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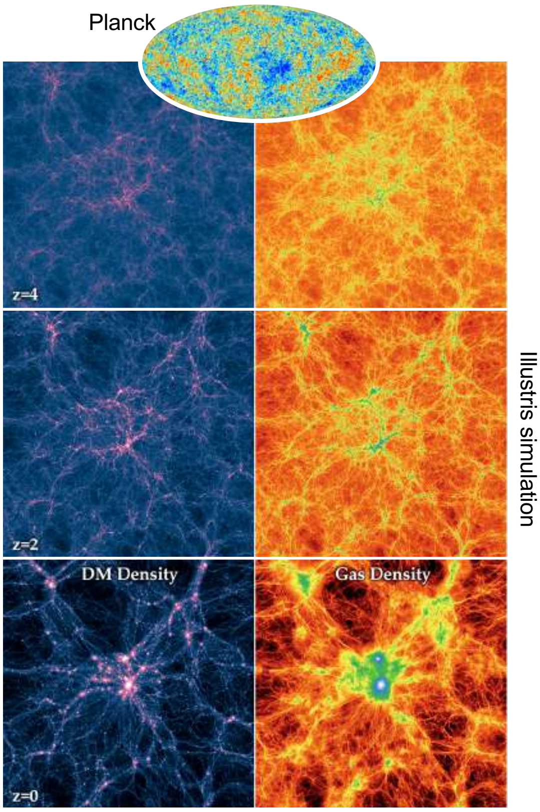
Dwarf Galaxies – Fossils of Galaxy Evolution

SFB 881

1. Dwarf Galaxies As Building Blocks

Hierarchical Structure Formation



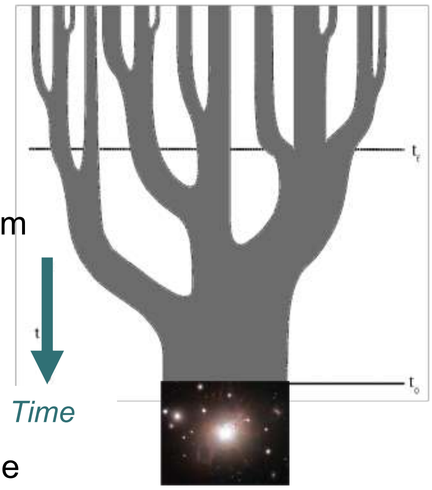
Fundamental scenario:
Large structures form through numerous mergers of smaller ones.

- ☐ 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.

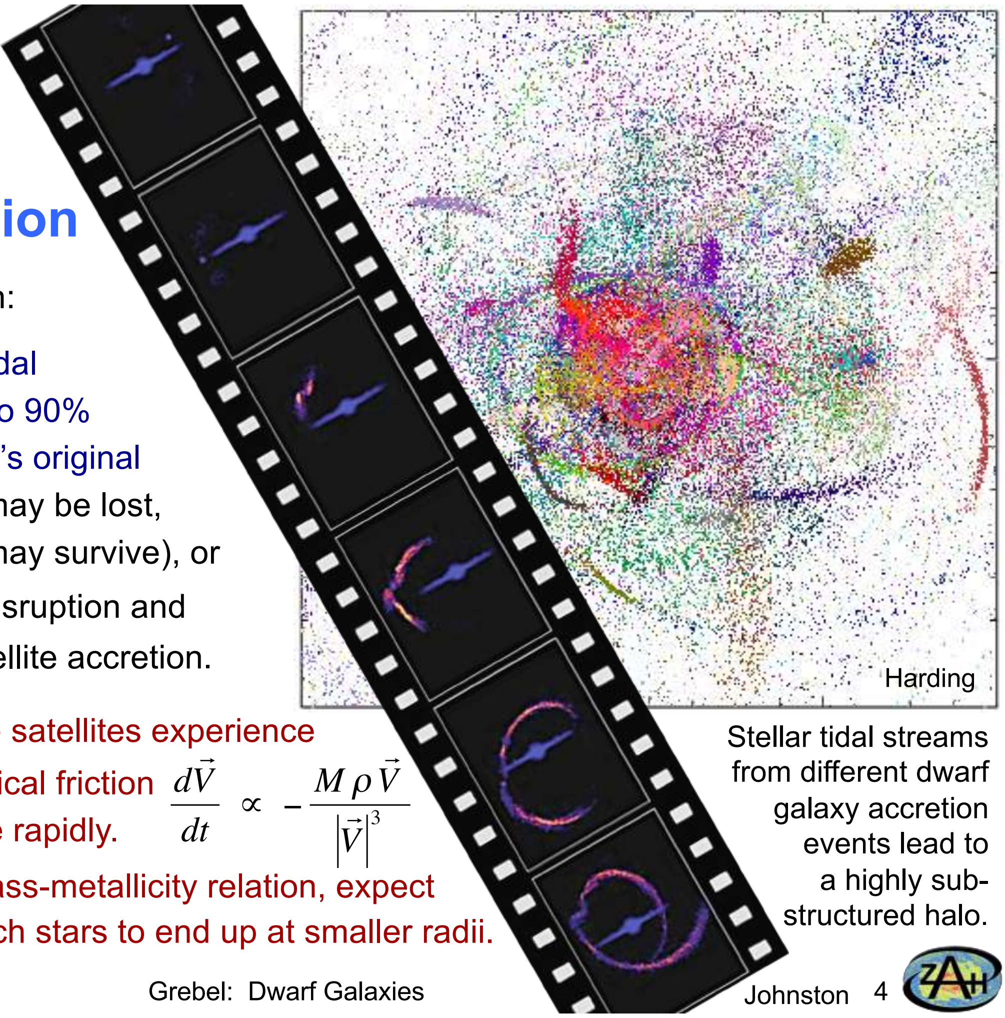
"Merger Tree"



Hierarchical Structure Formation:
Larger structures form through successive mergers of smaller structures.

(Here: only baryonic matter is shown. Courtesy of Shy Genel)

Satellite Disruption and Accretion



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

Johnston

Satellite disruption:

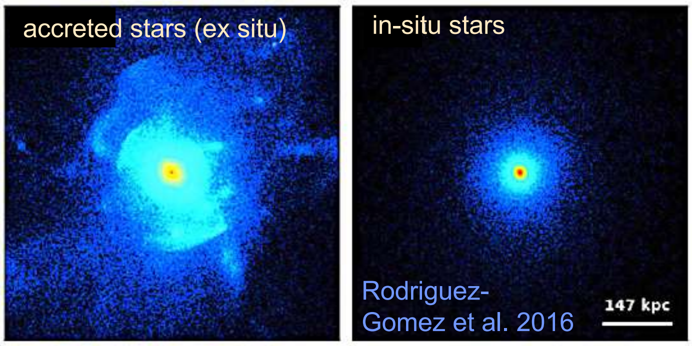
- may lead to tidal stripping (up to 90% of the satellite’s original stellar mass may be lost, but remnant may survive), or
- to complete disruption and ultimately satellite accretion.

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

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

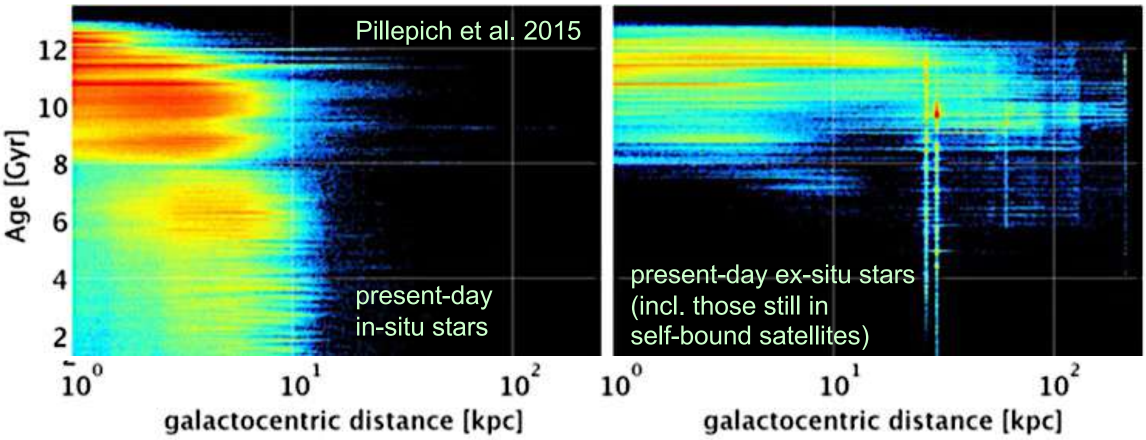
De Lucia & Helmi 2008; Cooper et al. 2010

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 $1 < z < 3$.



2. THE SURVIVORS: PRESENT-DAY DWARF GALAXIES

Dwarf Galaxy Types (≤ 1/100 $L_\star$; $M_V \geq -18$)

- ☐ **Dwarf elliptical galaxies**
- ☐ **Dwarf spheroidal galaxies**
- ☐ Ultra-compact dwarf galaxies

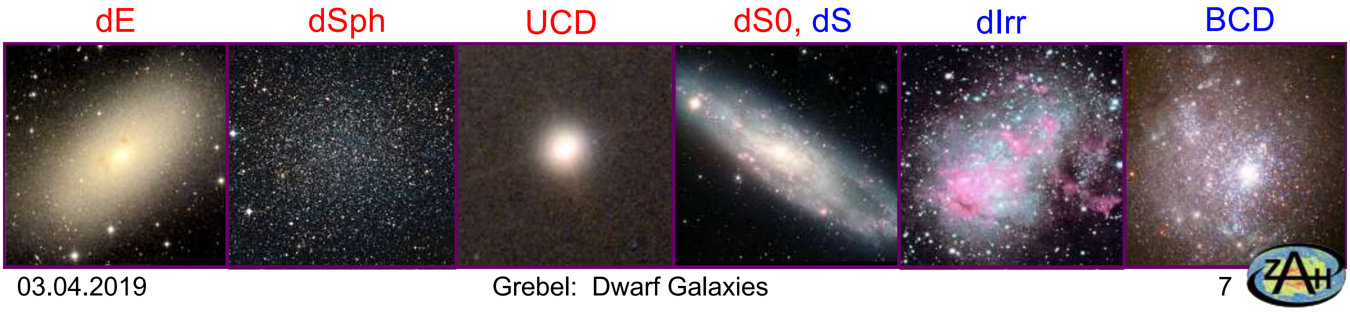
Early-type dwarfs.
Gas-deficient and now largely quiescent.
High-density regions preferred.

- ☐ Dwarf spirals / dwarf lenticulars
- ☐ **Dwarf irregular galaxies**
- ☐ Blue compact dwarf galaxies

Late-type dwarfs.
Gas-rich and usually star-forming.
Low-density regions preferred.

