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Dwarf Galaxies in the Local Group: Some Recent Findings

1. The Growing Local Group

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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.

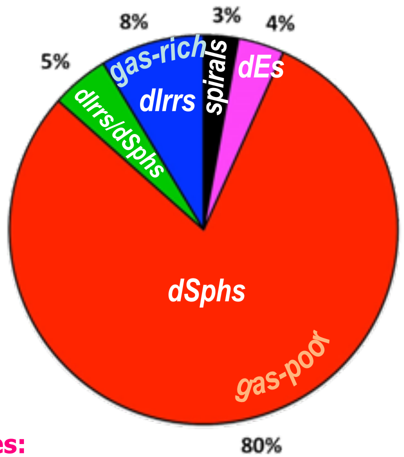
- Ultra-diffuse galaxies
- Tidal dwarf galaxies

Pictures not on same scale

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...



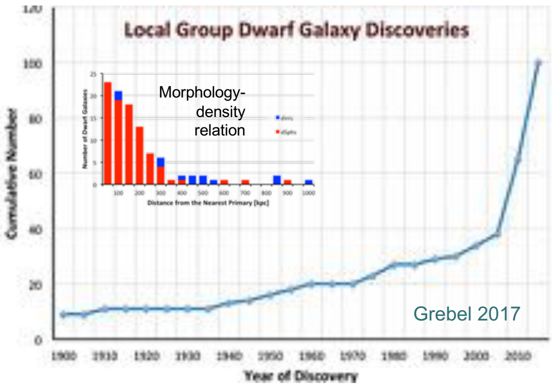
Gas-deficient, late-type dwarf galaxies:
dwarf elliptical (**dEs: 3; 1 cE**) & dwarf spheroidal galaxies (**dSphs: ≥ 83**)

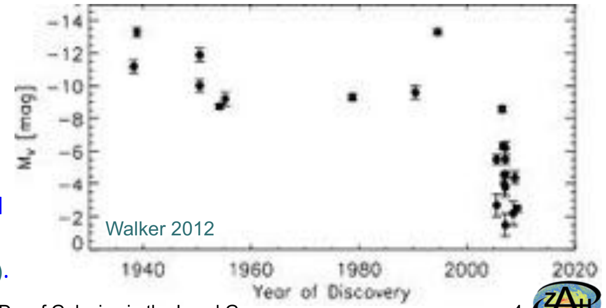
Gas-rich, early-type dwarf galaxies:
dwarf irregular galaxies (**dIrrs: 9**), transition types (**dIrrs/dSphs: 5**)

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).

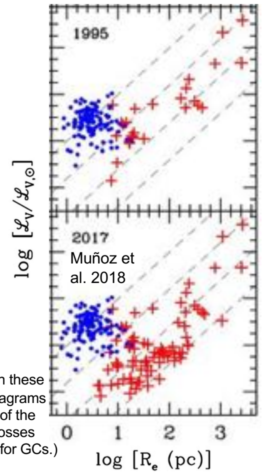




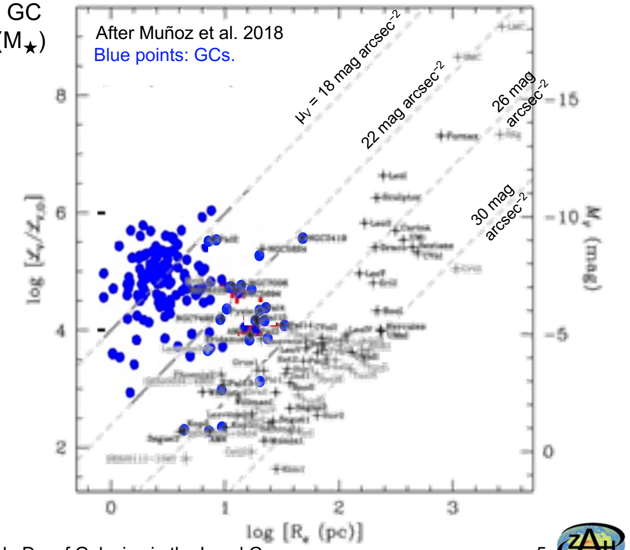
Total satellite population of the Milky Way estimated 142^{+53}_{-34} down to $M_V = 0$ in simulations (Newton et al. 2017).

