The internal kinematics of Local Group dwarf galaxies

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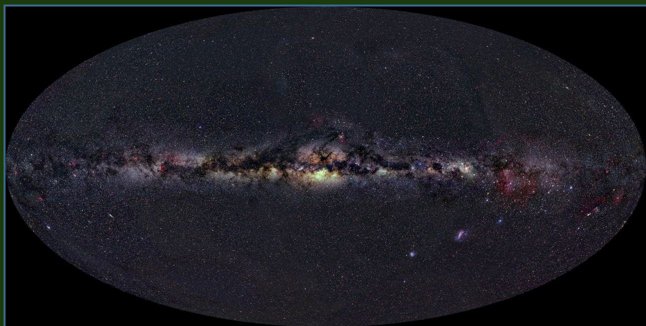
Recent review articles:

Battaglia, Helmi, Breddels 2013, New Astronomy Reviews
Walker 2013, Planets, Stars and Stellar Systems Vol. 5

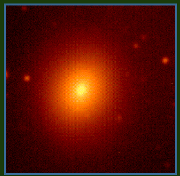
The inhabitants of the Local Group

Photo credits: Axel Mellinger, Eckhard Slawik, 1.1 Meter Hall Telescope, Lowell Observatory Bill Keel; Bruno Letarte; Belokurov et al 2010.

The Milky Way, LMC, SMC



Andromeda, M32, M33



& about 70 dwarf galaxies (so far) covering a wide magnitude range (-3 <~ M_V <~ -16)

Negligible in terms of stellar mass budget, but most numerous galaxy type -> What drives the evolution of the majority of galaxies?

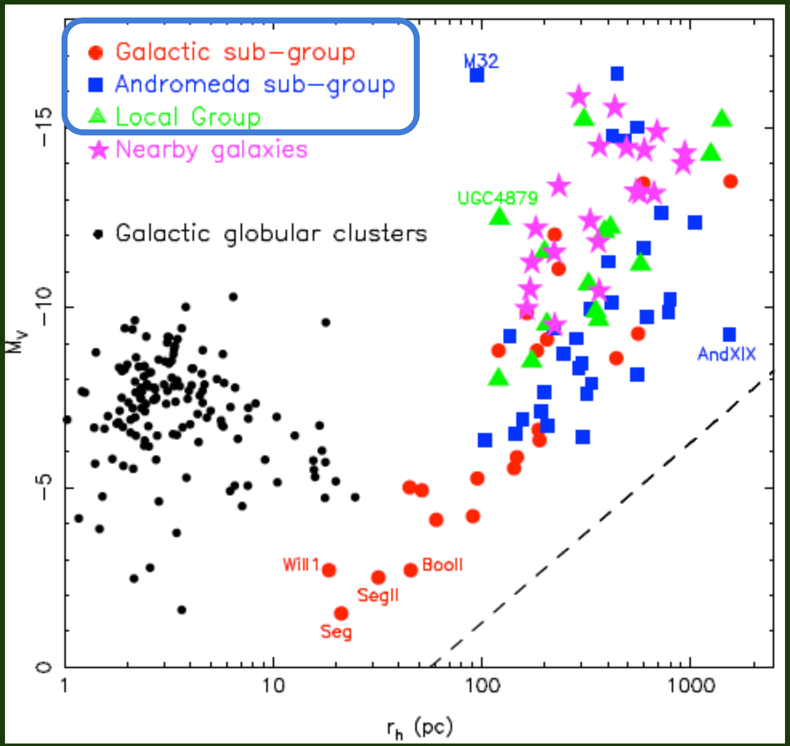


Fig. from compilation by McConnachie (2012)

Insights on several fundamental questions

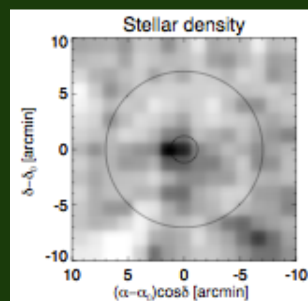
- Negligible in terms of stellar mass budget, but most numerous galaxy type -> What drives the evolution of the majority of galaxies?
- Overlap in luminosity and size with stellar clusters -> What distinguishes a stellar cluster from a galaxy? (Hint: the presence of dark matter...)
- Enourmous dynamical M/L (up to 1000s) -> What can we learn about the nature of dark matter?

What drives the evolution of dwarf galaxies? We ought to explain the existence of the various dwarf types

Without HI
No current star formation

With HI (only 14 out of 70 LG members)
Current SF — No current SF

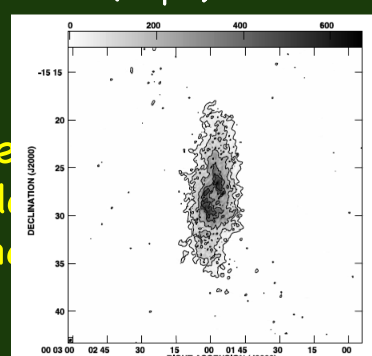
"Bright dwarf spheroidal (dSph)"

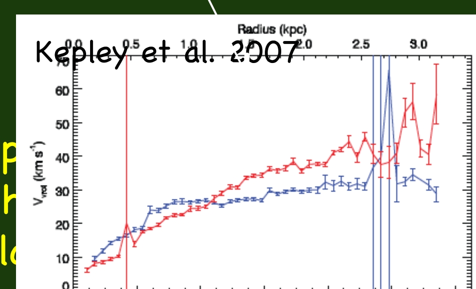


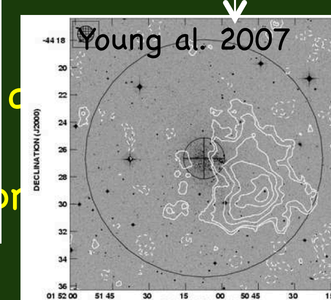
"Just a very faint dwarf spheroidal? (dSph)"

Dwarf irregular (dIrr)

"Transition type" (dT)



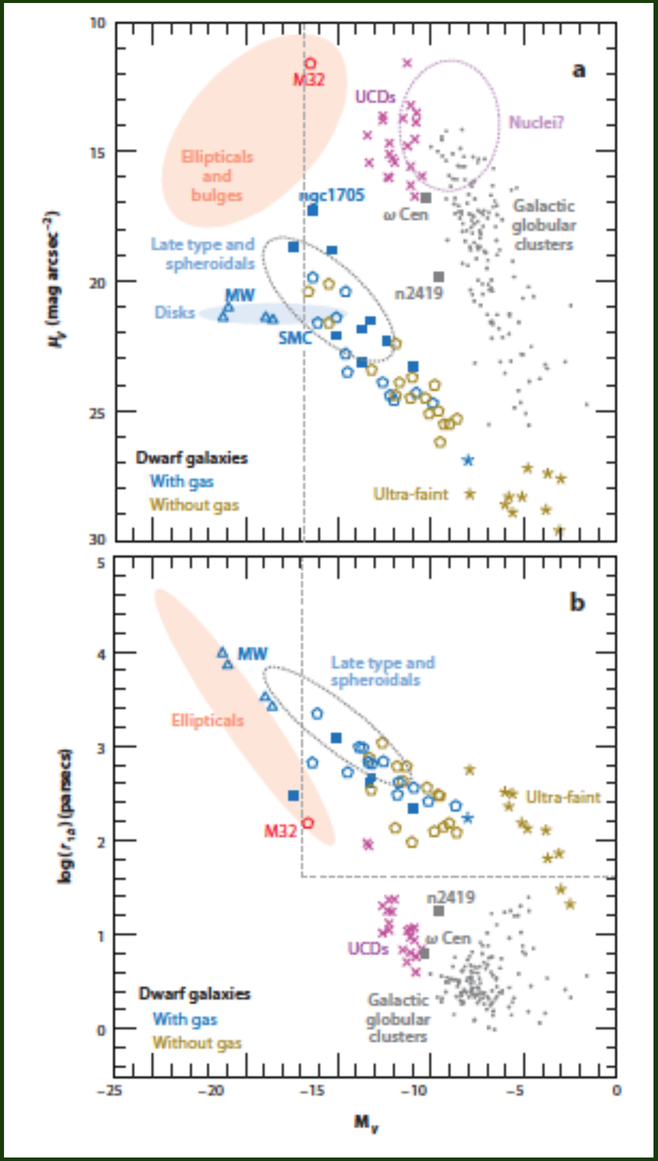




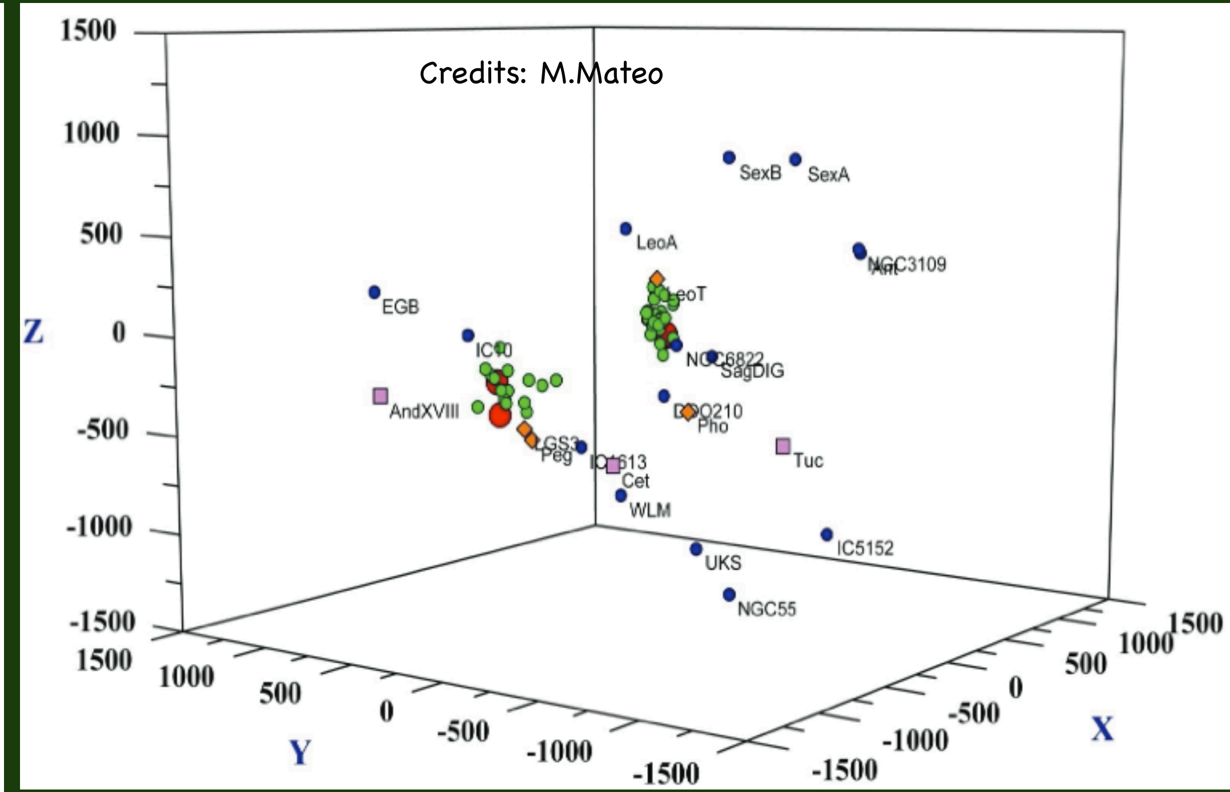
Step 1: Observational characte…
Step 2: Comparison (in what d…
Step 3: can we identify the m…

It is crucial to look at the evolved stellar component!

Global relations: evolutionary link?



Tolstoy, Hill & Tosi 2009, ARA&A, "Kormendy plot"



Dwarf irregulars

Dwarf spheroidals

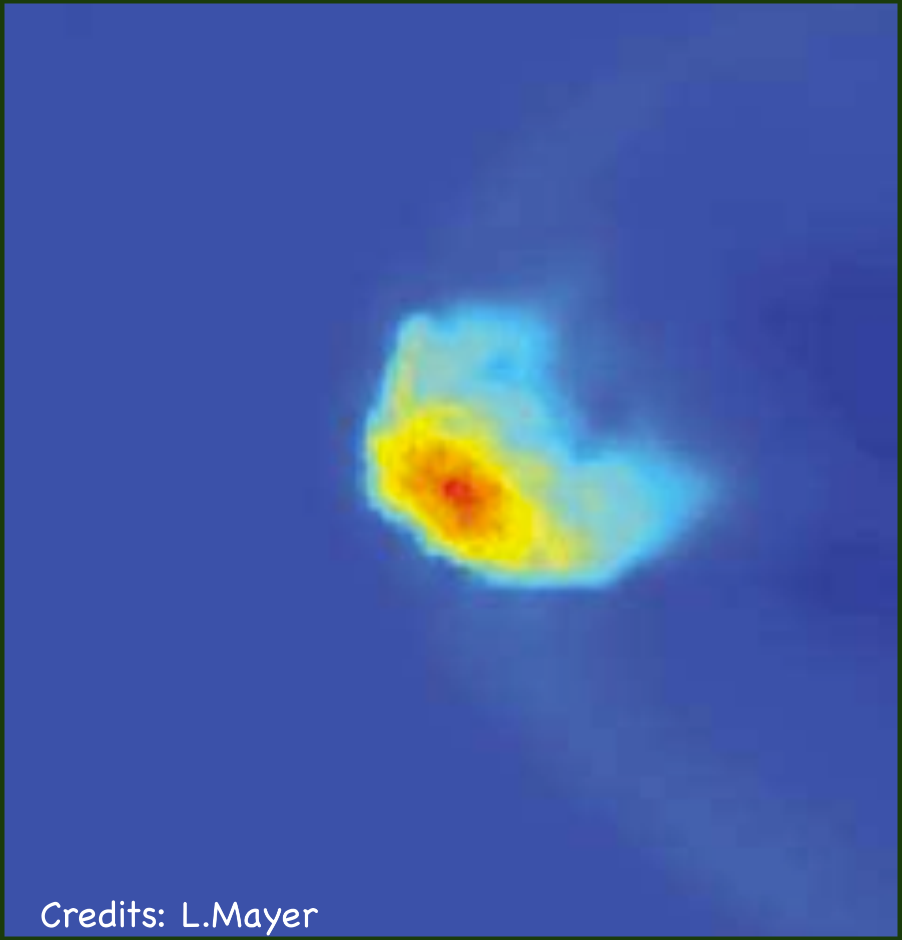
Transition dwarfs

Morphology density relation: a general characteristic of galaxy groups

Simple ram pressure stripping of the gas?

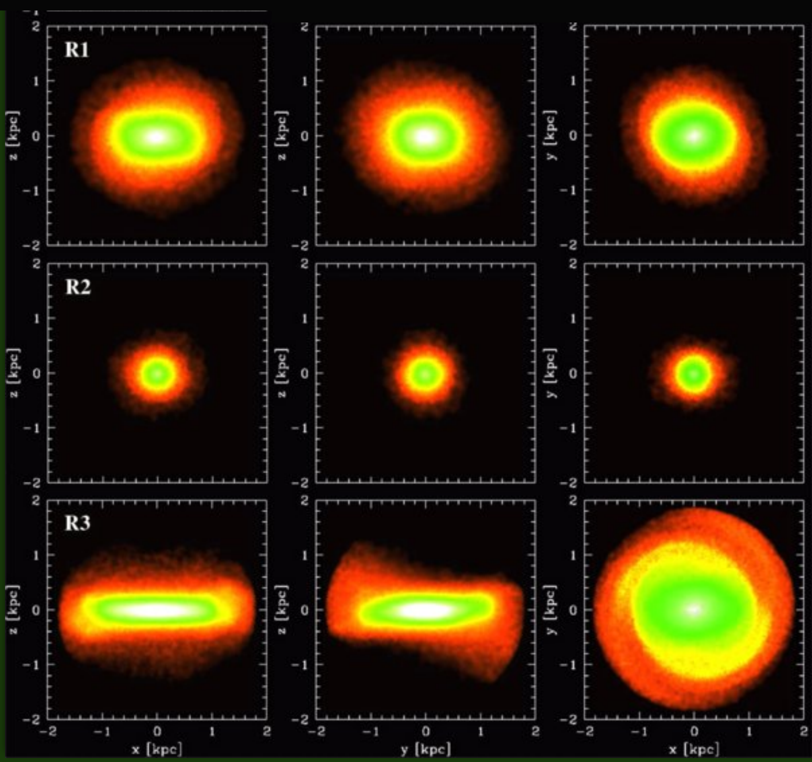
Only the gas is affected

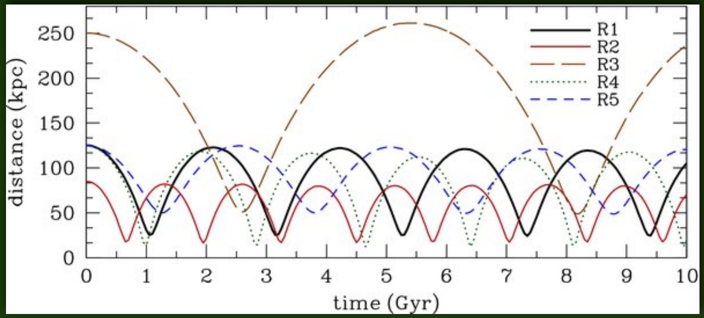
If late-type -> early-type:
no particularly different kinematics is expected for the stars



Most developed model on evolutionary links among late and early-type dwarfs (Mayer+2001, 2006, Kazantzidis+2011)

Both gas and stars are affected

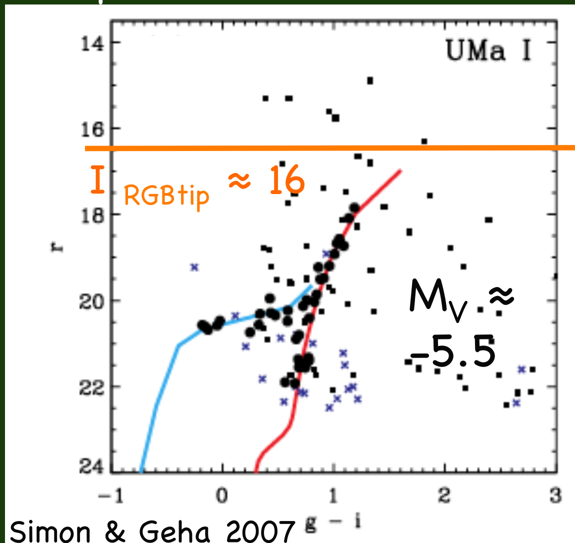




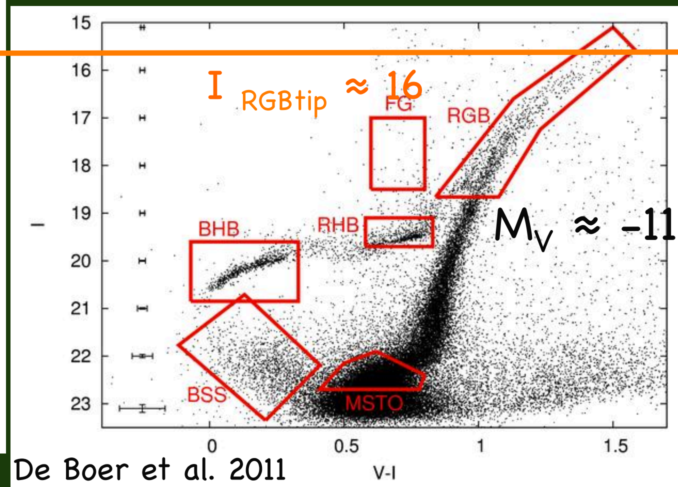
- A disky rotating dwarf galaxy (gas + stars) becomes spheroidal and non-rotating because of tidal stirring from the Milky Way.
- The gas is lost because of ram pressure stripping

Different issues throughout the Local Group

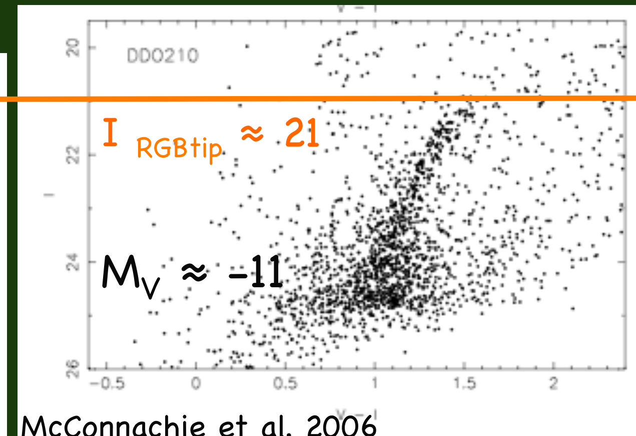
100kpc (within the MW halo)

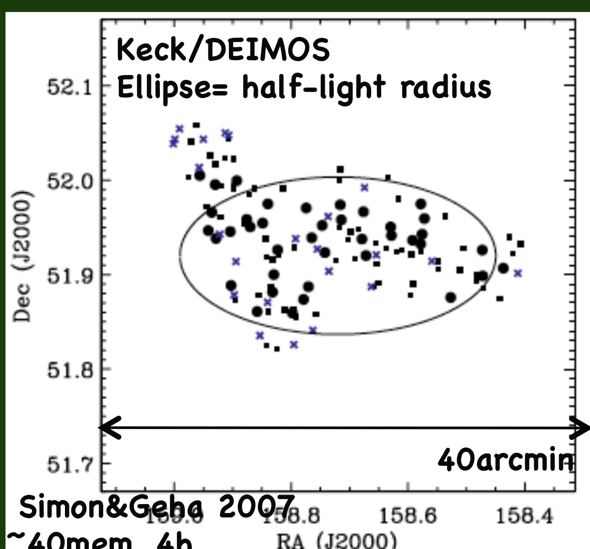


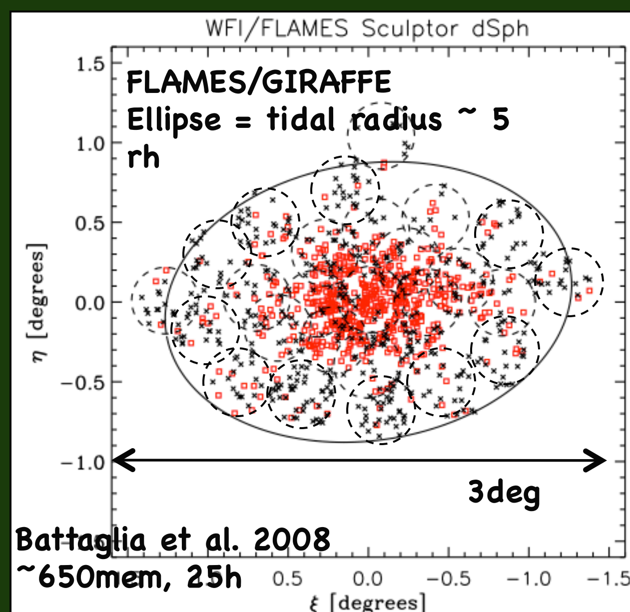
100kpc (within the MW halo)

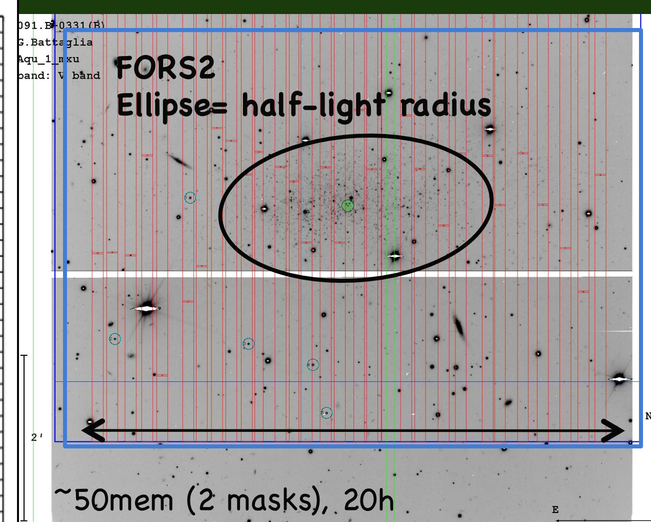


1 Mpc (Local Group outskirts)









Different samples throughout the Local Group: e.g. line-of-sight velocities and [Fe/H]

Very faint dSphs:

Predominanly within the half-light radius for 10-100 stars (mostly Keck/DEIMOS: Simon & Geha 2007, Martin et al. 2007, Kirby et al. 2011, Simon et al. 2011, Willman et al. 2011…)

Bright dSphs:

over a large area for 100s/1000s INDIVIDUAL stars (e.g., VLT/FLAMES: Tolstoy et al. 2004, Battaglia et al. 2008, 2011; Koch et al. 2006; WHT/WYFOS: Kleyna et al. 2002, 2004; Magellan/MIKE: Walker et al. 2007, 2009, Muñoz et al. 2006; Keck/DEIMOS: Koch et al. 2007, Sohn et al. 2007; MMT/Hectochelle: Mateo et al. 2008; ….)

