Complexities in the stellar kinematics of Local Group dwarf galaxies

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With thanks to:

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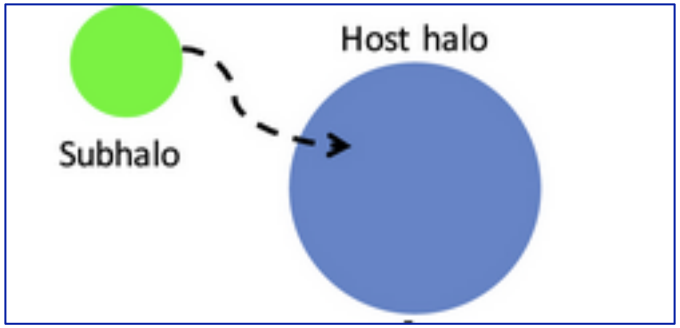
Outline

WORK IN PROGRESS!

The early properties of Local Group dwarf galaxies

what was their stellar mass at z> 2? And can we estimate how the associated stellar feedback affected their evolution and dark matter properties ? (Bermejo-Climent, Battaglia et al. in prep)



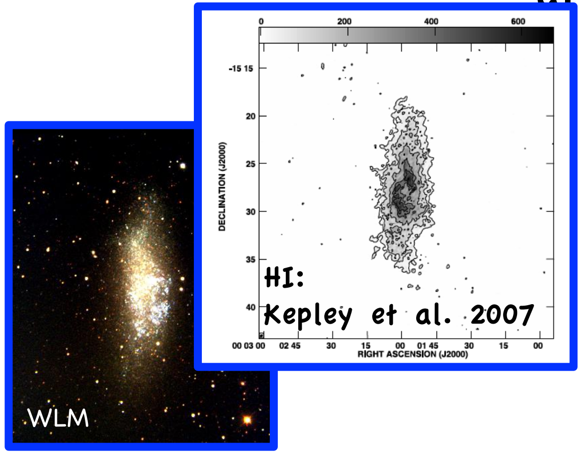
Possible accretion of sub-haloes at the smallest galactic scales

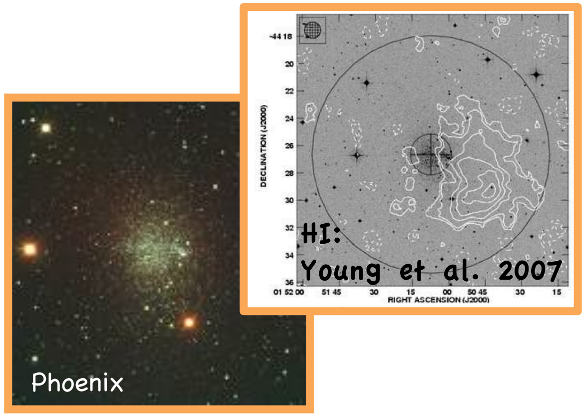
The unexpected kinematic properties of the Phoenix dwarf galaxy (Kacharov, Battaglia et a. 2017)

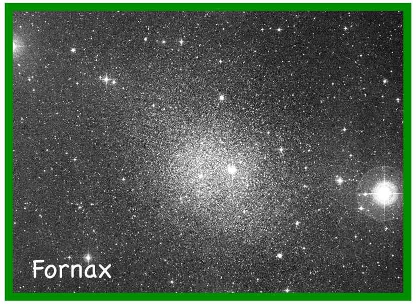
Late- & early-type dwarfs in the Local Group

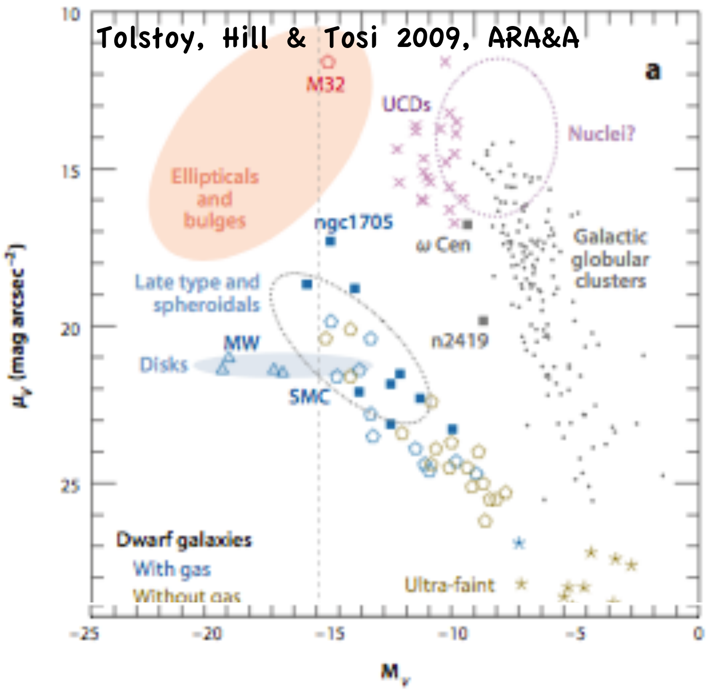
Dwarf irregulars, (transition types), dwarf ellipticals, spheroidals, ultra-faint...

