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NEAR-FIELD COSMOLOGY WITH DWARF GALAXIES

SFB 881

Motivation / Contents

Dwarf galaxies...

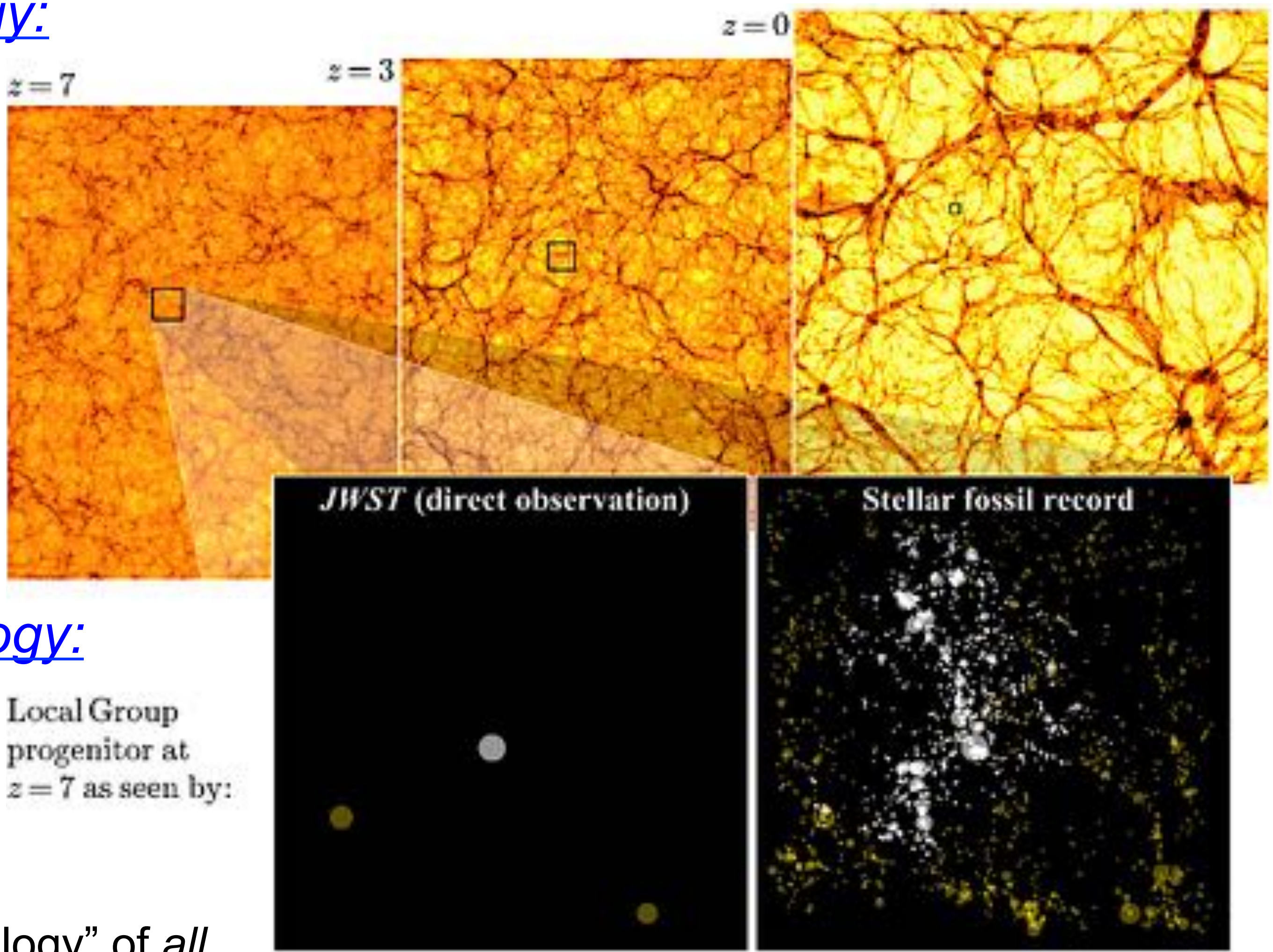
- as building blocks of more massive galaxies
- to constrain ΛCDM models of structure formation
- as indicators of early conditions of star formation in low-mass halos
- as probes of environmental effects on galaxy evolution
- to constrain galactic chemical evolution
- to constrain the nature of dark matter

1. Dwarf Galaxies As Building Blocks

Observing Galaxy Evolution

Far-field cosmology:

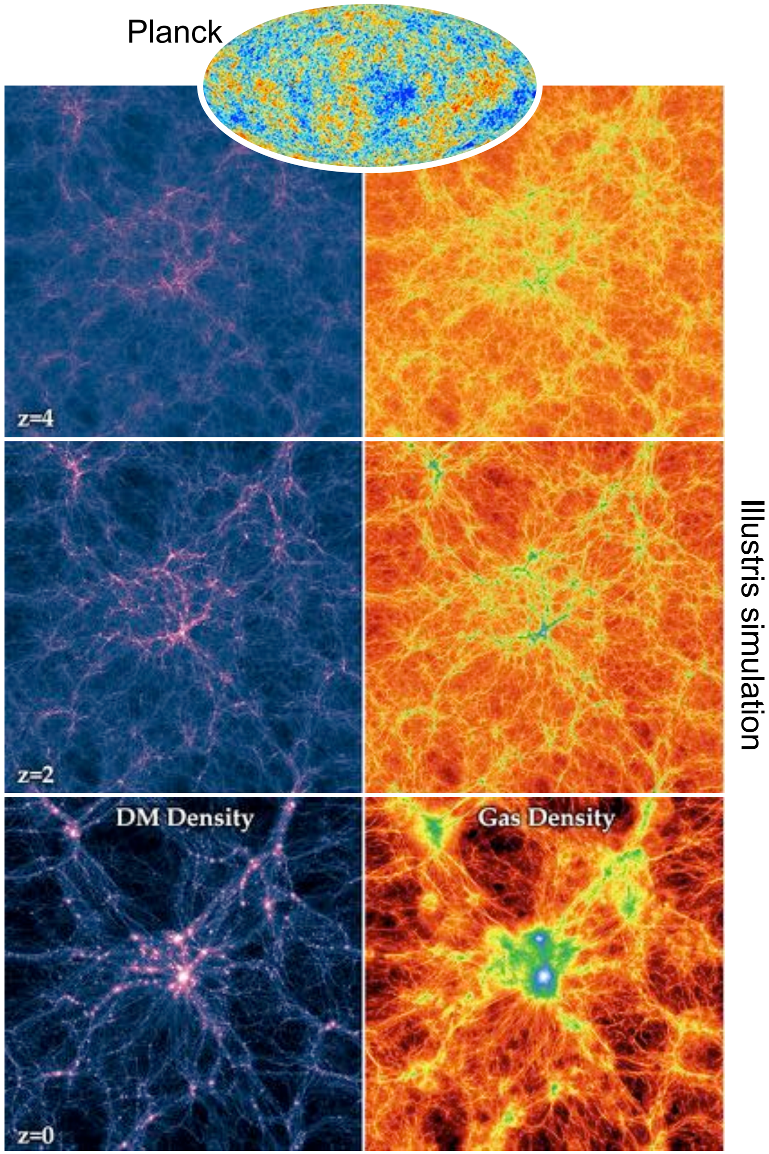
- ❑ High redshift, very distant.
- ❑ Early universe.
- ❑ Only most lumin-ous structures.
- ❑ Low resolution..



Near-field cosmology:

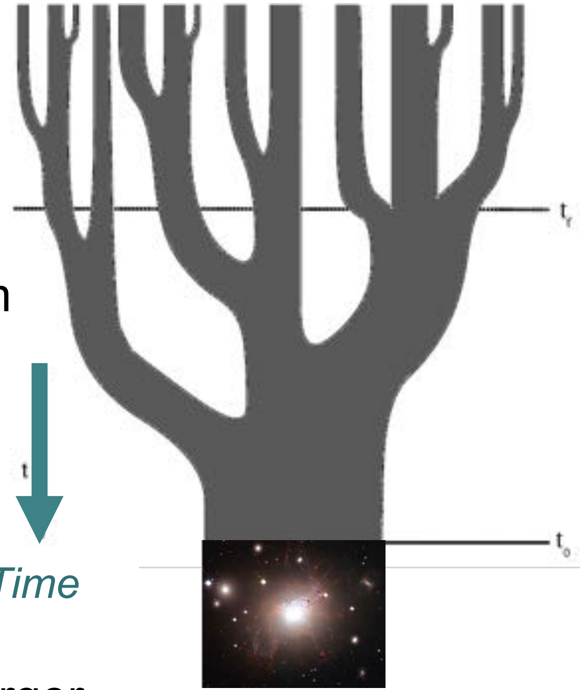
- ❑ Redshift 0, nearby.
- ❑ Evolved universe.
- ❑ Detailed "archaeology" of *all* structures at *high* resolution.

Boylan-Kolchin et al. 2016



Hierarchical Structure Formation

"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.

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

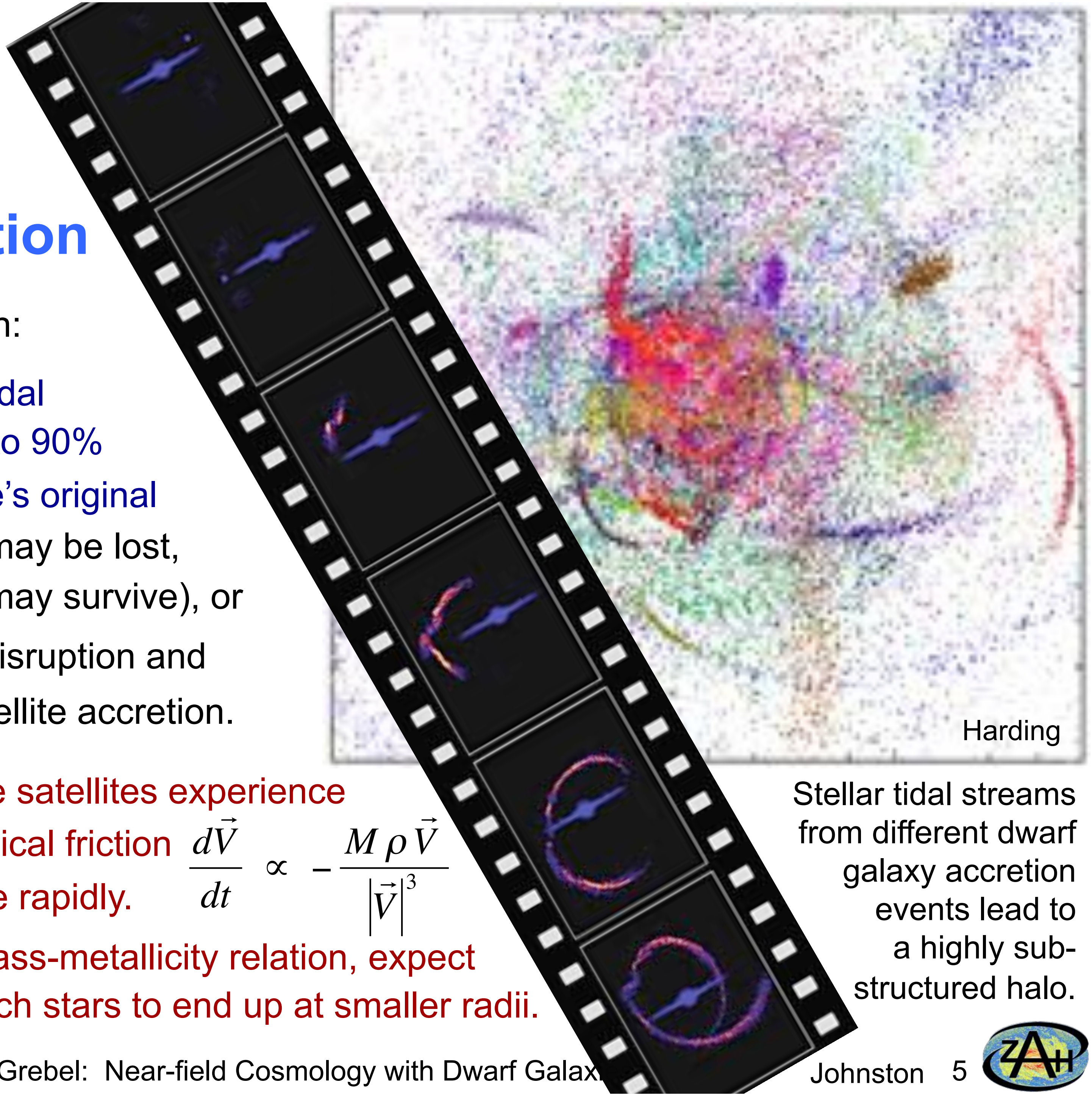
Satellite Disruption and Accretion

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 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.



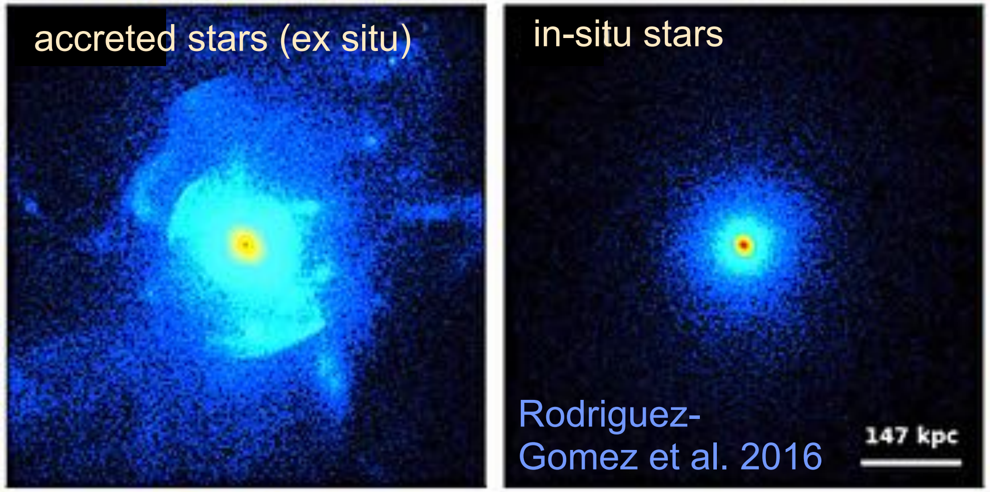
Stellar tidal streams from different dwarf galaxy accretion events lead to a highly sub-structured halo.

Johnston

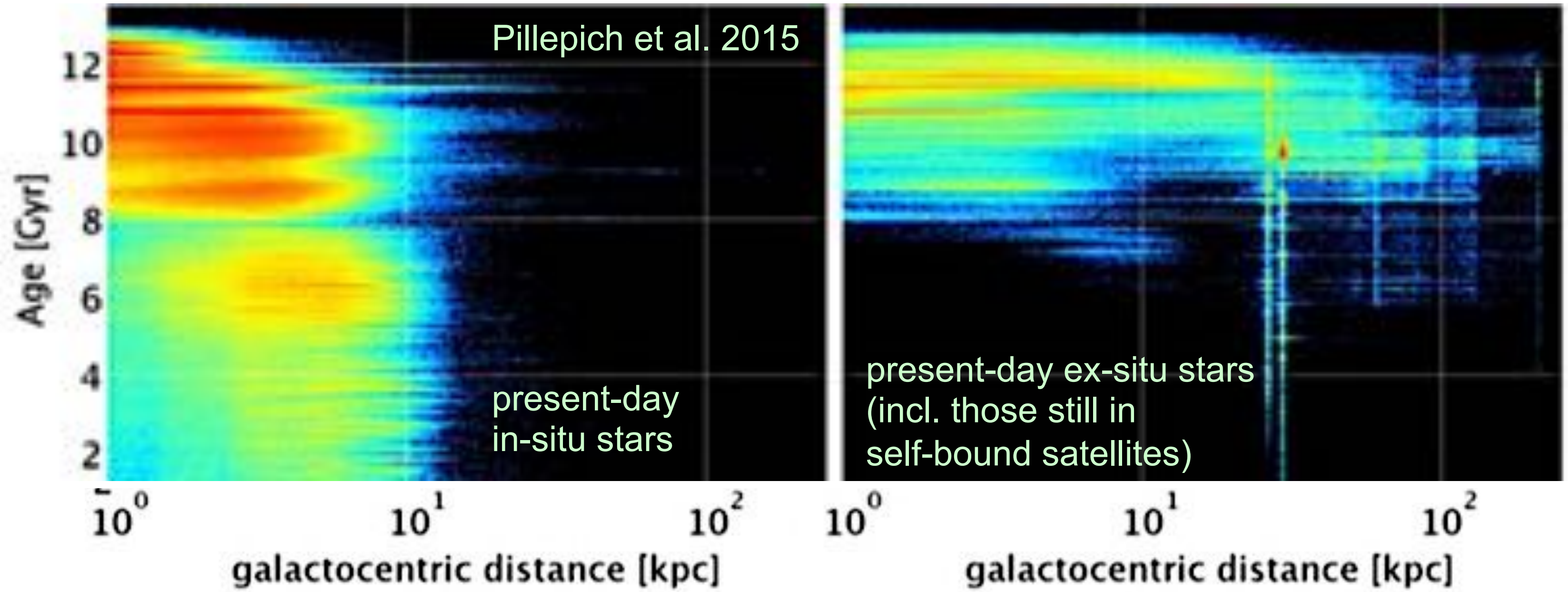
De Lucia & Helmi 2008; Cooper et al. 2010

Stellar Halo Origins

- 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. Small-scale Challenges in ΛCDM or the Importance of Baryons

The Missing Satellites Problem

ΛCDM simulations:

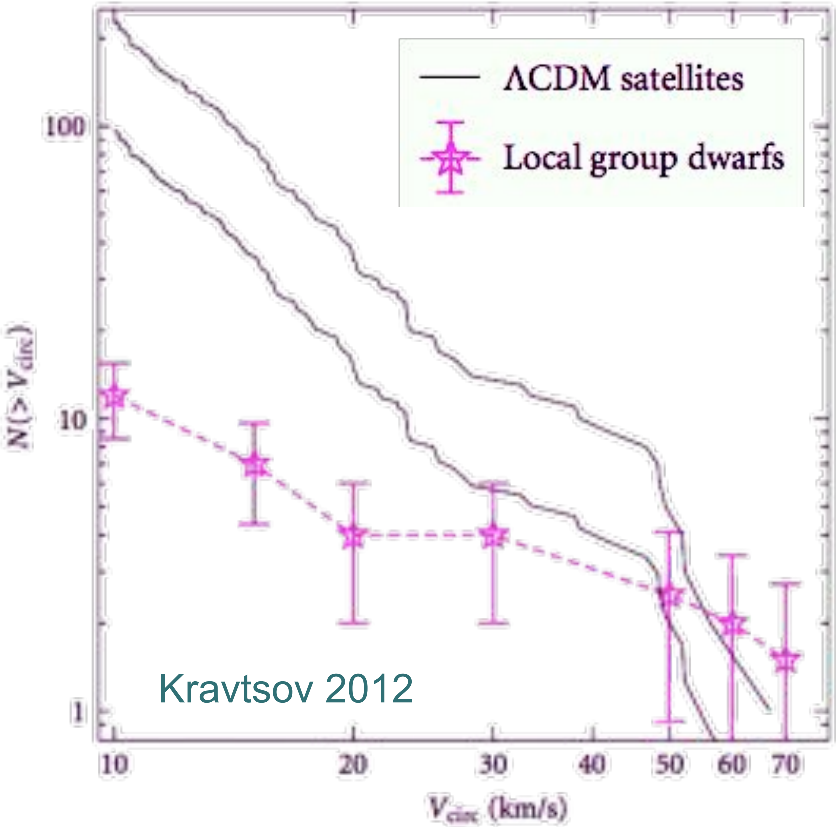
2 orders of magnitude more dark matter halos predicted than actual luminous satellite galaxies observed.

→ **Missing satellites** or **substructure problem**

Proposed solutions:

DM halos without baryons around massive galaxies?

Or undet-ected baryonic structure with DM?

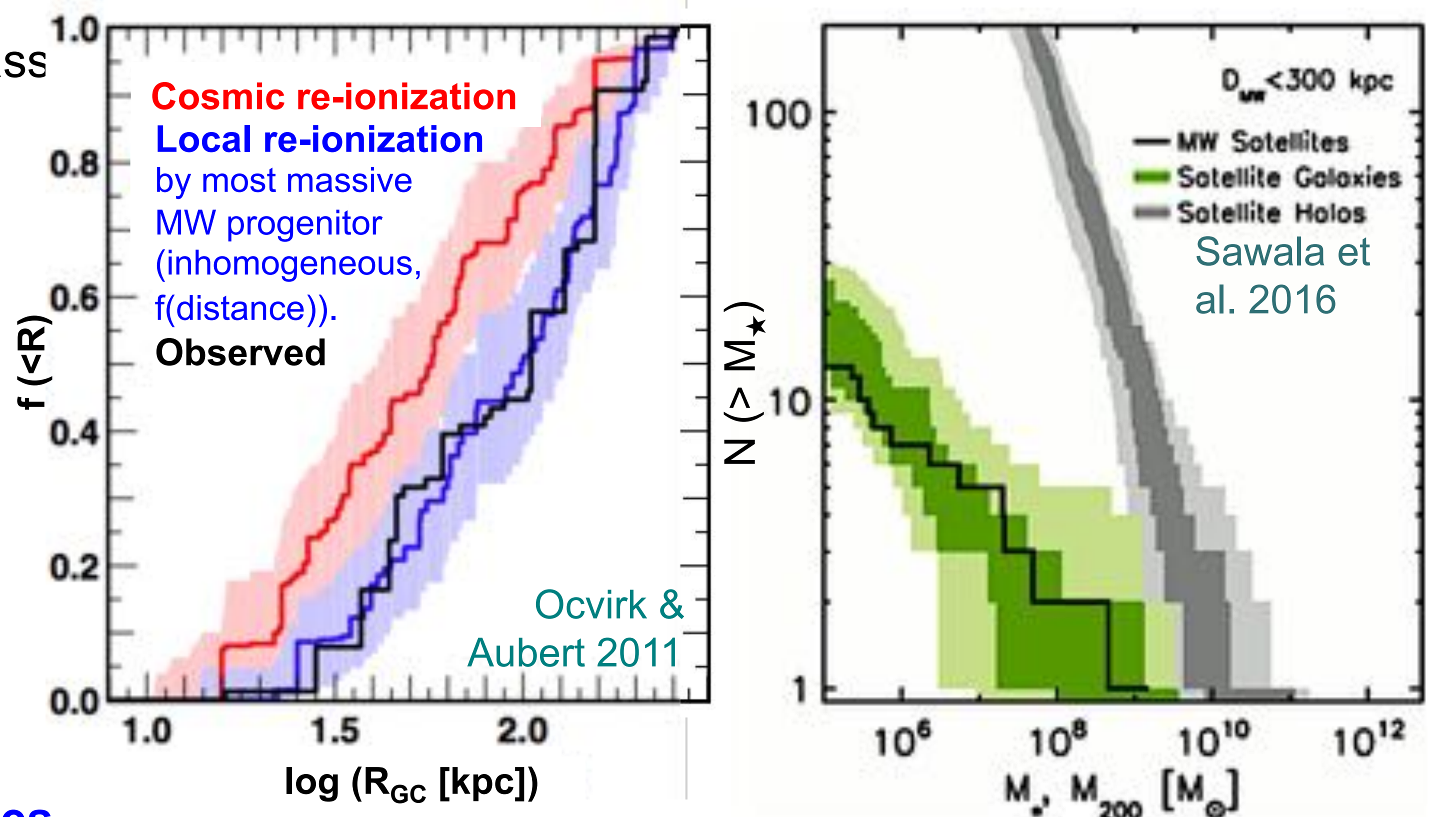


The Substructure or Missing Satellite Problem

Below a certain mass limit (**but which?**):

Dark matter halos cannot retain baryonic matter needed for star formation

→ lower limit on formation of luminous galaxies.



