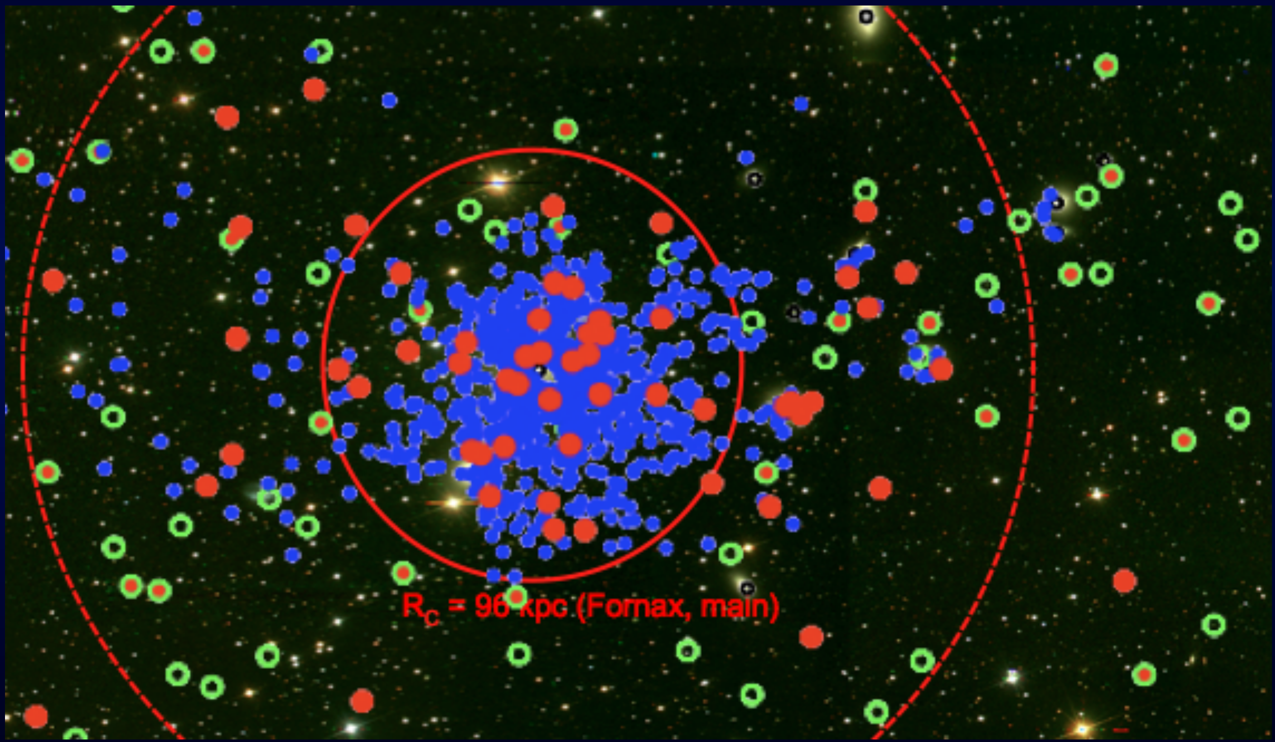
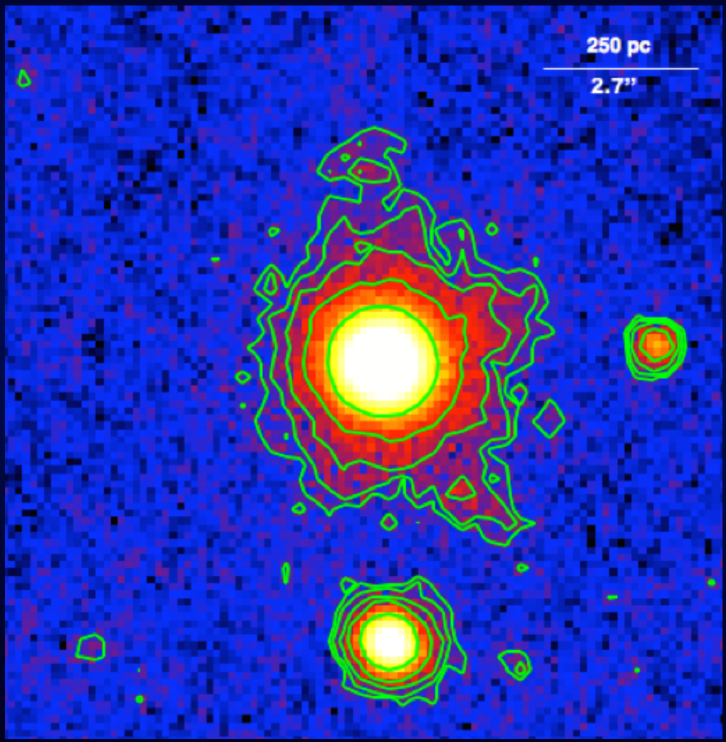
Ultra-compact dwarf galaxies as remnants of tidal disruption processes

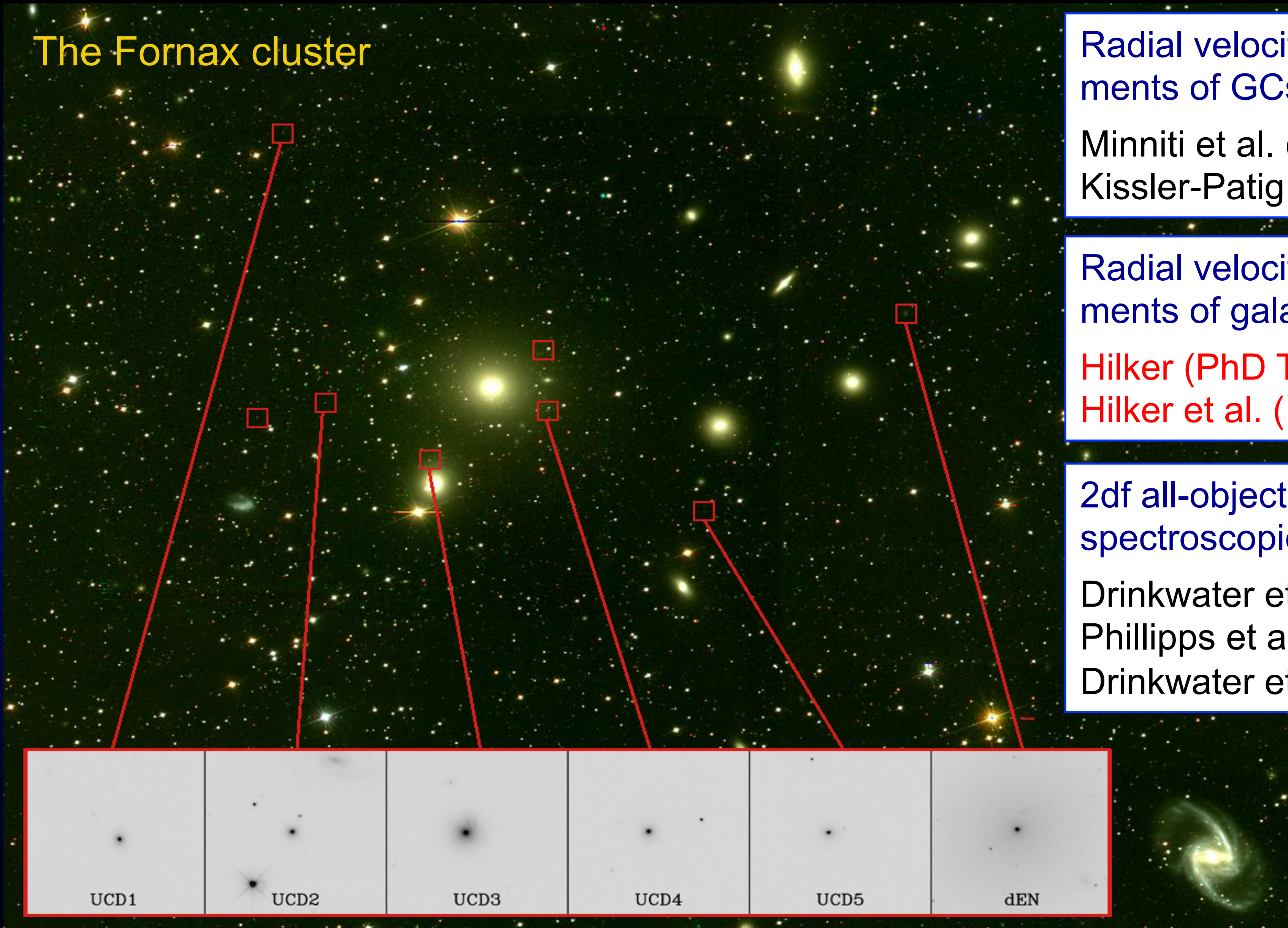
Michael Hilker, ESO (Garching)





Main collaborators: Matthias Frank, Thorsten Lisker, Steffen Mieske, Ingo Misgeld, Joel Pfeffer, Thomas Puzia, Tom Richtler, Anil Seth, Matt Taylor, Karina Voggel, Carolin Wittmann, …

The (undefined) definition of UCDs



Radial velocity measurements of GCs:

Minniti et al. (1998)
Kissler-Patig et al. (1999)

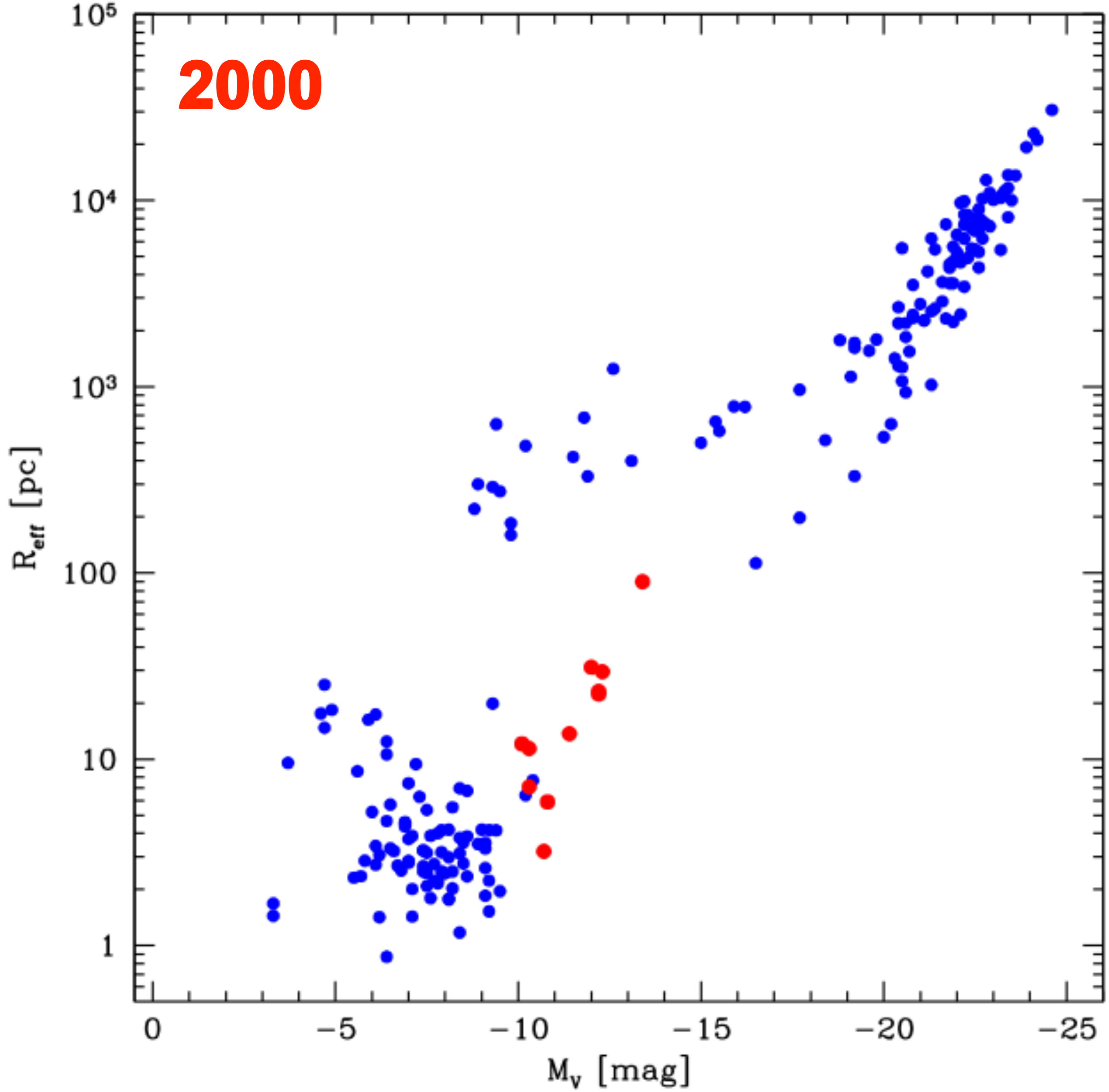
Radial velocity measurements of galaxies:

Hilker (PhD Thesis 1998)
Hilker et al. (1999)

2df all-object Fornax spectroscopic survey:

Drinkwater et al. (2000)
Phillipps et al. (2001)
Drinkwater et al. (2003)

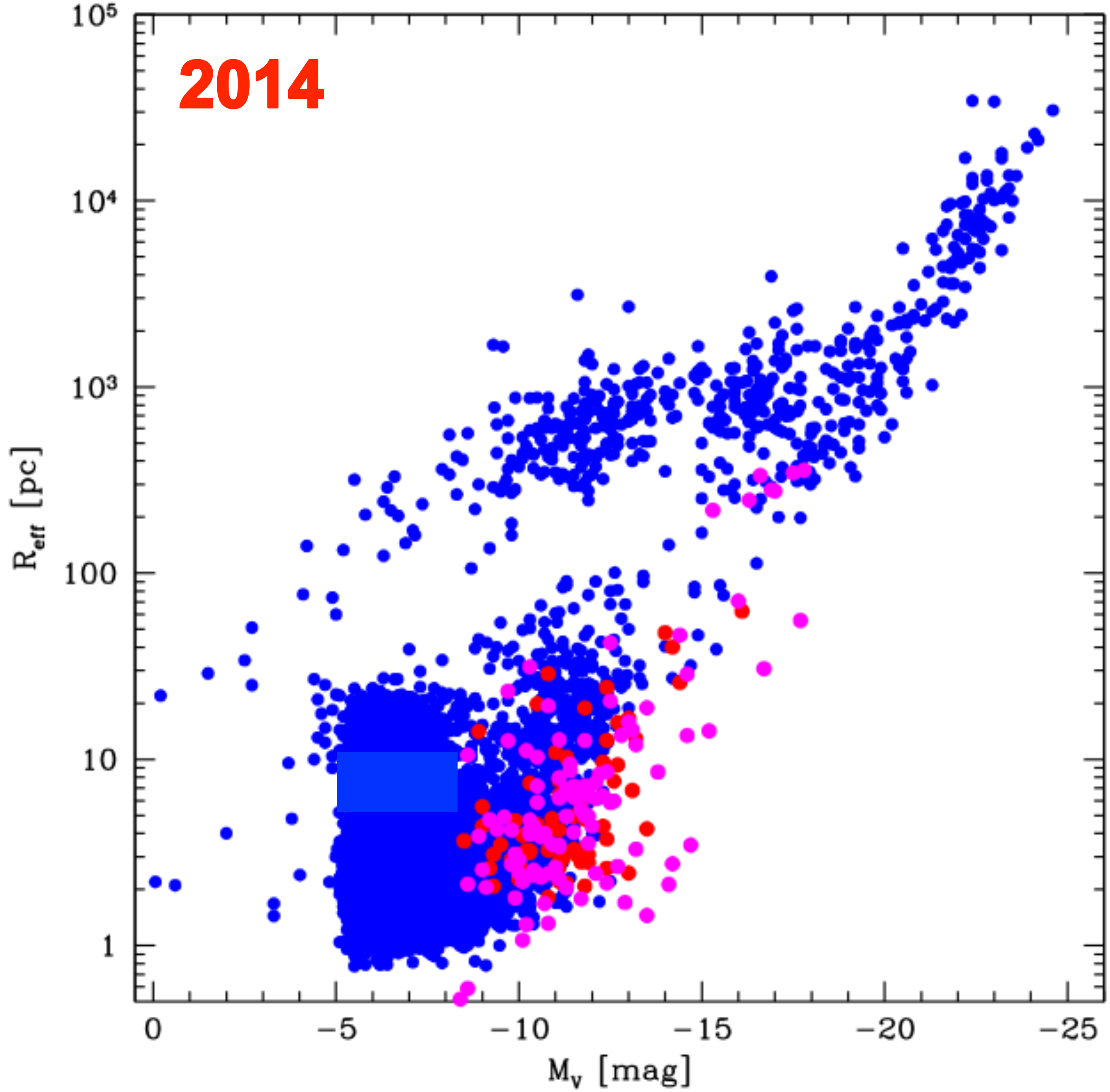
Early-type stellar systems in the luminosity-size plane



adapted from Misgeld & Hilker (2011)

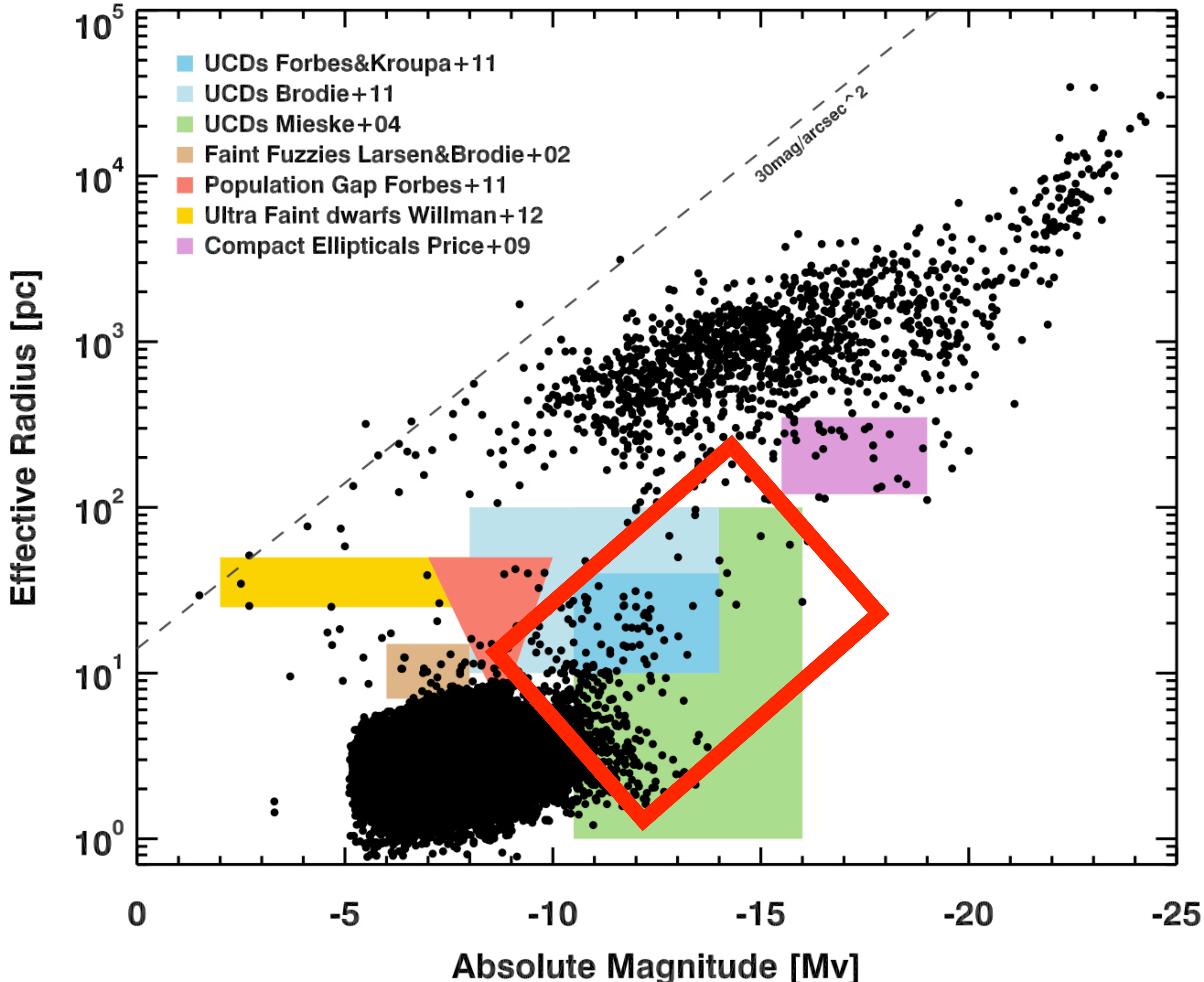
mainly based on
Bender et al. (1993)
Mateo (1998)
Harris (1998)
Holland et al. (1999)
Hilker et al. (1999)
Drinkwater et al. (2000)

