Chemistry and kinematics of stars in Milky Way dwarf spheroidal galaxies

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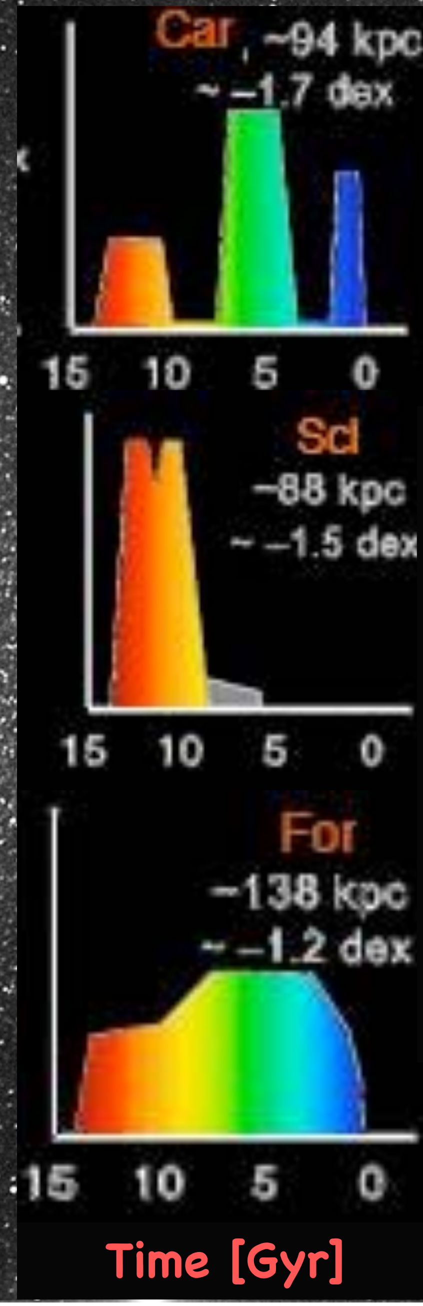
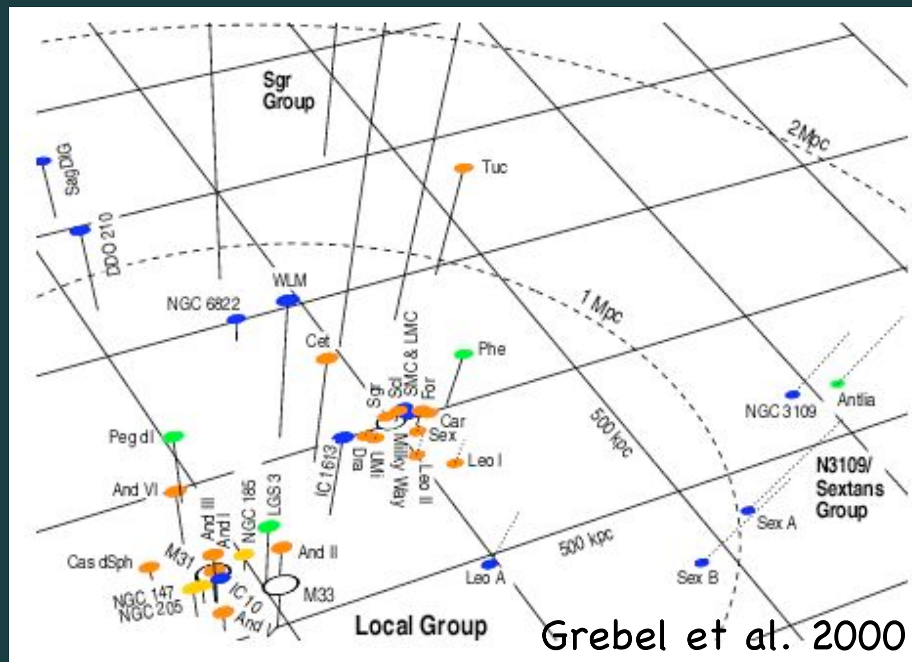
Dwarf spheroidal galaxies (dSphs): characteristics

- Faint
- Small
- Pressure supported
- Variety of SFHs (but all contain ancient stars, > 10 Gyr old)



Grebel, Gallagher & Harbeck 2007

The Local Group

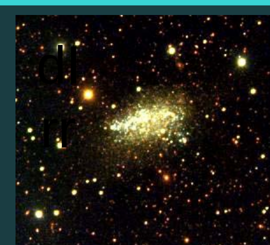


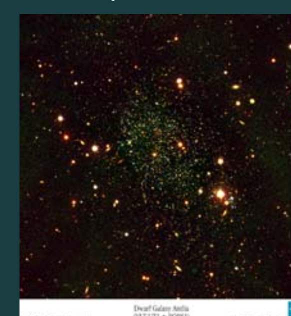
Large spirals

Dwarf ellipticals (dE); dwarf spheroidals (dSphs)

Dwarf irregulars (dIrr)

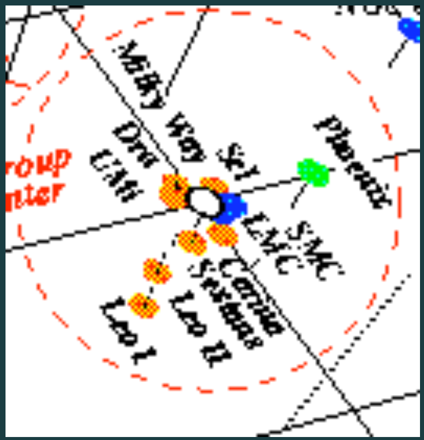
dSphs/dIrrs





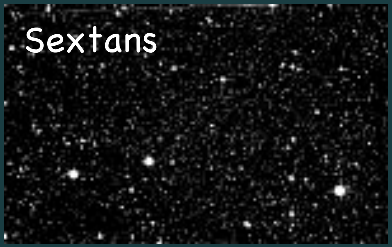
Large majority

The Milky Way halo
(before 2005...)



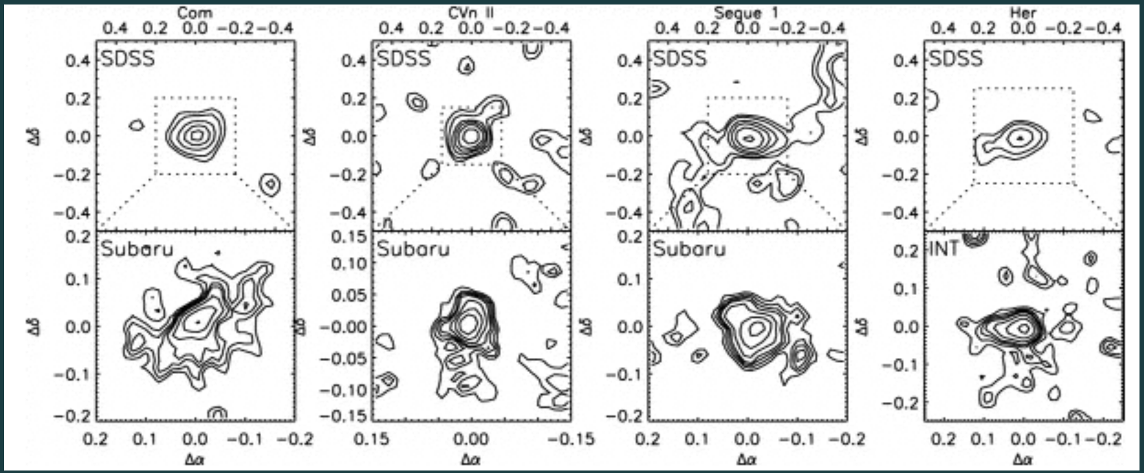
3 larger galaxies: LMC, SMC, Sagg
Distance: 25-60 kpc

8 dSphs: 65-250 kpc
Luminosity: 10^5 - 10^7 Lsun
Half light radius: 0.1 kpc - 1 kpc



After 2005, thanks to SDSS discovery of "Hobbit galaxies"

- Distance: 60-250 kpc
- Mv: -3, -8 mag
- Luminosity: 10^3 - 10^5 Lsun
- Half light radius: 0.02 kpc- 0.3 kpc

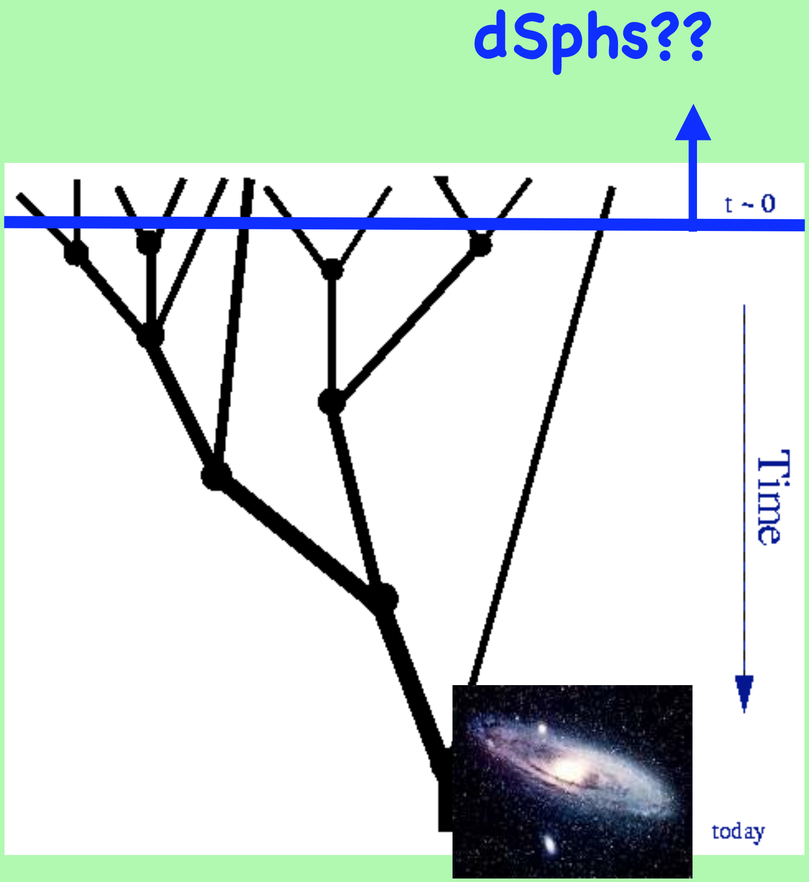


and more of them….