Moreover, below a certain mass limit **feedback processes,** **local and cosmic re-ionization** remove baryons required for star formation

→ lower limit on formation of luminous galaxies.

Pure DM simulations predict much larger numbers of small halos than dwarf galaxies observed. Cosmological *simulations accounting for baryonic effects* predict luminous satellite numbers in ~ agreement with observations.

The “Too Big To Fail” Problem

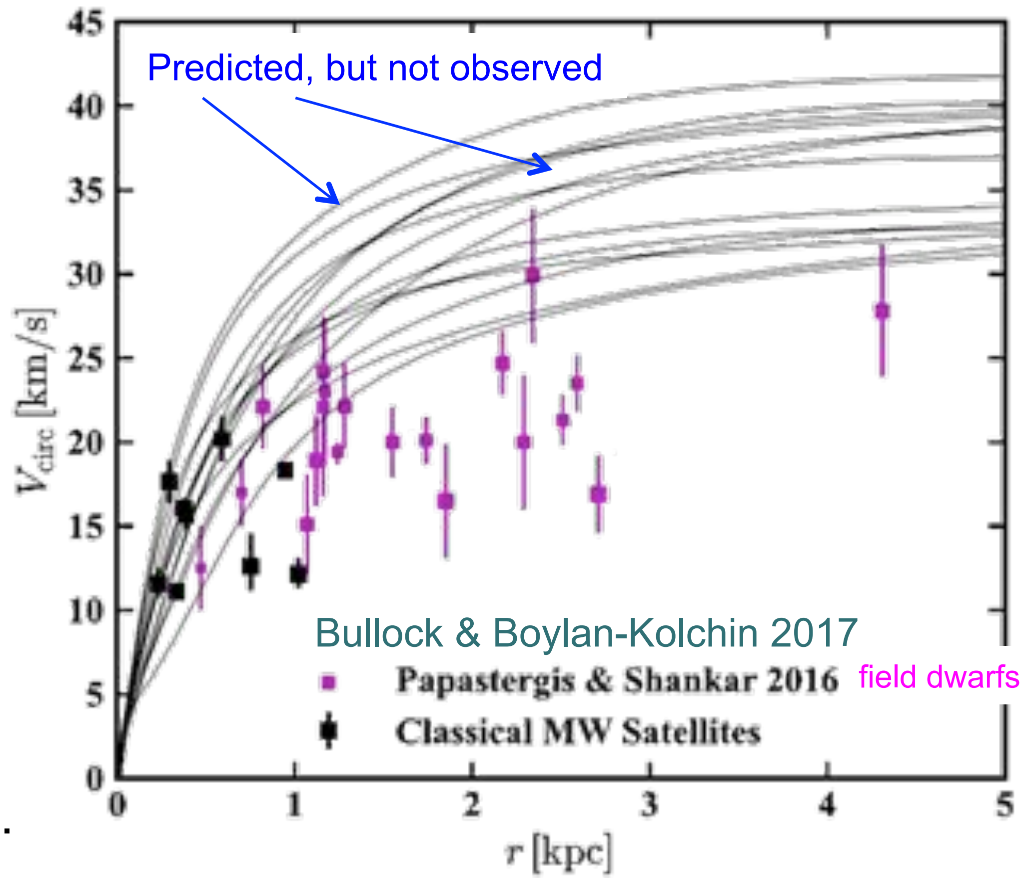
DM-only ΛCDM simulations:

More massive subhalos predicted, and **with higher central densities**, than luminous satellite galaxies observed. (Boylan-Kolchin et al. 2011)

→ **“Too Big To Fail” problem**

Expectation:

- ❑ Too massive to have failed to form stars.
- ❑ Observable as luminous, dense dwarf galaxies.
- ❑ No detection difficulties due to high luminosity at v_{max} > 30 km/s.



But if baryonic effects are included:

- ❑ Stellar feedback redistributes matter leading to shallower, cored DM distribution.
- ❑ Mass of each subhalo reduced; halos with v_{max} > 30 km/s affected by tidal stripping after infall, resolving TBTF (Sawala et al. 2016; Tomozeiu et al. 2016).

$\rho(r) \propto r^{-\alpha_{\rm int}}$

The Core – Cusp Problem

ΛCDM simulations:

- DM halos share a universal shape over many decades of mass. Parameterized by a simple fitting formula.

Observations:

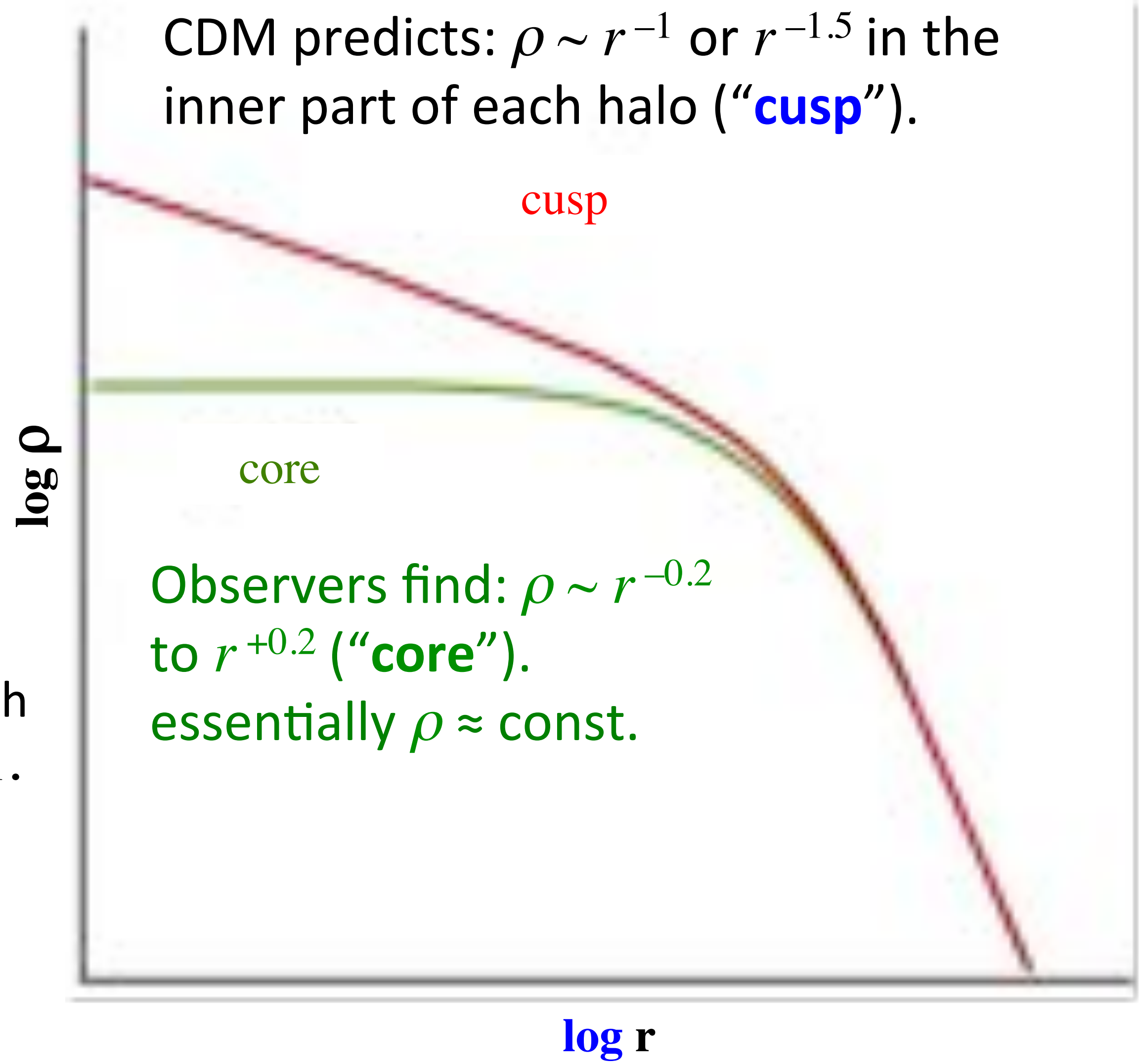
- Halos are **cuspy**: their density distributions follow $\rho(r) \propto r^{-\alpha_{\rm int}}$ at the smallest halo radii r with intrinsic inner slope $\alpha_{\rm int} \approx 1$.

- More generally: Navarro, Frenk, & White (NFW; 1996, 1997) profile:

$$\rho(r) = \frac{\rho_s}{(r/r_s)\,[1+(r/r_s)]^2}$$

(ρ_s, r_s: characteristic halo density and radius.)

CDM predicts: $\rho \sim r^{-1}$ or $r^{-1.5}$ in the inner part of each halo ("**cusp**").



Observers find: $\rho \sim r^{-0.2}$ to $r^{+0.2}$ ("**core**").
essentially $\rho \approx$ const.

Importance of Baryons

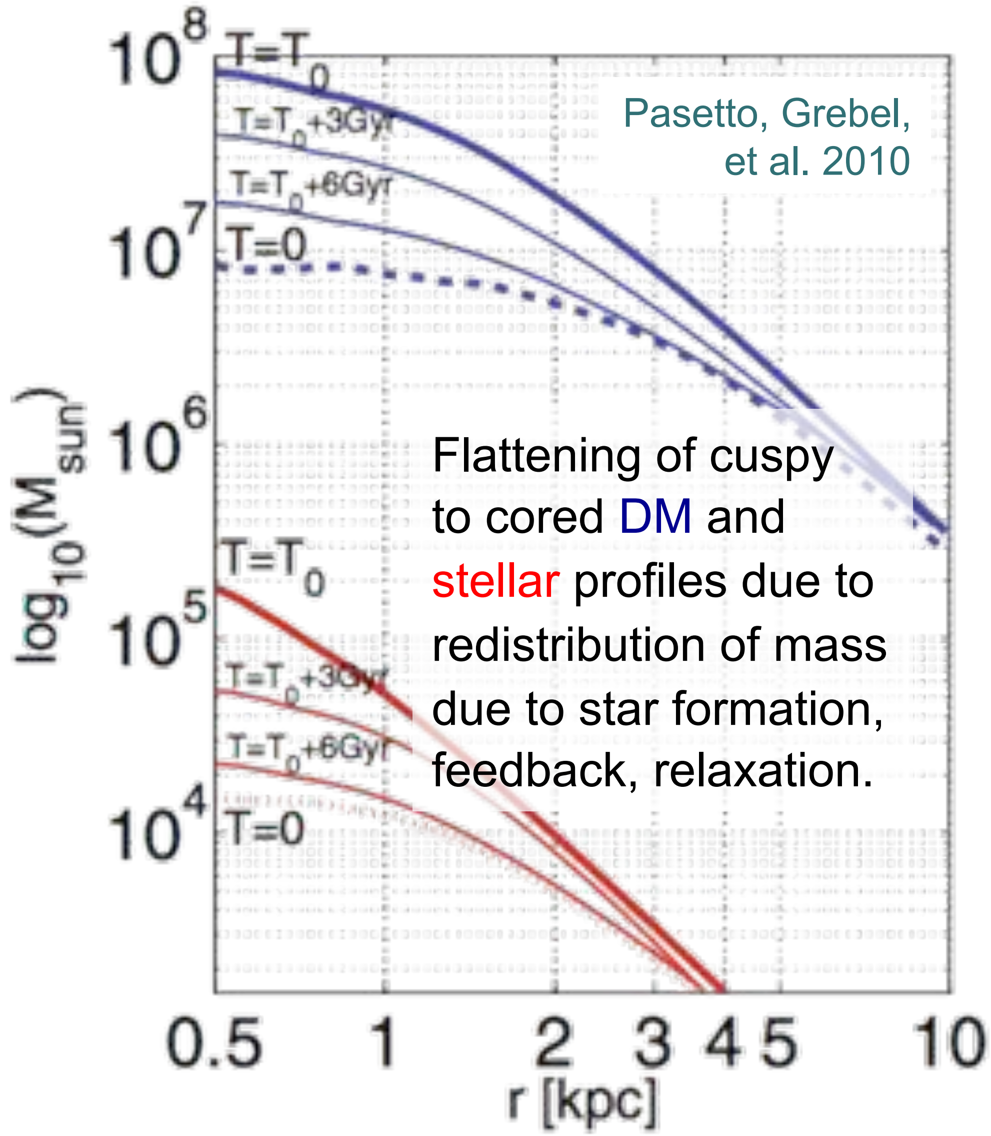
Cosmological simulations of Milky Way-mass galaxies with baryons *and* DM (in contrast to DM-only simulations):

- ❑ SN feedback reduces central DM densities of satellites with $M_\star < 10^7\ M_\odot$.
- ❑ In addition, baryonic disk of of host galaxy increases mass loss rate via tidal stripping. Also ram pressure stripping.

→ Lower v_{max}. Also, fewer surviving satellites.

→ Resulting v_{circ} and $(N > v_{max})$ agree with observational data.

→ Resolves missing satellites problem, too-big-to-fail problem, and core-cusp problem.



Brooks et al. 2013;
Brooks & Zolotov 2014;
Arraki et al. 2014;
Sawala et al. 2015, 2016.

3. Dramatis Personae

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

- 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.

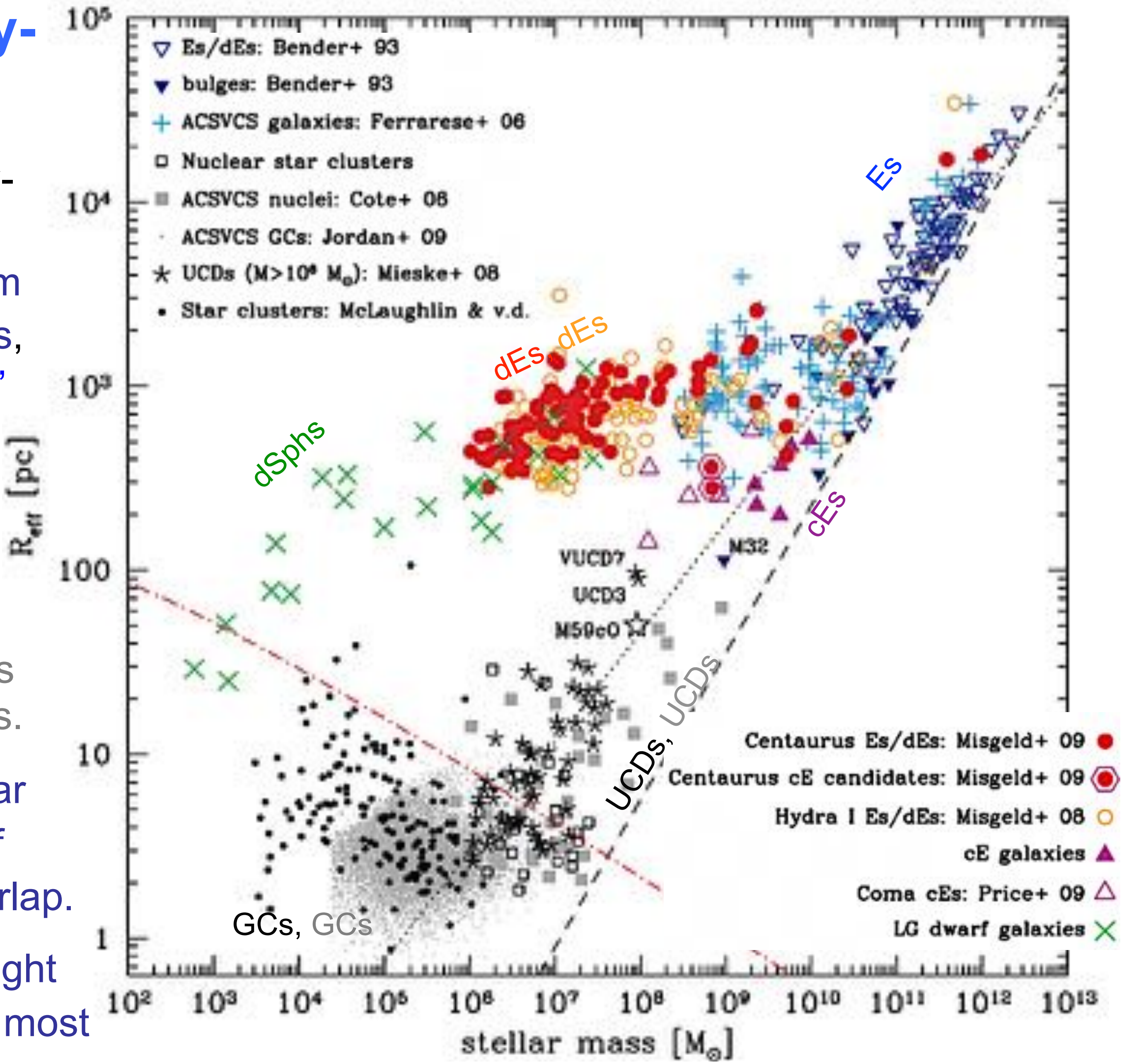
- Ultra-diffuse galaxies
- Tidal dwarf galaxies

Pictures not on same scale

dE | dSph | UCD | dS0, dS | dIrr | BCD

Families of Early-type Systems

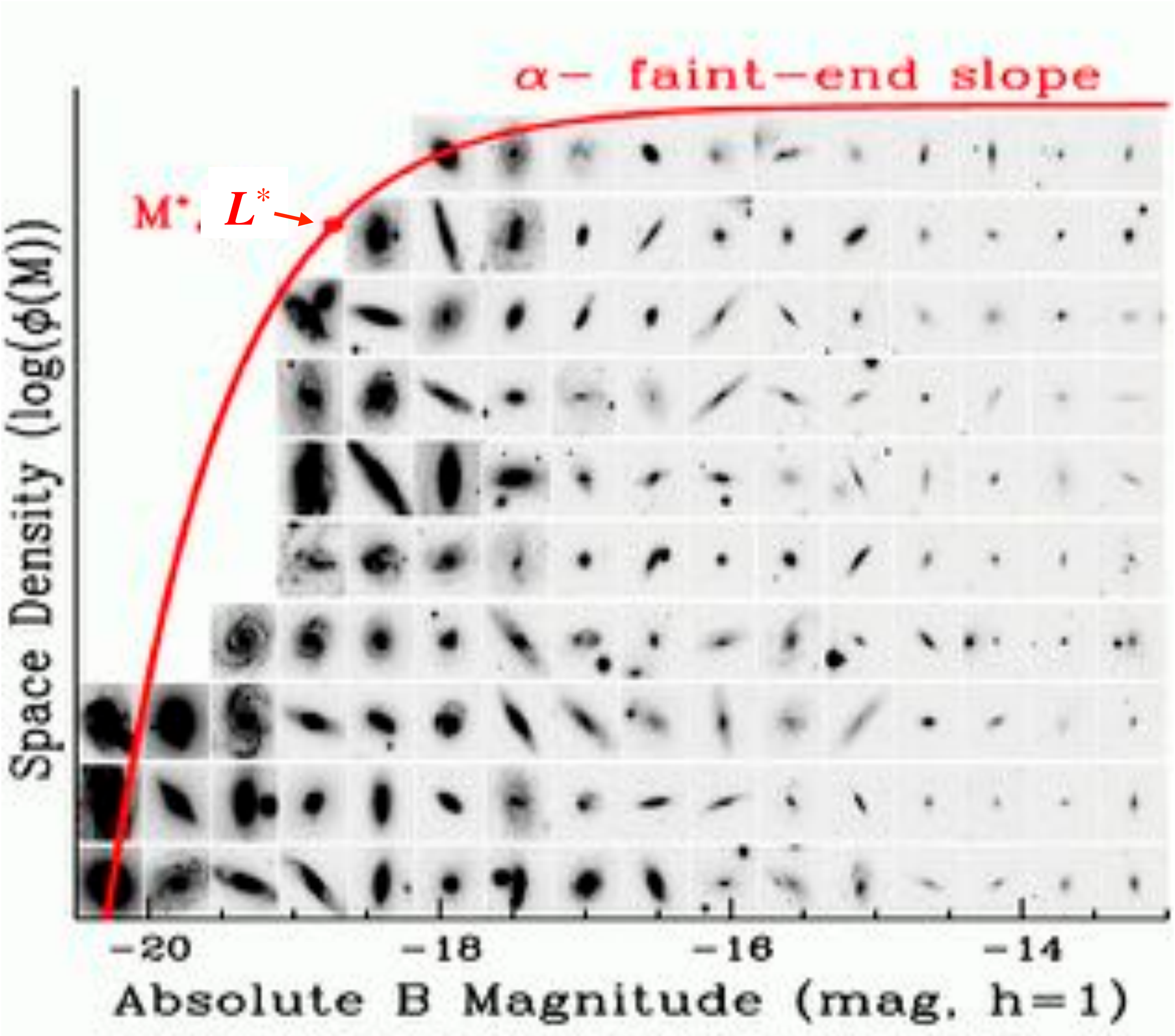
- Two families of early-type systems: The "galaxian" family from Es to dEs and dSphs, and the "star cluster" family from cEs to UCDs, nuclear star clusters and GCs.
- Massive Es: similar size-mass relation as cEs, UCDs, and NCs.
- Luminosity and stellar mass distributions of dSphs and GCs overlap.
- DSphs: typical half-light radii ≥ 100 pc, while most GCs have r_h ≤ 10 pc.