Fornax -> 2900 member stars

Sculptor -> 1700 member stars

dIrrs/dTs/dSphs outside of the MW system:

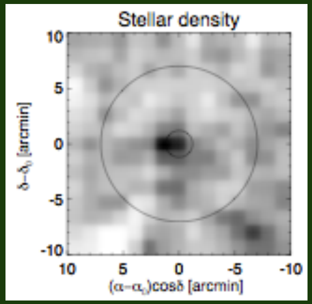
Smallest ones: reasonable spatial coverage

Large ones (e.g.ngc6822, IC1613): very restricted spatial coverage

Samples: 10s to 200 stars

(mostly Keck/DEIMOS, also FORS: Leaman et al. 2011, 2013, Kirby et al. 2012, 2013, etc.)

Exceptions: NGC147, NGC185, NGC205, AndII (several 100s stars over a wide-area, Geha et al. 2006, 2010, Ho et al. 2013)



Velocity gradients: possible causes and issues

- Intrinsic rotation

- Tidal disruption (e.g. Oh & Lin 1995 models of tidally disrupted dwarfs) -> likely negligible for isolated Local Group dwarfs

- We see the component along the line-of-sight : $v_{los} = v_{rot} * \sin i$

1) A bright late-type (isolated)

2) Bright early-types around M31

3) One "normally faint" late-type and one normally faint early-type (isolated)

4) "Normally faint" Milky Way early-types

WLM dI
(Leaman et al. incl. Battaglia 2012)

- M_V = - 14.6 (more luminous than dSphs, of the order of M31 dEs)
- Distance ≈ 1 Mpc
- Gas shows clear rotation (Kepley et al. 2007)
- CaT spectra gathered for 180 RGB stars with FORS and DEIMOS

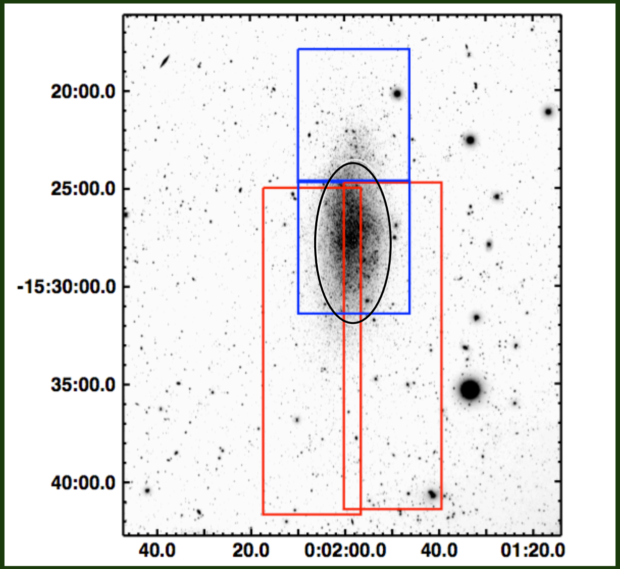


Figure from Leaman et al. 2012

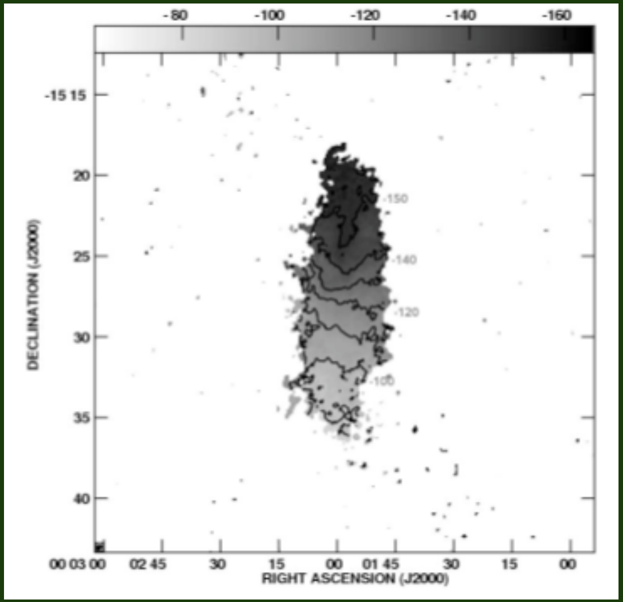
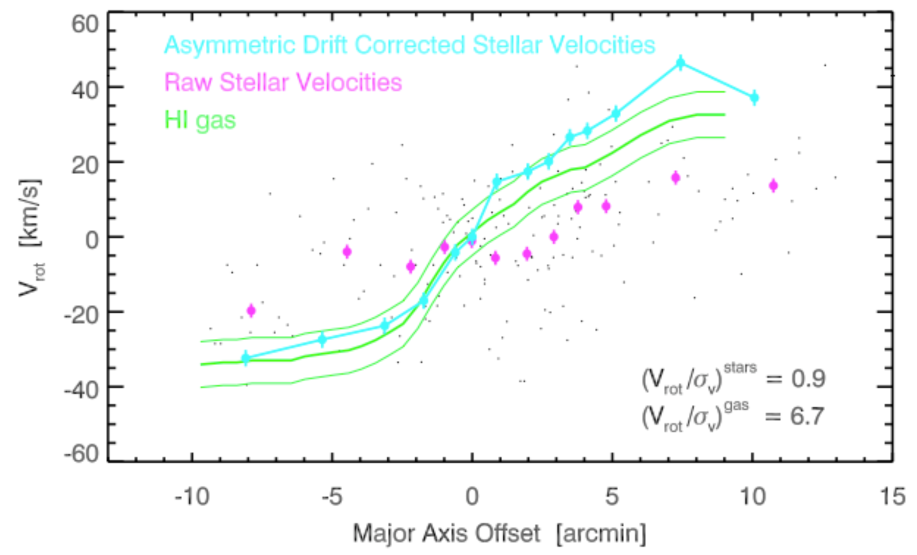
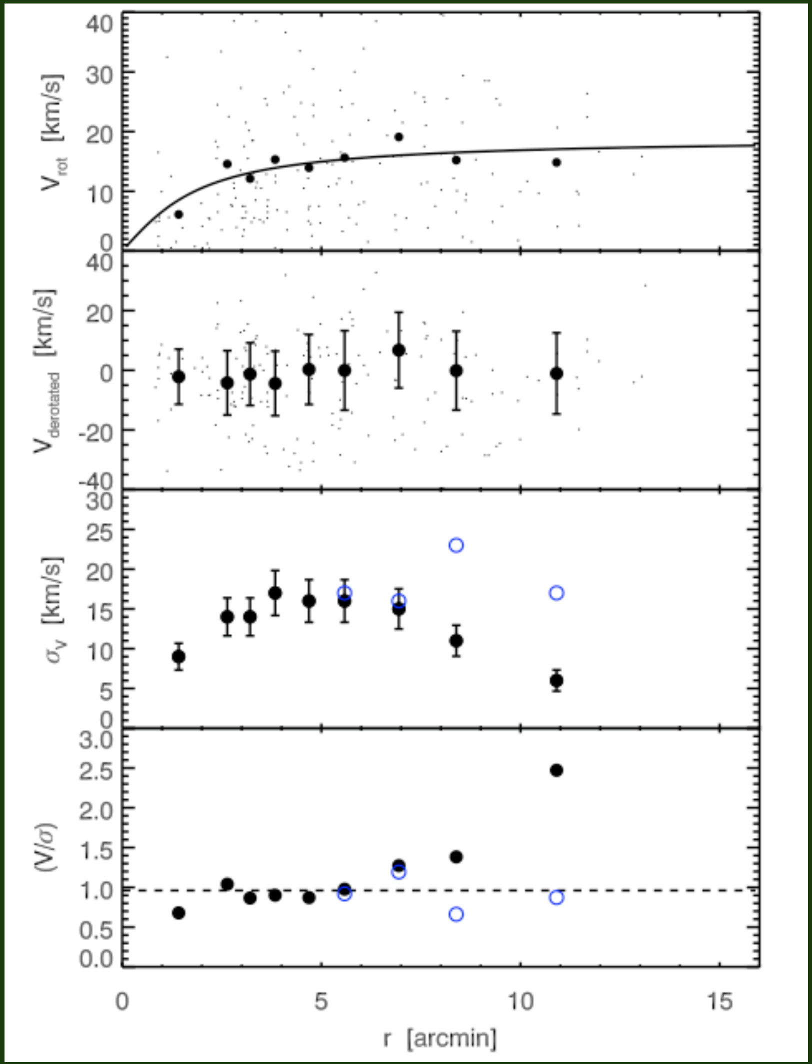


Figure from Kepley et al. 2007

Presence of rotation in the evolved stellar component
(v/sigma* is up to 2.5)

At face value the rotation in the HI gas and stars differ (max v/sigma* =2.5, max v/sigma_HI =6 -> one needs to correct for the asymmetric drift)





Dwarf ellipticals around M31

NGC147, NGC185 (M_V = -15.5), NGC205 (-16.6);

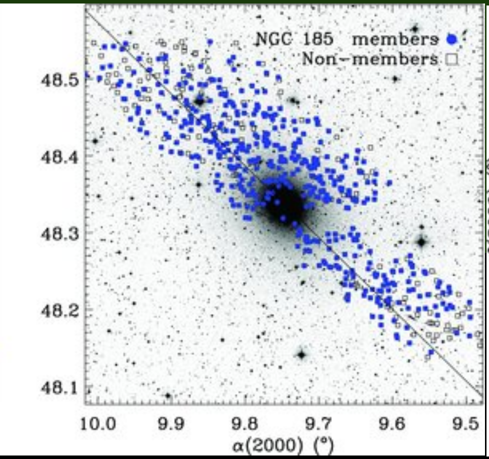
They kept forming stars until very recently.

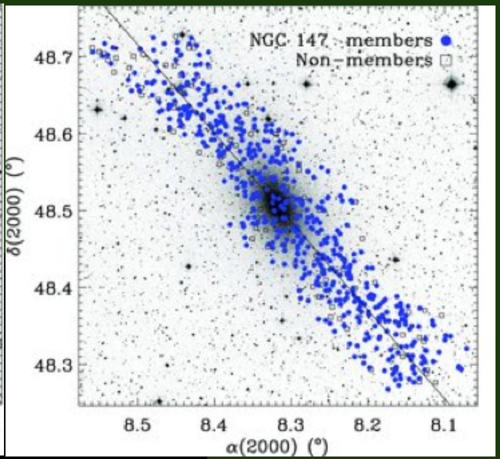
more luminous than dSphs and similar L to the WLM dIrr

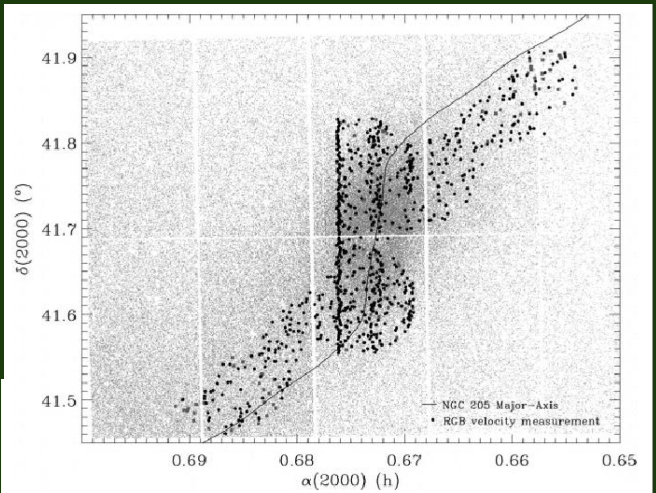
NGC 147, NGC 185, NGC205 (from Geha et al. 2006, 2010; spectra for a few hundreds RGB stars till 8 effective radii)

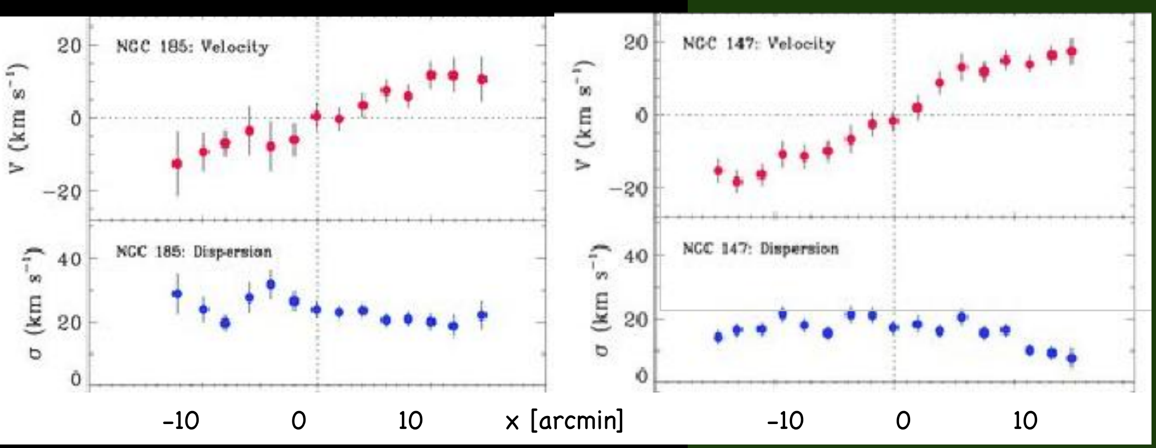
- -v/sigma increases with radius, to v/sigma = 0.5 (NGC185) & =2 (NGC147)
- -Very similar L and distance to M31
- -NGC185 ellipticity = 0.15 (almost "face-on"?)

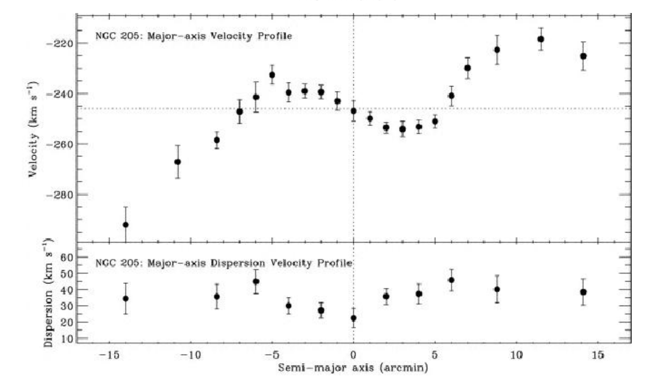
-NGC205: Velocity gradient with turn-around



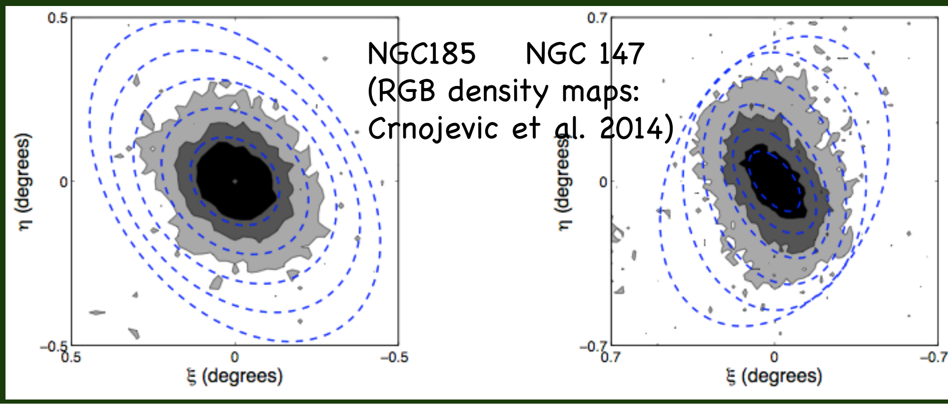




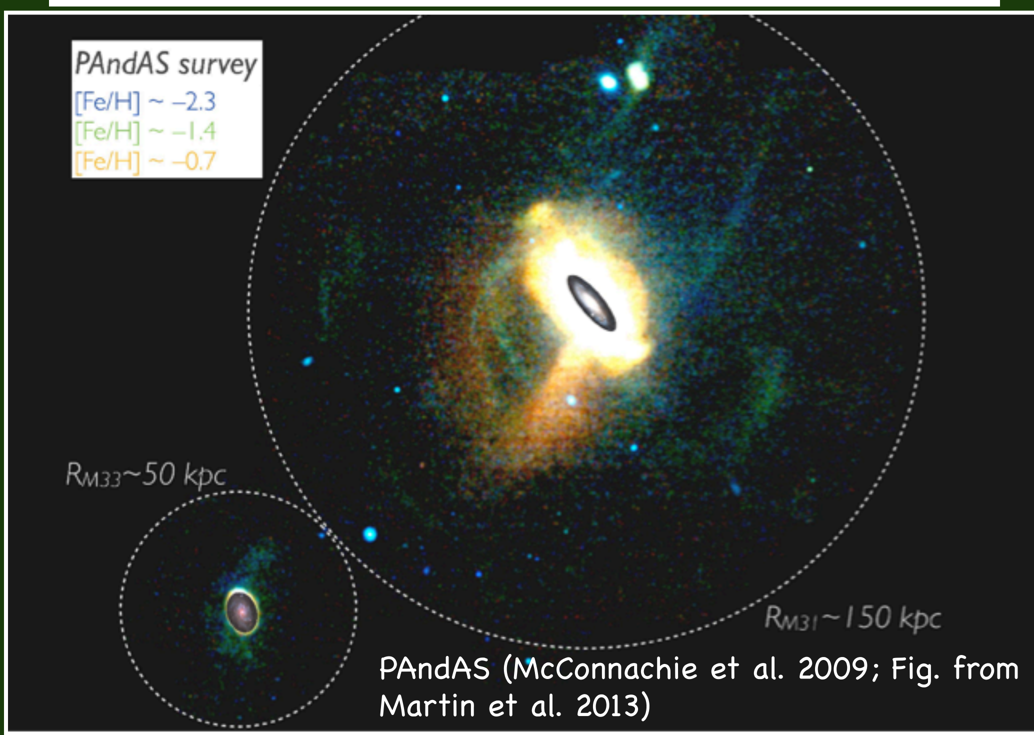




Two of them present clear signs of tidal disturbance



NGC185 NGC 147
(RGB density maps:
Crnojevic et al. 2014)



PAndAS (McConnachie et al. 2009; Fig. from Martin et al. 2013)

NGC205

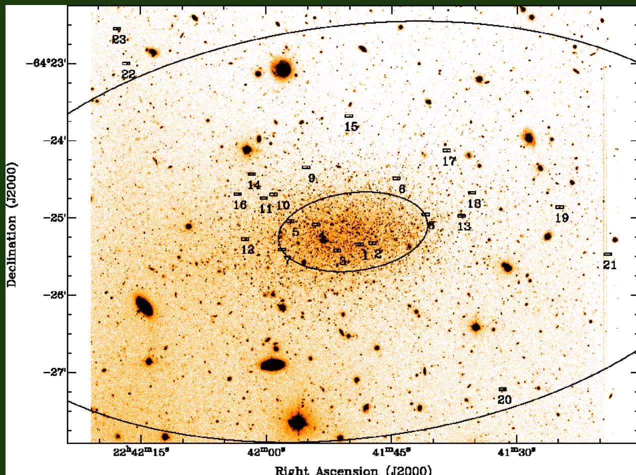
Credit & Copyright: Jean-Charles Cuillandre (CFHT) & Giovanni Anselmi (Coelum Astronomia), Hawaiian Starlight

A “normally faint” dSph and dT (isolated)

(far from both Milky Way and M31; tidal effects should be negligible)

Tucana dSph (M_V = -9.5; v/sigma ≈ 1)

Pegasus dT (M_V = -12.2; v/sigma ≈ 1-2)



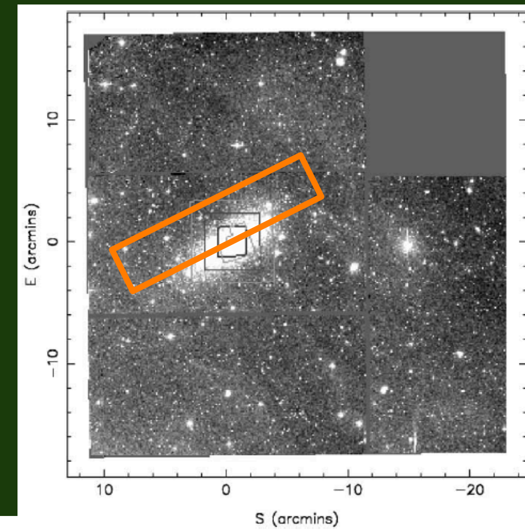
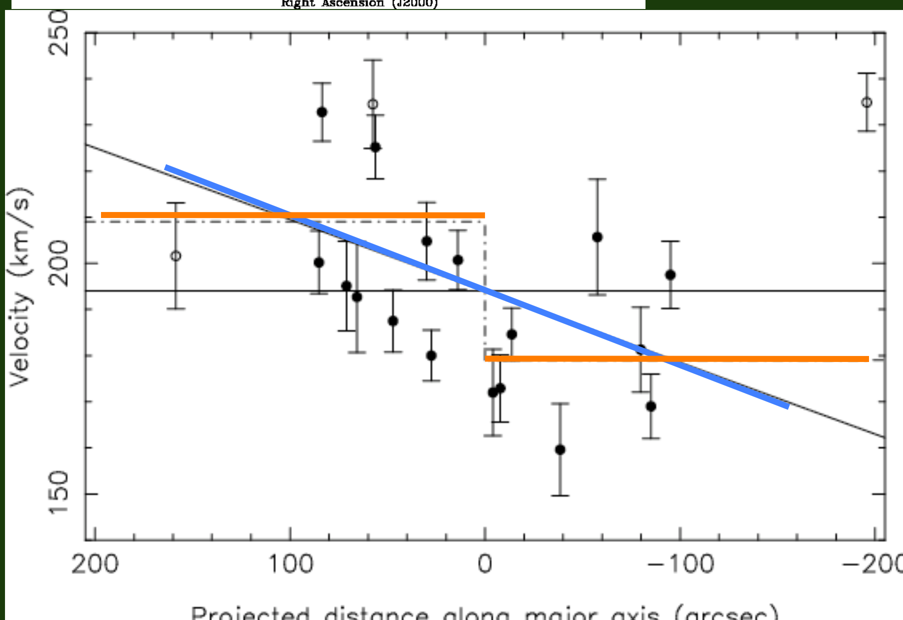
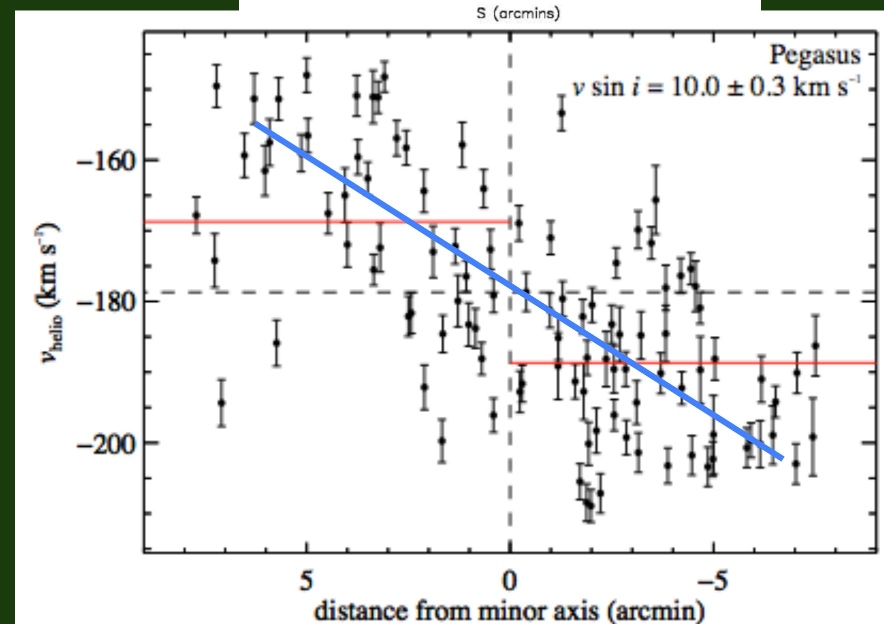


Fig. in McConnachie et al 2007



17 members observed with FORS2 (Fraternali et al. 2009)



100 members observed with Keck/DEIMOS (Kirby et al. 2014)

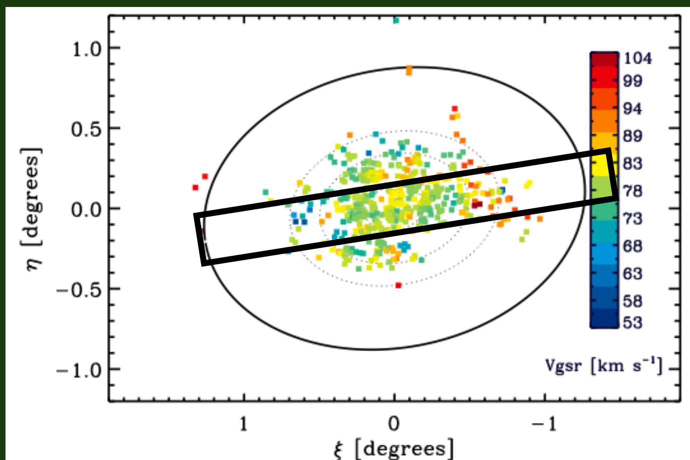
Milky Way dSphs

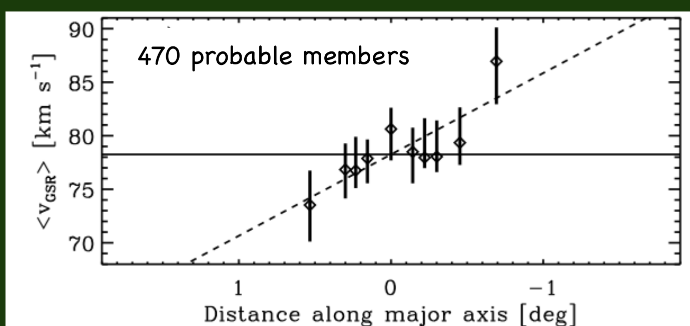
(they may be subject to tidal disturbance; only clear case of tidal disturbance seems to be the Carina dSph, e.g. Majewski et al. 2000, Muñoz et al. 2006, Battaglia et al. 2012, McMonigal et al. 2014)

Sculptor

Velocity gradient of $7.6^{+3.3}_{-2.2}$ km/s/deg along the projected major axis.