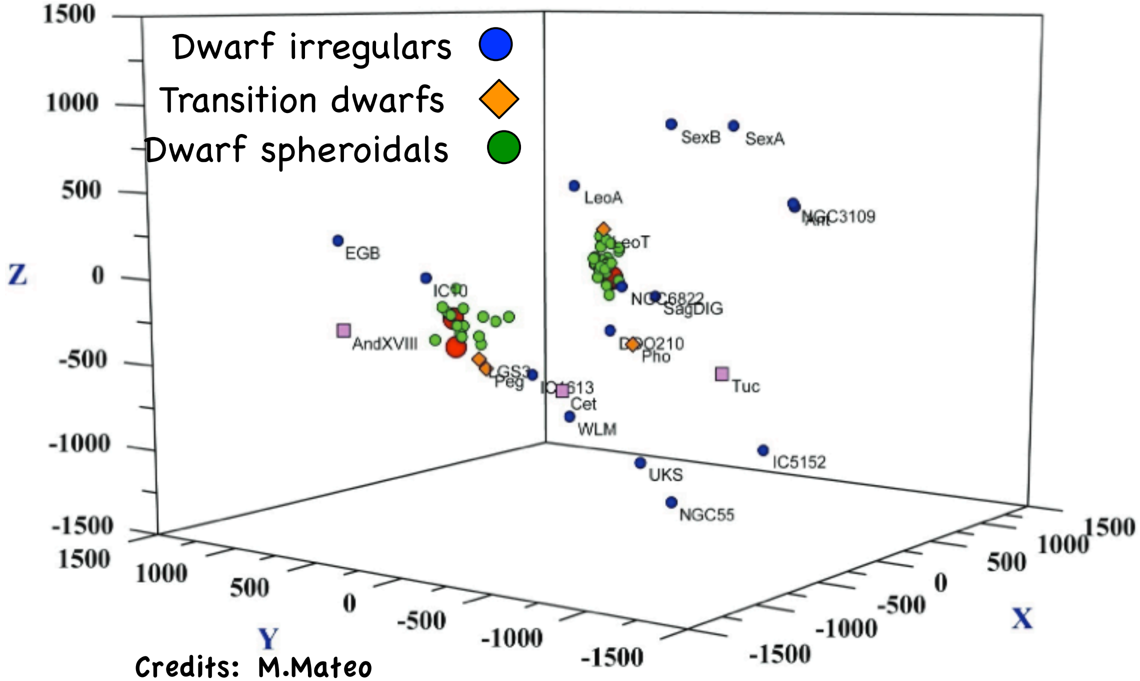
around 80 dwarf galaxies overall





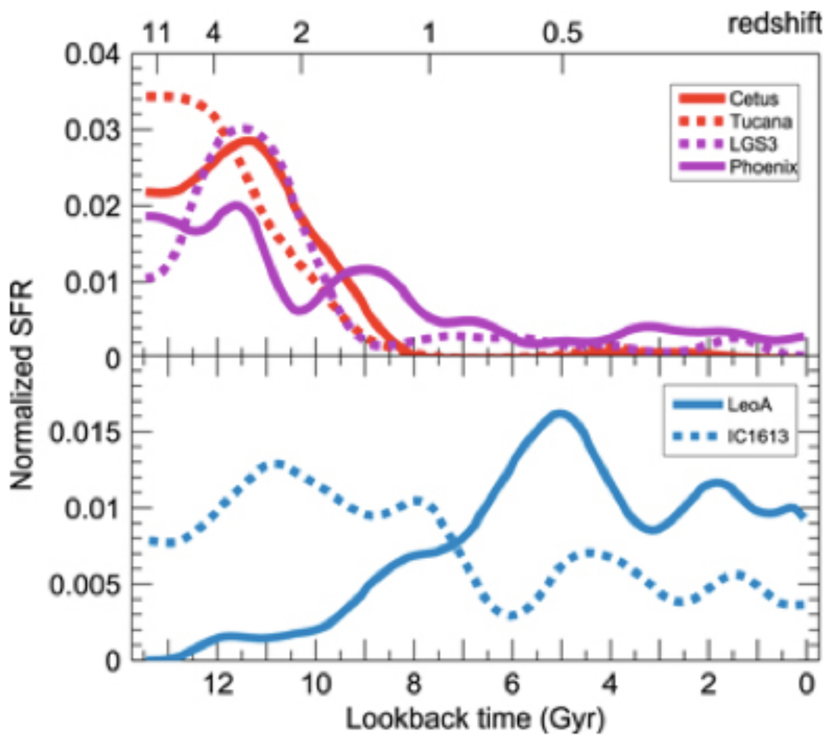




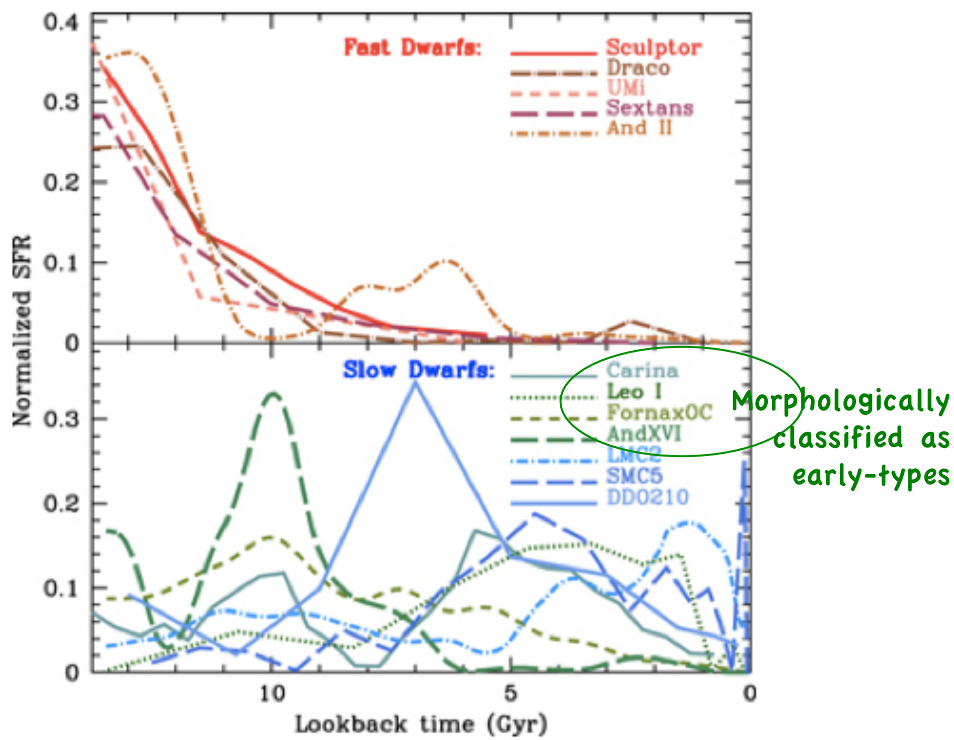


Morphological classification vs observed properties
Late-types / early-types vs "slow" / "fast"
(Gallart et al. 2015, incl. Battaglia)

- On the basis of accurate SFHs from very deep CMDs -> "Slow" and "fast" dwarfs
- "early" morphological types (dwarf spheroidals) do not always map into "fast"



Homogenous sample and analysis (from LCID program (Cole et al. 2007; Skillman et al. 2014; Hidalgo et al. 2009, 2011; Monelli et al. 2010a, 2010b)



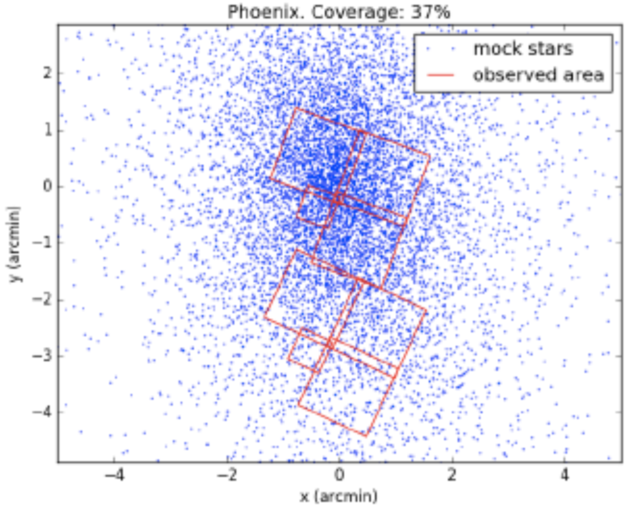
SFHs from the literature (Gallart et al. 1999; Aparicio et al. 2001; Carrera et al. 2002; Dolphin 2002; Lee et al. 2009; de Boer et al. 2012, 2014; del Pino et al. 2013; Weisz et al. 2014a, Noël et al. 2009; Cignoni et al. 2013; Meschin et al. 2014, Weisz et al. 2014b; M. Monelli et al. 2015; Cole et al. 2014)

How do Local Group dwarf galaxies compare in terms of early assembled stellar mass?
Goal : stellar mass formed z > 2

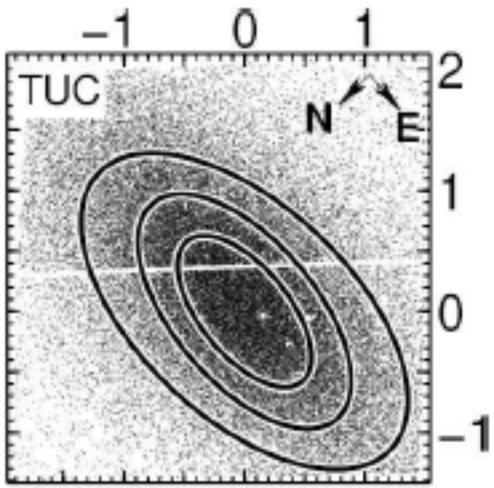
- Normalized SFHs -> star formation rates in absolute units (Msun/yr)

- Data from which SFHs are derived do not always cover a significant portion of the galaxy -> need to account for this missing coverage

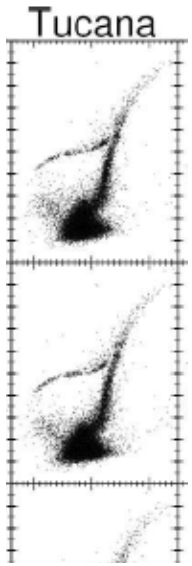
- Age gradients have been detected in Local Group dwarf galaxies -> the spatial distribution of stars in different age ranges follows different surface number density profiles