Misgeld & Hilker 2011

Galaxy Luminosity Function

$$\frac{dn}{dL} = \Phi(L) = \frac{n_*}{L_*} e^{-\frac{L}{L_*}} \left(\frac{L}{L_*}\right)^{\alpha}$$



Luminosity, Mass

L_*: Characteristic galaxy luminosity where exponential cut-off sets in.

n_*: Normalization factor at L_* (mean number density / Mpc ^{3}).

How bright are the *least luminous* galaxies?

What does the extreme faint-end slope look like?

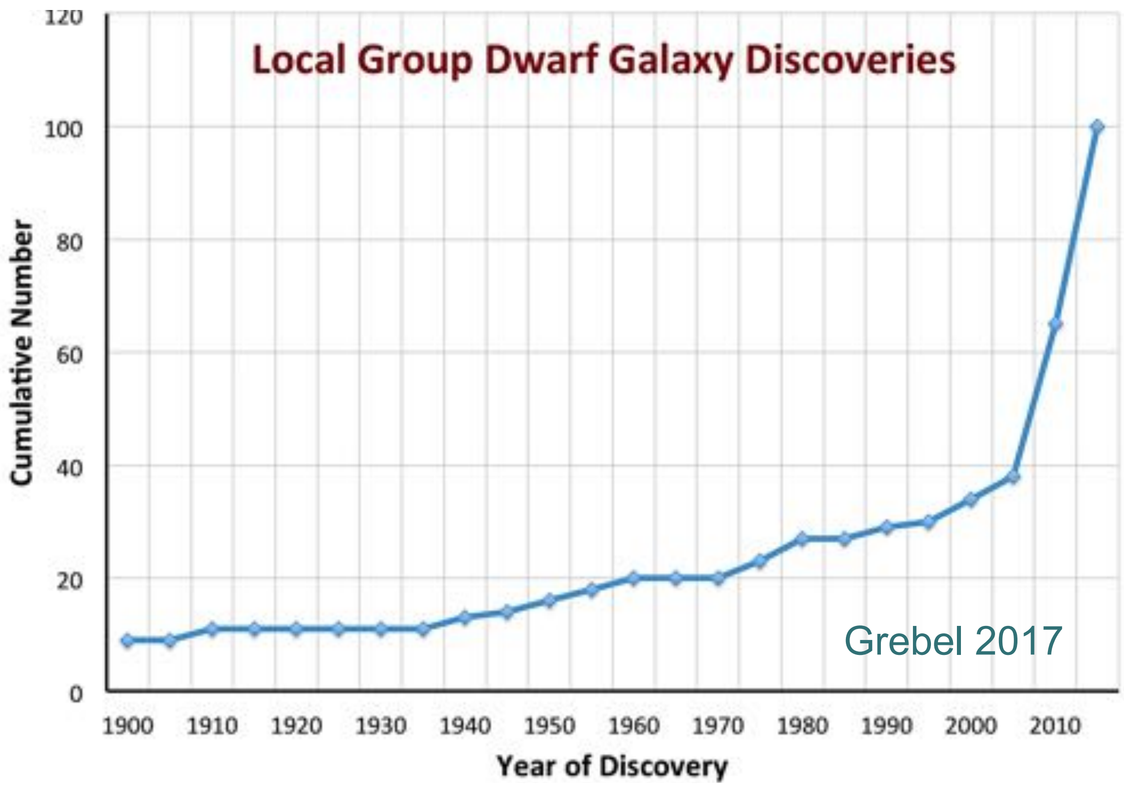
New Satellites of the Milky Way and M31 by year of publication

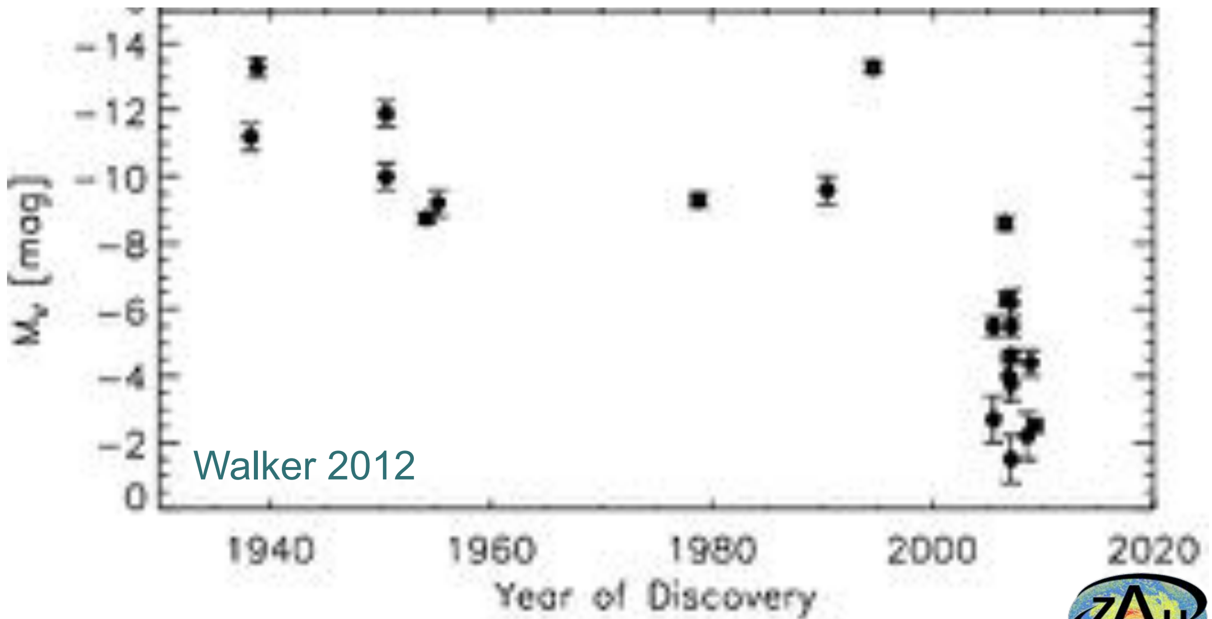
Mainly thanks to large imaging surveys in the northern hemisphere (esp. SDSS, PAndAS, PS1).

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

But: Far fewer than needed for missing satellites problem.

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





At Low Masses: Distinguishing Galaxies & Star Clusters

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

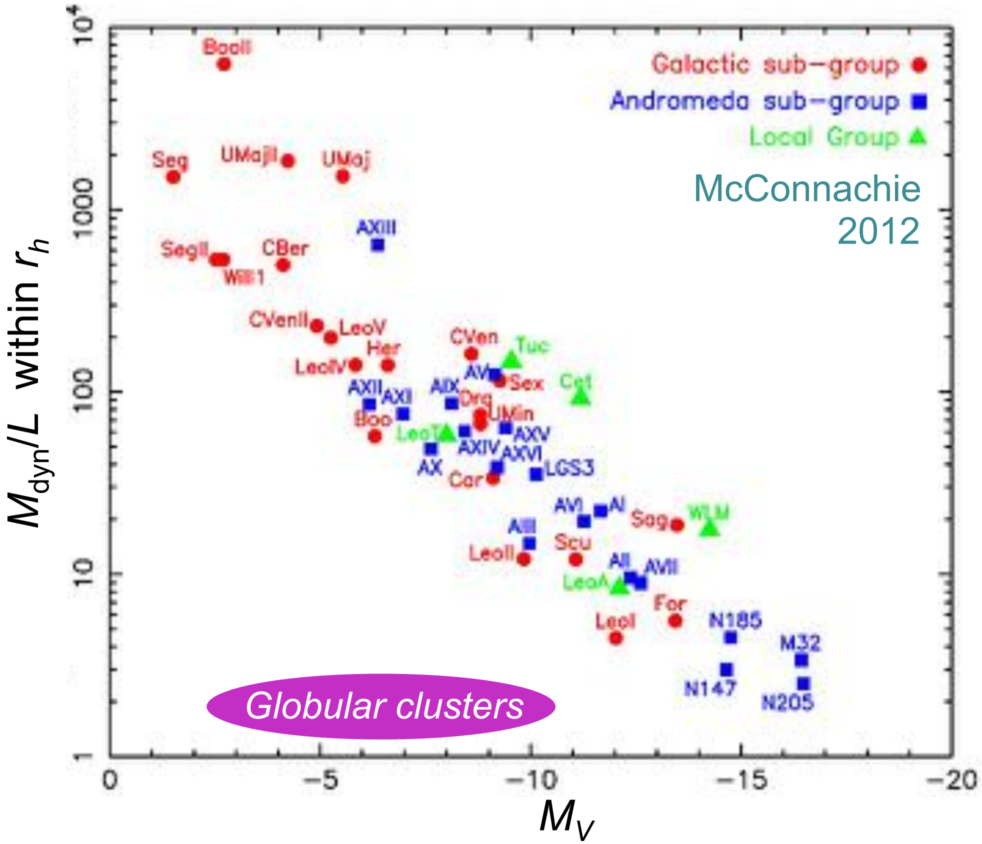
Galaxies:

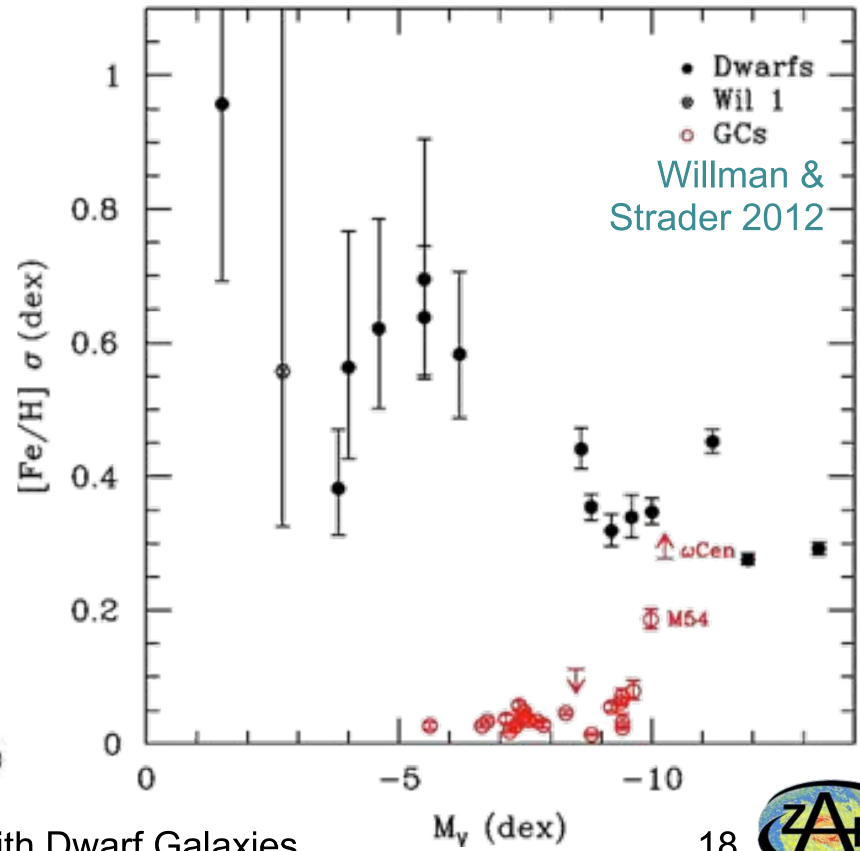
- ❑ Gravitationally bound
- ❑ Contain dark matter
- ❑ Considerable metallicity spread

Laevens 1 / Crater I

Star clusters:

- ❑ Gravitationally bound
- ❑ No dark matter
- ❑ Negligible metallicity spread





4. Near-field Cosmology: Detailed Properties of nearby Dwarf Galaxies

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

- **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.
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- Ultra-diffuse galaxies
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Pictures not on same scale

dE

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dE

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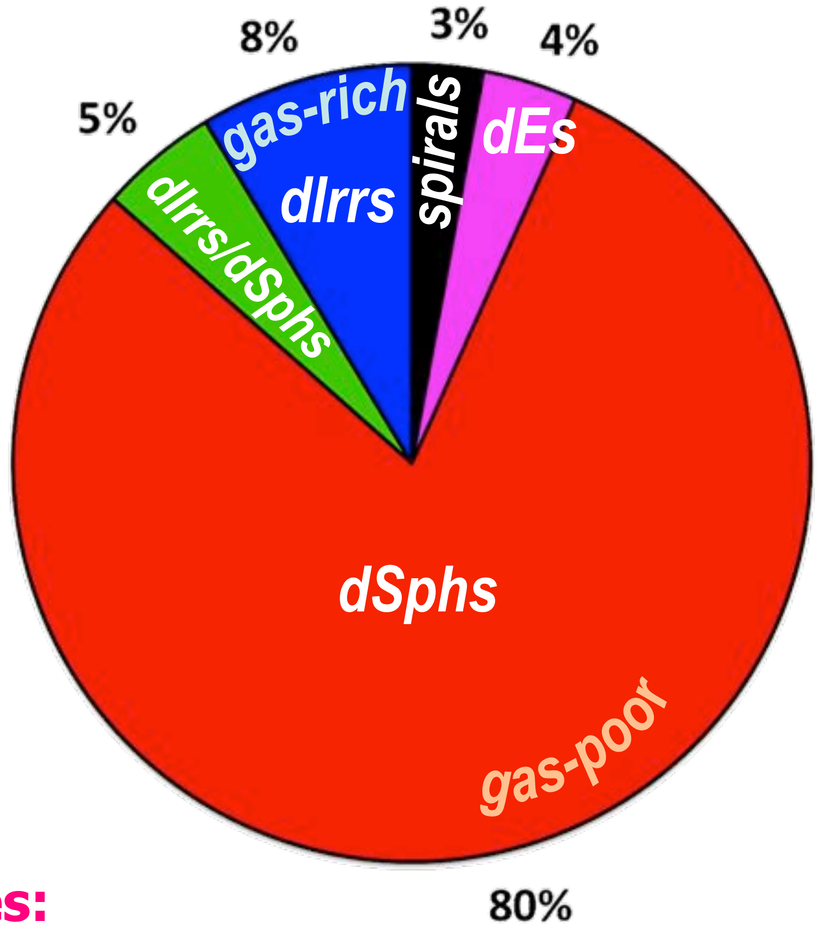
dIrr

The Galaxy Content of the Local Group

Certain or probable members:

≥ 104 galaxies within R_0 ~ 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:

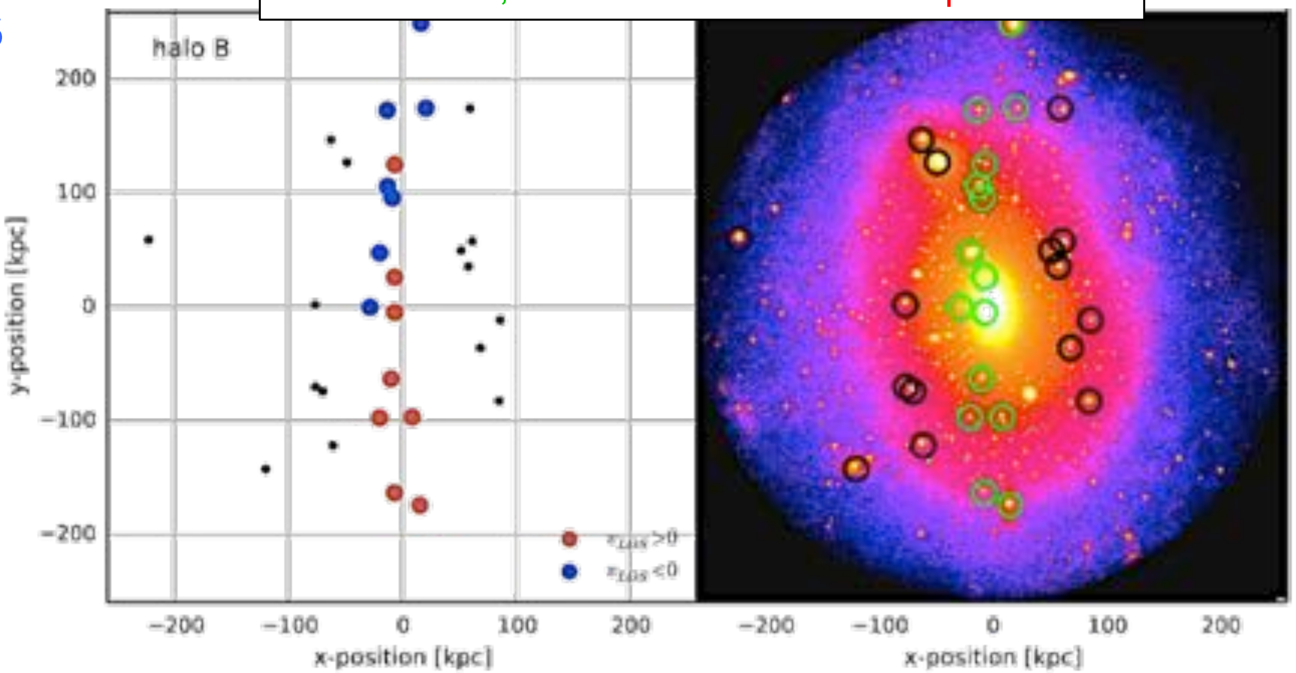
dwarf elliptical (**dEs: 3; 1 cE**) & dwarf spheroidal galaxies (**dSphs: ≥ 83**)

Gas-rich, early-type dwarf galaxies:

dwarf irregular galaxies (**dIrrs: 9**), transition types (**dIrrs/dSphs: 5**)

Satellite Planes

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



Buck et al. 2015

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).

ΛCDM simulations:

- Planes form through accretion along large filaments of DM around galaxies at high redshift.
- High-concentration massive halos tend to have thinner and richer planes.

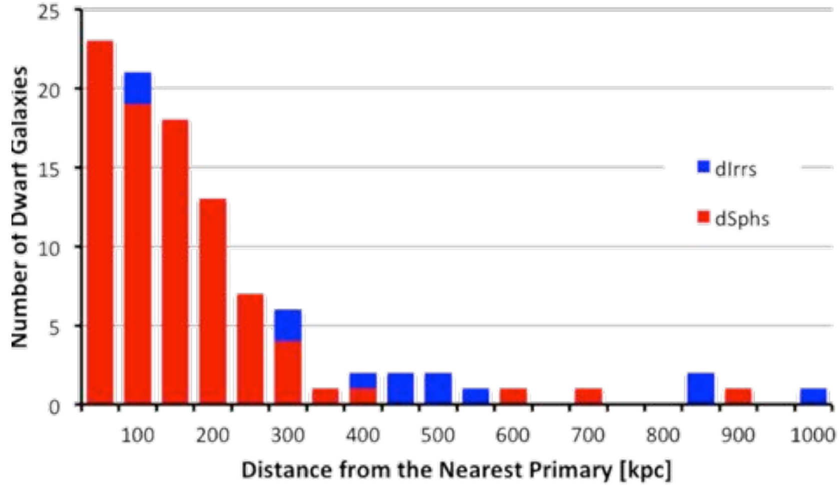
E.g., Libeskind et al. 2015; Buck et al. 2015.

- 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.
- Long-term survival of planes depends on orientation of their orbit.

E.g., Cautun et al. 2015; Buck et al. 2015; Gillet et al. 2015; Bowden et al. 2013; Fernando et al. 2016.

