



COLLABORATORS

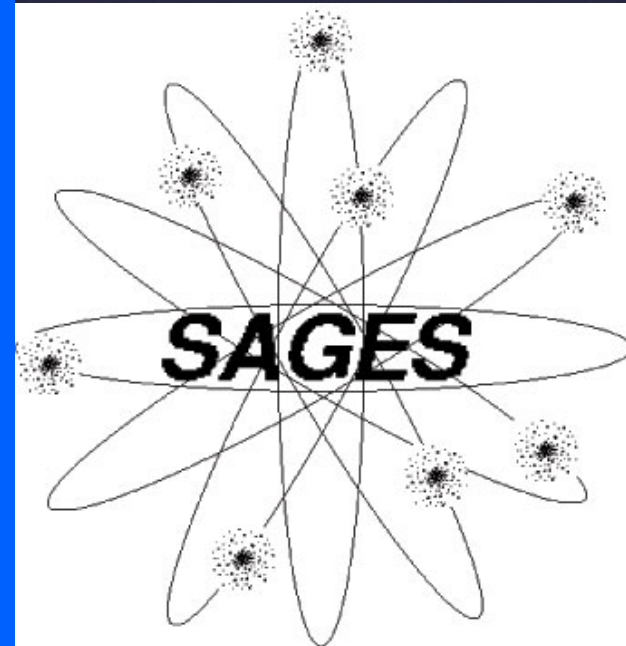
35 Active SAGES worldwide

Study
Astrophysics of
Globular
clusters in
Extragalactic
Systems

Jean Brodie
UC Observatories

Adebusola Alabi
Christina Blom
Theron Carmichael
Charlie Conroy
Duncan Forbes
Caroline Foster
Zachary Jennings
Joachim Janz
Justin Kader
Sreeja Kartha

Soeren Larsen
Mark Norris
Nicola Pastorello
Mark Peacock
Vincenzo Pota
Aaron Romanowsky
Lee Spitler
Jay Strader
Chris Usher
Alexa Villaume



The SLUGGS Survey

Brodie+ 2014

SAGES **L**egacy **U**nifying **G**lobulars and **G**alaxies

Photometry (Subaru) and spectroscopy (Keck)
DEIMOS (12 km/s)

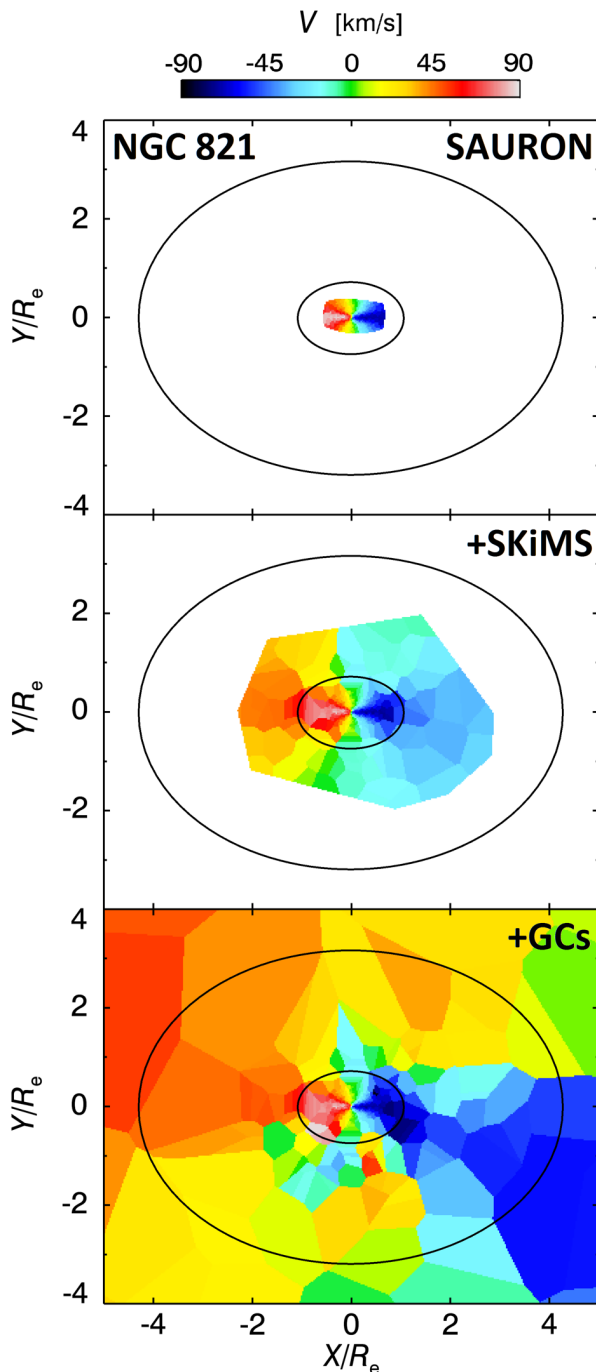
Chemodynamics for 25+ nearby early-type galaxies; range of properties (M , env, σ , v/σ)

Field stars to $\sim 3 r_{\text{eff}}$

Globular clusters to $\sim 10 r_{\text{eff}}$

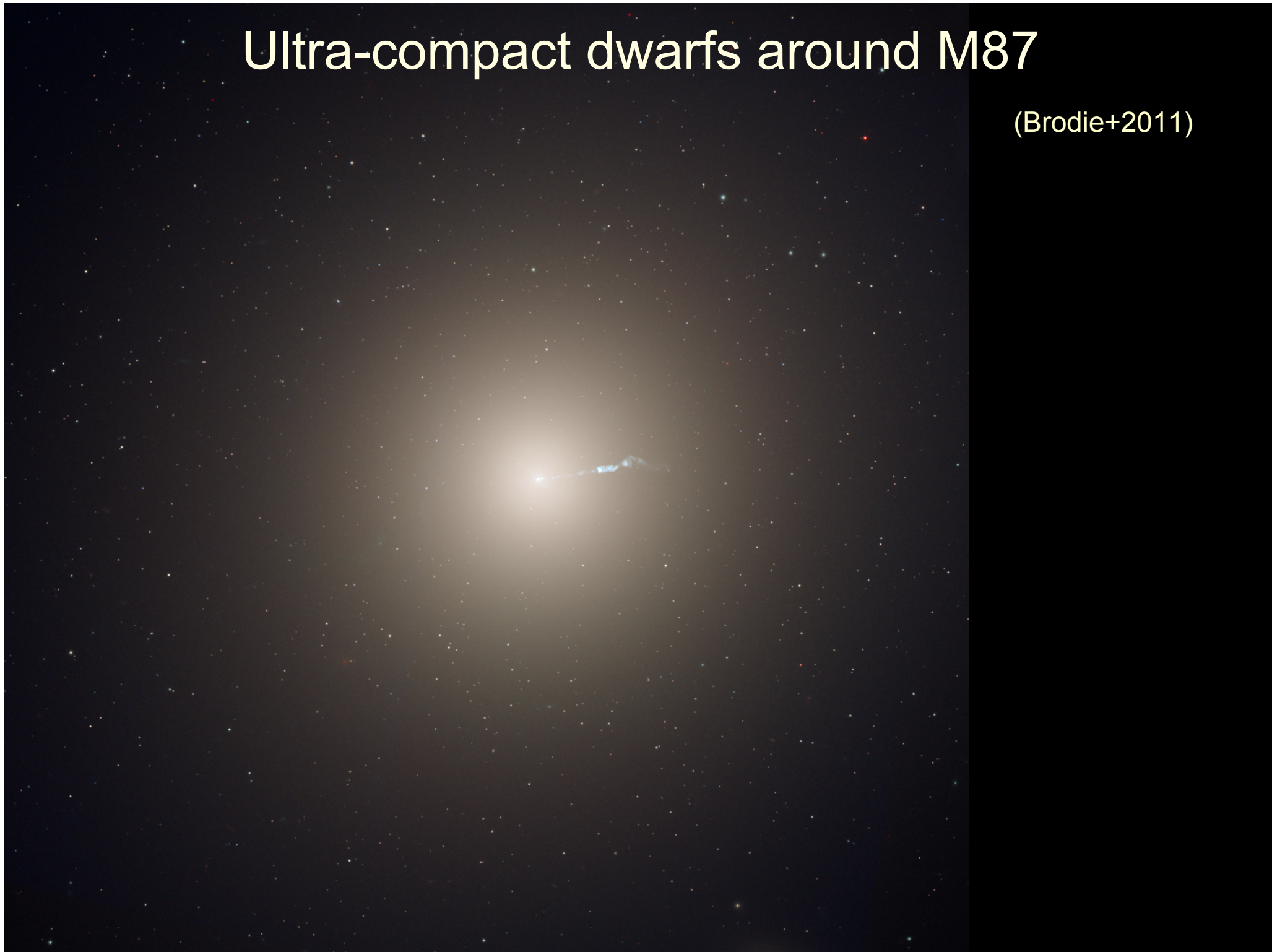
2-D kinematic and metallicity maps for GCs and galaxy stars

Observations nearing completion
 **~ 45 papers now published/
submitted** (<http://sluggs.ucolick.org>)



Ultra-compact dwarfs around M87

(Brodie+2011)