Early-type stellar systems in the luminosity-size plane



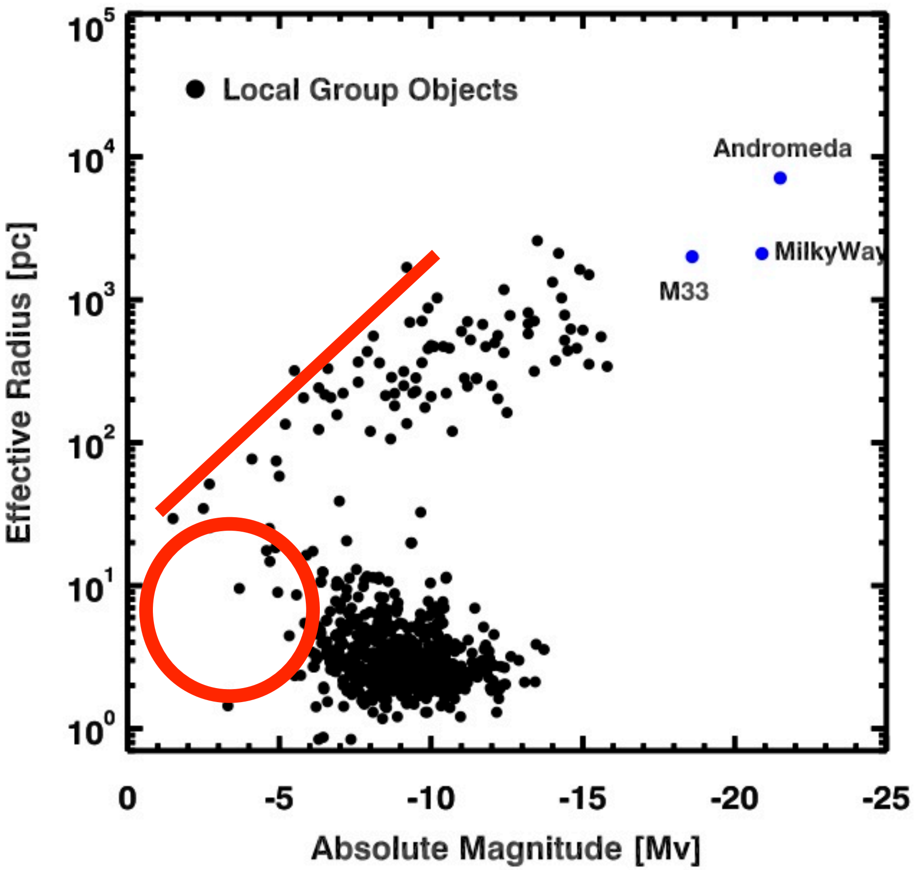
adapted from Misgeld & Hilker (2011)
Brodie et al. (2011)
Brüns & Kroupa (2012),
plus nuclear star clusters from Böker et al. (2004)
Rossa et al. (2006)
Cote et al. (2006)
Georgiev & Böker (2014)

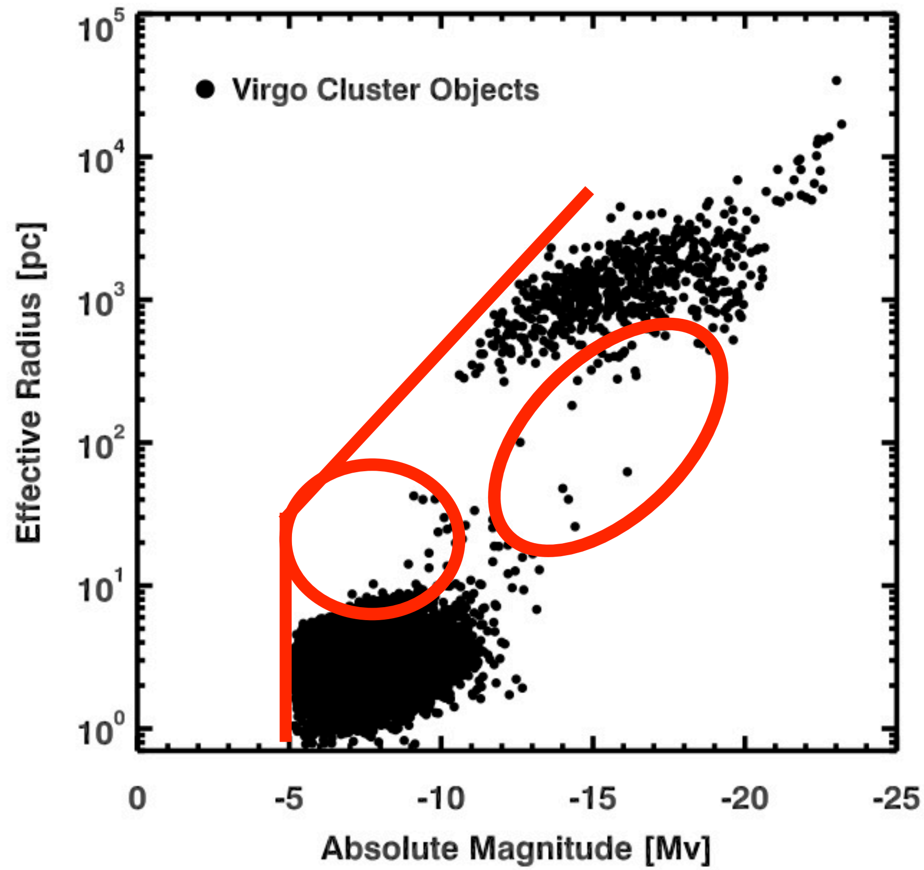
The (undefined) definition of UCDs



Voggel, Hilker, et al. (in prep.)

Splitting the ‚everything plot‘ into different environments





Voggel, Hilker, et al. (in prep.)

Formation scenarios of UCDs

UCD formation channels

There are two main lines of formation scenarios for UCDs:

1) UCDs are build up by star cluster formation processes

- they are the tip of the mass spectrum of a star cluster population
- formed in giant molecular clouds (maybe in clumps of high-z galaxies or in cooling flow filaments)
- or formed via the amalgamation of super star cluster complexes in merger induced star formation events

2) UCDs are remnants of disruptive galaxy evolution processes

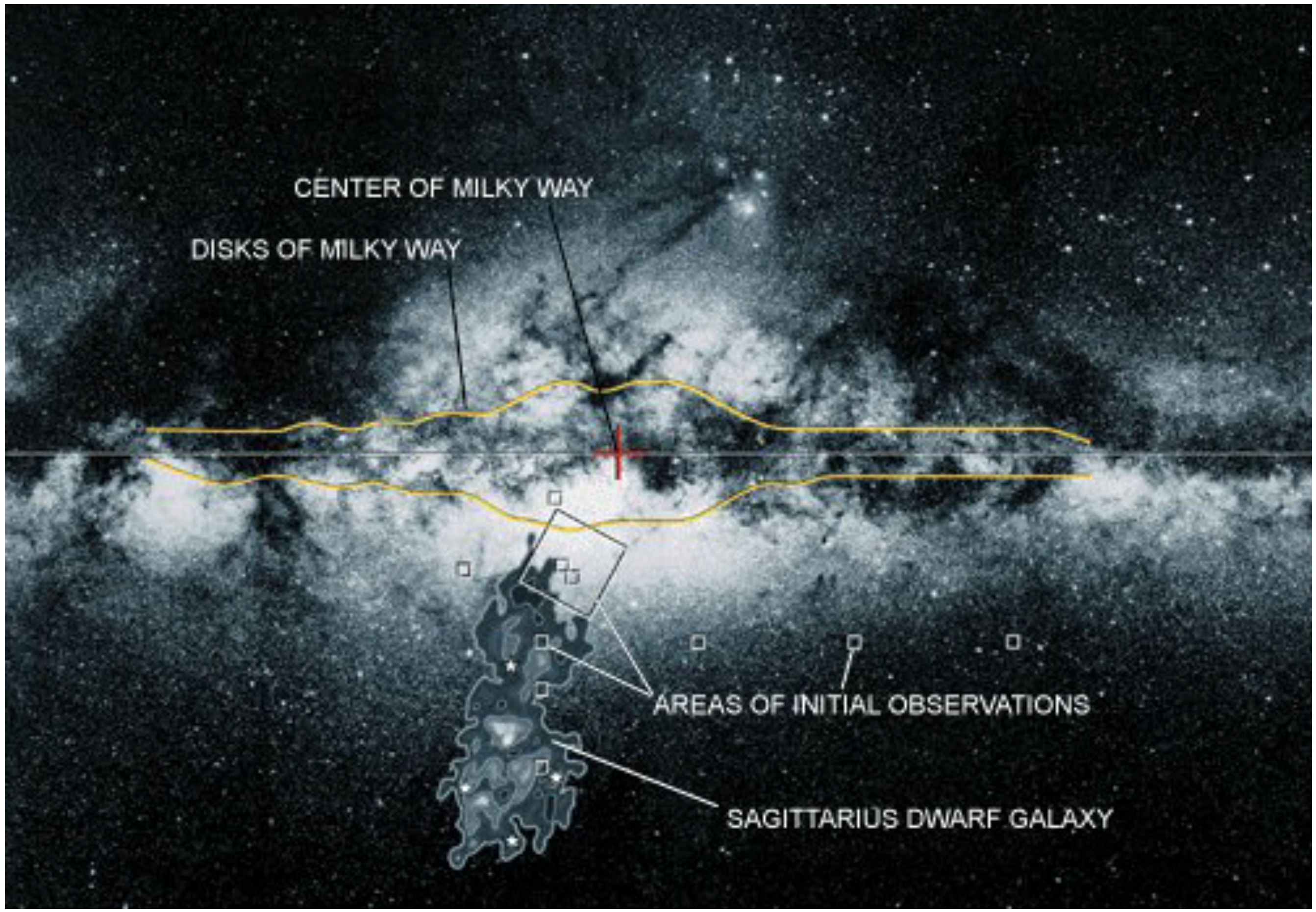
- UCDs were located in the centres of their host galaxies (nuclei)
- they followed the formation history of a nuclear star cluster
- they might be related to dark matter sub-structure

3) Exotic scenario: UCDs are recoiling 'runaway' SMBHs+stellar envelope originating from interactions of multiple SMBHs (Merritt 2009)

Dwarf galaxies exist in large numbers in galaxy clusters, so tidal stripping/destruction of some of them is inevitable.

About 70% of all dE galaxies contain nuclei in their centers with masses similar to UCDs.

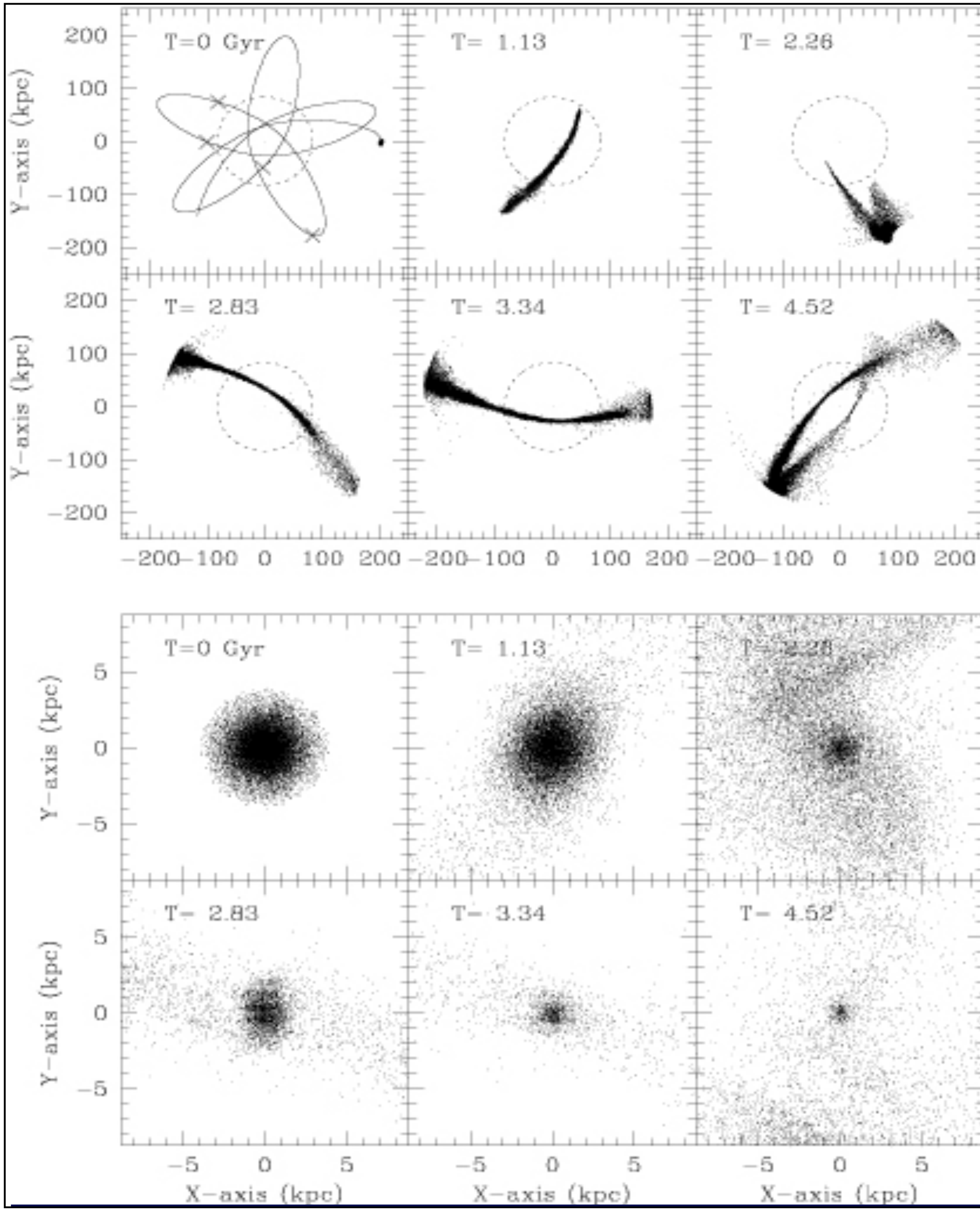
We actually see ongoing disruption of a dwarf galaxy in the Milky Way in the case of the M54/Sagittarius system.



The stripping (or threshing) scenario

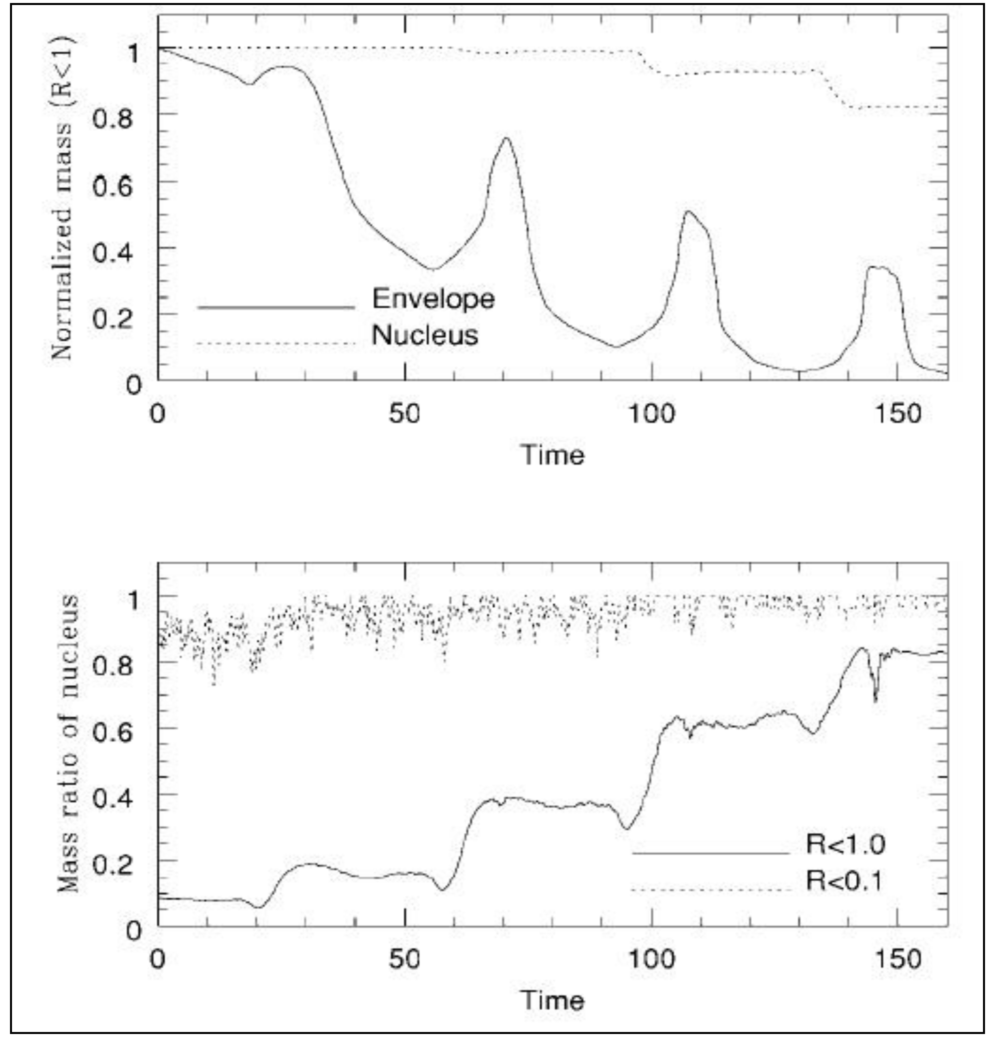
- Zinnecker et al. 1988: suggestion that massive GCs around M87 are NCs from stripped dE,Ns
- Bassino et al. 1994: numerical simulations of disrupting dE,Ns around M87
- Bekki et al. 2001, 2003: ‘self-consistent’ numerical simulation to explain the UCDs in the Fornax cluster by threshing dE,Ns
- Thomas et al. 2008: test particles in static potential and ‘threshing radius’ parameter for estimating numbers of UCDs in Fornax
- Goerdt et al. 2008: N-body/smoothed particle hydrodynamics simulations of NC formation, stripping and DM retention
- Pfeffer & Baumgardt 2013: disruption of nucleated galaxies with box orbits around host galaxy (to mimic complex cluster potential)
- **Pfeffer et al. 2014** (and PhD thesis): stripping of nucleated galaxies in a cosmological context (including dark matter and merger tree)

Simulation of UCD formation from the disruption of dwarf galaxies



orbit

nucleus mass and mass loss



Bekki et al. (2001, 2003)