Belokurov et al. 2007

dSphs as Galaxy formation probes

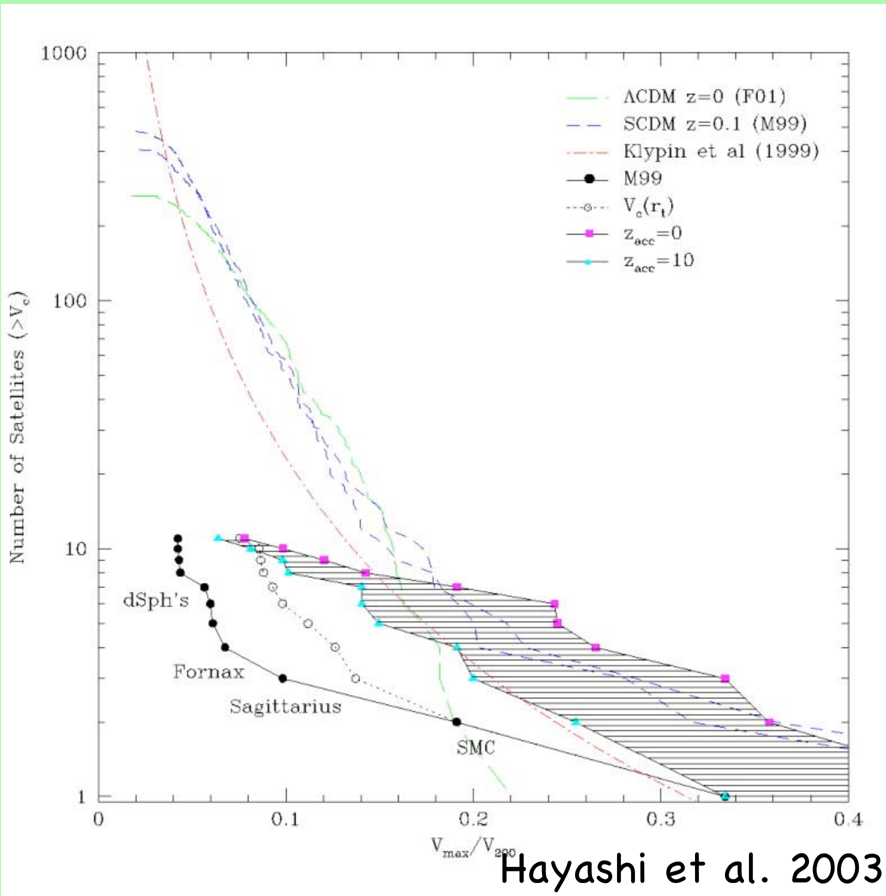
- Likely they are the most common type of galaxies
- Simple with respect to larger galaxies
- Possible role in the build up of larger galaxies



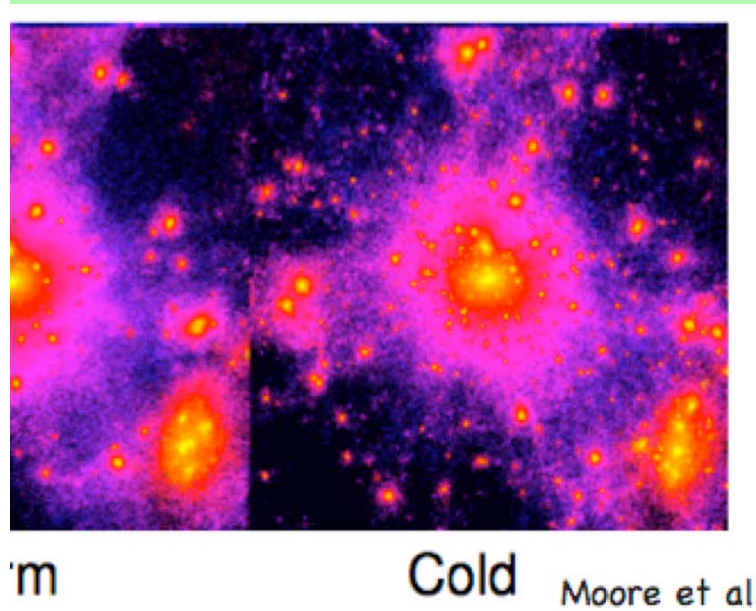
DSphs as Dark Matter (DM) Probes

Smallest objects whose kinematics requires DM

(M/L up to 100s)



Hayashi et al. 2003



Moore et al.

es

Cusps

Need accurate measurements of their mass content

DART:
Dwarf Abundances and Radial velocities Team

E.Tolstoy, M.Irwin, V.Hill, A.Helmi, G.Battaglia,
P.Jablonka, B.Letarte, K.Venn, M.Shetrone,
N.Arimoto, F.Primas, A.Kaufer, P.François,
T.Szeifert, T.Abel, K.Sadakane

@ Groningen, Paris-Meudon, Victoria, Caltech, Texas,
Geneva, ESO, NAOJ, Stanford

DART Large Progr. at ESO

- Large Progr. SAMPLE

Milky Way dSphs: Carina (HR only), Sextans, Fornax, Sculptor (80 kpc < d < 140 kpc)

- DATA

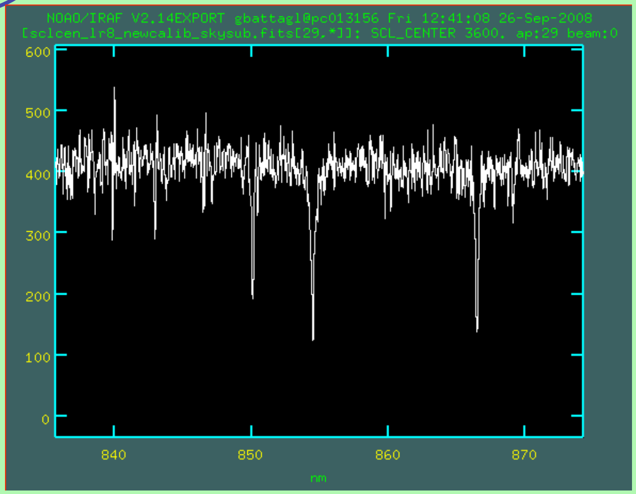
-ESO/WFI V and I photometry

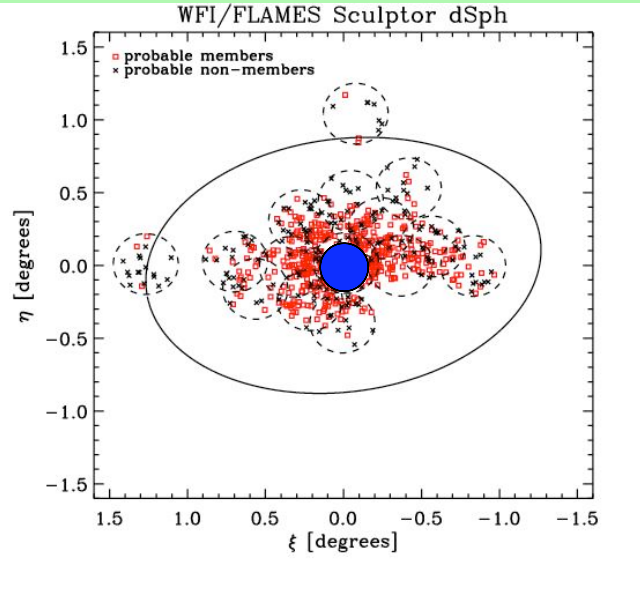
-VLT/FLAMES spectroscopy of Red Giant Branch stars:

1) Low Resolution around CaII triplet

(R ~ 6500, 8000-9000 Å)

2) High Resolution (R ~ 20000, 5300-6700 Å)

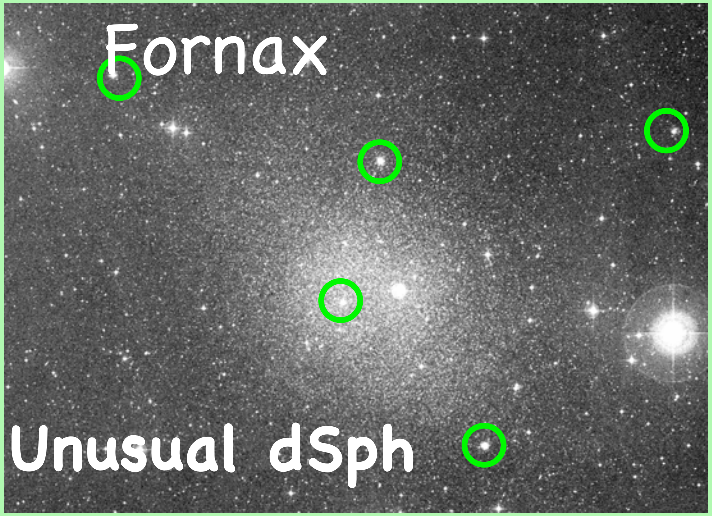




CaT [Fe/H] (±0.15dex) and l.o.s.velocities (±2 km/s) for hundreds probable members over a large area

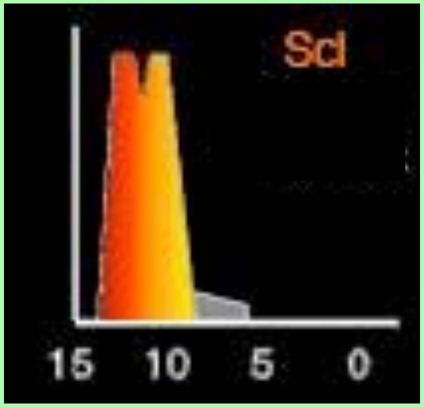
Abundances (Ca, Mg, Ti, etc) and l.o.s.velocities (±0.5 km/s) for ~ 80 members in the centre

versus



- Distance: 79 kpc
- Faint (Lv~ 10^6 Lsun) and metal poor
- Old, > 10 Gyr (e.g. Monkiewicz et al. 1999)

- Distance: 138 kpc
- Most luminous (Lv~10^7 Lsun) and metal rich of MW satellites
- Recent star formation (Stetson et al. 1998, Buonanno et al.1999, Saviane et al. 2000)



Time [Gyr]

SFH from

Grebel, Gallagher & Harbeck 2007

Time [Gyr]

Outline

Part I
General properties of Sculptor & Fornax

1) Photometry: properties of stellar populations from CMD analysis
2) Spectroscopy: Validity of CaT method to derive [Fe/H]
3) Spectroscopy: Kinematics and metallicity

Part II
Mass determination of Sculptor

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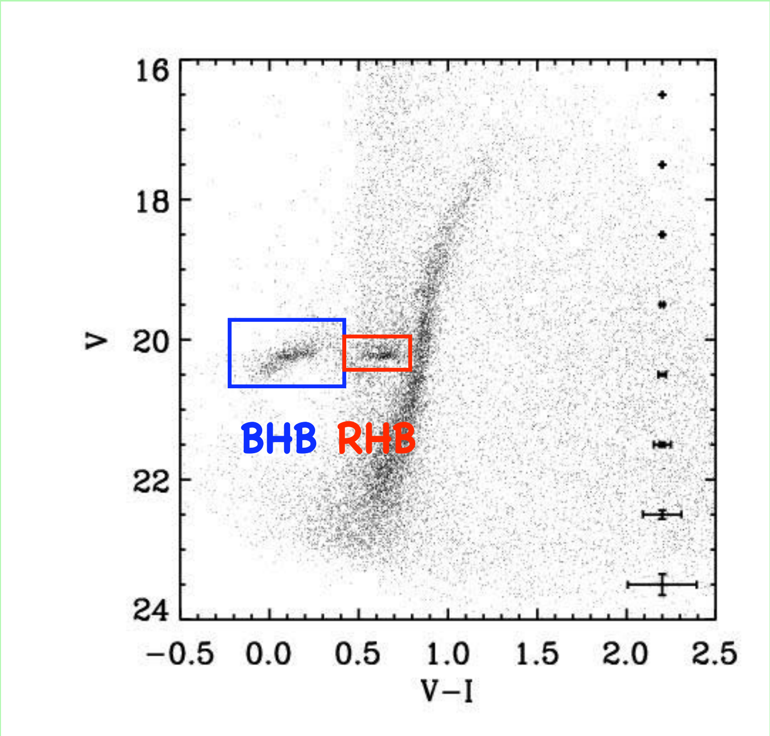
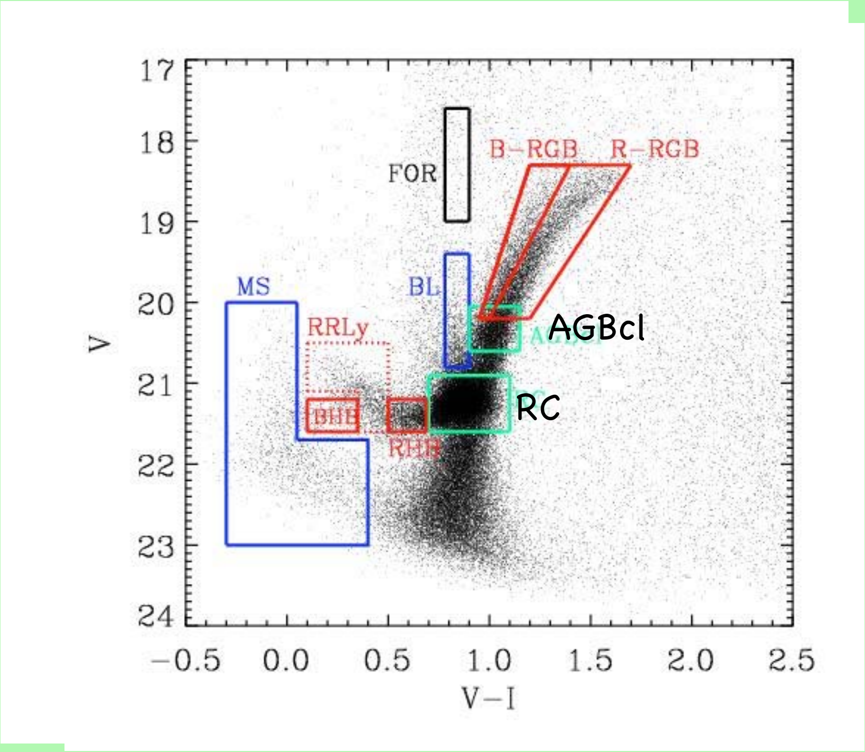
ESO/WFI photometry: Sculptor versus Fornax