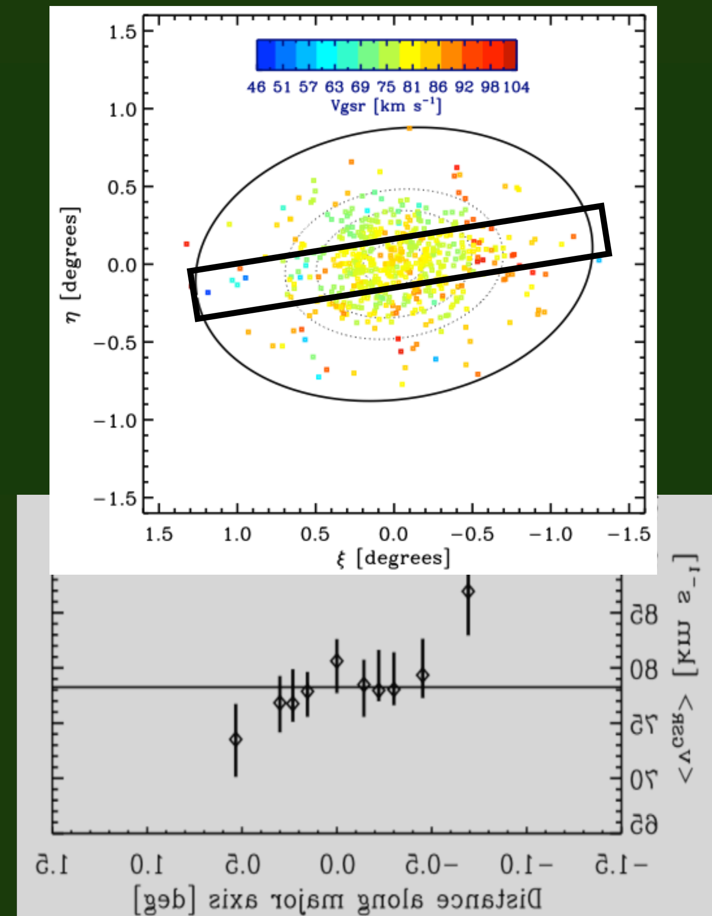
V/σ ≈ 0.6





Battaglia et al. 2008, ApJL, 681, 13

Velocities are corrected for the Local Standard of Rest and Sun motions

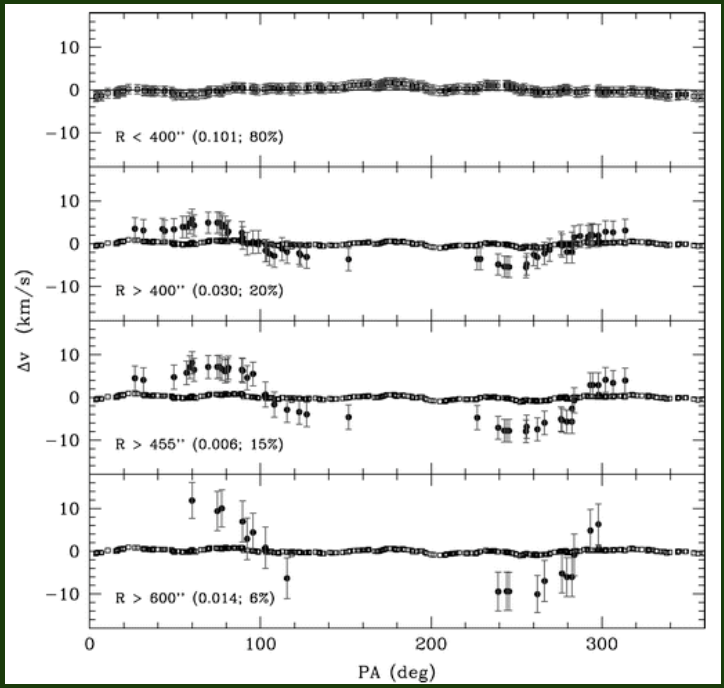


- Gradient still present when adding 150 members in the outer parts
- Confirmed by other studies (Walker et al. 2009,; Breddels et al. 2012)

Presence of velocity gradients in other MW dSphs

- 6.3±0.2 and 2.5±0.8 km/s/deg in Fornax and Carina (Walker et al. 2009)
- No measurements from wide-area surveys for Draco and Ursa Minor yet
- Not statistically significant in LeoII (Koch et al. 2007a), still uncertain for Sextans (Walker et al. 2009, Battaglia et al. 2011)
- Highly significant in LeoI when considering *only* the outer parts (Mateo, Olszewski, Walker 2008)

LeoI



Mateo, Olszewski, Walker 2008

Perspective effect

Effect due to the large extent of the sky of the object + the projection of the 3D motion along the line-of-sight;

it could be fully quantified when having accurate systemic proper motions

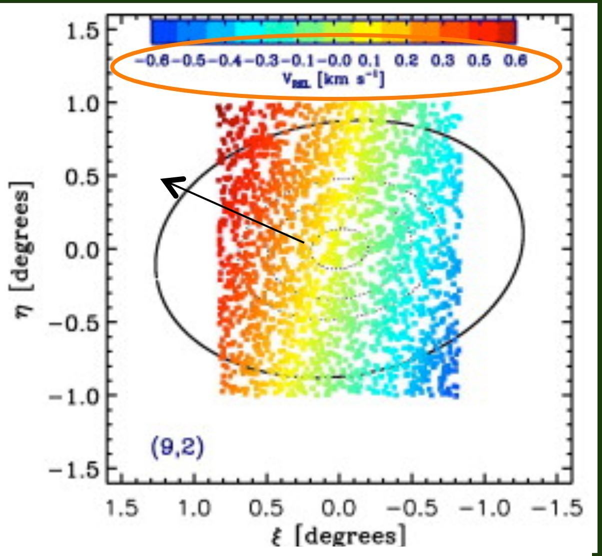
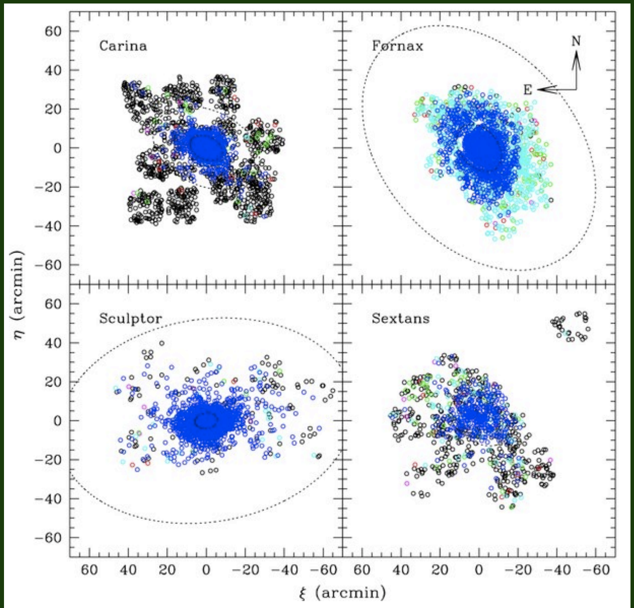


Fig. from Battaglia, Helmi, Breddels 2013, NARev; prop motion Piatek et al. 2006

Vel gradients due to transverse motion of the dSph onto the line-of-sight?



Walker et al. 2009

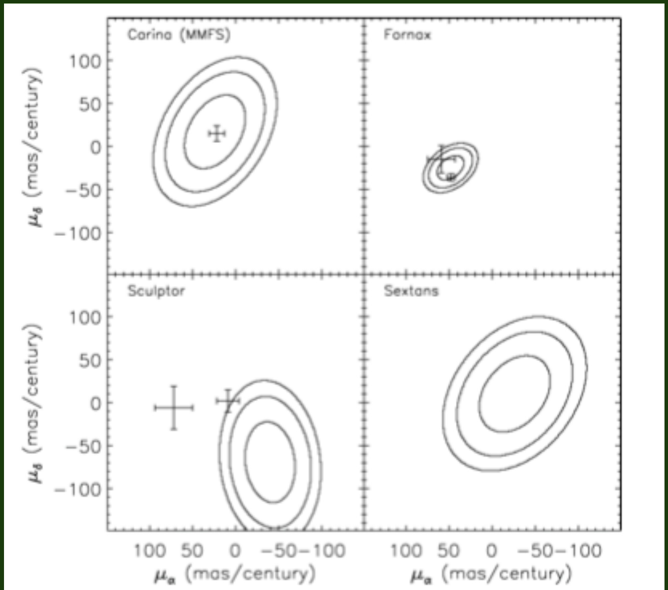


FIG. 1.—Proper motions measured from stellar redshift data. Contours indicate 1, 2, and 3 σ constraints on the PM of each dSph, obtained by evaluating eq. (6) using the MMFS velocity data. Points with error bars indicate published PM measurements derived from precise astrometry (Carina [Piatek et al. 2003]; Fornax [Dinescu et al. 2004; Piatek et al. 2007]; Sculptor [Schweitzer et al. 1995; Piatek et al. 2006]). Where two measurements exist, the *HST* measurement has smaller error bars.

- Gradient in Sculptor cannot be explained by proper motion alone (Walker et al. 2009; Breddels et al. 2012), in Carina and Fornax yes (Walker et al. 2009)
- Outer parts of Fornax, Sextans still to be explored
- Determination in Carina seems to contrast with much larger value by Muñoz et al. (2006)

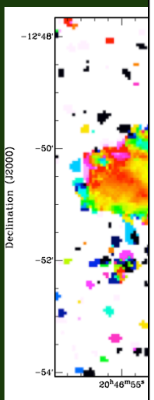
The HI gas (images not on scale)

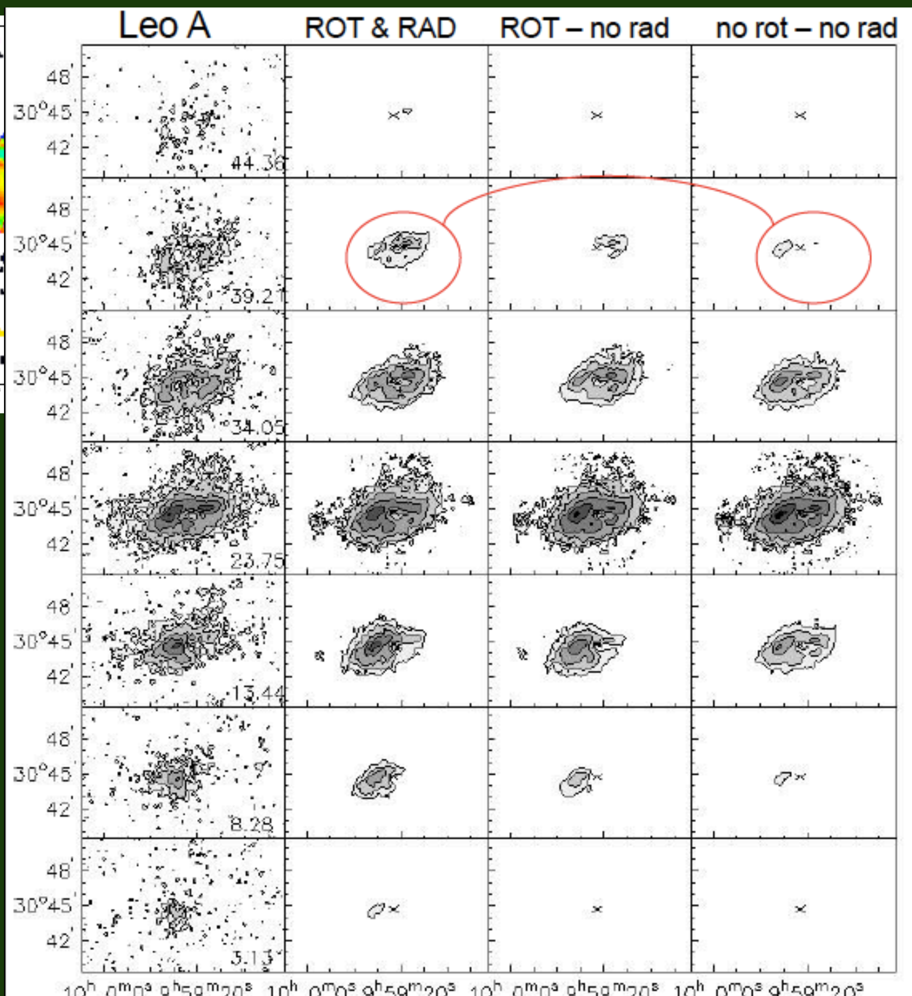
Aquarius dT: Mv = -10.6; vrot~ 6 km/s

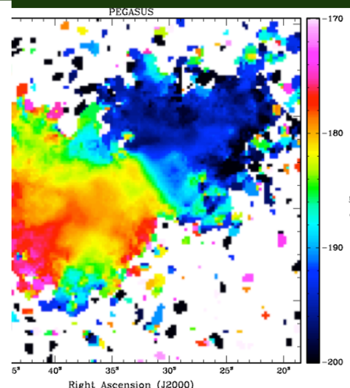
Sagittarius dIrr: Mv = -11.5; vrot~ ??

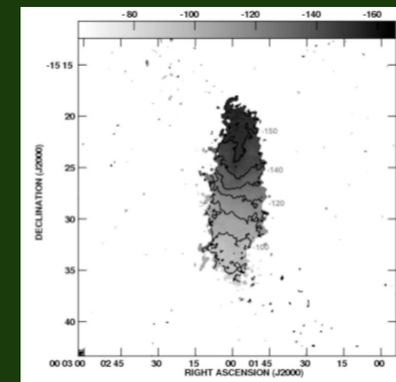
Pegasus dT: Mv = -12.2; vrot~ 10 km/s

WLM dIrr: Mv = -14.2; vrot~ 30 km/s









Kepley et al. 2007

dSph

LeoA dIrr; M_V = -12; vrot ≈ 3.5km/s (Robin-Gopala, master thesis)

- We are only beginning to explore the internal kinematic properties of evolved stars in LG dIrrs, dTs and isolated dS

For similarly luminous systems, the amount of rotational vs "pressure" support seems comparable (and increases with luminosity), no matter if we look at early or late-types.

Perhaps simple ram-pressure stripping of the gas would suffice in transforming a late- into an early-type dwarf

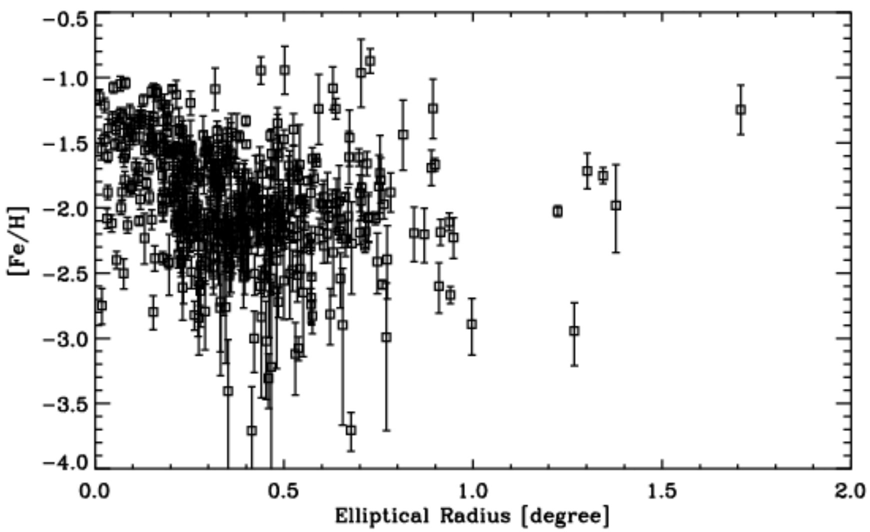
- Th … o ro … es (n … ore th

- We still lack a detailed quantification of the v/sigma in MW dSphs
- Systemic proper motions for MW dSphs from Gaia will allow us to define the vlos gradient due to the 3D motion of the system
- (We need an efficient pre-selection of likely RGB stars in the outer parts of MW dSphs)

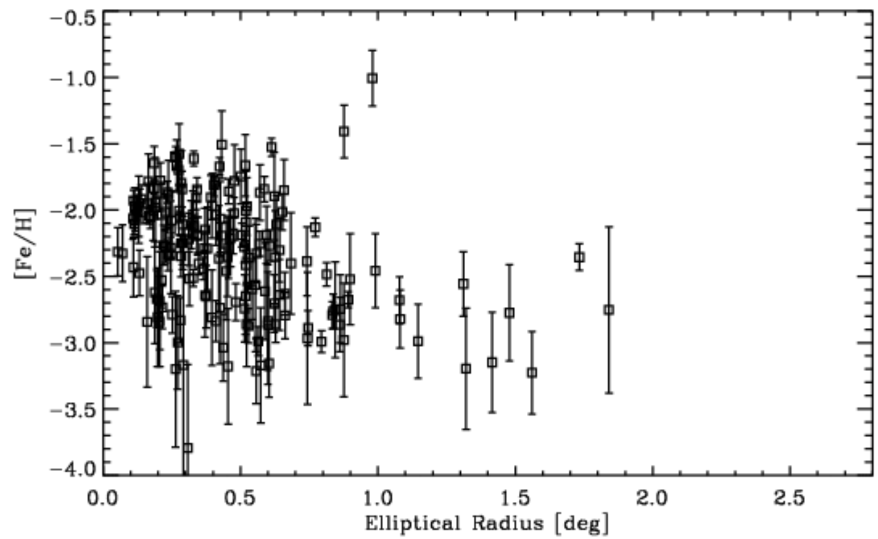
Links between internal kinematics and metallicity properties

Spatial variations of metallicity properties in MW dSphs from SPECTROSCOPY of RGB stars

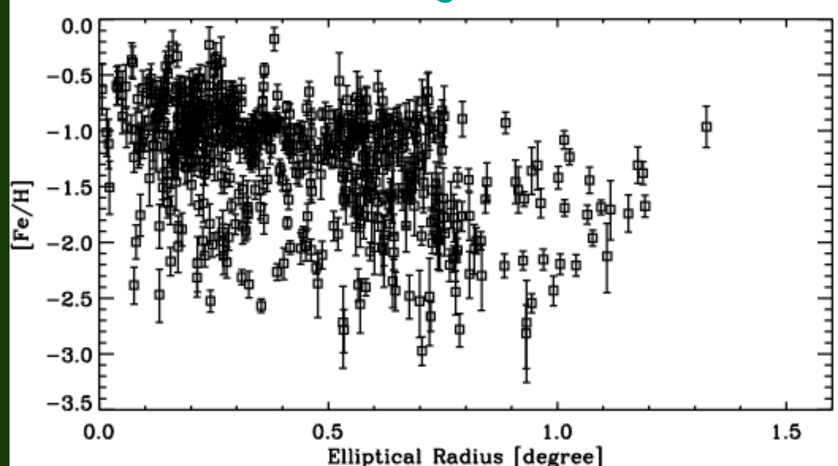
Sculptor (Tolstoy et al. 2004)



Sextans (Battaglia et al. 2011)



Fornax (Battaglia et al. 2006)



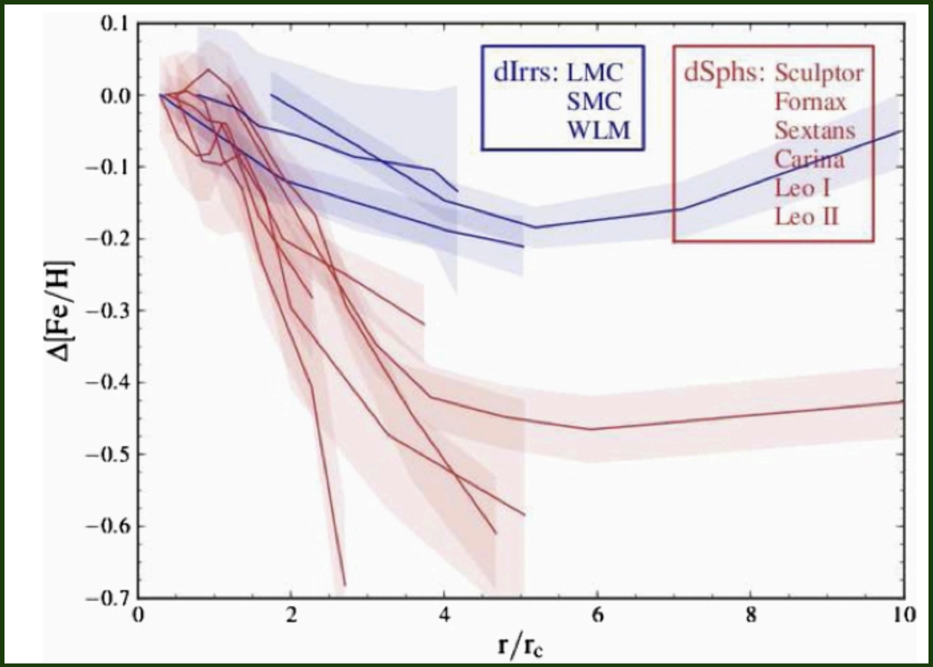
(see also e.g. Koch et al. 2006; Faria et al. 2007; Gullieuszik et al. 2009; Kirby et al. 2011)

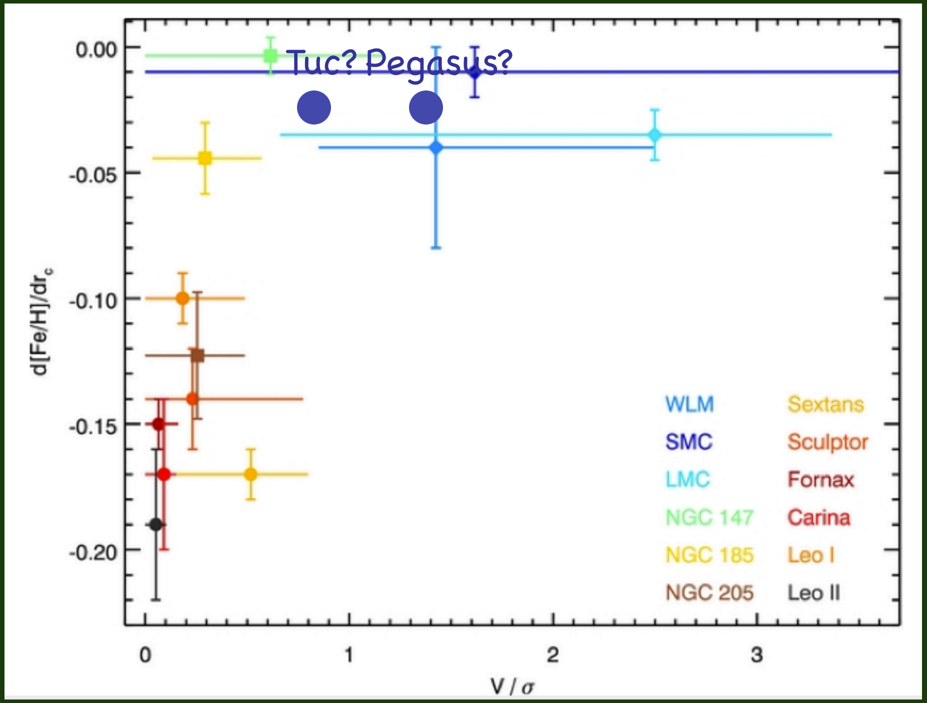
[Fe/H] from CaT lines calculated using the calibration from Starkenburg et al. 2010

Similar information is not yet in the literature for the great majority of dTs and dIrrs

A "centrifugal barrier" mechanism?