Size – Luminosity Relation

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



(NB: In these two diagrams some of the red crosses stand for GCs.)



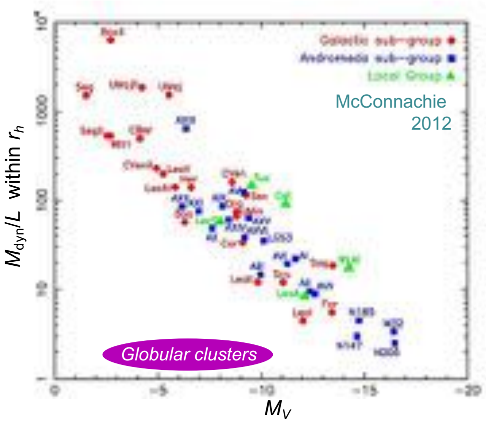
At Low Masses: Distinguishing Galaxies & Star Clusters

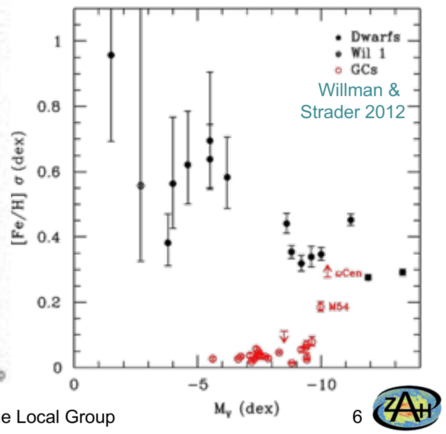
No general definition exists but conventionally the following criteria are used:

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


Laevens 1 / Crater I

Star clusters:
- ❑ Gravitationally bound
- ❑ No dark matter
- ❑ Negligible metallicity spread

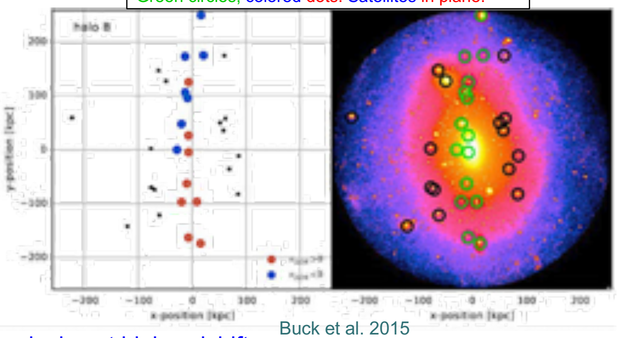




2. Satellite Planes: One of the Small-scale Challenges in ΛCDM?

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).

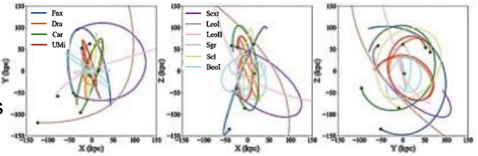
ΛCDM simulations:

- Planes form through accretion along large filaments of DM around galaxies at high redshift.
- 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.

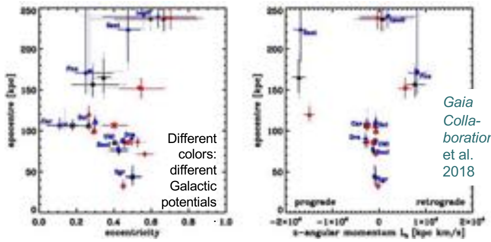
(Bowden et al. 2013; Fernando et al. 2016).

- 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.

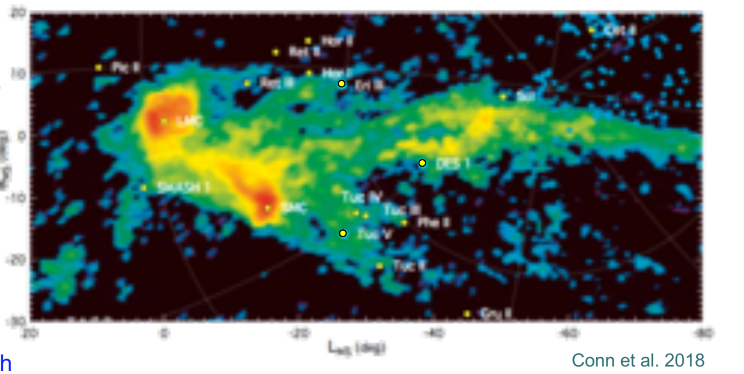
- HST & **Gaia** proper motions: MW dwarfs <u>not</u> on single narrow plane.
- Orbits typically ⊥ to MW disk, but span broad range of orientations (of 39, 11 co-orbit, 6 counter-orbit).