UCD formation in cosmological simulations

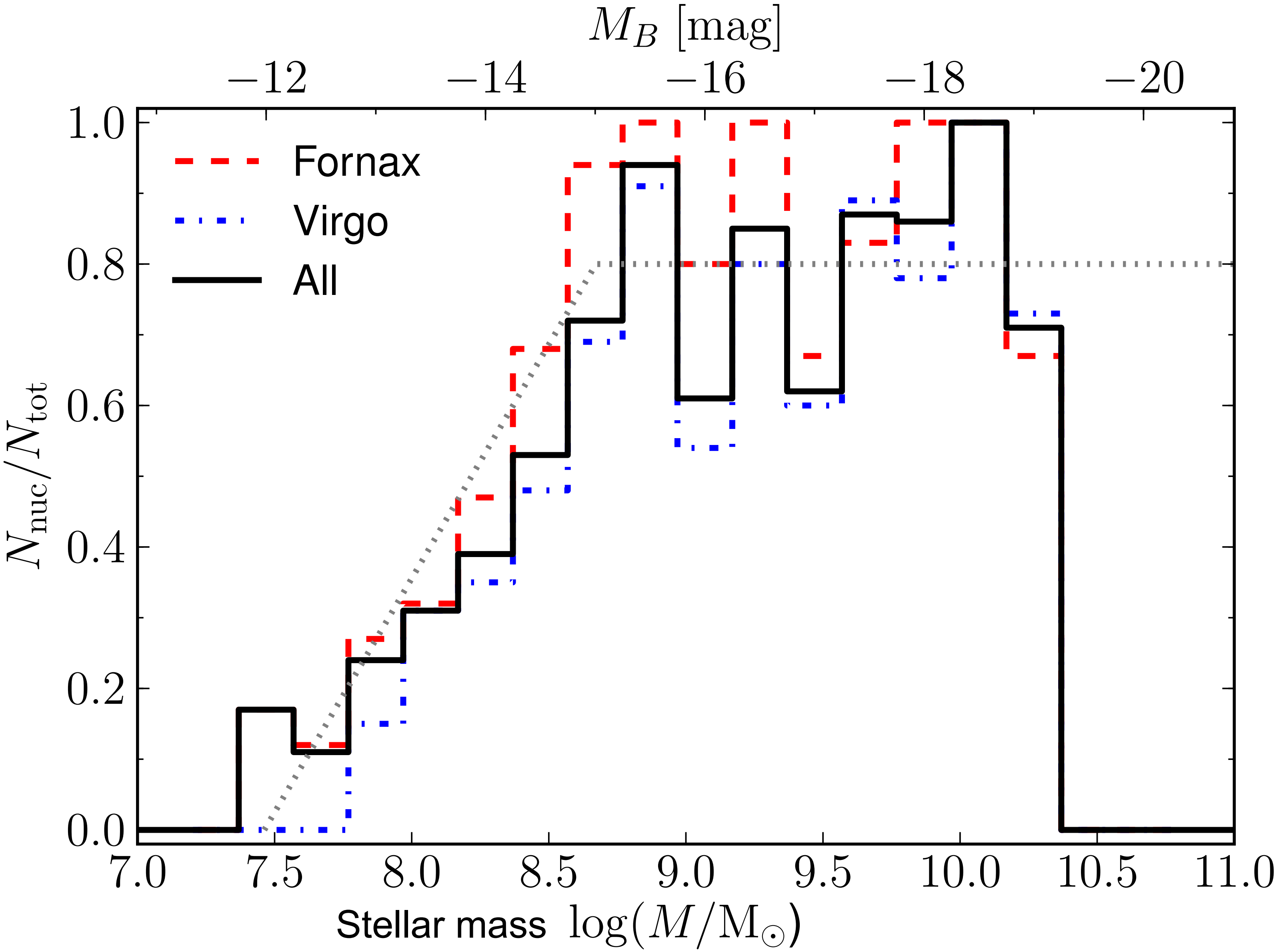
In order to test if the tidal stripping scenario also produces the right number and spatial distribution of UCDs, the Millennium-II simulation were taken as basis.

We used the semi analytic simulations by Guo et al. (2010) and looked for the positions of disrupted halos in galaxy clusters that resemble the Virgo/Fornax clusters.

We assumed that the nuclei of disrupted galaxies contained ~0.3% of the baryonic mass of the halos plus the observed scatter.

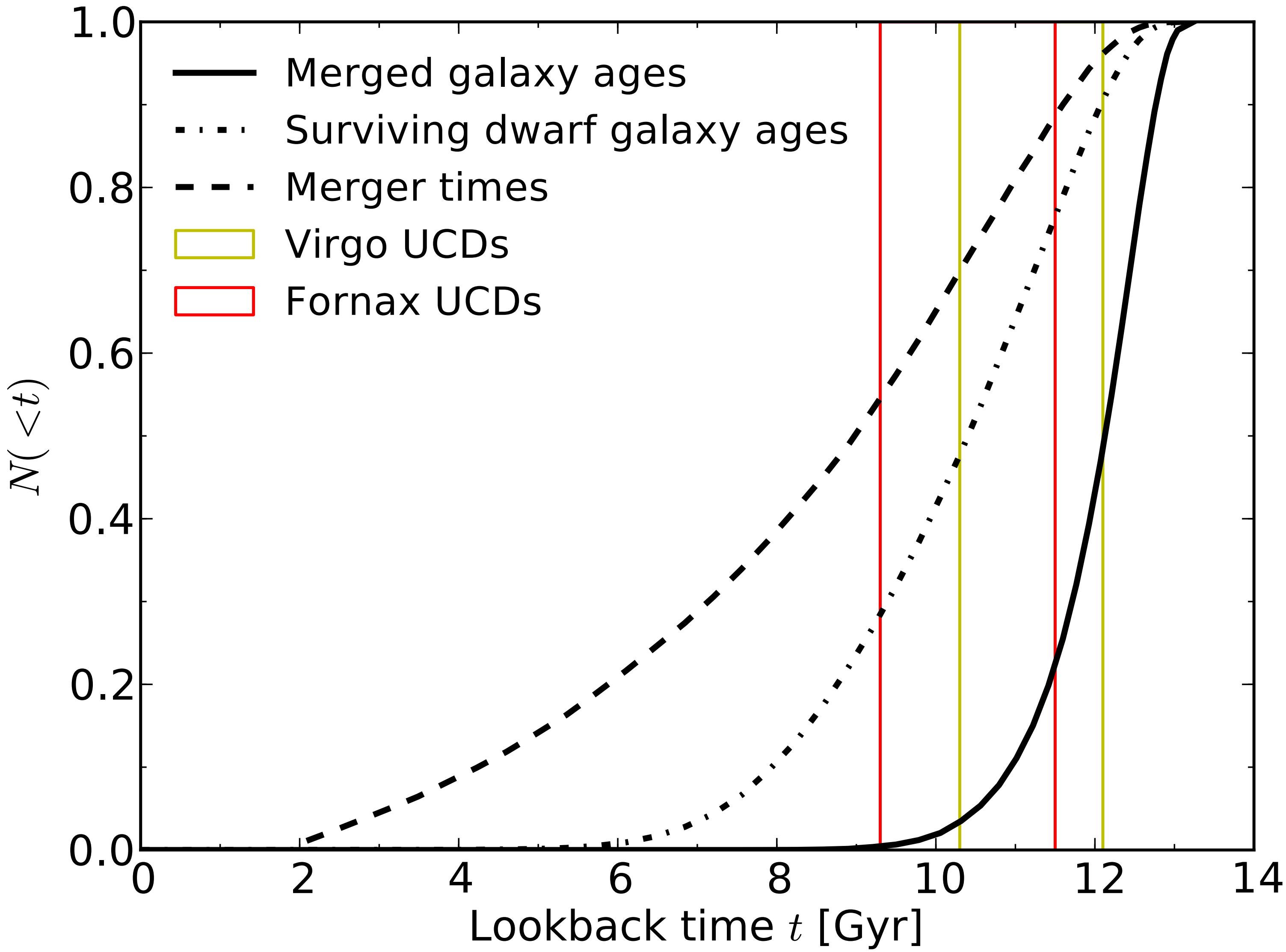
Pfeffer, Griffen, Baumgardt & Hilker (2014, MNRAS)

The nucleation fraction as function of galaxy mass



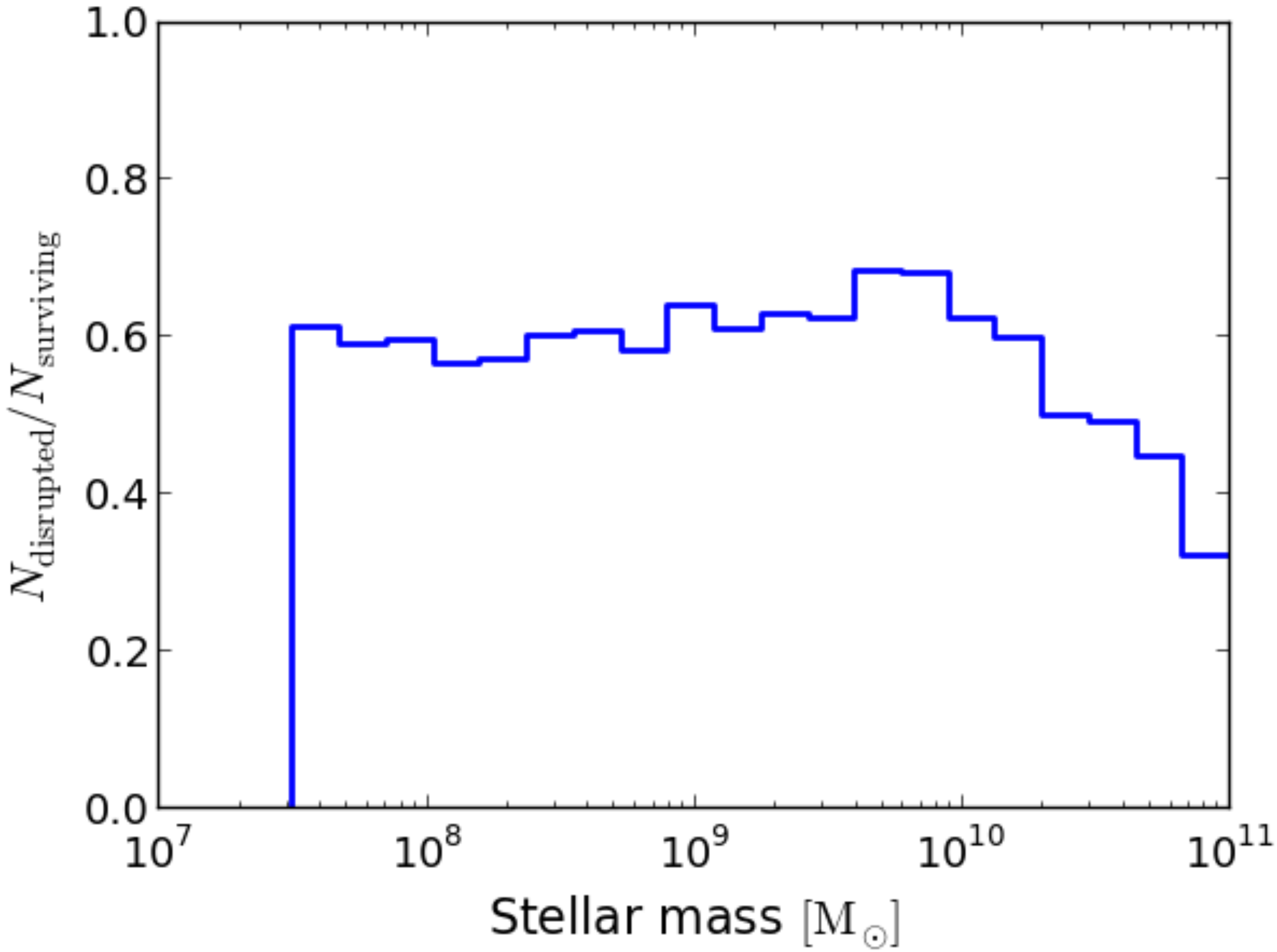
Pfeffer, Griffen, Baumgardt & Hilker (2014)

Ages of UCDs versus stripped nuclei ages



Pfeffer, Griffen, Baumgardt & Hilker (2014)

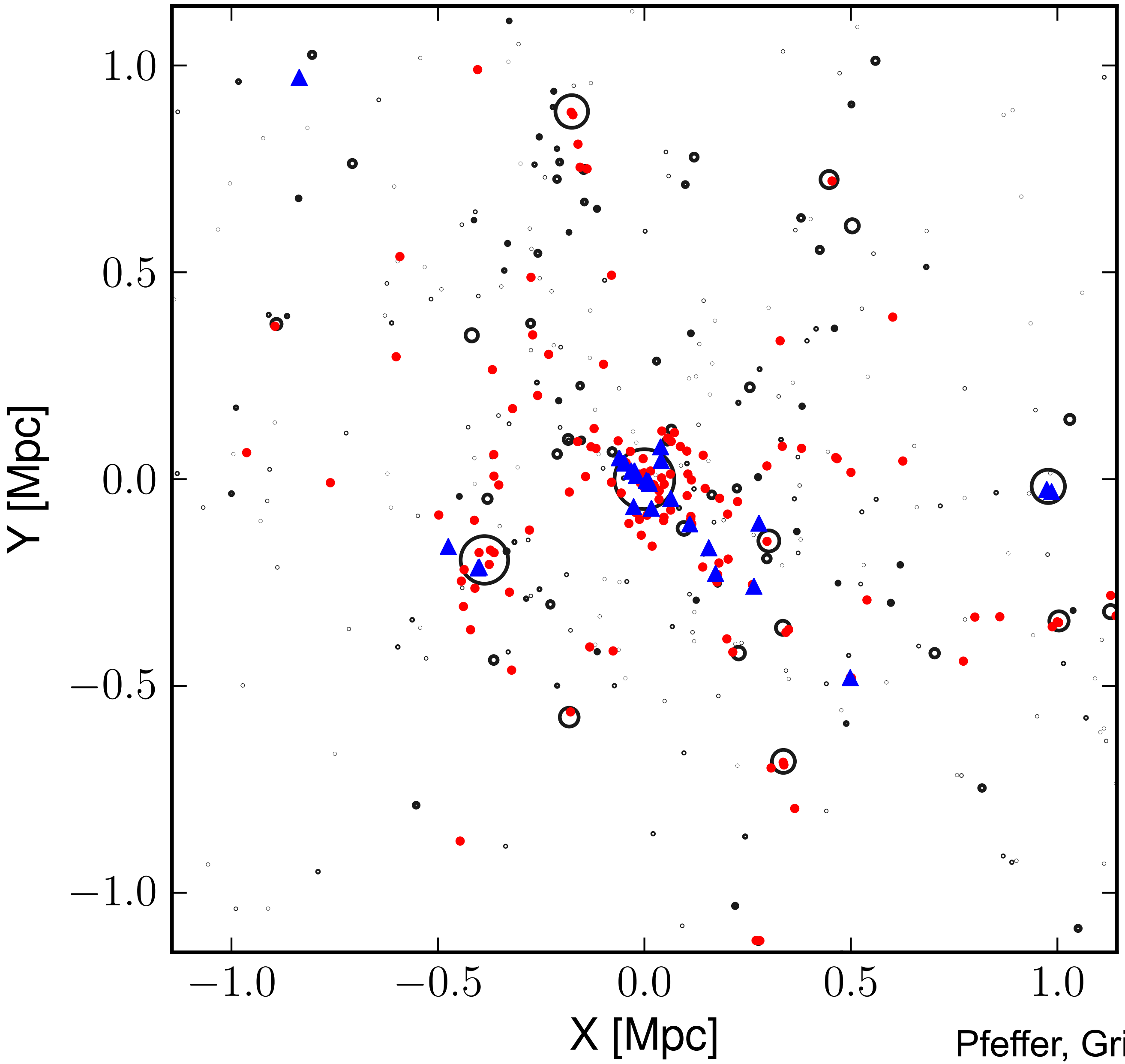
Fraction of disrupted vs. surviving galaxies



~40% of initially available satellite galaxies are disrupted at z=0

Pfeffer, Griffen, Baumgardt & Hilker (2014)

Spatial distribution of stripped nuclei in simulations



$M>10^7\ M_o$

$3x10^5<M<10^7\ M_o$

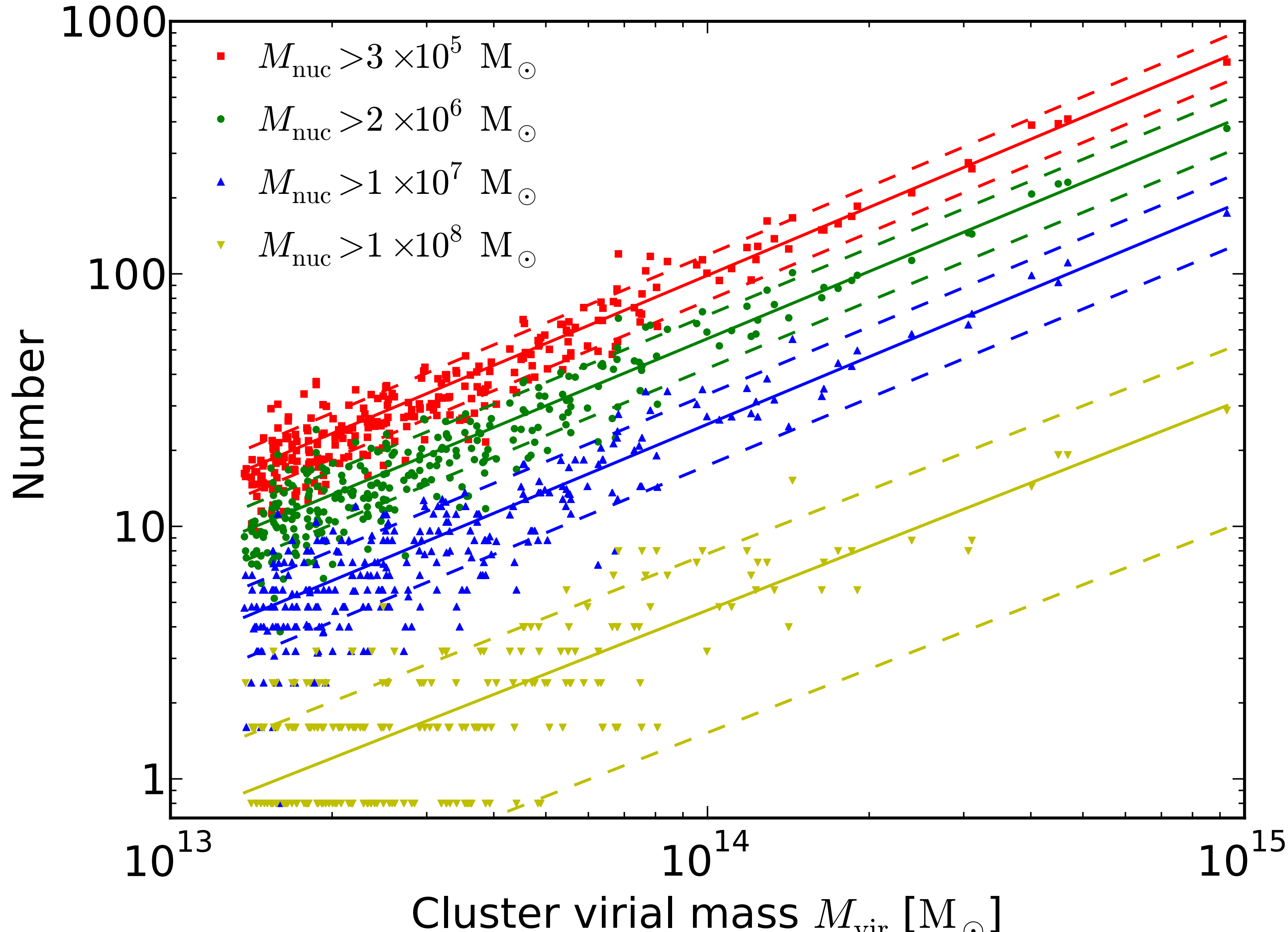
Virgo-sized cluster

Stripped nuclei are strongly concentrated towards the center of the cluster.

About 30% of stripped nuclei are around the satellite galaxies.