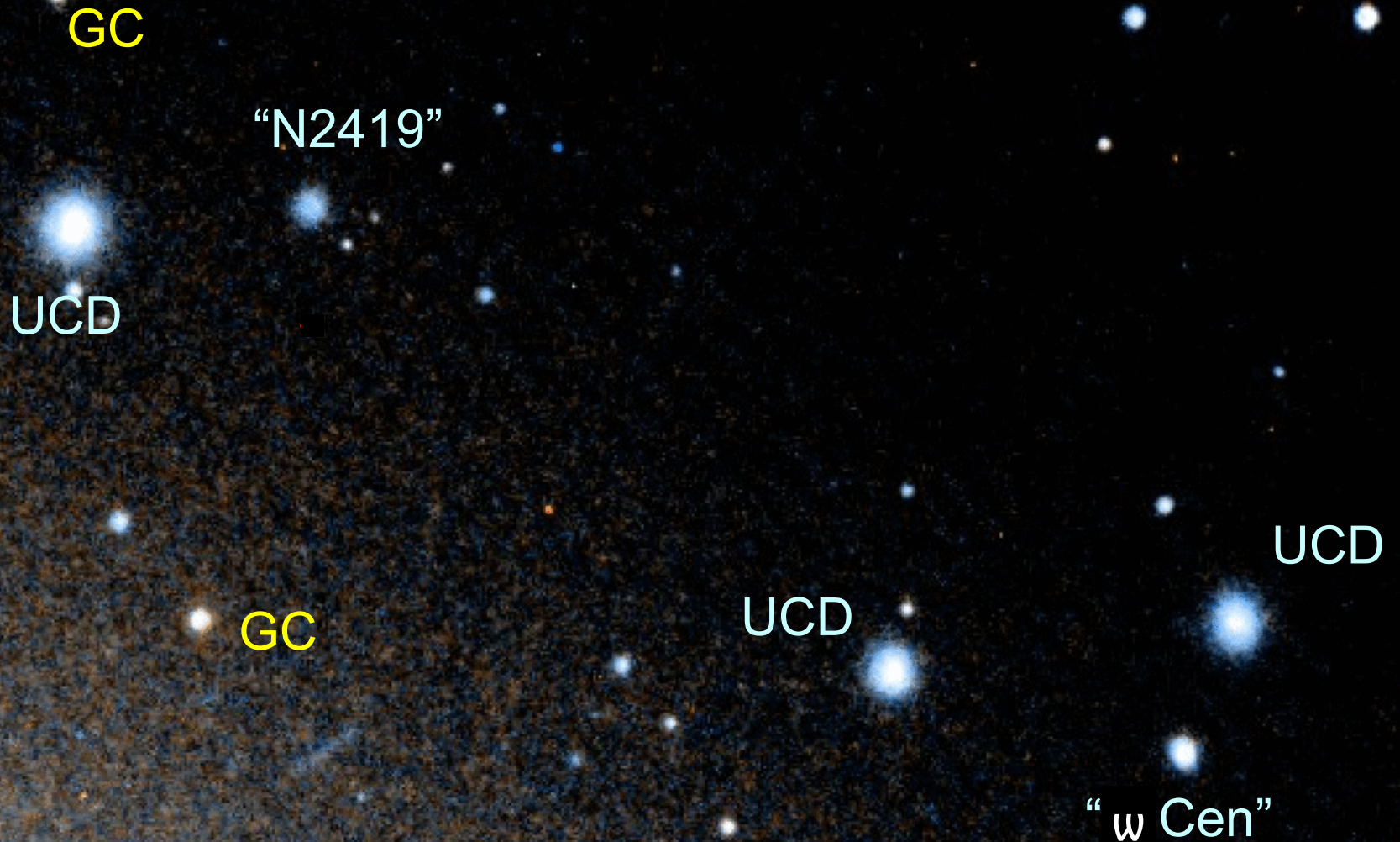
Ultra-compact dwarfs around M87

(Brodie+2011)



Ultra-compact dwarfs around M87

(Brodie+2011)



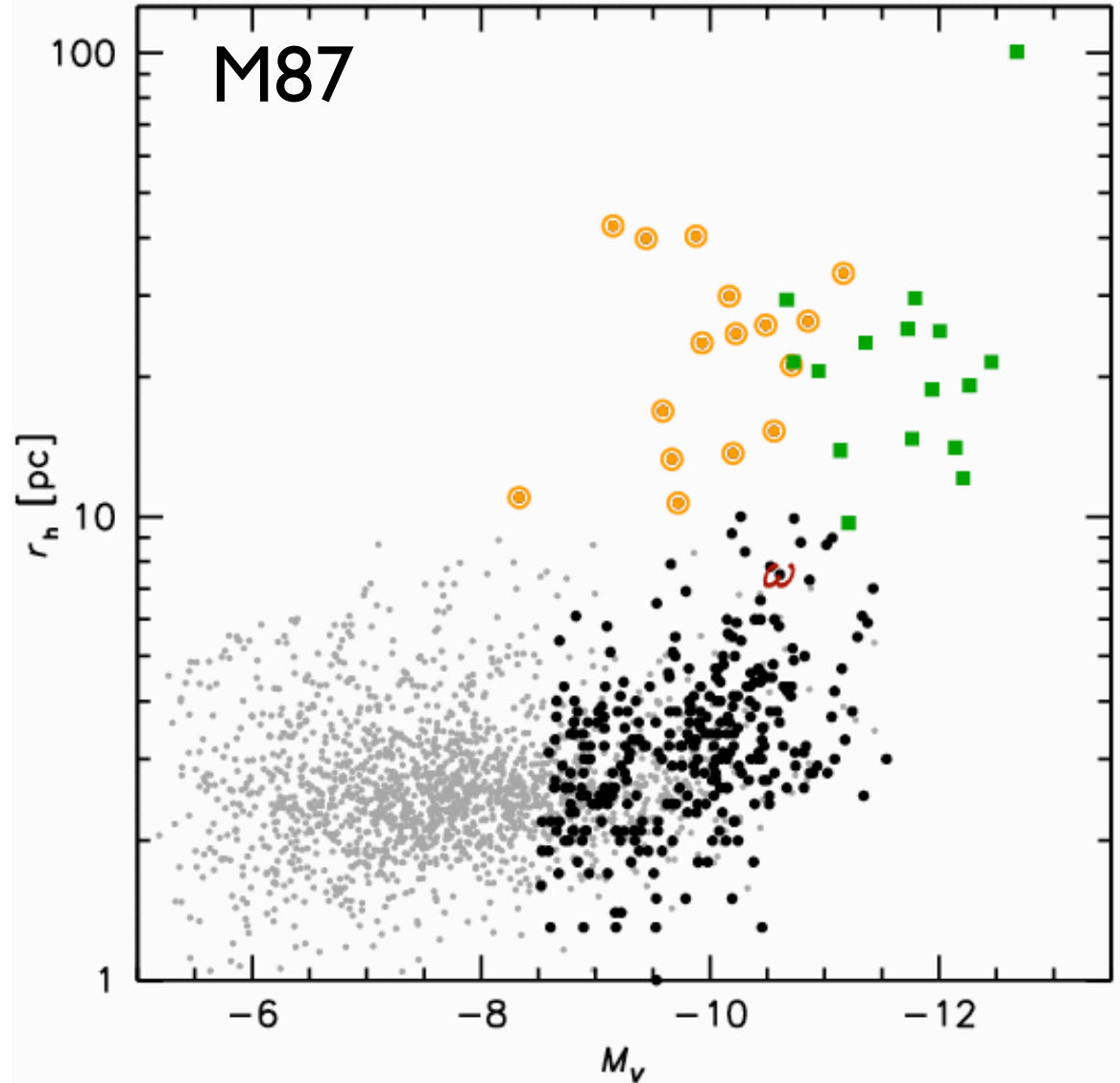
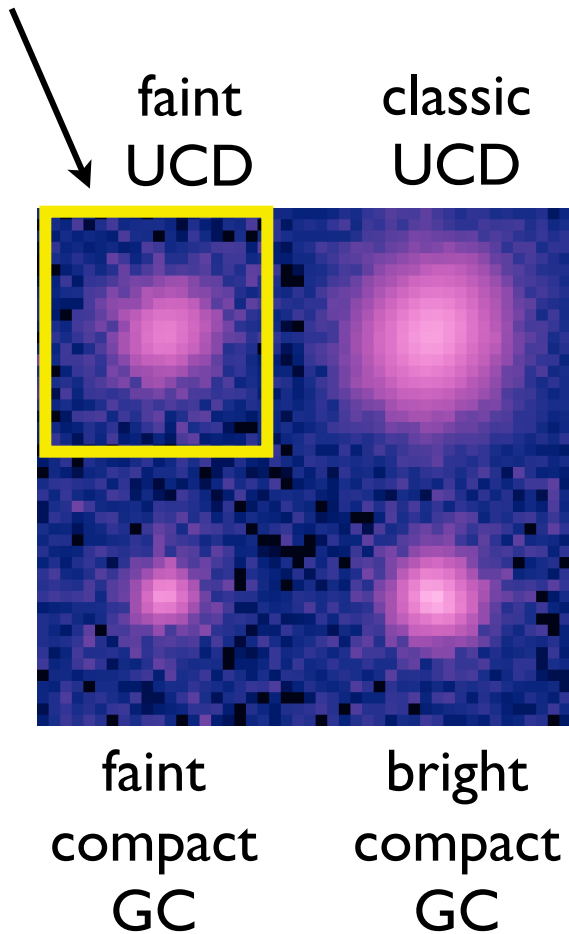
- UCDs: $\log L_V/L_{V,\text{Sun}} \sim 5.5-7$; $r_h \sim 10-40$ pc $\sigma \sim 20-40$ km s⁻¹
- Doubled sample size to 34, incl. new low-surface brightness regime

Ultra Compact Dwarfs (UCDs)

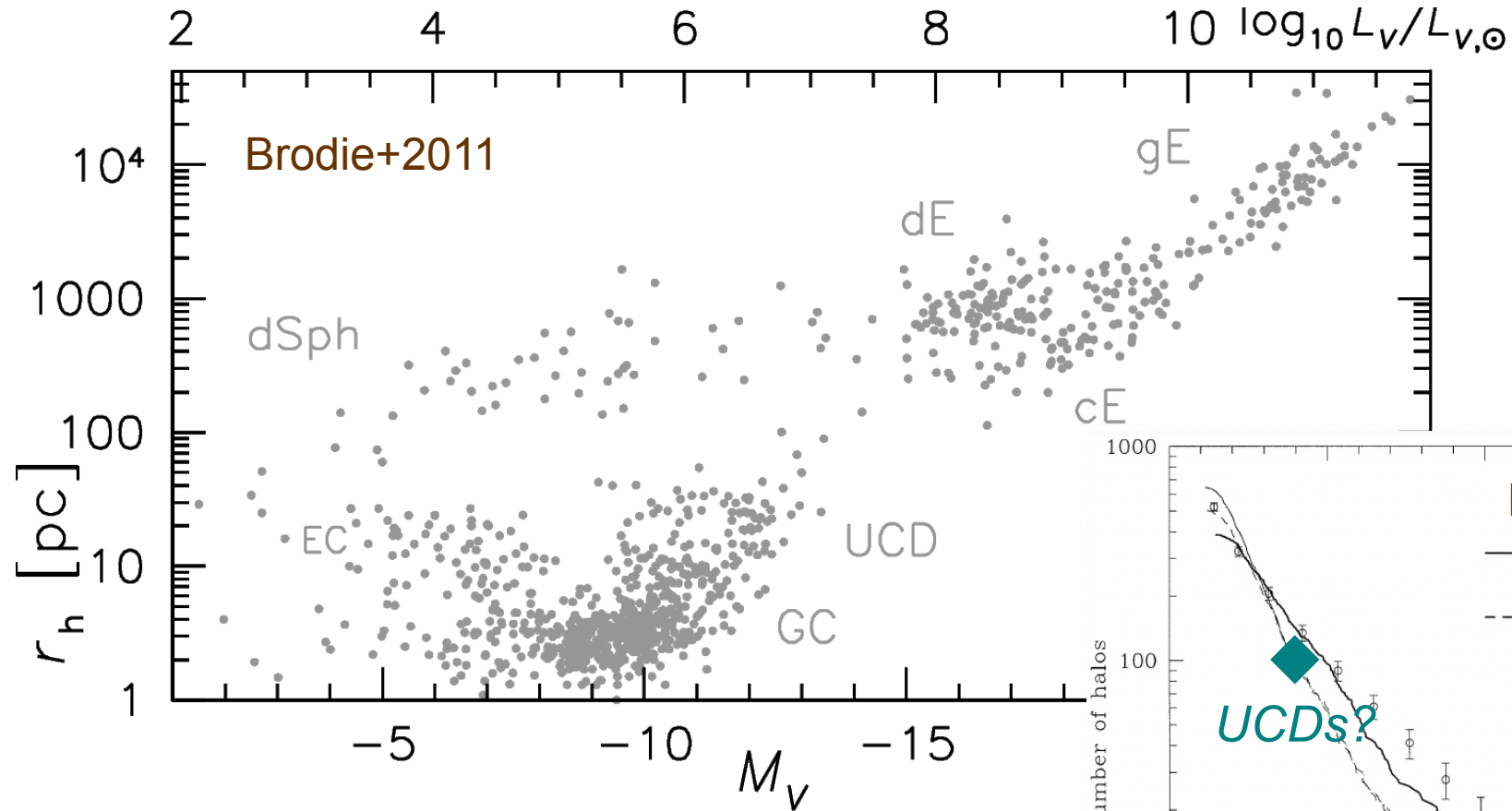
Stripped galaxies or large star clusters?
Brodie + 2011

No size-L relationship!