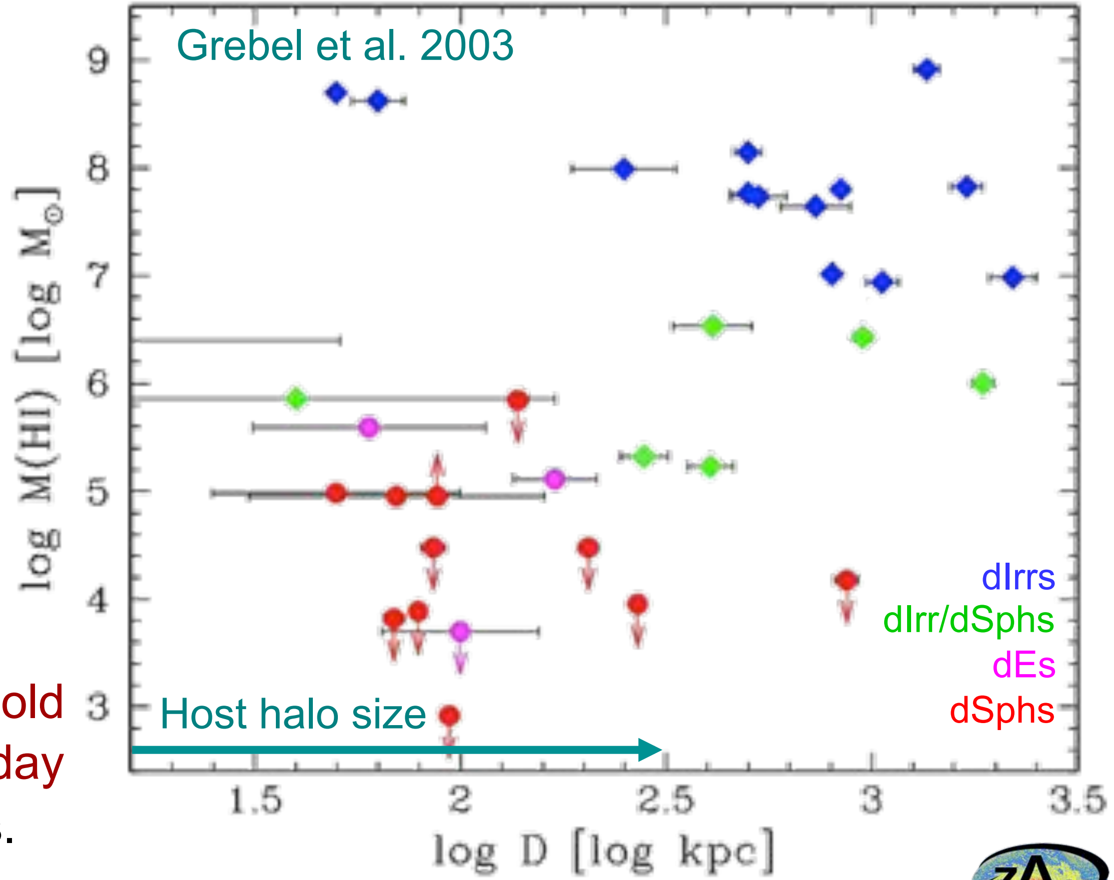
Present-day Dwarfs

Morphology-distance relation for Local Group
Grebel 2017

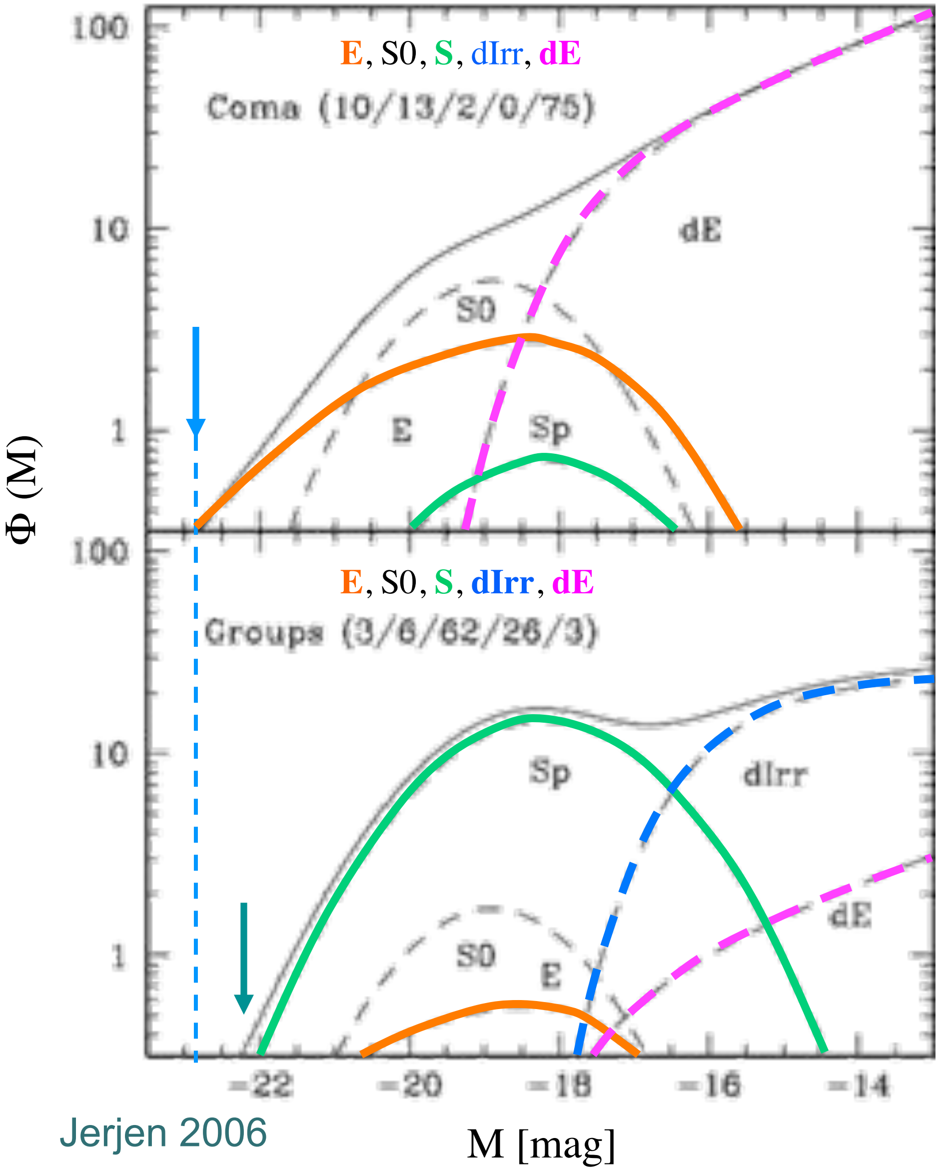


≠ dwarfs at time of accretion!

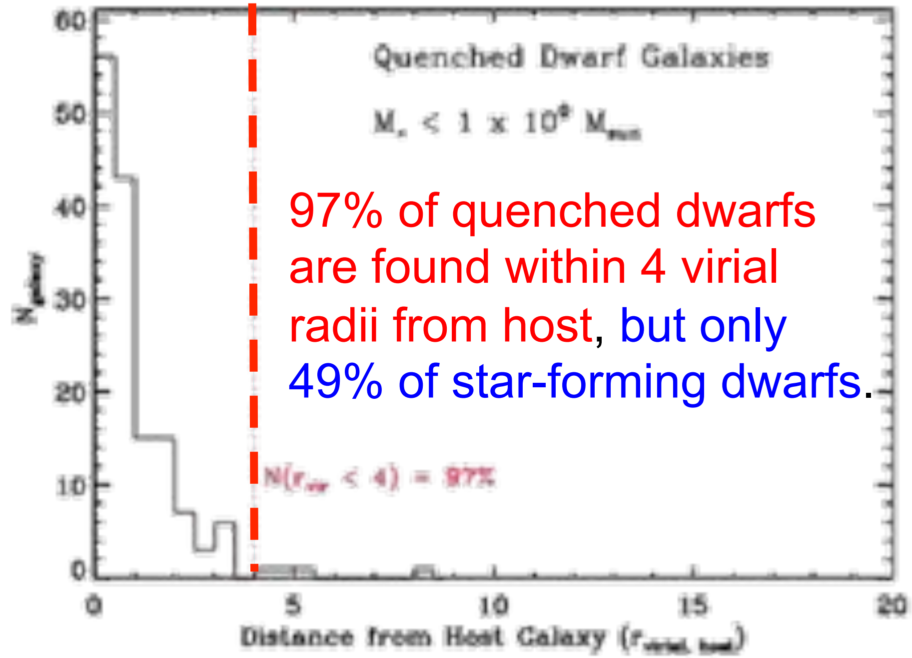
- Present-day dwarfs continued to evolve.
- Evolution governed by (1) intrinsic properties (mass, star formation, feedback, gas content), but also modified by
  (2) external influences (environment), including gas accretion, local and global re-ionization, ram pressure and tidal stripping.
- Most infall/accretion predicted at early times: ➞ we focus on old stellar populations in present-day dwarfs, especially in satellites.



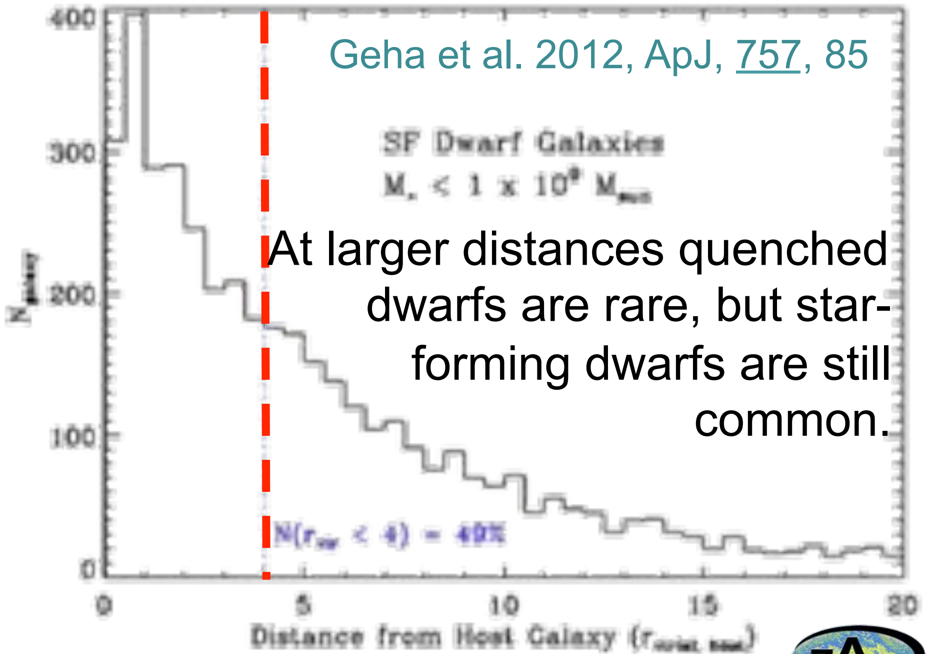
Impact of Environment



Jerjen 2006



97% of quenched dwarfs are found within 4 virial radii from host, but only 49% of star-forming dwarfs.



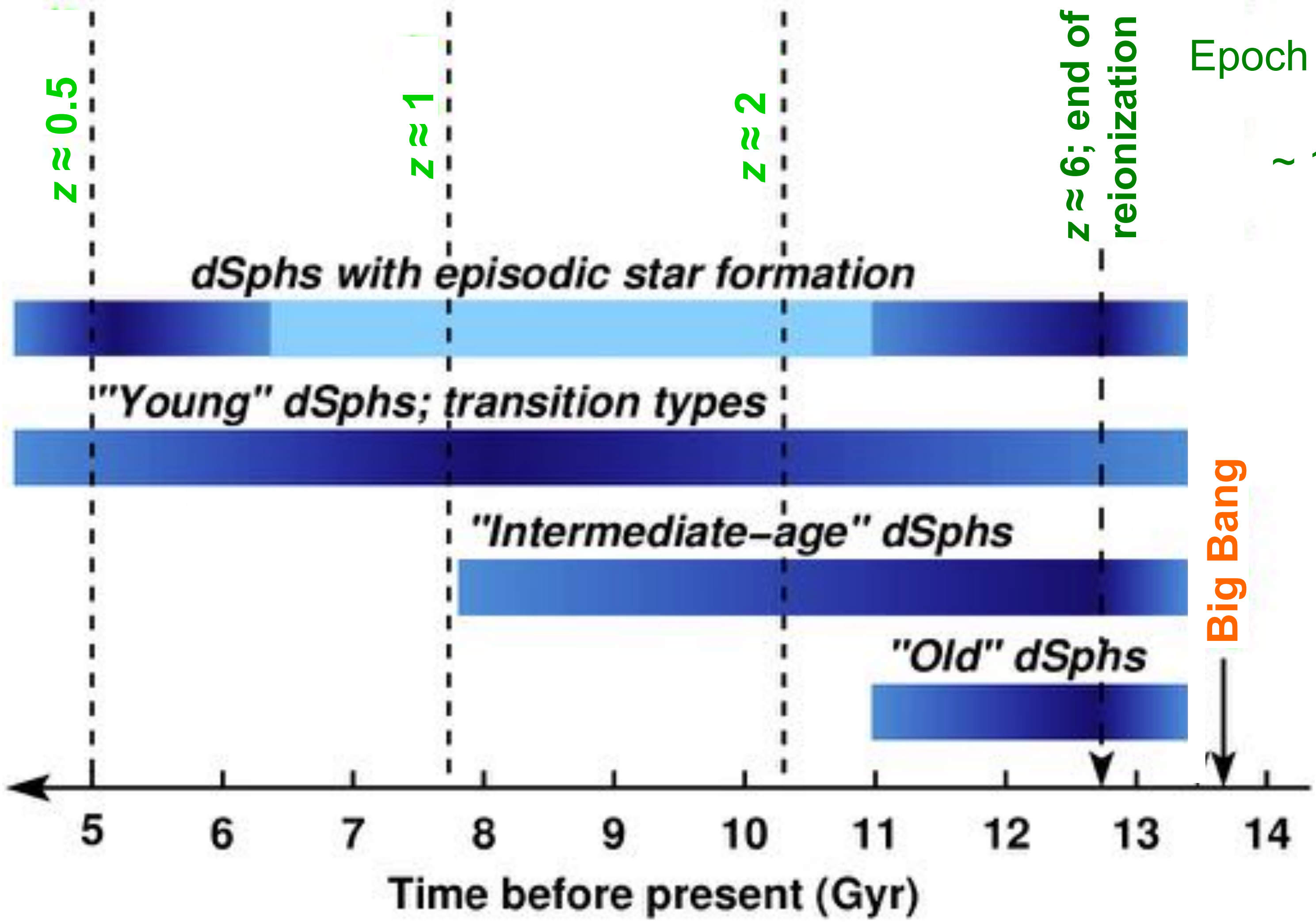
Geha et al. 2012, ApJ, 757, 85

At larger distances quenched dwarfs are rare, but star-forming dwarfs are still common.

Early Star Formation in Dwarf Galaxies

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

Grebel & Gallagher 2004



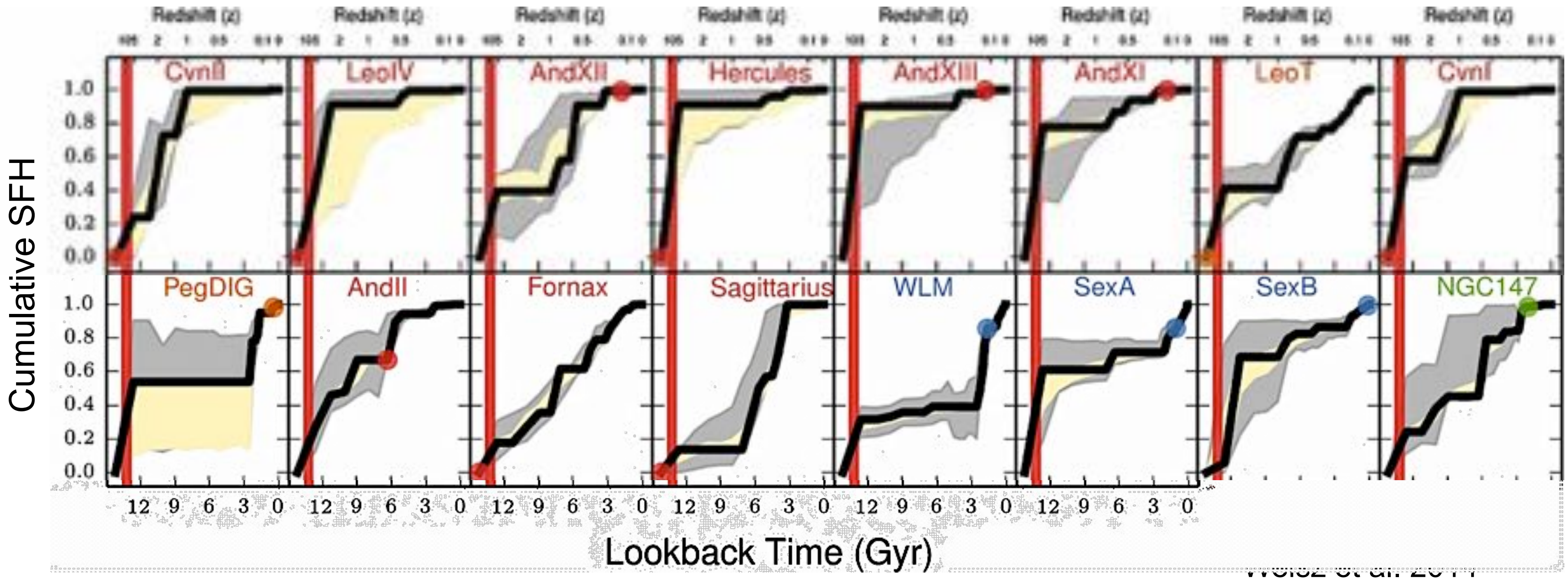
Epoch of re-ionization:
z ~ 6 – 14 or
~ 12.8 – 13.4 Gyr.

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

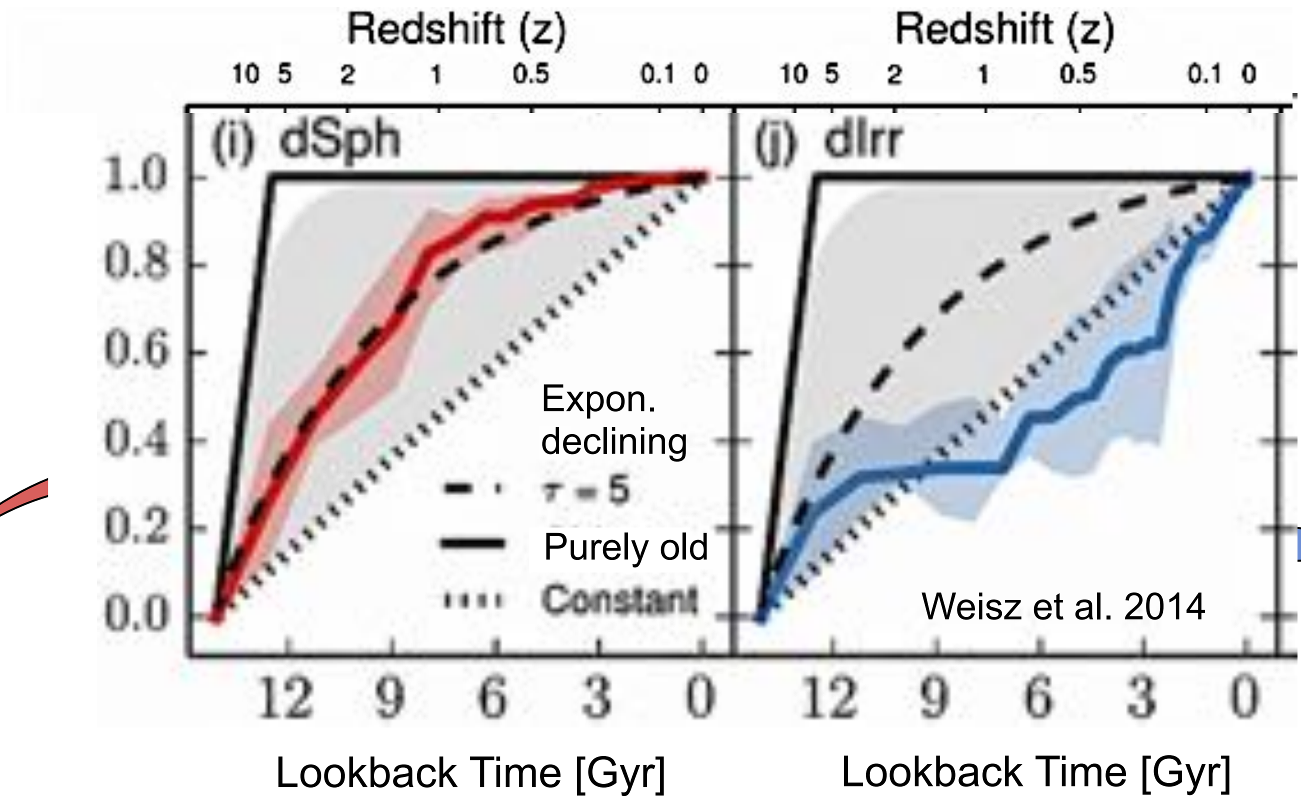
Early Star Formation in Nearby Dwarf Galaxies

Dwarfs generally continued to form stars after epoch of re-ionization.
Some ultrafaint dSphs formed most of their stars prior to/during re-ionization, but no evidence for general, significant re-ionization quenching.

Grebel & Gallagher 2004; Weisz et al. 2014



Average Star Formation Histories



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

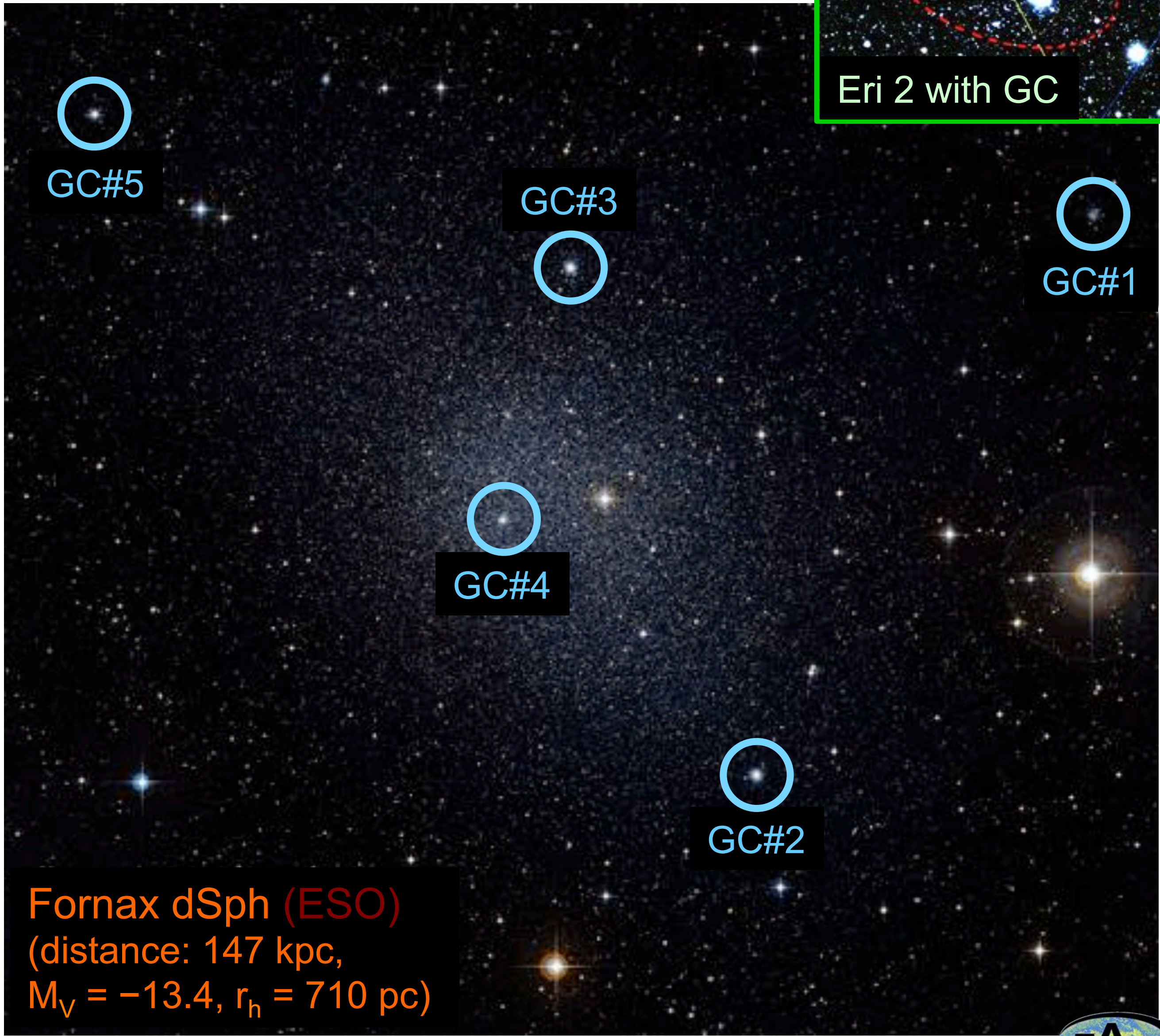
Dwarf Spheroidals and Globular Clusters

Dwarf spheroidal galaxies may contain globular clusters themselves.