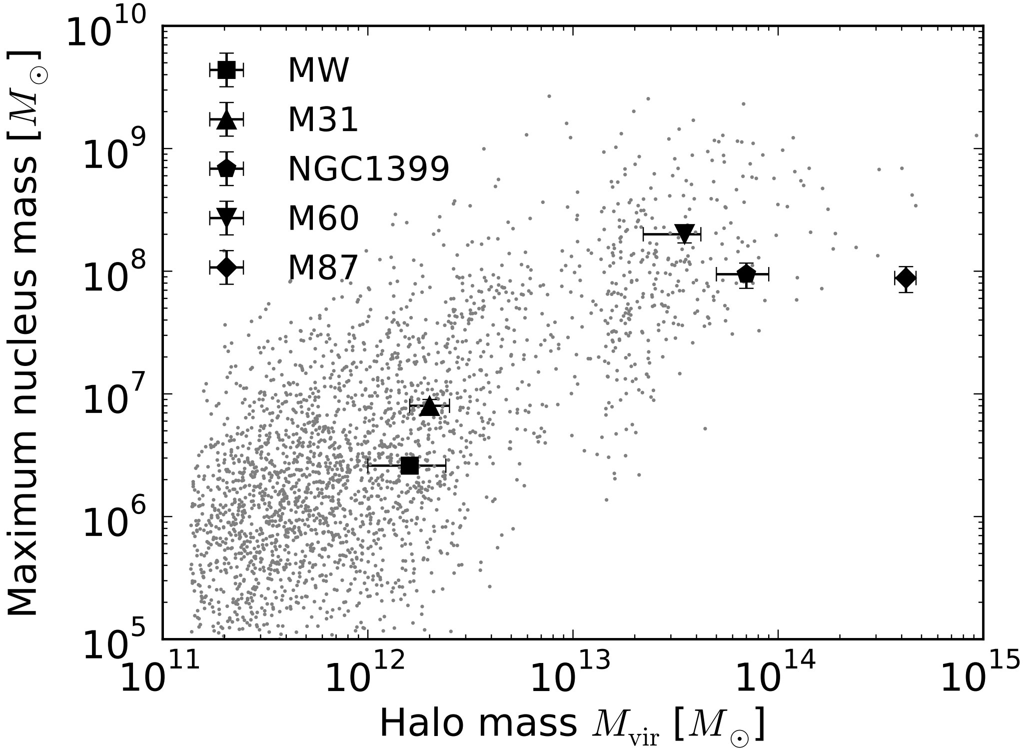
Pfeffer, Griffen, Baumgardt & Hilker (2014)

Absolute numbers of stripped nuclei

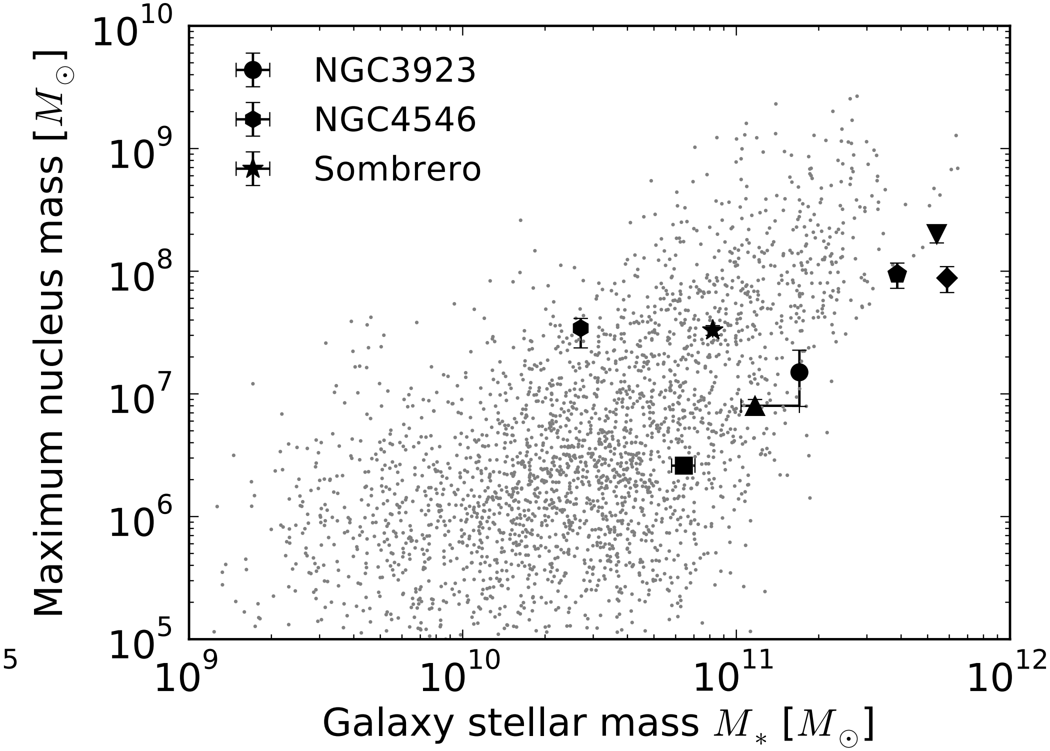


Pfeffer, Griffen, Baumgardt & Hilker (2014)

Mass of most massive stripped nucleus



as function of halo mass before infall



as function of galaxy stellar mass

Simulations are compatible with observed most massive UCDs.

Maybe the true most massive UCDs are still not discovered!

Pfeffer, Griffen, Baumgardt & Hilker (2014)

Observational parameters of UCDs, GCs and NCs

1) UCDs and NCs in the colour-magnitude plane

2) UCDs and GCs in the size-mass and density-mass planes

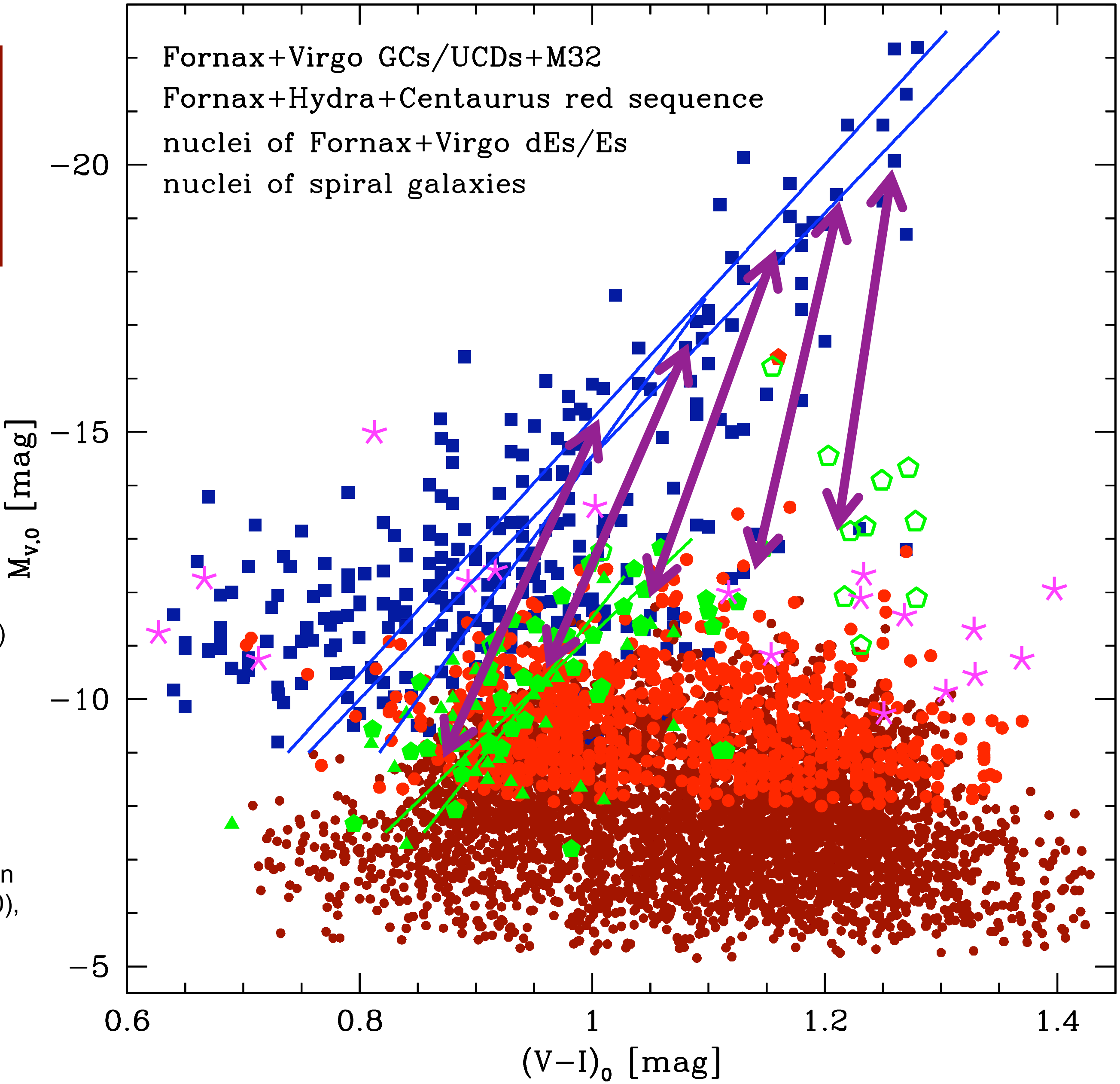
3) Chemical abundances of UCDs and NCs

4) Spatial distribution of UCDs and dE,Ns

5) Kinematics of UCDs vs. kinematics of GCs

CMD for massive GCs, UCDs, early-type galaxies and their nuclei

Similarities of UCDs to GCs and NCs



Galaxies:
Hilker et al. (2003). Mieske et al. (2007), Misgeld et al. (2008, 2009)

Nuclei of early-type galaxies:
Lotz et al. (2004), Cote et al. (2006)

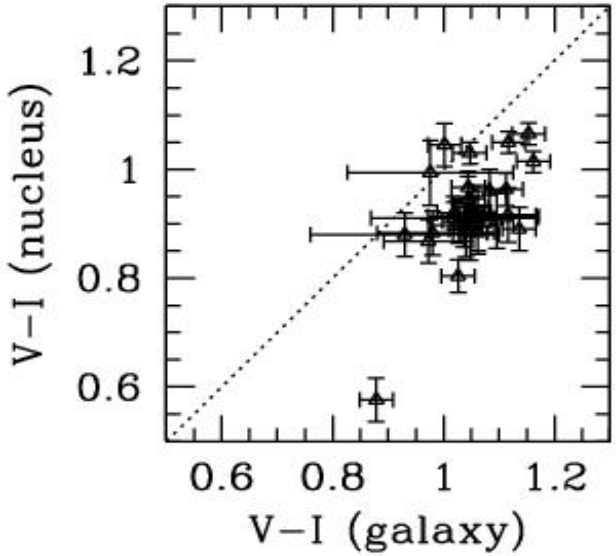
Nuclei of late-type galaxies:
Walcher et al. (2006), Boeker et al. (2002, 2004), Rossa et al. (2006)

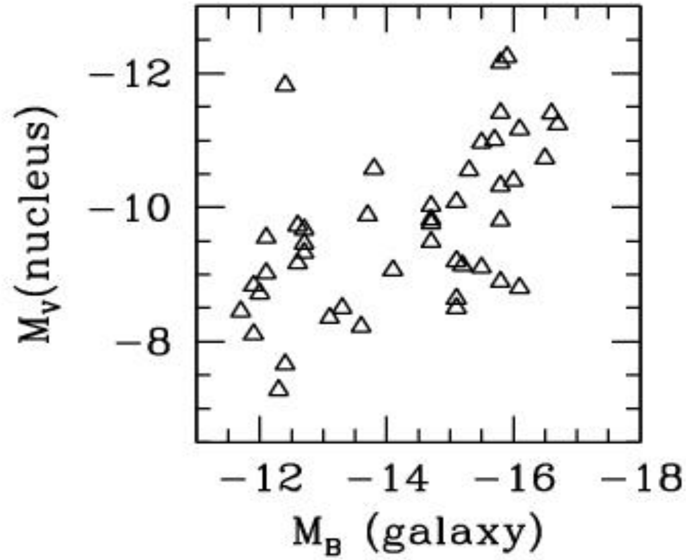
UCDs/GCs:
Drinkwater et al. (2000, 2003), Mieske et al. (2004, 2008), Hasegan et al. (2005), Schuberth et al. (2010), ... and many more ...

GCs (ACS photometry):
Jordan et al. (2009), Peng et al. (2006)

Nuclear properties of dwarf ellipticals

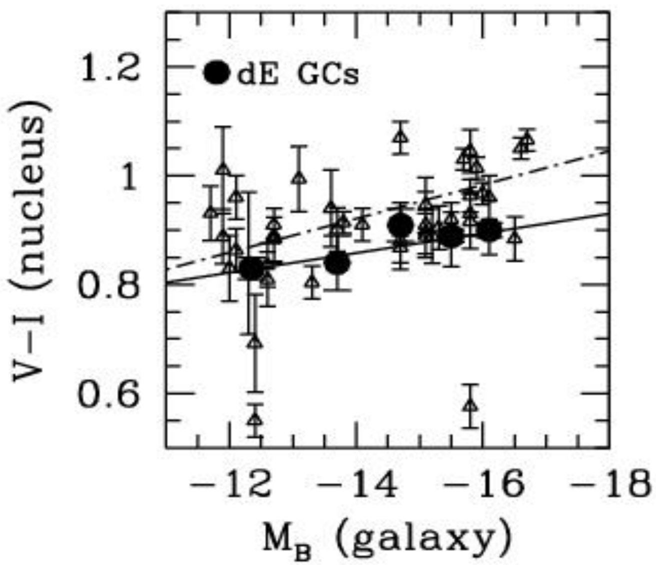
Nuclei are bluer than the galaxy light

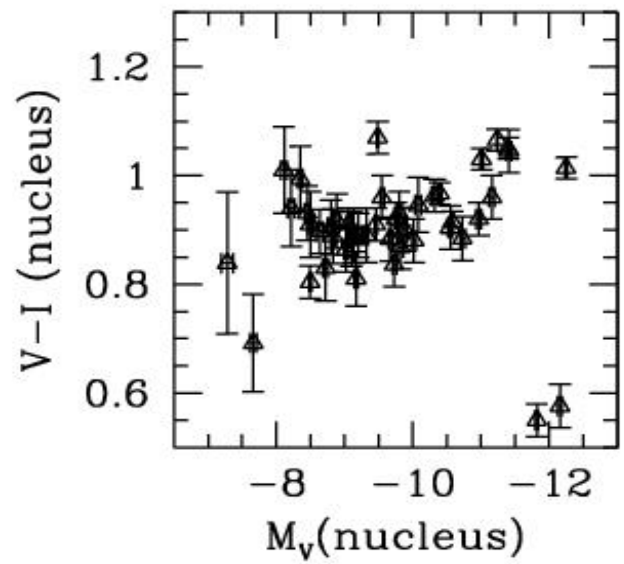




The brighter the galaxy, the brighter the nucleus

Nuclei are Redder than GCs in the same galaxy

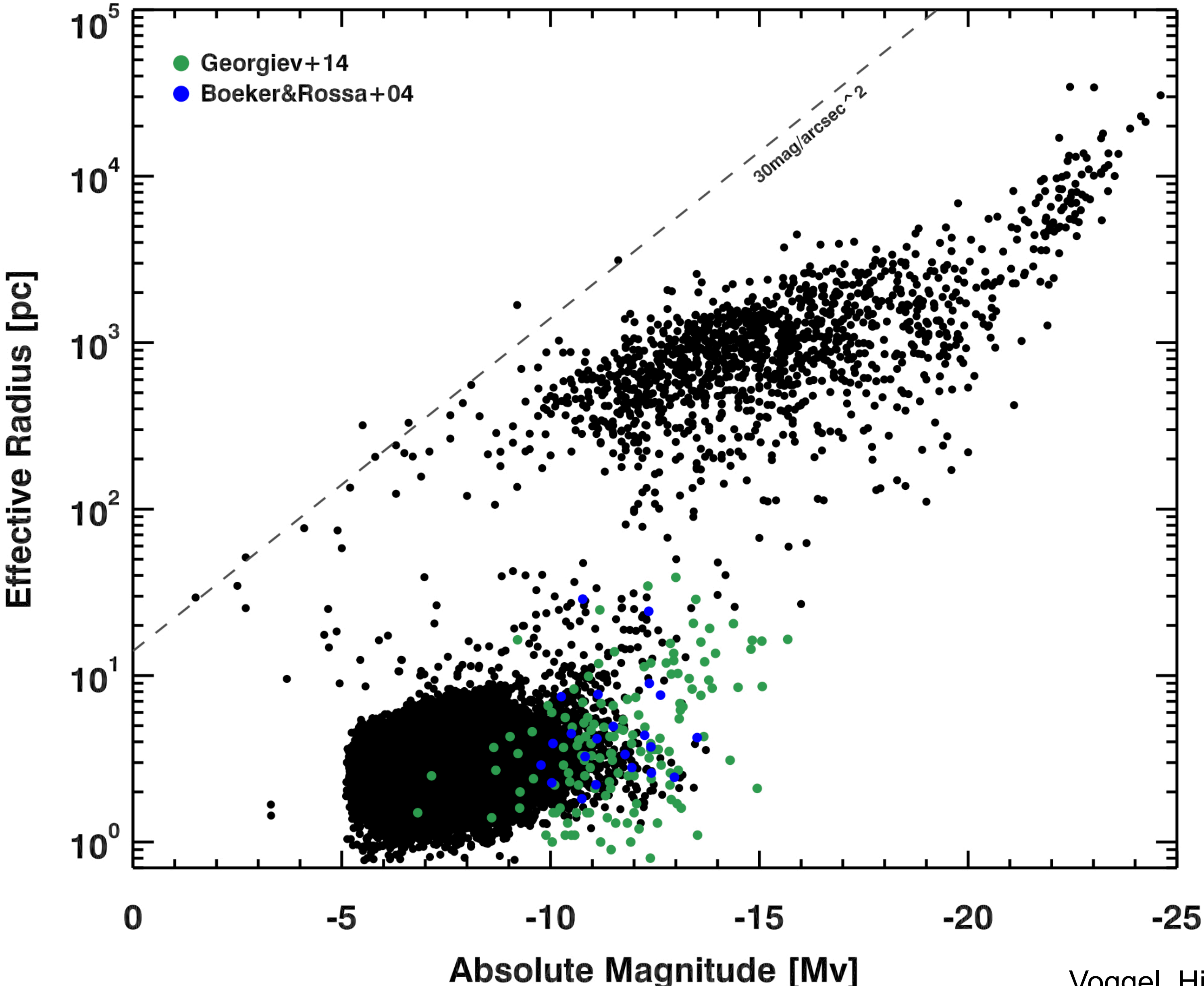




The brighter the nucleus, the redder the nucleus

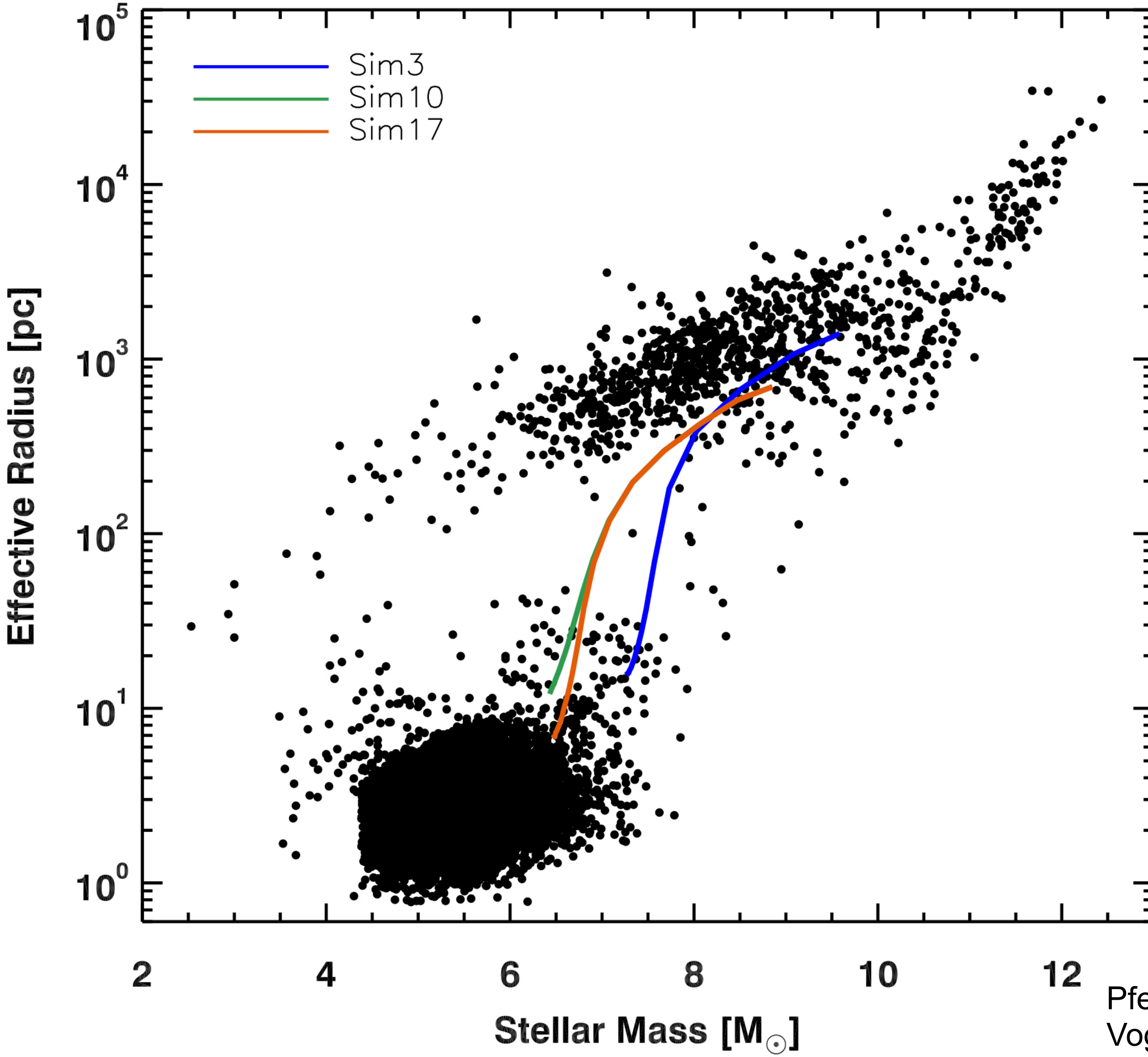
Lotz, Miller, & Ferguson 2004 (ApJ 613, 262)