New area of parameter space



The Everything Plot

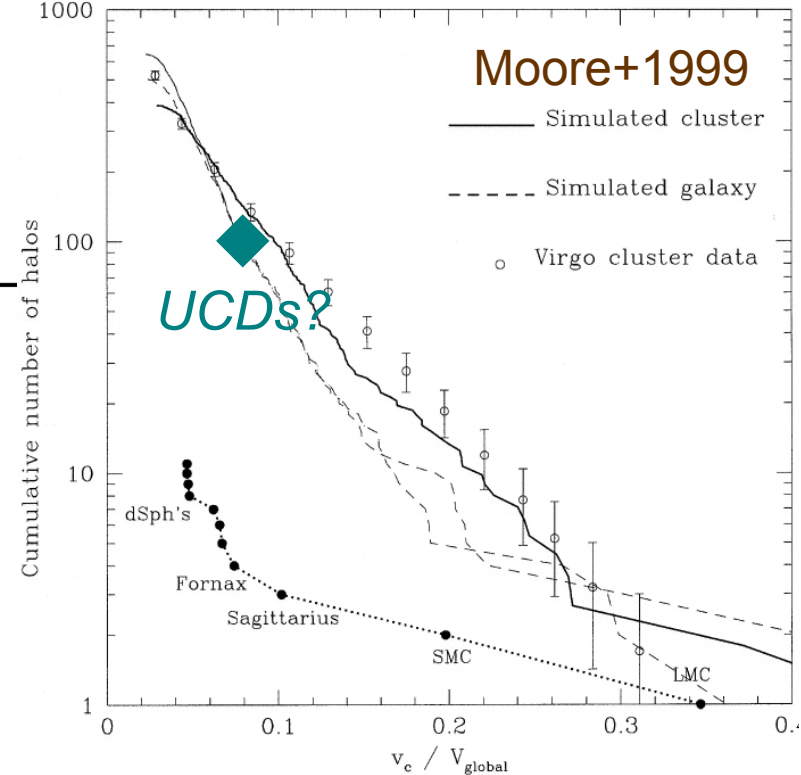


M87 ~100 UCDs out to ~200 kpc:

How many UCDs have DM now?

Unclear how to assign to early DM halos but may significantly affect cosmic accounting

– vanished DM halos? Pfeffer+2014

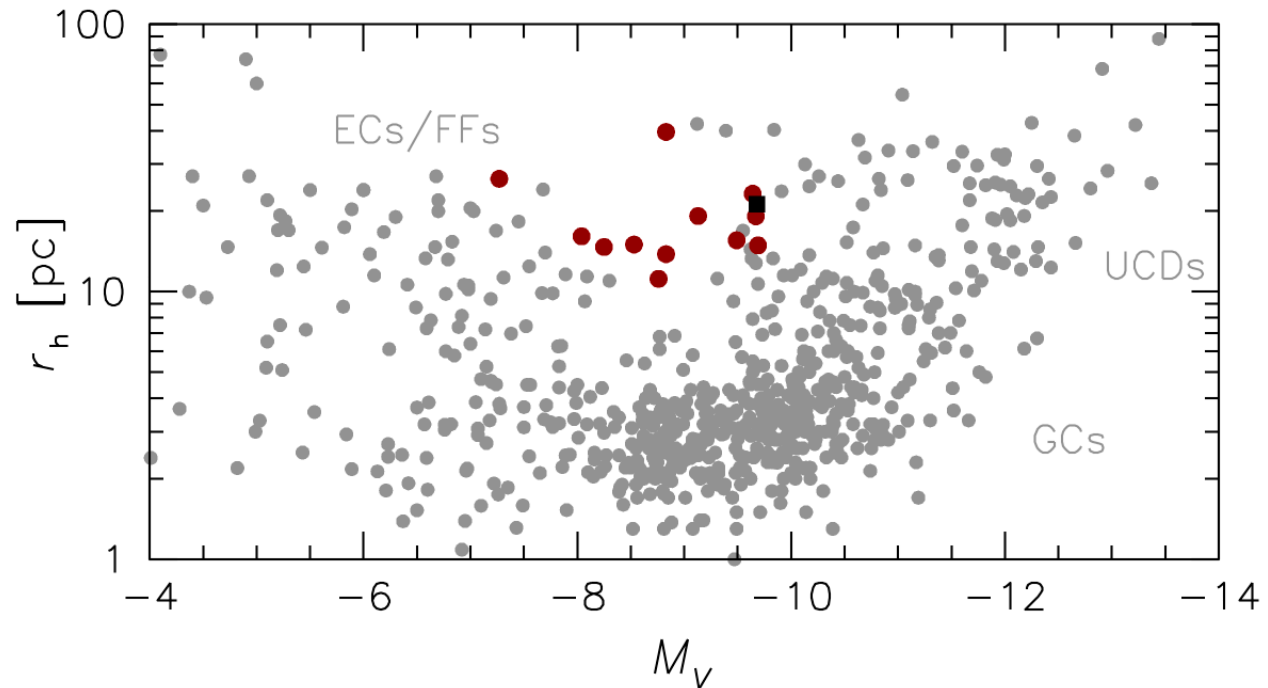


Don't Mind the Gap!



Gap between low
luminosity UCDs
and Faint Fuzzies is
filling up

Forbes+ 2013



The Densest Galaxy

M60-UCD1

Strader et al 2013

Most massive
UCD known

$2 \times 10^8 M_{\odot}$

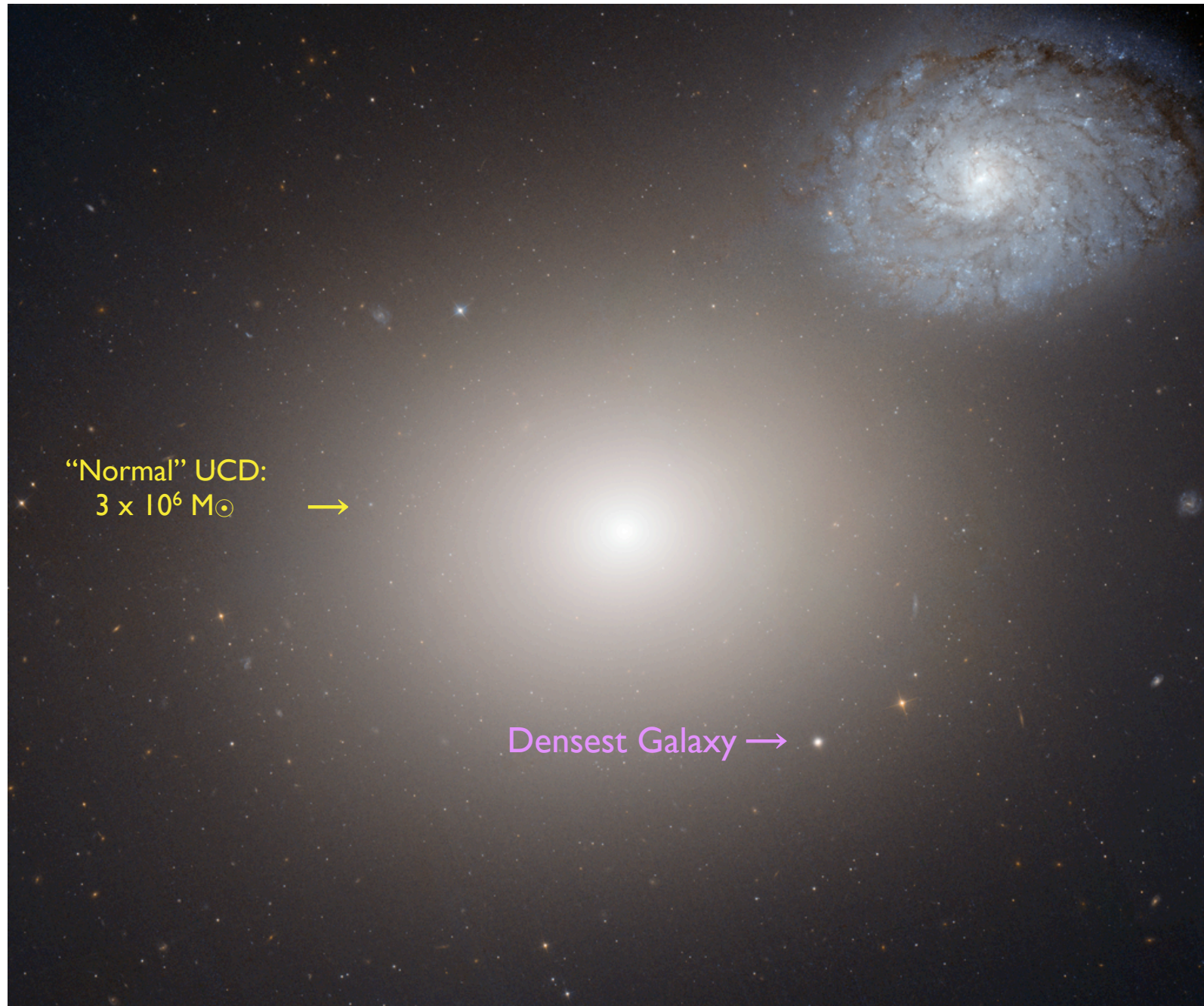
$R_h \sim 24 \text{ pc}$

$\sigma \sim 70 \text{ km/s}$

2 structural
components

Central X-ray
source \rightarrow
black hole?