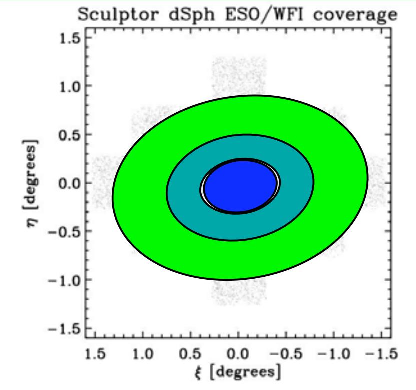
Tolstoy et al. (2004)



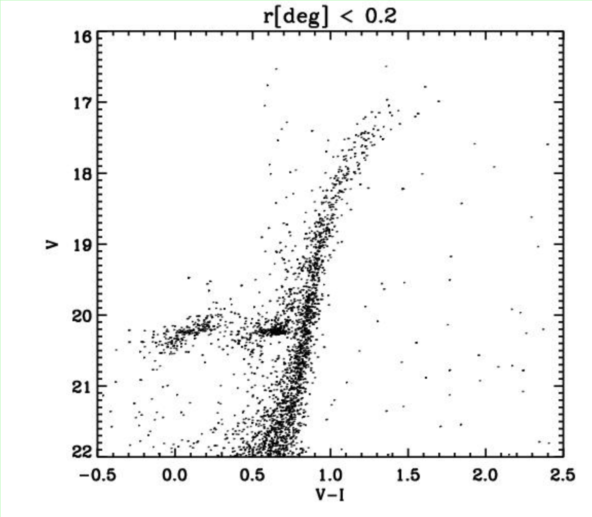
Battaglia et al. (2006)

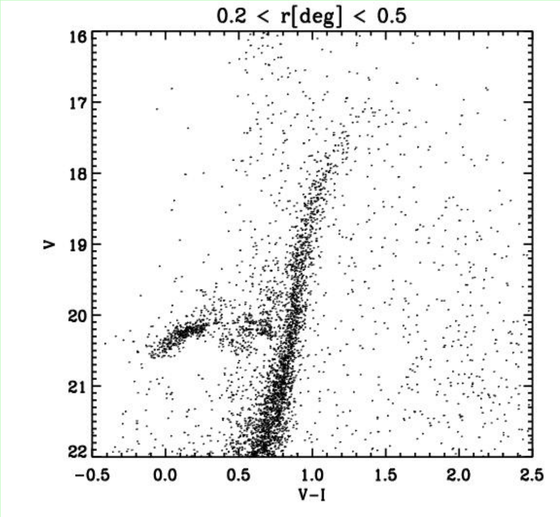
V and I photometry covering the whole galaxy

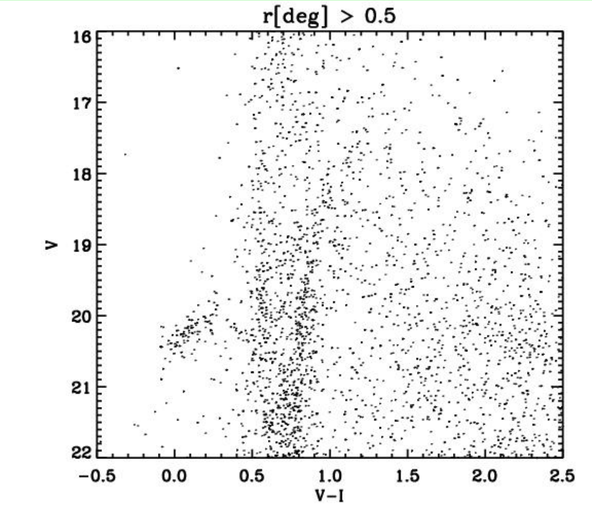
Spatial variation of stellar population: Sculptor



Normalized



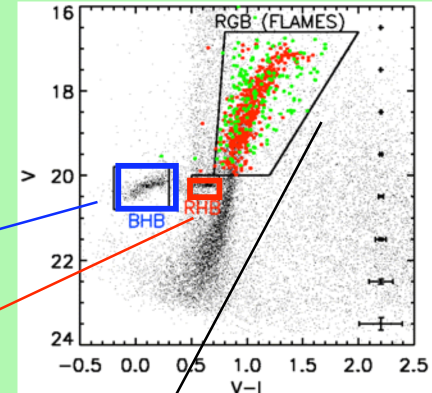




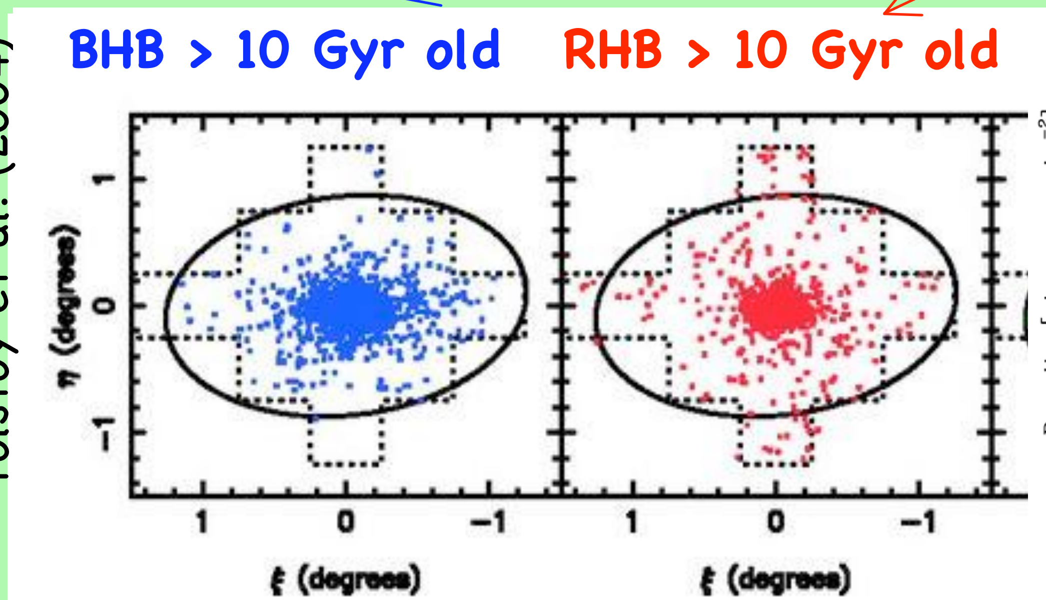
Horizontal Branch morphology changes with radius

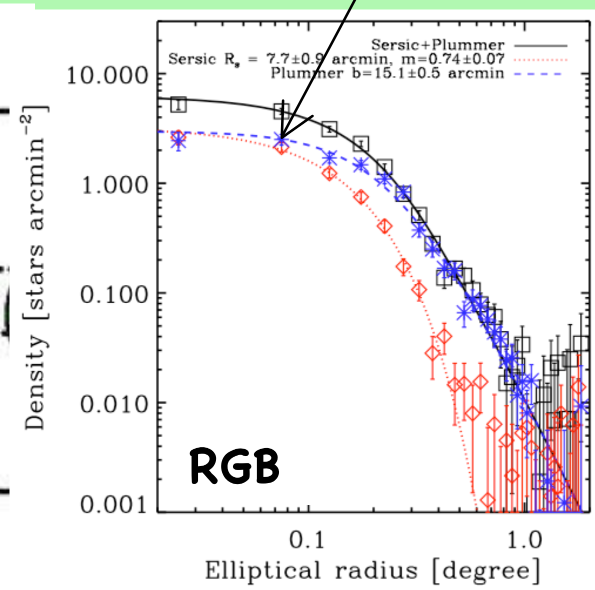
(see also Harbeck et al. 2001)

Spatial variation of stellar population: Sculptor



Tolstoy et al. (2004)