Size-luminosity relation of early-type stellar systems



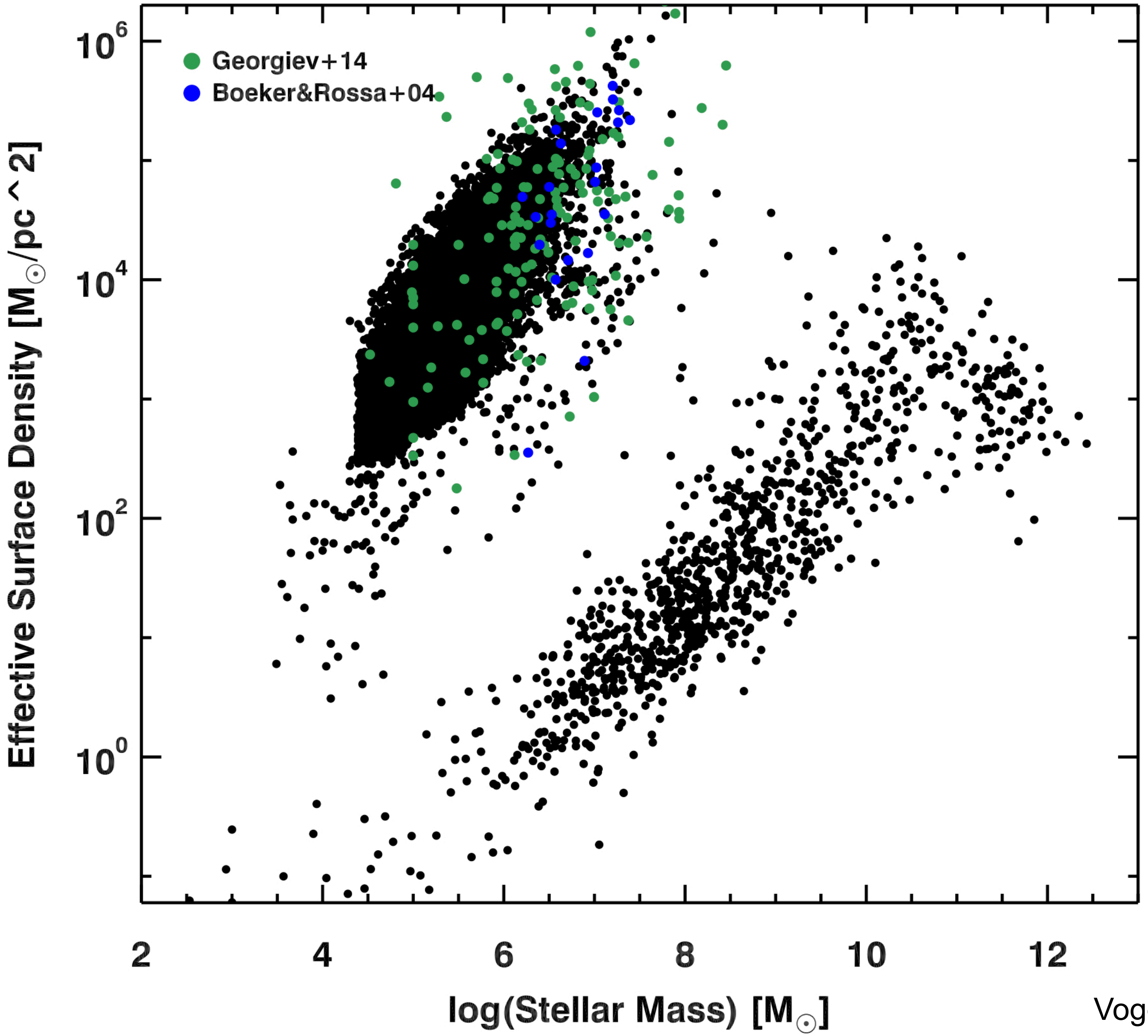
Voggel, Hilker, et al. (in prep.)

Stripping tracks in the mass-size plane



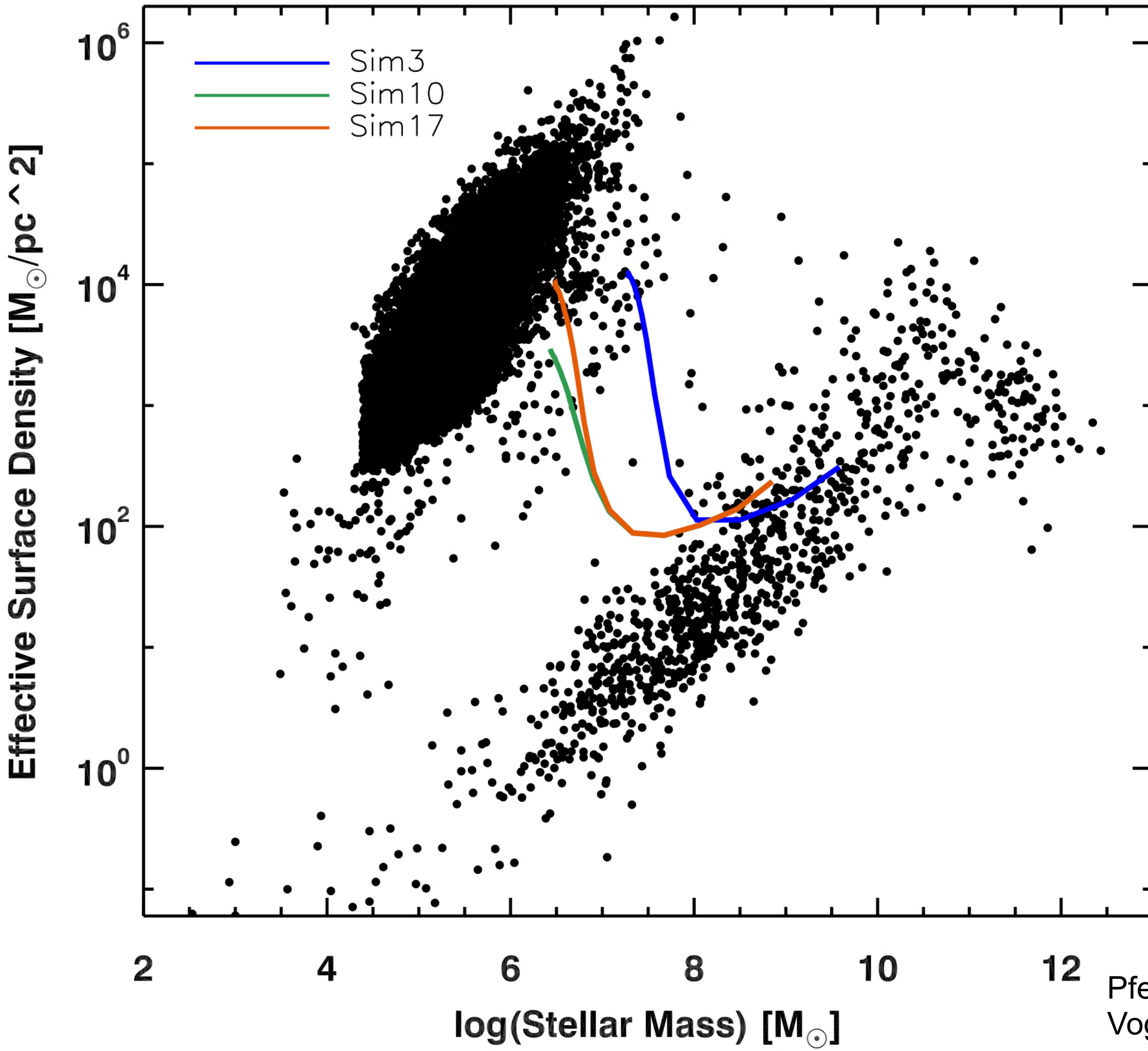
Pfeffer & Baumgardt (2013)
Voggel, Hilker, et al. (in prep.)

Surface density-mass relation of early-type stellar systems



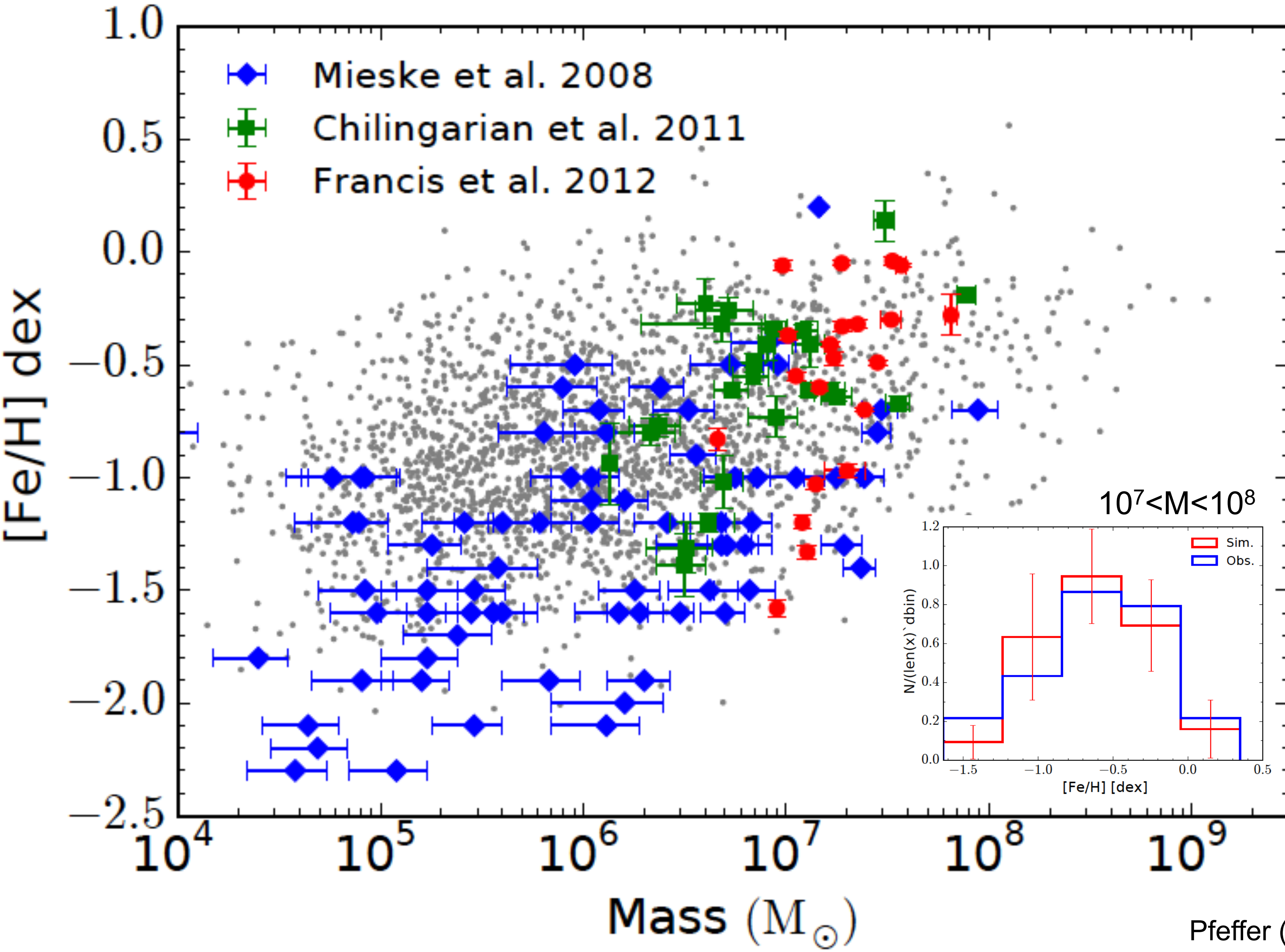
Voggel, Hilker, et al. (in prep.)

Stripping tracks in the mass-density plane



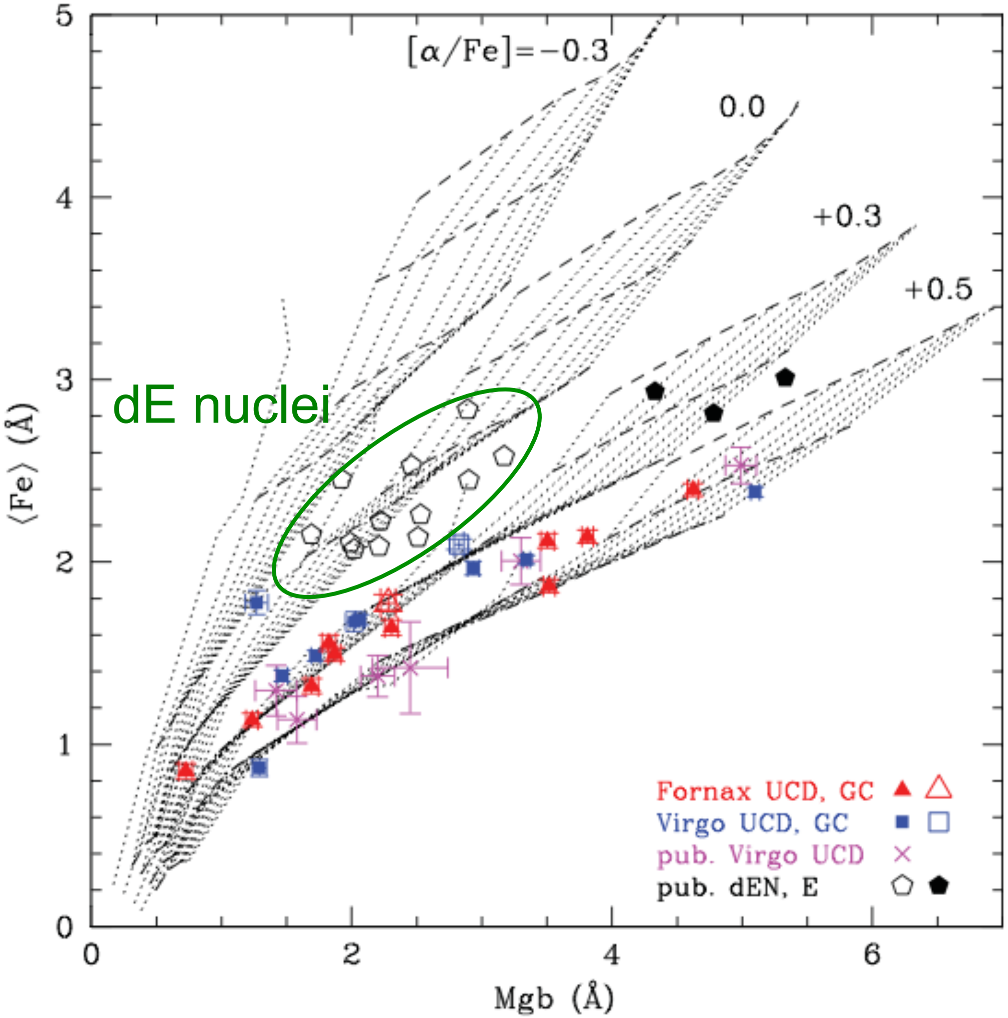
Pfeffer & Baumgardt (2013)
Voggel, Hilker, et al. (in prep.)