Quantification of age gradients in Local Group dwarf galaxies



Hidalgo et al. 2013



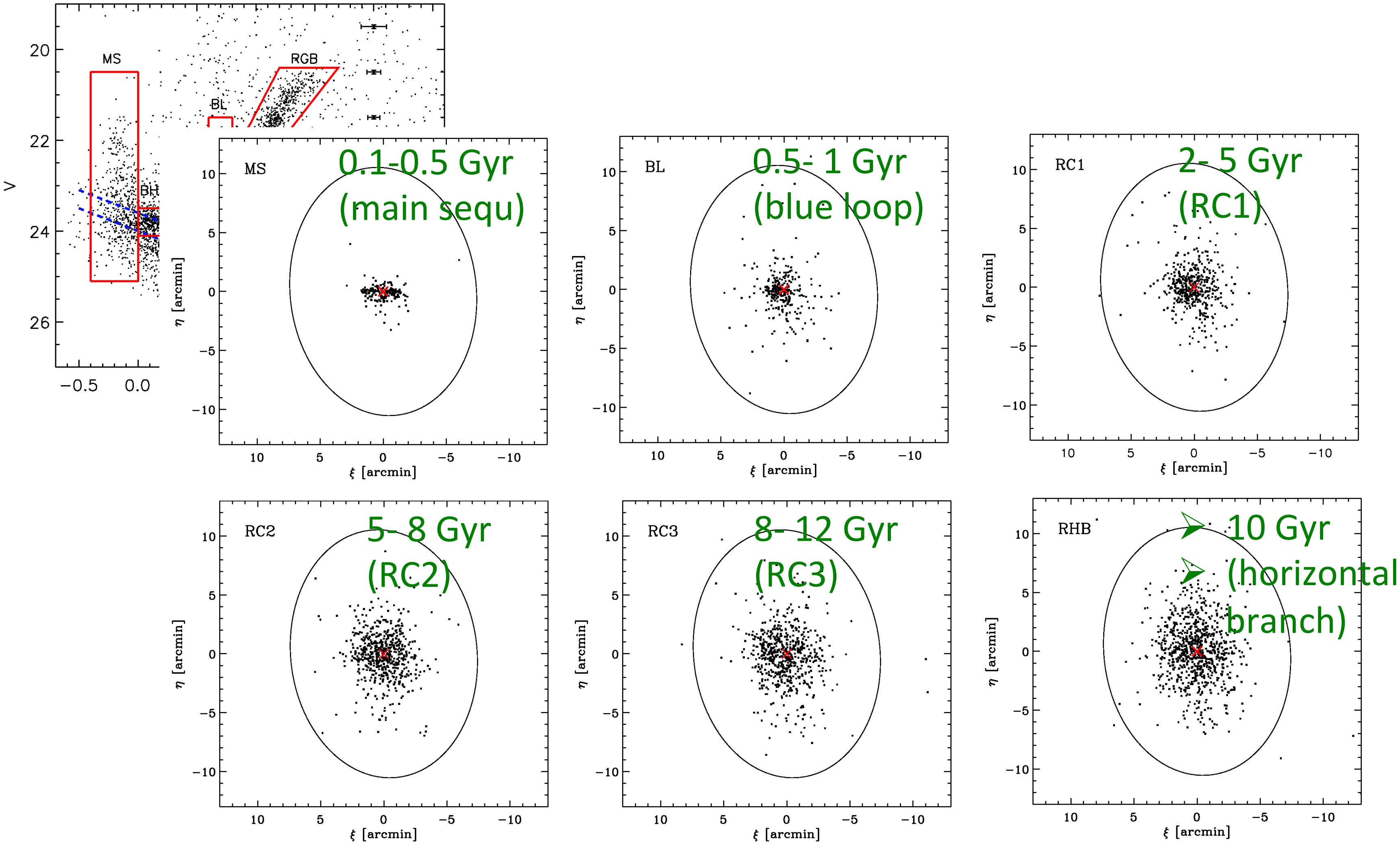
-> SFH R1

-> SFH R2

Scale length as a function of time.

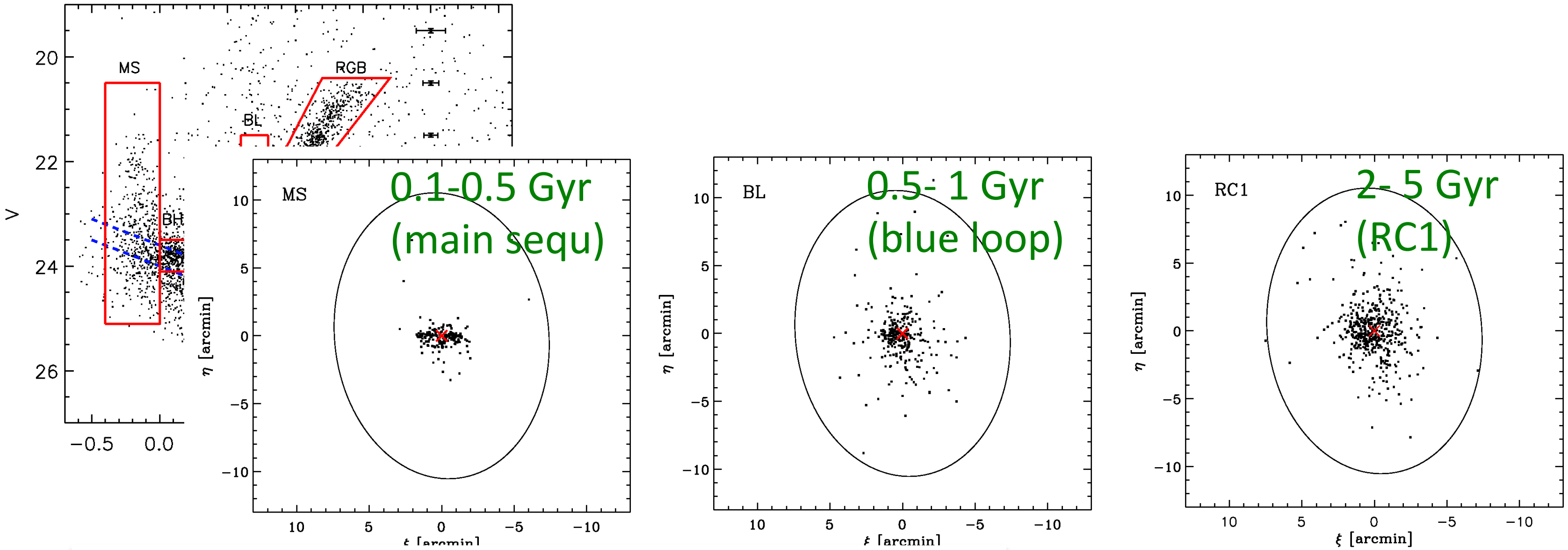
Galaxy	$t \geq 10$ Gyr	$5 \leq t < 10$ Gyr	$2 \leq t < 5$ Gyr	$1 \leq t < 2$ Gyr	$t < 1$ Gyr
			α_ψ (pc)		
CETUS	226 ± 5	169 ± 15	...	...	...
TUCANA	141 ± 7	84 ± 7	...	...	...
LGS-3	165 ± 16	81 ± 6	83 ± 7	83 ± 3	55 ± 4
PHOENIX	526 ± 293	205 ± 31	110 ± 5	68 ± 8	70 ± 8

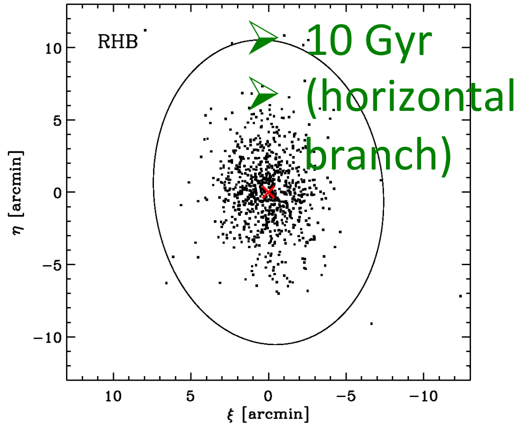
Quantification of age gradients in Local Group dwarf galaxies



Battaglia et al. 2012

Quantification of age gradients in Local Group dwarf galaxies





A
g
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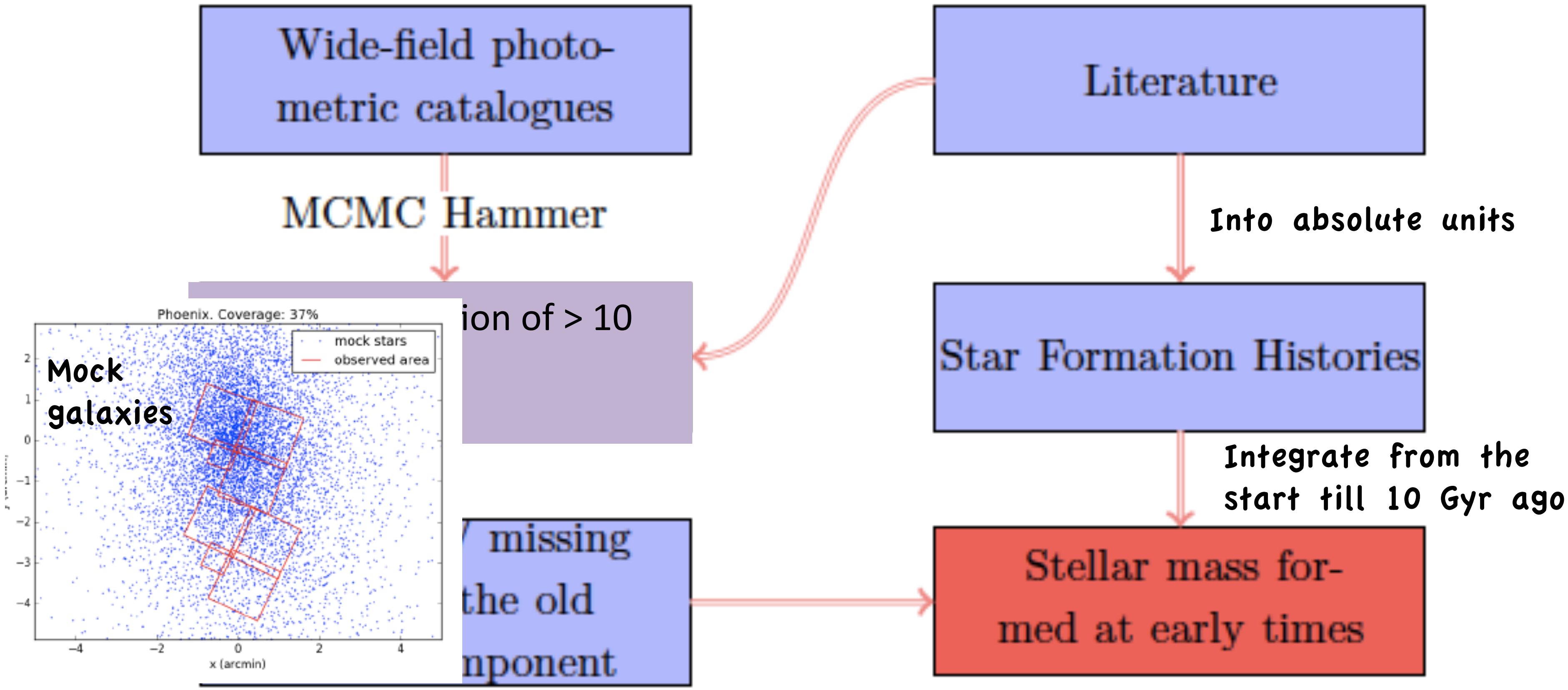
Stellar evolutionary phase	Plummer b[arcmin]	$\chi^2_{red,min}$
BL	1.47 ± 0.09	0.9
RC (23.2–23.4)	1.79 ± 0.06	1.9
RC (23.4–23.6)	2.00 ± 0.06	3.0
RC (23.6–23.8)	2.36 ± 0.06	3.7
RGB bump	2.34 ± 0.06	2.2
RHB	2.57 ± 0.04	5.8
BHB 10	2.89 ± 0.15	1.8