Note:
 \sim normal M/L



Tiny Galaxy, Big Black Hole

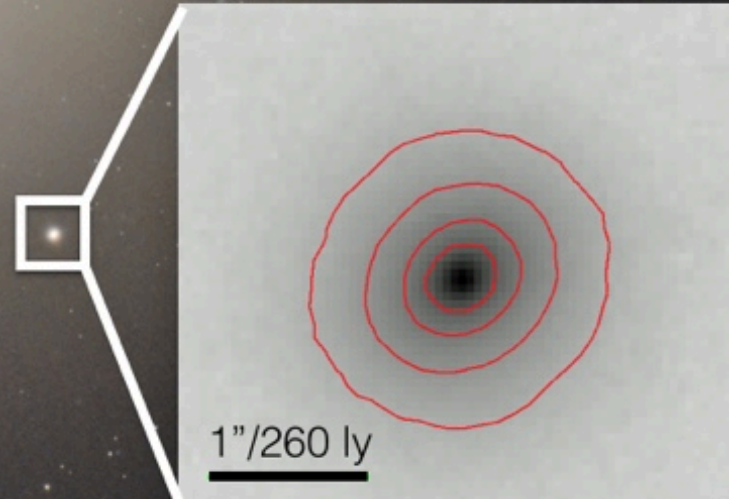
Seth+ 2014, Nature



NGC 4647

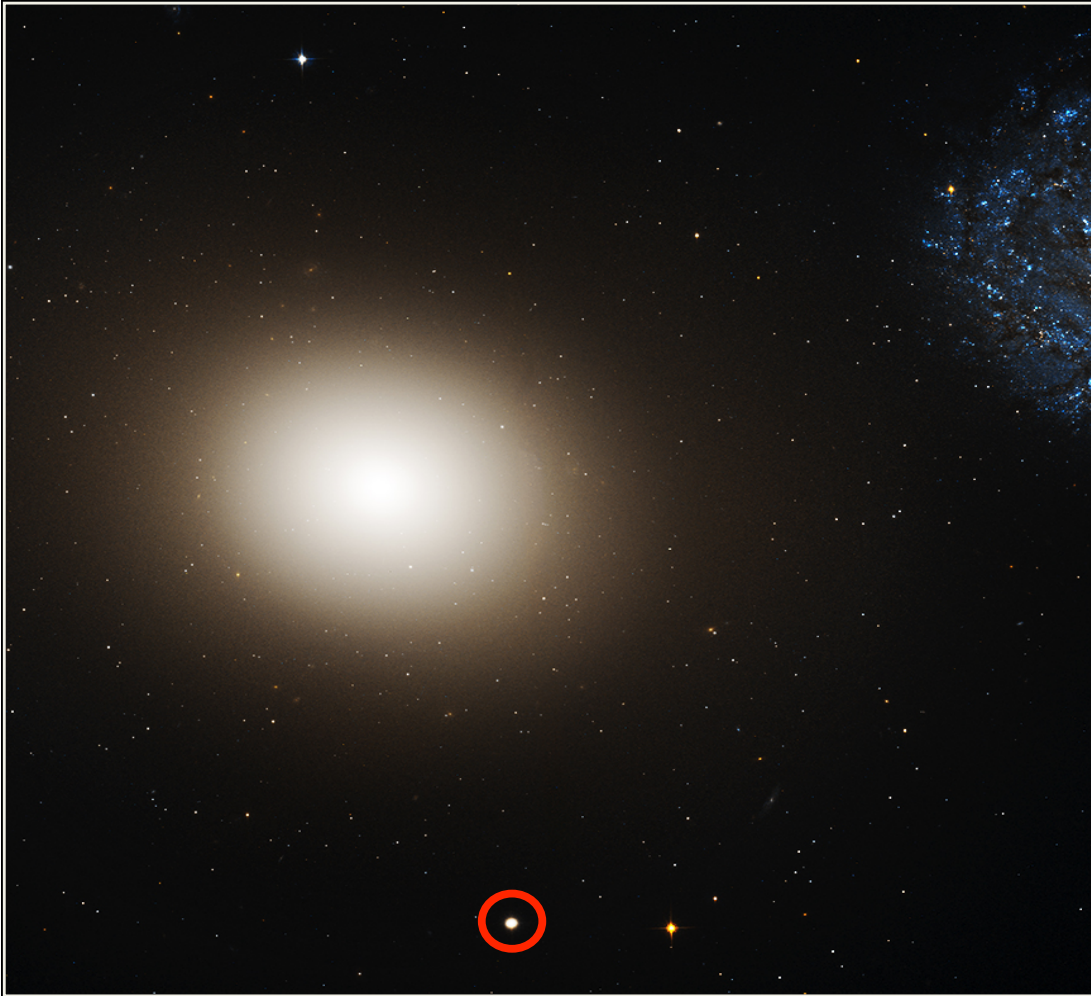
M60

M60-UCD1

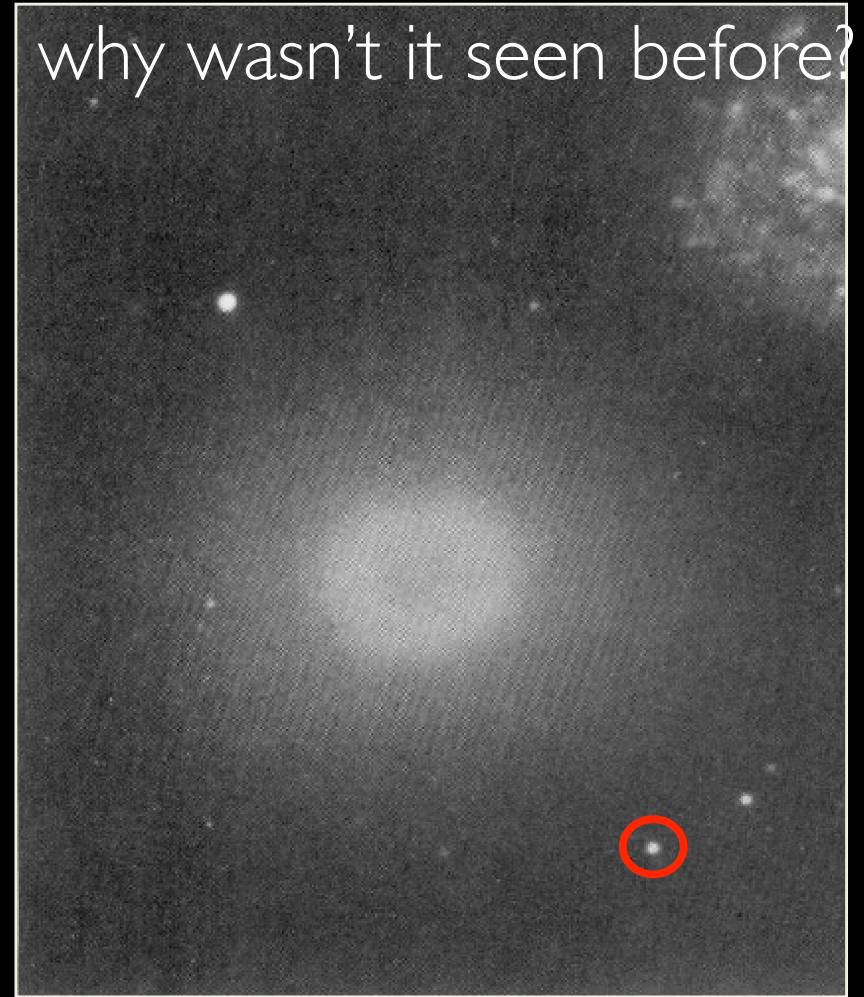


1"/260 ly

The densest galaxy



M60-UCD1:
dwarf galaxy orbiting
giant elliptical galaxy M60

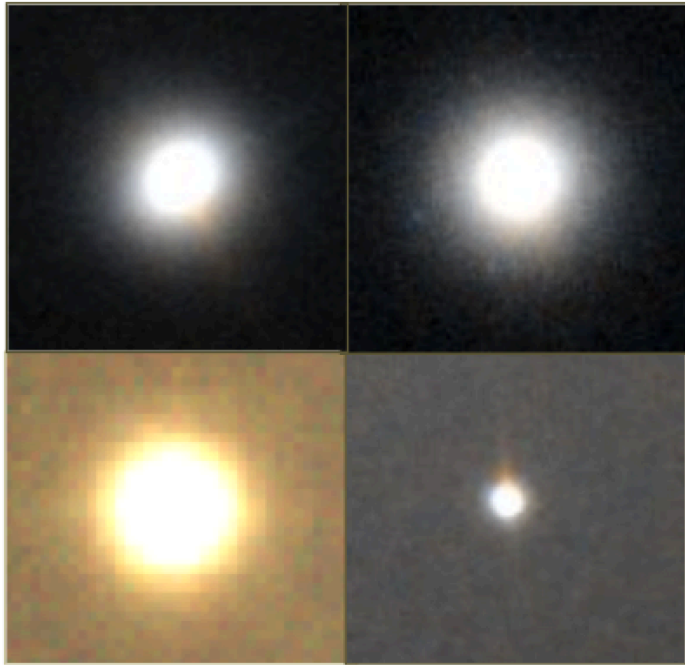


Hubble, 1922,
100-in Hooker

Denser and Denser!

M60-UCDI

M59cO



UCDX

HCCI

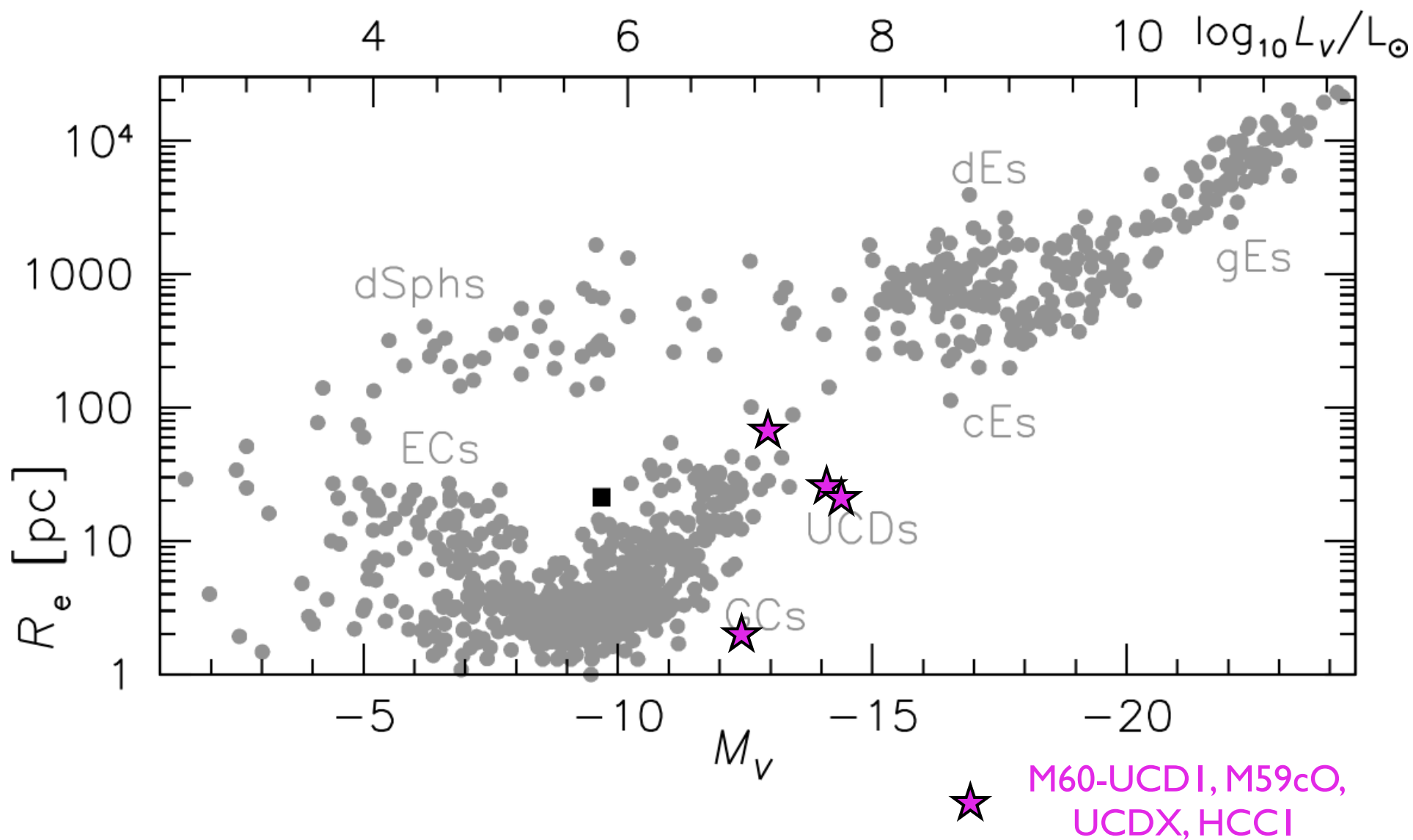
UCDX: M60-UCDI analog but
30% higher luminosity