- ☐ Ultra-diffuse galaxies
- ☐ Tidal dwarf galaxies

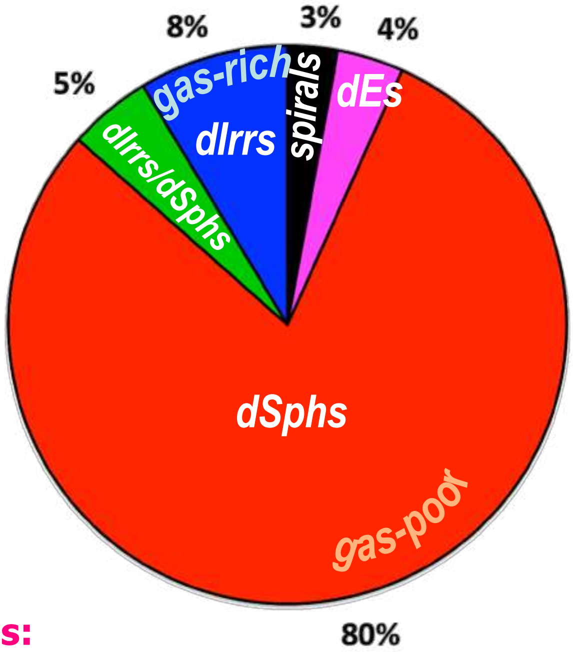
Pictures not on same scale



The Galaxy Content of the Local Group

Certain or probable members:
≥ 104 galaxies within $R_0 \sim 1$ Mpc.

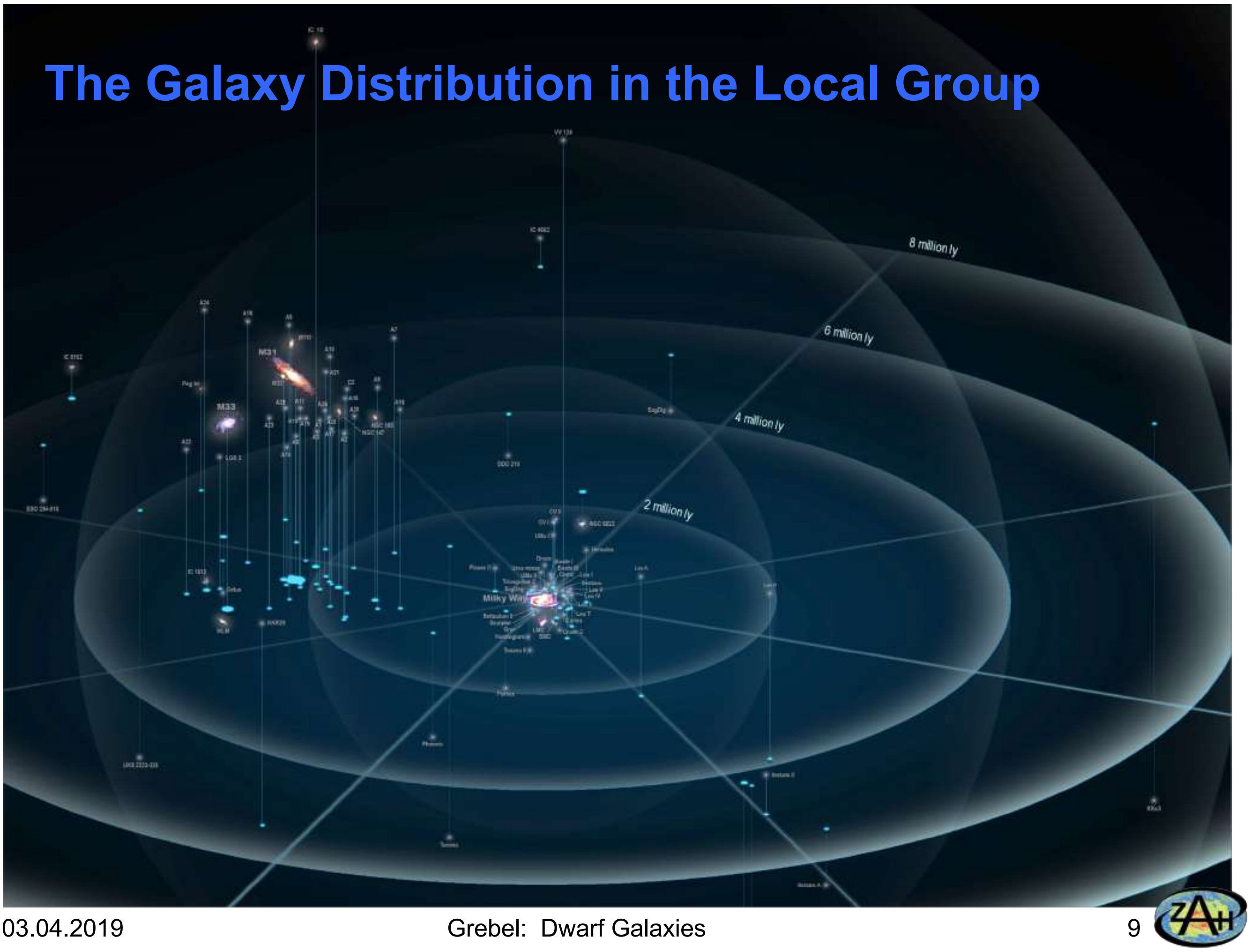
- 3 spiral galaxies (~ 95% mass).
- ≥ 101 dwarf and satellite galaxies (typically, $M_V \geq -18$).
- Some satellites have own satellites...



Gas-deficient, late-type dwarf galaxies:
dwarf elliptical (**dEs: 3; 1 cE**) & dwarf spheroidal galaxies (**dSphs: ≥ 83**)

Gas-rich, early-type dwarf galaxies:
dwarf irregular galaxies (**dIrrs: 9**), transition types (**dIrrs/dSphs: 5**)

The Galaxy Distribution in the Local Group

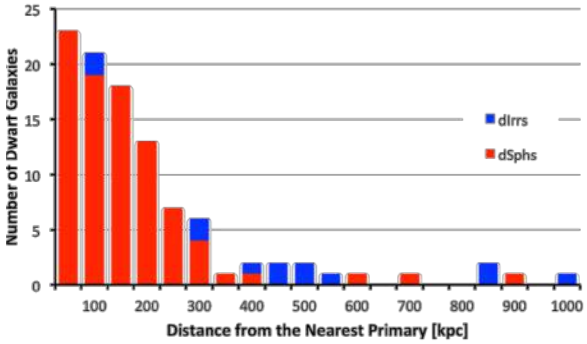


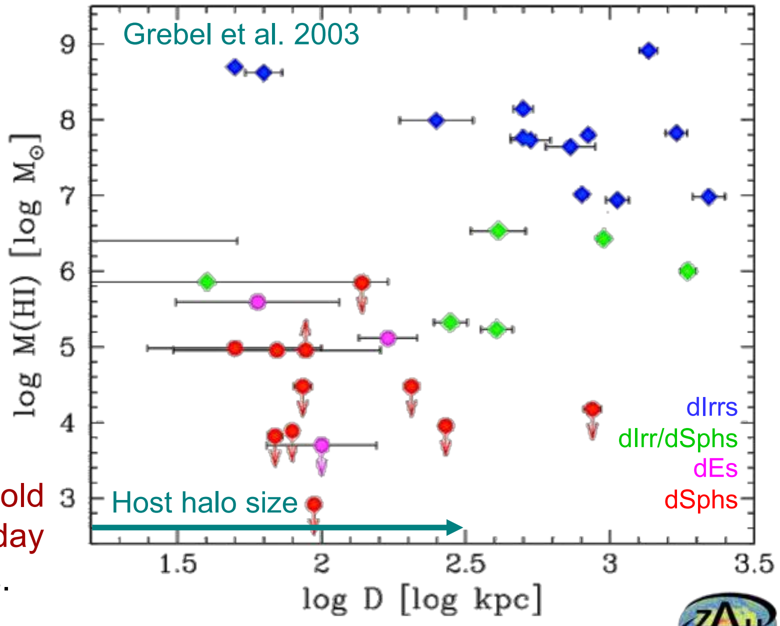
Present-day Dwarfs

≠ dwarfs at time of 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.

Morphology-density relation



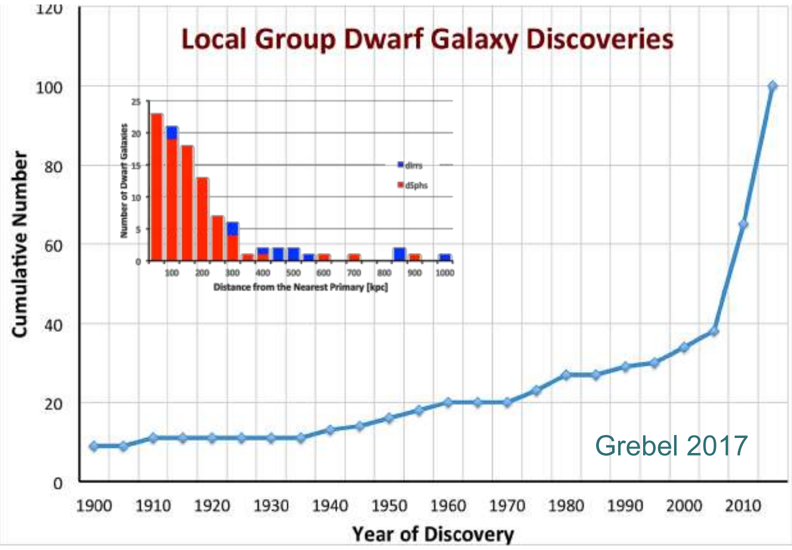


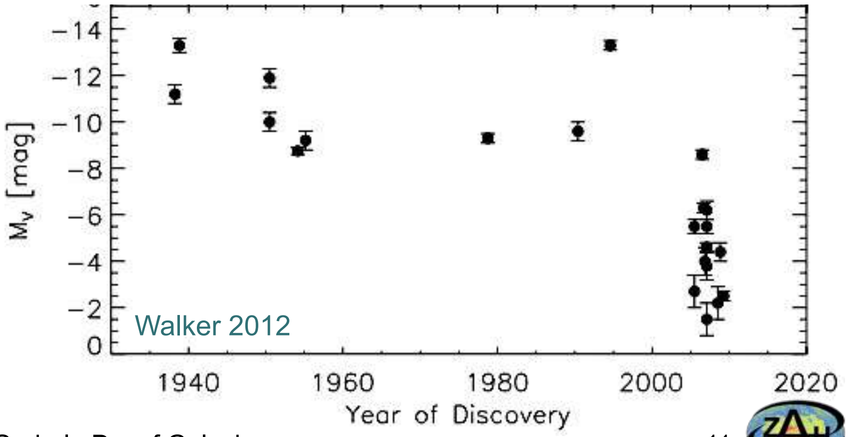
New Satellites of the Milky Way and M31 by Year of Publication

Mainly thanks to large imaging surveys in the northern hemisphere (esp. SDSS, PAndAS, PS1).

Increasingly also southern hemisphere (e.g., DES, VST-ATLAS, Subaru).

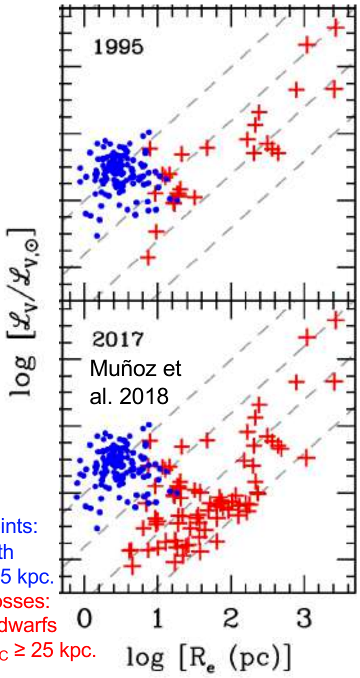
Total satellite population of Milky Way estimated 142^{+53}_{-34} down to $M_V = 0$ in simulations (Newton et al. 2017).