Battaglia et al. 2012

Method



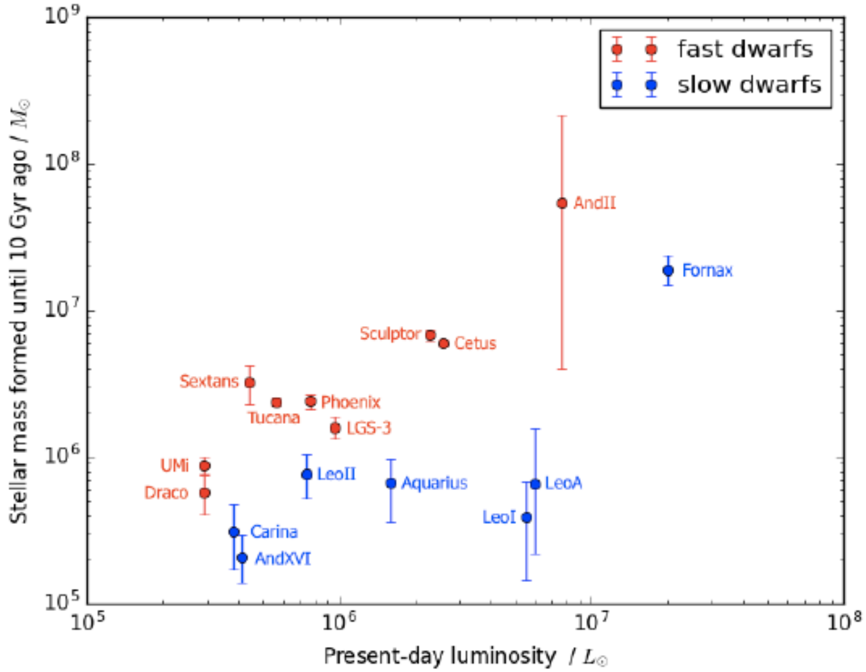
Wide-field photo-metric catalogues
MCMC Hammer
ion of > 10
Literature
Into absolute units
Star Formation Histories
Integrate from the start till 10 Gyr ago
Stellar mass for-med at early times
missing
the old
nponent
Phoenix. Coverage: 37%
mock stars
observed area
Mock galaxies
x (arcmin)

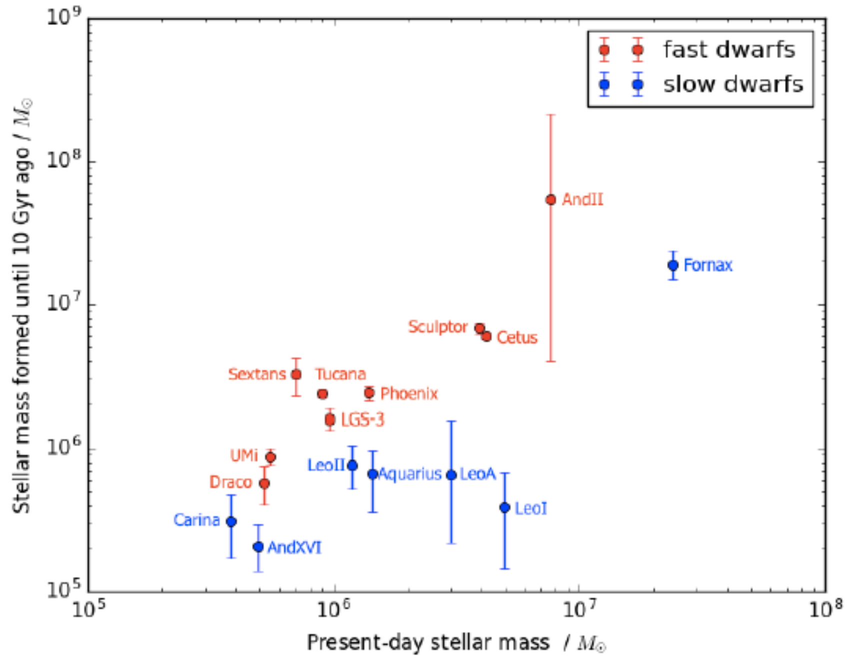
Some considerations

1) In general, "fast" dwarfs had assembled more mass at early times

2) For a given early assembled stellar mass, "slow" dwarfs are today much more luminous than "fast" ones -> had their SF not be truncated, "faint" galaxies like Draco/Ursa Minor could be ~1 order of magnitude more luminous

3) < SFRs > = Mstar,formed(z>2)/3.5Gyr = a few times 10^-5, 10^-2 [Msun/yr]





Assuming stellar (M/L)_V by Woo et al. 2008

Can feedback from supernovae explosions get rid of the gas or core the dark matter profile?

Calculate the SNII energy transferred to the gas or dark matter (from the stellar mass formed at z> 2) and compare it to the gravitational potential of the dark matter halo at z=2

- We focus on SNII, assume that stars with M > 6.5 Msun produce SNII and integrate a Kroupa (2001) IMF; we take E_SNII = 10^51 erg

- Estimate global dark matter halo properties at redshift =2 (assuming NFW):

    * abundance-matching relations (Brook et al. 2014) -> Mhalo(z=0)
    * Fakhouri et a. 2010: Mvir (z~2) about 40-50% than Mvir(z=0) for haloes in our mass regime (~10^10 Msun) (assuming Mhalo ~ Mvir)
    * Dutton & Maccio' (2014) cvir-Mvir relation at z=2

Truncation of SFH because of gas removal?

In which cases is the SNII energy transferred to the gas (from the stellar mass formed at z> 2) larger than the galaxy potential (at z> 2) ?

- Extreme case : fraction of energy transferred to the gas 100% ($\varepsilon_{SN}=1$); all energy injected at once ->

  * Fornax, AndII, Sculptor, Cetus, Sextans, Tucana would lose the gas because of SN feedback
  * Among those that wouldn't lose the gas at z=2, UMi, Draco are OBSERVED to have stopped forming stars by that time -> external mechanism (ram pressure?)

  * caveat: Fornax stopped forming stars 50 Myr ago! -> ε_{SN} is too large

- More reasonable limits : 0.05 (Revaz & Jablonka 2012); not more than 0.4 (Governato et al. 2010)

-> with ε_{SN} = 0.05 no galaxy would lose its gas at z=2 because of feedback and with ε_{SN} = 0.5 only AndII would lose its gas

Cusp into core?

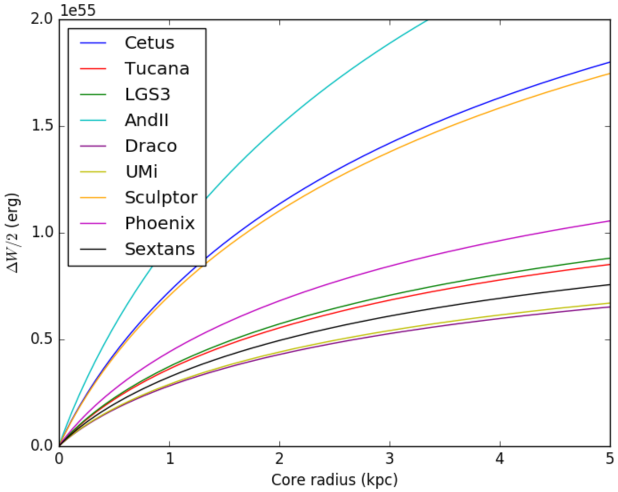
Following the reasoning and formalism of Peñarrubia et al. 2012:

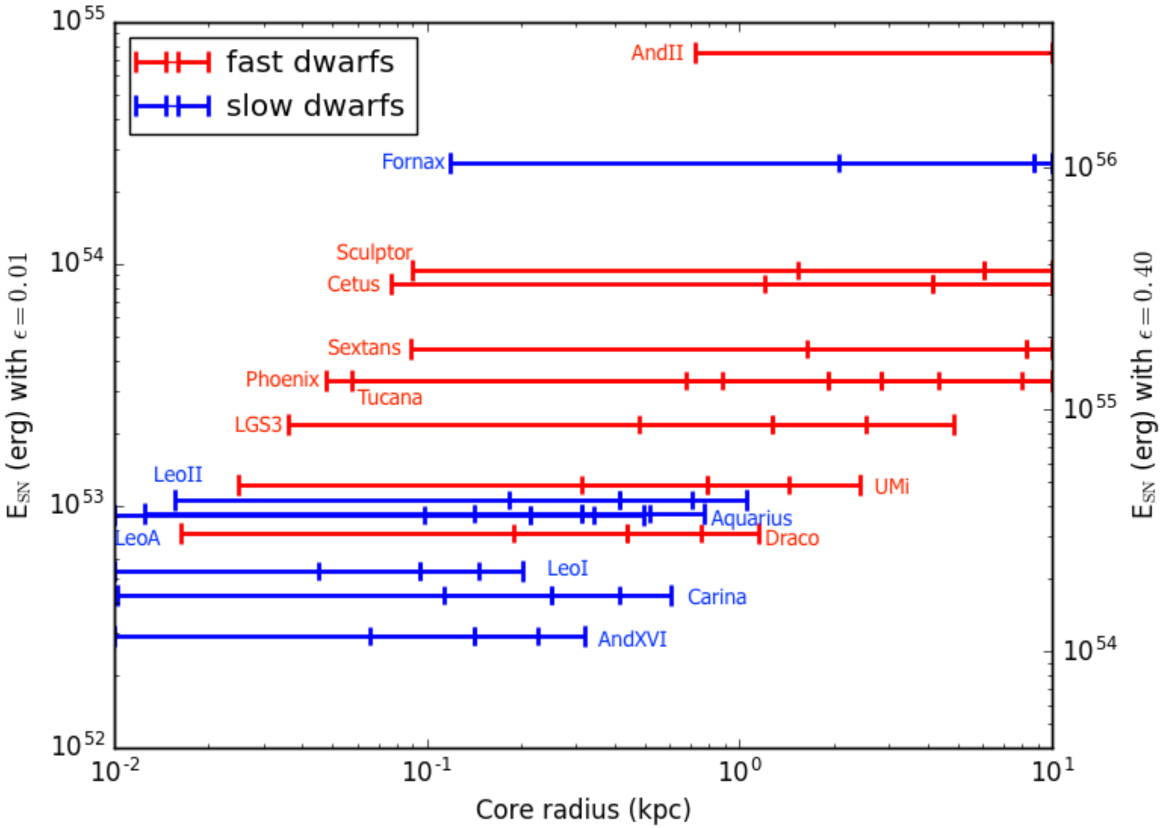
Fraction of SN feedback transferred to DM less then transferred to the gas (and anyway ε_DM likely to be at most = 0.4 from simulations)

The minimum energy required to transform a centrally divergent cusp into a constant-density core is ΔE = ΔW/ 2 = (W_core - W cusp) / 2, where

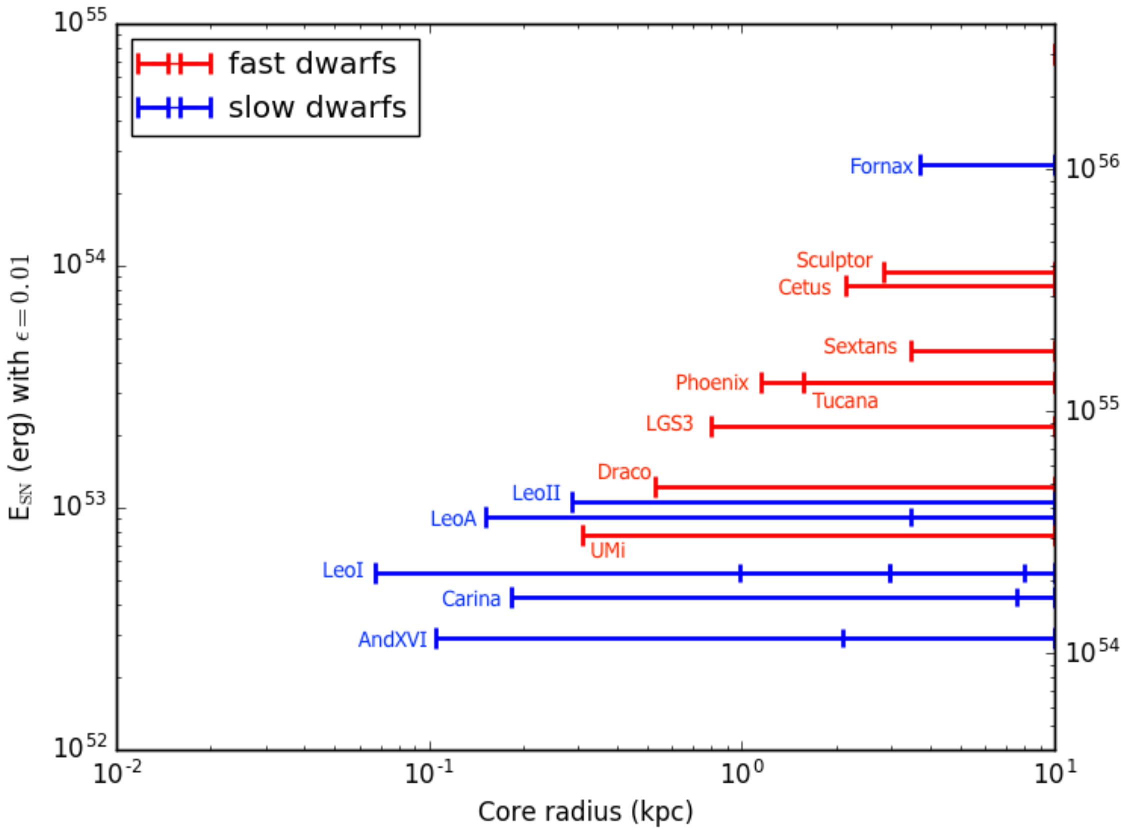
$$W = -4\pi G \int_0^{R_{\rm vir}} \rho(r) M(r) r\, dr$$

$$\rho_c(r) = \frac{\rho_s r_s^3}{(r_c + r)(r_s + r)^2}$$





Cusp into core? (z=6 case)



Points for discussion (part I)

Supernovae feedback cannot be the only responsible for causing the slow/ fast (broad) "dichotomy" of SFHs :

- Not even in the most extreme case (fraction of energy transferred to the gas 100%, i.e. $\varepsilon\_SN=1$; all energy injected at once) all "fast" dwarfs would lose their gas
- Under more realistic conditions, none of them would

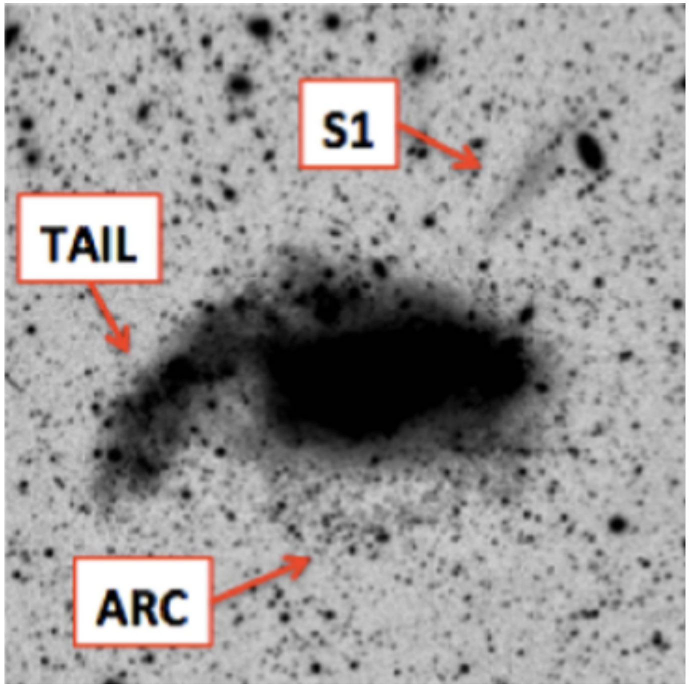
Among the examined galaxies, those more likely to have a cored DM distribution due to SN feedback are: AndII, Fornax, Sculptor, Cetus, Sextans. Observationally "confirmed" for Fornax & Sculptor (Walker & Peñarrubia 2011, Amorisco & Evans 2012; but see e.g. Breddels & Helmi 2013…)

Should we expect cusps in the other systems? Draco (see J.Read' talk) (e.g. we have ignored spiraling in of massive molecular clouds, e.g. Nipoti & Binney 2015)

And how much of this result is driven by the adopted abundance-matching relation? (dwarfs of different luminosities live in relatively similarly massive DM haloes)

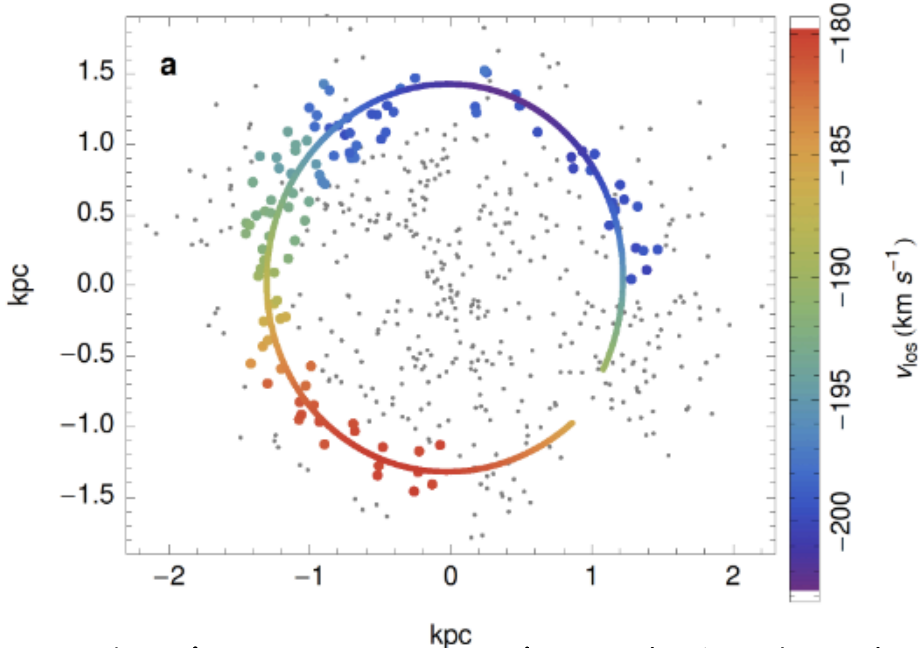
Merging of sub-haloes at the scales of dwarf galaxies ?