→ 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).



Gaia Collaboration et al. 2018

Infall of Dwarf Groups



Conn et al. 2018

- 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.

3. Abundances and Implications

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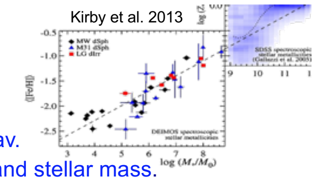
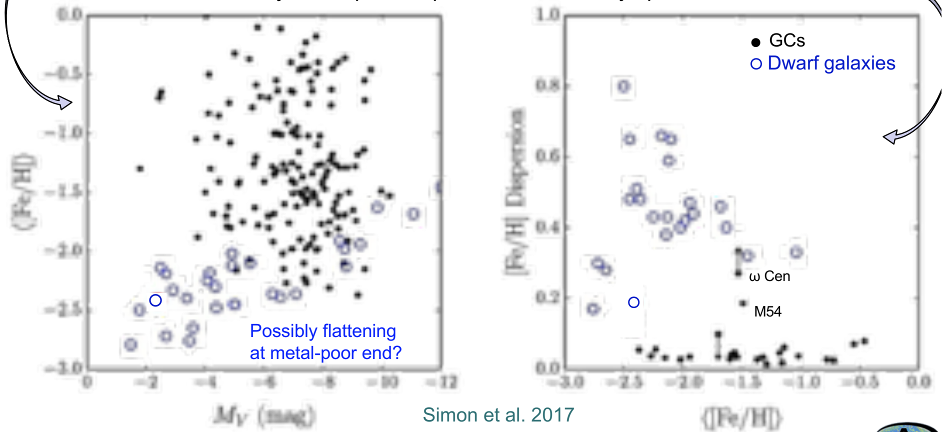
Metallicity Scaling Relations

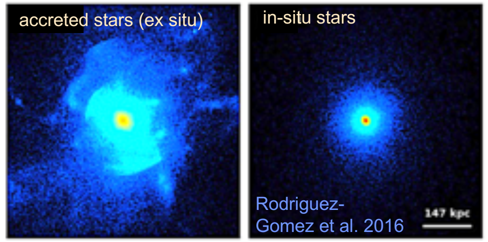


- (Dwarf) galaxies: clear metallicity – luminosity relation
- Signature of galaxies' ability to retain metals in their grav. potential wells or of correlation between SF efficiency and stellar mass.
- GCs: No such relation. Also, don't extend to as low [Fe/H] as ultrafaint dSphs.
- Even ultrafaint, very metal-poor dSphs show metallicity spread and extended SFHs.