There are indications for a relation between v/sigma and steepness of the metallicity gradient (Leaman et al. 2012)





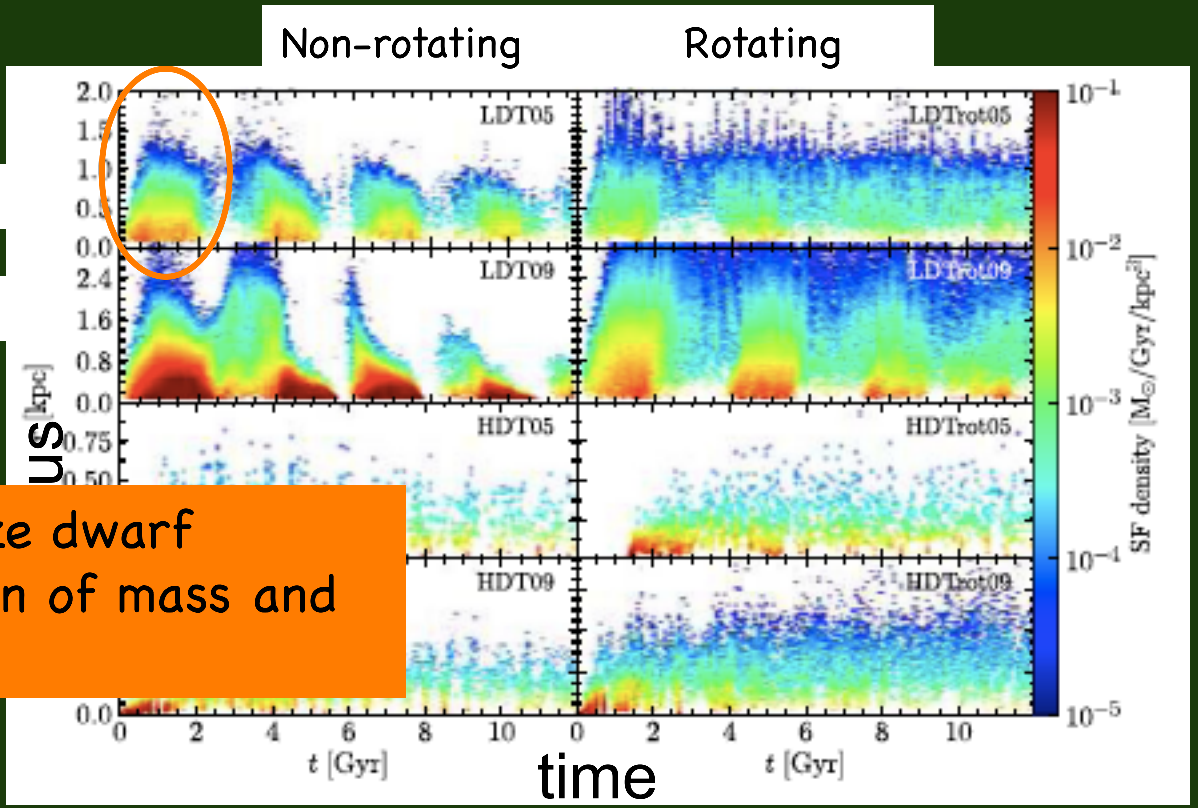
A "centrifugal barrier" mechanism?

Simulations show that the main parameters driving the gradients are:

-(Total) Mass : the larger the stronger the gradient
-Angular momentum: the lower, the stronger the gradient
(e.g. Schroyen et 2011, 2013), in agreement with findings outside of the Local Group (e.g. Koleva et al. 2011)

Less massive (Mdm ~ 5 x 10^8 Msun)

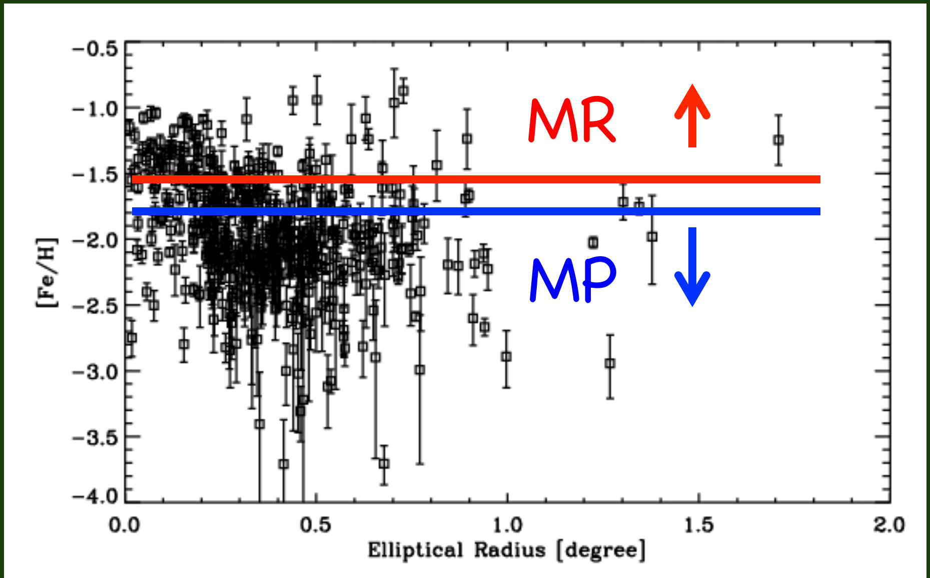
More massive (Mdm ~ 3 x 10^9 Msun)

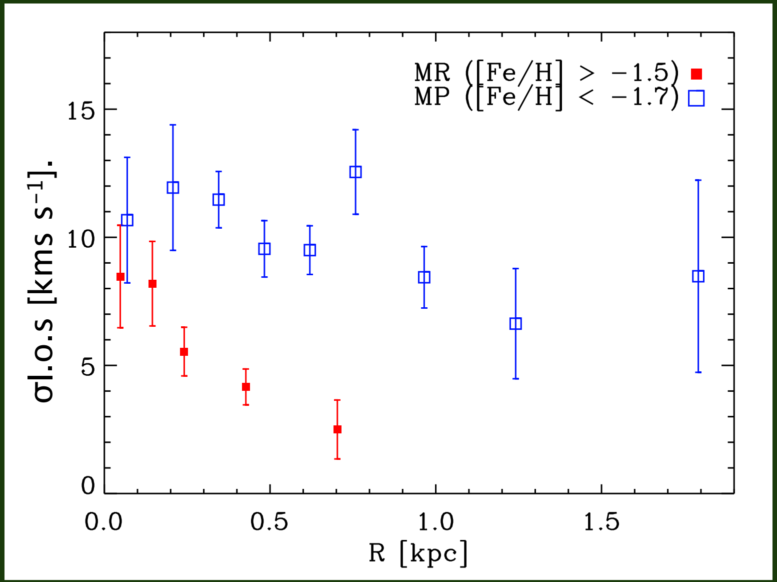


Interesting to analyze dwarf galaxies as a function of mass and angular momentum

"Chemo-dynamical" stellar components found in the MW dSphs Sculptor, Fornax, Sextans (Tolstoy et al. 2004, Battaglia et al. 2006, 2008, 2011) and Draco

(Walker, talk at the workshop "Satellite galaxies and dwarfs in the Local Group", 2014)

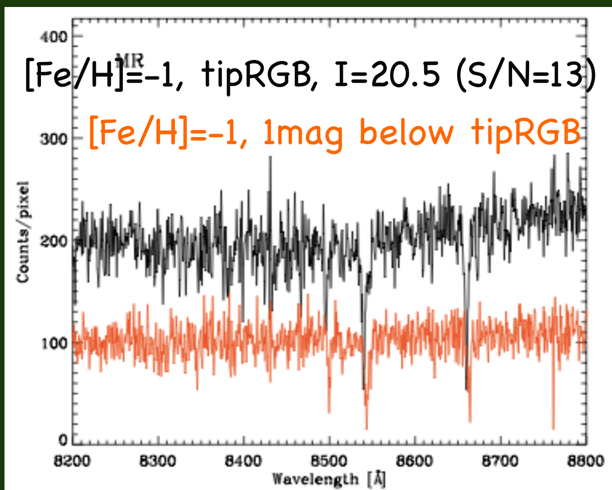


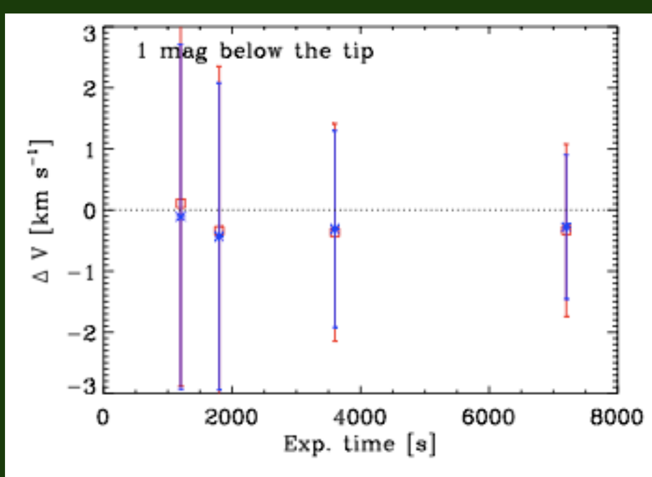


- Useful to place constraints on the slope of the dark matter halo density profile (e.g. Battaglia et al. 2008, Walker & Peñarrubia 2011, Amorisco & Evans 2012, Agnello and Evans 2012)
- Further observational constraint for models of the evolution of MW dSphs
- If this is a general characteristics of dwarf galaxies, what effect does it have on measurements from integrated light spectroscopy? (in most cases the populations are both very old, > 8 Gyr)

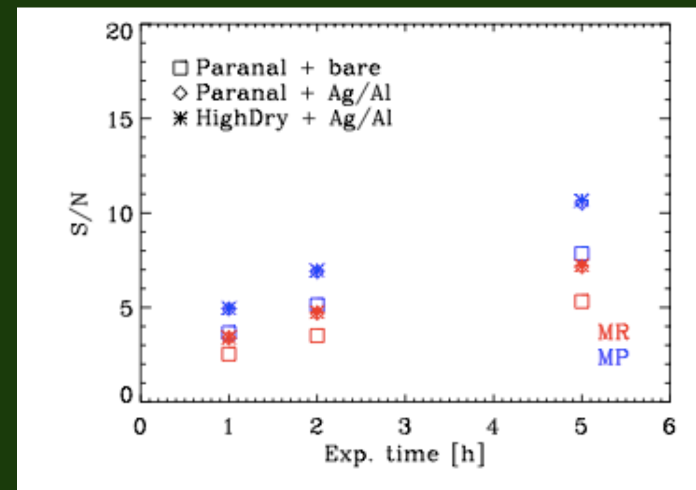
Expected performance with first light E-ELT spectrograph (HARMONI-like) – simulations by G.Battaglia within the E-ELT Design Reference Mission (plots consider 1 spaxial pixel,50masx50mas; LTAO; R=6500; D= 42m; target overlaid onto the galaxy background) (see talk by N.Thatte)

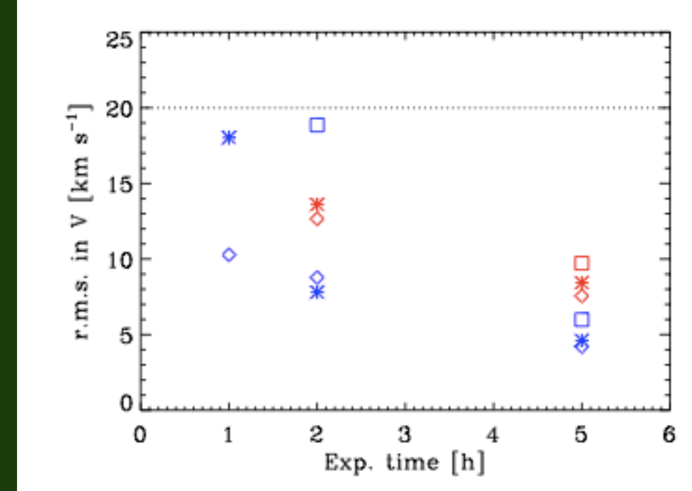
20min; target at 800kpc





target at 4Mpc; I=23.8/24





Dwarfs & E-ELT spectrographs (e.g. E-ELT IFU & MOSAIC): within the Local Group

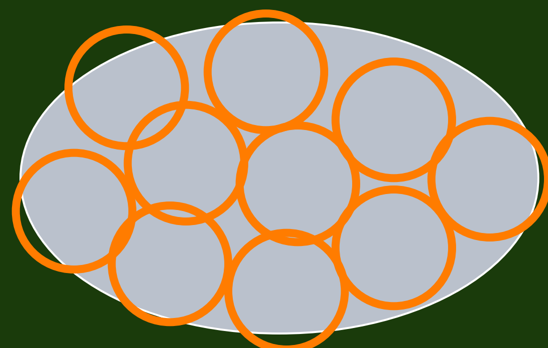
MOSAIC (fov rad = 3.5’)

HARMONI (max fov 10” x 5”)

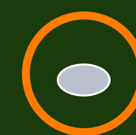
Placed at 100kpc

Placed at 1Mpc

UFD Bootes-like
(rh = 100pc)

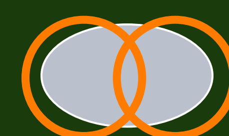


r= 5 rh = 15’



r= 5 rh = 1.5’

dSph Sculptor-like
(rh = 300pc)



r= 5 rh = 5’

Dwarfs & E-ELT spectrographs (e.g. E-ELT IFU & MOSAIC): within the Local Group

MOSAIC (fov rad = 3.5')

HARMONI (max fov 10" x 5")

Placed at 2Mpc

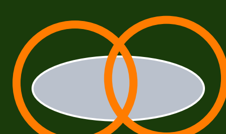
Placed at 4Mpc

MOSAIC SUITED FOR A WIDE-AREA VIEW

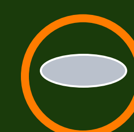
dSph Sculptor-like
(rh = 300pc)

r= 5 rh = 2.5'

dE NGC205-like
(rh = 600pc)

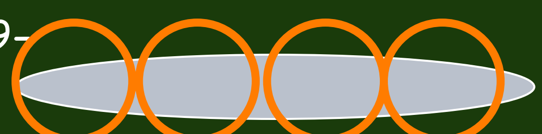


r= 5 rh = 5'

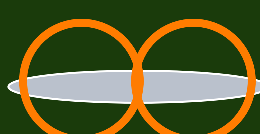


r= 5 rh = 2.5'

Small spiral NGC3109-like
(rh = 1600pc)



r= 5 rh = 15'



r= 5 rh = 7.5'

Outlook

- UFDs around the MW: E-ELT/MOSAIC

- Outer parts of MW dSphs -> WHT/WEAVE & VISTA/4MOST (accurate systemic proper motions are crucial)

- M31 system of dwarfs & isolated LG dwarfs: VLT/MOONS, CFHT/MSE, E-ELT/MOSAIC (fiber spectrographs allow flexibility in target allocation)

- Beyond the Local Group: E-ELT/HARMONI (central parts), E-ELT/MOSAIC (wide-area view)

In the hypothesis of dynamical equilibrium:
Extended dark matter halos

- Aaronson et al. (1983): 3 carbon sta Draco dSph -> M/L about one order magnitude larger than for globular c

- Samples of 10s (including red giant b stars yielding the central value of l. velocity dispersion (e.g. Armandroff & Da Aaronson & Olszewski 1987; Hargreaves et al. 19

-> Mass-follows-light isotropic King r assumed; no info on INNER dark mat density PROFILE)

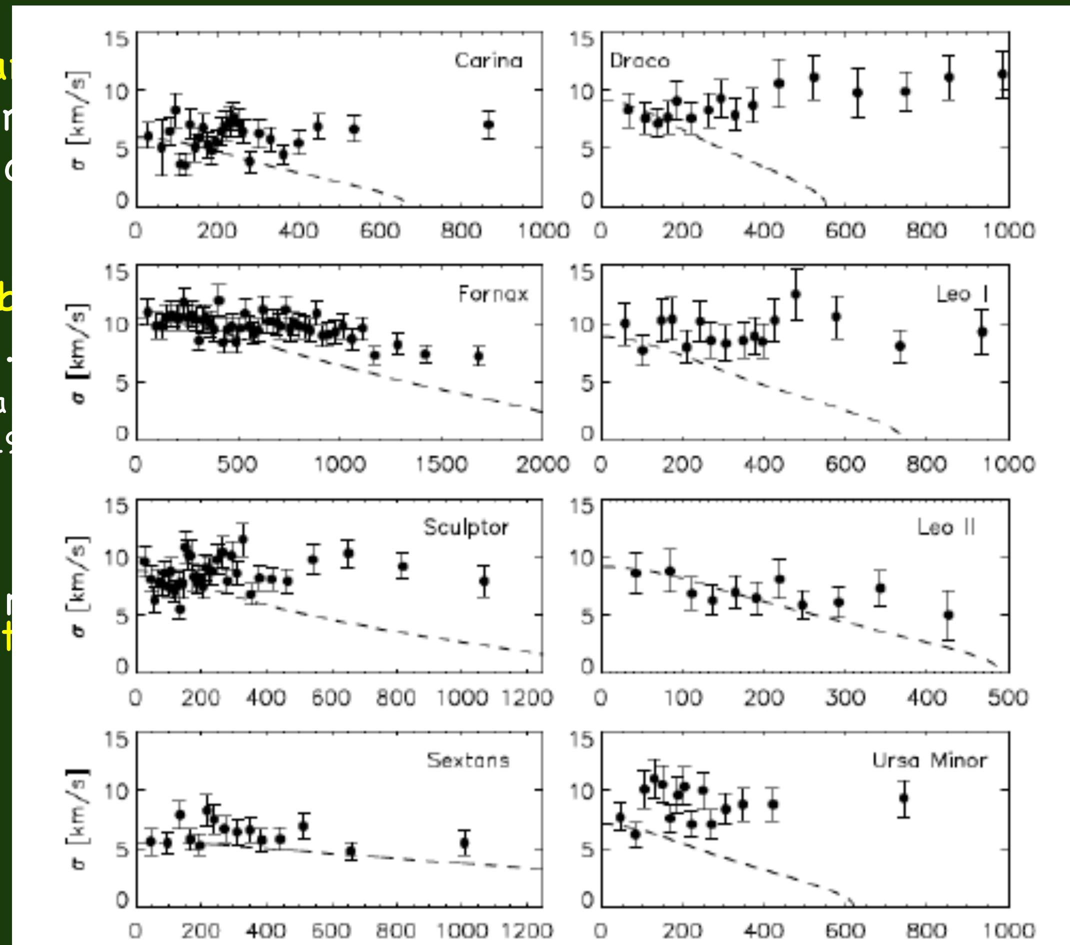


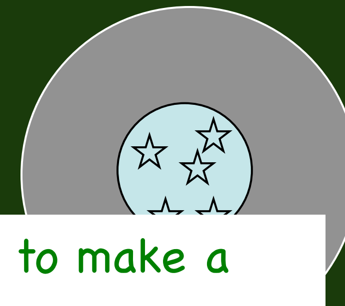
Figure from Walker 2012

Glossary: Mass-follows-light when the mass distribution is proportional to the light distribution (i.e. dynamical M/L constant with radius)

First σl.o.s "profile" from Mateo et al. 1991 (30 stars at two locations in Fornax)

One-(stellar) component Jeans modeling

key observable is the l.o.s. velocity dispersion (profile)



Assumptions: system is spherical and in equilibriur

The observed l.o.s. velocity dispersion profile is comp
from different DM models

Using the Jeans equation $\sigma_{los,\ PREDICTED}(R) = f(\Sigma_*, \beta_*, M)$, whe

$\Sigma_*(R)$ = spatial distribution of tracer population -> observab

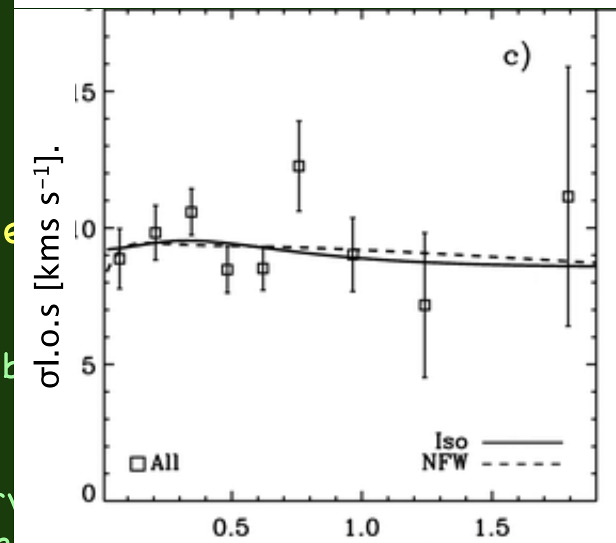
$\beta_*(r)$ = orbital anisotropy of tracer population -> not observ
(one needs to make assumptions -> mass – anisotropy degen

$M(r)$ = total mass distribution (for dSphs the luminous matte
negligible)

Not possible to make a distinction:

-Rcore = 0.5kpc, beta from 0 to slightly radial

-NFW (cusp) c=35, slightly tangential beta



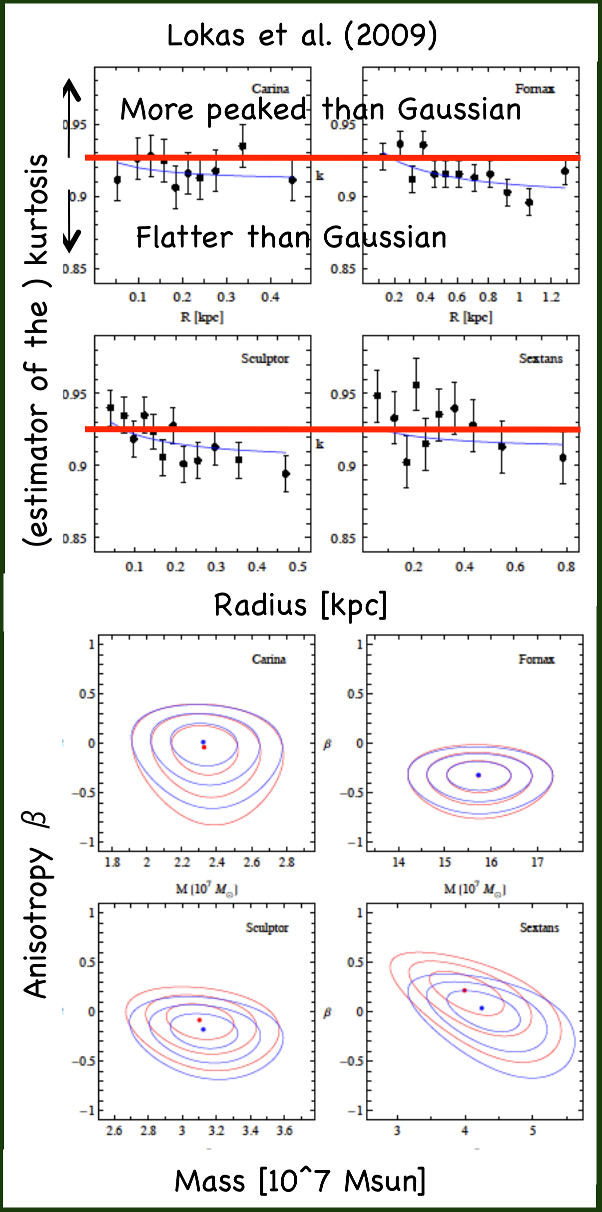
Battaglia et al.(2008)

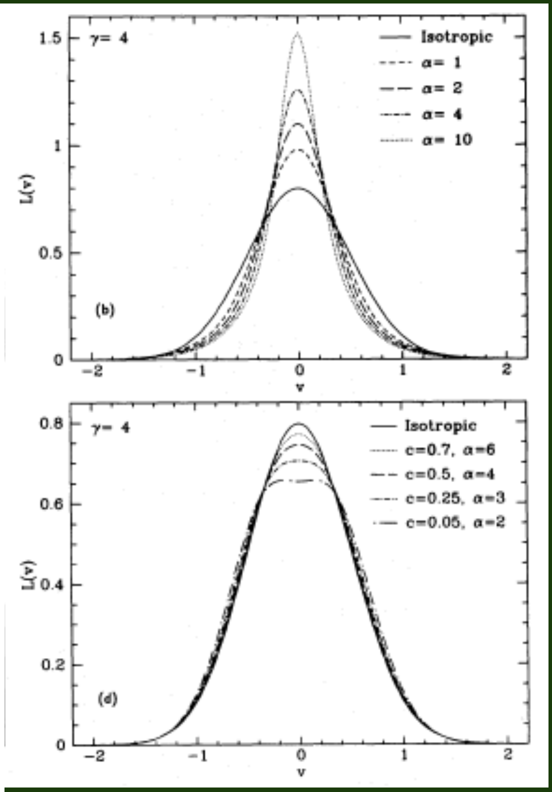
Dynamical M/Ls of 100s $(M/L)_{V,sun}$ within a couple of kpc (e.g. Kleyna et al. 2001; Wilkison et al. 2004; Koch et al. 2007; Walker et al. 2007; Battaglia et al. 2008...)