DDO 68 (13 Mpc):
10^8 Msun;
S1 : 2-5 x 10^5 Msun



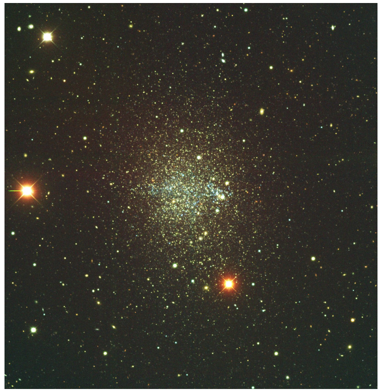
Annibali et al. (2016)

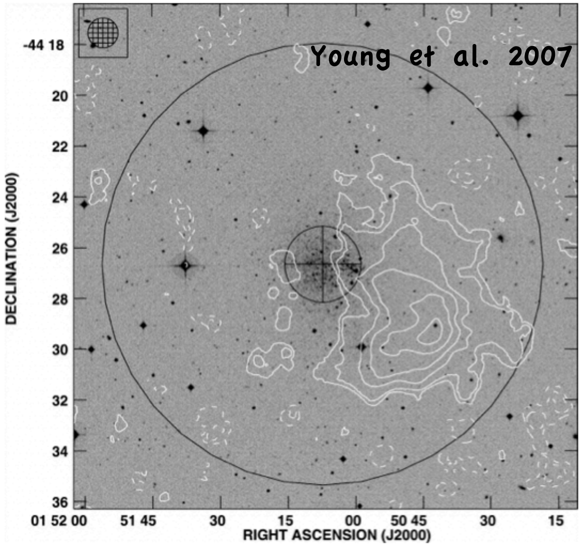
Local Group:
Andromeda II stellar mass ~ 10^7 Msun;
accreted system LV > 10^6 Lsun

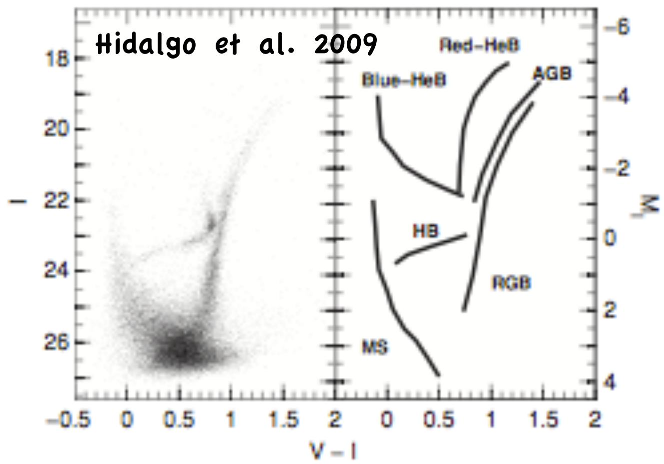


Amorisco, Evans & van de Ven (2014, Nature)

The Phoenix transition type dwarf (d=400 kpc)







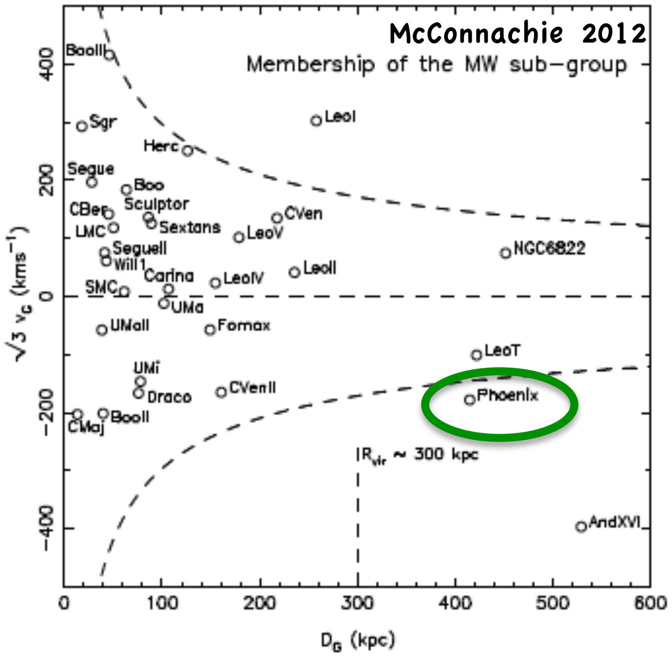
Lv ~ 10^6 Lsun, Mv = -10, as a typical MW dSph

Outside of the MW virial radius

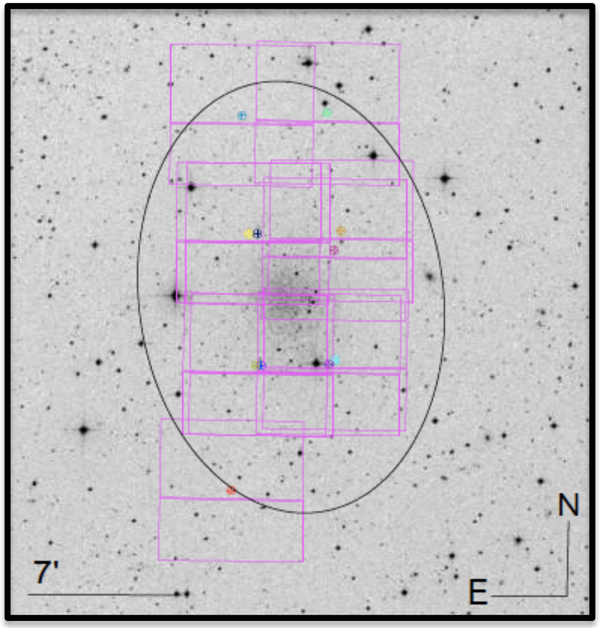
Associated to a nearby HI cloud (MHI ~ 10^5 Msun)

Vhel, HI cloud = -23 km/s; optical velocity from small samples of individual stars: -13 ± 9 km/s (Irwin & Tolstoy 2002); -52 ± 6 km/s (Gallart et al. 2001)

Likely approaching the Milky Way for the first time

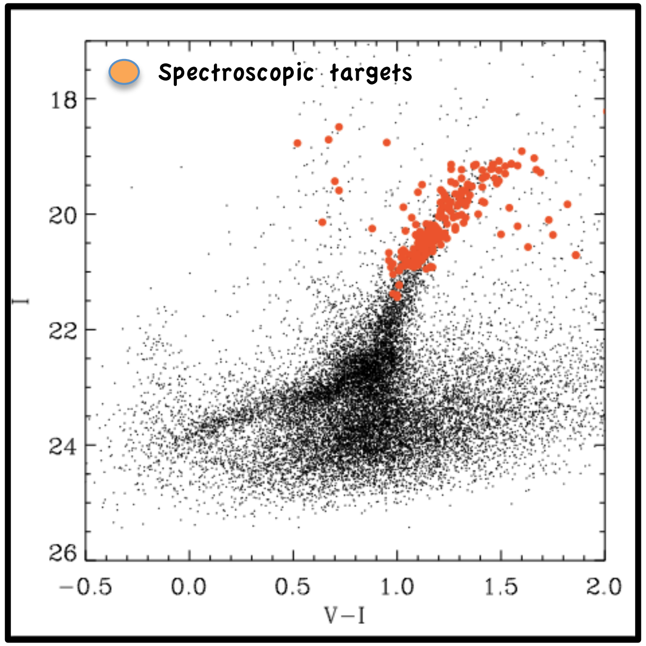


VLT/FORS2 wide-area photometry and MXU spectroscopy



Coverage V & I photometry

MXU spectroscopy

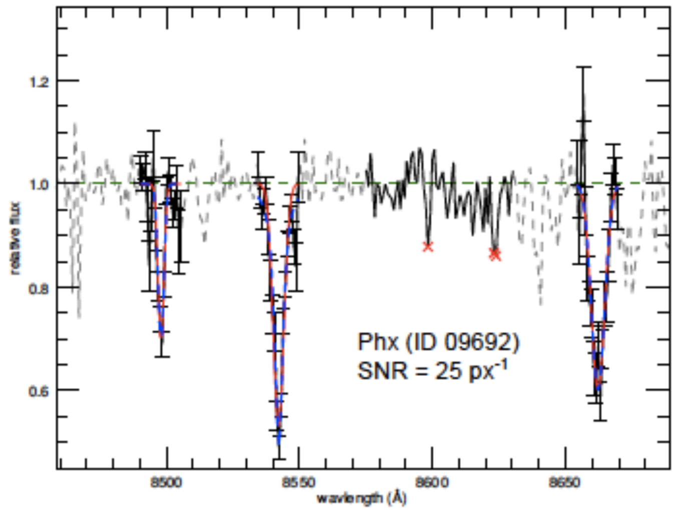


FORS2 MXU 1028z grism + OG590+32 OS (7730 - 9480Å ; R~2600)