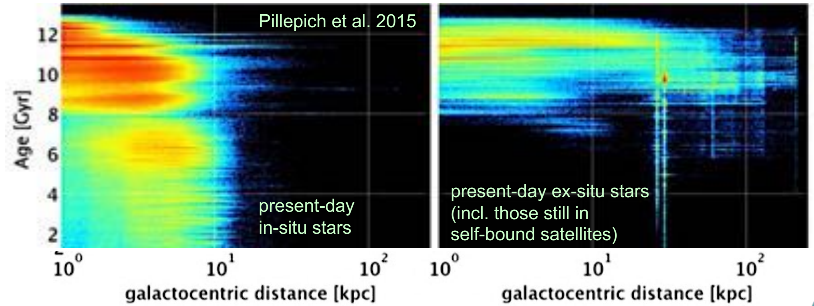


De Lucia & Helmi 2008; Cooper et al. 2010

Stellar Halo Origins



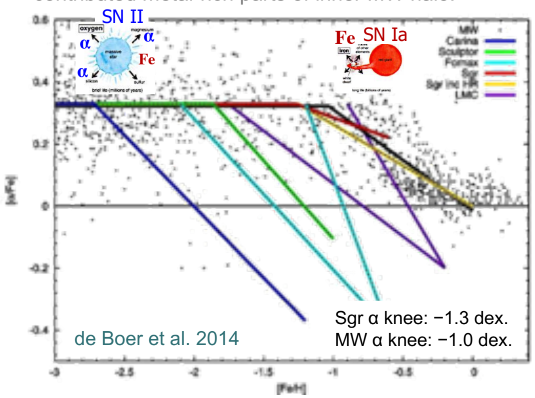
- Stellar halos composed in part of accreted stars and in part of stars formed in situ.
- Halos grow from "from inside out".
- Wide variety of satellite accretion histories from smooth growth to discrete events.
- ≤ 5 luminous satellites (10^8 – 10^9 $M_\odot$) are the main contributors to stellar halos.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

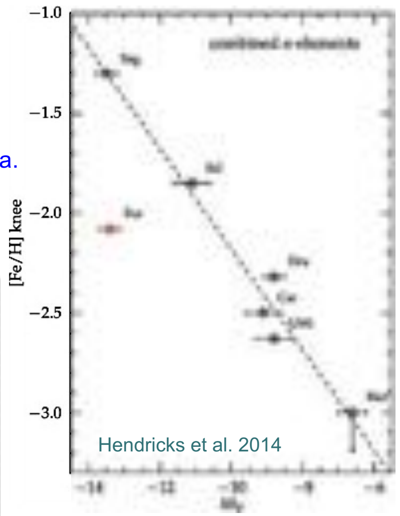


[Fe/H] vs. [α/Fe] in Dwarfs

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.



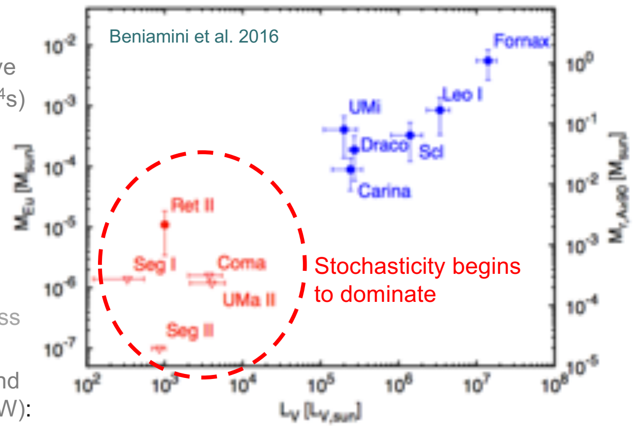


Position of "α knee" correlates with dSph luminosity (or stellar mass).

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.
r-process retention when events not too energetic. Low r-process frequency (models: ~ 0.07 of u.f. dSphs) ∝ with σ([Eu/Fe]) in MW metal-poor stars. (Beniamini et al. 2018)
Models suggest that in an initial, metal-poor ISM stochastic effects dominate.
Inhomogeneous pollution, few SNe (Marcolini et al. 2008).

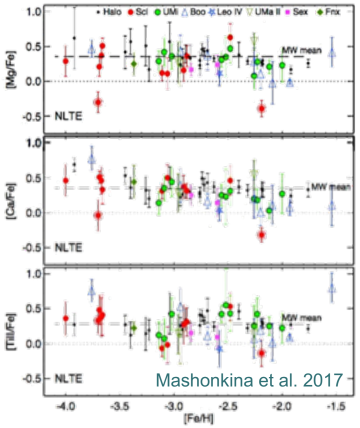
Trends in Individual Element Abundance Ratios

For $-4 \le$ [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.



Mashonkina et al. 2017

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

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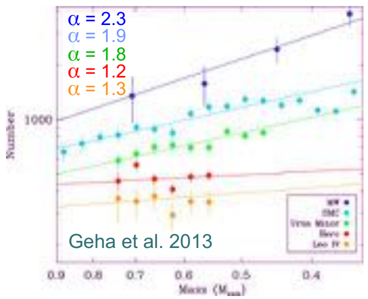
4. Other Highlights