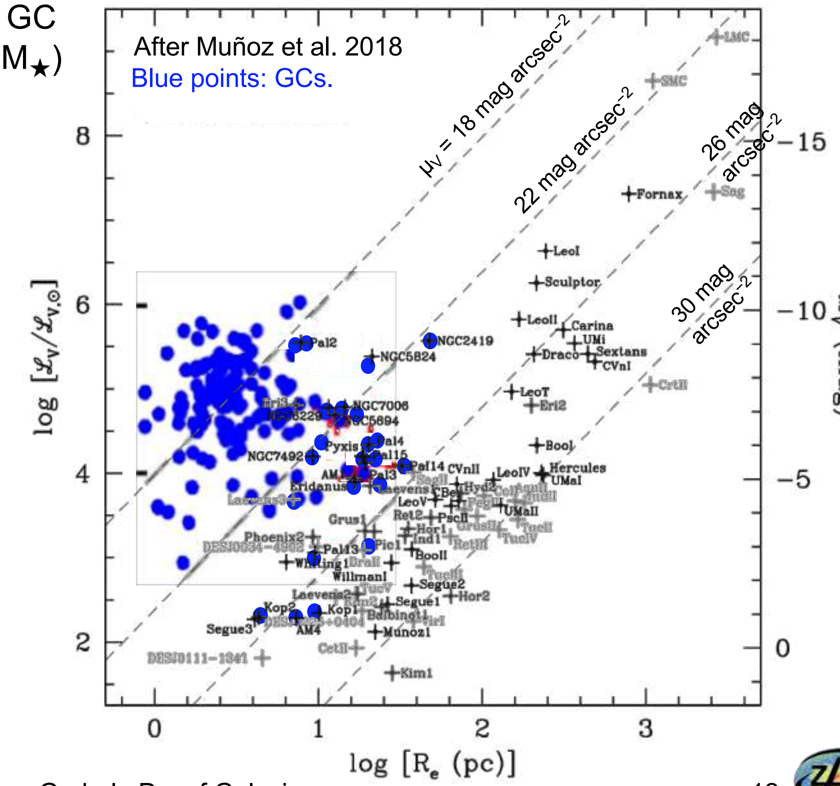


Size – Luminosity Relation

- New discoveries mainly have mainly very low surface brightnesses.
- Note overlap between GC and dSph locus in L_V ($M_\star$)



Blue points: GCs with $R_{GC} \leq 25$ kpc.
Red crosses: GCs & dwarfs with $R_{GC} \geq 25$ kpc.



After Muñoz et al. 2018
Blue points: GCs.

At Low Masses: Distinguishing Galaxies & Star Clusters

No general definition exists but conventionally the following criteria are used:

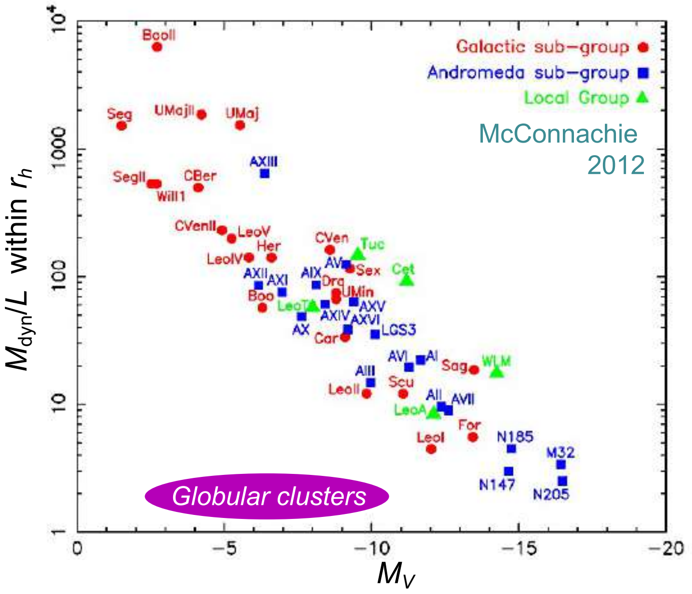
Galaxies:

- Gravitationally bound
- Contain dark matter
- Considerable metallicity spread

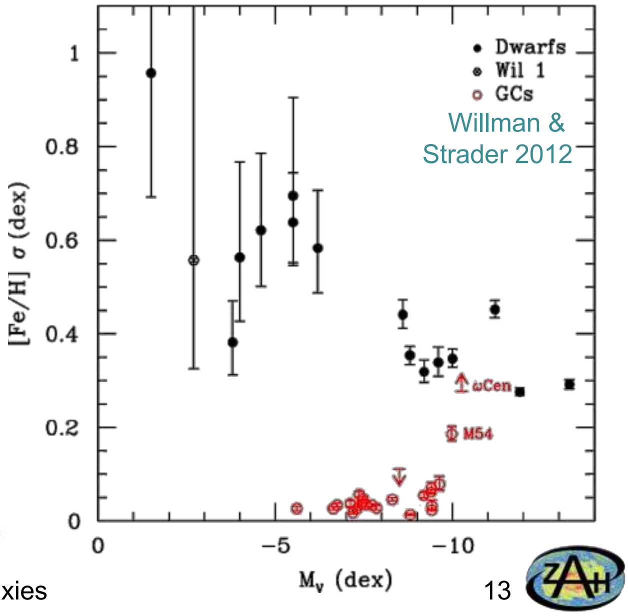
Laevens 1 / Crater I

Star clusters:

- Gravitationally bound
- No dark matter
- Negligible metallicity spread

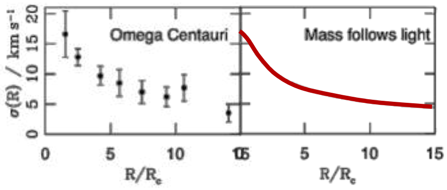


McConnachie 2012



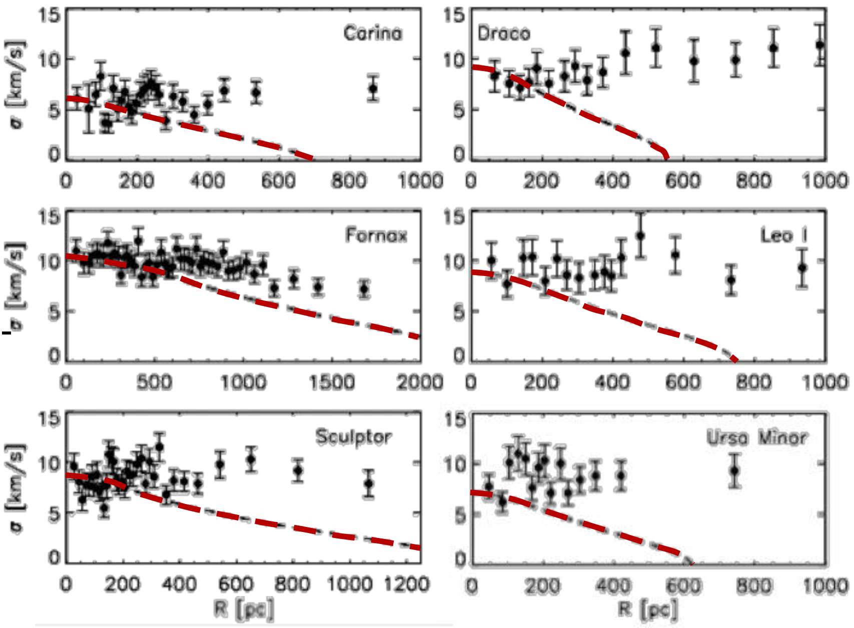
Willman & Strader 2012

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



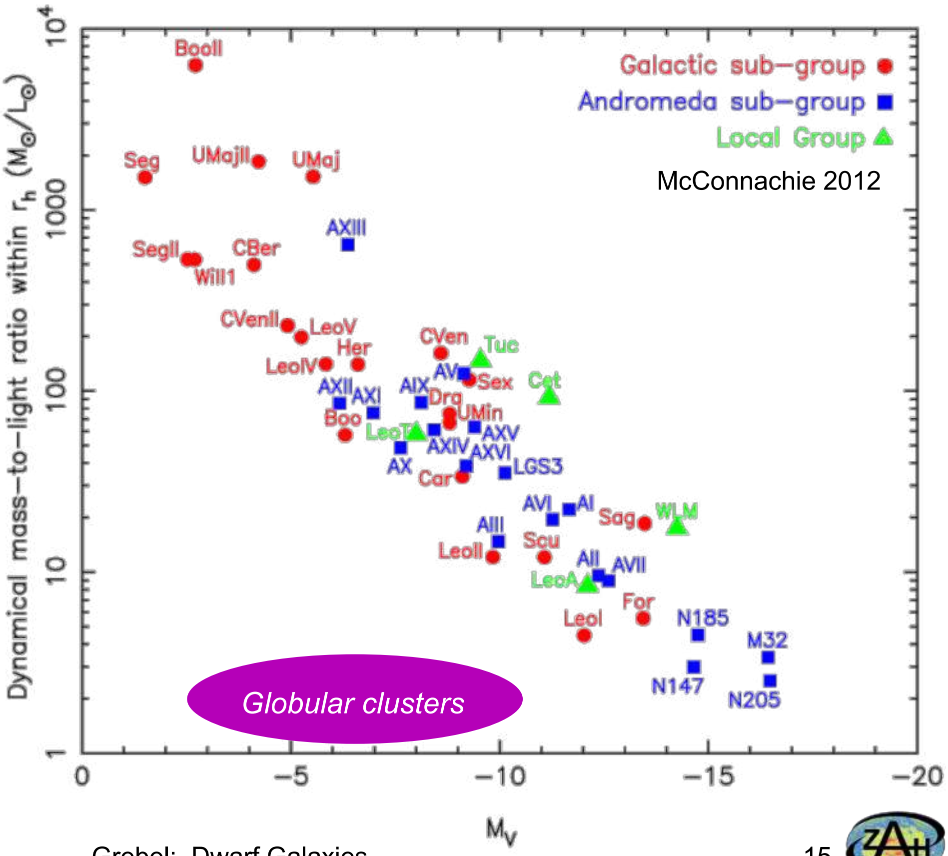
- High velocity dispersions at large radii: dominant and extended DM halos.
- But MOND can also reproduce these flat profiles, → M/L = 1 – 4 (Alexander et al. 2017)