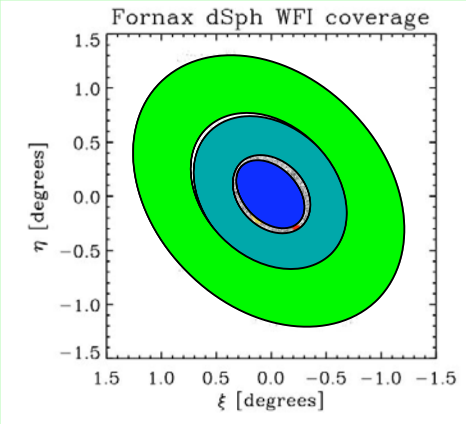


BHB: more extended
Best fit by
Plummer law

RHB: centrally
concentrated
Best fit by
Sersic profile

RGB: composite profile
(BHB+RHB) provides good
fit to data

Spatial variation of stellar population: Fornax



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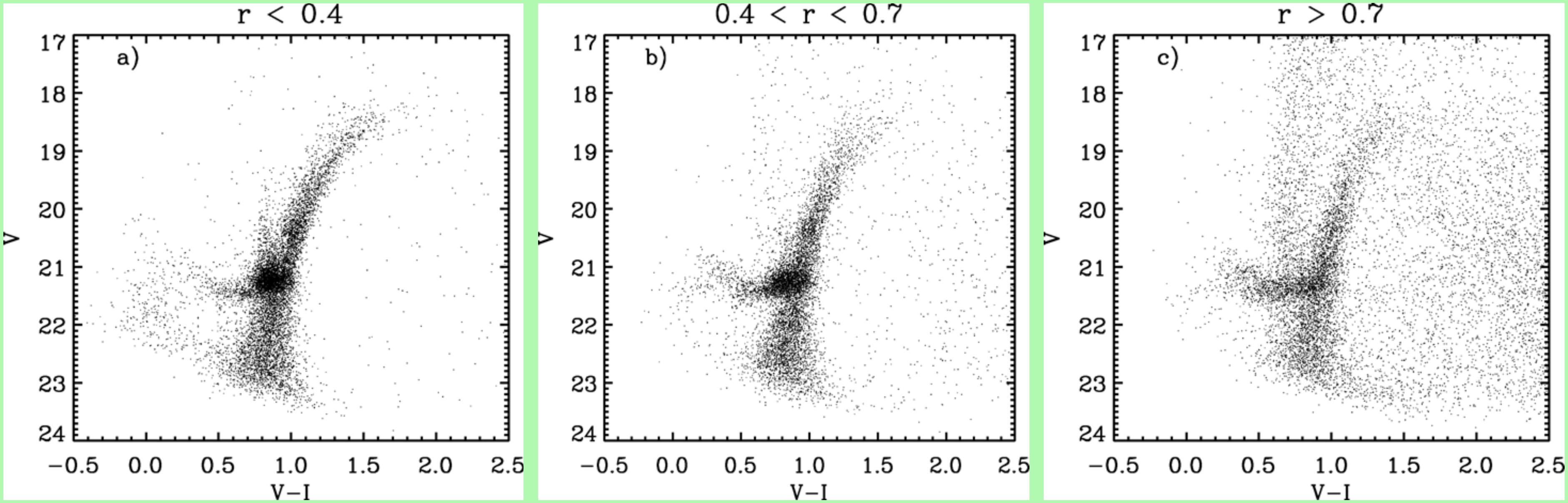
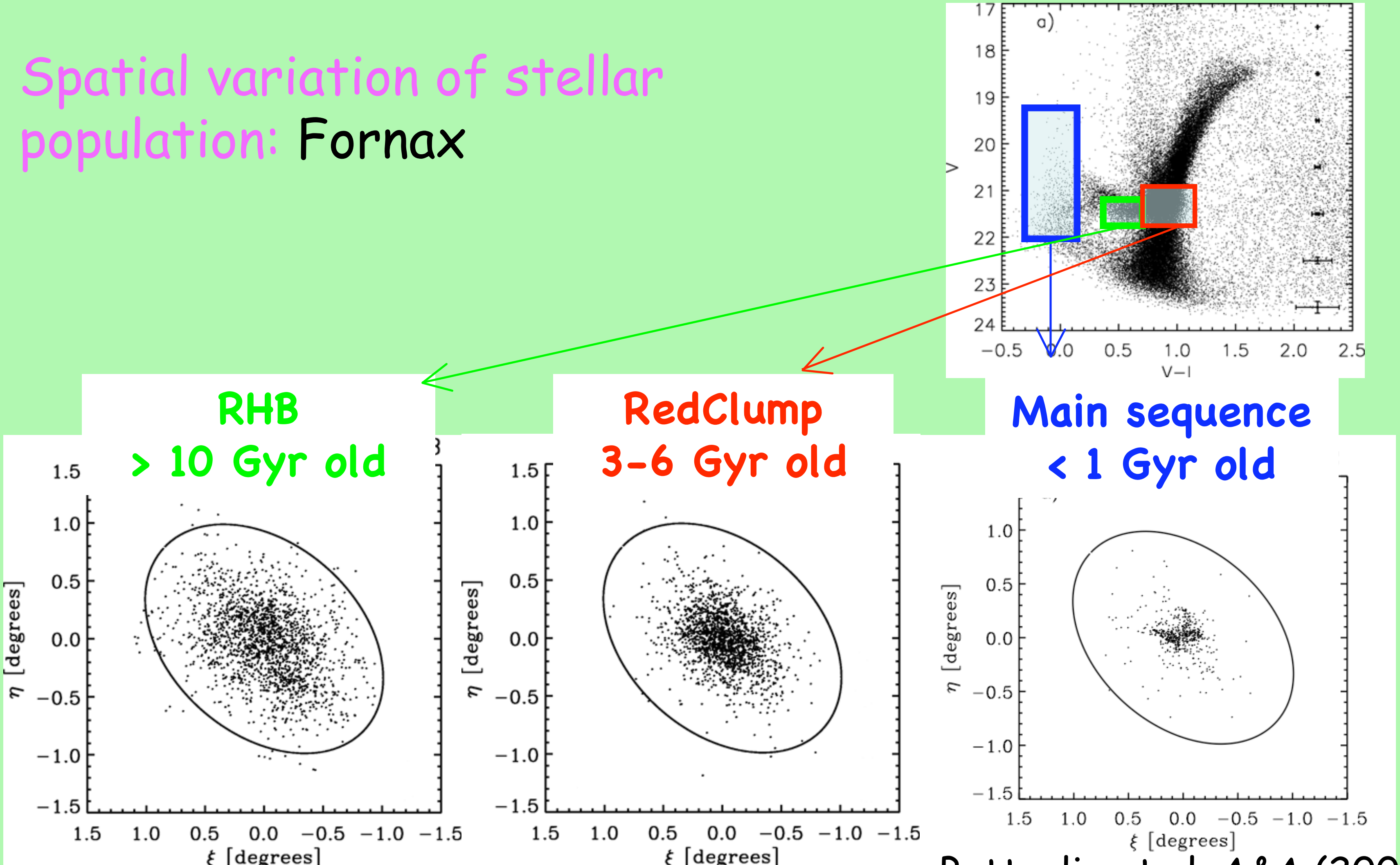


Young stars (< 1 Gyr old) found at r < 0.4 deg

Blue Horizontal Branch (BHB) more visible at r> 0.4 deg

Red Giant Branch (RGB) bluer for increasing radii

Spatial variation of stellar population: Fornax



Battaglia et al. A&A (2006)

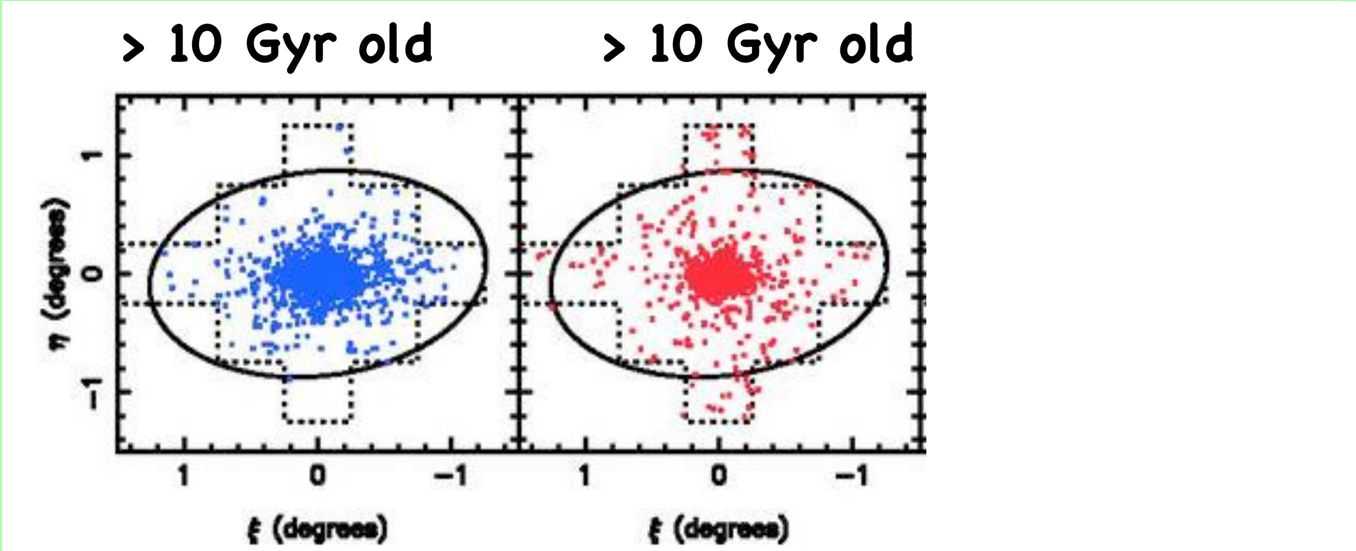
Intermediate age stars (RC, 3-6 Gyr) less extended and more centrally concentrated than old stars (RHB, >10 Gyr)

Young stars (MS, < 1 Gyr) centrally concentrated with asymmetric distribution (see also Stetson et al.1998)

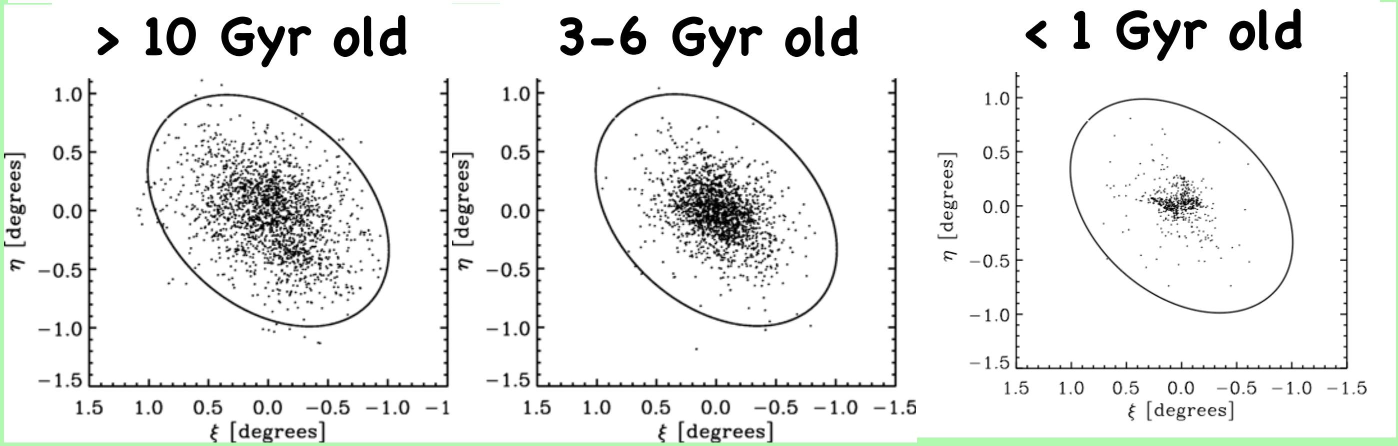
Summary I

Spatial variations of stellar populations are present both in Scl and Fnx

Scl



Fnx



but for different age ranges

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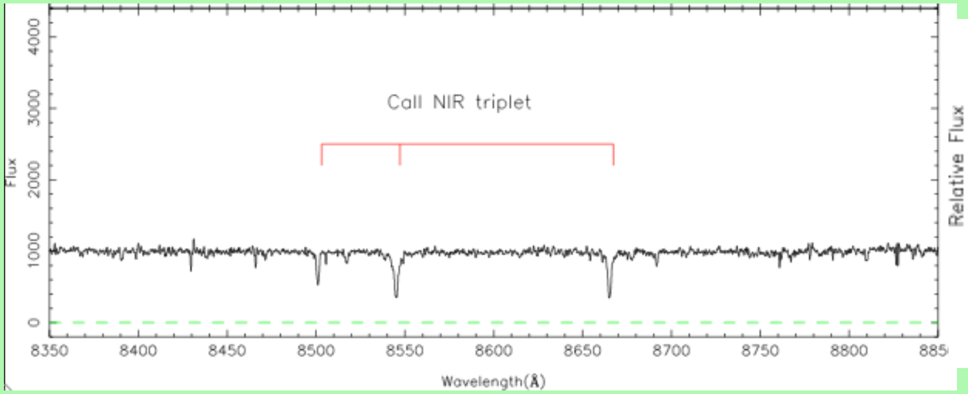
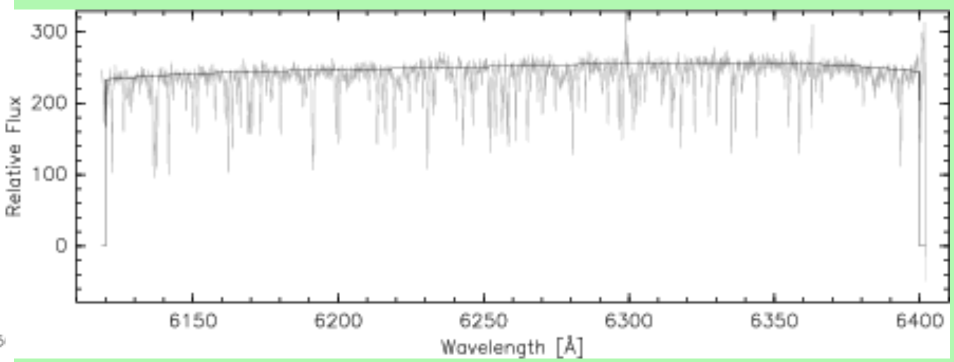
3) Spectroscopy: Kinematics and metallicity

LR around Ca II Triplet vs HR





3 CaT lines give accurate velocities: δv_r ~ 2 km/s

Many lines!! δv_r ~ 0.5 km/s

Calibration between CaT EW and [Fe/H] allows metallicity determination (δ[Fe/H] ~ 0.15 dex)

Abundances of many elements

=> [Fe/H] not directly measured

[Fe/H] directly measured from more than 60 Fe lines

But HR much more time consuming than LR!