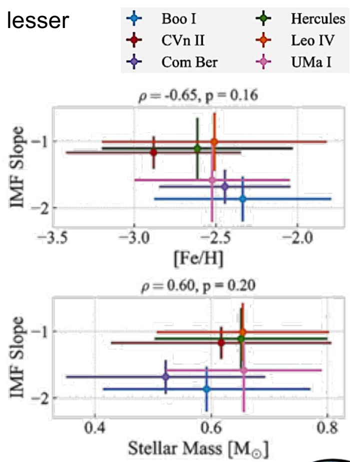
Wheeler et al. 2018

Flat, Bottom-Light (Initial) Mass Functions

- ❑ Subsolar stellar IMF in ultrafaint dSphs: flatter and more bottom-light than in MW.
  - ❑ Accessible mass range: ~ 0.45 – ~ 0.8 $M_\odot$.
  - ❑ Salpeter: −2.3. Here: −1 to −1.9. ➔ More low-mass stars in MW.
- ❑ IMF slope correlates with mean [Fe/H] and to a lesser degree with galaxy $M_\star$ and velocity dispersion.
- ❑ Slope variation within ultrafaint dSph sample.
- ➔ Suggests that IMF is not universal.
- ❑ (Giant Es: steeper slope at low masses!)



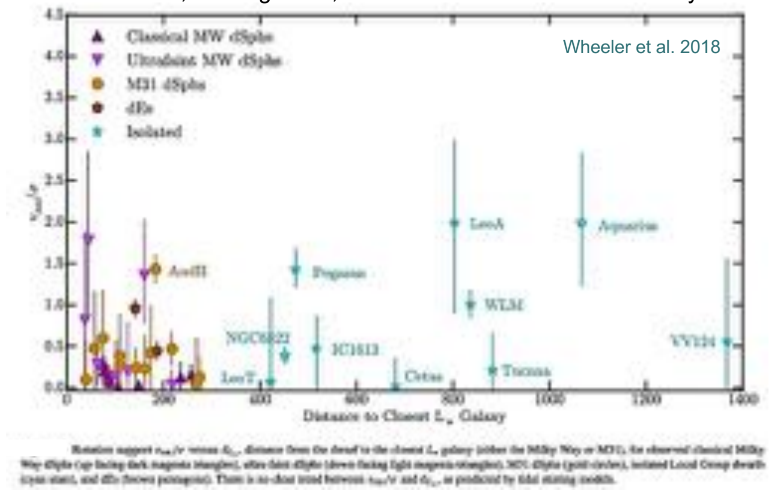
Geha et al. 2013



Gennaro et al. 2018

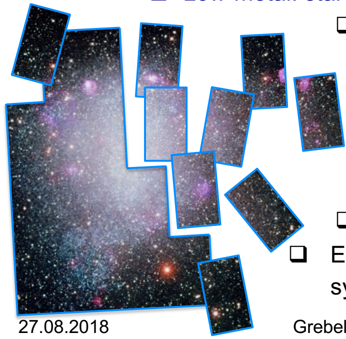
Dispersion- vs. Rotation-supported Systems

- ❑ 40 dSphs and dIrrs ($M_\star = 10^{3.5} - 10^{8}\ M_\odot$): 80% dispersion-supported; $v_{rot}/\sigma < 1$.
- ➔ Even isolated systems seem to form as puffy, dispersion-supported systems (!) rather than cold, rotating disks; without need for transformation by tidal forces.



Brief Summary of Recent Findings for LG Dwarfs

- Vast number of new, very faint satellite discoveries.
  In size – luminosity diagram: fill gap between dSphs and GCs.
- Satellite planes: ΛCDM simulations suggest infall along filaments and that planes are partly fortuitous and transitory features.
  - Gaia DR2 & HST proper motions: Only subset of dwarfs co-orbits w. plane.
  - LMC infall with own small entourage of ultrafaint dSphs.
- Well-defined mass-metallicity relation over ~ 9 decades of galaxian $M_\star$.
  - Argues against major mass loss for satellites. May flatten at low-metal end.
    - Low-metal. stars in dwarfs and MW in general: abundance consistency.



- α knee: constraints on dwarf galaxy accretion. Early accretion favored.
  - Enrichment before onset of SNe Ia (α knee) correlates with galaxy luminosity.
  - Abundance inhomogeneities & spreads,
  → localized, stochastic enrichment.
- Flat, bottom-light IMF. Not universal! Galaxian $M_\star$?
- Even isolated dIrrs may form as dispersion-supported systems; no need for tidal stirring.