Dynamical M/L Ratios Increase with Decreasing Luminosity

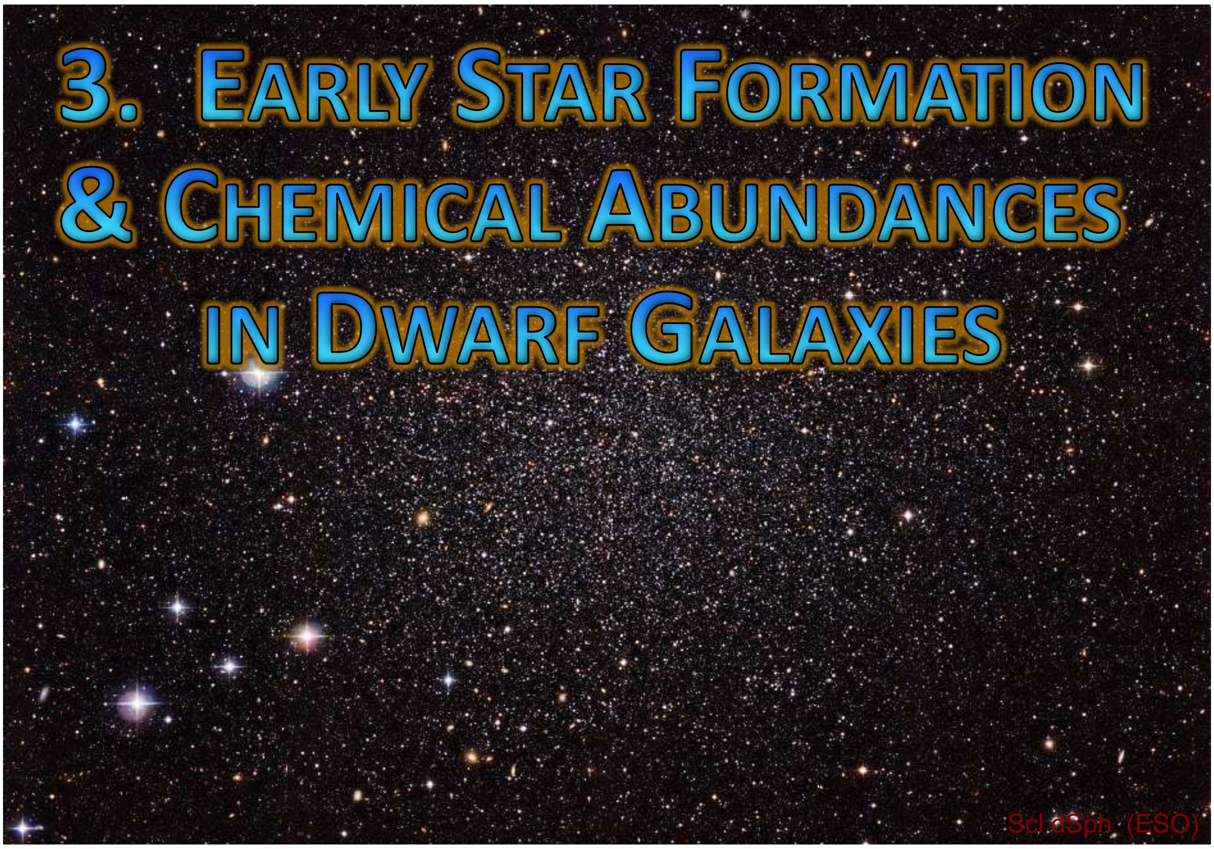
Faintest dSphs are the most dark-matter-dominated ones (of all galaxy types!).

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



3. EARLY STAR FORMATION & CHEMICAL ABUNDANCES IN DWARF GALAXIES

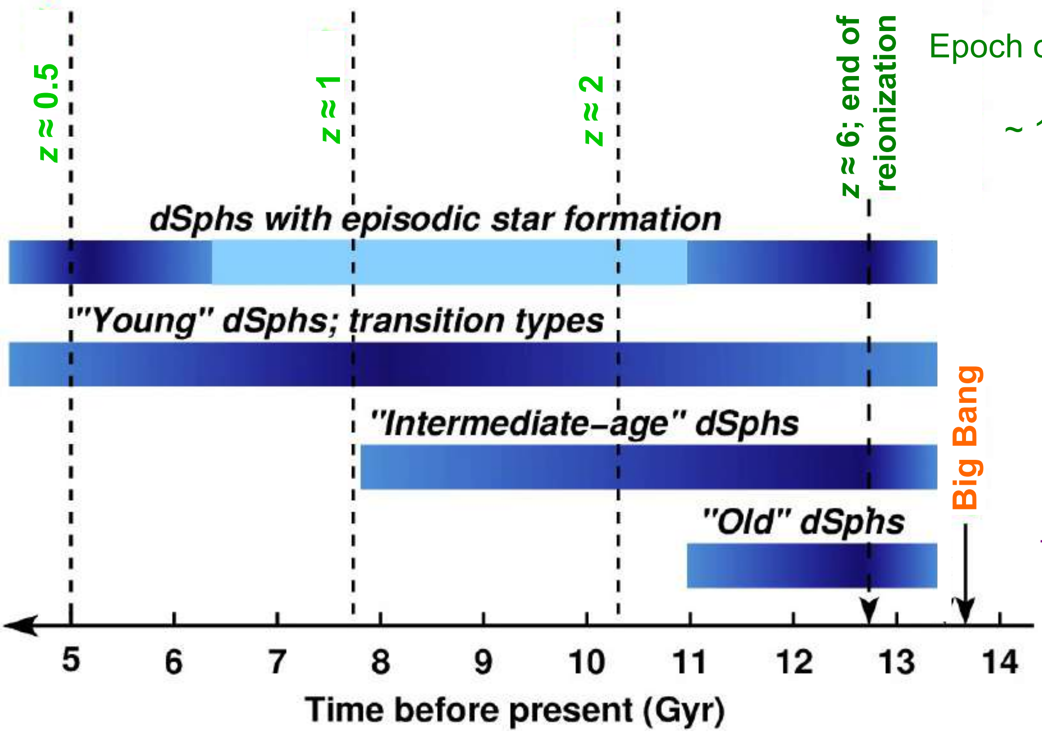


Scl dSph (ESO)

Early Star Formation

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

Grebel & Gallagher 2004

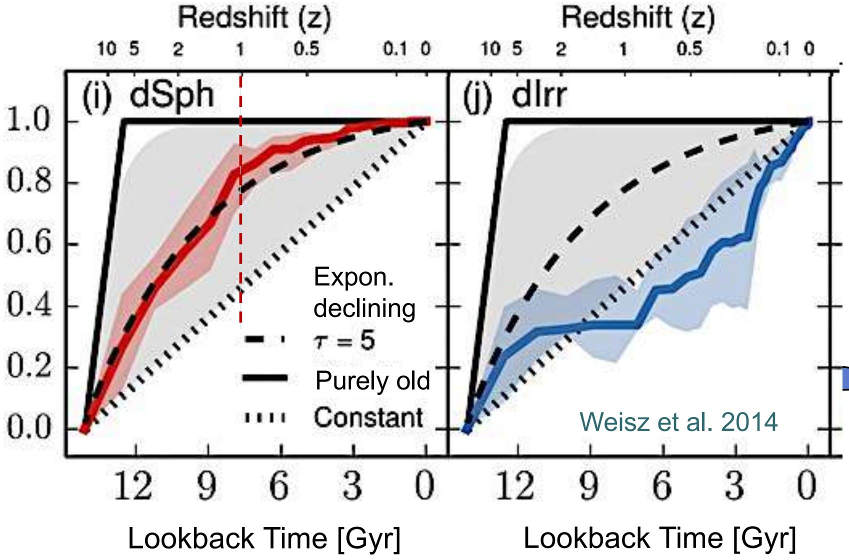


Epoch of re-ionization:
$z \sim 6 - 14$ or
~ 12.8 – 13.4 Gyr.

Interestingly, not even ultra-faint dSphs are simple stellar populations.

Average Star Formation Histories

Cumulative SFHs based on modeling of deep HST CMDs



Dwarf satellites generally formed bulk of their stellar populations prior to $z = 1$.
Mean dSph SFH well approximated by exponentially declining model;
mean dIrr SFH roughly constant with time (but note considerable individual deviations).
Higher-mass galaxies formed larger fraction of their mass at later times ("upsizing").

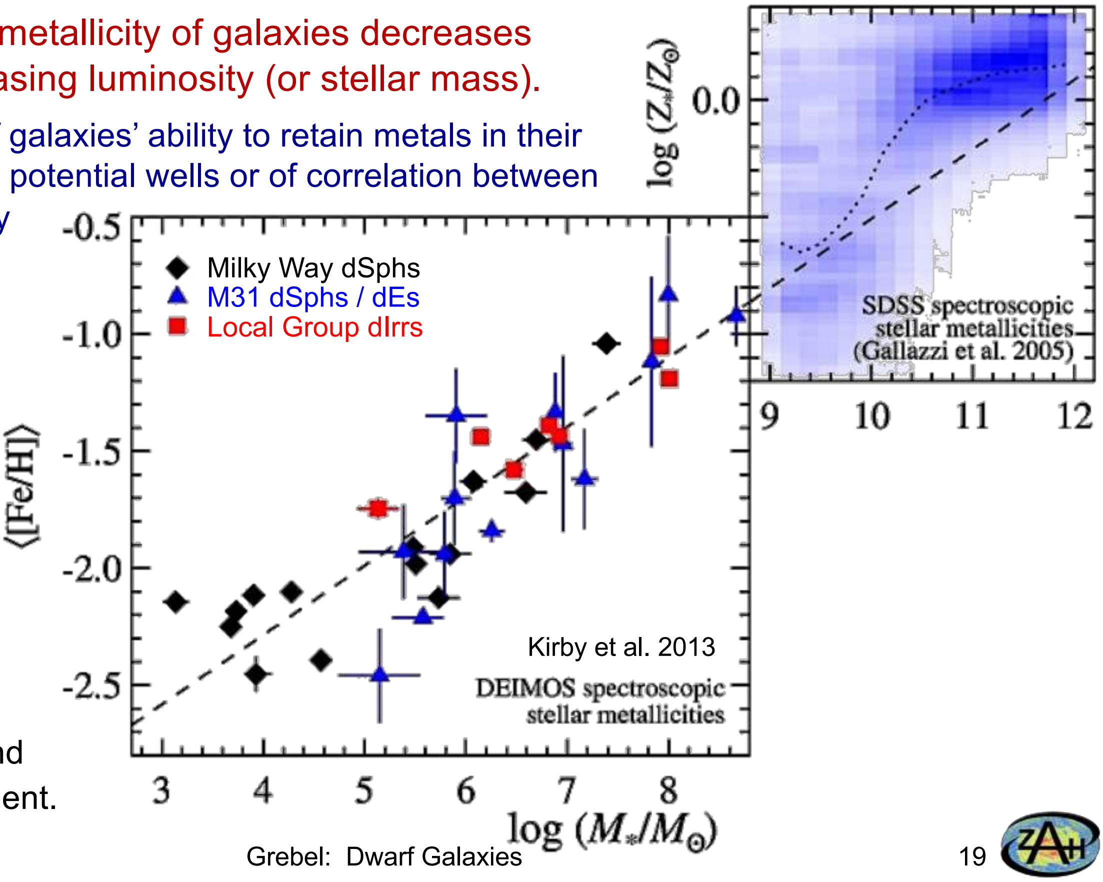
Weisz et al. 2014

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.