HCCI: “hypercompact cluster”:
 $L_V \sim 10^7 L_\odot, r_h \sim 2 \text{ pc}$

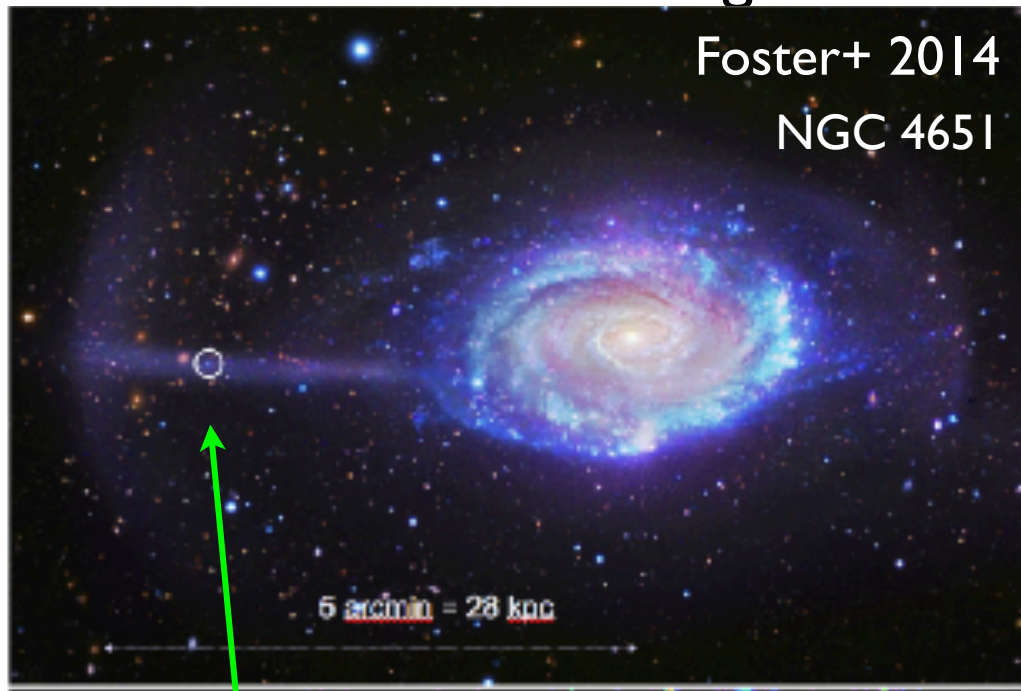
Host galaxies have halo
substructures: UCDs are nuclear tags of minor merger histories



The Everything Plot + “dense objects”

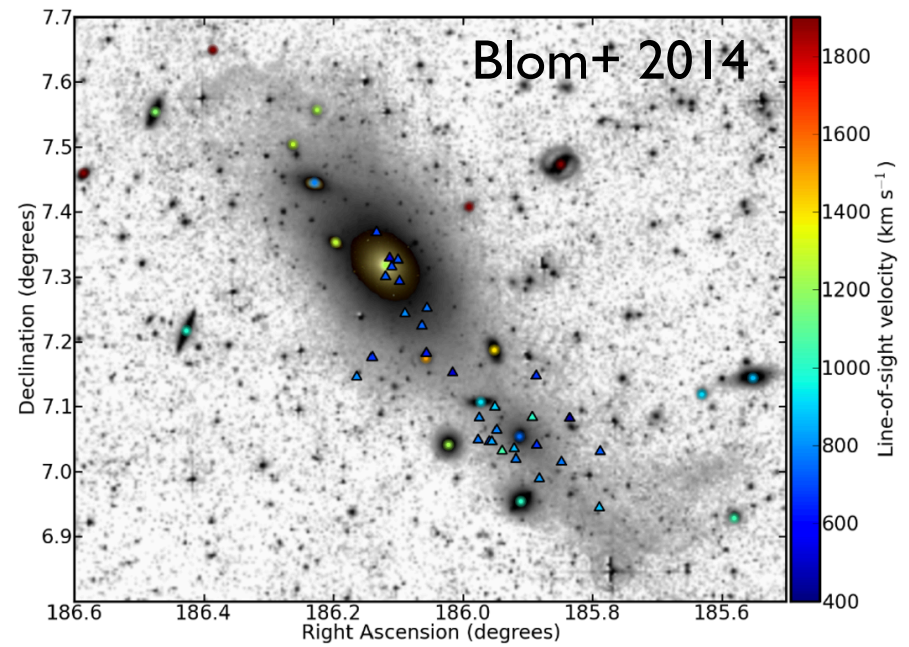


Novelties: Markers of tidal interactions/mergers

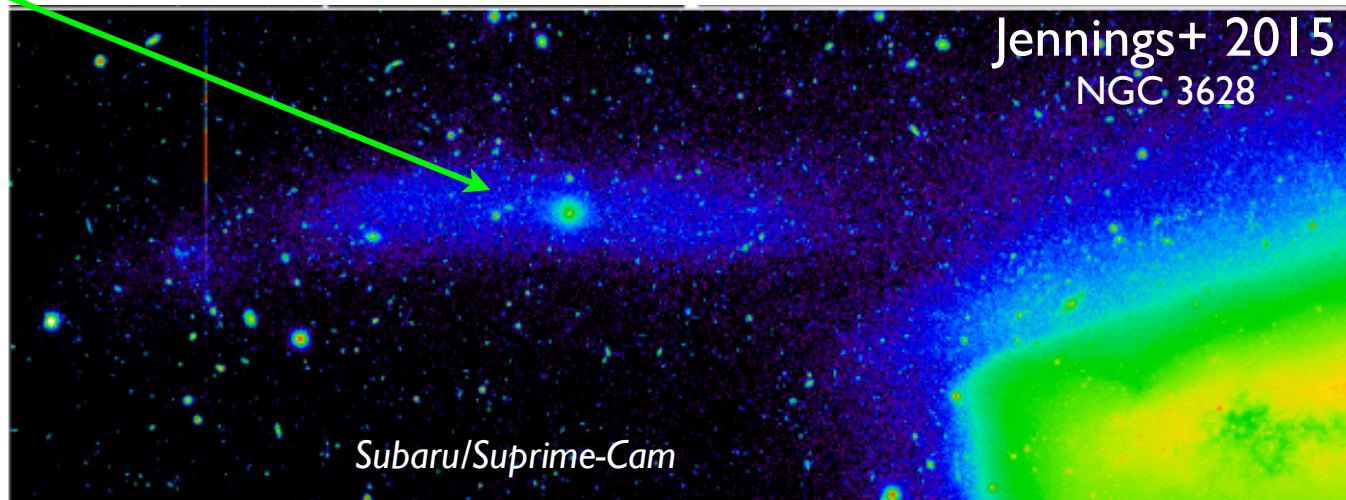


Omega Cen in formation!

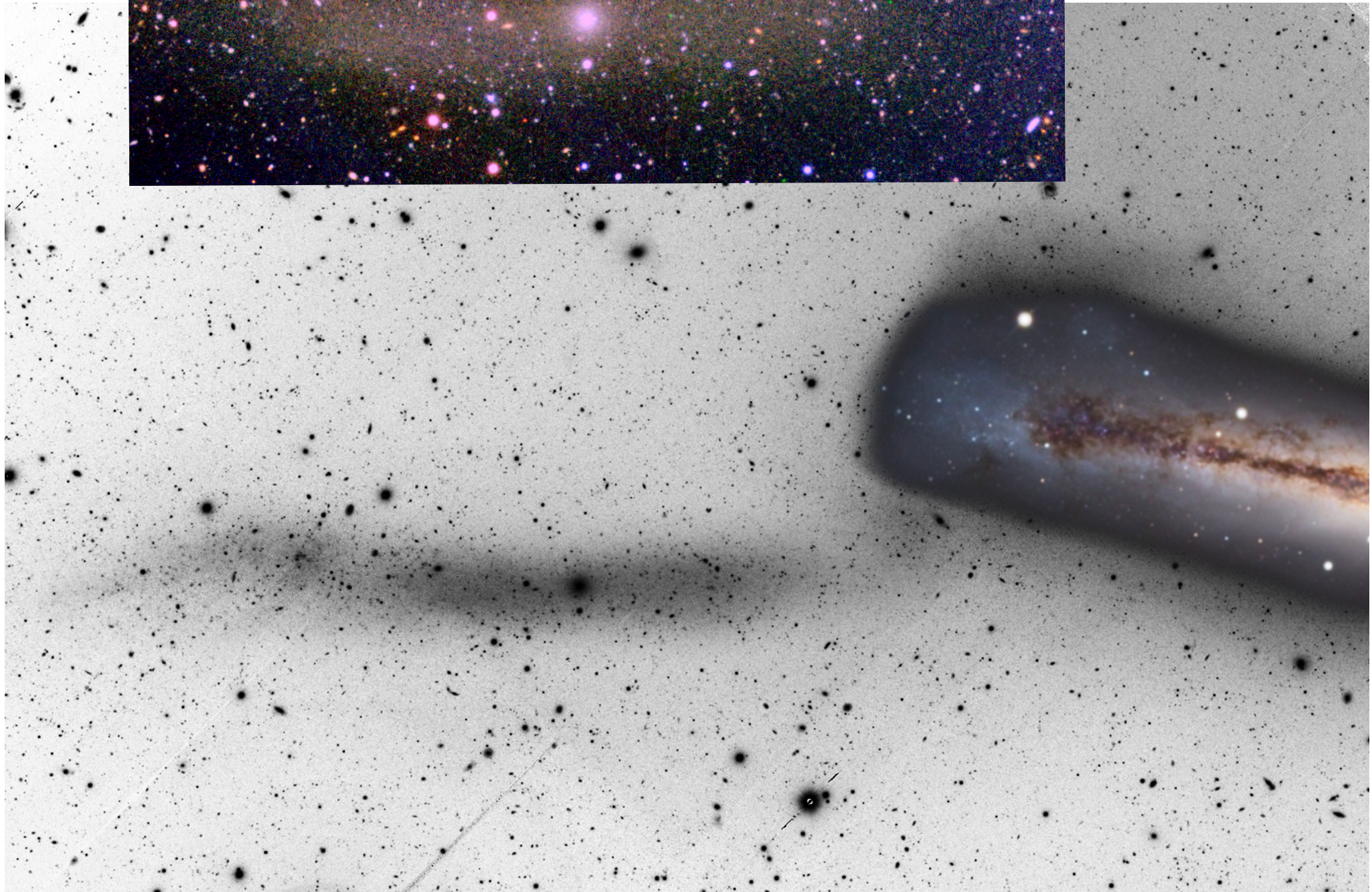
GCs embedded in Sgr stream analogs



Red nugget NGC 4342 is being stripped by NGC 4365: GCs and stream stars share velocity and stellar pop characteristics