Information from the 4th moment of the LOSVD

-Details depend on the gravitational potential and the stars' distribution function
-Outer parts are where the information on the anisotropy can be better recovered

- Tangential anisotropy -> flat-topped
- Radial anisotropy -> more peaked than Gaussian
-> Information encoded in the 4th moment of the LOSVD



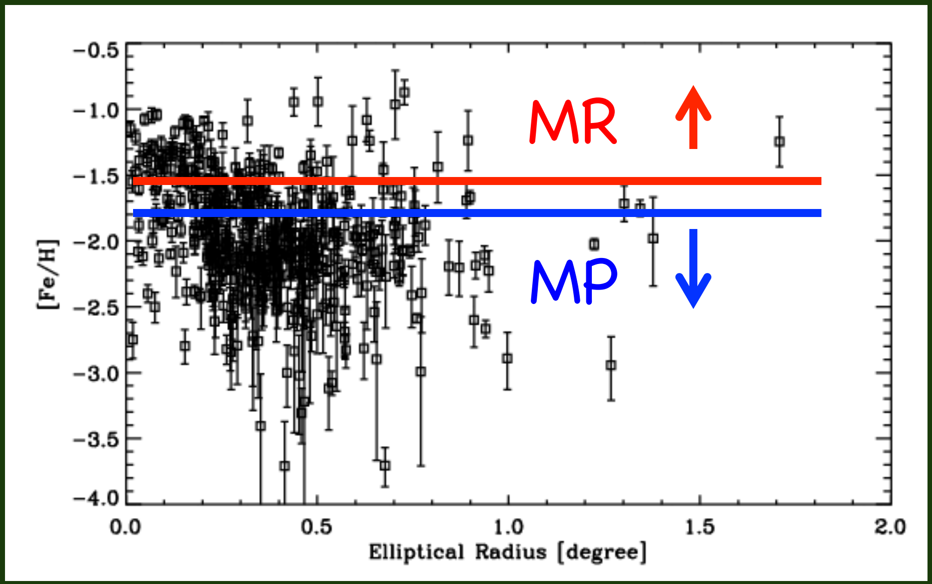


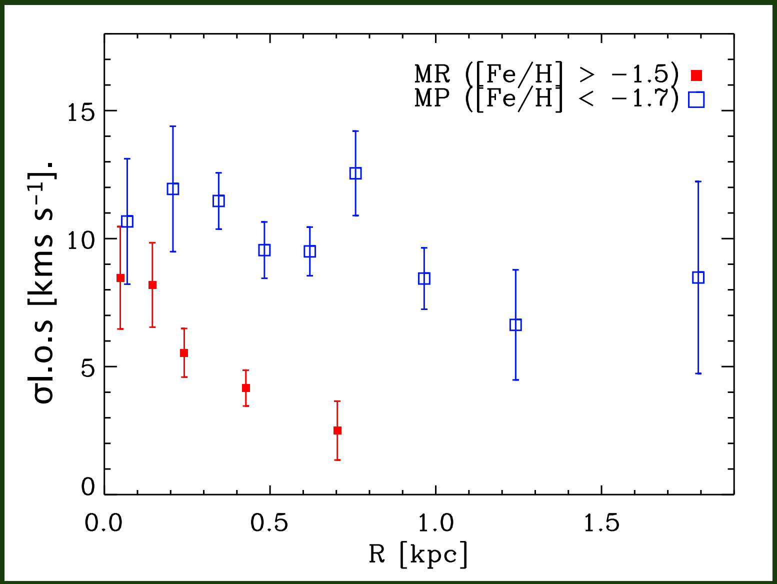
Gerhard 1991, 1993; but also Dejonghe 1987; Merrifield & Kent (1990) Wilkinson et al. 2002 etc.

The velocity anisotropy of dSph stars
Is neither strongly radial nor strongly tangential
(e.g. Lokas et al. 2005, 2009; Breddels et al. 2012; Breddels & Helmi 2012; 2013; Amorisco & Evans 2012)

Fit to σ l.o.s.
Fit to σ l.o.s. + kurtosis

Using the metallicity information:
the "chemo-dynamical" stellar components found in Sculptor, Fornax & Sextans (Tolstoy et al. 2004, Battaglia et al. 2006, 2008, 2011)



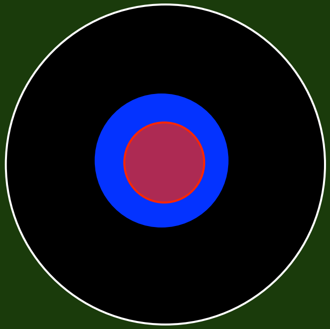


DM +

One (stellar) component

DM +

two (stellar) components



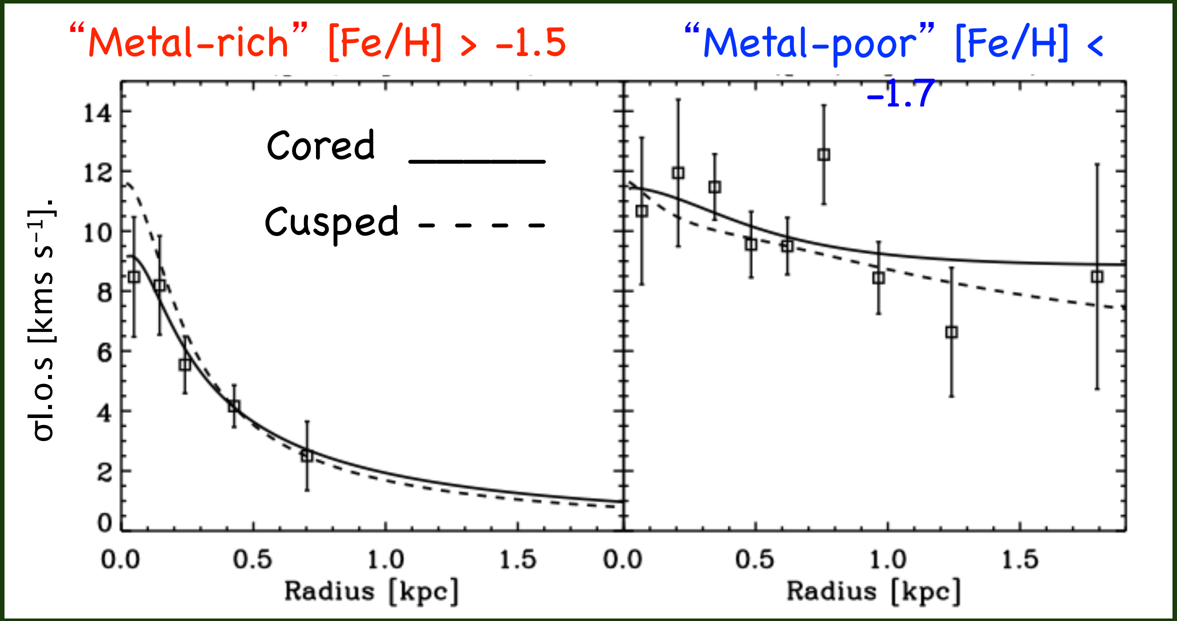
(partially) relieving the mass-anisotropy degeneracy

-Models with constant anisotropy for MR and MP stars do not fit well the data

-Kinematics of multiple stellar components prefer a cored profile to a cuspy one (Battaglia et al. 2008)

- M/L = 160 $(M/L)_{V,sun}$ within 1.8 kpc

Line-of-sight velocity dispersion profiles:

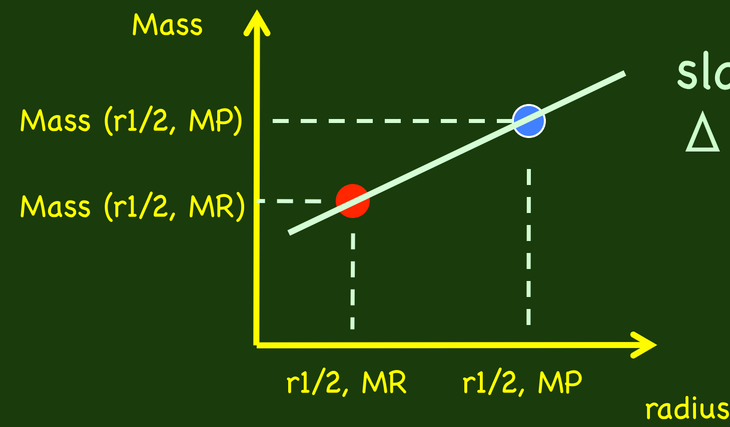


Battaglia et al. (2008)

Robust mass estimates within r ½ (Wolf et al. 2010, see also Strigari et al. 2008; Walker et al. 2009) and multiple components (Walker & Peñarrubia 2011; see also Amorisco & Evans 2012; Agnello & Evans 2013)

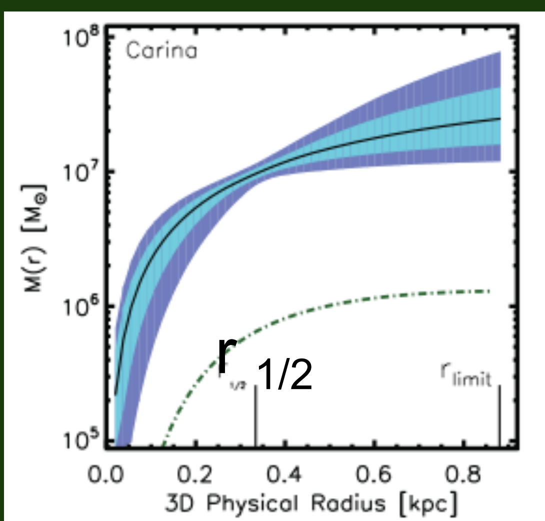
$M(r_{-3}) = 3\ G^{-1} \langle\sigma_{l.o.s}^{2}\rangle\ r_{-3}$ & $r_{-3} \cong r_{1/2}$

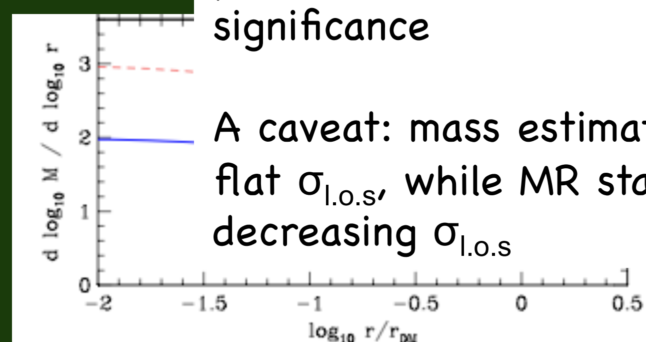
(Wolf et al. 2010)

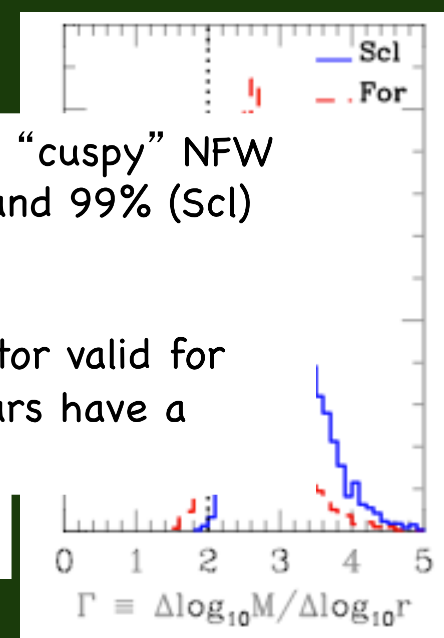


Very useful for ultra-faint dwarfs

For a spherical system in dynamical equilibrium, there exists one radius where M(r) is insensitive to the anisotropy







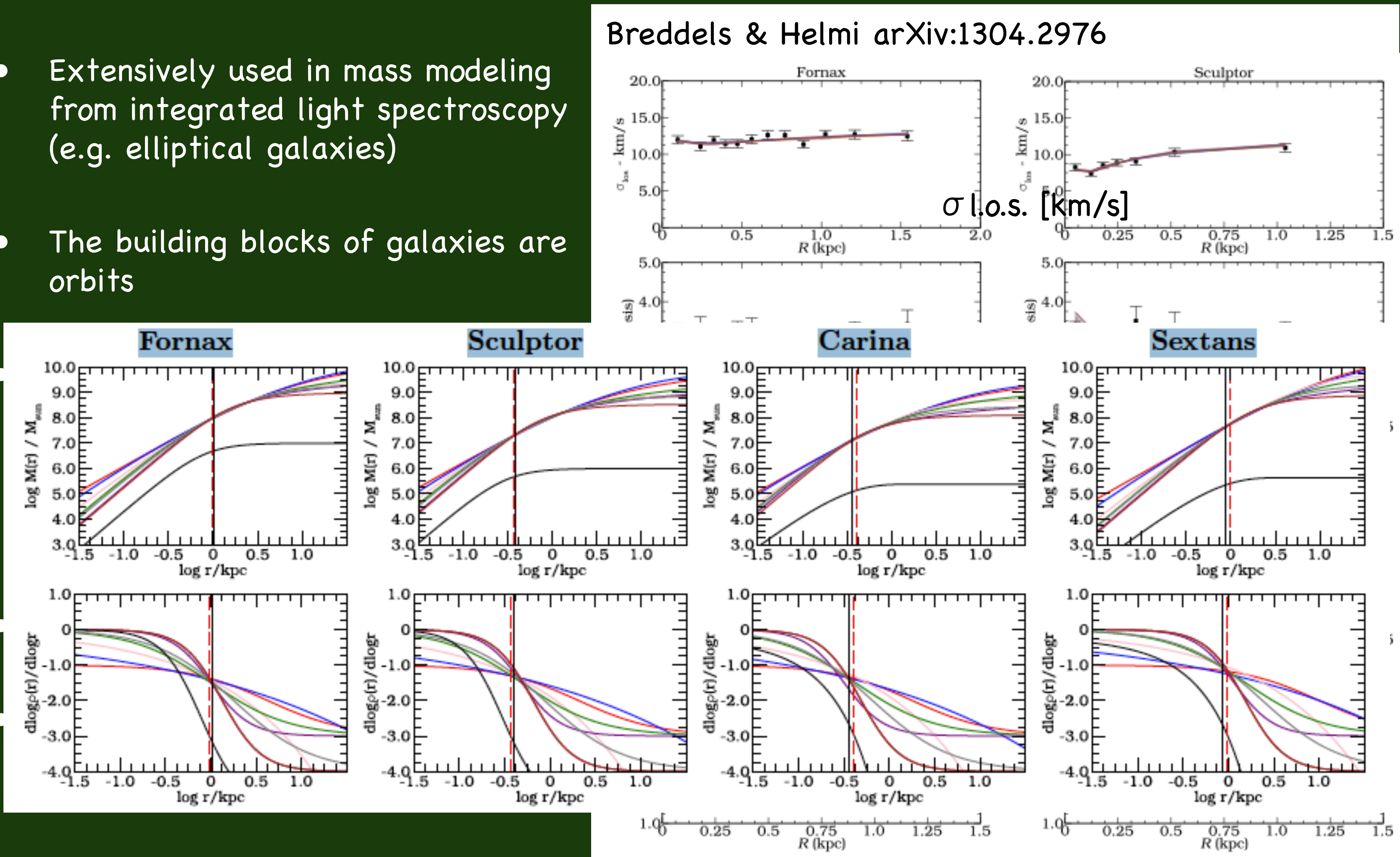
This analysis rules out "cuspy" NFW profiles at 96% (Fnx) and 99% (Scl) significance

A caveat: mass estimator valid for flat $\sigma_{l.o.s}$, while MR stars have a decreasing $\sigma_{l.o.s}$

Schwarzschild modeling applied to dSphs
(Breddels et al. 2013; see also Jardel & Gebhard 2012)

- Extensively used in mass modeling from integrated light spectroscopy (e.g. elliptical galaxies)

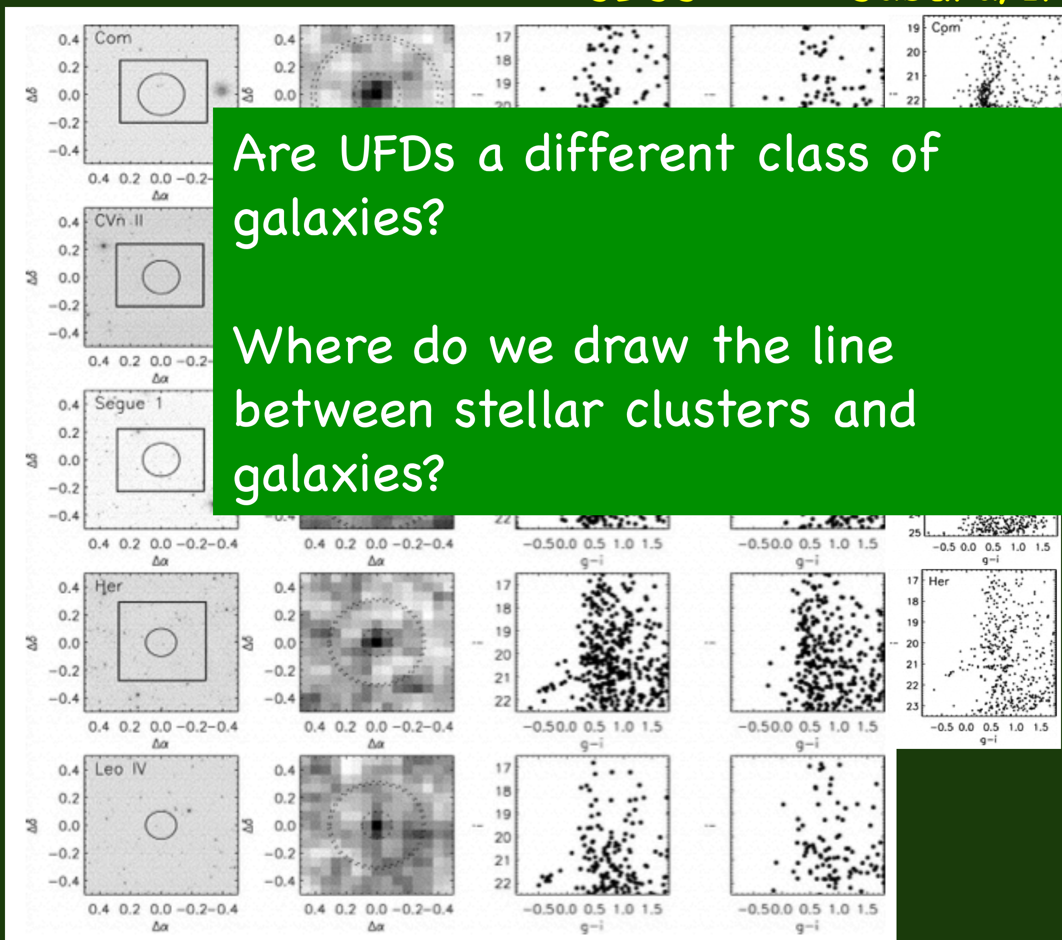
- The building blocks of galaxies are orbits



The Milky Way "Ultra-Faint" dwarfs (i.e. post-SDSS early-type dwarfs), record-holders:

The faintest, smallest, lowest surface brightness, most metal-poor galaxies

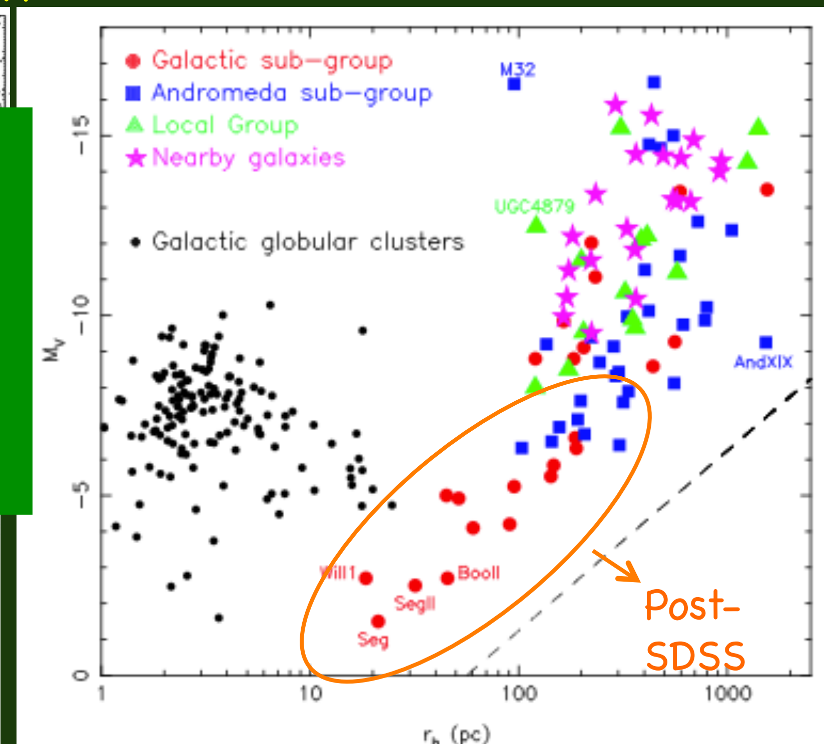
SDSS Subaru/INT



Are UFDs a different class of galaxies?

Where do we draw the line between stellar clusters and galaxies?

Belokurov et al. 2007

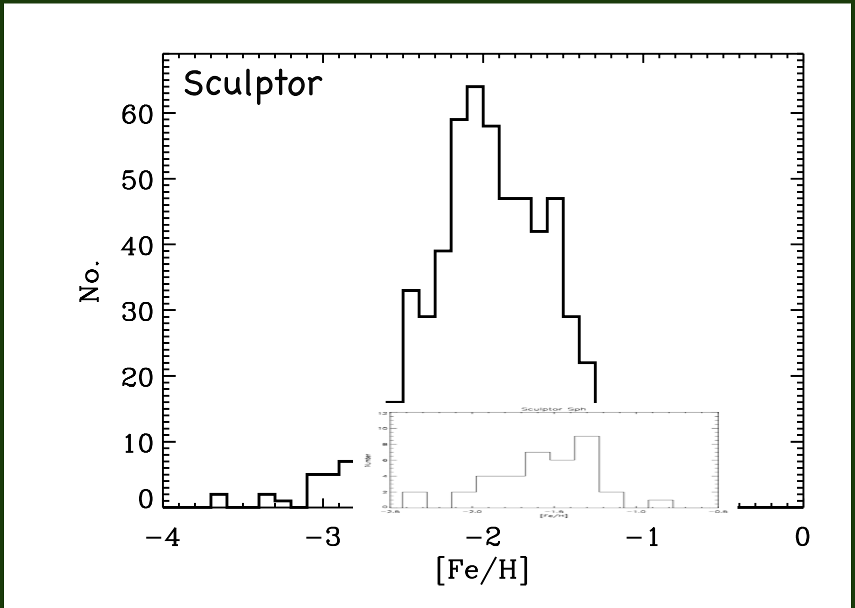


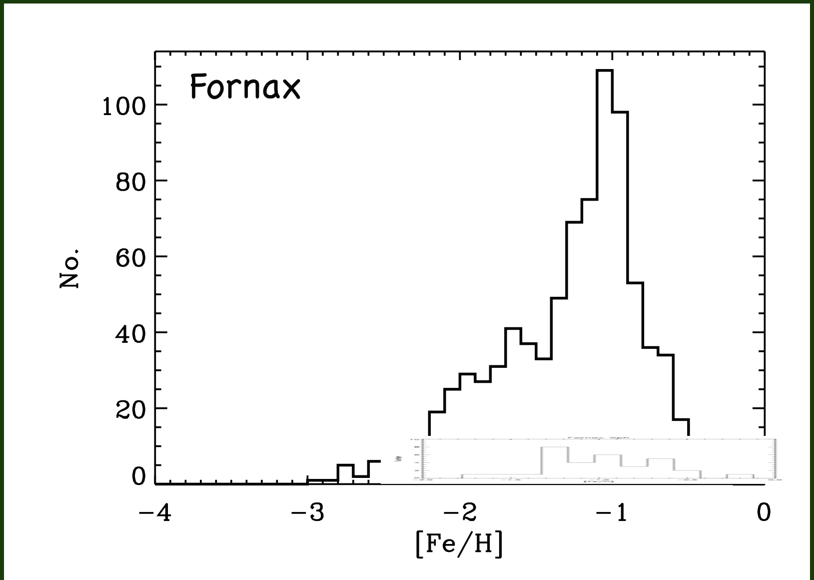
McConnachie 2012

Insights on general properties of dwarf galaxies

Large samples vs small samples

VLT/FLAMES: Tolstoy et al. 2004, Battaglia et al. 2006, 2008, 2011, Starkenburg et al. 2010