=> We need to check that CaT-[Fe/H] calibration works

[Fe/H] reliability check: HR vs LR spectroscopy

- For RGB stars in single stellar populations (stellar clusters):

$[Fe/H] = a + b\,[\,\Sigma EW_{CaT} + c\,(V - V_{HB})]$

(e.g. Rutledge et al. 1997, Cole et al. 2004)

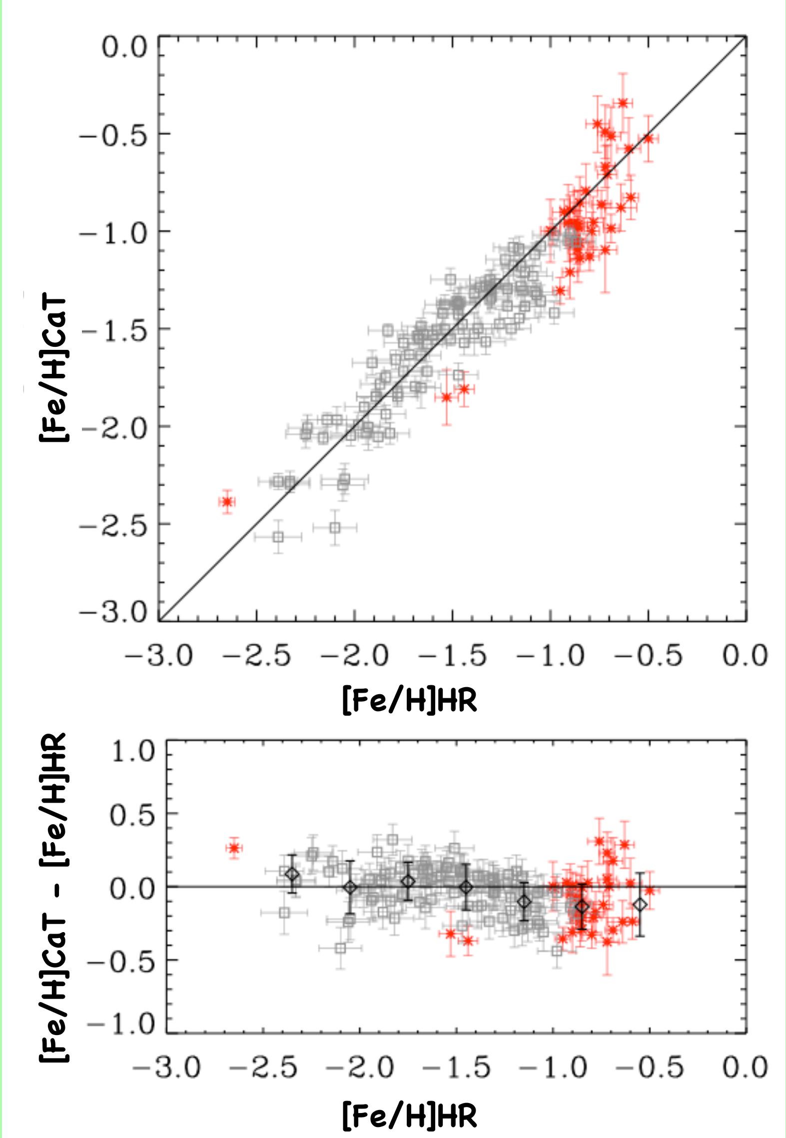
- And for composite stellar populations (galaxies)?

Overlapping stars between our LR and HR sample (93 in Scl, 36 in Fnx):

- HR: [Fe/H] directly measured from 60 Fe lines
- LR: [Fe/H] from CaT EW

Present a trend with metallicity

<u>Good overall comparison!</u>



Battaglia et al. 2008, MNRAS, 383, 183

Summary II

CaT method can be applied with confidence to composite stellar populations in the range $-2.5 < [Fe/H] < -0.5$

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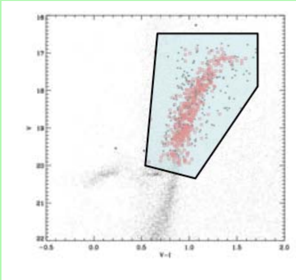
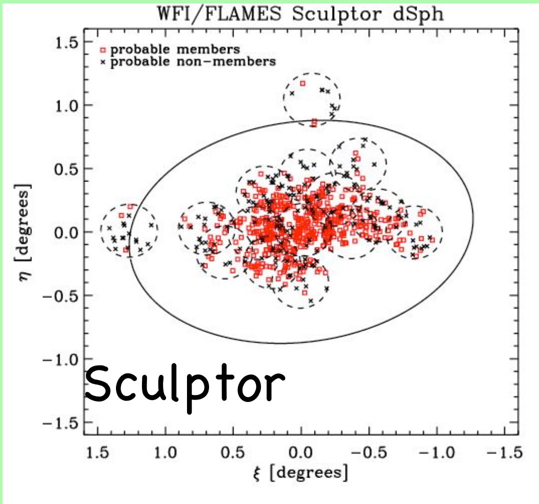
3) Spectroscopy: Kinematics and metallicity

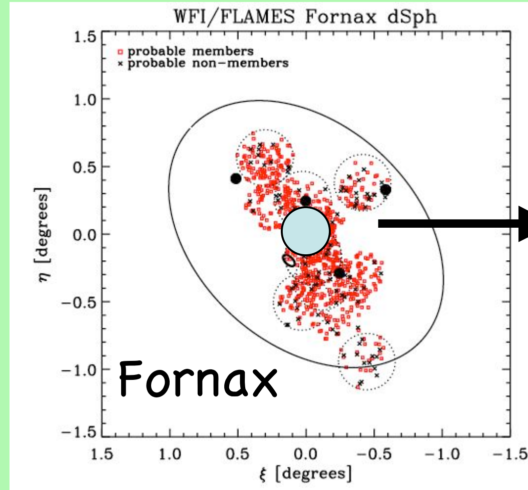
Overview of VLT/FLAMES LR data



→ Targetted RGB stars



Tolstoy et al.(2004) + 7 new fields



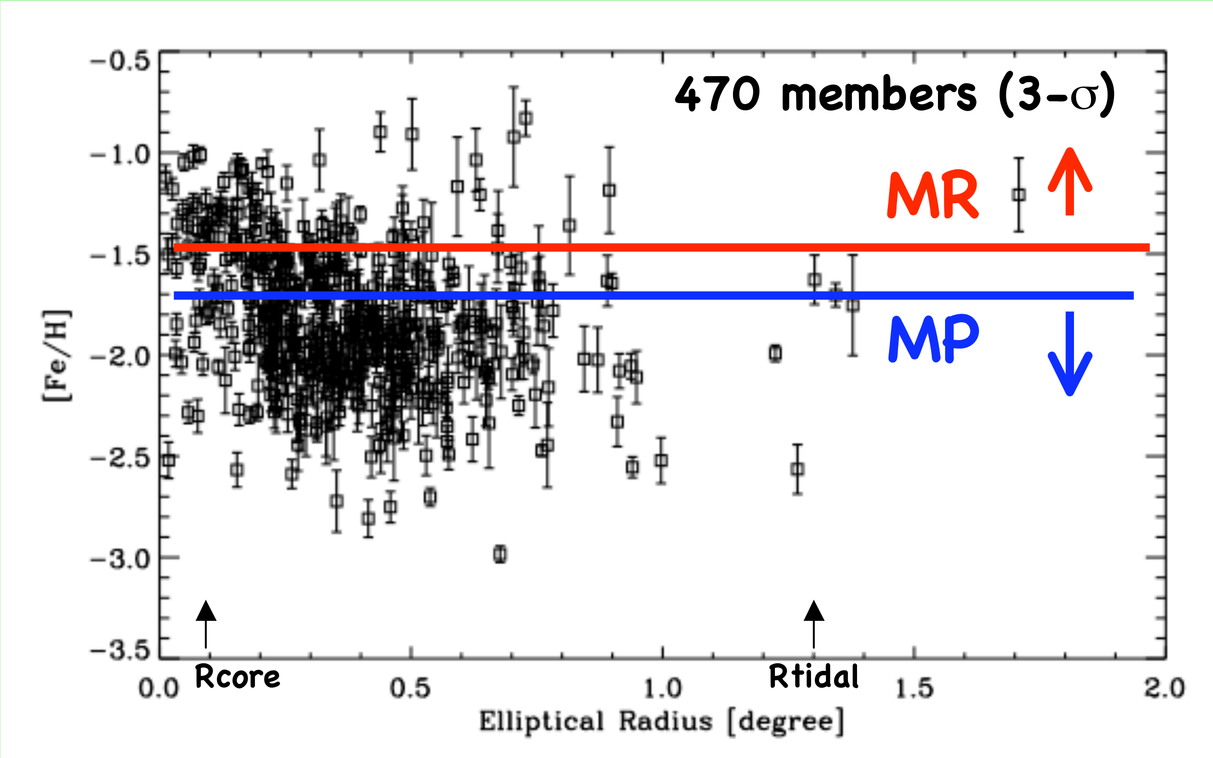
Pont et al. (2004)

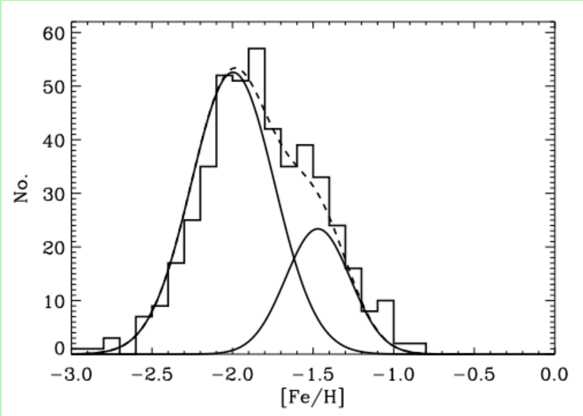
Battaglia et al.(2006) + 4 new fields

- Applied S/N, error in velocity, visual inspection criteria
- Probable Membership from simple velocity selection (more sophisticated approach when deriving velocity dispersion profiles)

- # Targets: 1013 1063
- Final sample: 648 stars 944 (in this talk 641 stars)