[Fe/H] vs. [α/Fe]

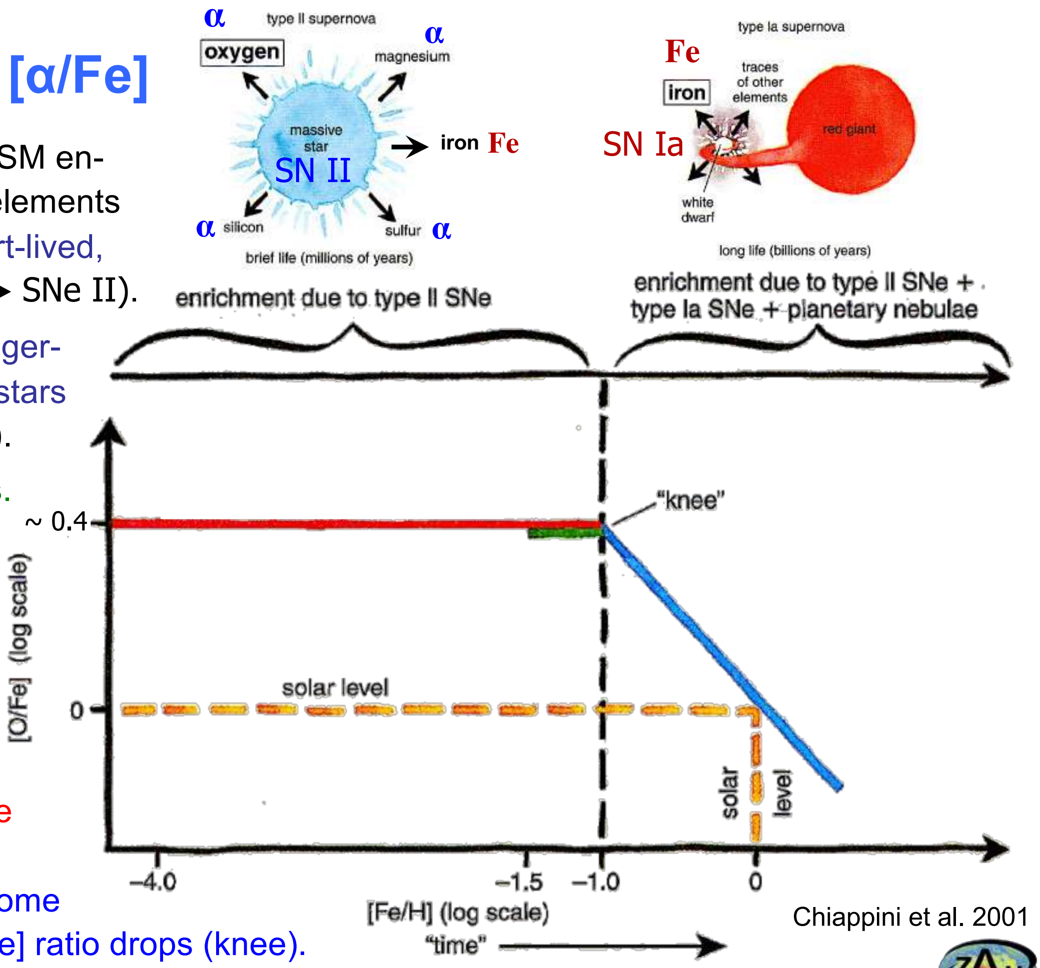
At early times: ISM enriched faster in elements produced in short-lived, massive stars (→ SNe II).

Later also by longer-lived, low-mass stars (→ SNe Ia, AGB).

Ratio of O (α) vs. Fe: "Clock" to gauge SF and enrichment time scales.

Initially: O, Fe produced by SNe II at ~ same rate (plateau).

Once SN Ia become important: [O/Fe] ratio drops (knee).



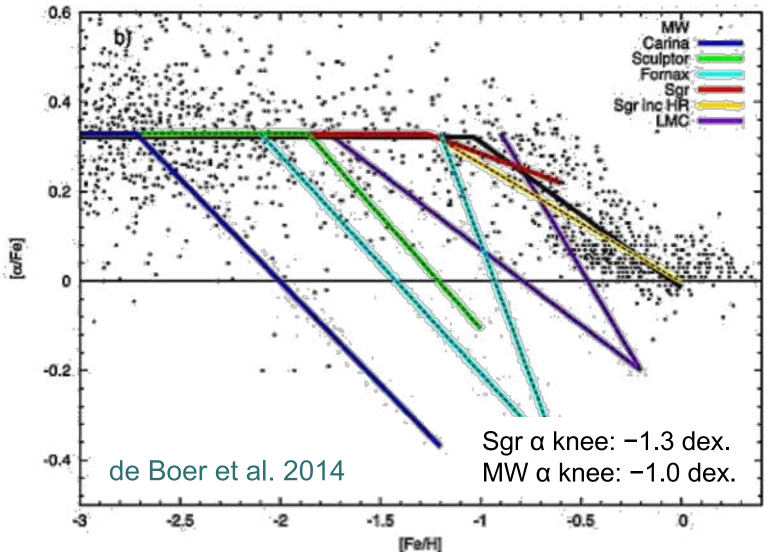
Chiappini et al. 2001

[Fe/H] vs. [α/Fe] in Dwarfs

Position of turnover ("α knee") shows how far enrichment could proceed until onset of SNe Ia.

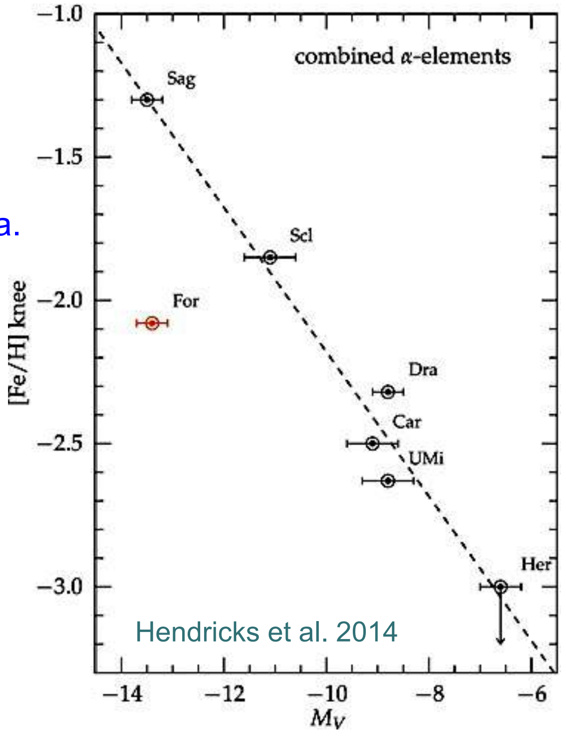
Measure of SFE and retention of enriched ejecta.

Sgr dSph: Position of "knee" shows: 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 Individual Element Abundance Ratios

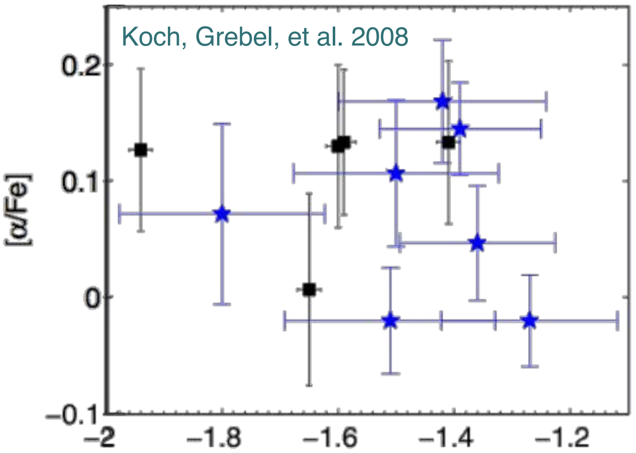
- ❑ Abundance spreads in dSph field stars of up to > 1 dex even in dwarfs dominated by old populations (e.g., Shetrone et al. 2001; Norris et al. 2008)
- ❑ At given metallicity: scatter in α abundance ratios (e.g., Koch, Grebel, et al. 2008)

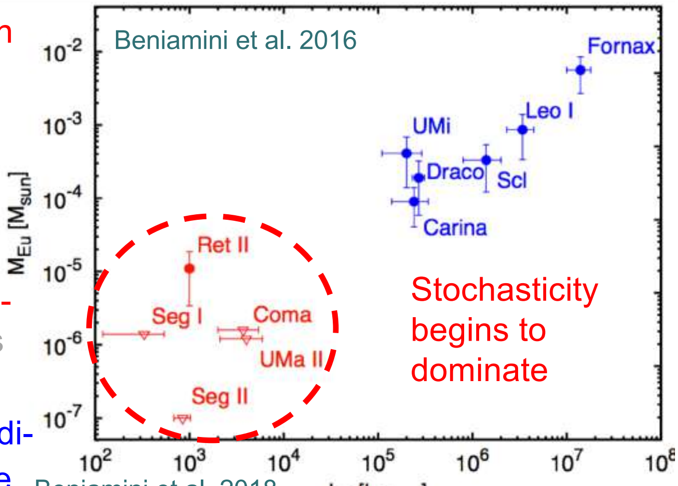
➜ Slow, stochastic SF, low star formation efficiency, inhomogeneous pollution; dwarfs not well mixed.

r-process: n-rich nuclei formed rapidly in massive stars via n-capture (~10^4s) and β decay, e.g., **Eu**:

- ❑ large scatter in abundances of r – process elements (and derivatives, mass number A ≥ 90) in metal-poor dSphs

As with α elements: contributions from individual events; stochastic effects dominate





Stochasticity begins to dominate

Beniamini et al. 2018

Trends in Individual Element Abundance Ratios

For –4 ≤ [Fe/H] ≤ –2 (small sample sizes still):

- ❑ α elements in classical dSphs and MW halo very similar. Plateau at [α/Fe] ≈ 0.3. Enrichment by massive stars with “normal” IMF.
- ❑ Fe peak, Al, Na in dSphs follow MW halo trends

➜ Produced in same nucleosynthetic processes (C burning) independent of host galaxy mass.

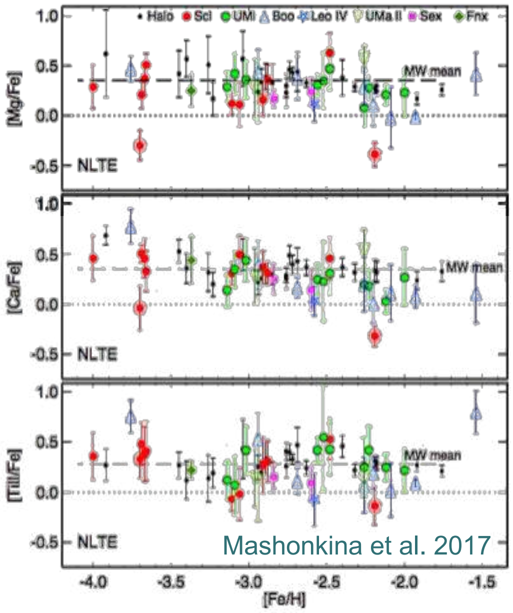
- ❑ Ultra-faint dSphs (Boo I, Leo IV) show evidence for pollution by SNe Ia (SF must have lasted at least about 1 Gyr). ➜ “Long-lasting” SF.
- ❑ Ultra-faint dSph UMa II: No SN Ia enrichment!

n-capture elements Sr, Ba:

- ❑ Classical dSphs and MW halo show large dispersion in [Sr/Fe] below [Fe/H] ~ –3.
- ❑ Same [Sr/Ba] dichotomy in classical dSphs and MW halo:

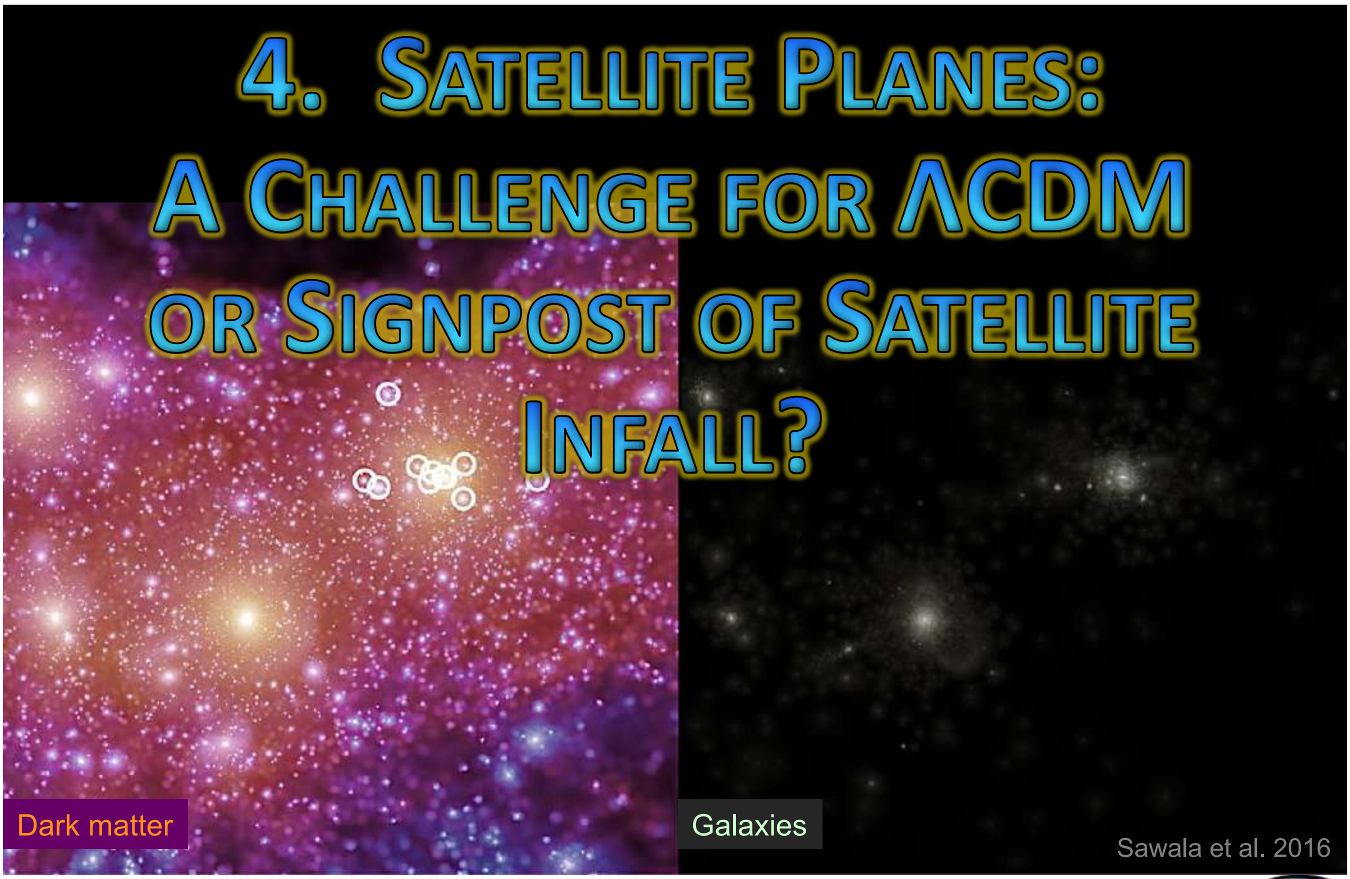
➜ two nucleosynthesis channels for Sr.

- ❑ Ultra-faint dSphs: mainly distinctly low [Sr/Ba] values. Lack 2nd channel of Sr production. Possibly due to undersampling of IMF at high-mass end.



(see also Tafelmeyer et al. 2010; Koch et al. 2013; Frebel & Norris 2015; Battaglia et al. 2017)

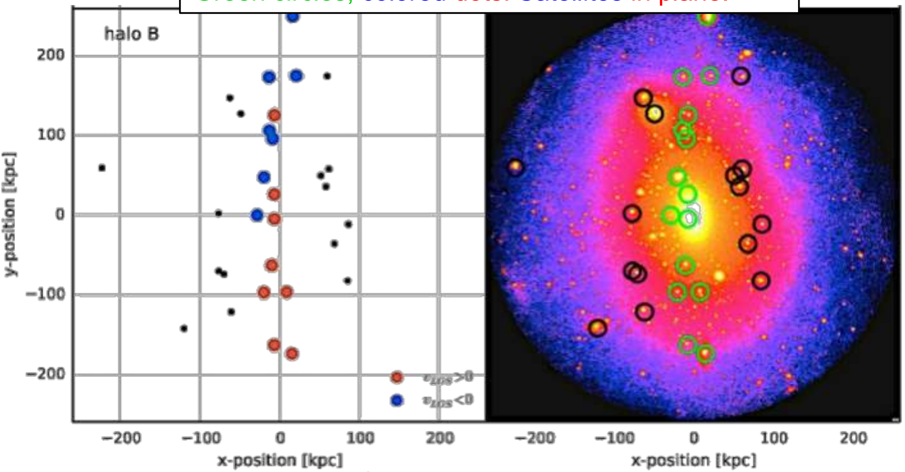
4. SATELLITE PLANES: A CHALLENGE FOR ΛCDM OR SIGNPOST OF SATELLITE INFALL?



Sawala et al. 2016

Satellite Planes

Thin planes of satellites around MW and M31
(e.g., Kunkel & Demers 1976; Lynden-Bell 1976; Koch & Grebel 2006; Pawlowski et al. 2012; Ibata et al. 2013).



Black dots, black circles: Satellites not in the plane.
Green circles, colored dots: Satellites in plane.

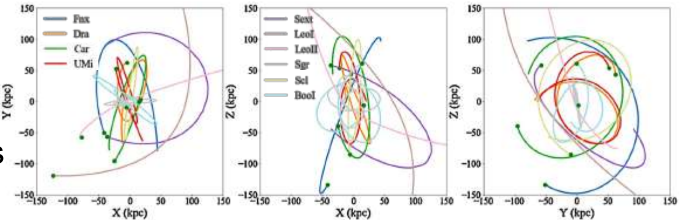
Buck et al. 2015

ΛCDM simulations:

- Planes form through accretion along large filaments of DM around galaxies at high redshift.
- Dwarf galaxy accretion is highly anisotropic, takes place preferentially in the plane determined by the major and intermediate axes of the DM host halo shape, and, within this plane, is clustered along the shape major axis.
- High-concentration massive halos tend to have thinner and richer planes.
- Most satellites were accreted along the richest filaments.
- Group accretion (multiple satellites) is more common for fainter satellites.
- Degree of anisotropic accretion higher for most massive satellites.

E.g., Libeskind et al. 2015; Buck et al. 2015, Shao et al. 2018.

Satellite Planes



Gaia Collaboration et al. 2018
Orbit backward integration
for 2.5 Gyr.

❑ Long-term survival of planes depends on orientation of dwarfs' orbit.

➞ Thin plane survives only if aligned with one of the semi-major or semi-minor axes of a triaxial halo, or in the polar or equatorial planes of a spherical halo.

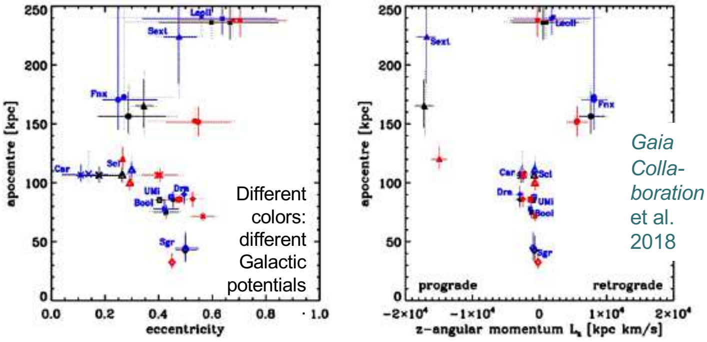
(Bowden et al. 2013; Fernando et al. 2016).

❑ Satellite planes at least partially fortuitous.

❑ Planes may contain co-rotating pairs of satellites, but planes need not co-rotate.

❑ Planes not kinematically coherent structures as a whole; transitory features.

E.g., Cautun et al. 2015; Buck et al. 2015; Gillet et al. 2015; Bowden et al. 2013; Fernando et al. 2016; Lipnicky & Chakrabarti 2017.



Different colors: different Galactic potentials

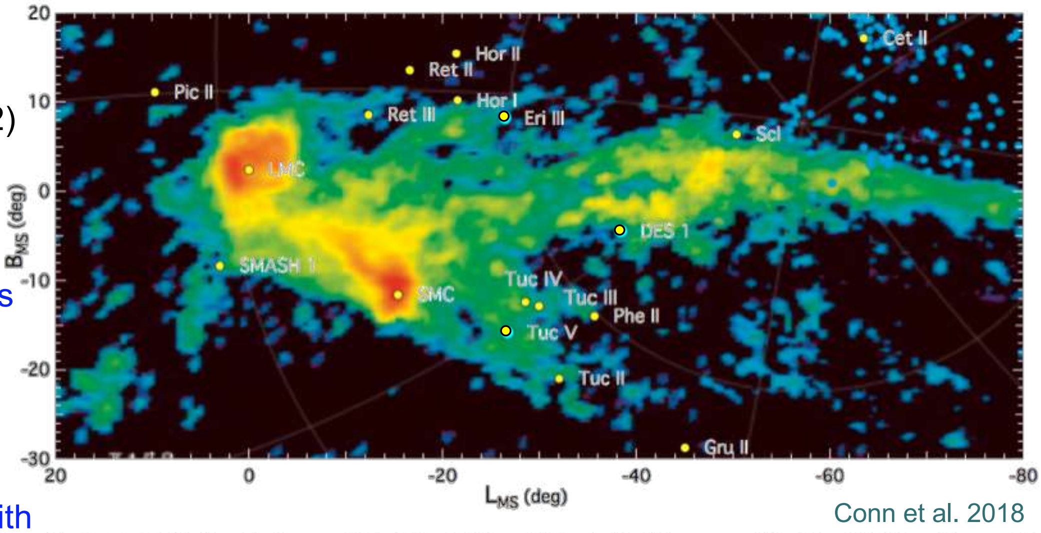
Gaia Collaboration et al. 2018

❑ HST & **Gaia** proper motions: MW dwarfs <u>not</u> on single narrow plane.

❑ Orbits typically ⊥ to MW disk, but span broad range of orientations (of 39, 11 co-orbit, 6 counter-orbit).

➞ Single major event excluded, but multiple infall along cosmic web filament aligned with Z-axis possible. (Gaia Collaboration et al. 2018; Fritz et al. 2018; Simon 2018; Casetti-Dinescu et al. 2018, Sohn et al. 2017; Massari & Helmi 2018; Kallivayalil et al. 2018).

Infall of Dwarf Groups



Conn et al. 2018

On sky distribution of all known Milky Way satellite candidates in the distance range $30 < D_{GC} < 100$ kpc with respect to the Magellanic Clouds and the neutral hydrogen gas of the Magellanic stream. The HI column density ($\log(N_{HI})$) in units of cm^{-2}) is shown over six orders of magnitudes, ranging from $\log(N_{HI}) = 16$ (black) to 22 (red). For more details we refer to Nidever et al. (2010).