VLT/FORS: Tolstoy et al. 2001

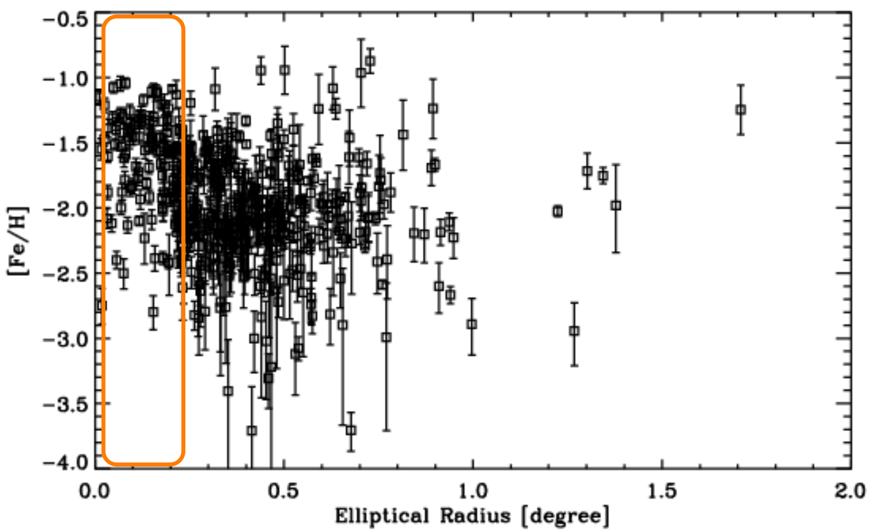
Much wider range of [Fe/H] values within each galaxy than previously thought -> this should give indications on the galaxy's capability to retain its ISM -> potential well

Presence of (rare) extremely metal-poor stars (see also Kirby et al. 2009, Frebel 2010, Tafelmeyer et al.2010)

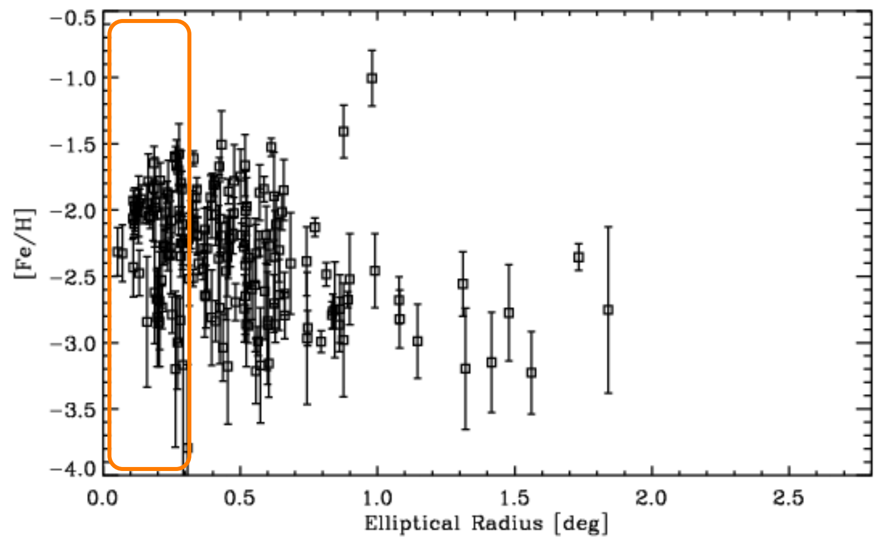
Spatial variations of metallicity properties in MW dSphs

[Fe/H] from CaT lines calculated using the calibration from Starkenburg et al. 2010

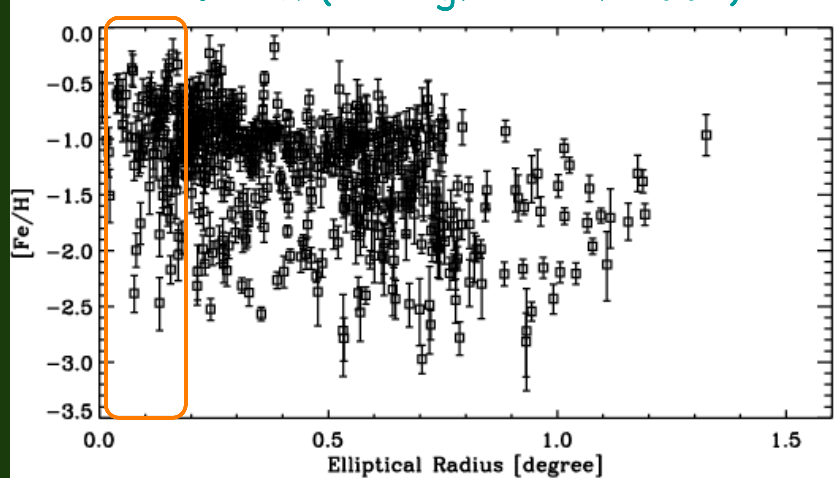
Sculptor (Tolstoy et al. 2004)



Sextans (Battaglia et al. 2011)



Fornax (Battaglia et al. 2006)

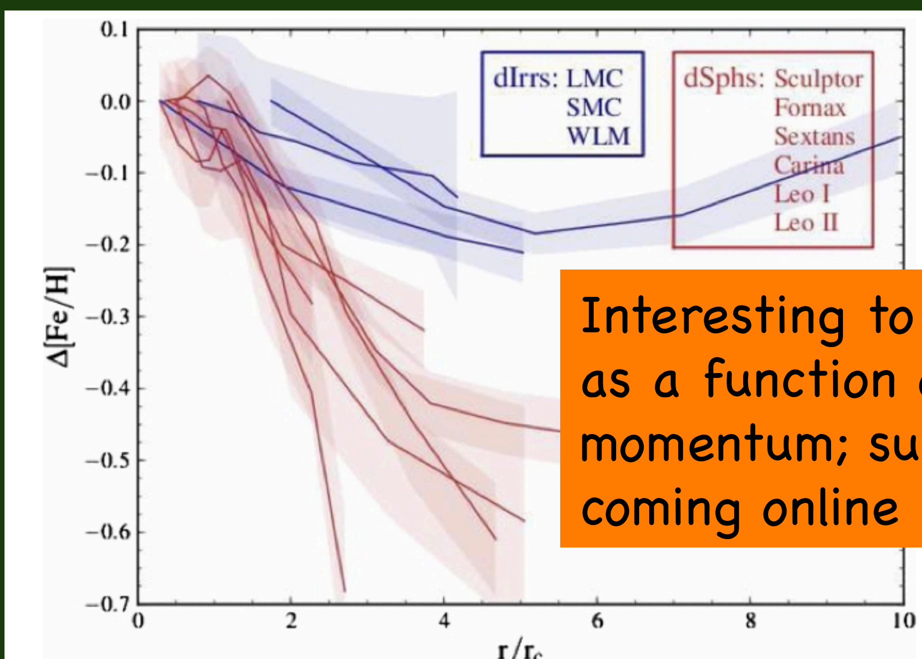


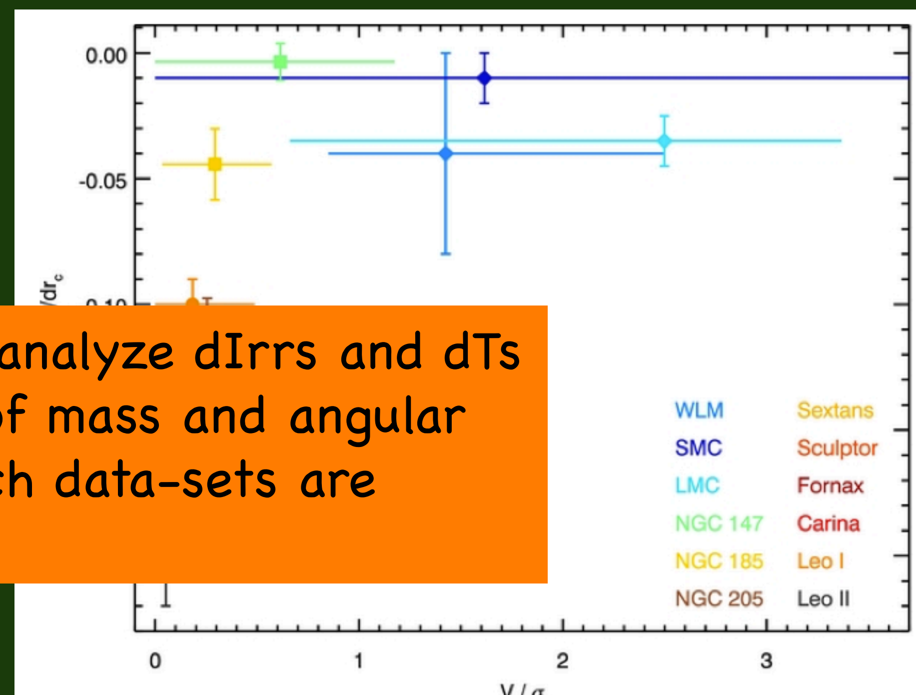
(see also e.g. Koch et al. 2006; Faria et al. 2007; Gullieuszik et al. 2009; Kirby et al. 2011)

A “centrifugal barrier” mechanism?

There are indications for a relation between v/sigma and steepness of the metallicity gradient (Leaman et al. 2012)

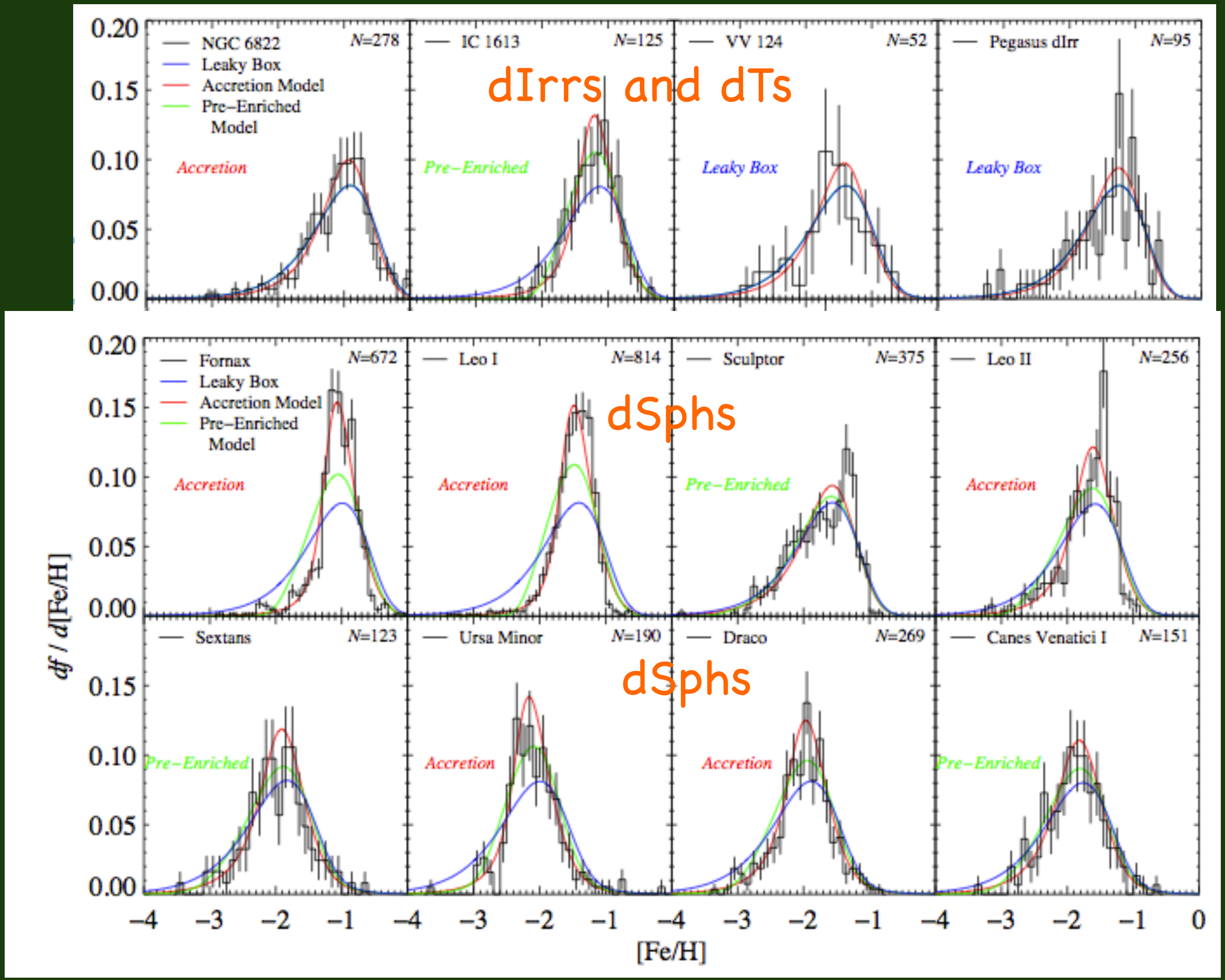
Simulations show that angular momentum can act as second parameter (after mass) in driving such gradients (e.g. Schroyen et 2011), in agreement with findings outside of the Local Group





Interesting to analyze dIrrs and dTs as a function of mass and angular momentum; such data-sets are coming online

Closed box, galactic winds, infall? (see also e.g. Lanfranchi & Matteucci 2004)



Leaky box: pristine gas, gas can be expelled

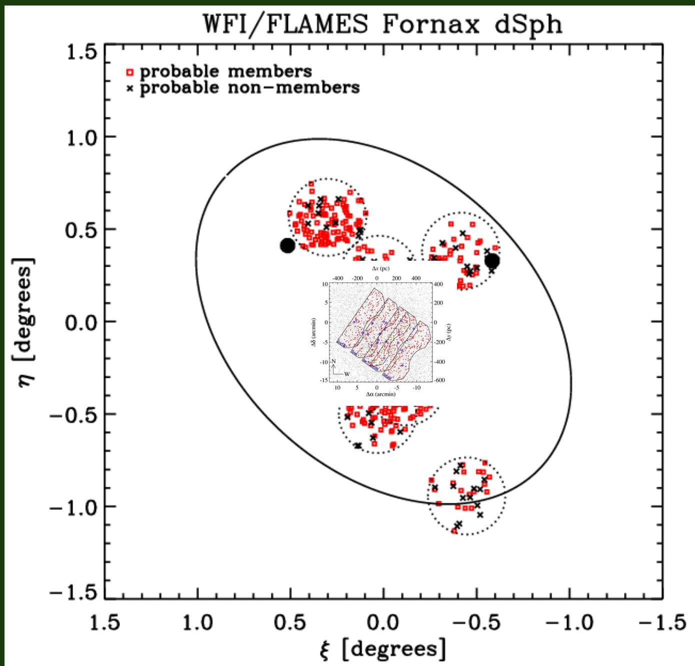
Pre-enriched: as above, but gas has an initial metallicity, [Fe/H]0

Accretion: as Leaky-box, but has accretion allowed

From Kirby et al. 2013 (only galaxies with Nspectra > 50)

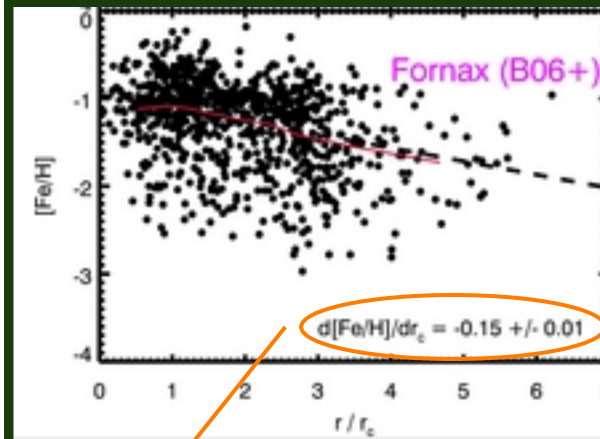
some words of caution on the samples from which the MFD is drawn

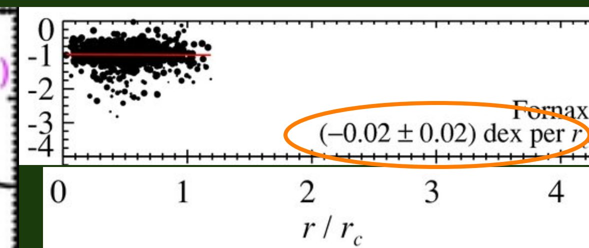
Spatially extended vs centrally concentrated samples

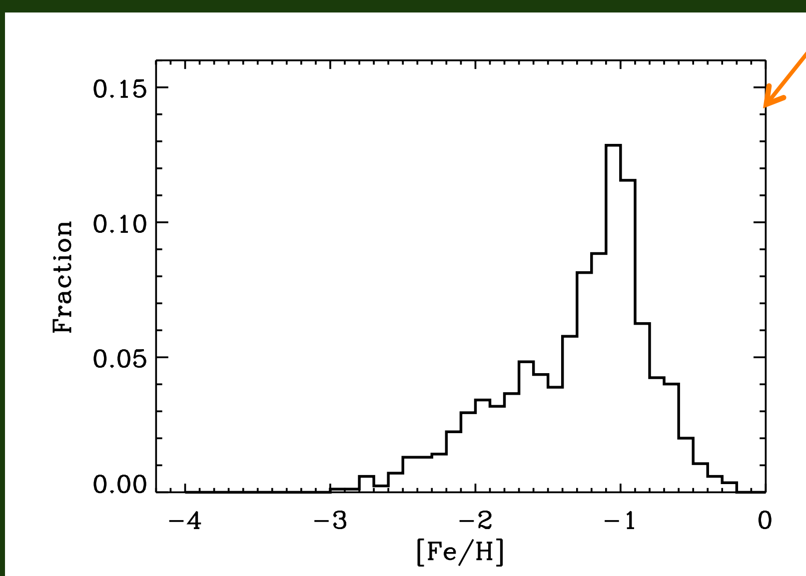


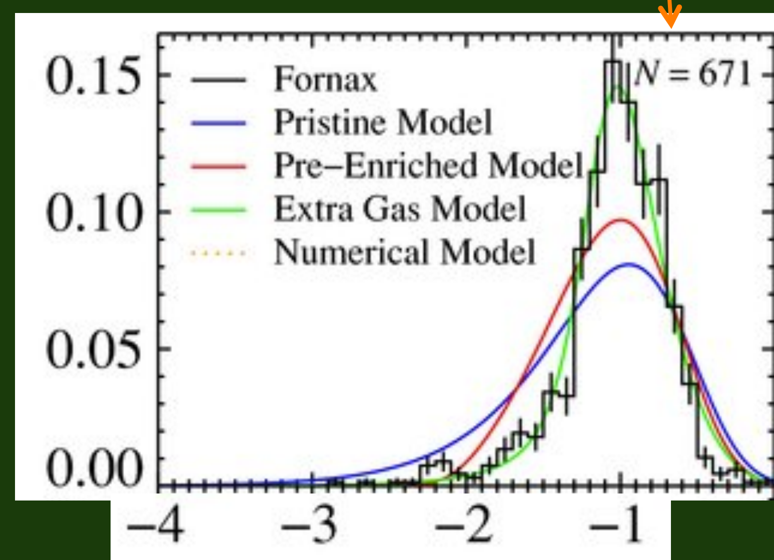
Different samples with similar number of stars

Kirby et al. 2010, 2011







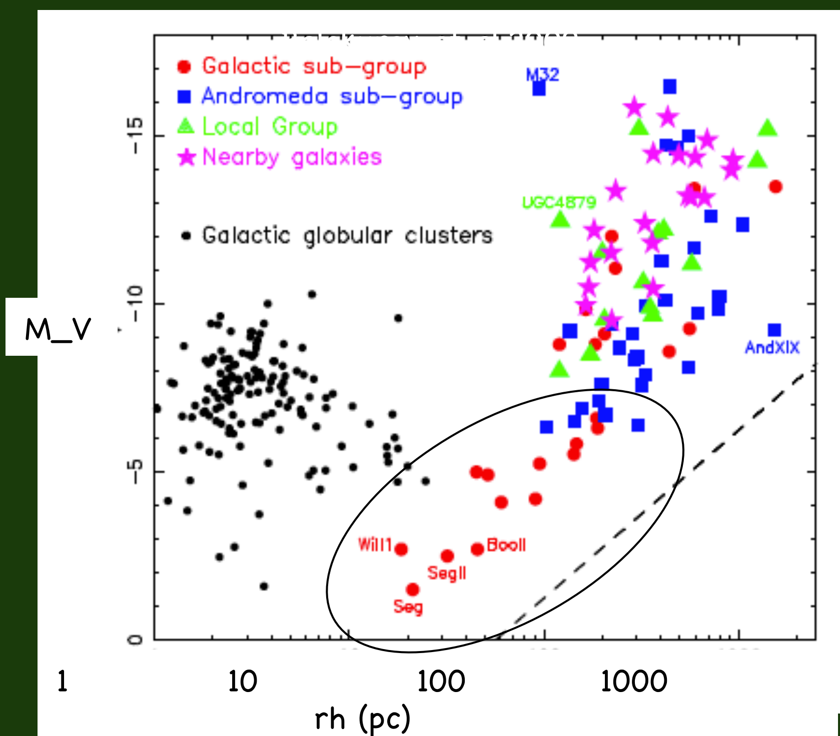


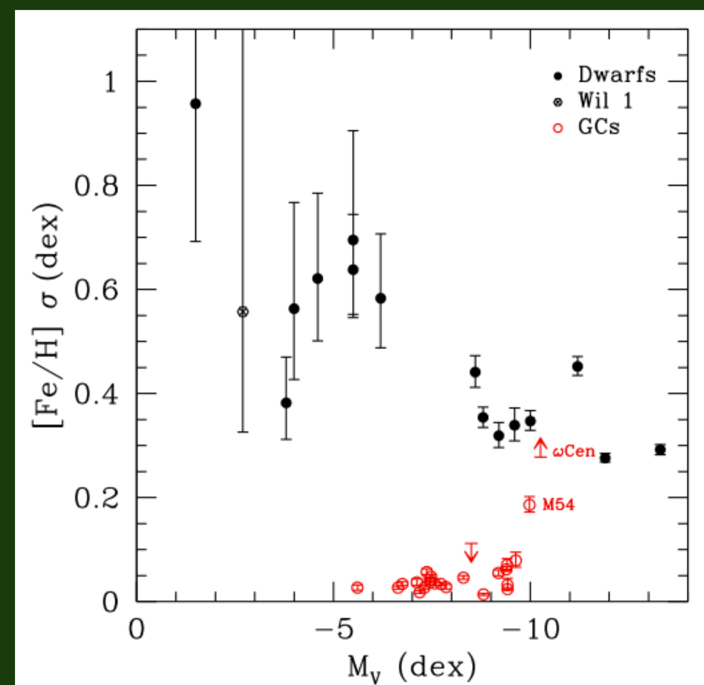
Are all UFDs actual galaxies?

Are all UFDs galaxies?

- Large velocity dispersions -> large dynamical M/L: very large ratios of dark-to-luminous matter or tidally disrupted (or other effects)?

-> The presence of spreads in [Fe/H] would distinguish them from stellar clusters and classify them as galaxies (absence of Na-O anti-correlations, but that's difficult!)

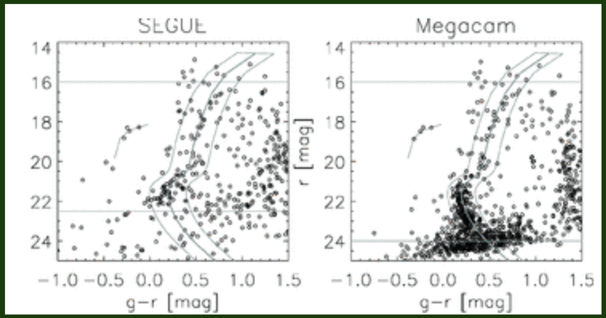




Willman & Strader 2012

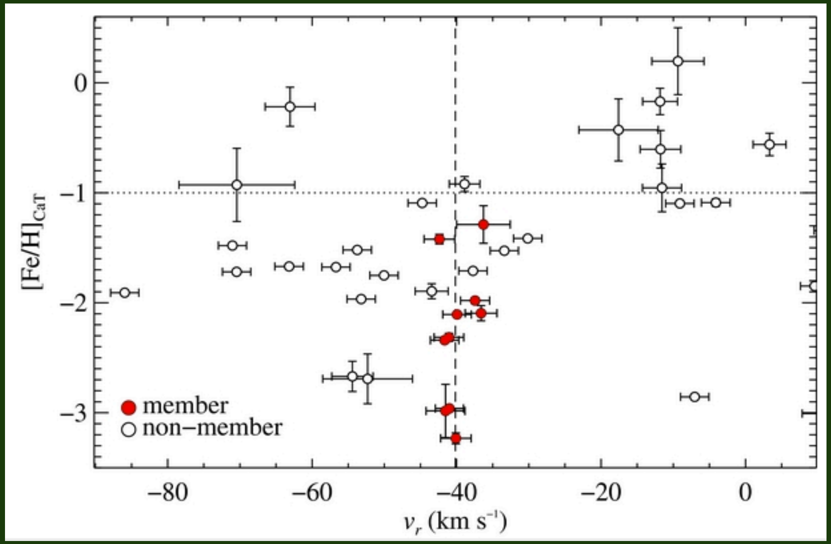
The example of Segue2

Discovered in 2009 by Belokurov et al., luminosity of 900Lsun, systemic velocity strongly overlaps with the Milky Way disc

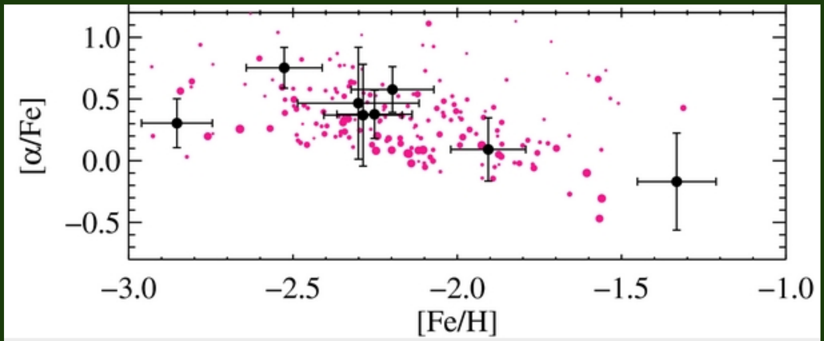


Belokurov et al.2009

Contamination by foreground/background Milky Way stars is an issue! (also for other systems, e.g. Wilman1)



Wide range of [Fe/H] values (11 stars); decline in [alpha/Fe] vs [Fe/H] (retained supernovae ejecta?)