Metallicity distribution: Sculptor



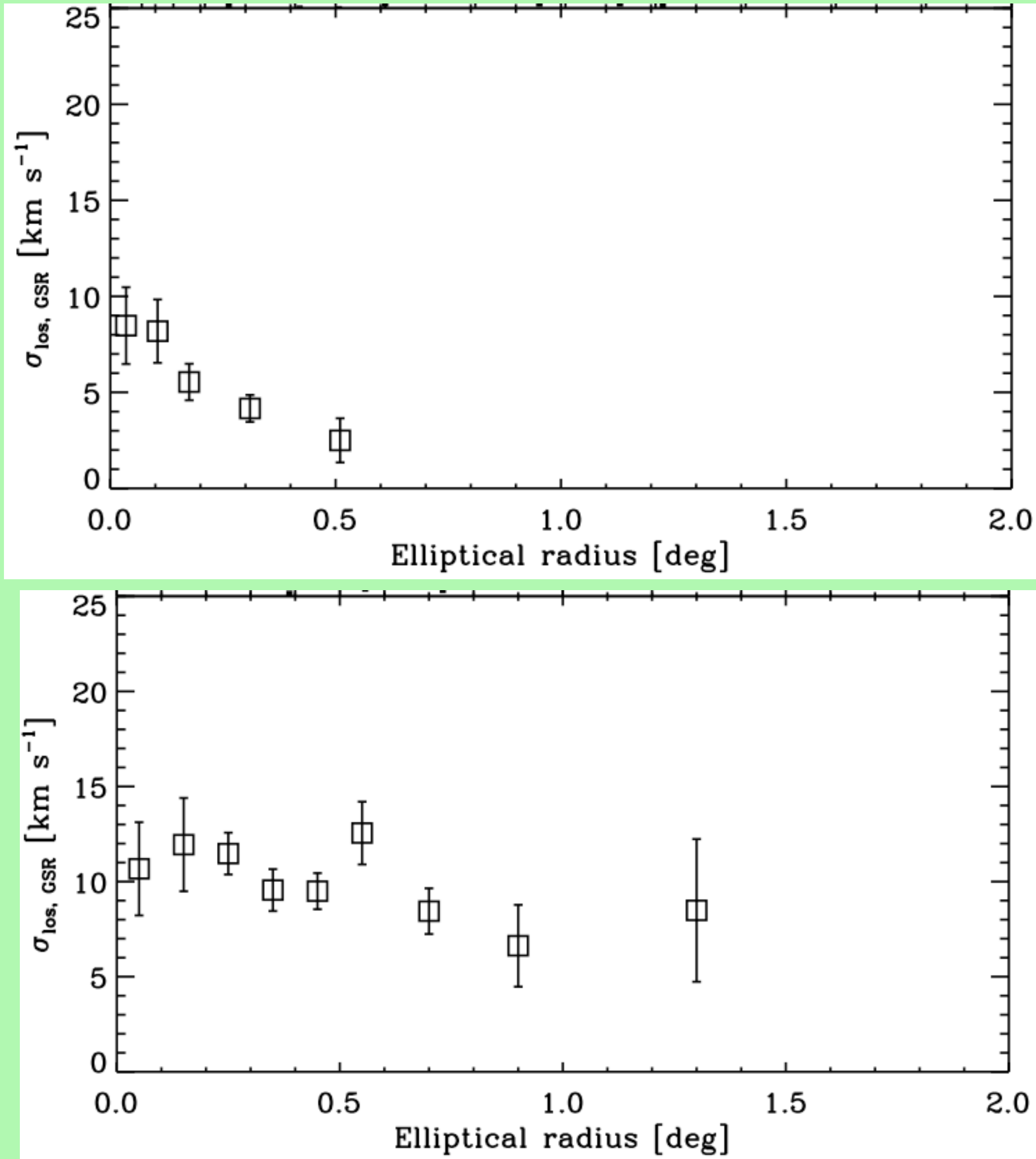


Metallicity variation on the same scale as RHB/BHB variation

And it correlates with kinematics… =>

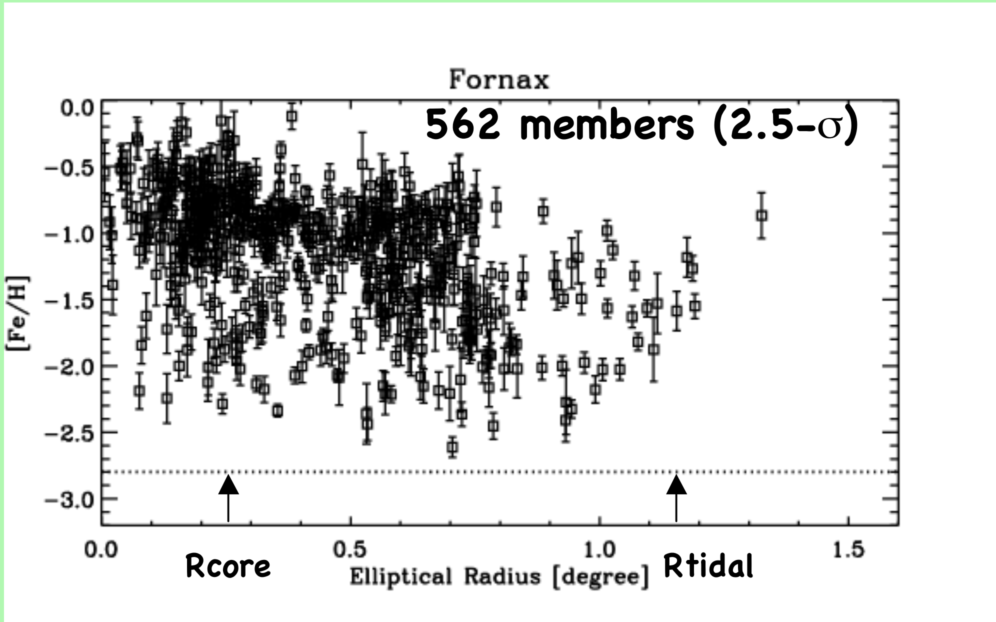
Metallicity variation with radius: metal poor stars found throughout the galaxy (they represent the majority); more metal rich stars more centrally concentrated

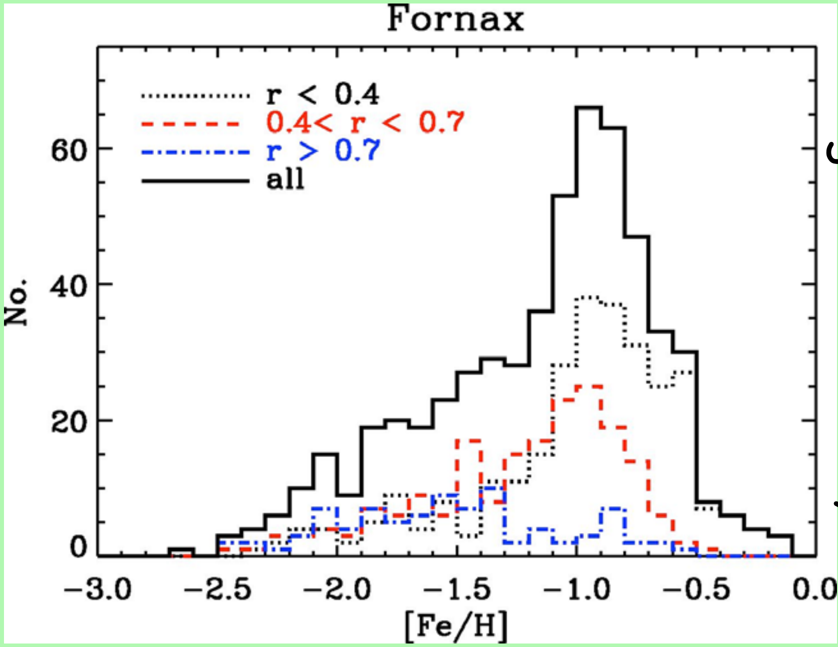
Chemo-dynamics: Sculptor



Scl stars of different metallicity have different spatial distribution and kinematics

Metallicity distribution: Fornax





Battaglia et al.2006, A&A

- Metal poor stars (>10 Gyr old) found throughout the galaxy
- Metal rich stars (3-6 Gyr old) mostly at r < 0.7 deg. They represent the large majority.
- Stars with [Fe/H] < -0.7 (1-2 Gyr old) at r < 0.4 deg

Summary III
On the evolution of Scl and Fnx: similarities

- MP/older stars are spatially extended; MR/younger stars are more centrally concentrated

  =>Removal of Gas/metals from the outer regions

- Different kinematics for different metallicity components in both Scl and Fnx

  => due to readjustment of the location where star formation took place?

Summary III
On the evolution of Scl and Fnx: differences

Scl

(Formed stars until 10 Gyr ago)

- MP stars dominant (70%)
  =>First phase of SF more intense

- Efficient removal of gas/metals on a short time scale

Fnx

(Formed stars until 200 Myr ago)

- Intermediate age (3-6 Gyr old)/MR stars (57%) dominant => first phase of SF not very intense

- Slower removal of gas/metals

If Scl is less massive than Fnx supernovae explosions, ram pressure, tides might be more efficient

Outline

Part II
Mass determination of Sculptor

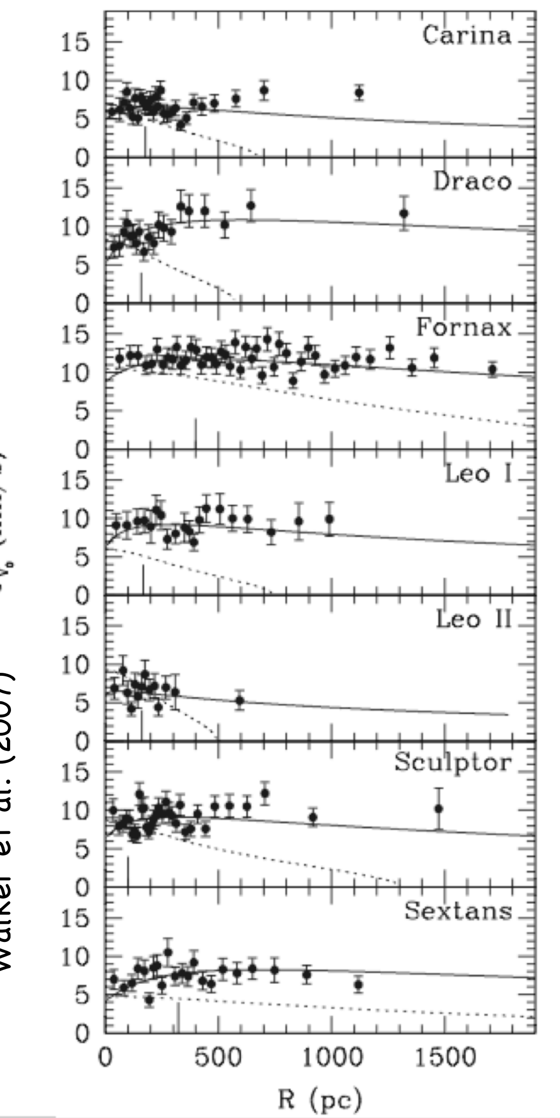
- The mass is likely a key parameter to understand the evolution of galaxies
- potentially good test grounds for dark matter theories

NB: Dynamical analyses give the mass enclosed within the last measured point -> important to go as farther out as possible

Dark matter in dSphs: how much and what kind?

- Aaronson et al. (1983): 3 carbon stars in the Draco dSph -> M/L ~ 31
- After Mateo et al. (1997), velocity dispersion profiles over a large area from hundreds stars (e.g., FLAMES: Tolstoy et al. 2004, Battaglia et al. 2006, Koch et al. 2006; WYFOS: Kleyna et al. 2002, 2004; MIKE: Walker et al. 2007, Muñoz et al. 2006; DEIMOS: Koch et al. 2007, Sohn et al. 2007) -> M/L up to 100s
- Mass-follows-light models provide a poor description -> extended DM halos
- Both cores and cusps are compatible with observations (e.g., cores: Gilmore et al. 2007; cusps: Walker et al. 2007)

Known degeneracies in modeling pressure-supported systems make it difficult to distinguish between DM models!



Walker et al. (2007)

In this part

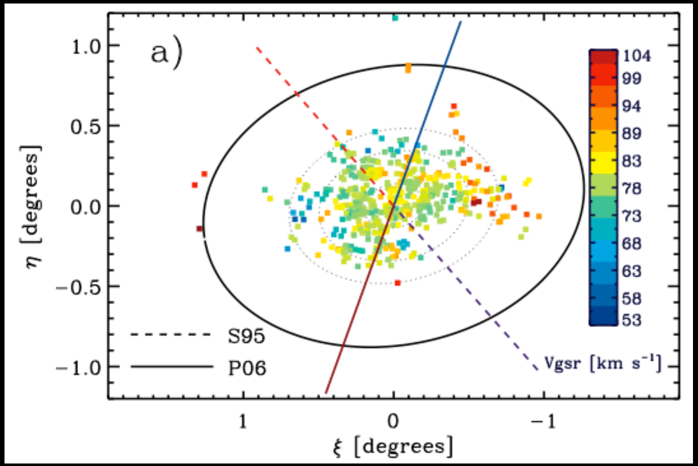
Improved determination of the mass content of Sculptor, by taking into account the presence of the 2 stellar components

- Observed internal kinematics of Sculptor
  - Kinematic status (rotation)
  - Velocity dispersion profile of stellar components
- Mass determination
  - One-(stellar) component modeling (discussion of degeneracies)
  - Two-(stellar) components modeling (NEW APPROACH)

Kinematic status

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

Battaglia et al. 2008, ApJL, 681, 13



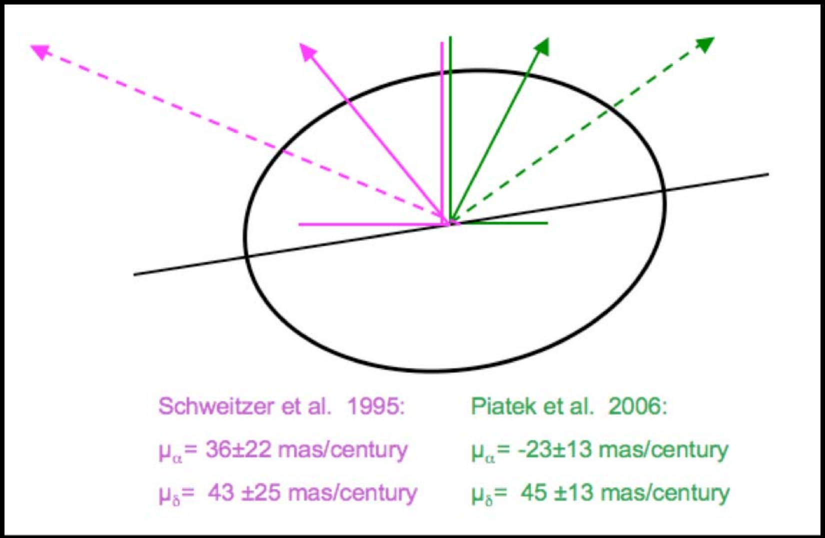
- Vel. gradient does not align with the proper motion direction

