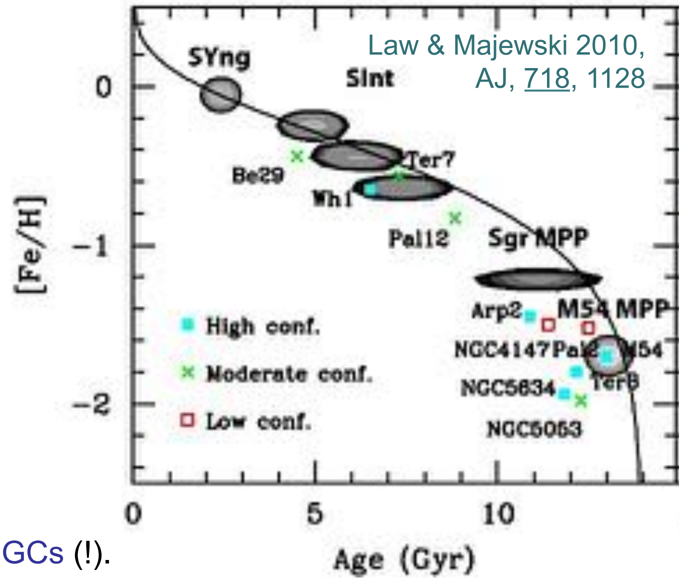


red & green points: Law & Majewski model

Huxor & Grebel 2015

Globular clusters contributed by the Sgr dSph





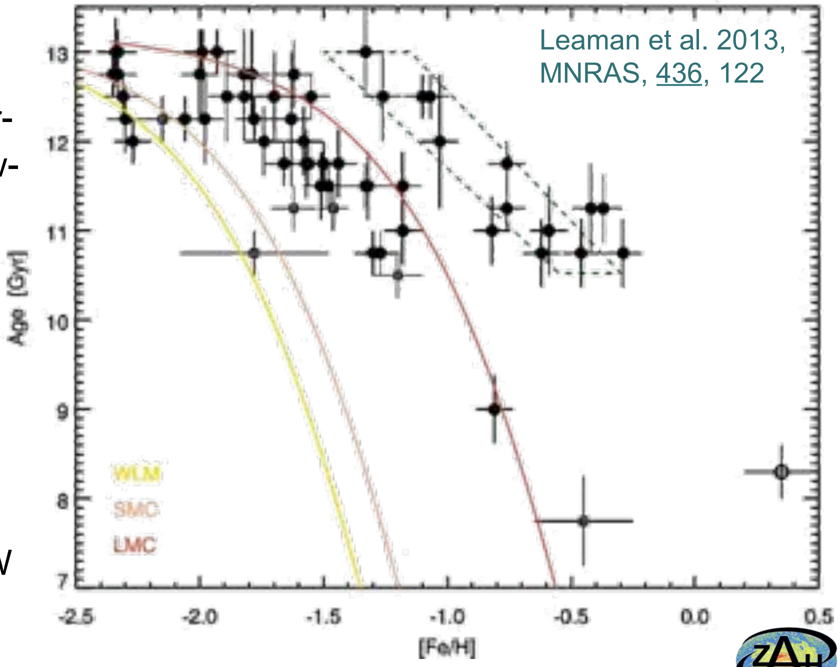
Law & Majewski 2010, AJ, 718, 1128

- 5 high-, 4 moderate, 2 low-confidence GC members. ~ 8 ± 2 genuine GCs.
- In the (HB-type, [Fe/H] plane), Sgr is contributing "young halo" (Arp 2, NGC4147) and old halo GCs (!).
- When fully disrupted, Sgr will (probably) have contributed up to 3 – 4 metal-rich young objects to the Galactic halo, which have no counterparts even among the so-called "young halo globular clusters".

Substantial GC Accretion from Dwarf Galaxies?

Assume: GC metallicity traces host galaxy metallicity at time of formation.

- Offset in MW GC age-metallicity relation: 0.6 dex.
- According to mass-metallicity relation: ∝ stellar mass difference of ~ 2 dex (low-(metallicity branch: 10^8 $M_\odot$)
- Halo GCs on metal-poor branch: well-fitted by AMR of LG dIrrs.
- Metal-rich branch: formed in situ in MW disk/bulge.

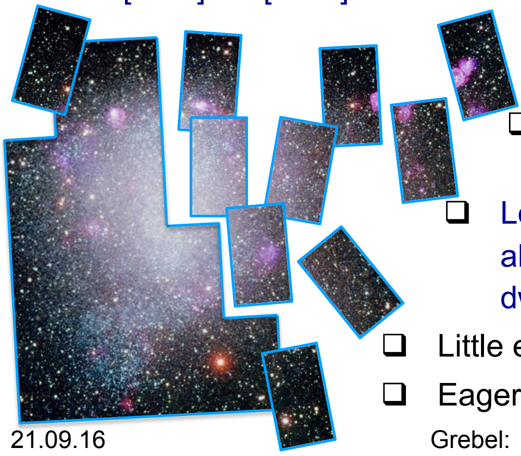


Leaman et al. 2013, MNRAS, 436, 122

4. SUMMARY

Dwarf Galaxies – Fossils of Galaxy Evolution

- ☐ Old populations ubiquitous. Fractions vary.
  Oldest age-dateable populations coeval within measurement accuracy.
  No evidence of significant cosmological re-ionization quenching.
- ☐ Well-defined mass-metallicity relation over ~ 9 decades of galaxian $M_\star$.
- ☐ (Radial) population gradients in metallicity (and kinematics and age).
- ☐ Dwarfs: Element abundance inhomogeneities and spreads,
  both at a given metallicity or at a given age (→ localized (SN Ia) enrichment).
- ☐ [α/Fe] vs. [Fe/H]: Inefficient chemical enrichment, low SFR and SFE.
  Enrichment before onset of SNe Ia (α knee)
  correlates with galaxy luminosity.



- ☐ Old extremely metal-poor stars in dSphs:
  ~ consistent with halo EMP stars.
- ☐ Low-metallicity stars in dwarfs and MW in general:
  abundance consistency. α knee: constraints on
  dwarf galaxy accretion. Early accretion favored.
- ☐ Little explored: Outer halo; key for future surveys.
- ☐ Eagerly awaited: 6-D phase space data from Gaia!