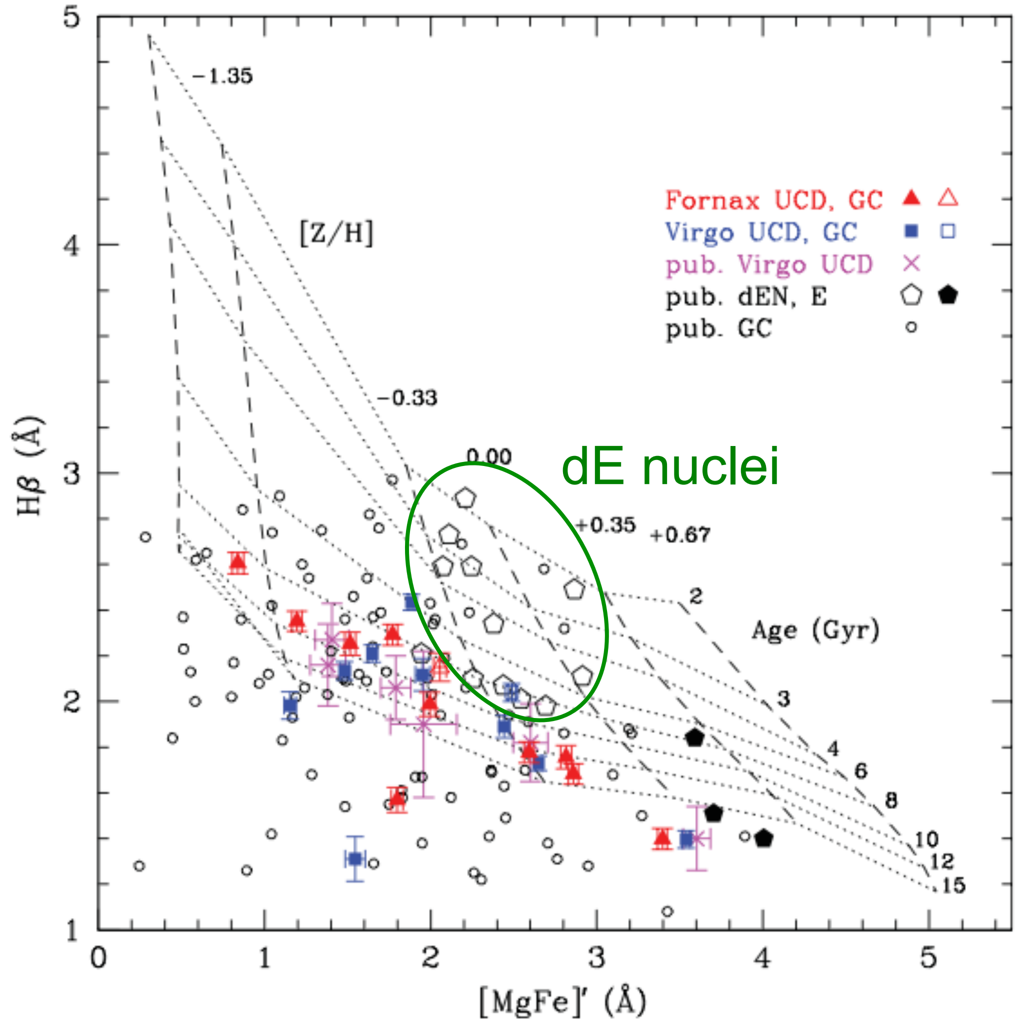
Observed vs. expected iron abundances of UCDs and stripped nuclei



Pfeffer (PhD thesis)

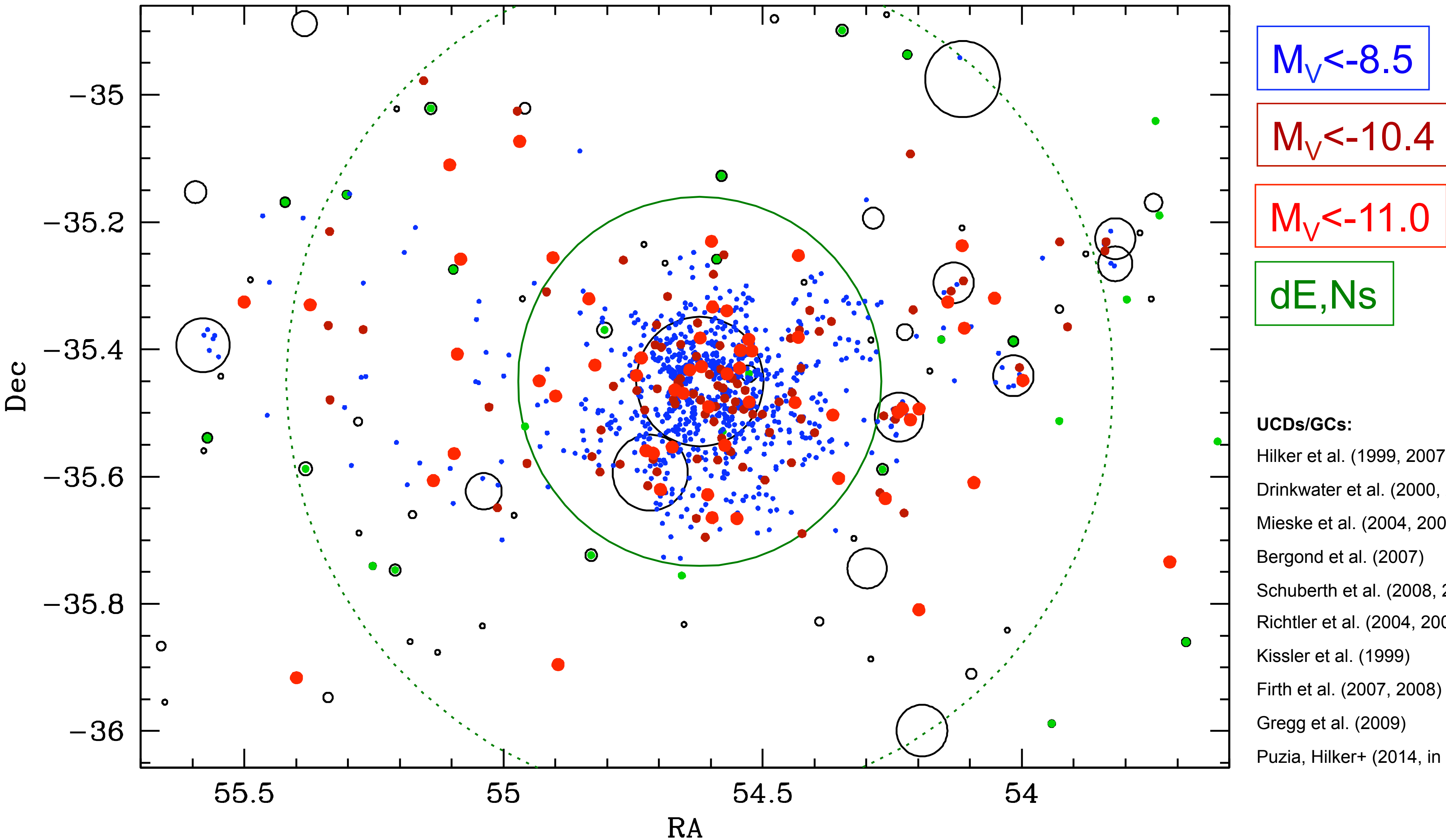
Abundances and ages of UCDs in Fornax and Virgo





Francis et al. (2013)

Distribution of confirmed UCDs/GCs and dEs in Fornax



UCDs/GCs:

Hilker et al. (1999, 2007)

Drinkwater et al. (2000, 2003)

Mieske et al. (2004, 2008)

Bergond et al. (2007)

Schuberth et al. (2008, 2010)

Richtler et al. (2004, 2008)

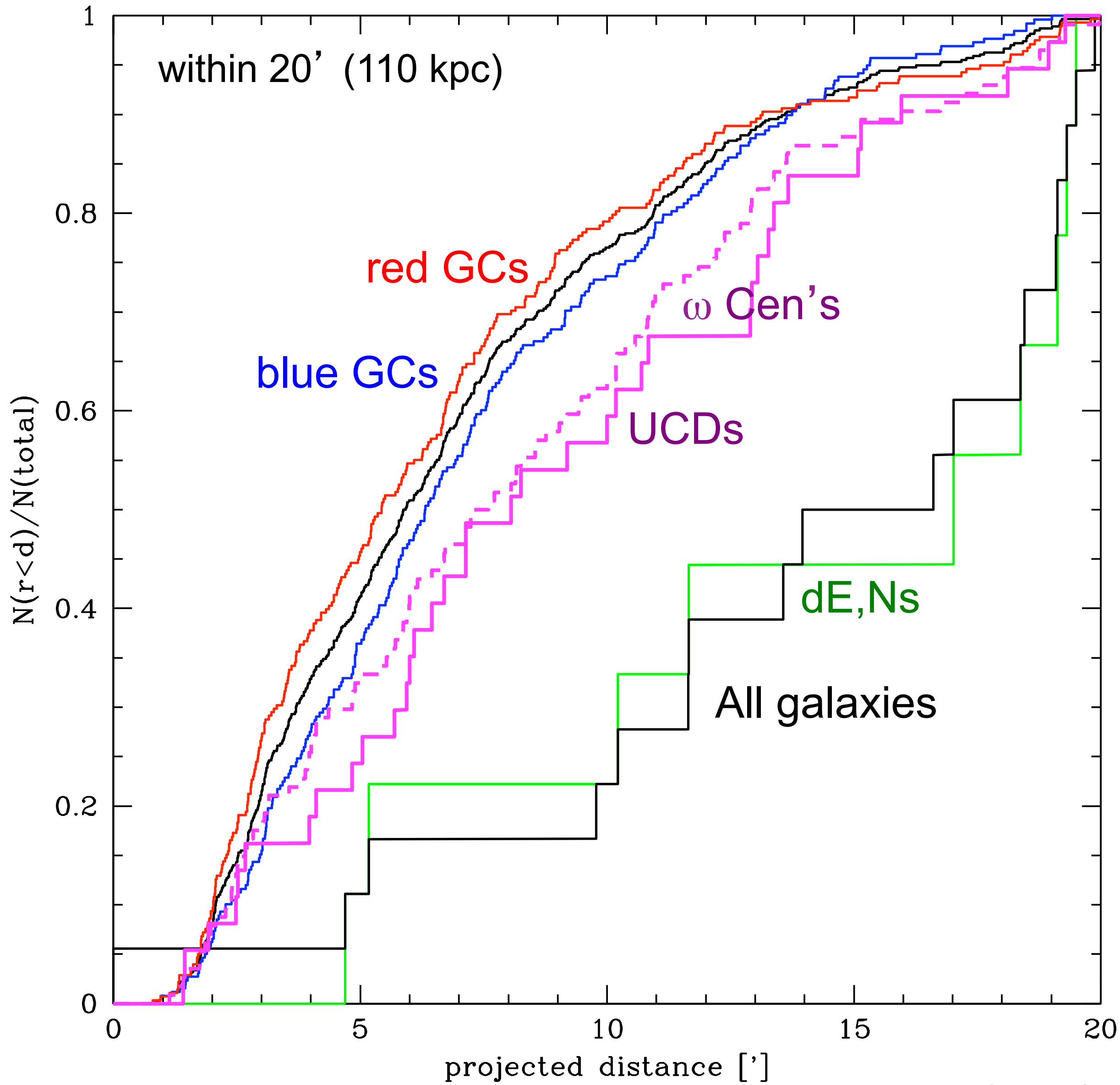
Kissler et al. (1999)

Firth et al. (2007, 2008)

Gregg et al. (2009)

Puzia, Hilker+ (2014, in prep.)

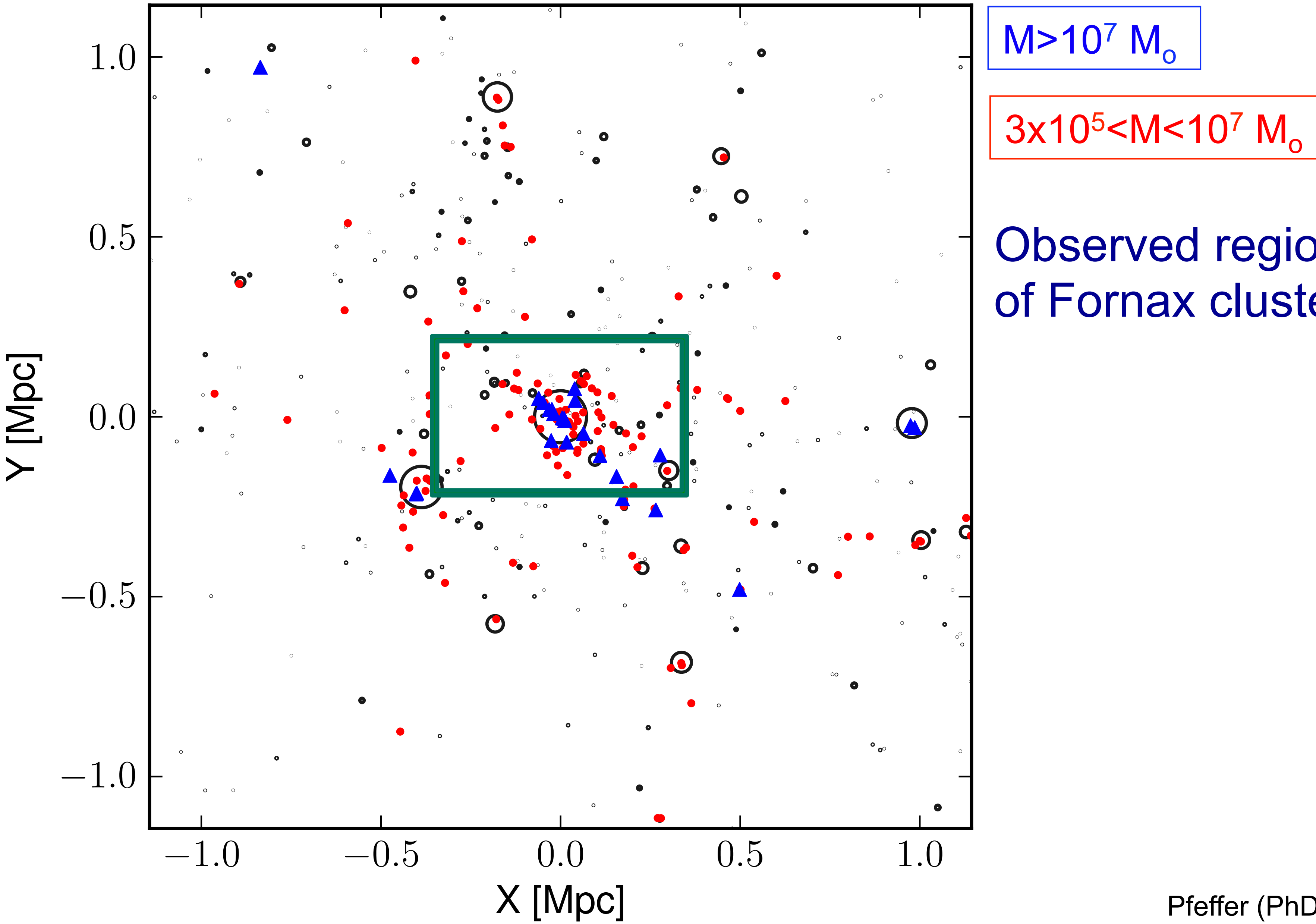
Cumulative radial distribution of GCs, UCDs and dE,Ns



Hilker (2010)

red GCs < blue GCs < ωCen's < UCDs < dE,Ns < dEs < all galaxies

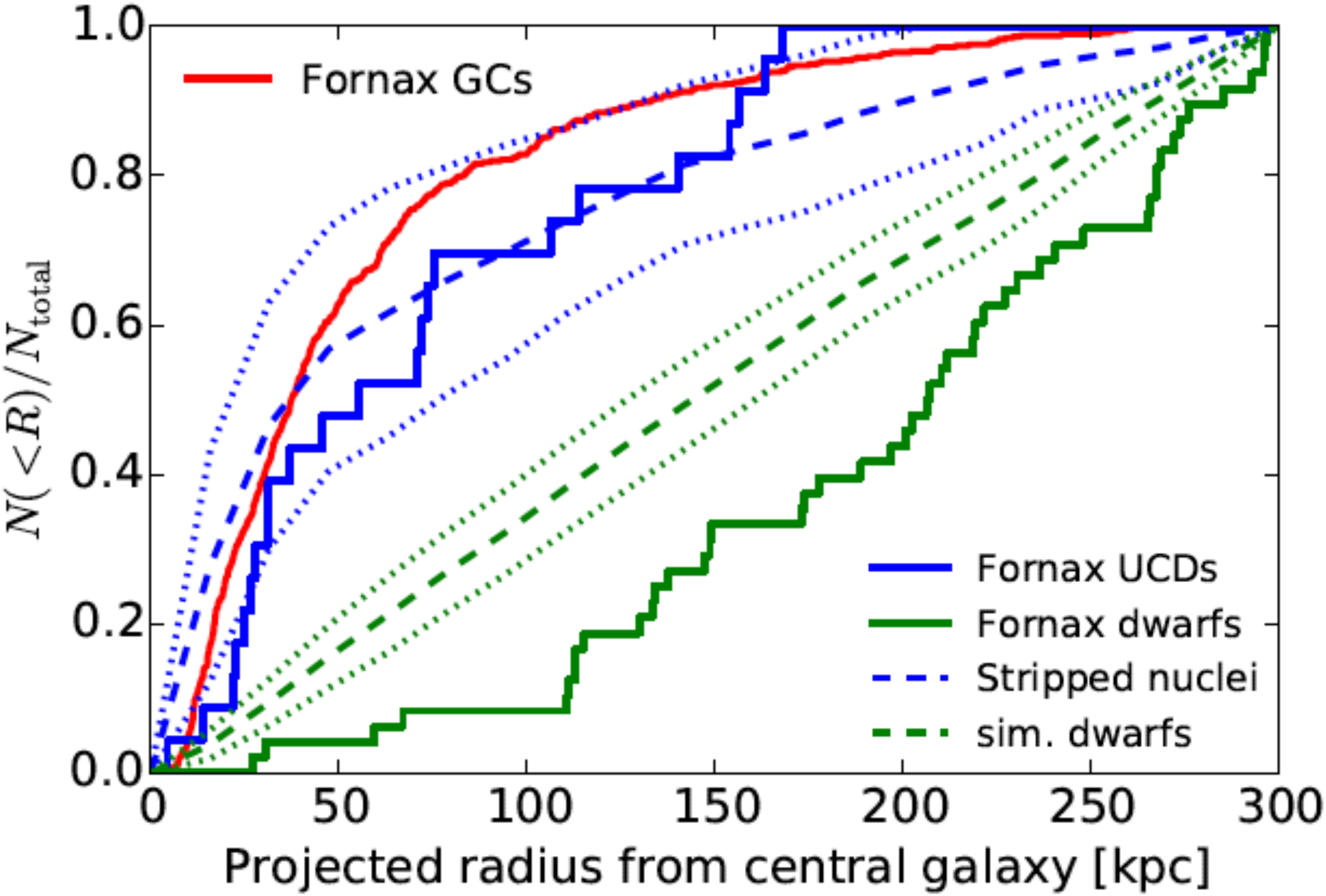
Spatial distribution of stripped nuclei in simulations



Observed region of Fornax cluster

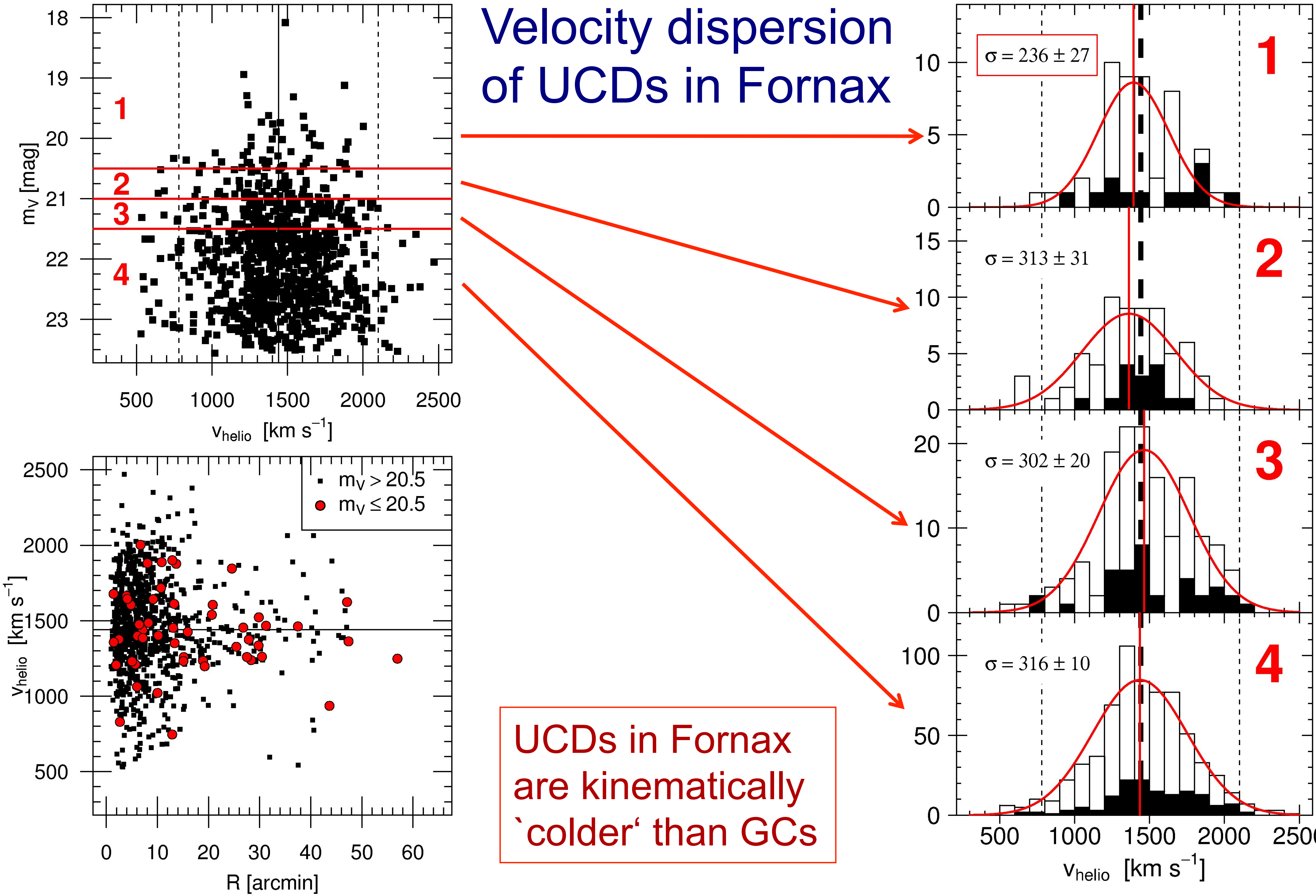
Pfeffer (PhD thesis)