- Approaching and receding velocities observed in the opposite side of the galaxy than predicted for tidal disruption (orbits courtesy of L.Sales)

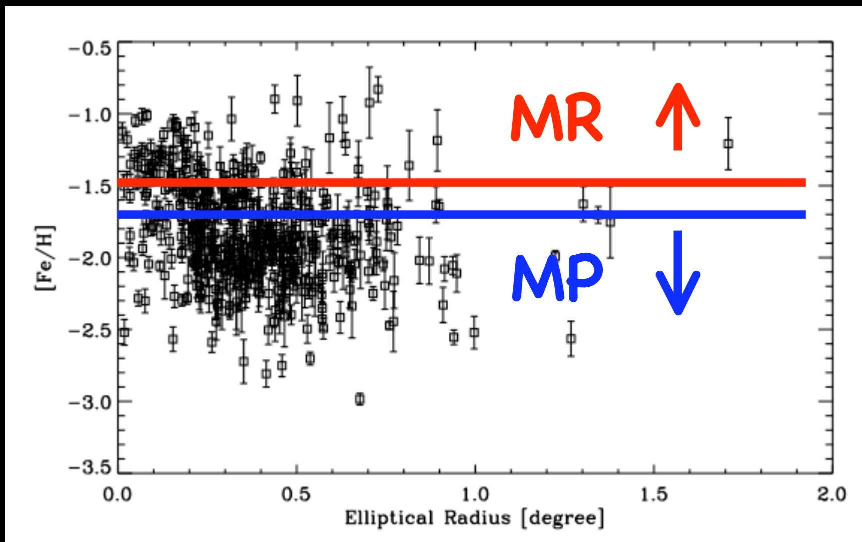
- Flattened shape would be consistent with being due to rotation

- No tidal tails and S-shaped contours are found in our photometric data (Battaglia 2007, PhDthesis; 2008, in prep)

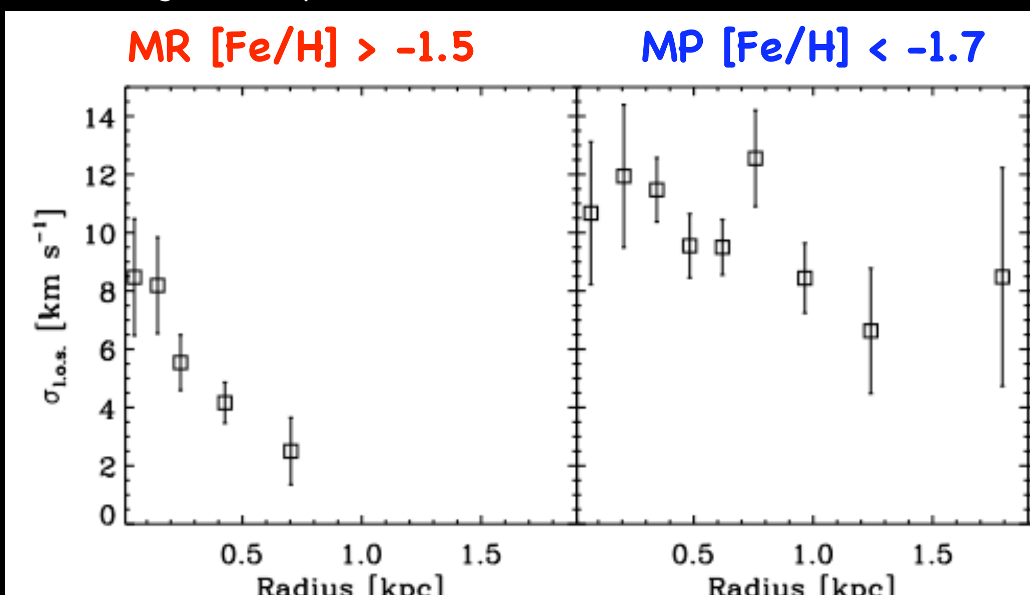
=> Vel. gradient likely due to INTRINSIC ROTATION



Two stellar components:
observed velocity dispersion profiles



1 deg = 1.4 kpc



Rotation has been subtracted to the individual velocities

Maximum likelihood approach to predict number of foreground stars with radius and per [Fe/H] component using Besancon model

Mass determination with Jeans equation

We are going to compare the observed l.o.s. velocity dispersion profile to the predictions from different DM models

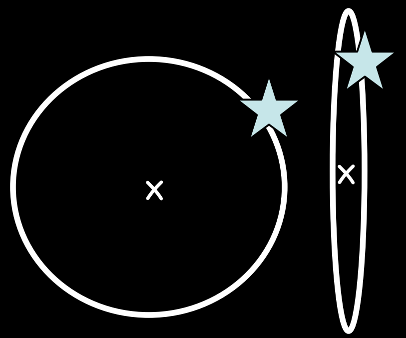
Assumptions: the system is spherical and stationary

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

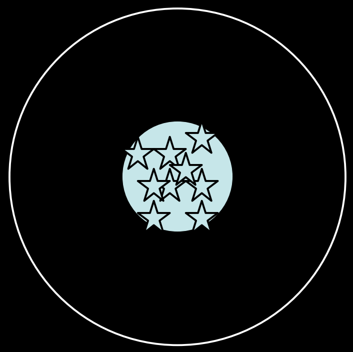
$\Sigma_*(R)$ = spatial distribution of tracer population -> observable

$\beta_*(r)$ = velocity anisotropy of tracer population -> not observable yet

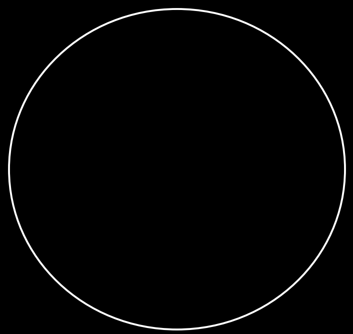
$M(r)$ = total mass distribution (for dSphs the luminous matter is negligible)



One-(stellar) component modeling



DM



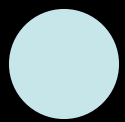
Core: Isothermal sphere

(core radius and mass)

Cusp: NFW sphere

(concentration and mass)

All RGB stars



Velocity anisotropy β :

-constant with radius

-Osipkov-Merrit anisotropy

Spatial distribution: Observed (from WFI photometry)

-For a range of parameters (Iso: rc, β, M; NFW: c, β, M) we derive $\sigma_{los,PREDICTED}(R)$

- compare $\sigma_{los,PREDICTED}(R)$ to $\sigma_{los,\ OBSERVED}(R)$ -> χ^2

- minimize χ^2

One-component modeling: results

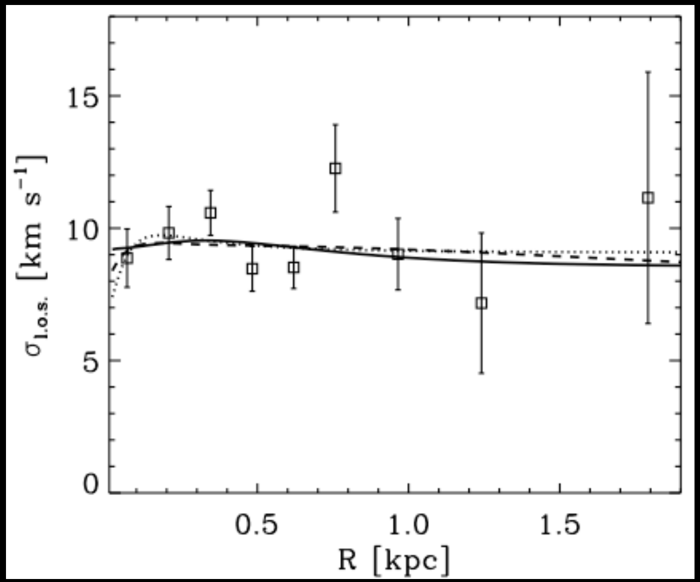
$\beta(r)$ = const. :

- Cored: reduced $\chi^2 = 1.1$
  rc=0.05 kpc, M(<1.8kpc)=1.3±0.2 x 10^8 M_{sun}
- Cusped: reduced $\chi^2 = 1.2$
  c=35, M(<1.8kpc)=1.4±0.5 x 10^8 M_{sun}

$\beta(r) = \beta$ O.M. :

- Cored: reduced $\chi^2 = 1.2$
  rc=0.5 kpc, M(<1.8kpc)=3.2±0.5 x 10^8 M_{sun}

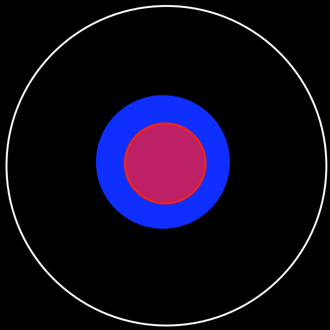
Battaglia et al. 2008



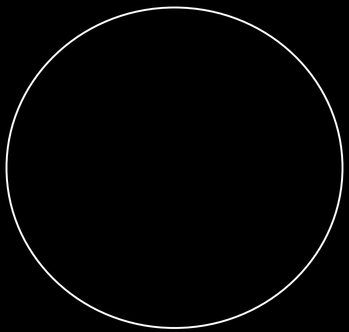
Both cored and cusped models give good fits

These fits are undistinguishable!

Two-(stellar) components modeling



DM



Core: Isothermal sphere

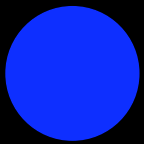
(core radius and mass)

Cusp: NFW sphere

(concentration and mass)

MR stars

MP stars



Velocity anisotropy:

-constant with radius

-Osipkov-Merrit anisotropy

Spatial distribution: Observed (from WFI photometry)

-For a range of parameters (Iso: rc, β_{MR}, β_{MP}, M; NFW: c, β_{MR}, β_{MP}, M)
we derive $\sigma_{los,MR,PREDICTED}(R)$ and $\sigma_{los,\ MP,\ PREDICTED}(R)$

-compare $\sigma_{los,\ MR,\ PREDICTED}(R)$ to $\sigma_{los,\ MR,\ OBSERVED}(R)$ -> $\chi_{MR}{}^2$

-compare $\sigma_{los,\ MP,\ PREDICTED}(R)$ to $\sigma_{los,\ MP,\ OBSERVED}(R)$ -> $\chi_{MP}{}^2$