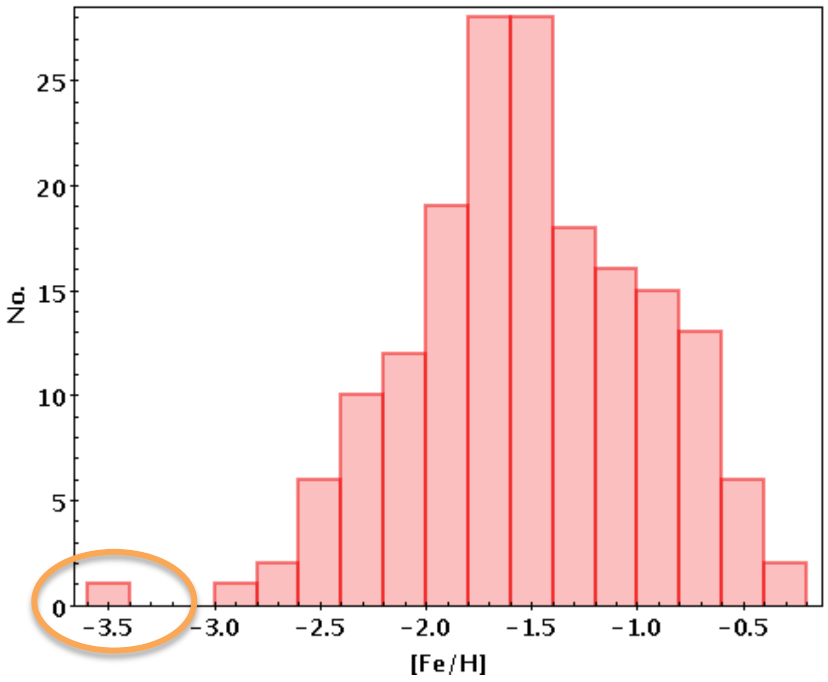
11 masks; exp time: from 1h to 3h per mask + 47tuc and M15 for calibration

234 target stars (RGB + random allocation of otherwise empty slits)

nIR CaT -> l.o.s. vel and [Fe/H] (calibration by Starkenburg et al. (2010, incl. Battaglia, tested over -4 < [Fe/H] < -0.5)



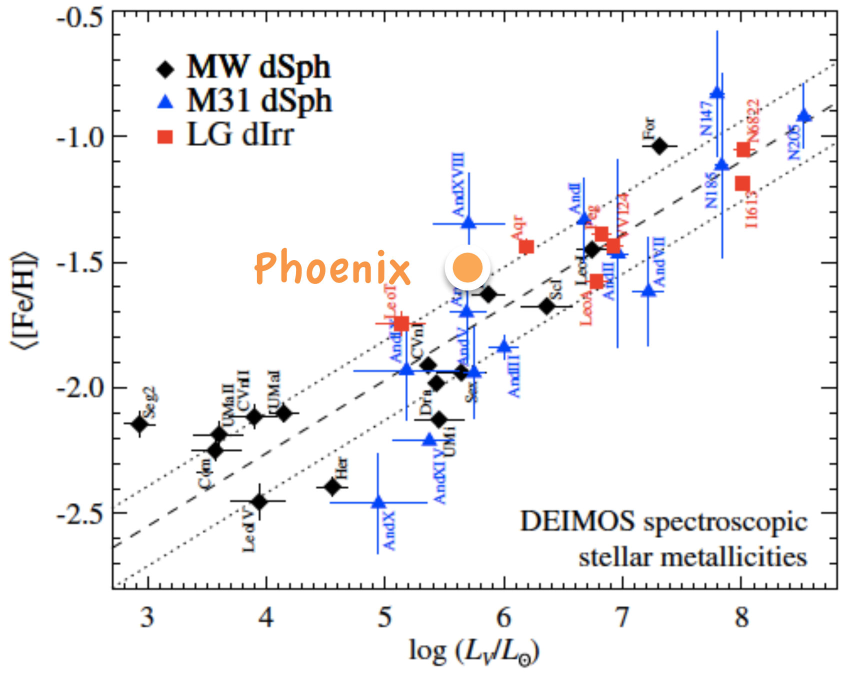
Overall metallicity properties



Broad distribution

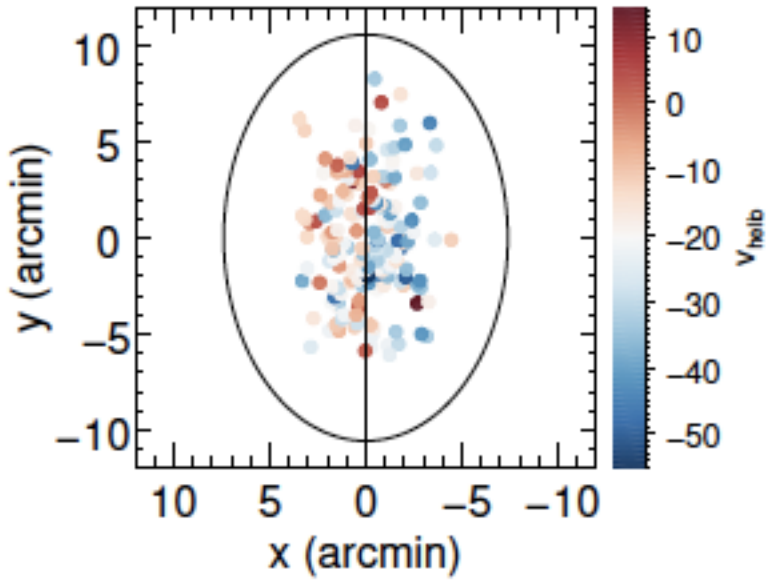
Median [Fe/H] = -1.5

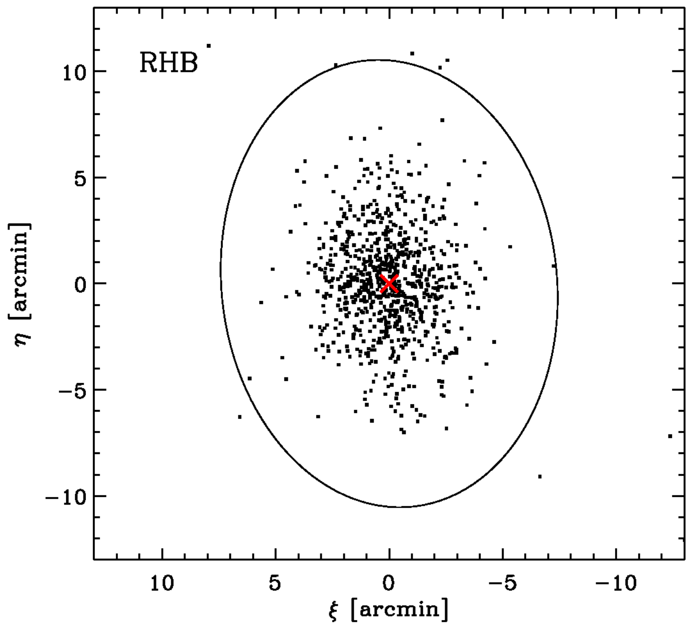
Candidate EMP star

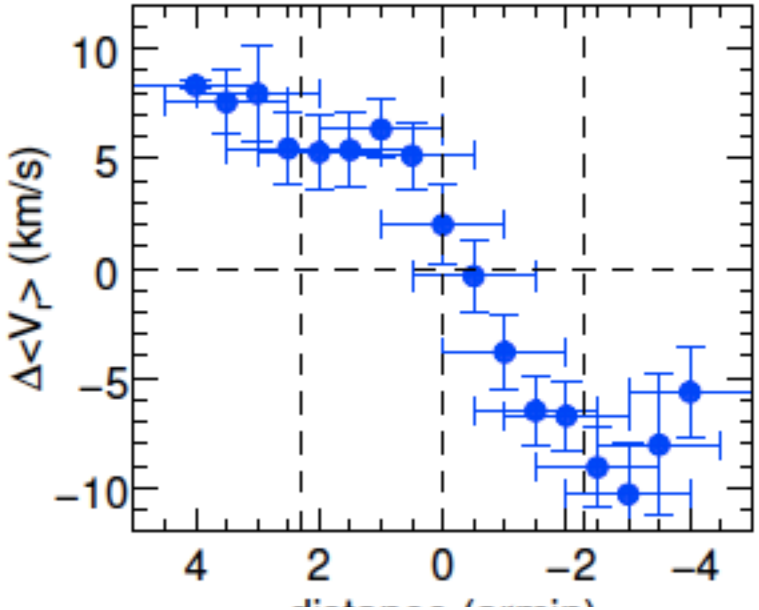


Kirby et al. 2014

Prolate rotation (Kacharov, Battaglia et al. 2017)