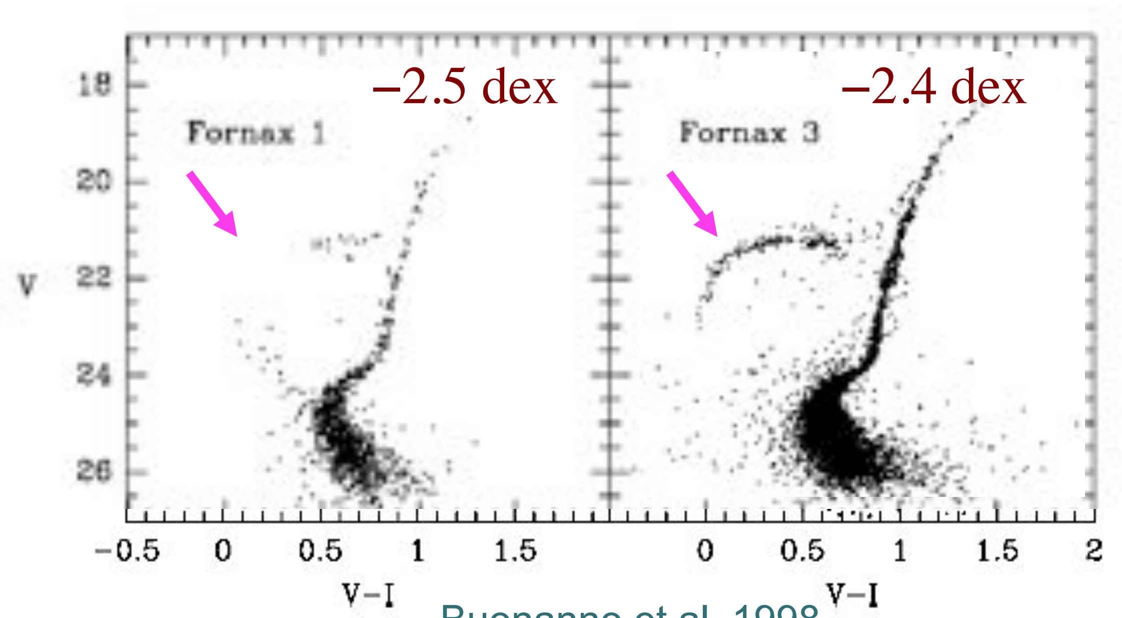
Least luminous dSph known to contain a GC: Eri 2 (M_V = −7.4)
GC: M_V=−3.5, [Fe/H] =−2.4

Age-dated GCs: Indistinguishable in age from oldest GCs in the Milky Way.

Few GCs studied in the needed detail such far, but light element abundance anomalies have been found in, e.g., Sgr (Na-O anticorrelation).



Globular Clusters in the Fornax dSph



Buonanno et al. 1998

Note 2nd parameter effect in ~ coeval, metal-poor GCs!

Smith et al. 1996

This is of interest when considering the old argument about "young" halo GCs having been accreted from dwarf galaxies – dwarfs can actually contribute both "old" and "young" halo GCs.

Horizontal branch morphology can be reproduced when assuming 2nd generation stars in GCs #2, #3, #5, while GC #1 may only host 1st generation stars. D'Antona et al. 2013

Structural Properties at the Low-Mass End

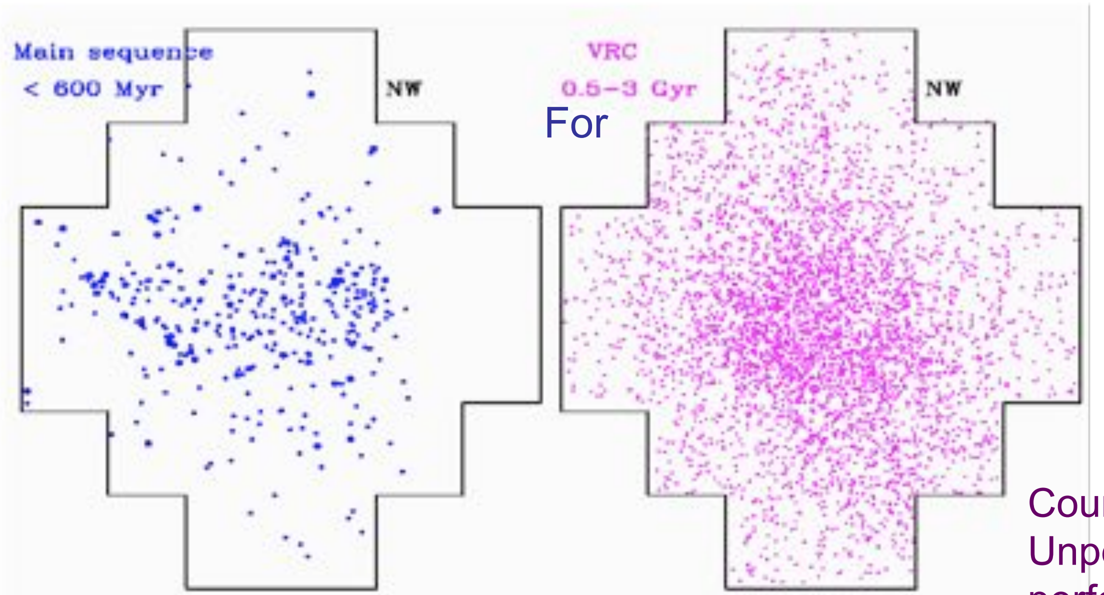
- Many dSph galaxies show flattened profiles:

$$0.1 \le \varepsilon \equiv 1 - \frac{b}{a} \le 0.7$$

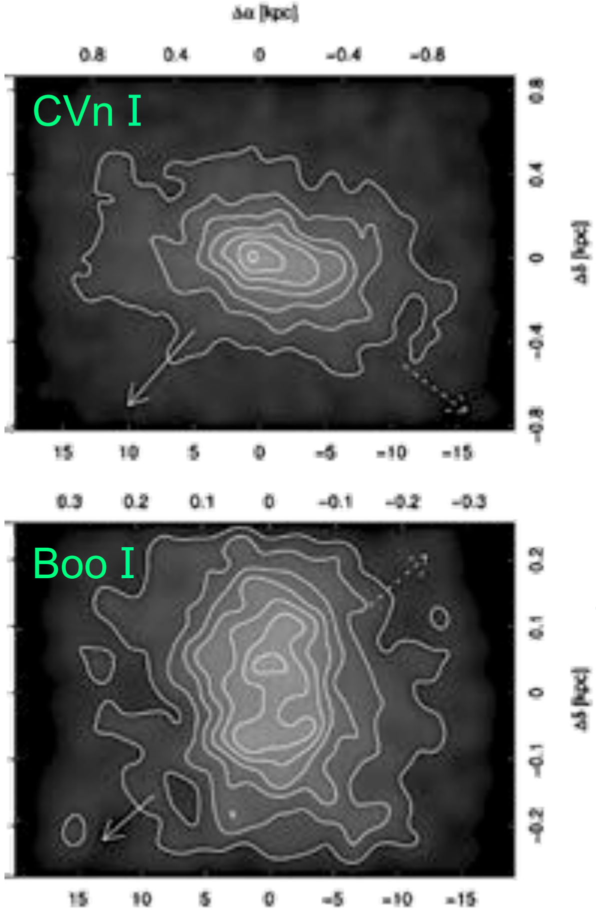
Past interactions?
Ongoing disruption?
Some: dwarf mergers!

Others are unperturbed and perfectly symmetric.

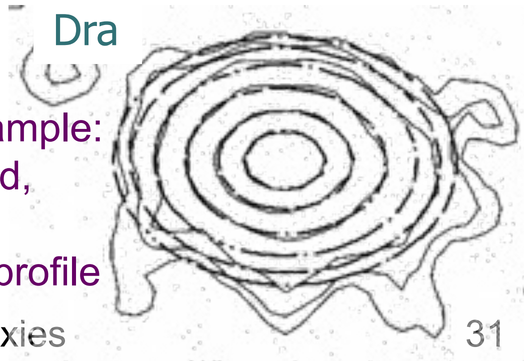
- DSphs may contain kinematically, chemically, and spatially distinct stellar subpopulations.



Grebel & Stetson 1999



Okamoto et al. 2012

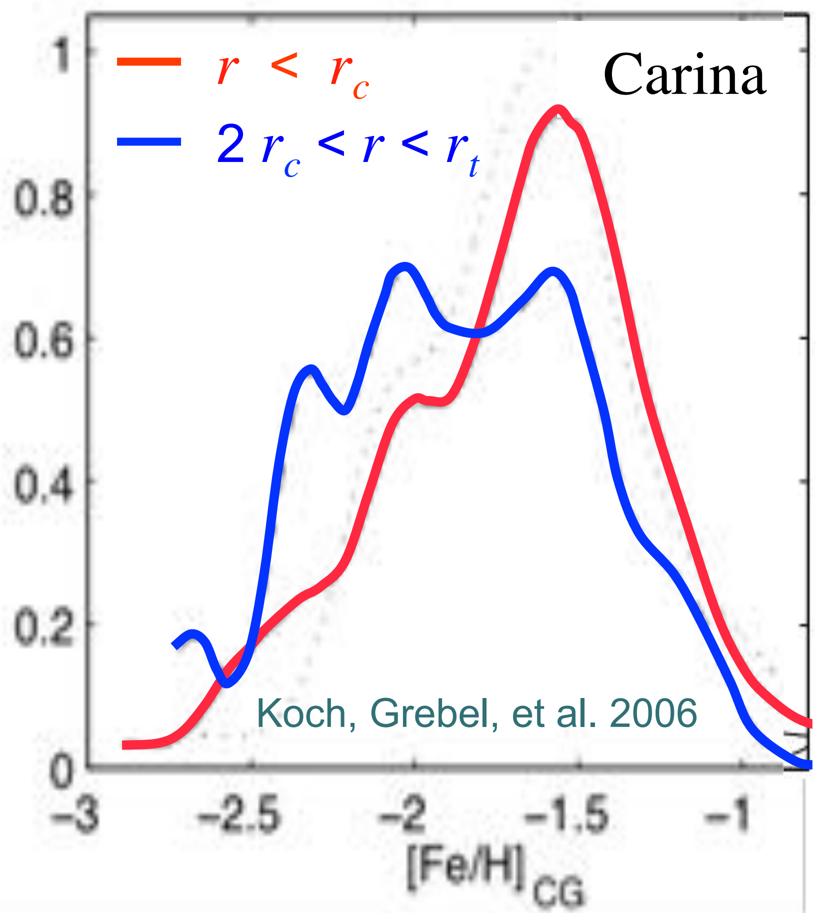


Counterexample: Unperturbed, perfectly symmetric profile

Odenkirchen et al. 2001

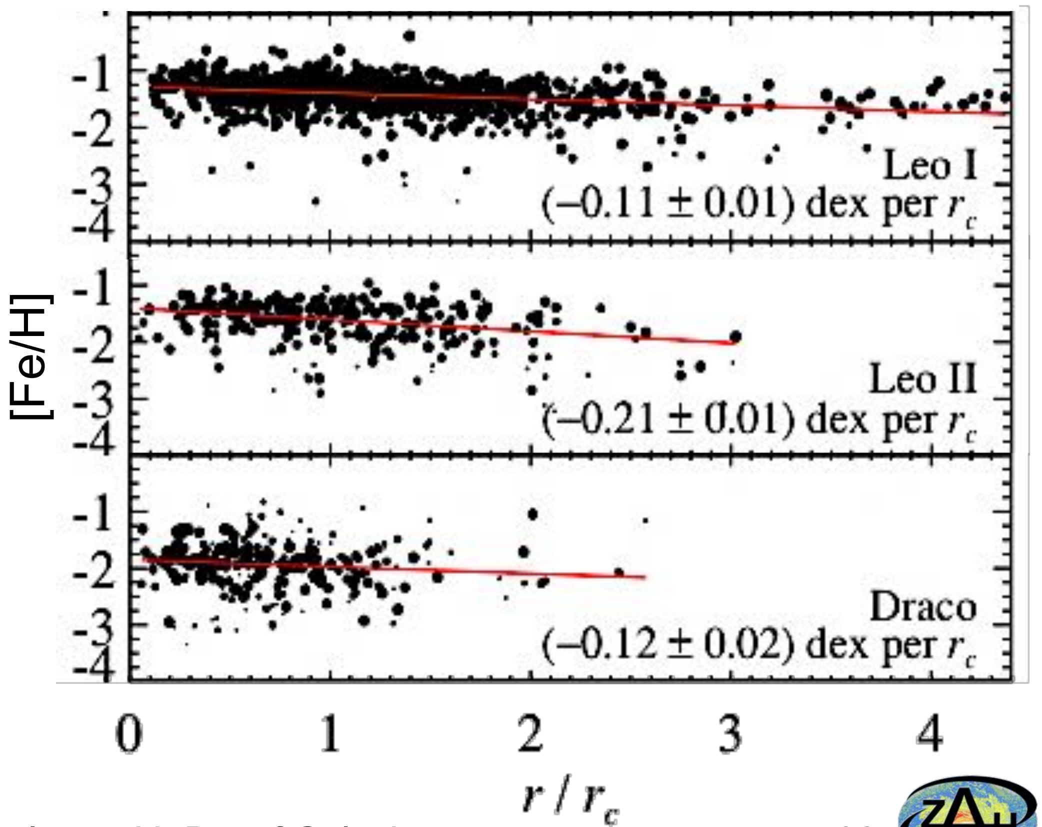
Metallicity Gradients (Population Gradients) in Dwarfs

Younger and/or more metal-rich stars:
more centrally concentrated
(Harbeck, Grebel et al. 2001)
and kinematically colder.



Radial abundance gradients in disks of spirals and Irrs/dIrrs:
e.g., Pilyugin, Grebel, et al. 2014a, 2014b, 2015.

Shown here: Gradients in Galactic dSphs
Kirby et al. 2011

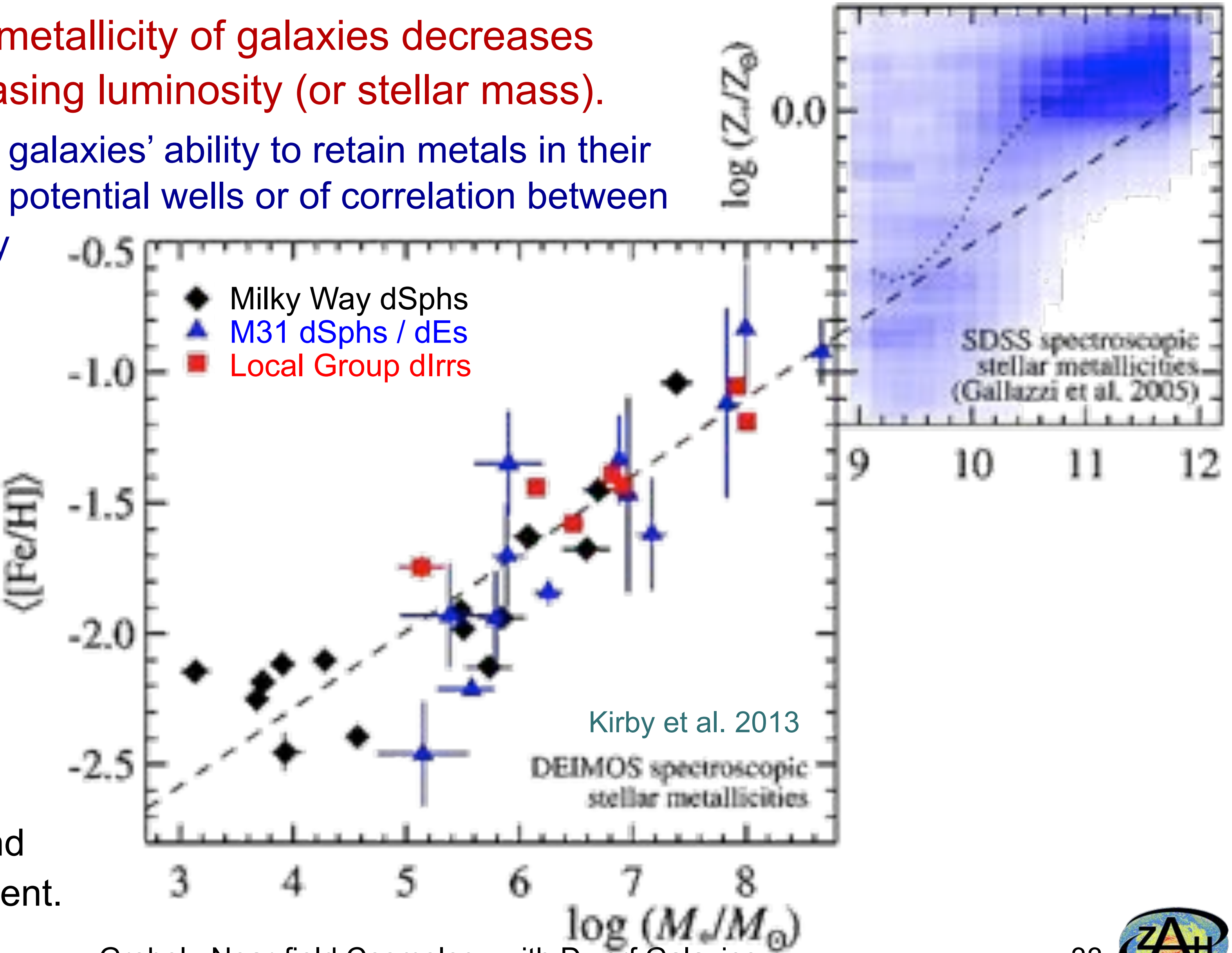


The Metallicity – Mass Relation

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]

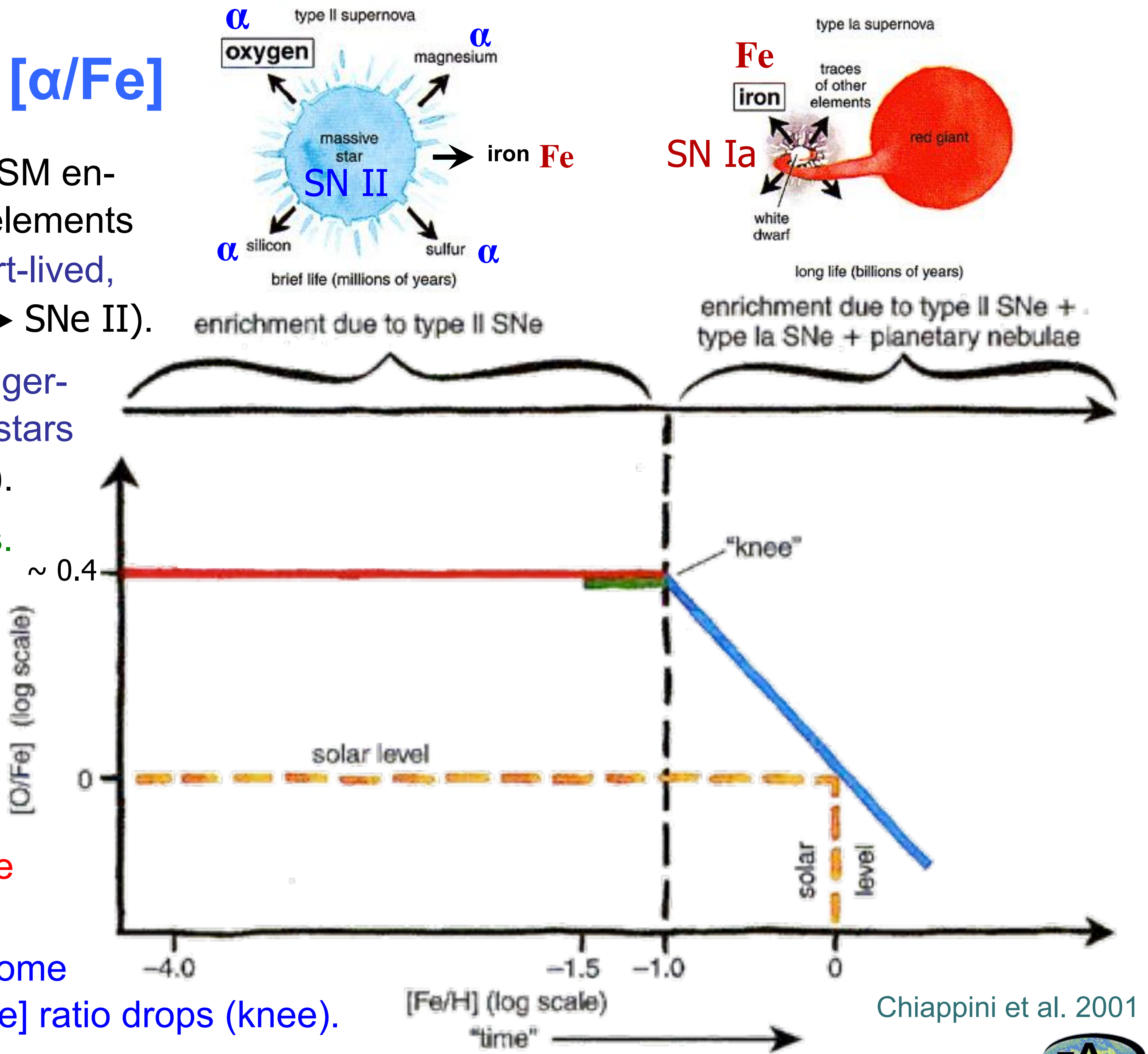
At early times: ISM enriched faster in elements produced in short-lived, massive stars (➔ SNe II).

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.

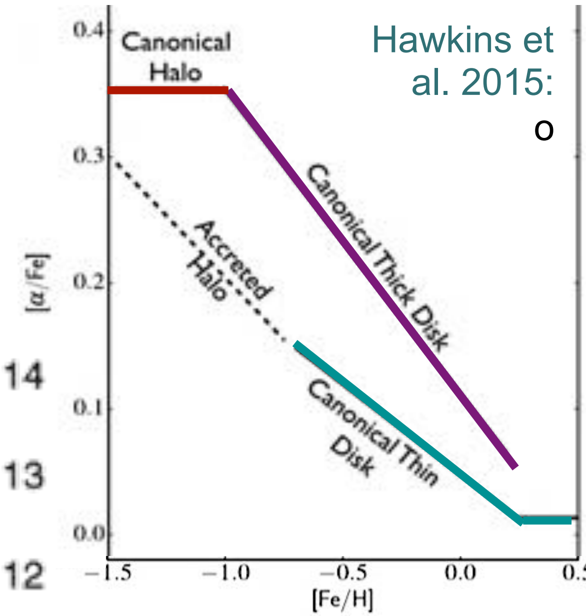
Initially: O, Fe produced by SNe II at ~ same rate (plateau).