-Minimization of $\chi^2_{MR} + \chi^2_{MP}$

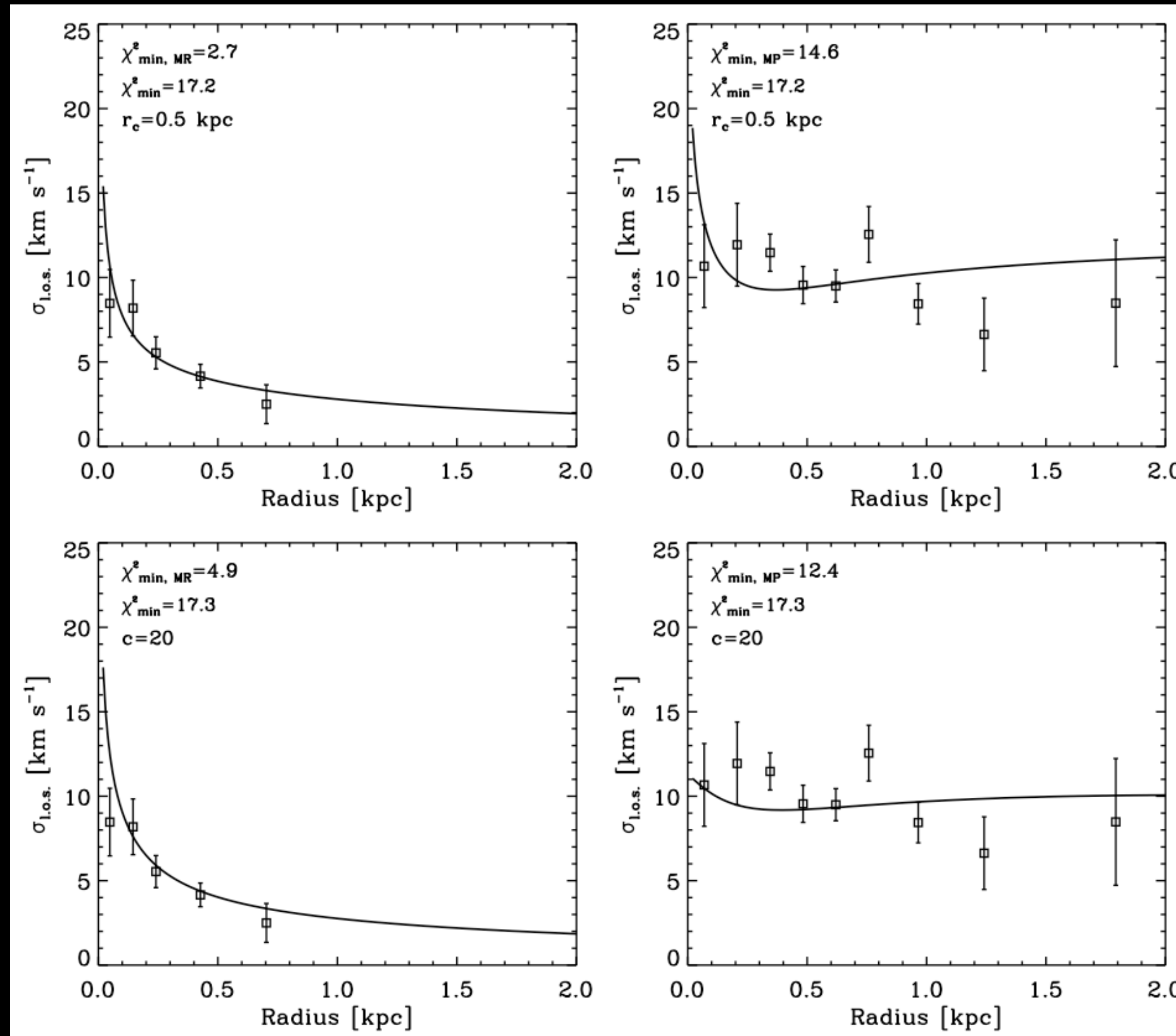
Two-component modeling: ß= const

MR

MP

Iso
rc=0.5 kpc

NFW
c=20



These best-fitting models are not a good representation of the data, both for cored and cusped profiles (also for ≠ rc and concentrations)

Two-component modeling: ß O.M.

MR MP

Iso
rc=0.5 kpc

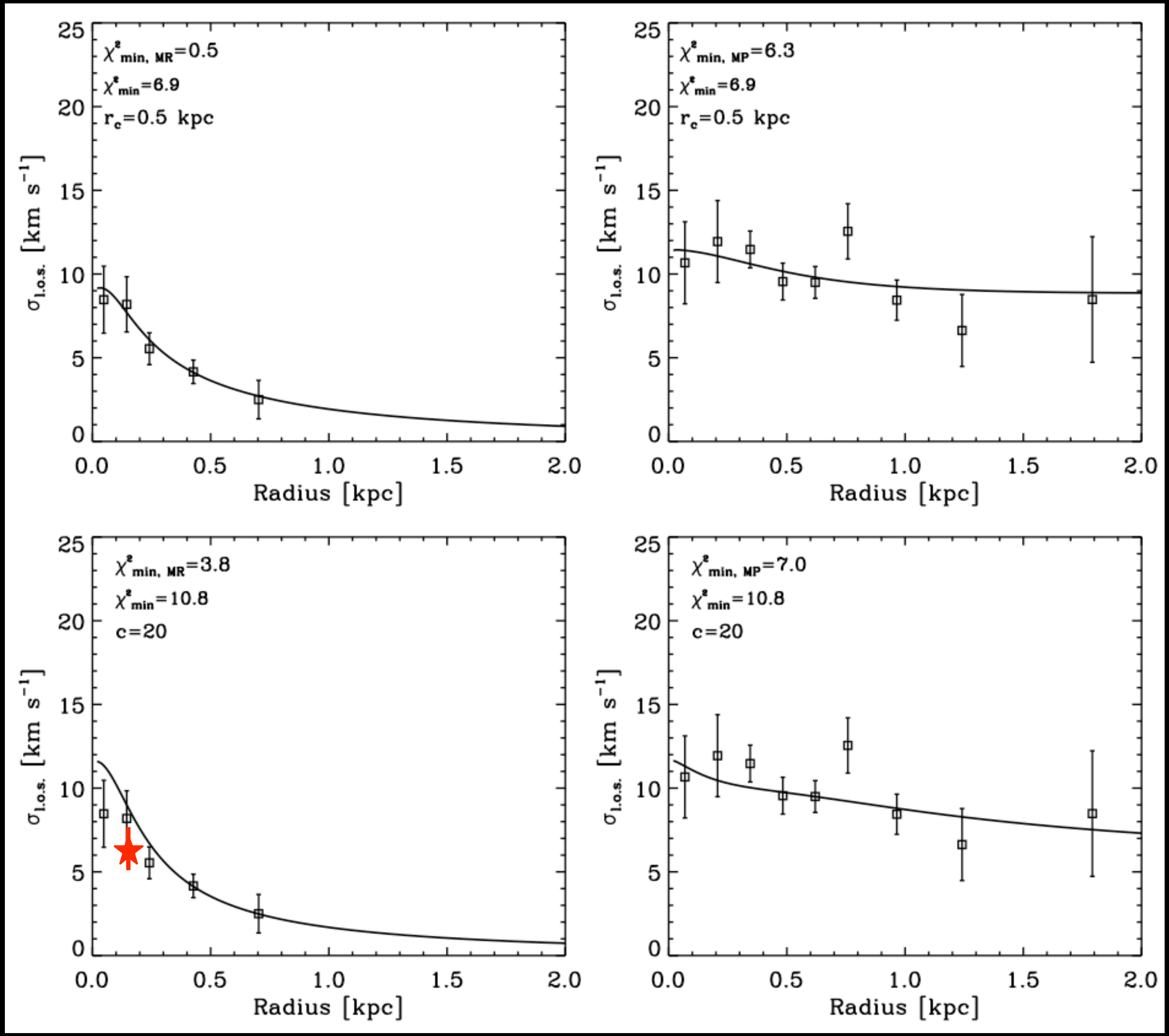
-Cored model: excellent fit for large core

M(<1.8kpc)= 3.4±0.7 x 10^8 M_{sun}

NFW
c=20

-Cusped model: statistically consistent; but yields poorer fit for MR stars

M(<1.8kpc)=$2.2_{-0.7}^{+1.0}$ x 10^8 M_{sun}



M(<1.8kpc) consistent between the 2 models

HR data (Δv ~ 0.5km/s) reduce quality of NFW fit

Summary IV

- The combined fit of MR and MP stars allows us to relieve the mass-anisotropy degeneracy (combined velocity and [Fe/H] information is important!)
- Assuming an O.M. anisotropy, an isothermal model with large core radius is favoured $M(<1.8\text{kpc}) = 3.4\pm0.7 \times 10^8\ M_{sun}$
- Mass within last point well constrained. Mass within smaller radii agrees with other measurements (e.g., Strigari et al. 2007; Peñarrubia et al. 2007)
- $M/L = 158 \pm 33\ (M/L)_\odot$ within 1.8 kpc

Discussion: dark matter content

- Cores vs Cusps:

  Cored profile slightly favoured by the two-component modeling, but observational determination of β is still needed

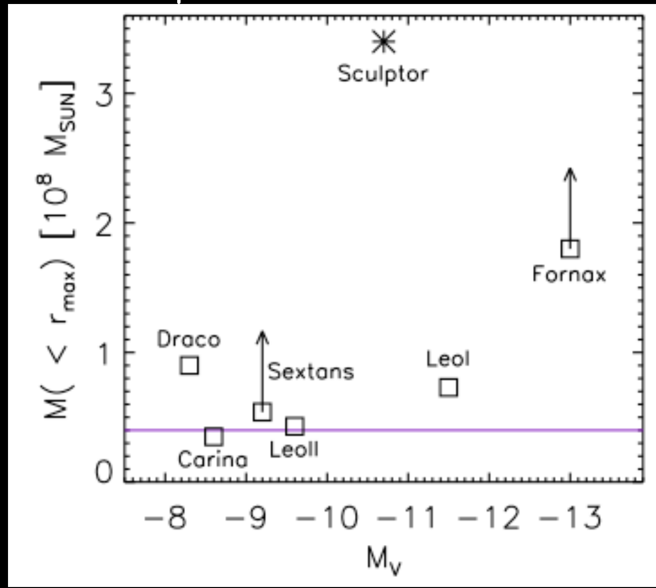
- No clear indication that dSphs inhabit haloes of similar mass. Indication of a minimum mass?

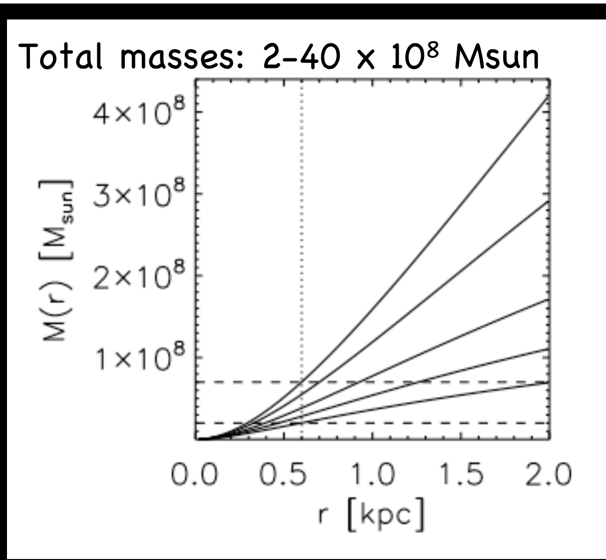
- Mass content at small radii not necessarily indicative of the total mass

- We need to take into account that the system is not spherical etc..

Scl: this work

Other dSphs: Walker et al. (2007)





Discussion: velocity gradients

- For the first time a statistically significant velocity gradient, likely due to intrinsic rotation, was found in a dSph.
- Large coverage, statistics and accurate velocities are important for assessing the presence of velocity gradients
- Velocity gradients are present also in isolated dSphs (Cetus: Lewis et al. 2007; Tucana: Fraternali et al. in prep.) where environment is likely to play a smaller role => rotation as intrinsic property of dSphs?
- Do the stellar components of dwarf irregulars and transition types rotate? And with the same characteristics?

Discussion: stellar populations

- Stellar populations in dSphs are complex. What are the driving factors in the evolution ?

- Models of *isolated* dSphs can reproduce variety of star formation histories and overall [Fe/H] distributions (N-body + SPH: e.g. Jablonka et al in prep.; 3D hydrodynamical simulations: Marcolini et al. 2006, 2008) => key-parameter is the total mass

- Models cannot get rid of the gas => environmental effects are invoked

- No attempts yet to reproduce the detailed properties such as metallicity gradients & kinematics

- Observational study of properties of isolated dwarfs in the Local Group could give important insights

Global conclusions

- Reliable metallicities from CaII triplet method in the range $-2.5 < [Fe/H] < -0.5$
- Stellar populations in dSphs are complex
- Found a statistically significant rotation in Scl (first time for a dSph)
- Scl is very massive (best DM profile is cored)
- Combination of wide area photometric, kinematic and metallicity information important!