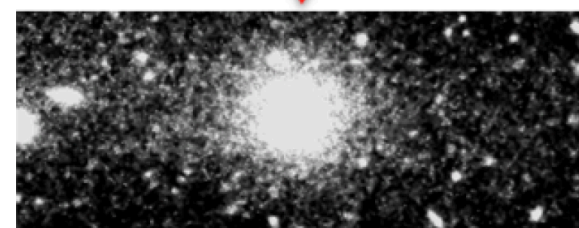
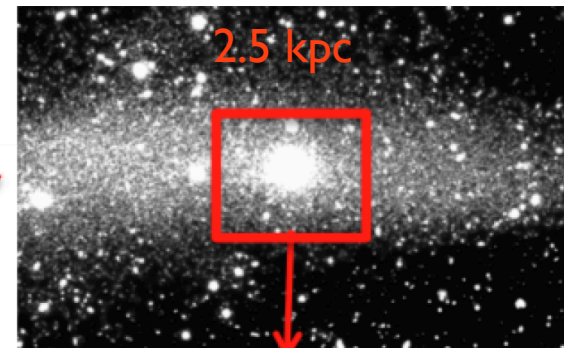
← disturbed spiral



NGC 3628-UCD I

Embedded in tidal stream

Jennings + 2015



UCDI:

$g-i \sim 0.86$

$L_i \sim 10^6 L_\odot$

$R_h = 10 \text{ pc}, \sigma \approx 23 \text{ km/s}$

$[Z/H] = -0.95$

age $\sim 8 \text{ Gyr}$

PROGENITOR:

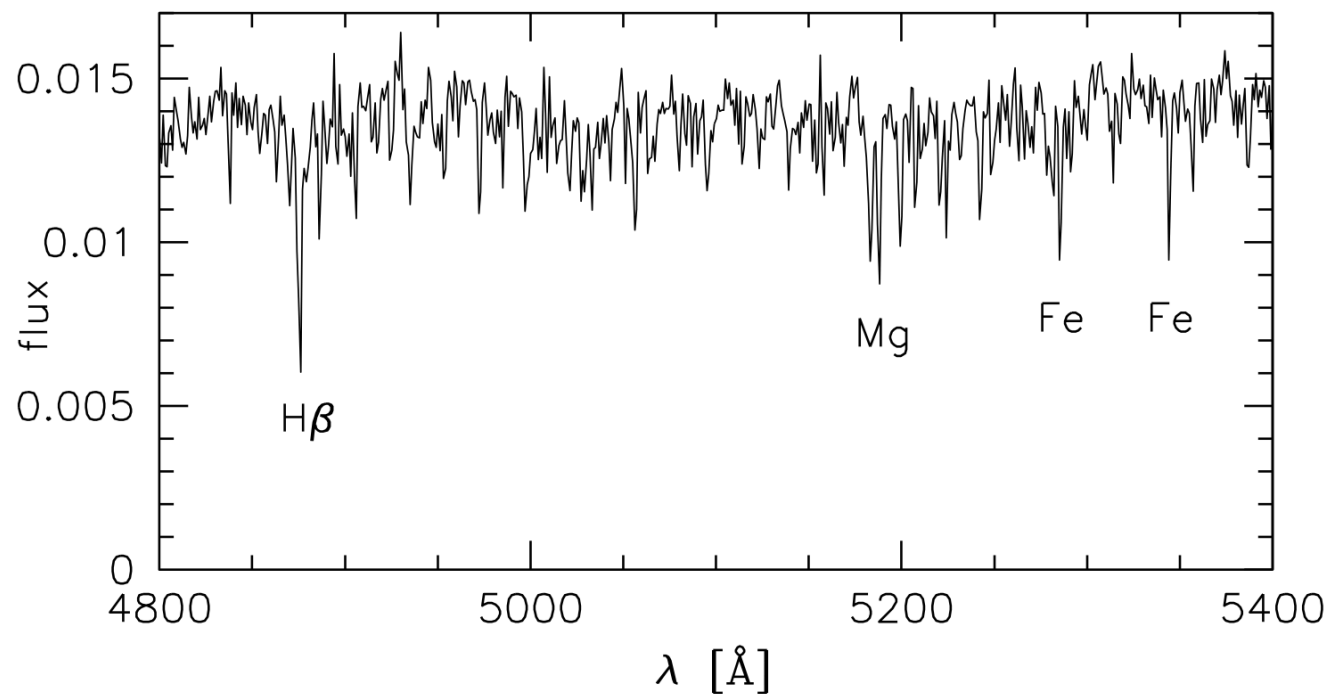
$g-i = 1.01$

$L \gtrsim 10^9 L_\odot$

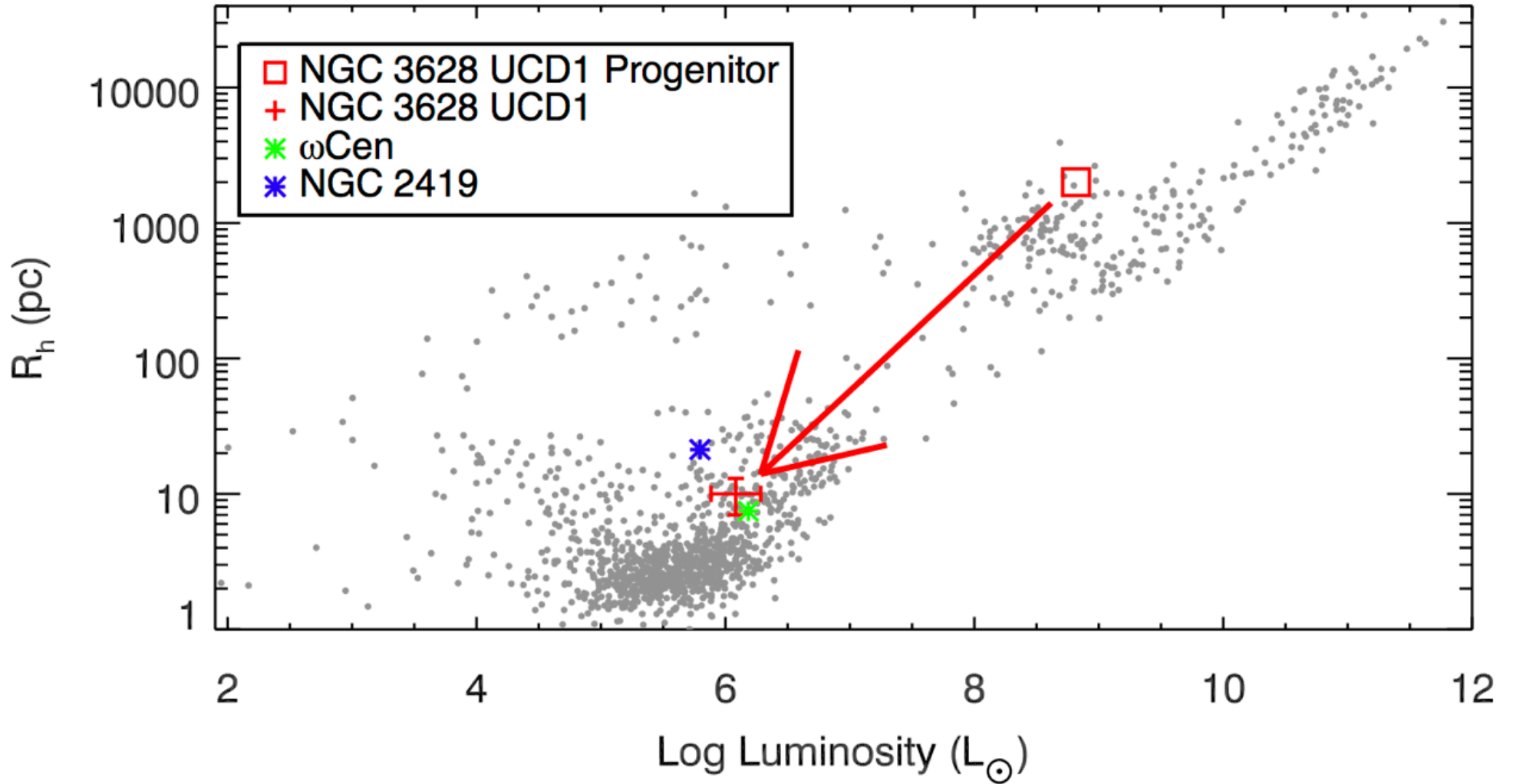
STRIPPING PROCESS

$\rightarrow \times 100 \text{ size}, \times 1000 L$

NGC3628-UCD1, ESI spectrum



Stripping Trajectory



Estimate size of progenitor from width of stream

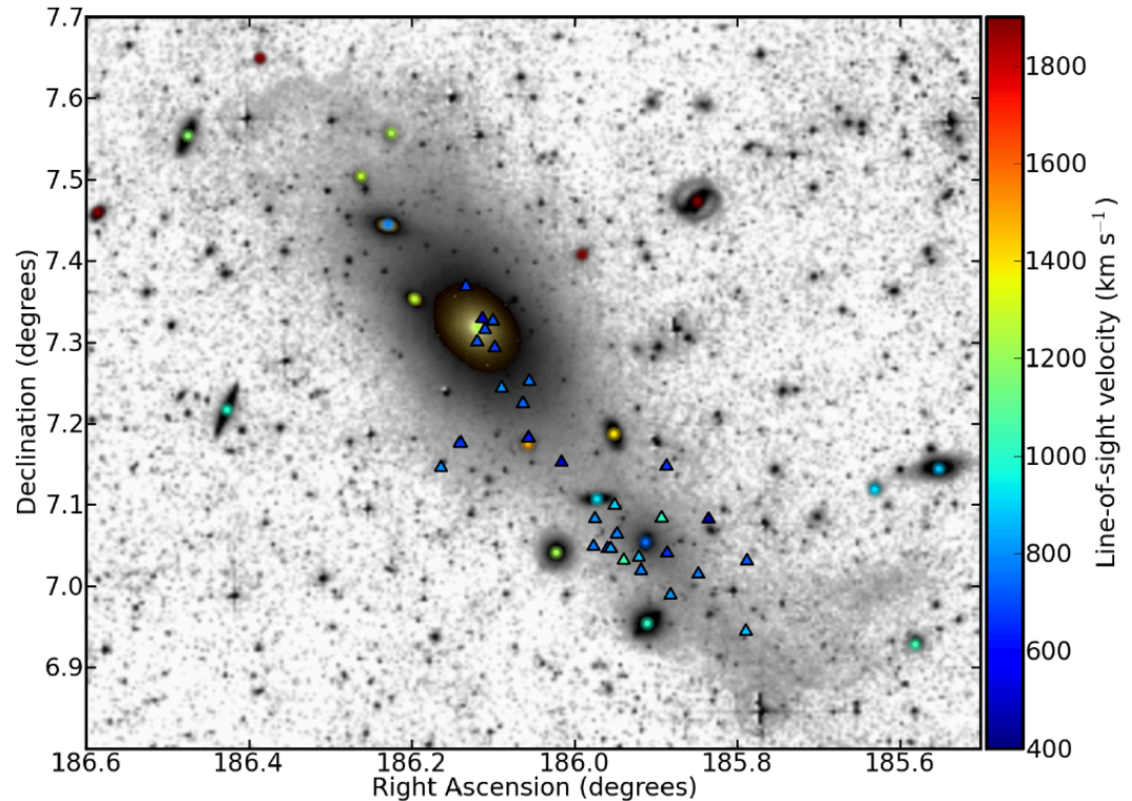
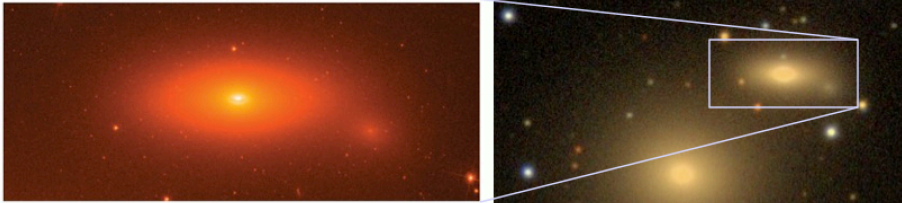
Lower limit on progenitor mass by measuring the luminosity in the stream