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

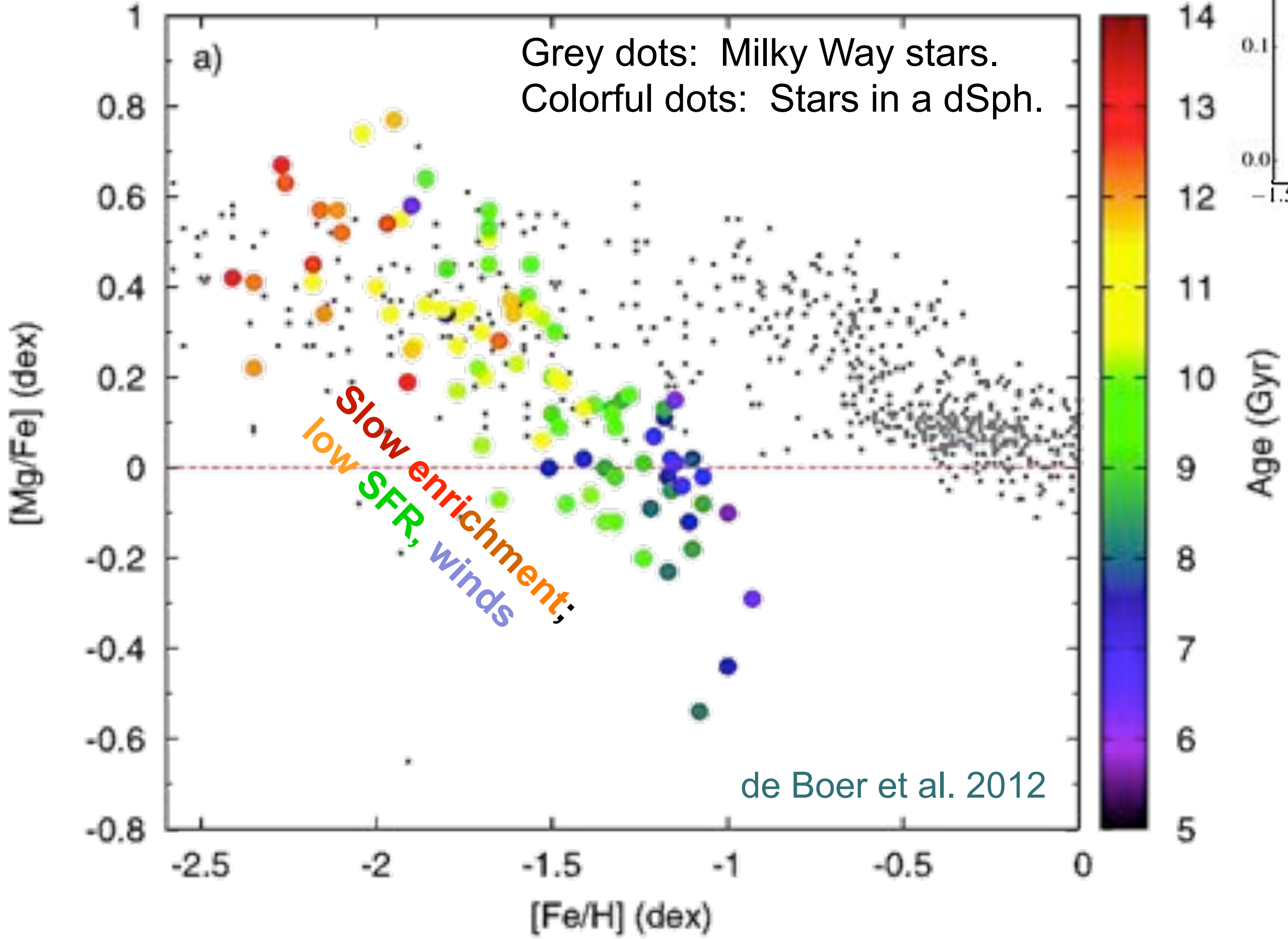


Chiappini et al. 2001

[Fe/H] vs. [α/Fe]



Stars formed in earliest stages of self-enriching systems (prior to SNe Ia): high levels of [α/Fe]

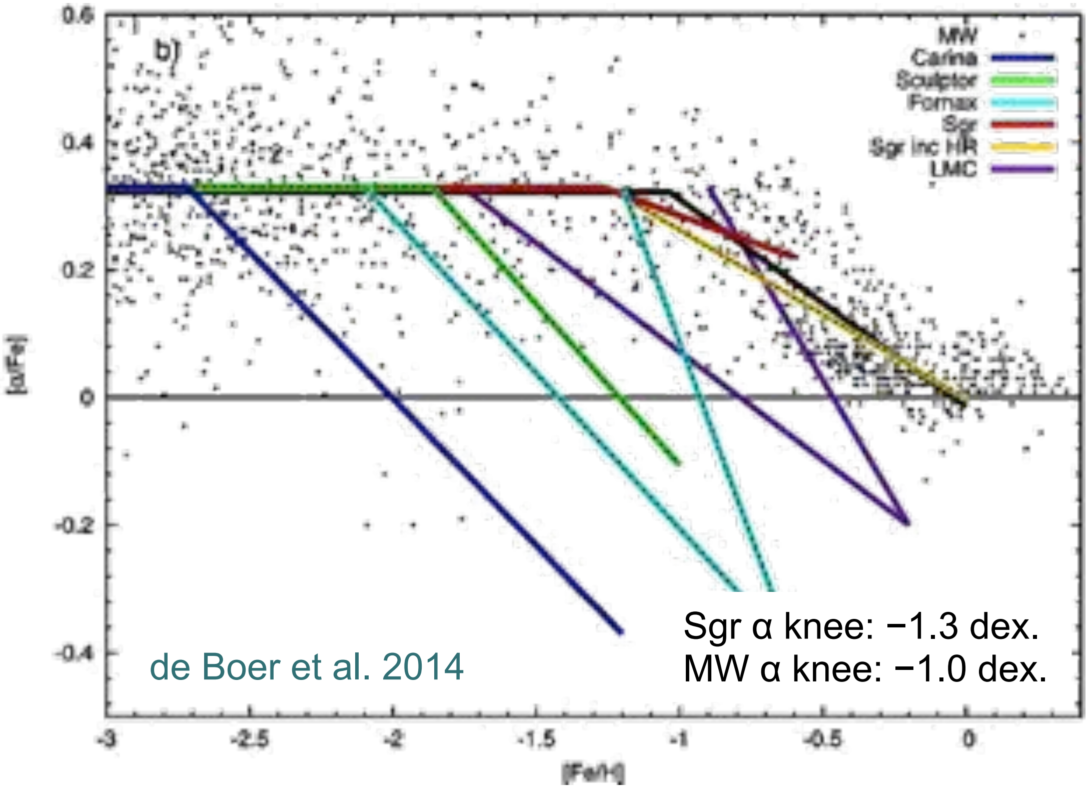


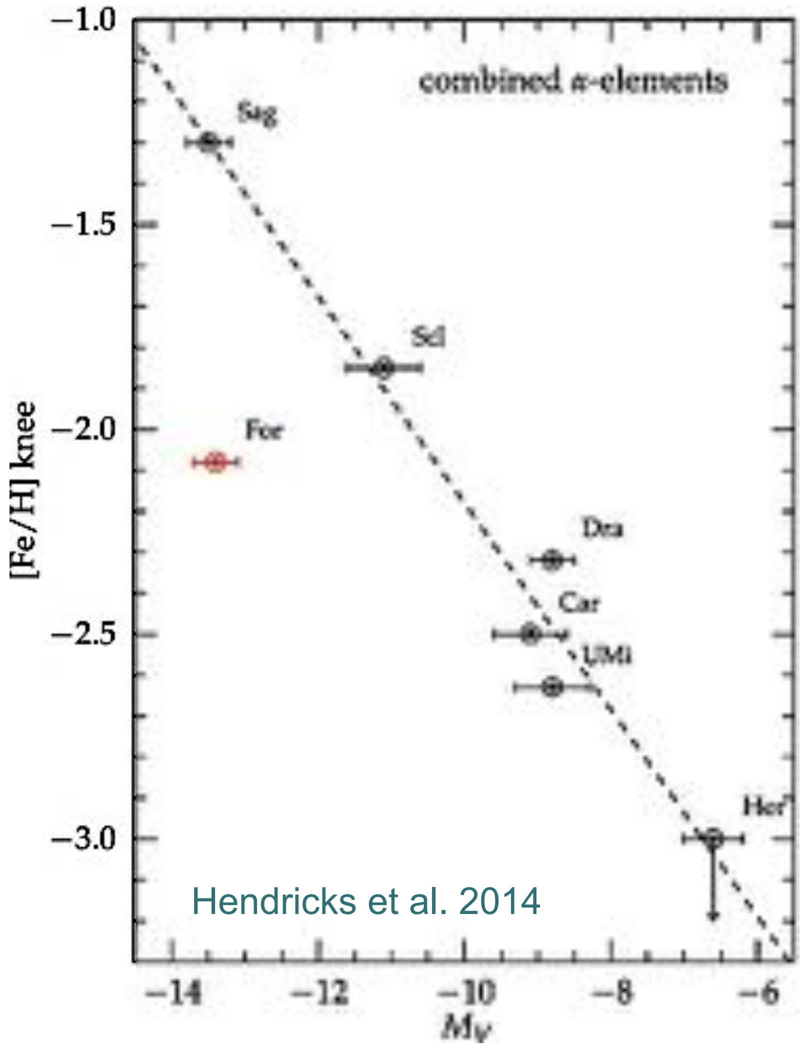
Position of turnover ("knee") shows how far enrichment could proceed until onset of SNe Ia.

Measure of SFE and retention of enriched ejecta.

[Fe/H] vs. [α/Fe] in Dwarfs

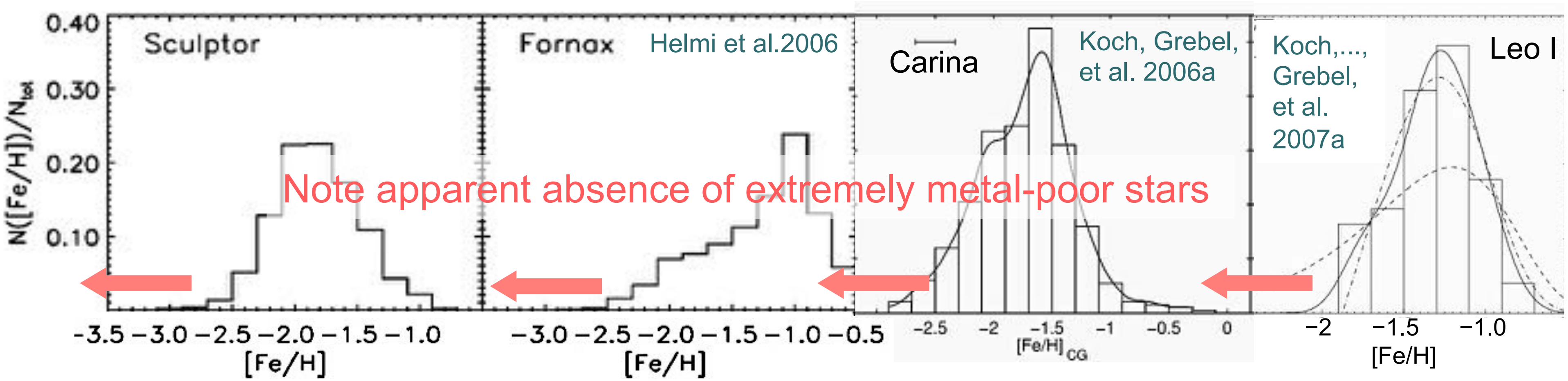
Sgr dSph: Position of “α knee” shows that early accretion (before knee formed) of Sgr-like galaxies could have contributed metal-rich parts of inner MW halo.





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

Metallicity Distribution Functions and Metal-Poor Stars



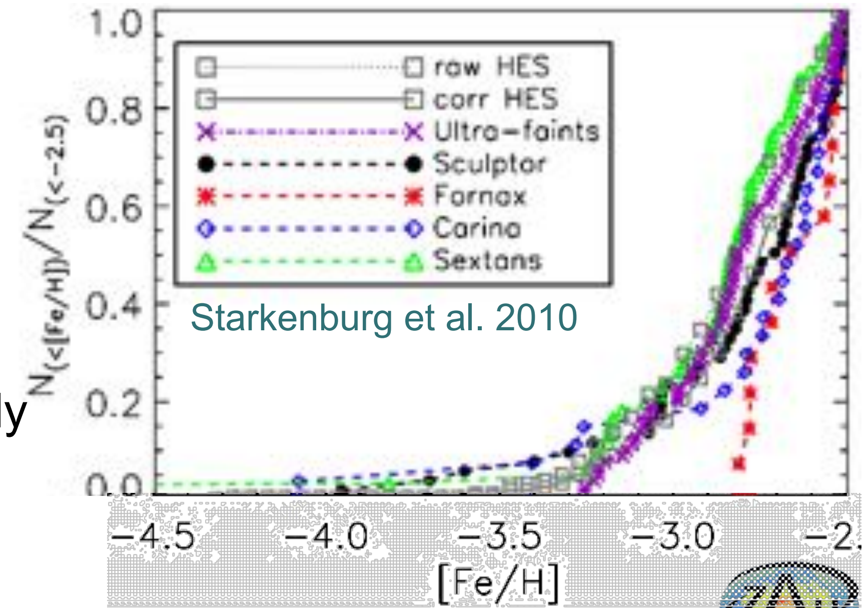
But then: Detection of "extremely metal-poor" giants in classical and ultra-faint dSphs.

Lowest [Fe/H] so far: in Sculptor dSph, [Fe/H] = –3.96 ± 0.06. (Tafelmeyer et al. 2010)

Scaled MDFs of Milky Way dSphs with newly discovered extremely metal-poor stars agree with inner MW halo at metal-poor end.

Paradigm shift!

In particular, accreted ultrafaint dSphs may have been an important contributor of extremely metal-deficient stars to the Galactic halo.

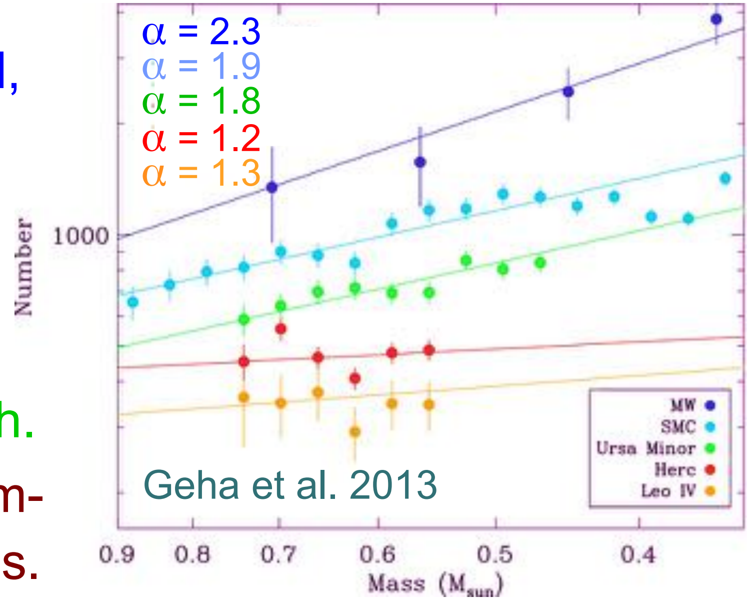


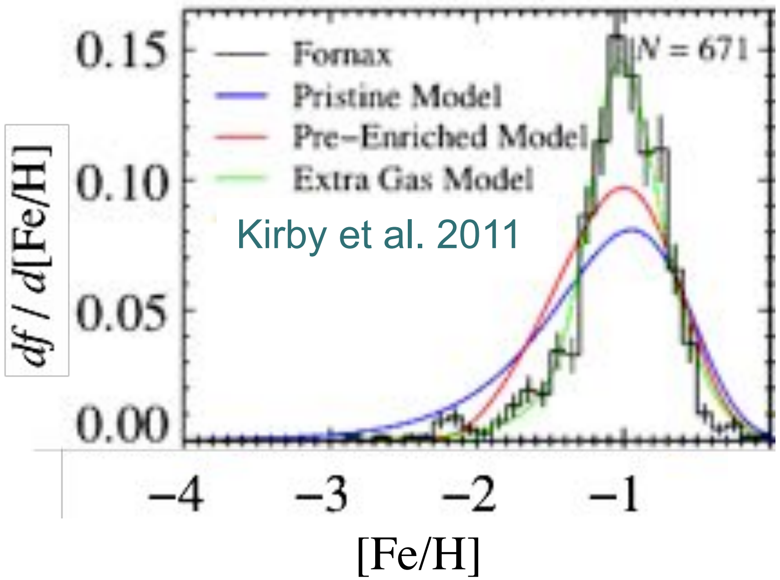
Metallicity Distribution Functions and Chemical Evolution

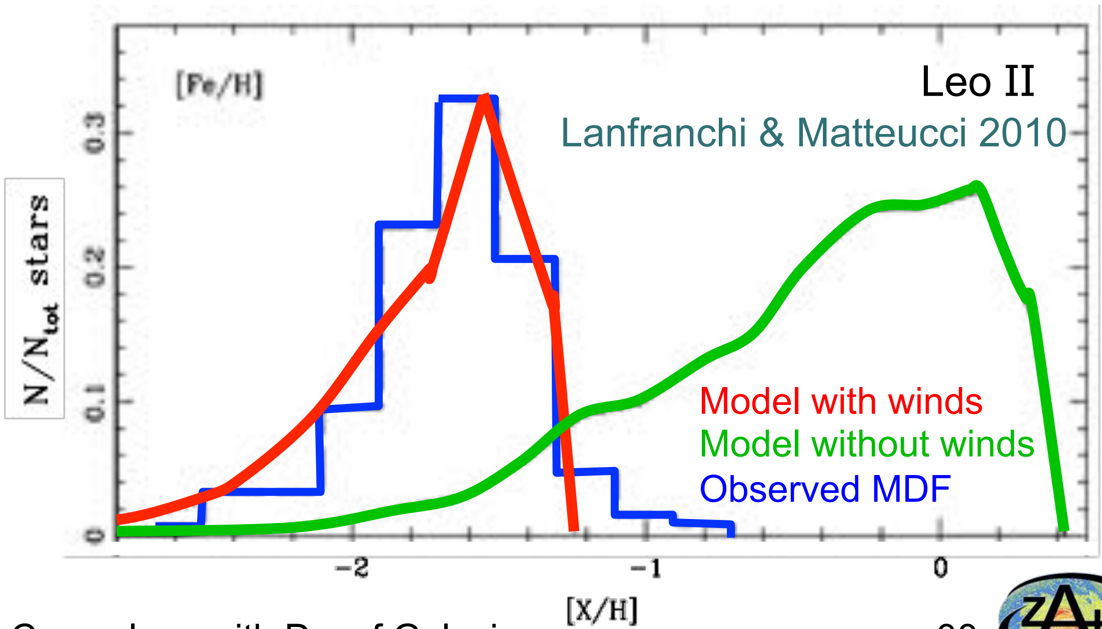
Chemical evolution models with slow gas infall, low-efficiency SF, and strong galactic winds:

- ❑ Reproduce well MDF and abundance ratios.
- ❑ *Drop at high-metallicity tail:* SF cessation due to removal of gas.
- ❑ Without strong winds: MDF far too metal-rich.

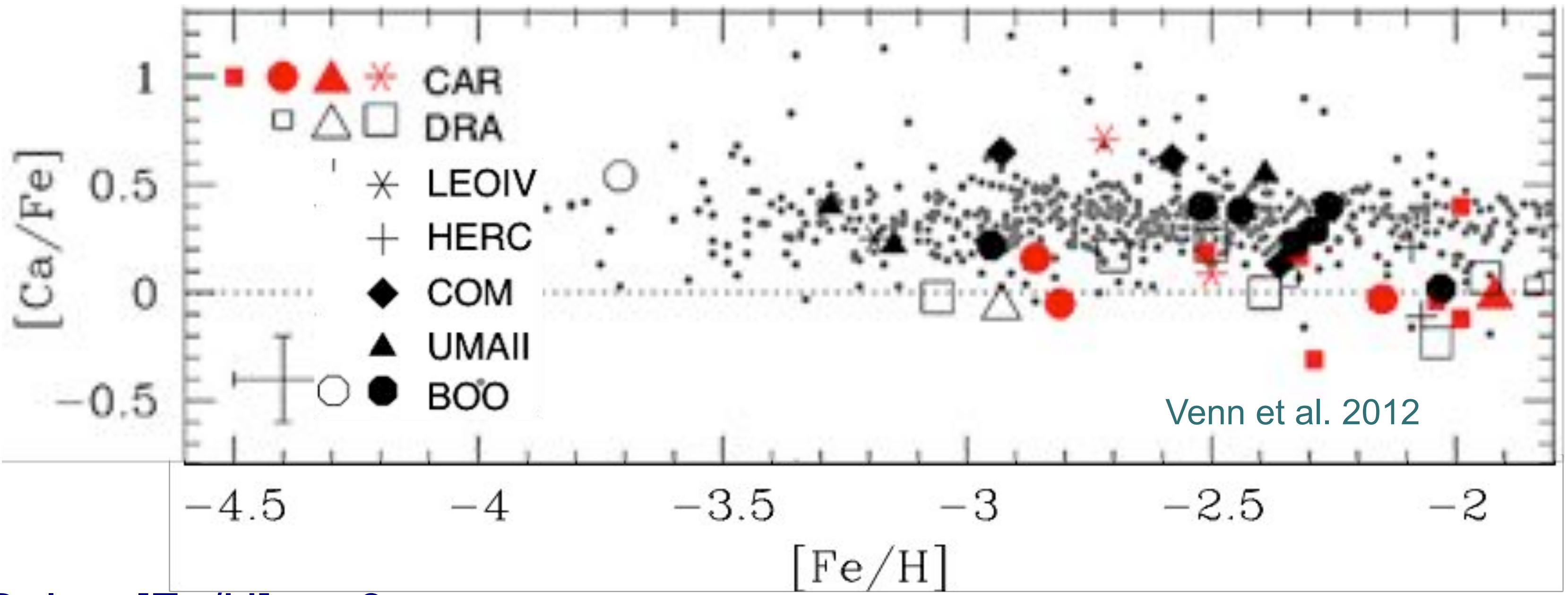
Present-day **mass functions** increasingly bottom-light/flat with lower galaxy mass: More SNe/winds.