Spatial distribution of stripped nuclei: observations vs. simulations



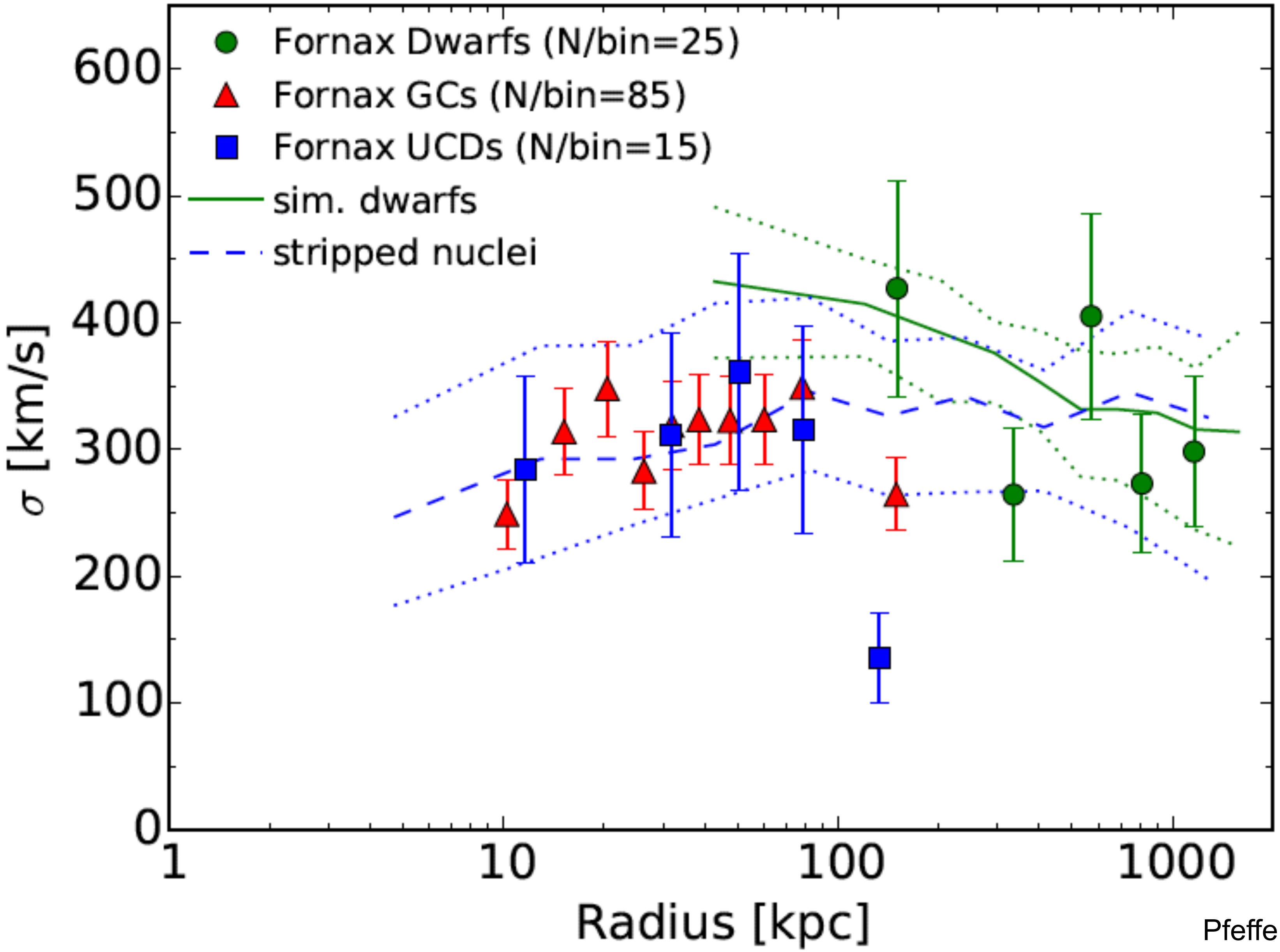
Pfeffer (PhD thesis)

Velocity dispersion of UCDs in Fornax



UCDs in Fornax are kinematically `colder' than GCs

Velocity dispersion of stripped nuclei: observations vs. simulations

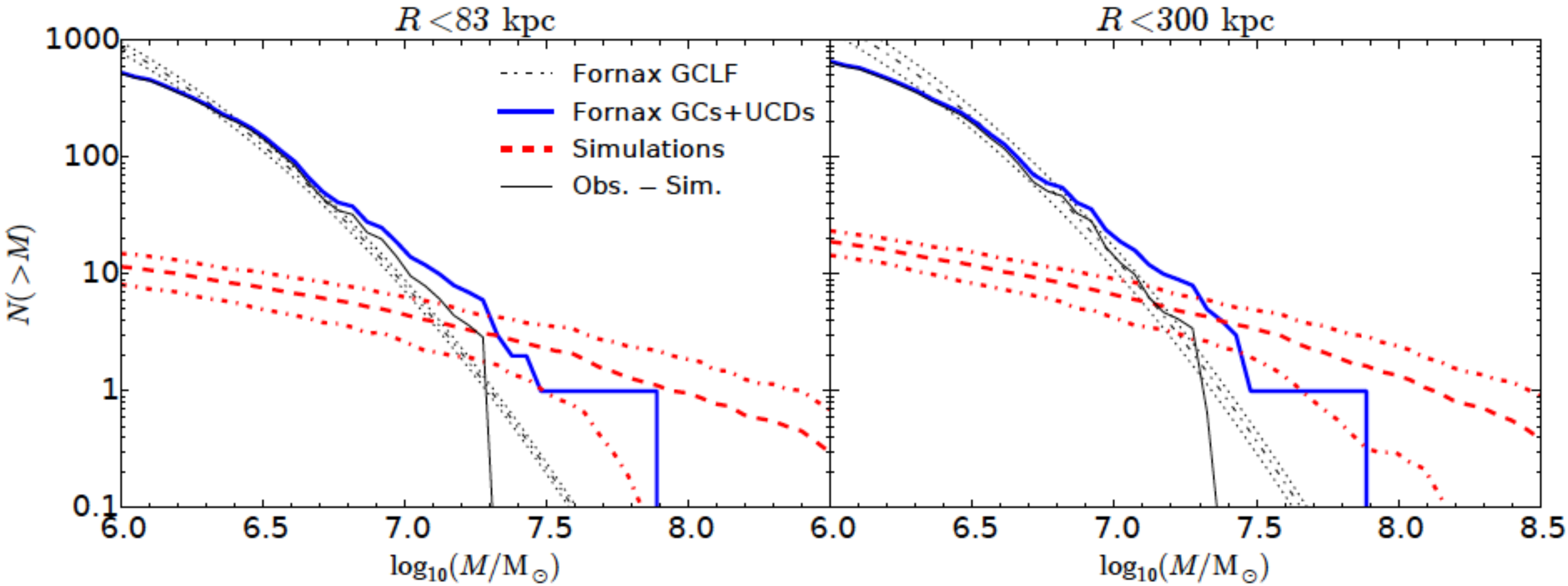


Pfeffer (PhD thesis)

Tidal stripping produces objects that resemble UCDs!

The question is how often does it happen?

Mass function of stripped nuclei and GCs/UCDs: observations vs. simulations



Pfeffer (PhD thesis)

Numbers of stripped nuclei in simulations versus observed numbers UCDs/GCs in the Fornax cluster

Mass ($M_\odot$)	$R < 83$ kpc pred.	$R < 83$ kpc obs.	$R < 300$ kpc pred.	$R < 300$ kpc obs.
$> 2 \times 10^6$	$20.2^{+13.6}_{-12.3}$	>146	$35.2^{+15.5}_{-13.2}$	>193
$> 10^7$	$8.0^{+4.7}_{-3.9}$	16	$12.1^{+6.9}_{-5.7}$	23
$> 10^8$	$0.8^{+1.5}_{-0.8}$	0	$1.0^{+1.8}_{-1.0}$	0

<20% of all UCDs in Fornax with masses larger than $2\text{x}10^6$ M_o and ~50% of those with masses larger than 10^7 M_o are stripped nuclei.

Numbers of stripped nuclei in a Milky Way sized galaxy halo

We predict that 2.8+/-1.5 GCs in the Milky Way with a mass larger than 10^5 M_o and 1.8+/-1.1 GCs with a mass larger than 10^6 M_o are stripped nuclei.

Currently 7 Galactic GCs are thought of being the remnants of dwarf galaxies due to either a spread in heavy-element abundances (ω Cen, M22, NGC 1851, NGC 2419, NGC 3201, NGC 5824) and/or Ages (ω Cen, Terzan 5).

Our results are compatible with a scenario where ω Centauri and two or more of the other massive GCs are stripped nuclei.

‚Smoking gun‘ indicators for stripped nuclei

1) **SMBHs in UCDs**

2) **UCDs that are embedded in tidal tails or extended envelopes and/or have associated companion GCs**

3) **Young stellar population ages of UCDs**

4) **Spread in heavy element abundances in UCDs**

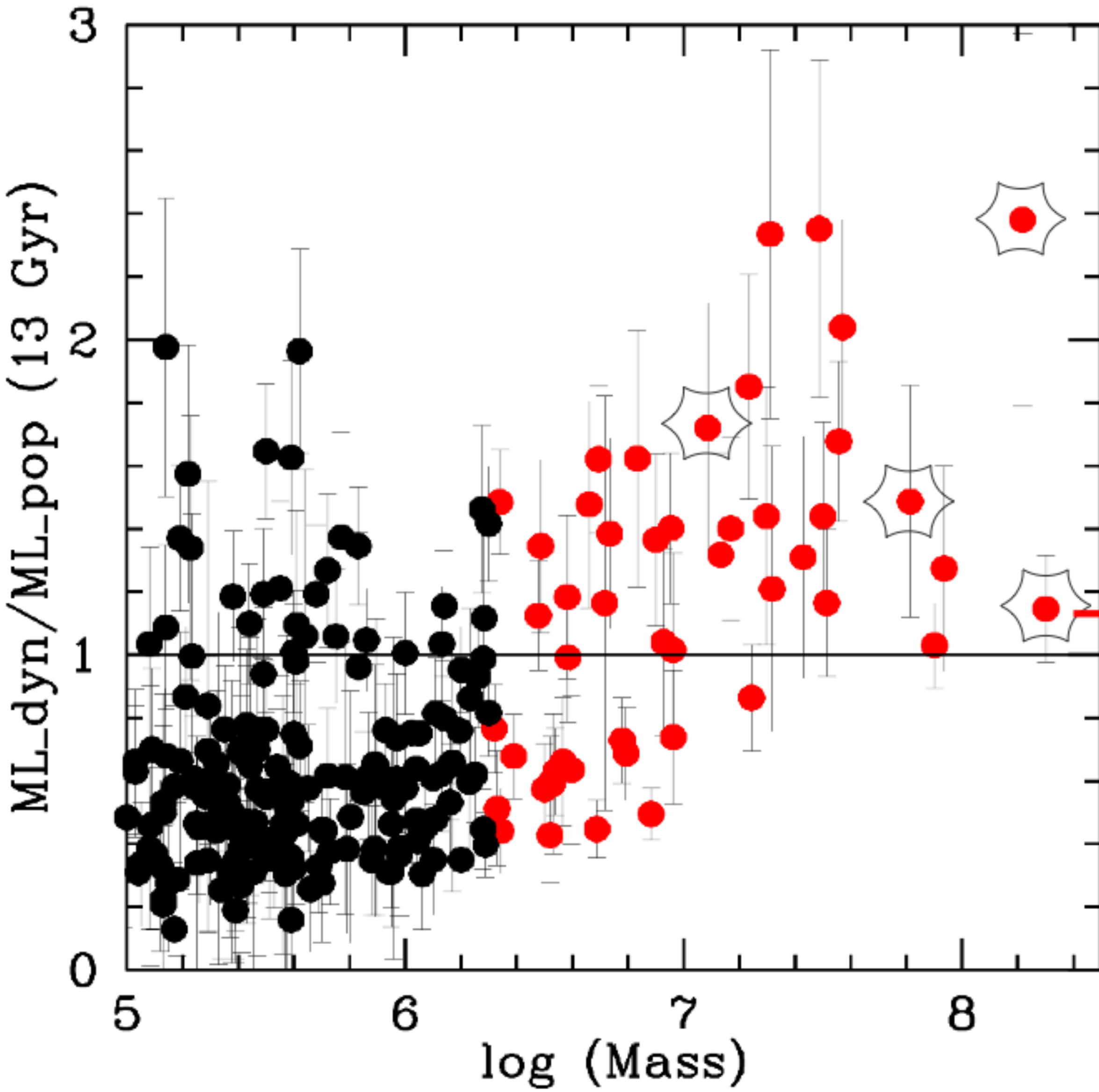
1) **SMBHs in UCDs**
   [but: Pavel knows how to form a SMBH within a massive GC without being the nucleus of a galaxy]
   Note: an elevated mass-to-light ratio is not enough since it can also be explained by a non-canonical IMF or viewing the tidal debris of a disrupting UCD in the line-of sight

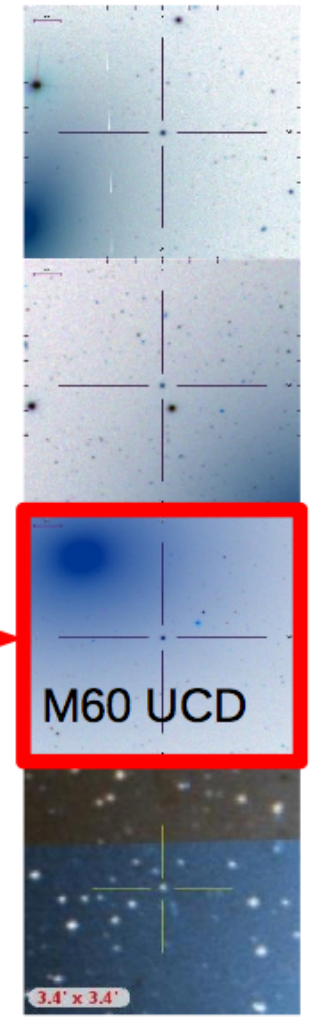
2) **UCDs that are embedded in tidal tails or extended envelopes and/or have associated companion GCs**
   [but: also GCs can get tidally disrupted and merged super star clusters can show extended envelopes and companion GCs]

3) **Young stellar population ages of UCDs**
   [but: could also be a merged super star cluster formed in a recent galaxy interaction]

4) **Spread in heavy element abundances in UCDs**
   [but: could also be very massive GCs that self-enriched]

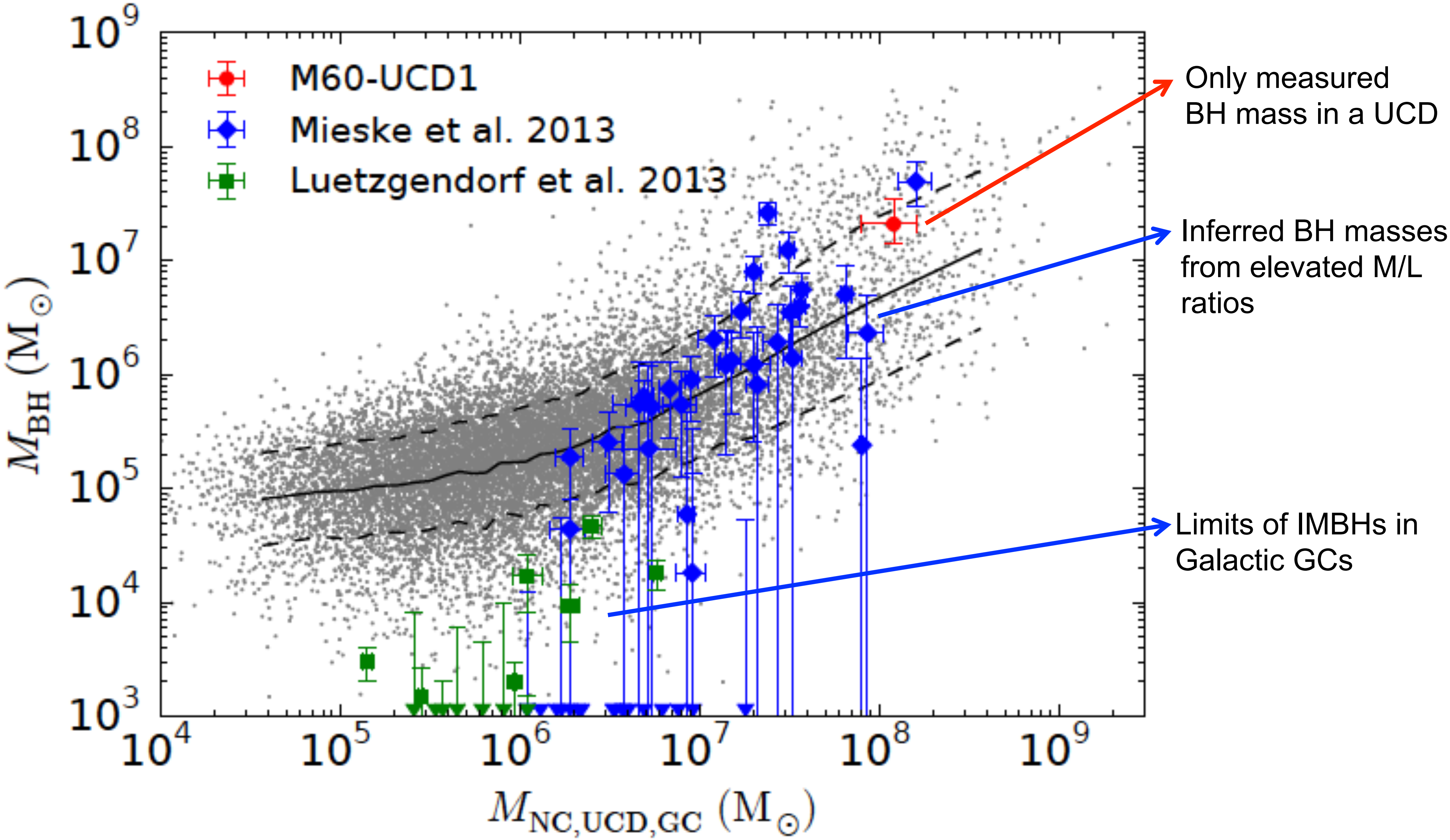
It has been known for some time that many UCDs are a bit overweight. They just appear to be too heavy for the luminosity of their stars.