❑ Proper motions (Gaia DR2) and radial velocities of ultra-faint dSphs near MCs:

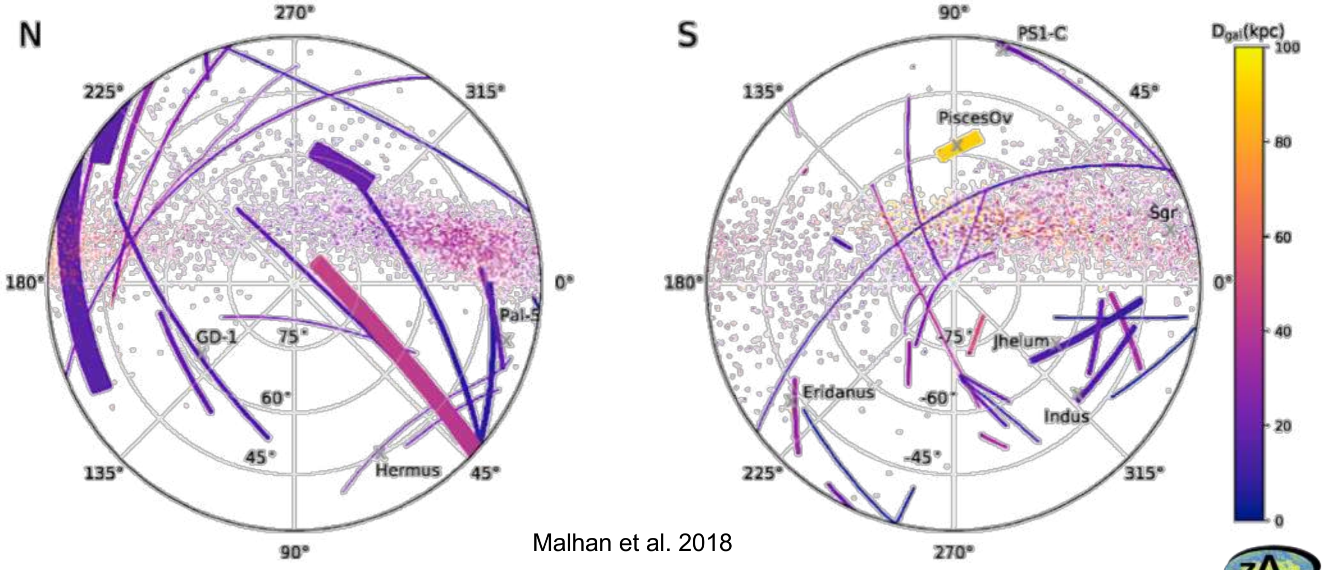
- 4 (Hor 1, Car 2, 3, Hyd 1) came in with MCs.
- Possibly also Hyd 2, Dra 2. 3 (Ret 2, Tuc 2, Gru 1) uncertain.
- 4 are unlikely (Tuc 3, Cra 2, Tri 2, Aqu 2).
- Remaining ones: no proper motions yet. (Kallivayalil et al. 2018)
- 4 – 6 LMC satellites: Consistent with expectations from ΛCDM.

5. FOSSIL REMNANTS IN THE GALACTIC HALO

Grillmair & Carlin 2016
Huxor & Grebel 2015
Shipp et al. 2018
Malhan et al. 2018

Stellar Halo (observed): 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.

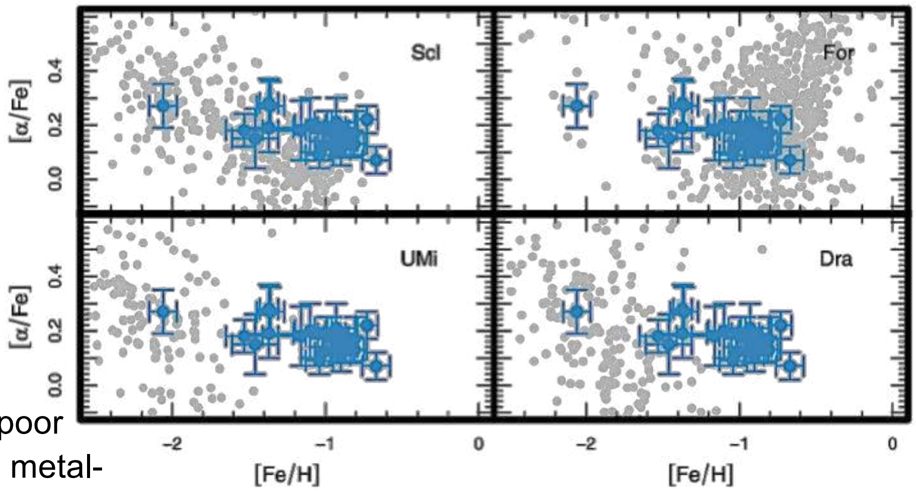


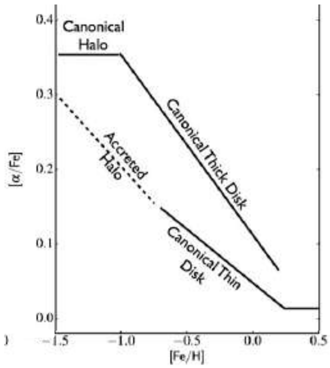
Malhan et al. 2018

SDSS

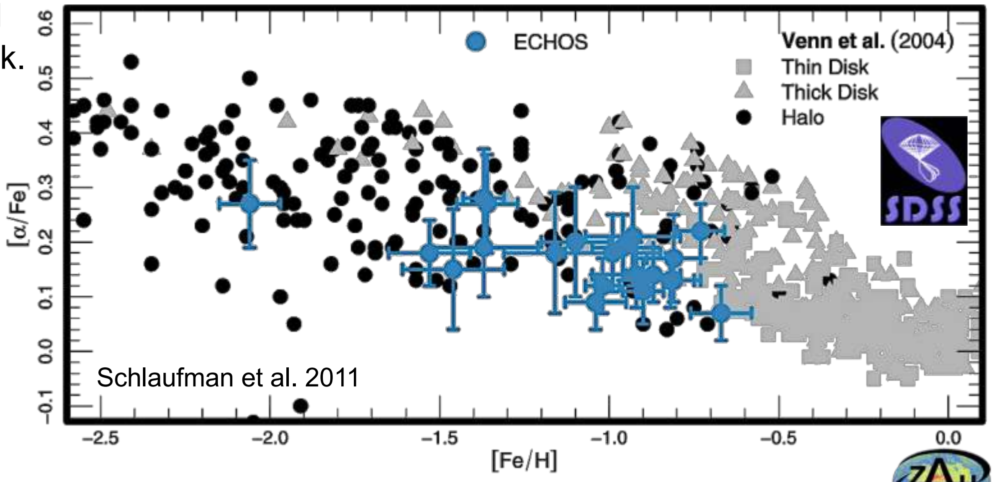
“Elements of Cold Halo Substructure”

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

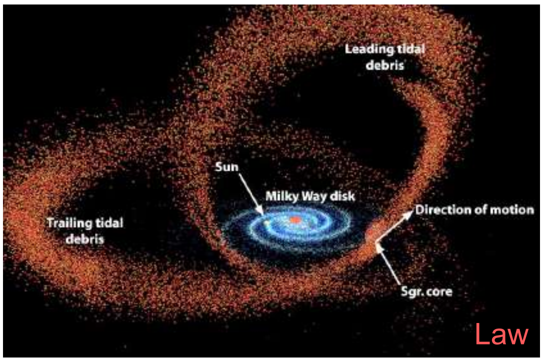


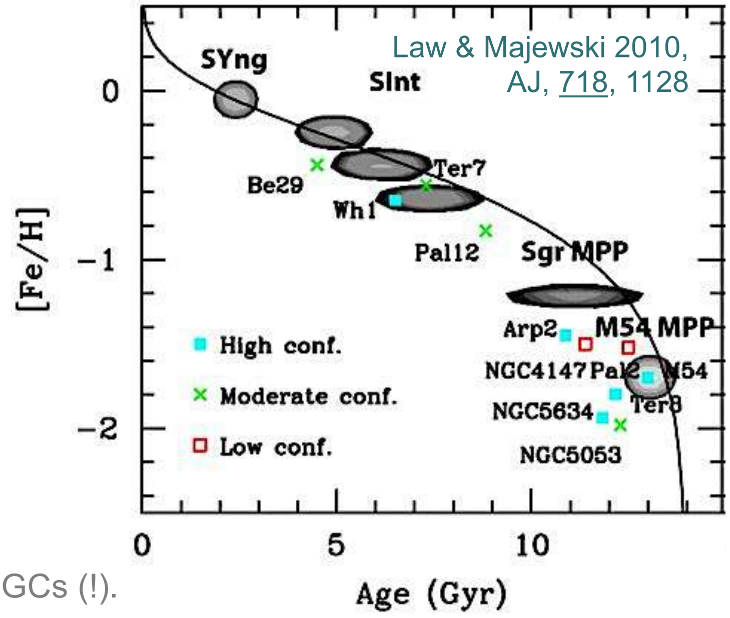


Hawkins et al. 2015



Globular Clusters Contributed by the Sgr dSph



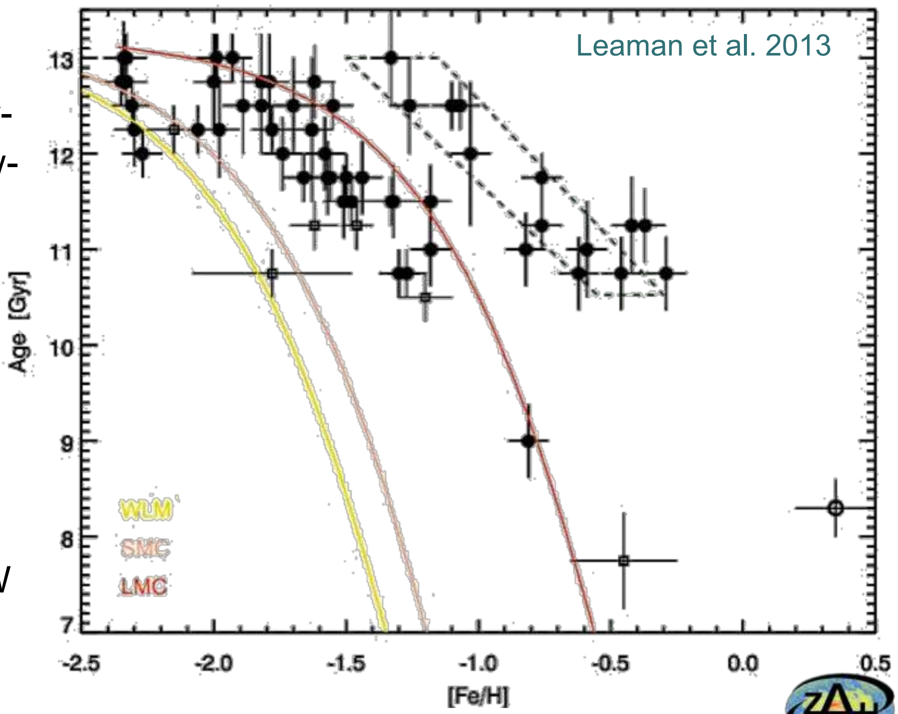


- 5 high-, 4 moderate, 2 low-confidence GC members.
  ~ 8 ± 2 genuine GCs.
- In the (HB-type, [Fe/H] plane), Sgr is contributing “young halo” (Arp 2, NGC4147) and old halo GCs (!).
- When fully disrupted, Sgr will (probably) have contributed up to 3 – 4 metal-rich young objects to the Galactic halo,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

Substantial GC Accretion from Dwarf Galaxies?