Trends in Individual Element Abundance Ratios



Below [Fe/H] = –3:

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

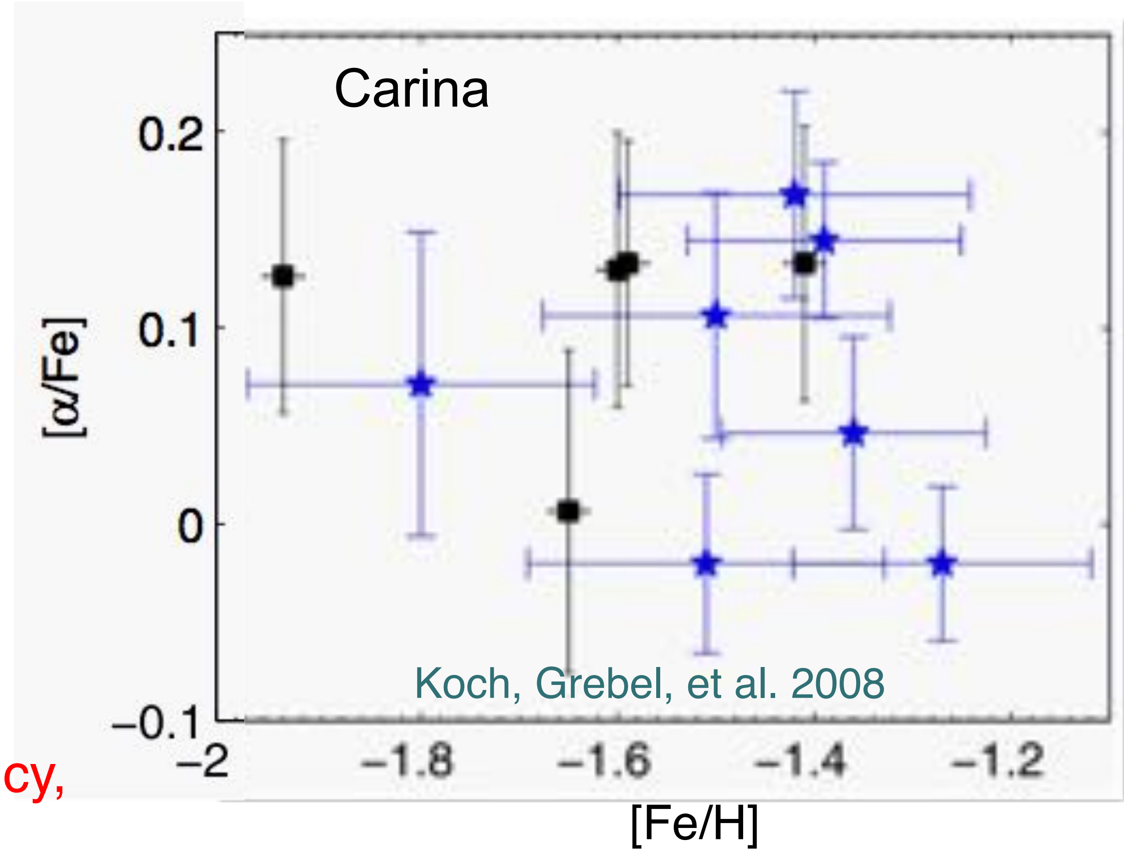
Tafelmeyer et al. 2010

Ultra-faint dSphs mainly have distinctly low n-capture and low [Sr/Ba] values, whereas brighter dSphs and the halo do not – small sample sizes still, but differences not yet understood.

Koch et al. 2013; Frebel & Norris 2015

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; Norris et al. 2008)
- At a given age:
  scatter in abundances
  e.g., SMC (Glatt, Grebel, et al. 2008),
  Sex B (Kniazev, Grebel, et al. 2005).
- At a given metallicity:
  scatter in α abundance ratios (e.g., Koch, Grebel, et al. 2008)

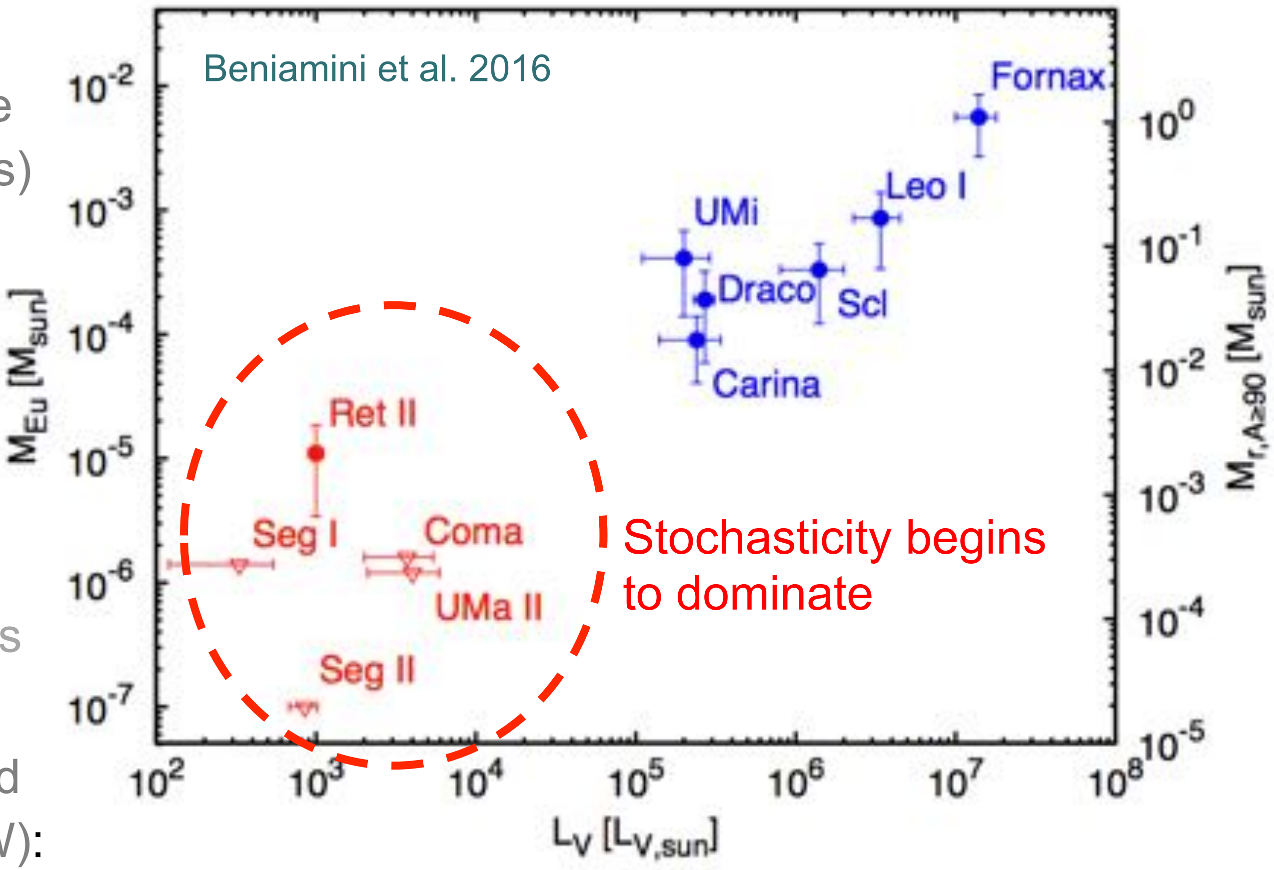


➜ Slow, stochastic SF,
low star formation efficiency,
dwarfs not well mixed.
May be composite, consisting of multiple progenitor halos themselves.

Trends in Individual Element Abundance Ratios

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

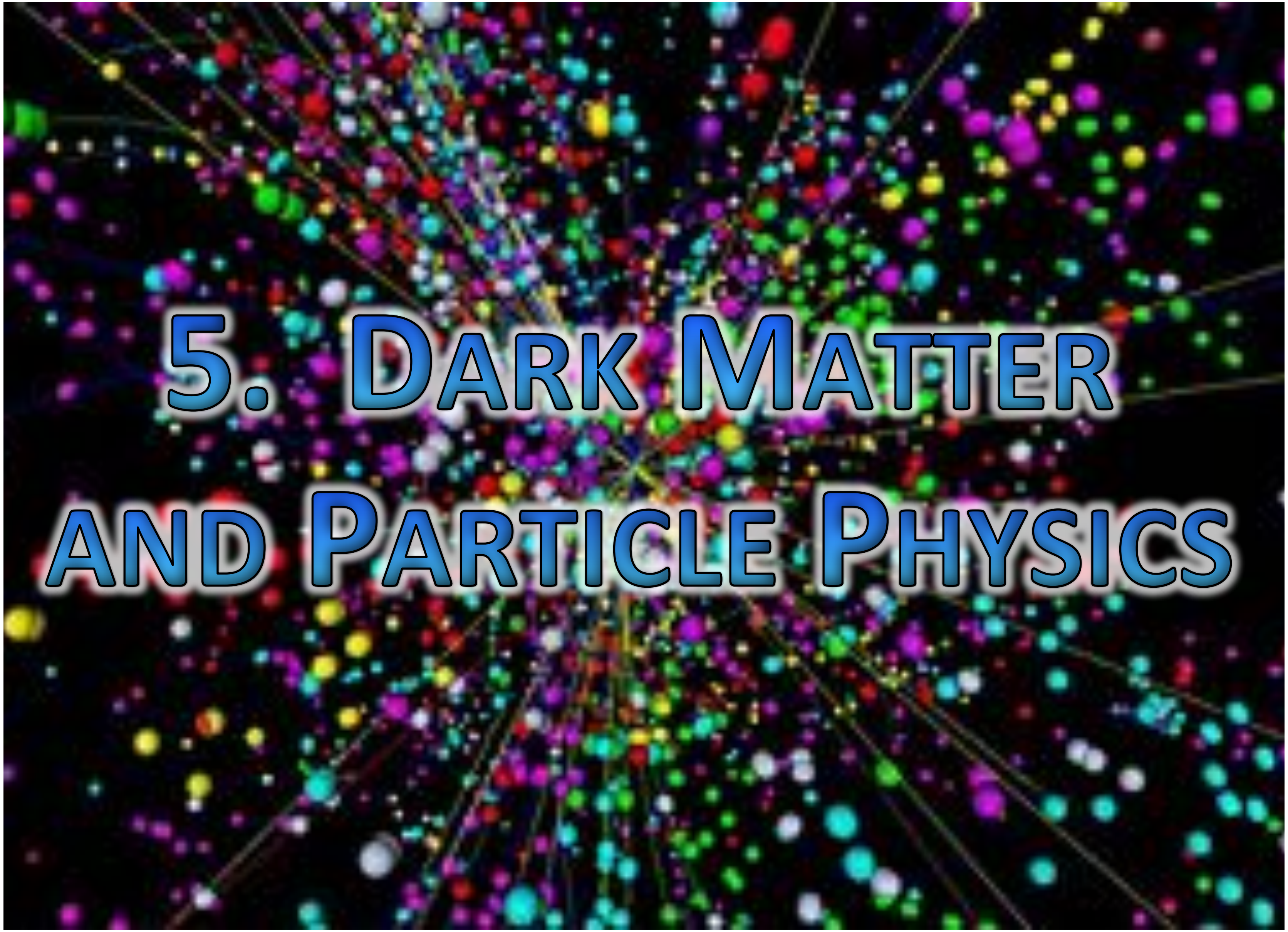
- Eu mass in ultra-faint dSphs *and*
- large scatter in abundances of *r* - process elements (and derivatives, mass number A ≥ 90)



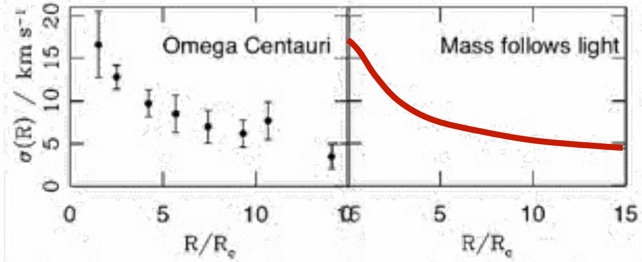
in metal-poor dSphs (and in metal-poor stars in MW):
Produced in rare events! Possibly in neutron star mergers. (Beniamini et al. 2016)
As with α elements, we see contributions from individual events.

Models suggest that in an initial, metal-poor ISM stochastic effects dominate.
Inhomogeneous pollution, few SNe (Marcolini et al. 2008).

5. Dark Matter and Particle Physics

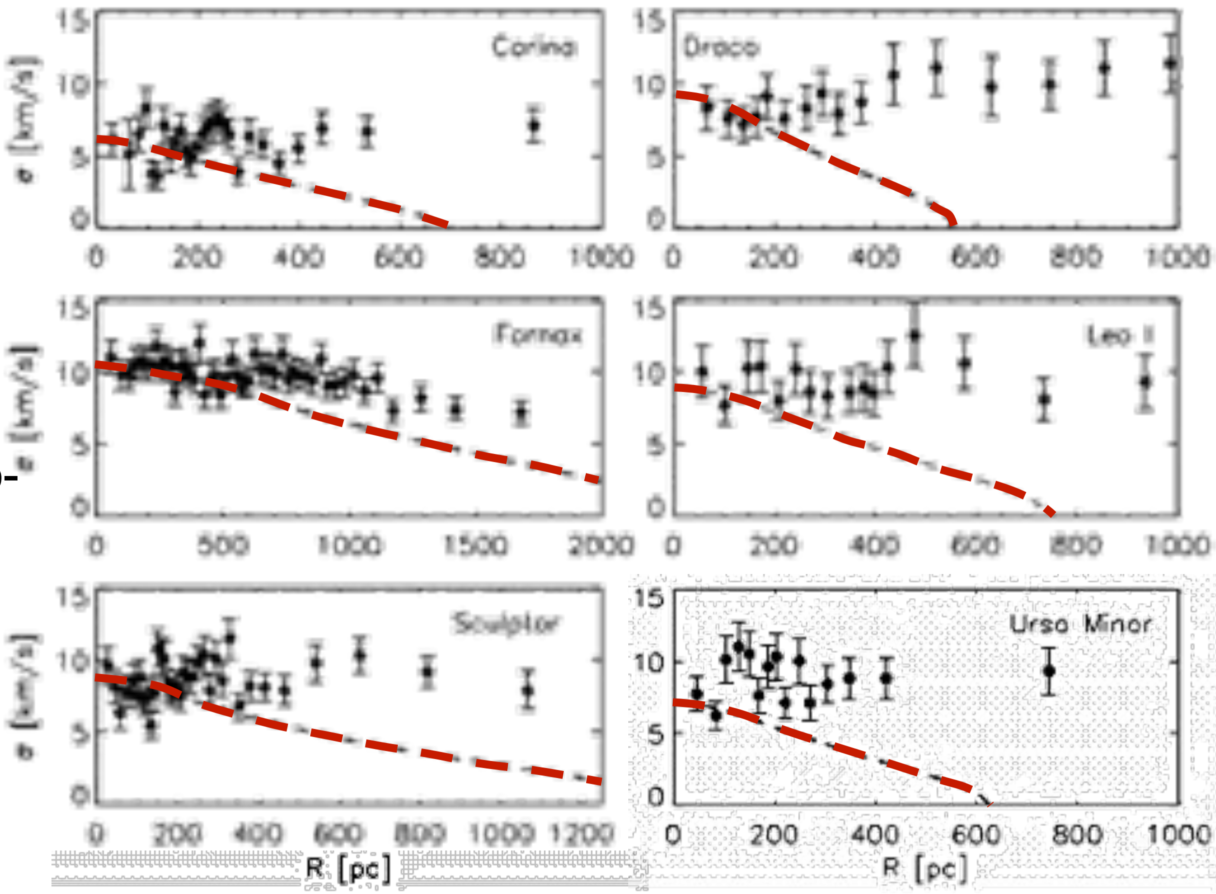


Radial Velocity Dispersion Profiles



- *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



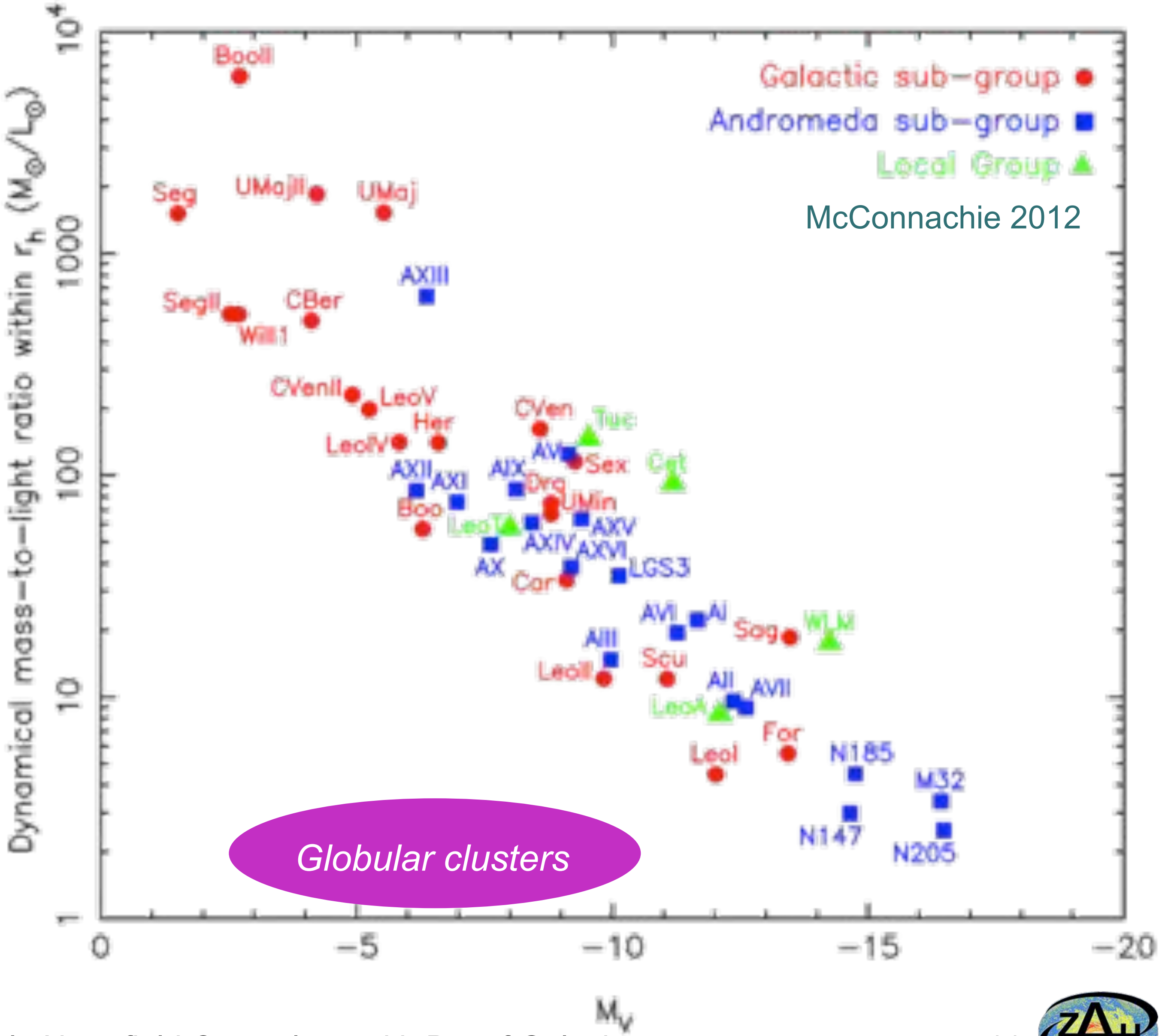
- High velocity dispersions at large radii: dominant and extended DM halos.
- But MOND can also reproduce these flat profiles, → $M/L = 1 - 4$ (Alexander et al. 2017)

Dynamical M/L ratios increase with decreasing luminosity

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

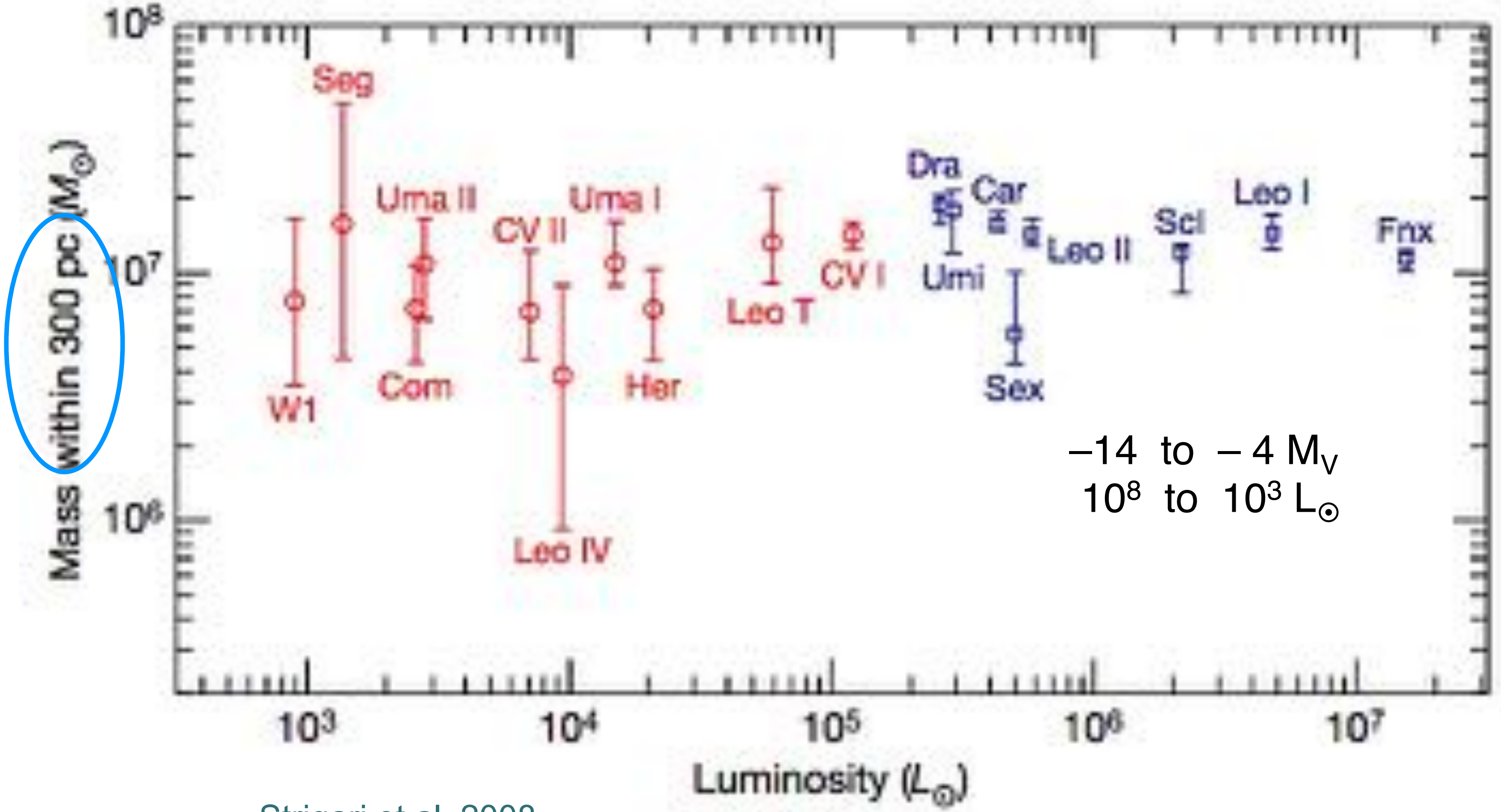
Discontinuity in dynamical M/L_V between dSphs and globular clusters seems to mark a boundary between objects with dark matter and without.

e.g., Walker 2013



A Common dSph Mass?