$L > 10^9 L_{\odot}$

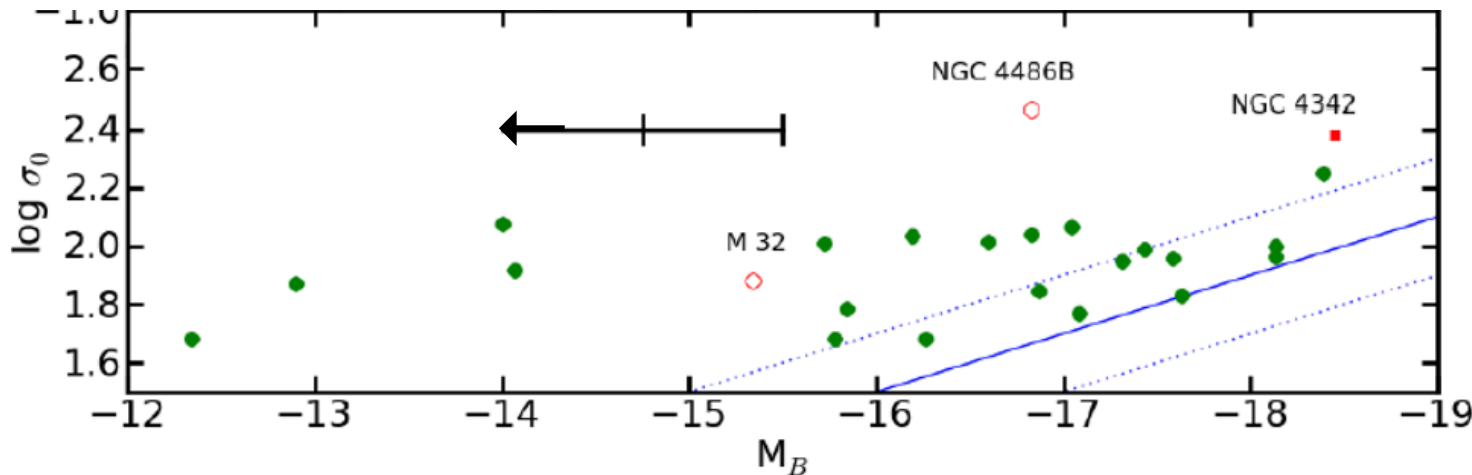
Local “Red Nuggets” may be stripped galaxy remnants

An over-massive black hole in the compact lenticular galaxy NGC 1277

Remco C. E. van den Bosch^{1,2}, Karl Gebhardt², Kayhan Gültekin³, Glenn van de Ven¹, Arjen van der We



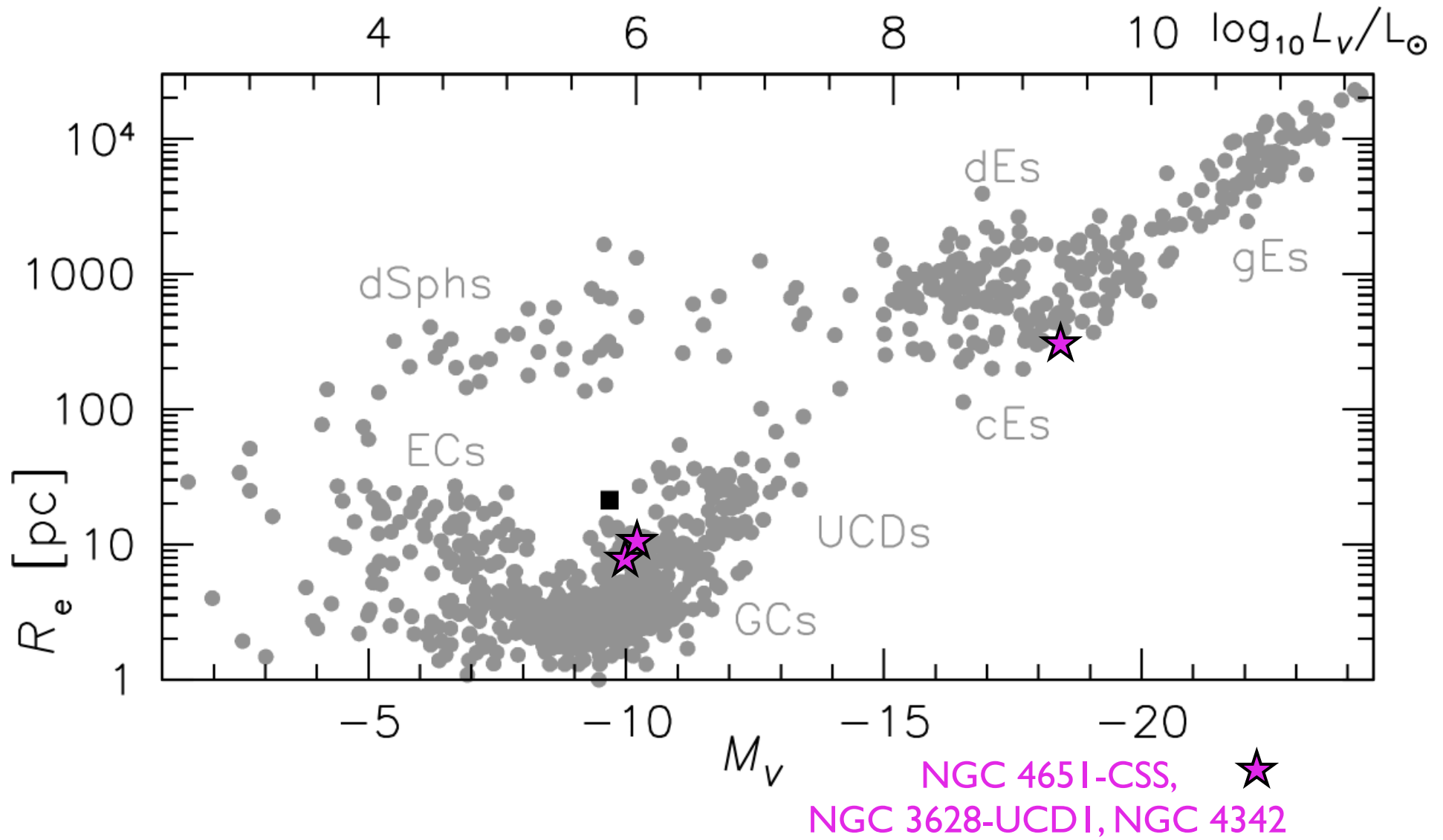
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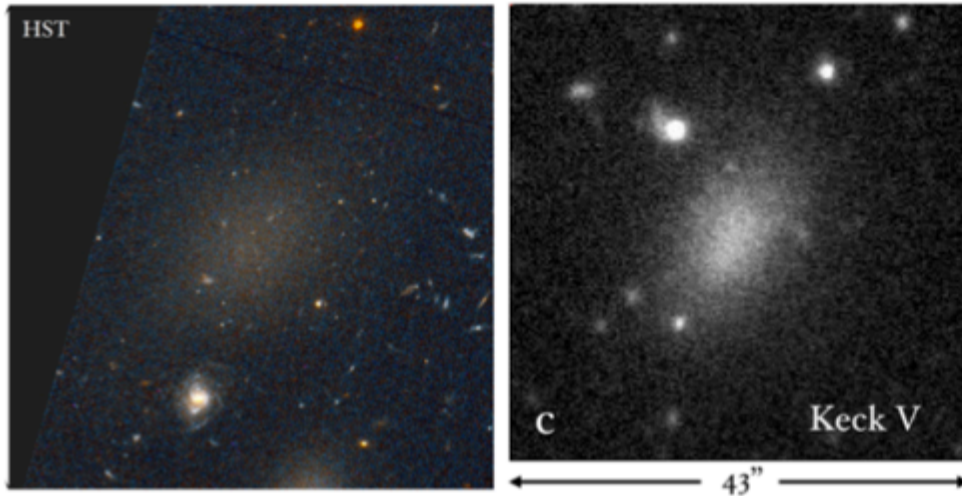
Blom+ 2014