Kirby et al. 2012

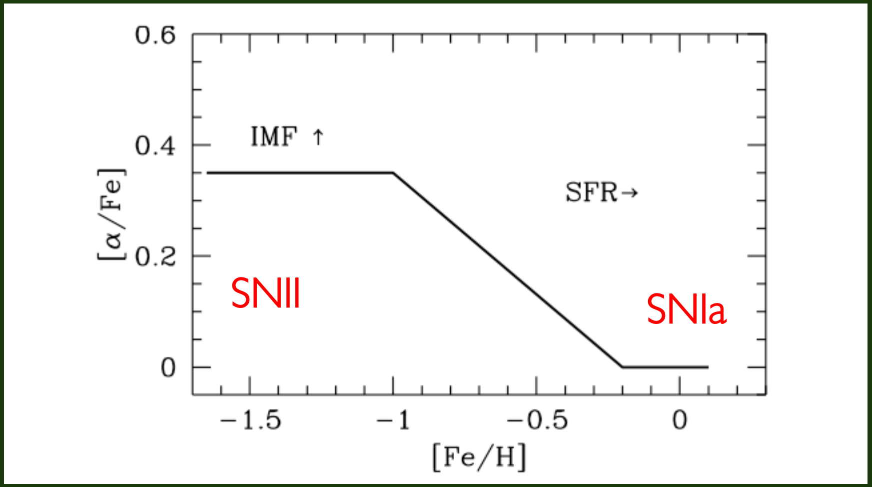
What objects contributed to the build-up of the Milky Way halo?

[α/Fe] vs [Fe/H]: a star formation rate "clock"

- α-elements produced by SNII -> progenitors of SNII are massive stars (with very short life-times, 1-40 Myr) -> enrichment in α-elements closely follow star formation rate

- Fe mainly produced by SNIa -> a range of life-times (35 Myr – Hubble time)

- "Time-delay" model (Tinsley 1979) -> delay of injection of Fe into ISM relative to the fast production of α-elements produces a typical signature in [α/Fe] vs [Fe/H] ("knee")



Comparison with the Milky Way halo

Hill et al. 2012, in prep., Geisler et al. 2005, Shetrone et al. 2003 AJ, Letarte et al. 2010 A&A, Koch et al. 2008, Venn et al. 2012 ApJ, Lemasle et al. 2012 A&A , Sbordone et al. 2007,Venn et al. 2004

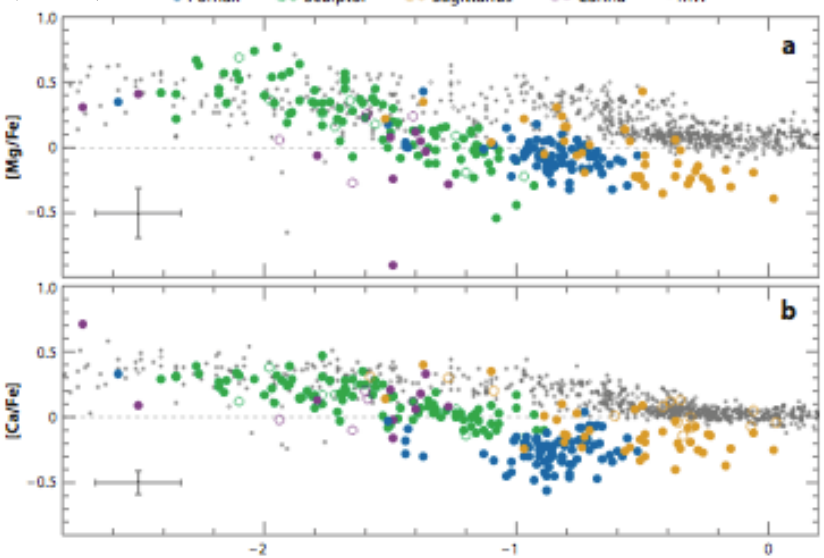
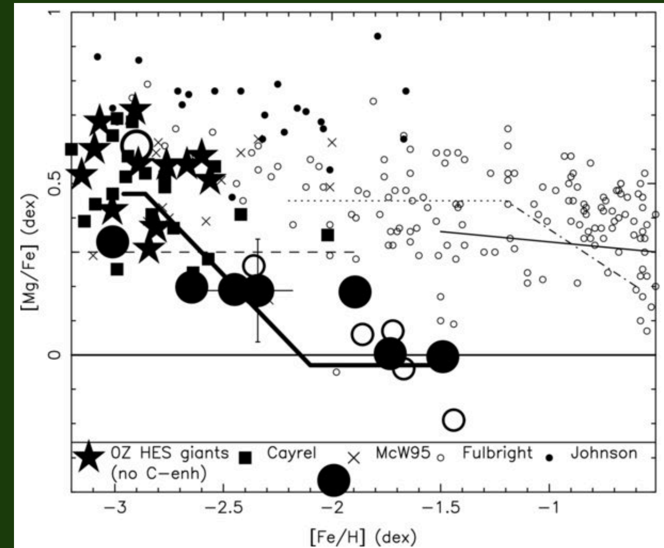
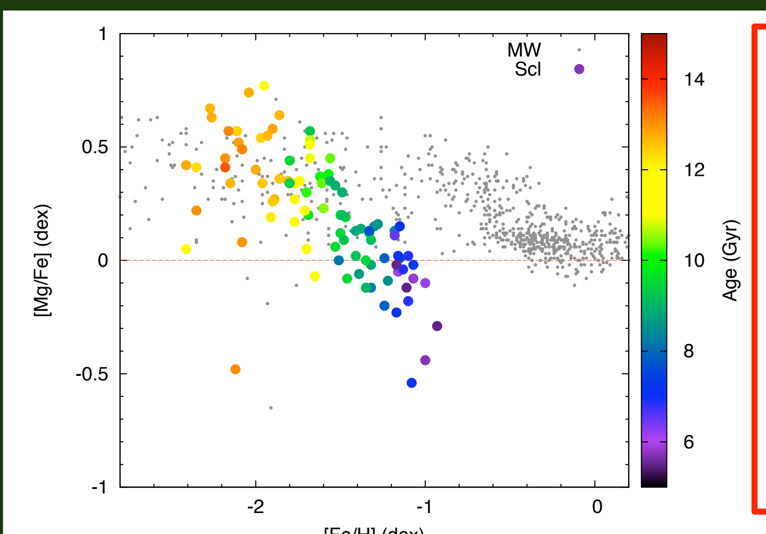


Figure from Tolstoy, Hill & Tosi (2009), ARA&A

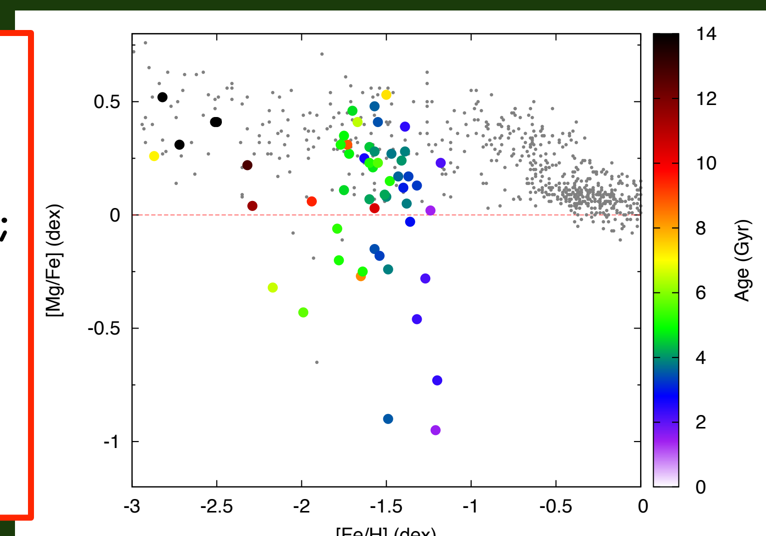
Draco: Cohen & Huang 2009





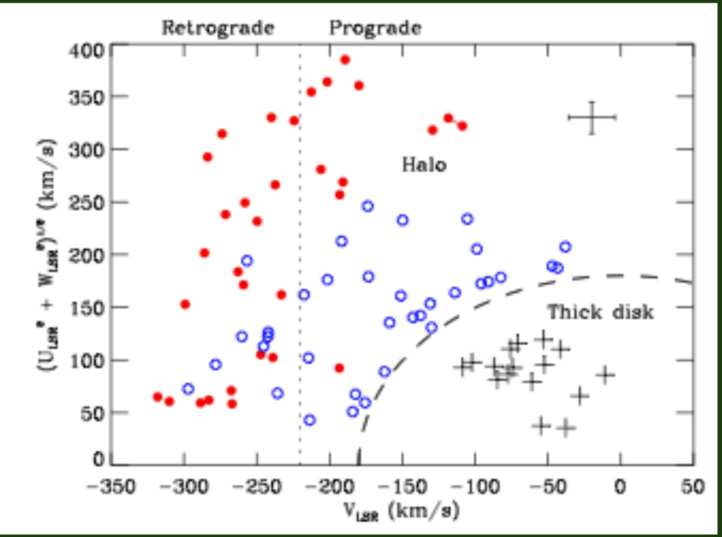
"Knee" in Scl occurred ~2±1 Gyr after star formation began;

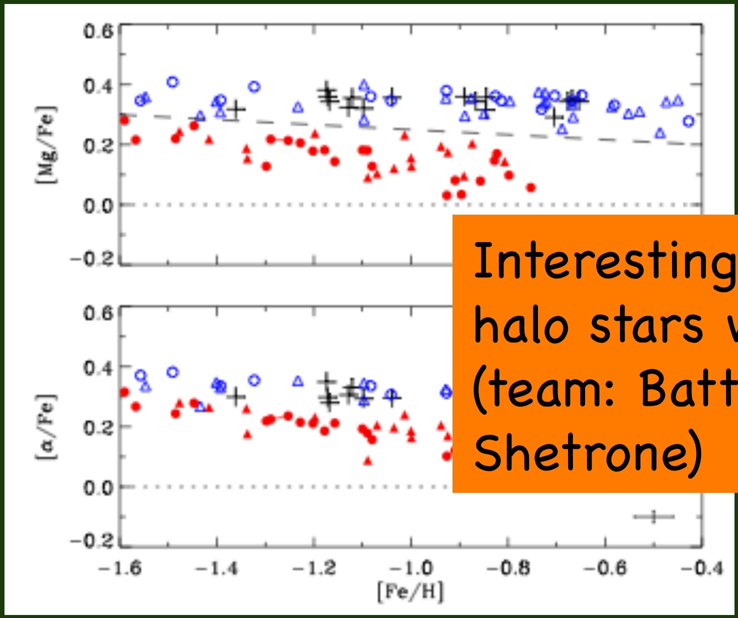
Carina is complicated but larger scatter than in the halo



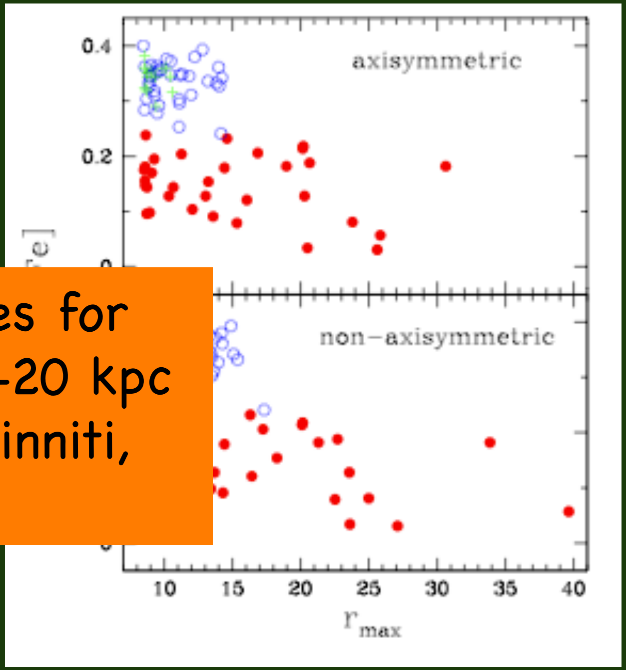
Dual nature of the Milky Way halo (e.g. Searle & Zinn 1979 from globular clusters, Carollo et al. 2007, … ; A. Font's talk)

- Inner halo: rather flattened & prograde rotation
- Outer halo: more spherical & no (or some retrograde) rotation
- Transition region at R ~ 15-20 kpc
- Solar Neighbourhood samples are dominated by inner halo stars at [Fe/H] > -2





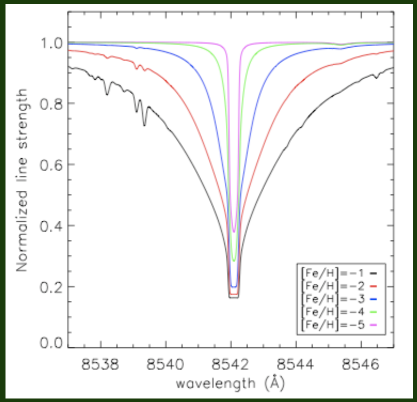
Nissen &



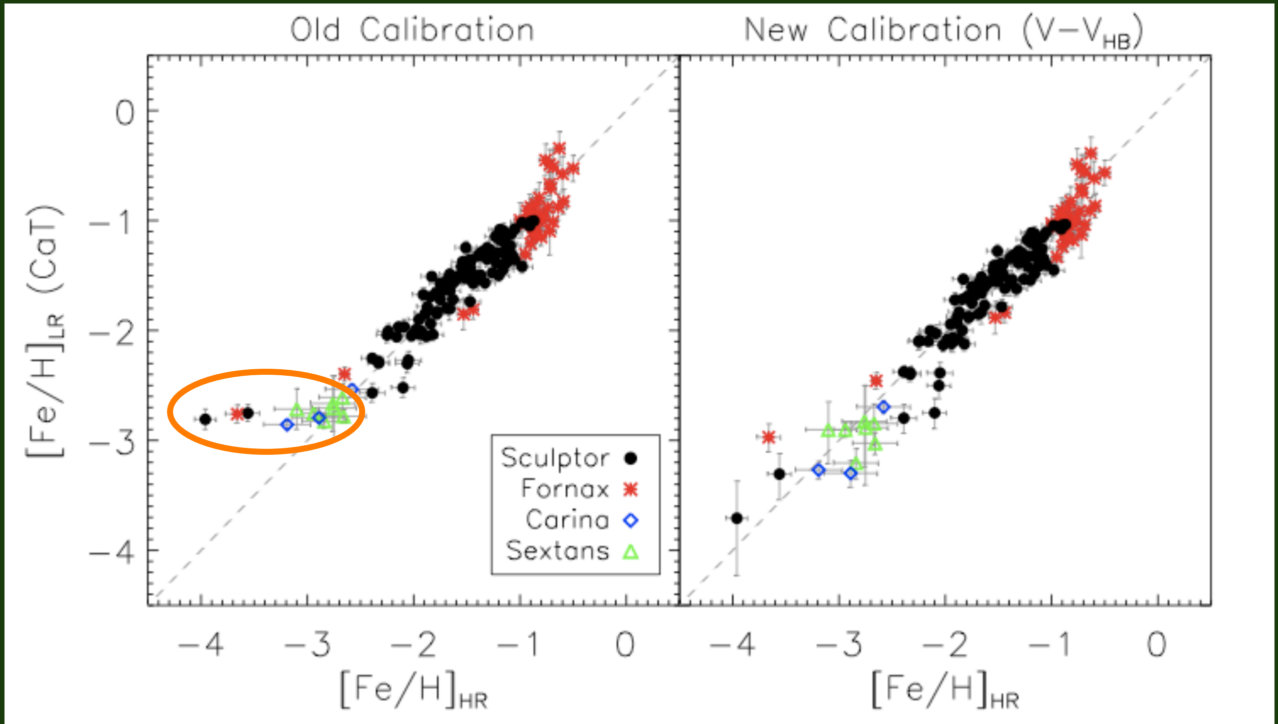
Interesting to get abundances for halo stars with distance > 15-20 kpc (team: Battaglia, Jablonka, Minniti, Shetrone)

CaT EW-[Fe/H] calibration from synthetic spectra and tested against data down to [Fe/H] =-4 (Starkenburg et al. 2010)

- Profile of CaT lines changes from wing dominated to core dominated as metallicity drops



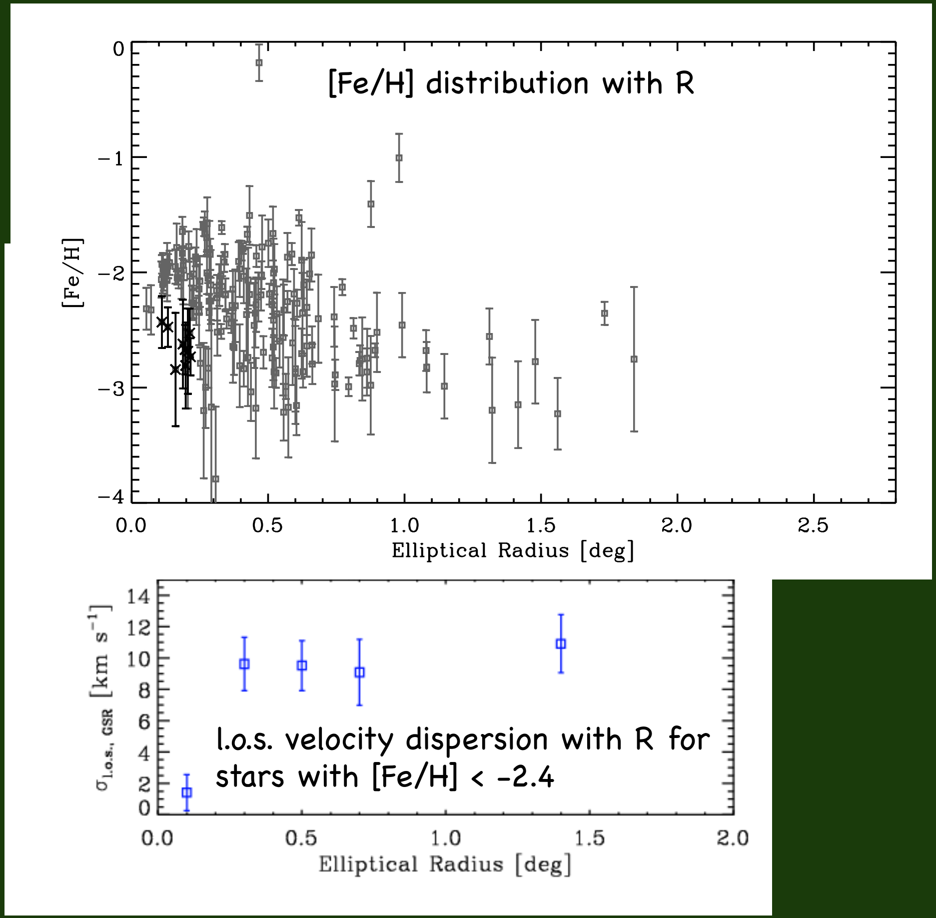
- Relations based on globular clusters and synthetic spectra agree down to [Fe/H] = -2.5, then empirical relation saturates



Chemo-dynamical substructures in Sculptor & Sextans: Disrupted (very metal-poor!) stellar clusters?

Kinematically cold: velocity dispersion = 2.4±0.7 km/s (Scl) 1.4±1.2 km/s (Sext)

Sextans (Battaglia et al. 2011)



Very metal-poor:

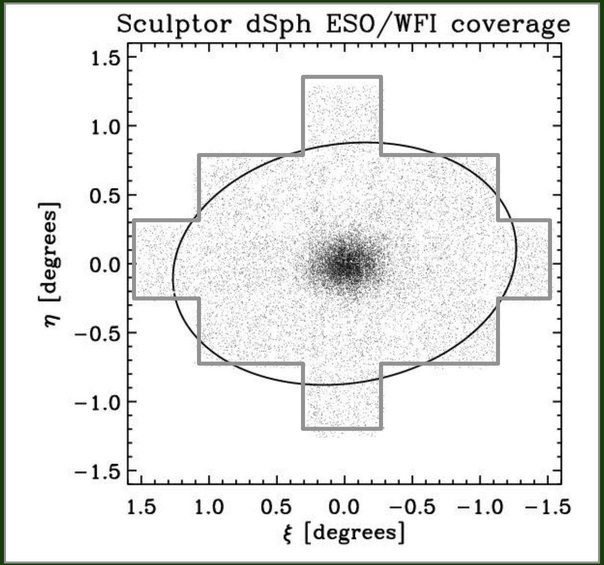
<[Fe/H]> = -2 (Scl) -2.6 (Sext)

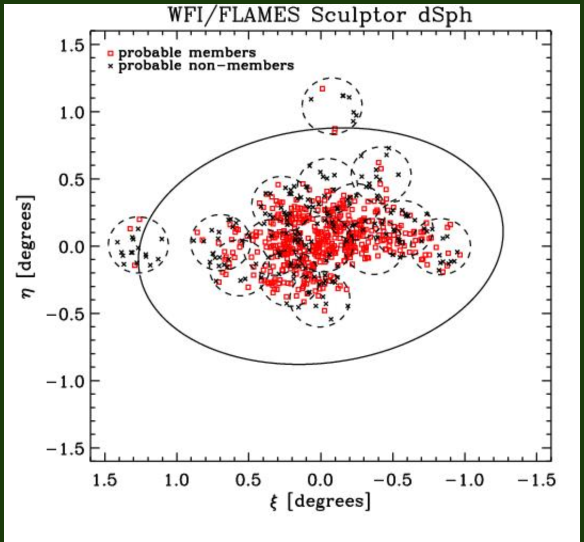
[Fe/H] spread consistent with zero, given the errors on the [Fe/H] measurements

Estimated V luminosity in the range of globular clusters:

3 x 10^4 Lsun (Scl) & 2 x 10^4 Lsun (Sext)

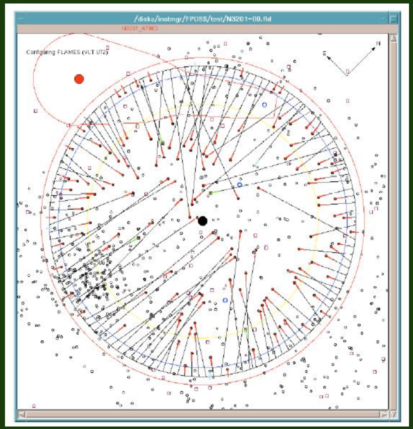
Sample of 4 Milky Way dSphs





ESO/VLT

130 fibres
over
25 arcmin



Study of the 2D structure, star formation and chemical enrichment history over a wide-area, internal kinematics, elemental abundances and comparison with the Milky Way, constraints to models of dwarf galaxy evolution -> these are the best studied galaxies to date with the most complete data-set!

(Tolstoy et al. 2004, Battaglia et al. 2006, Helmi et al. 2006, Battaglia et al. 2008a,2008b, Aoki et al. 2009, Revaz et al. 2009, Letarte et al. 2010, Starkenburg et al. 2010, Tafelmeyer et al. 2010, Battaglia et al. 2011, Battaglia & Starkenburg 2012; de Boer 2011, 2012a, 2012b, Starkenburg et al. 2013)

Evolutionary links?