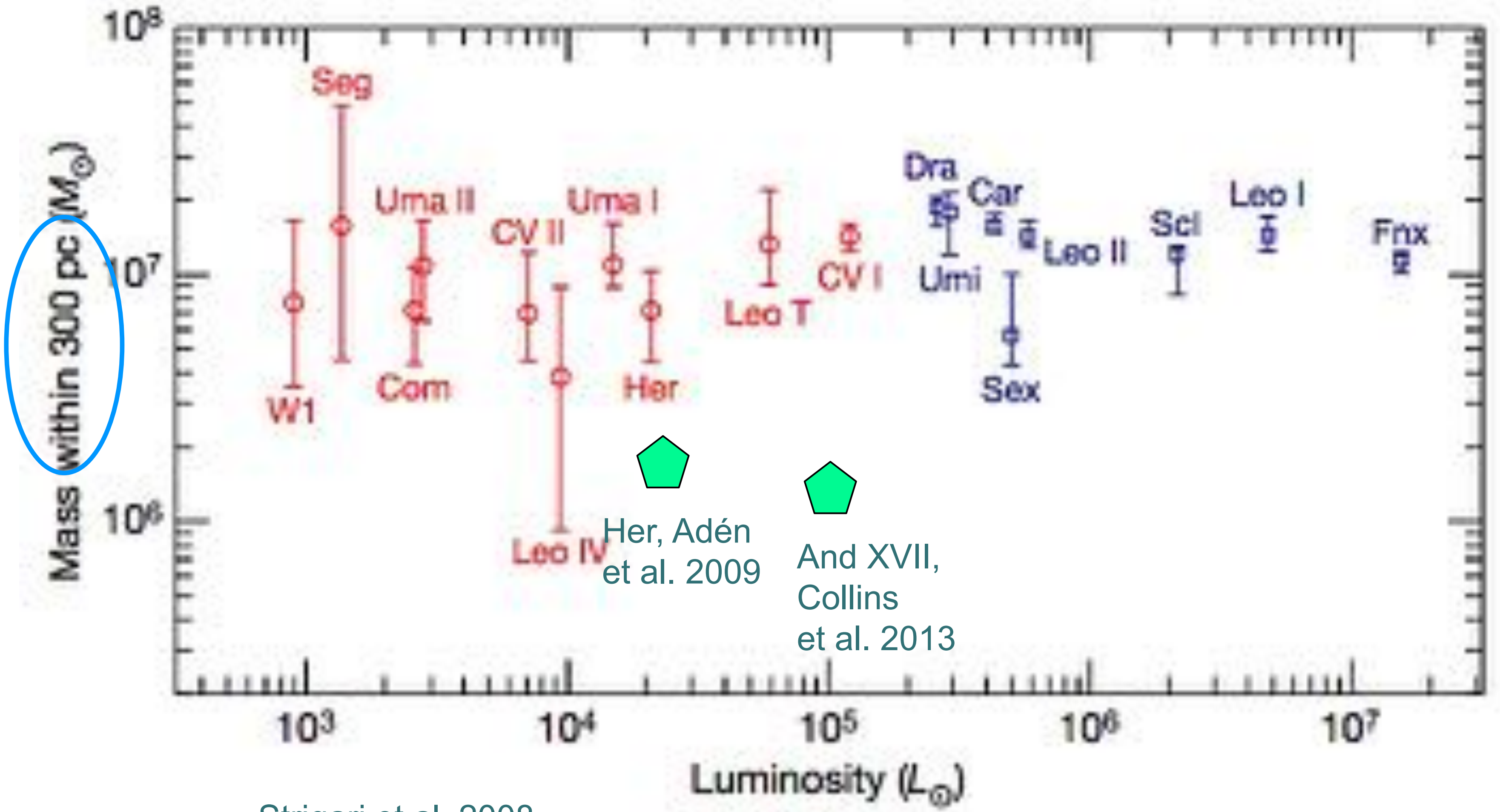
- Is each dSph embedded in DM halo of a few times $10^7\ M_\odot$?
- Is there a common mass profile? Note: $20 \leq r_{h,\ dSph} \leq 2000$ pc!



Strigari et al. 2008

A Common dSph Mass?

- Beware of interlopers (Adén et al. 2009) inflating σ of ultrafaint dwarfs!
- Also, host's baryon-to-DM halo ratio may affect dwarfs (Collins et al. 2011)

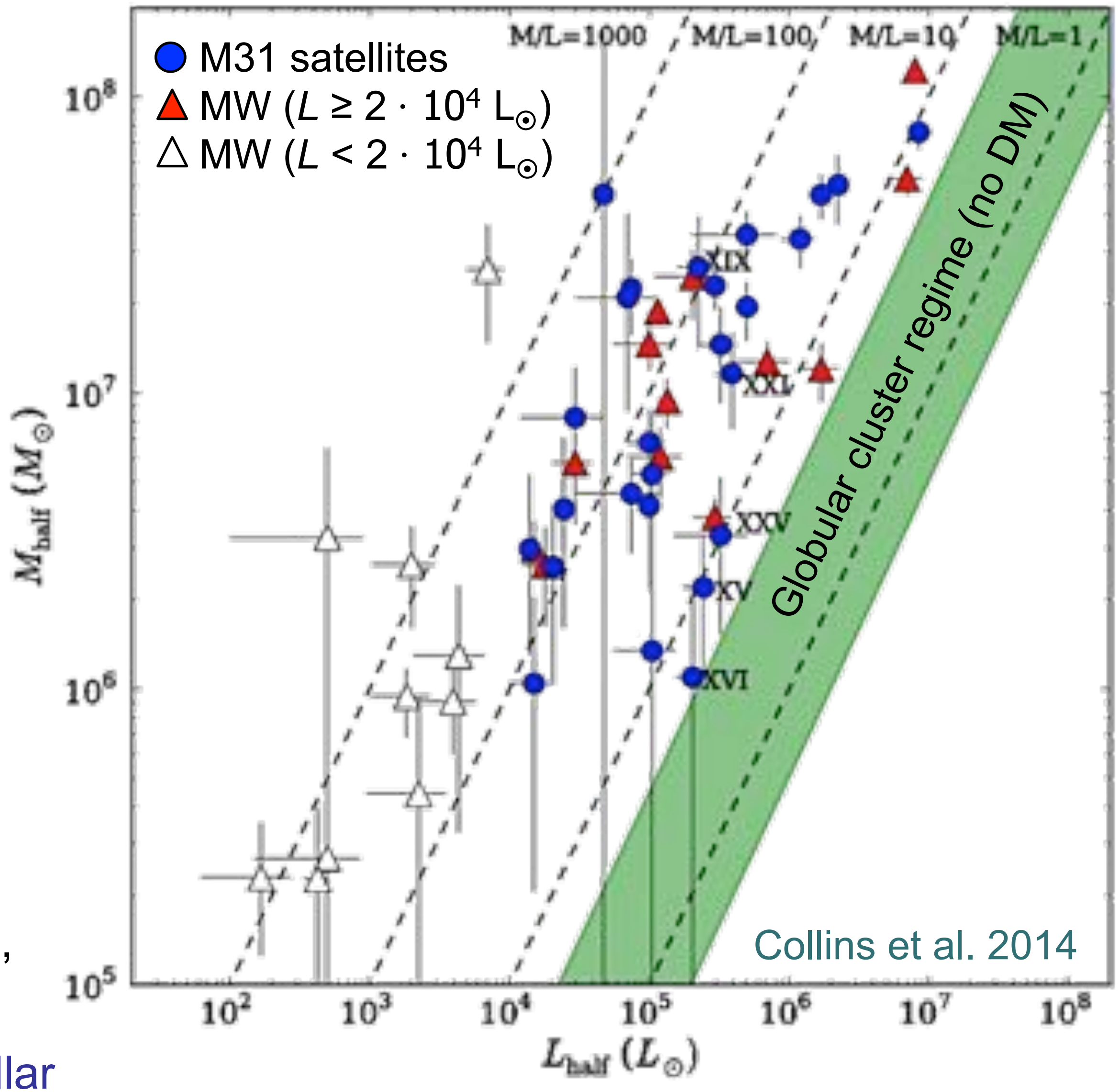


Strigari et al. 2008

DM Content

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

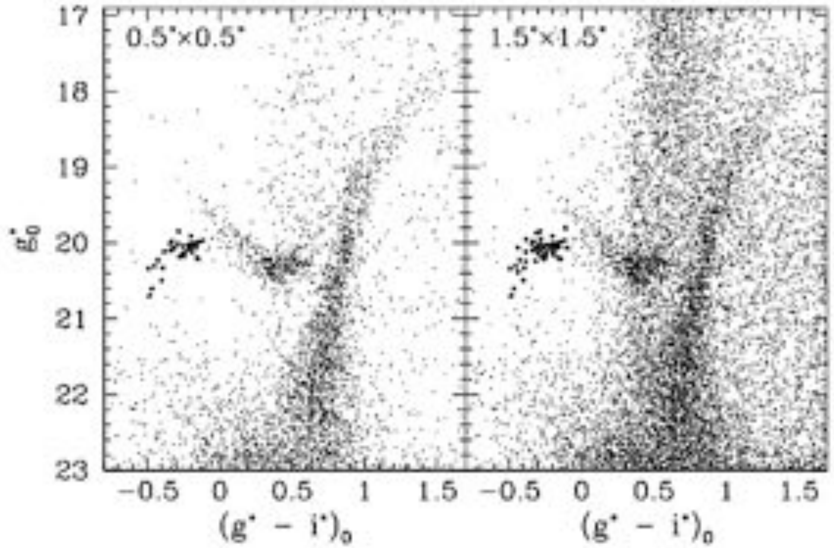
- ❑ Considerable scatter, no universal mass profile (Adén,..., Grebel, et al. 2009; Collins et al. 2014).
- ❑ High M/L at low L
- ❑ In low M/L regime: may have suffered substantial tidal stripping (as in cosmological DM + baryon simulations of, e.g., Brooks & Zolotov 2014).



→ Not necessarily disruption, but mass loss.

→ Expect corresponding stellar contributions to MW / M31 (outer) halo, *but* (!) first substantial amounts of DM must be stripped prior to stellar stripping (galaxies that lose ~ 80% of total DM only lose 10% stars). (Smith et al. 2016)

Unbound Tidal Remnants Without Dark Matter



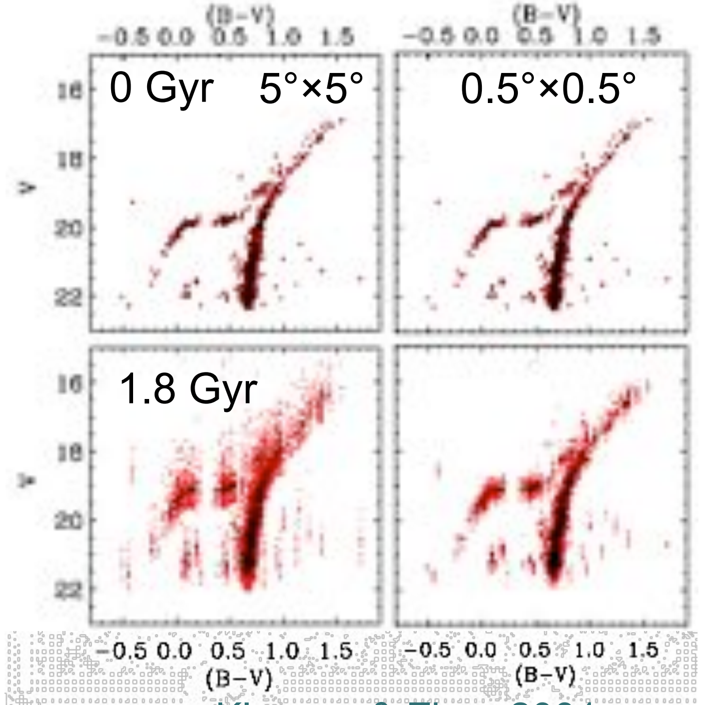
Observations

Draco Depth Extent:

Horizontal branch width remains small and constant regardless of the area sampled

→ Depth extent negligible

Simulations



Klessen & Zhao 2001

Blue Horizontal Branch Width of Draco

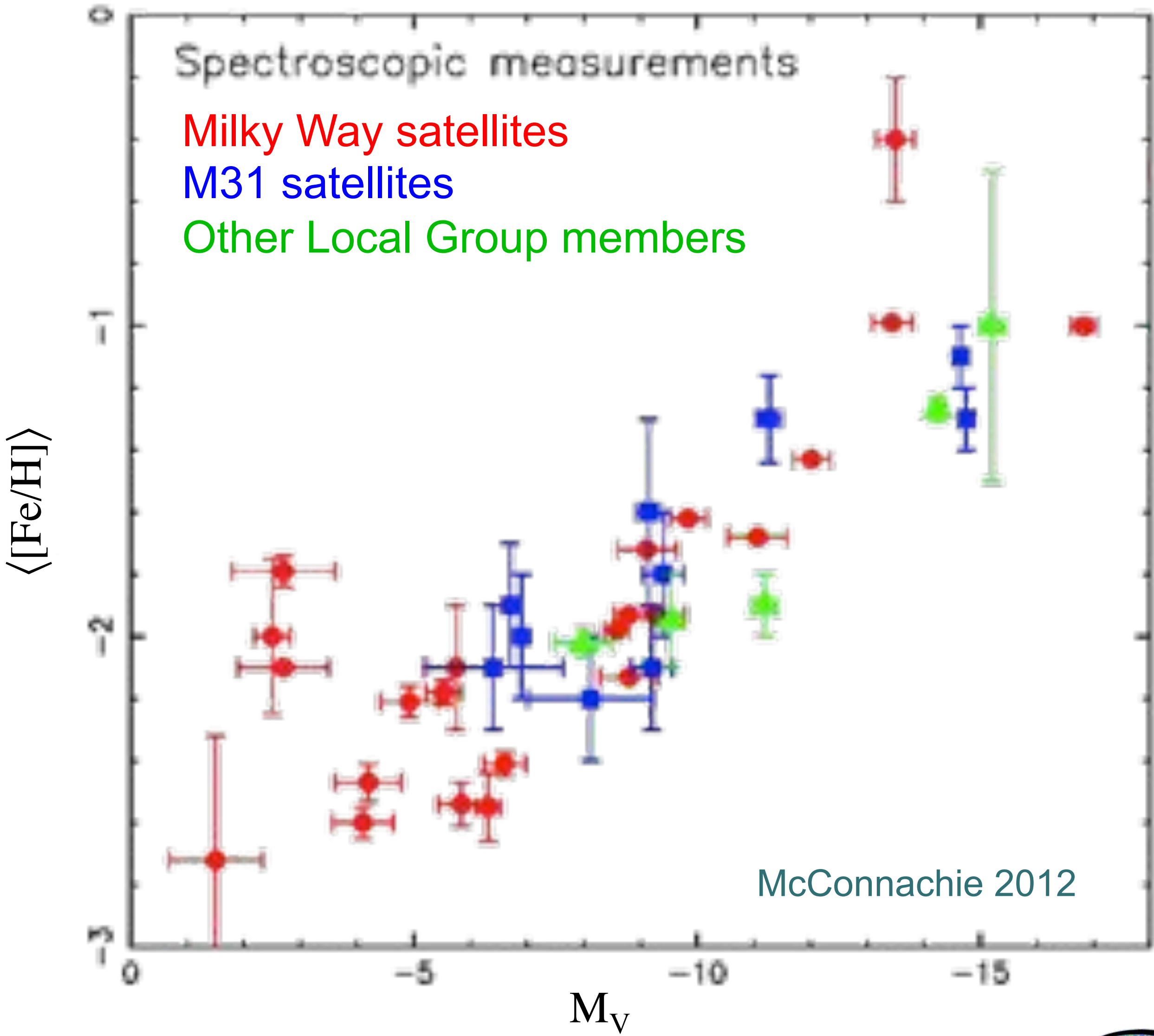
Area (deg) (1)	$\langle \Delta g^*_0 \rangle_{HB}$ (mag) (2)	Predicted $\langle \Delta V \rangle_{HB}$[a] (mag) (5)
0.25 × 0.25	0.12	0.125 ± 0.023
0.50 × 0.50	0.13	0.138 ± 0.023
1.00 × 1.00	0.13	0.162 ± 0.020
1.50 × 1.50	0.14	0.185 ± 0.018
2.00 × 2.00	0.13	0.207 ± 0.017
2.50 × 2.50	0.14	0.225 ± 0.016

Klessen, Grebel, & Harbeck 2003

Unbound Tidal Remnants Without Dark Matter

Is the existence of a metallicity-luminosity relation consistent with dSphs being unbound tidal remnants without dark matter?

Relation has been cited as evidence that dSphs did not experience drastic mass loss in the past.



Using DSphs to Constrain Nature of Dark Matter

- If DM consists of WIMPs, γ rays from self-annihilation may be observed.
- Advantage of γ rays: Can be traced back to point of origin (in contrast to other potential decay products such as charged particles).

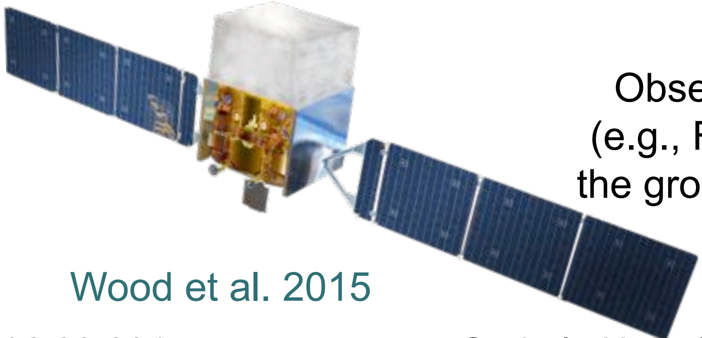
Expected DM signal $\propto$ to line-of-sight integral of DM distribution ("J-factor").

Very high DM density in Galactic Center (J-factor should be an order of magnitude higher than from dSphs), but also bright diffuse astrophysical foregrounds.

Advantage of dSphs:

- DM-dominated
- Mainly located at high-latitude regions where diffuse γ ray background is lower.
- To date: No evidence for significant γ ray emission from any of the individual dSphs or from the combined sample.

→ Limits on WIMP annihilation cross section



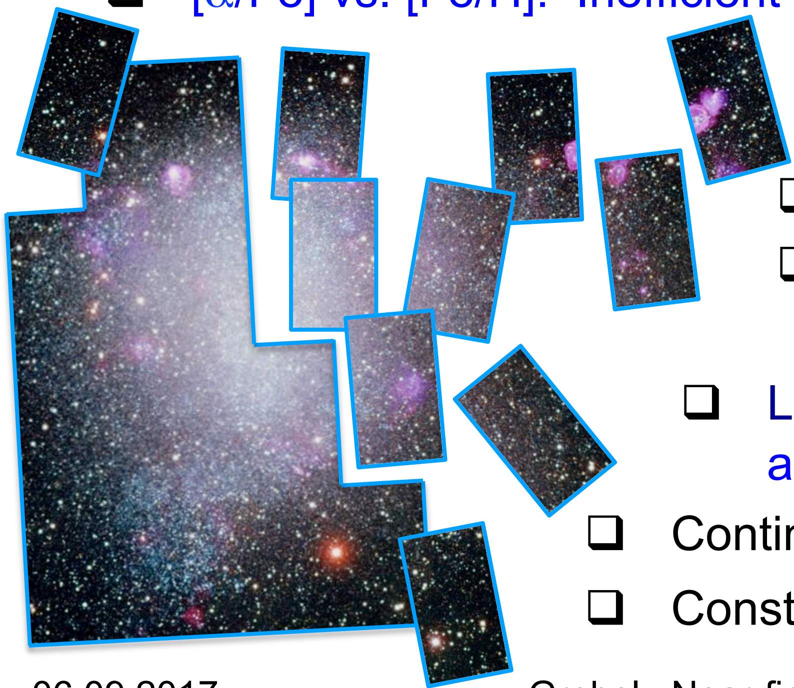
Observations from space (e.g., Fermi LAT) and from the ground (e.g., H.E.S.S.).

Wood et al. 2015

6. Summary

Near-Field Cosmology With Dwarf Galaxies

- 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.



- Dwarf MDFs: Gas infall/winds. Flatter MFs.
- Old extremely metal-poor stars in dSphs: ~ consistent with MW halo EMP stars.
- Low-metallicity stars in dwarfs and MW in general: abundance consistency. Early accretion favored.
- Continued discoveries at faint end. Lower limit?
- Constraints on nature of dark matter.