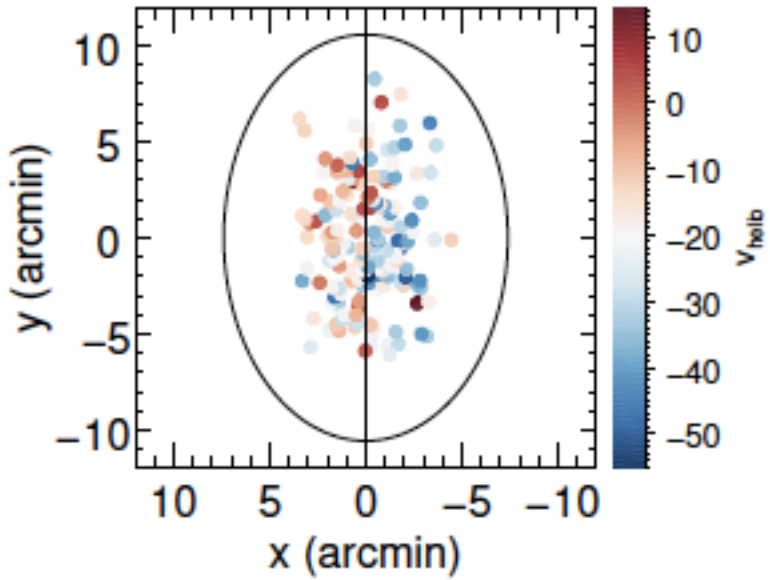


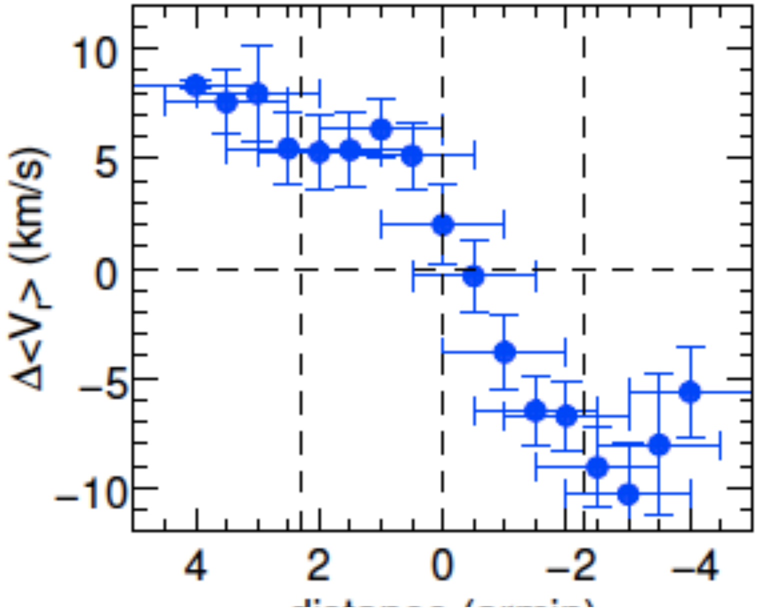


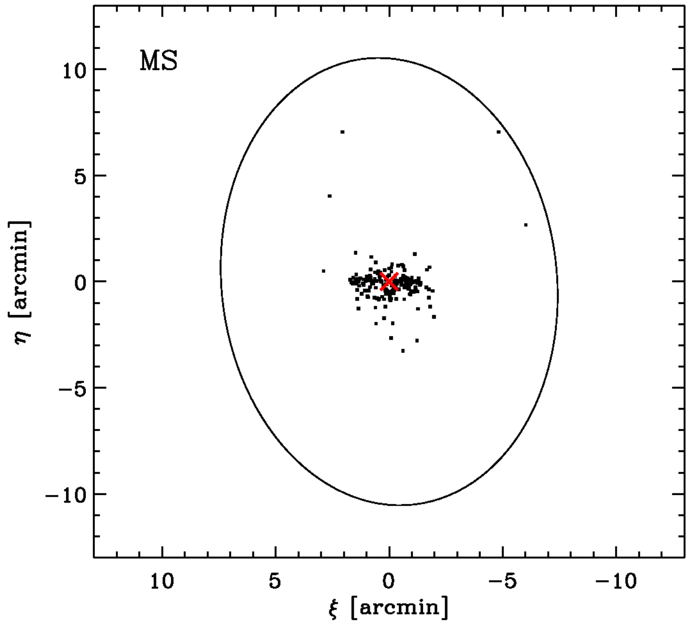
Maximum rotation signal aligned with:

- the projected minor axis -> prolate rotation; only 1 other known case in the LG (AndII, see Ho et al. 2012)
- the (tilted) distribution of the young stars

Prolate rotation (Kacharov, Battaglia et al. 2017)







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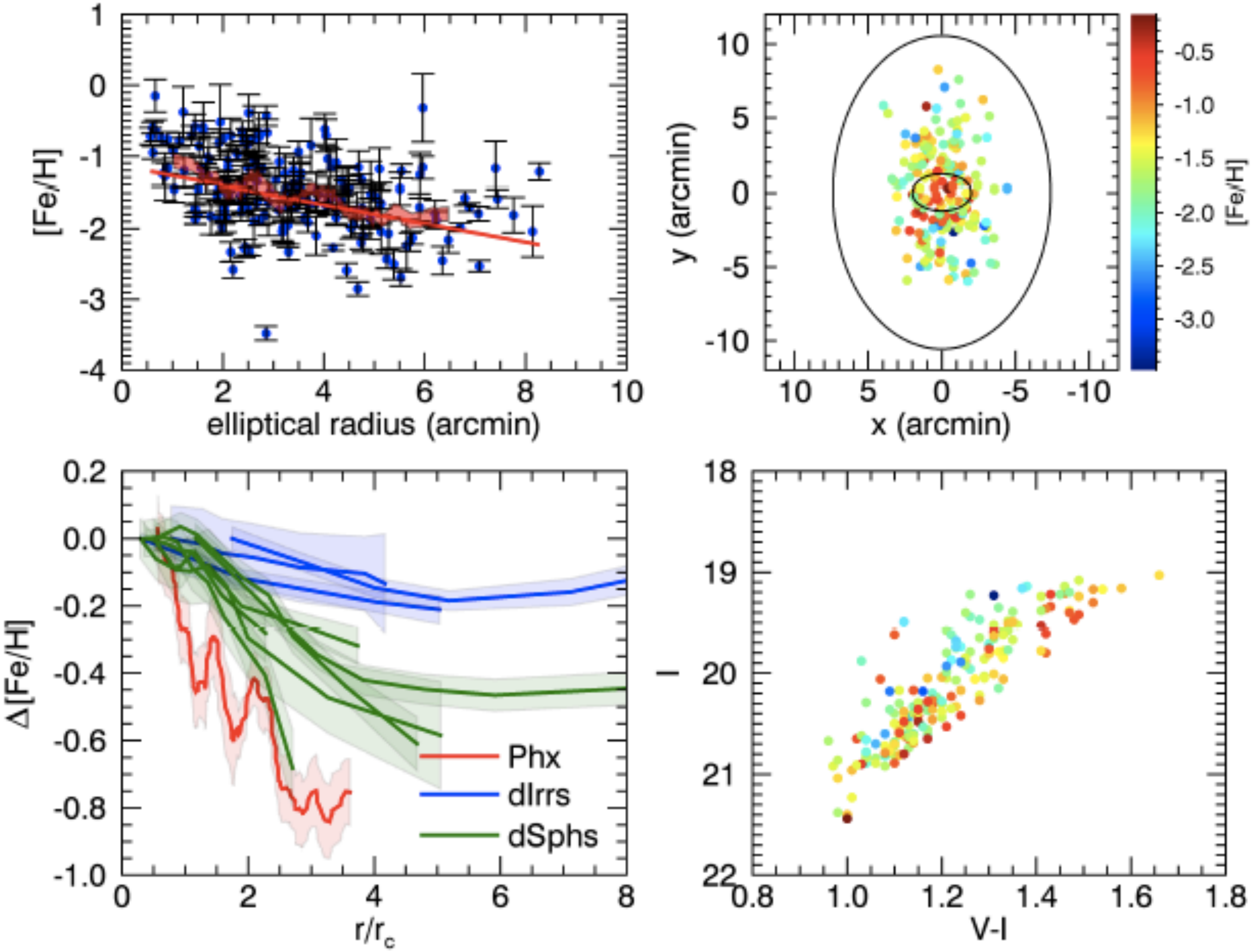
Metallicity gradient (Kacharov, Battaglia et al. 2017)



Points for discussion (part II)

- Is a merger/accretion event the only possible explanation for the observed signatures?

- How many of such mergers/accretion events do we expect for Local Group dwarf galaxies?