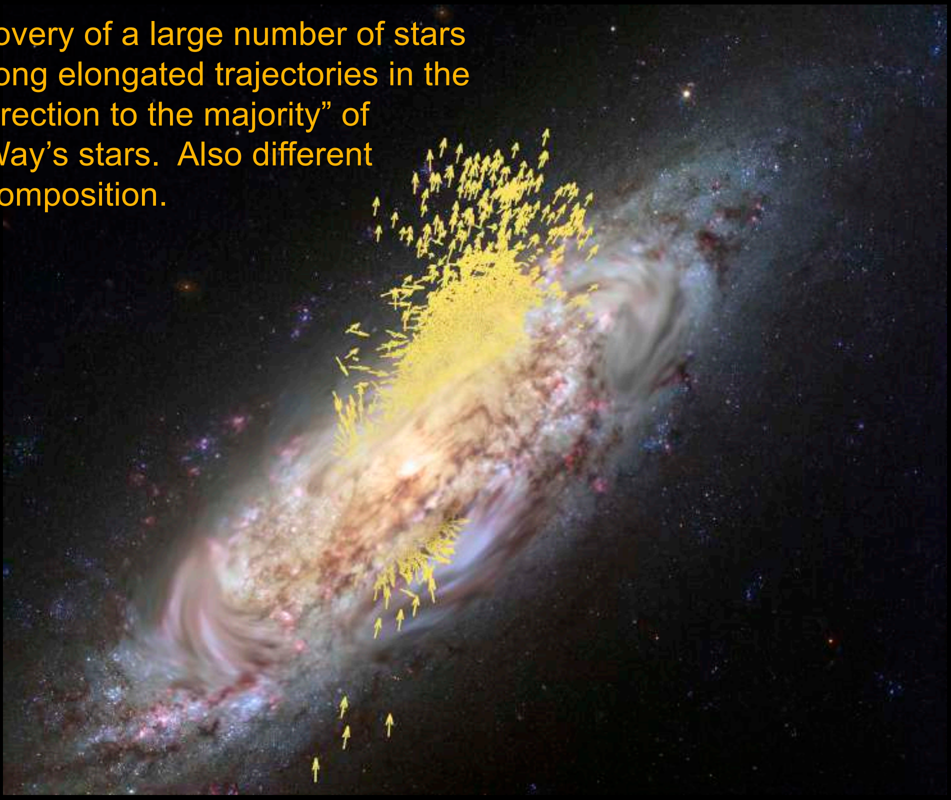
Assume: GC metallicity traces host galaxy metallicity at time of formation.

- 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.



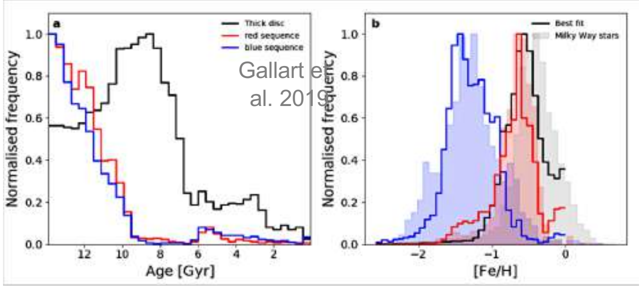
Gaia-Enceladus: Merger with Milky Way ~ 10 Gyr Ago

Gaia: Discovery of a large number of stars moving “along elongated trajectories in the opposite direction to the majority” of the Milky Way’s stars. Also different chemical composition.



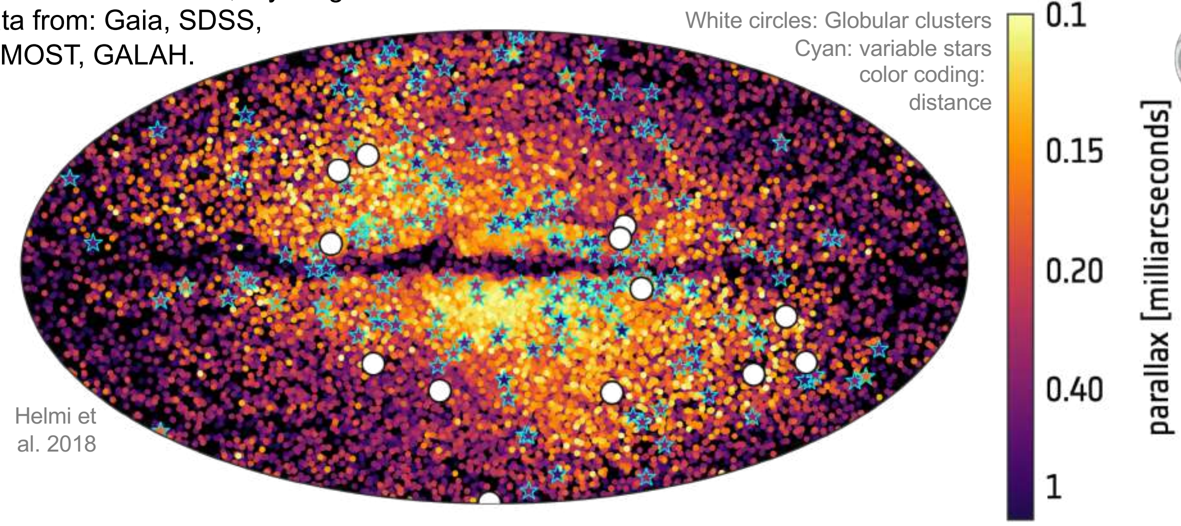
ESA, Koppelmann, Villalobos, Helmi

Gaia-Enceladus; Gaia Sausage



Gallart et al. 2019

ESA/Gaia/DPAC, Helmi et al. 2018. *See also:* Gallart et al. 2019 and the "Gaia Sausage", Belokurov et al. 2018; Myeong et al. 2018. Data from: Gaia, SDSS, LAMOST, GALAH.



White circles: Globular clusters
Cyan: variable stars
color coding:
distance

Helmi et al. 2018

- ❑ At time of accretion: 1:4 merger, a bit more massive than SMC. $M_{\mathrm{vir}} \sim 10^{10}\ M_{\odot}$.
- ❑ Stars as old as old MW stars, but clearly lower metallicity.
- ❑ Merger formed inner halo and thick disk; contributed > 10 globular clusters.

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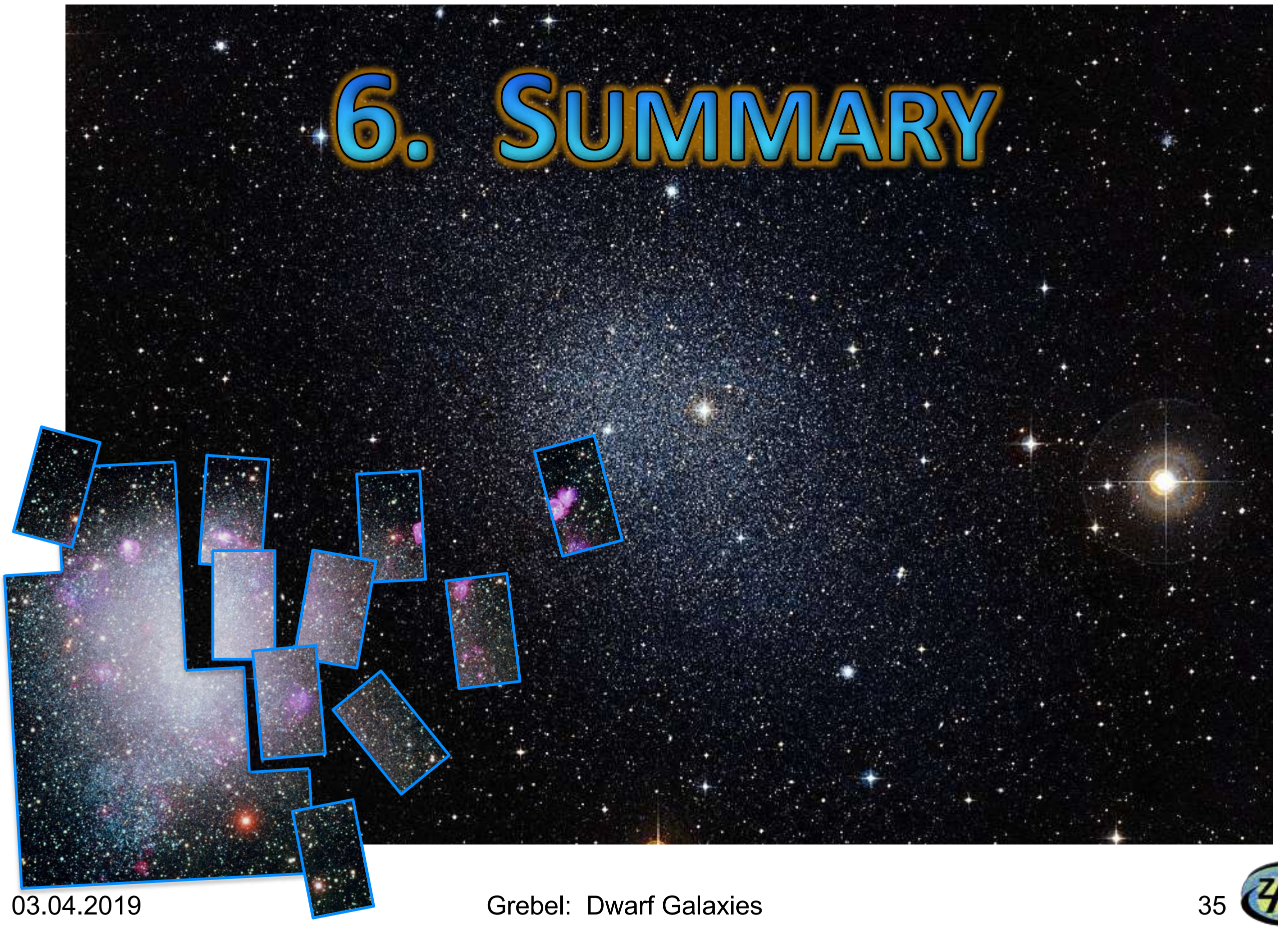
6. SUMMARY



Dwarf Galaxies – Fossils of Galaxy Evolution

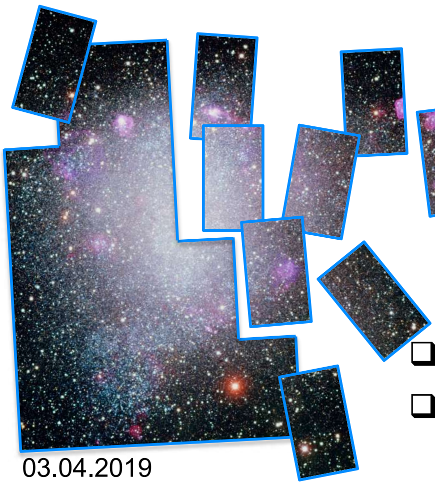
- Old populations ubiquitous. Fractions vary.

  Oldest age-dateable populations in satellites and in the Milky Way coeval within measurement accuracy.

  No evidence of significant cosmological re-ionization quenching.

- Well-defined mass-metallicity relation over ~ 9 decades of galaxian $M_\star$.
- Dwarfs: Radial gradients; 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.
- Massive progress expected via Gaia!