With HI and forming stars

No HI and no longer forming stars

Late-types

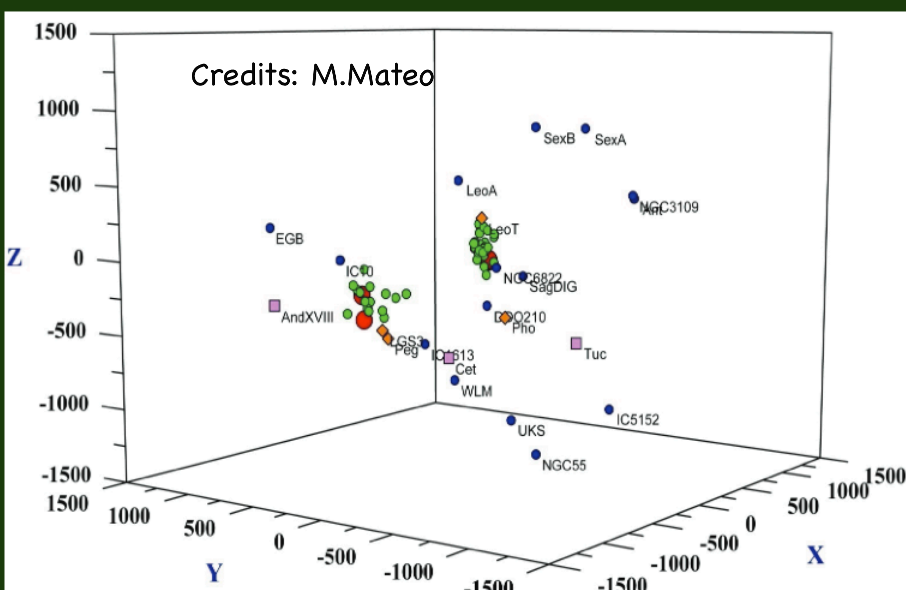
Early-types

Dwarf irregulars

Transition dwarfs

Dwarf spheroidals

Morphology density relation: a general characteristic of galaxy groups



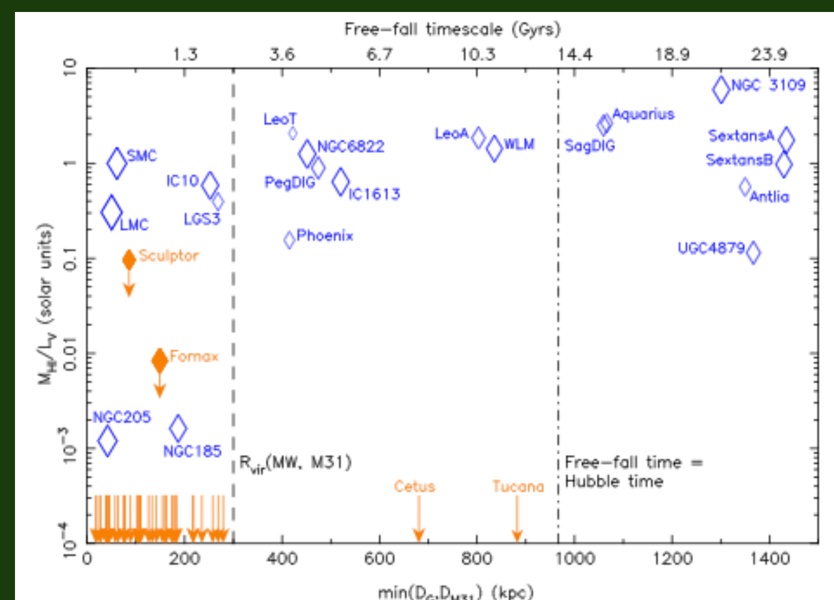
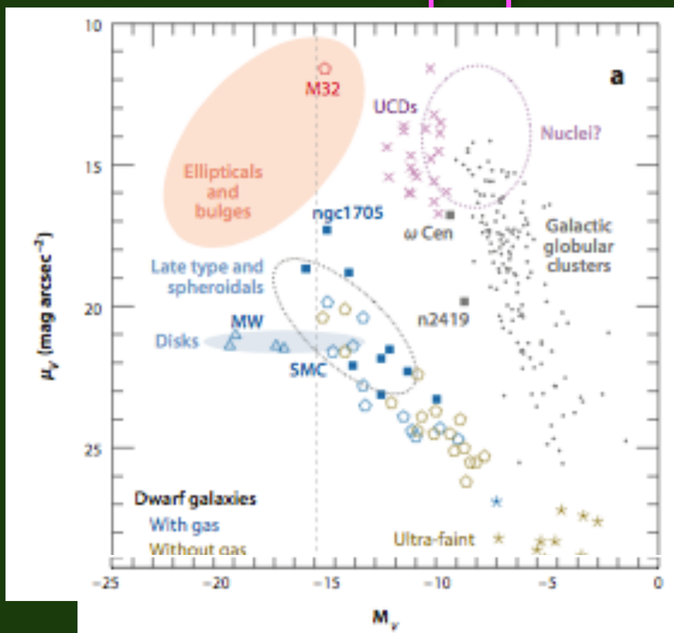


Figure from McConnachie 2012

What processes dominate the evolution of the most numerous galaxy population?

Continuum of properties

Tolstoy, Hill & Tosi 2009, ARAA



Morphology density relation

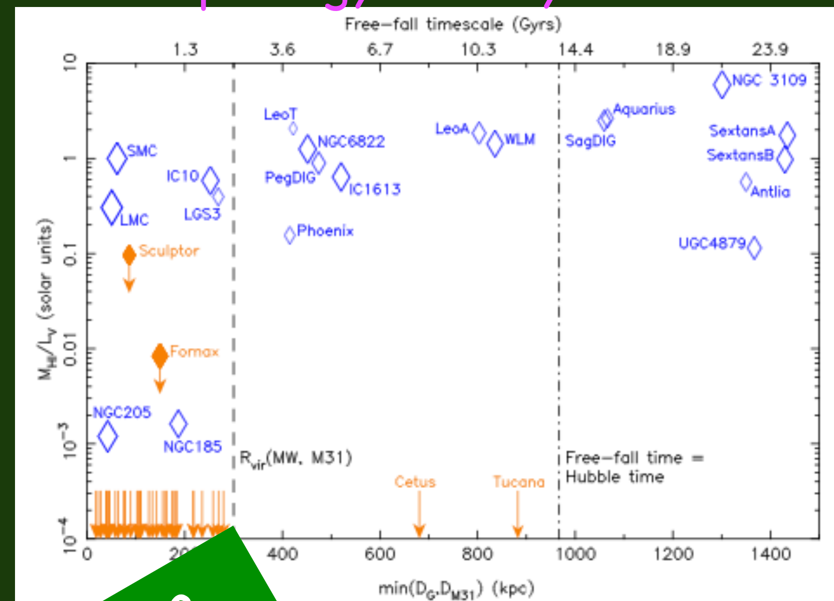
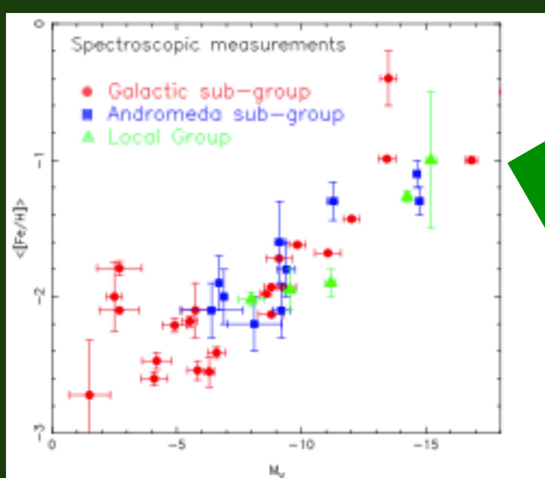


Figure from McConnachie 2012

Evolutionary link?

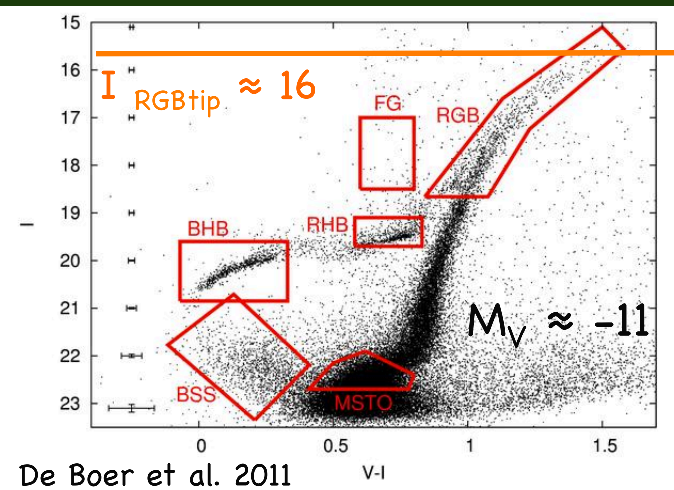
McConnachie 2012



Can dIrrs transform into dSphs? And how?

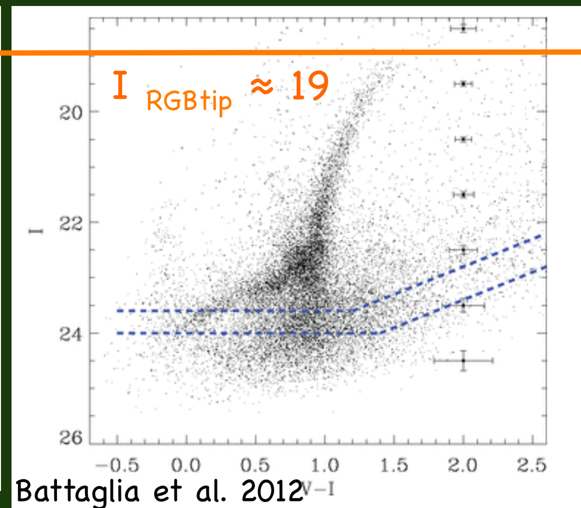
Throughout the Local Group

100kpc (within the MW halo)



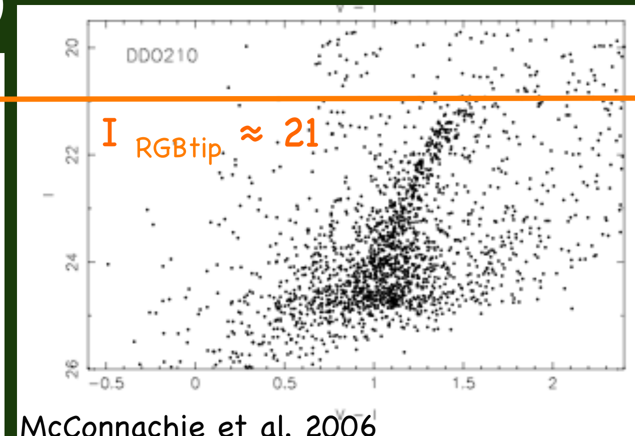
De Boer et al. 2011

400kpc (outside of the MW halo)

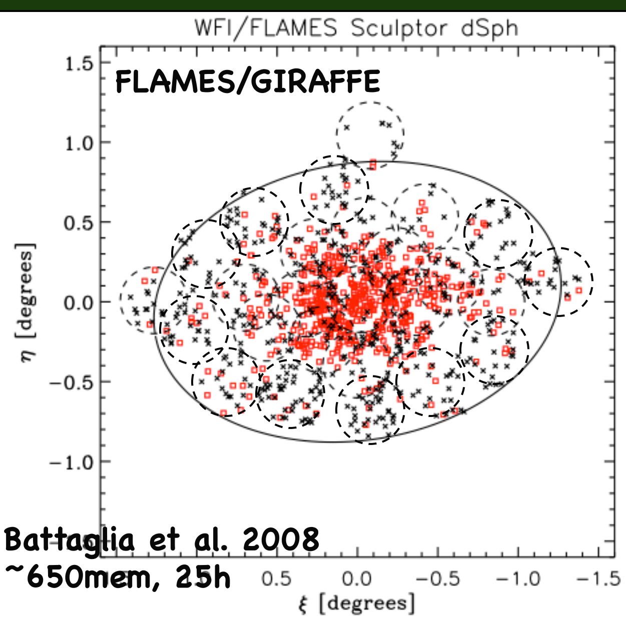


Battaglia et al. 2012

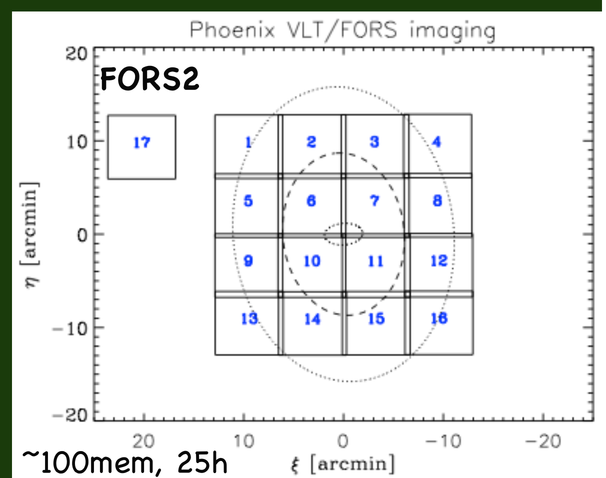
1 Mpc (Local Group outskirts)



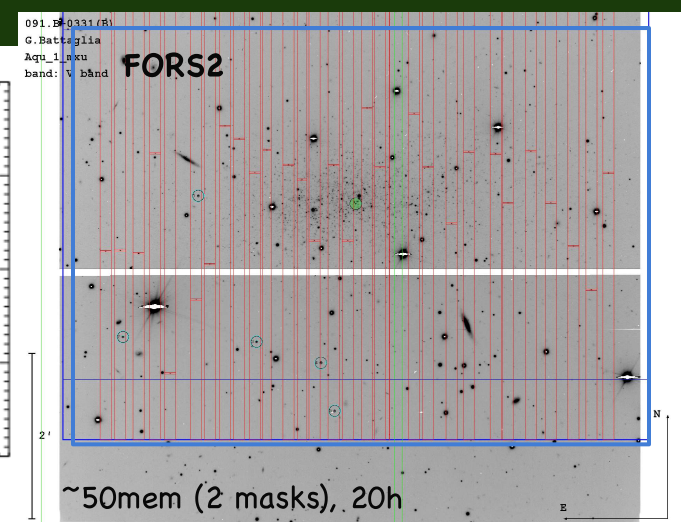
McConnachie et al. 2006



Battaglia et al. 2008
~650mem, 25h



~100mem, 25h



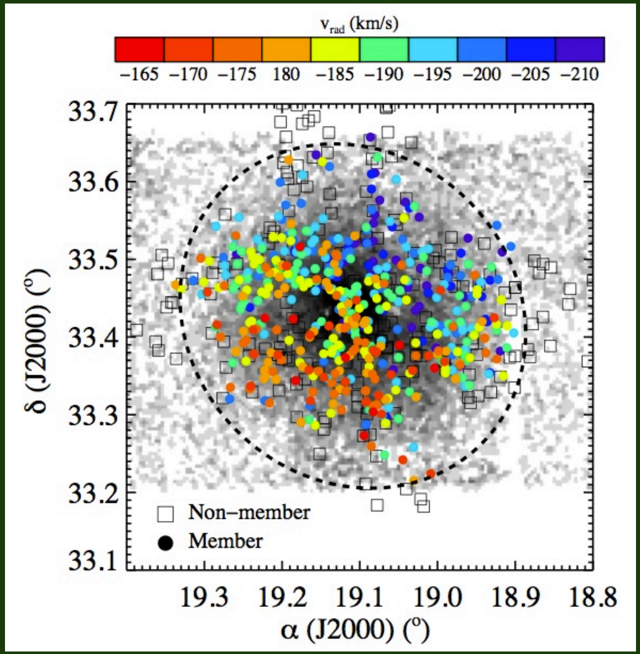
~50mem (2 masks), 20h

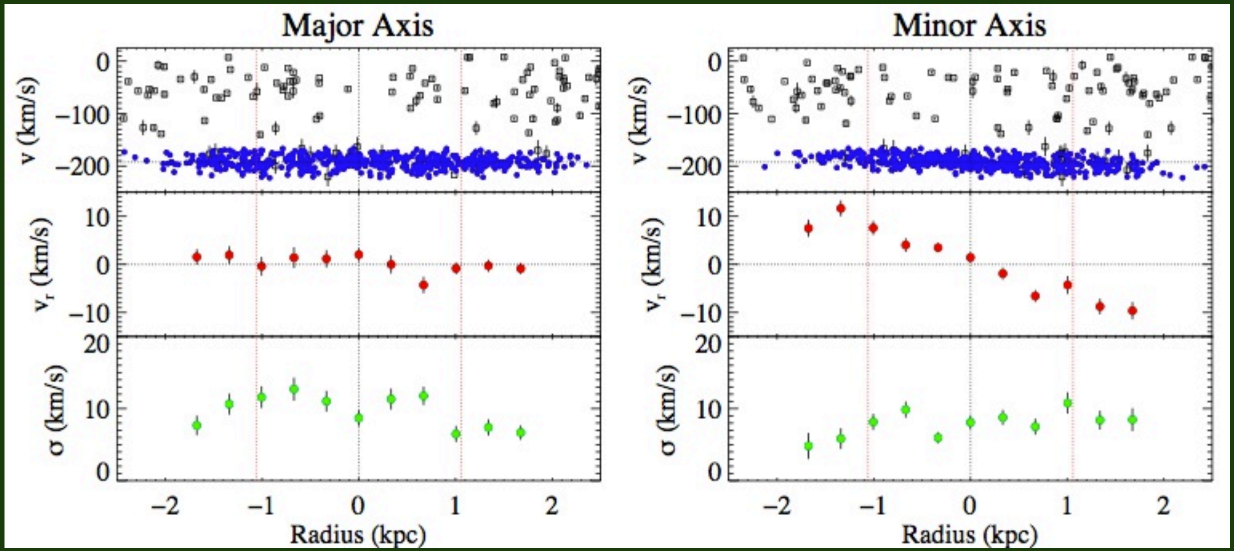
And II dSph (M_V = -12.6)

-530 probable members

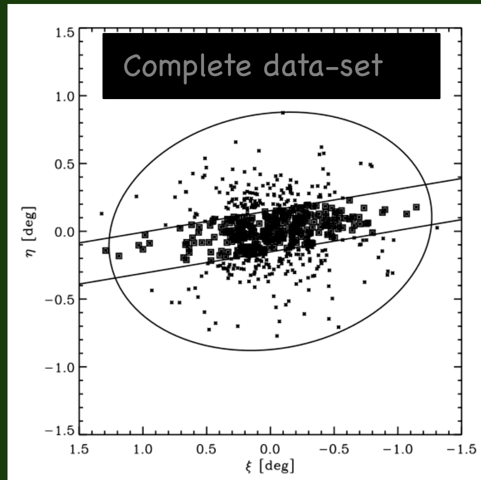
-kinematic major axis almost coincident with photometric minor axis

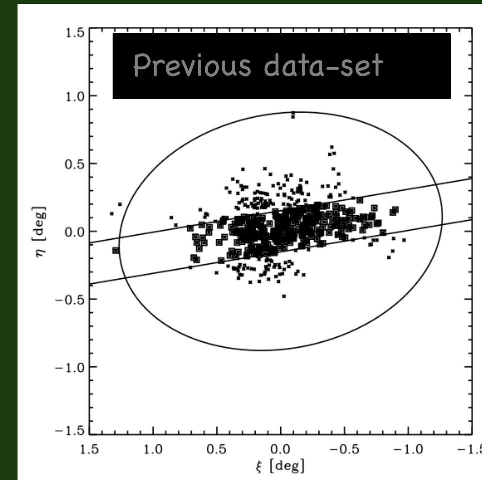
-v/sigma = 1.4

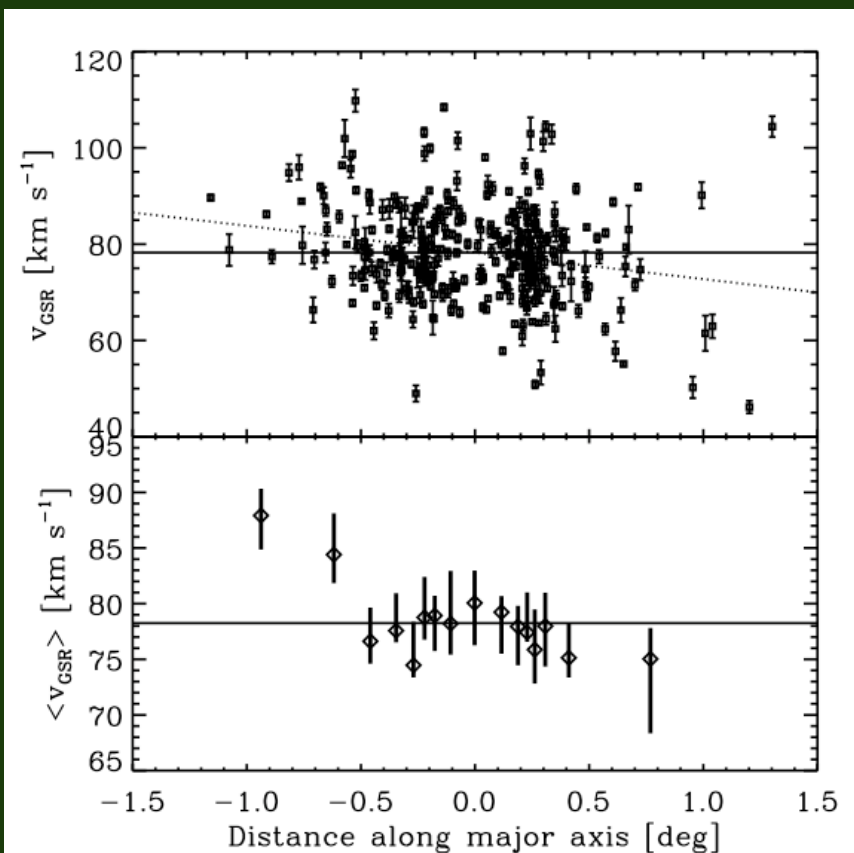


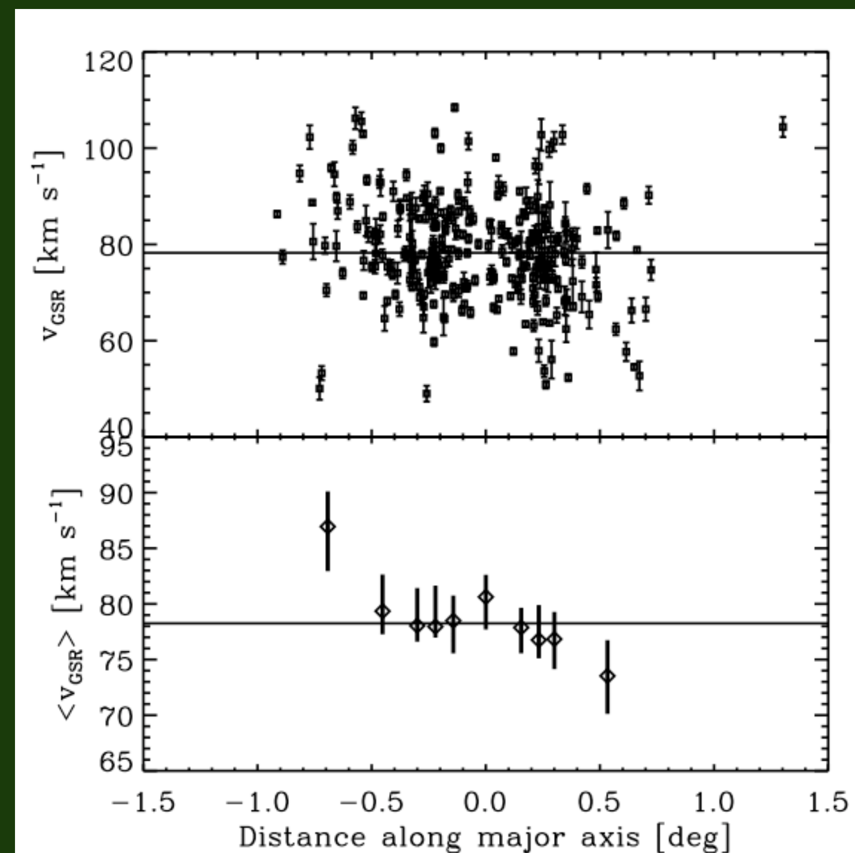


Ho et al. arXiv:1209.2116


Complete data-set
η [deg]
ξ [deg]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5


Previous data-set
η [deg]
ξ [deg]
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5


v_{GSR} [km s^{-1}]
120
100
80
60
40
$\langle v_{GSR} \rangle$ [km s^{-1}]
95
90
85
80
75
70
65
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
Distance along major axis [deg]


v_{GSR} [km s^{-1}]
120
100
80
60
40
$\langle v_{GSR} \rangle$ [km s^{-1}]
95
90
85
80
75
70
65
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
Distance along major axis [deg]

Summary: velocity gradients
(intrinsic rotation, tidal disruption or projection effect?)

- Large coverage, statistics and accurate velocities are important for assessing the presence of velocity gradients. Have the observed dSphs been explored well enough to detect and fully quantify these gradients?
- Overall, a zoo of properties….
- If presence of velocity gradients in isolated dSphs (Cetus: Lewis et al. 2007; Tucana: Fraternali et al. 2010) is confirmed => rotation as intrinsic property of dSphs
- Stars in dIrrs and dTs?
- Accurate proper motions would allow to quantify projection effects in MW dSphs
- More observations and model predictions are needed to quantify tidal disruption