Mieske, Hilker, et al. (2008)
Mieske et al. (2013)

Predicted masses of central black holes in stripped nuclei

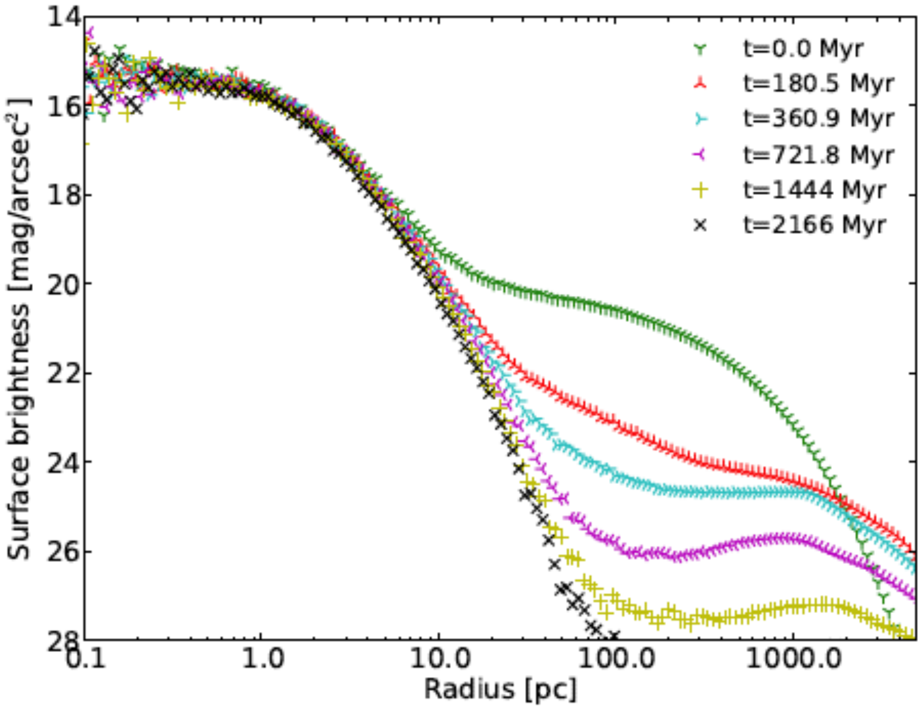


Simulations: BH masses are based on M_*-M_{BH} relation of progenitor galaxies

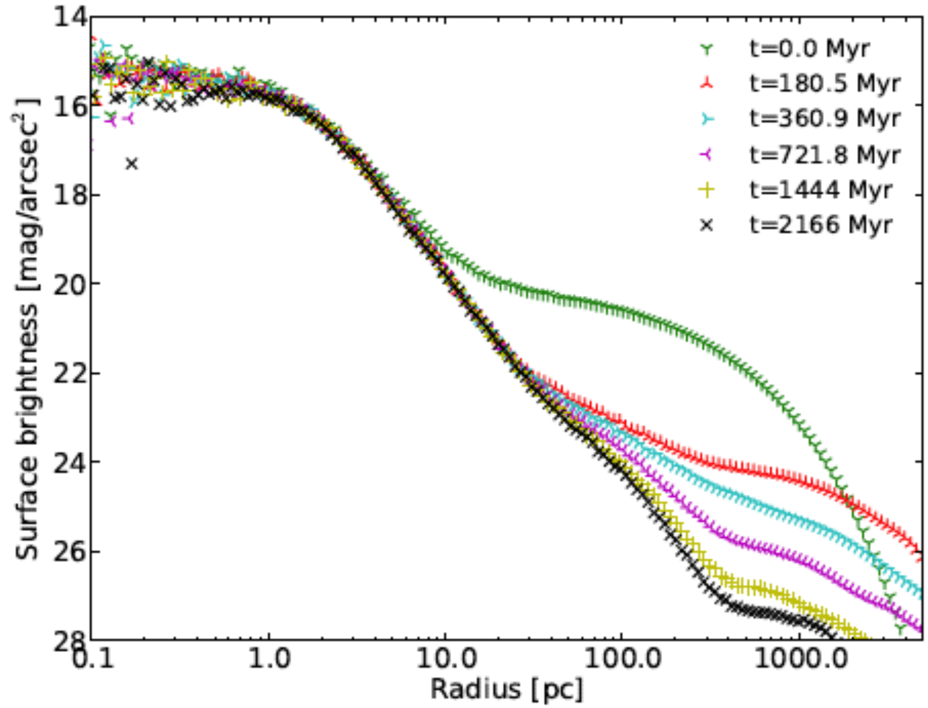
Pfeffer (PhD thesis)

Tidal stripping of dwarf galaxies

Strong tidal interaction

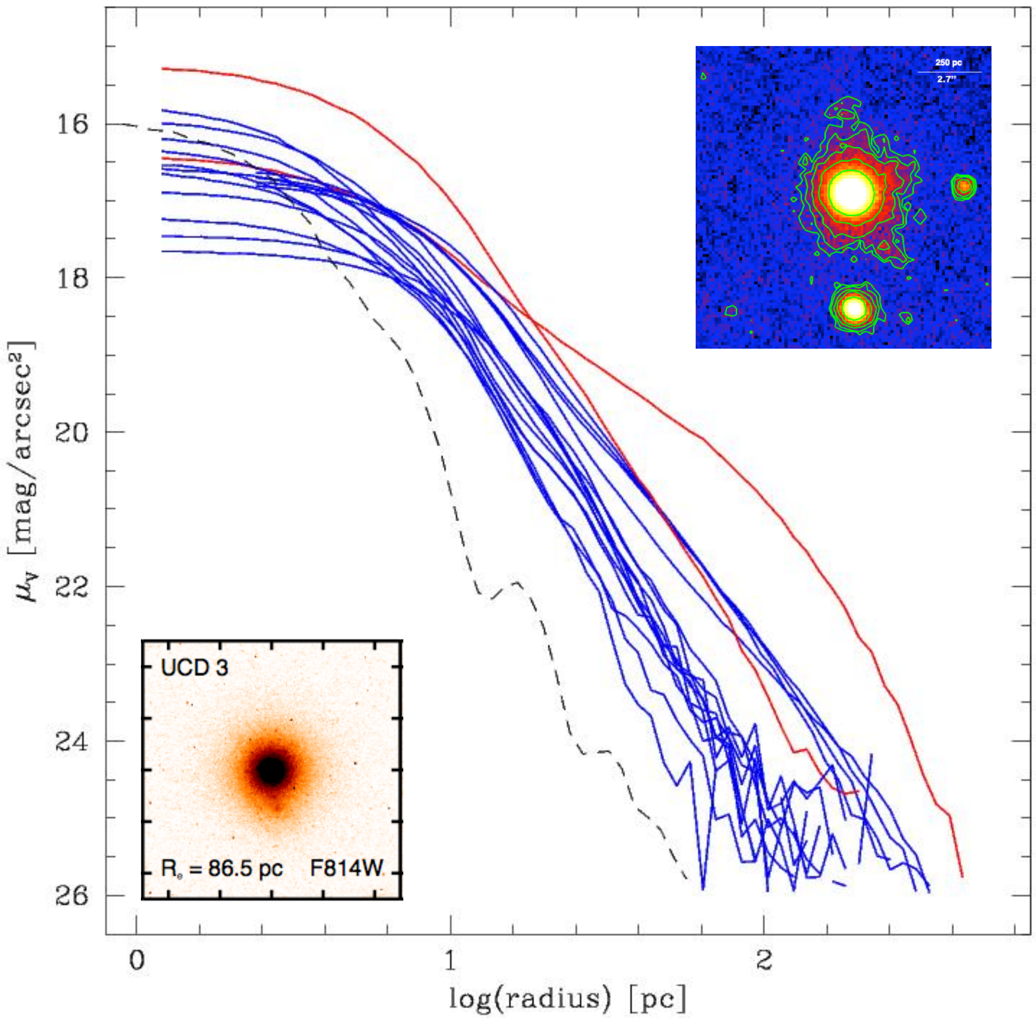


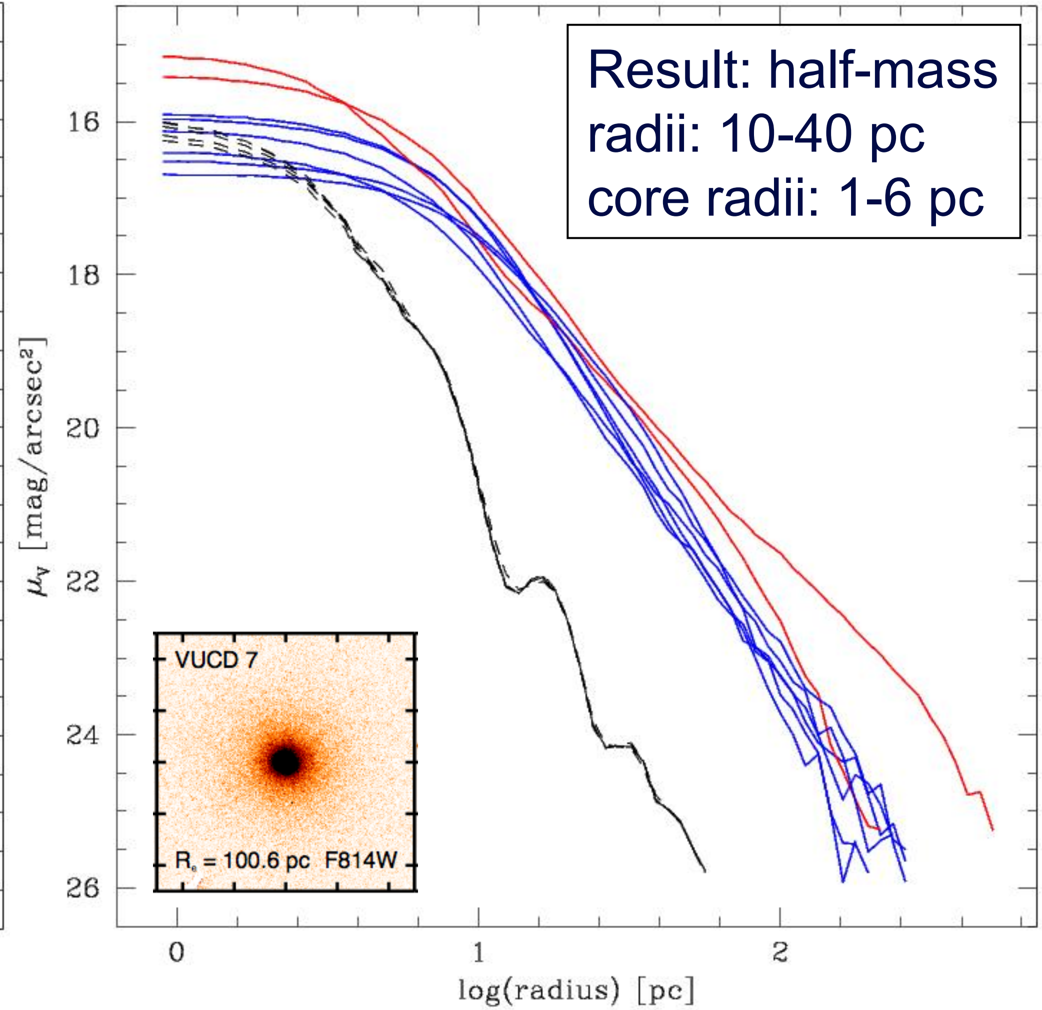
Weaker tidal interaction



Pfeffer & Baumgardt (2013)

Surface brightness profiles of ultra-compact dwarfs (HST/ACS+STIS) in **Fornax** and **Virgo**





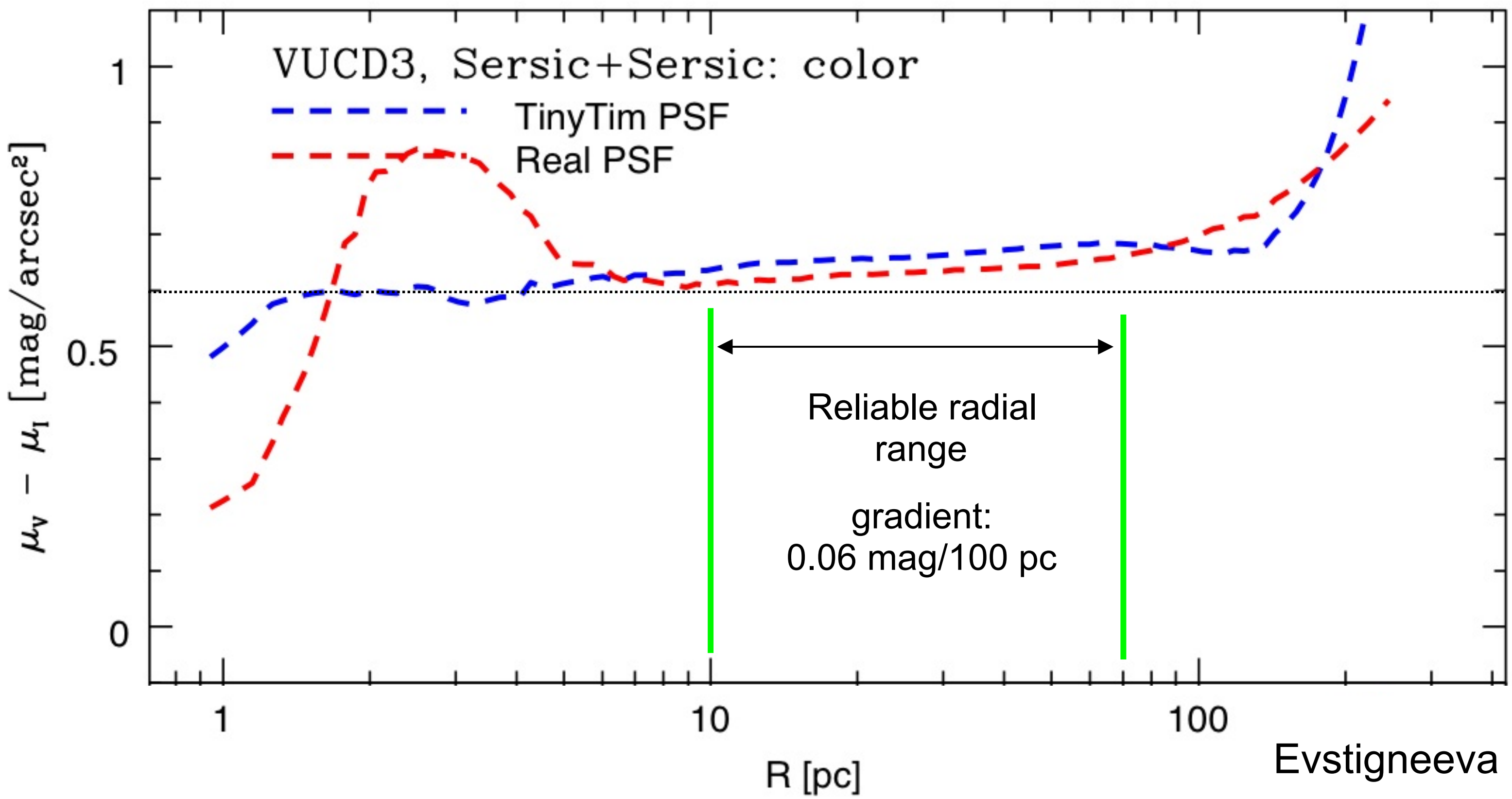
A few UCDs have envelopes with effective radii of 40-100 pc

Drinkwater, Gregg, Hilker et al. (2003)
Evstigneeva et al. (2007, 2008)

Multiple stellar populations in UCDs?

Motivation: ω Cen and G1 have complex stellar populations

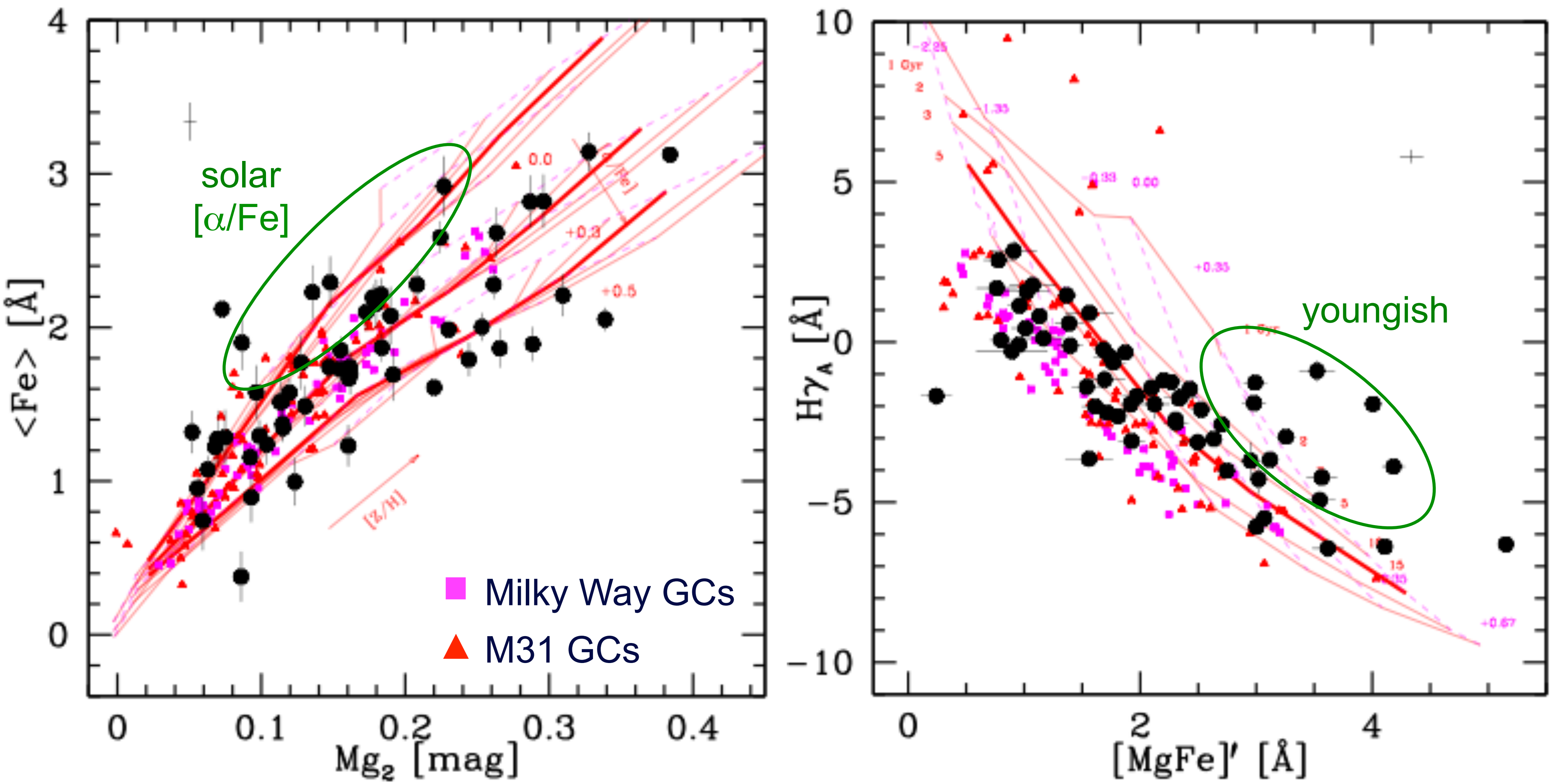
Colour gradients within UCDs from HST photometry:



Evstigneeva et al. (2008)

Positive colour gradient (getting redder outside) found in several of the most massive Fornax and Virgo UCDs.

Abundances and ages of GCs/UCDs in the Fornax cluster



High S/N VLT/FORS spectra of ~60 bright GCs/UCDs in Fornax (M_V<-9.5)

Puzia, Hilker et al. (in prep.)

Summary

- Tidal disruption of nucleated galaxies is observed.
- There is considerable overlap in observation space between UCDs and nuclear star clusters.
- Masses, sizes, metallicities, spatial distribution and kinematics of many UCDs in Fornax can be explained by the stripping scenario: Note: the size of the nucleus is barely changed, the larger sizes of UCDs results from a remaining envelope!
- Stripping of nucleated galaxies in a cosmological framework cannot explain the total number of UCDs, but ~50% of UCDs with a mass $>10^7$ M_o are compatible with stripped nuclei.
- Still the studies of the UCD populations in nearby clusters suffer from incompleteness effects, even at the masses of 10^8 M_o
  → more spectroscopic surveys!
- Is there an ultimate 'smoking gun' observation for NC-UCDs?

Thank you!