- cEs
- E/S0s

The Everything Plot + stream nuclei

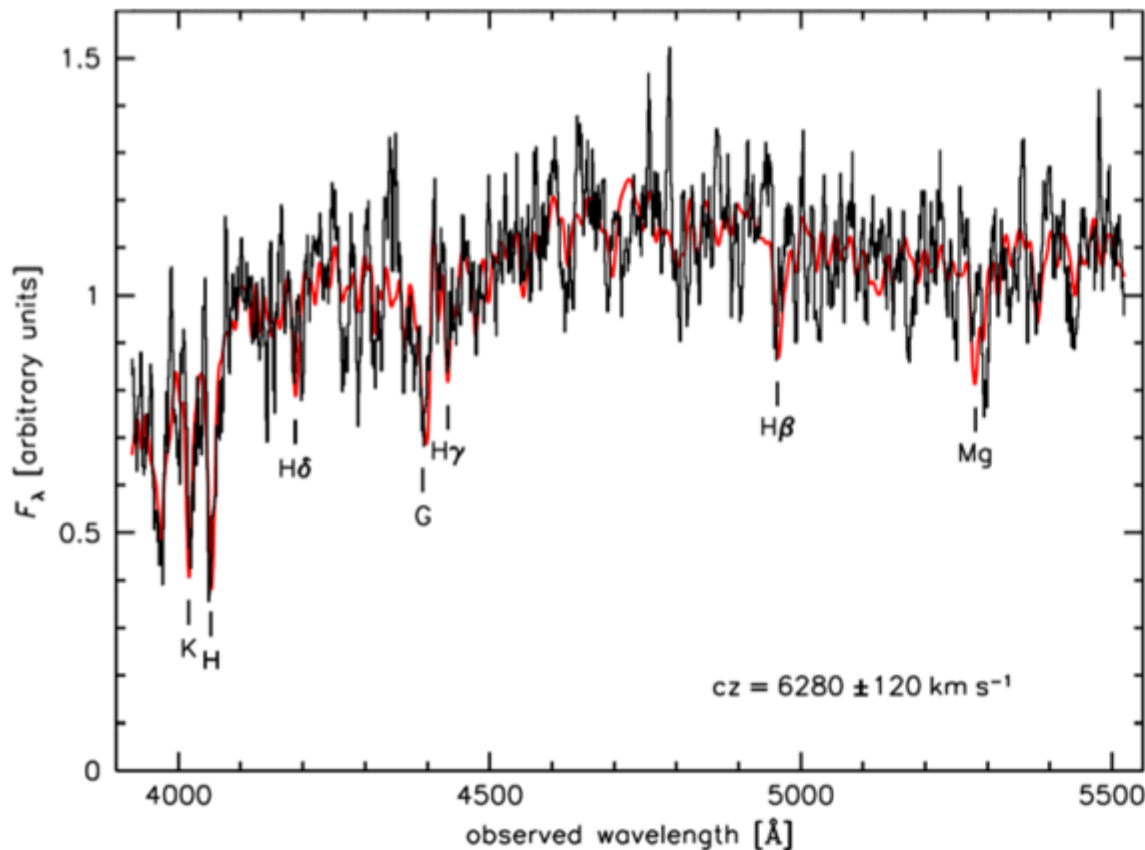


Ultra-diffuse dwarf galaxy in Coma cluster



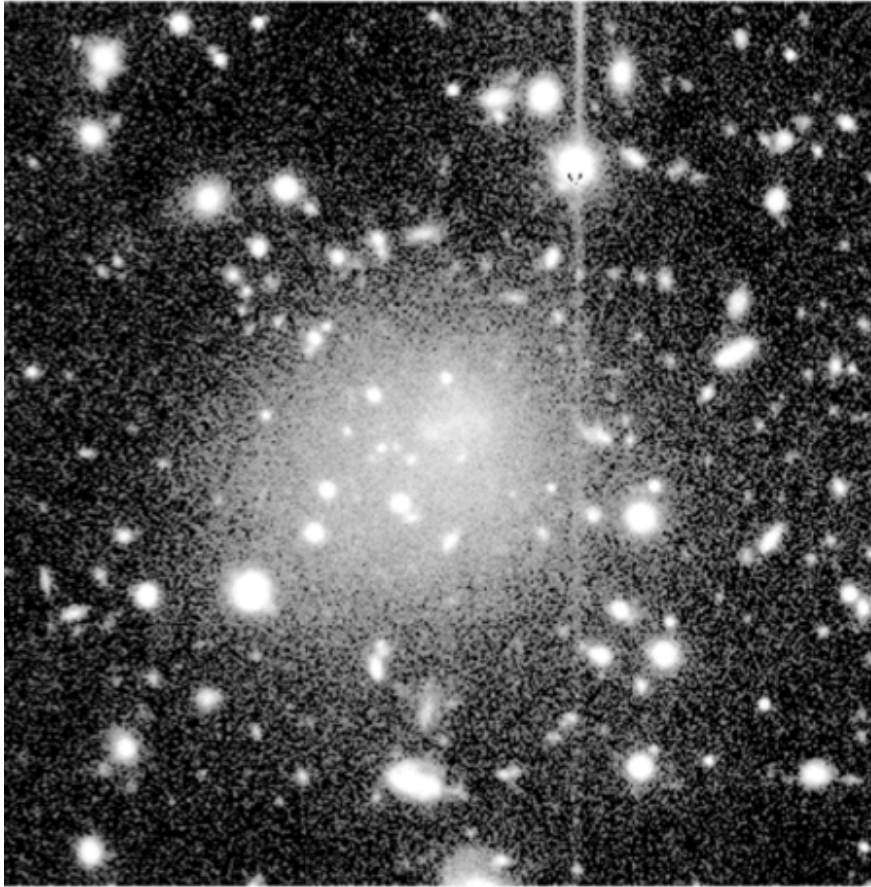
DF44: $M_V \sim -16$, $R_e \sim 4$ kpc
Keck/LRIS, 1.5 hr exptime

quiescent stellar population
 $cz = 6280 \pm 120$ km s $^{-1}$:
Coma cluster association!
no tidal disturbances seen



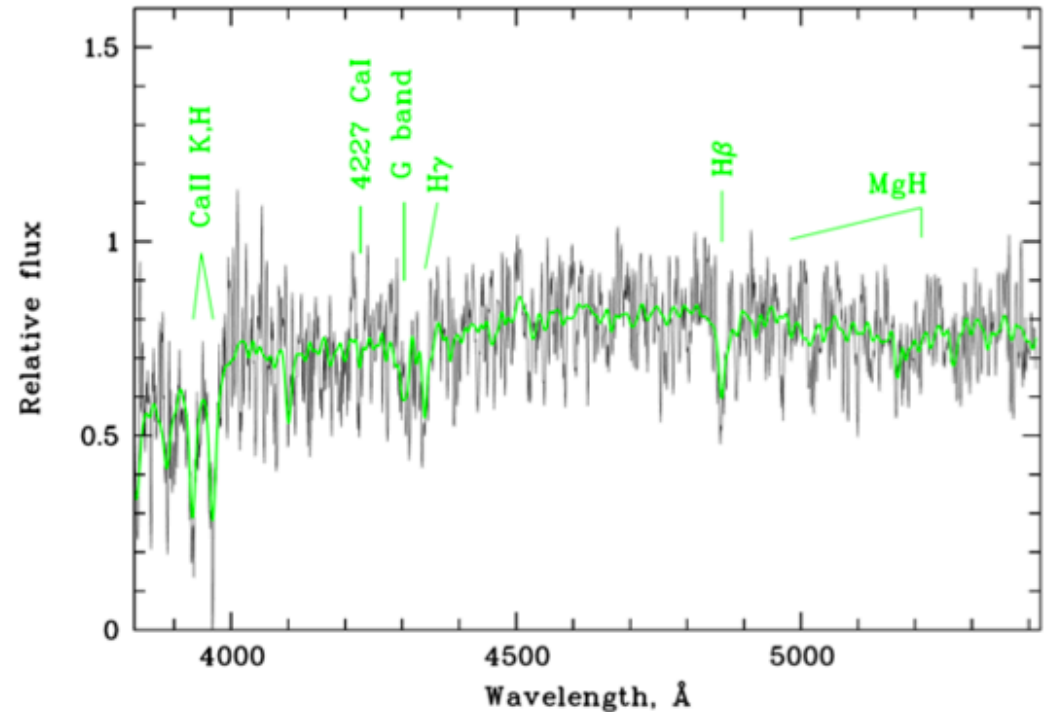
van Dokkum,
Romaowsky, Abraham,
Brodie et al 2015 ApJL
in press
arXiv: 1405.03320

DGSAT I: another UDG in Pisces-Perseus



SAO/SCORPIO, 7 hr exptime

Martinez-Delgado+2015



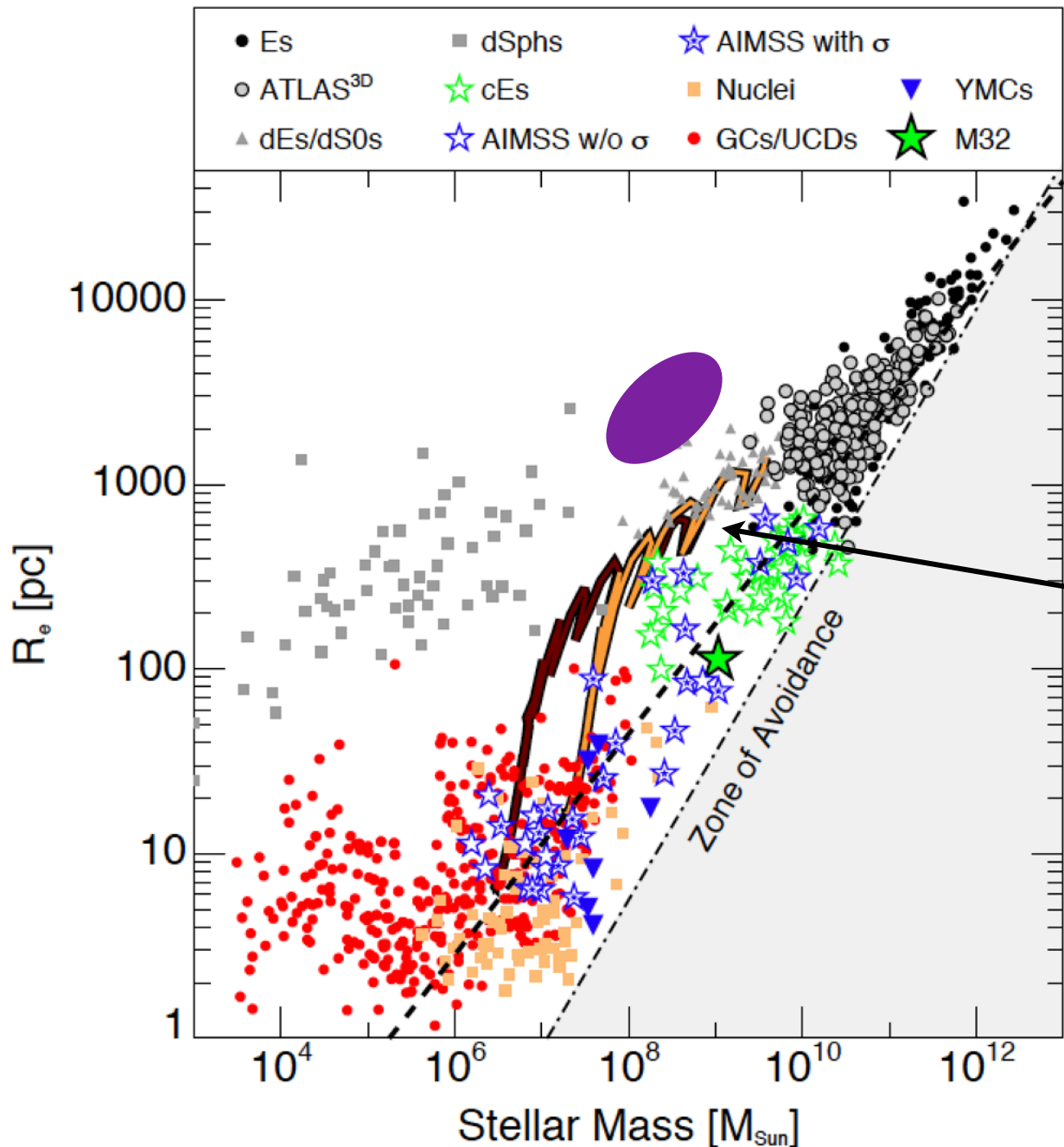
quiescent stellar population

$$\underline{cz} = 5453 \pm 111 \text{ km s}^{-1},$$

$$\underline{\sigma} = 130 \pm 55 \text{ km s}^{-1} (!!!)$$

may imply halo mass of $> \sim 10^{12} M_{\odot}$
for stellar mass of $\sim 5 \times 10^7 M_{\odot}$!!

How do the fluffiest galaxies form?



AIMSS CSS Survey - HST
archive + Keck, SOAR, SALT
Archive of Intermediate Mass Stellar
Systems
Norris + 2014

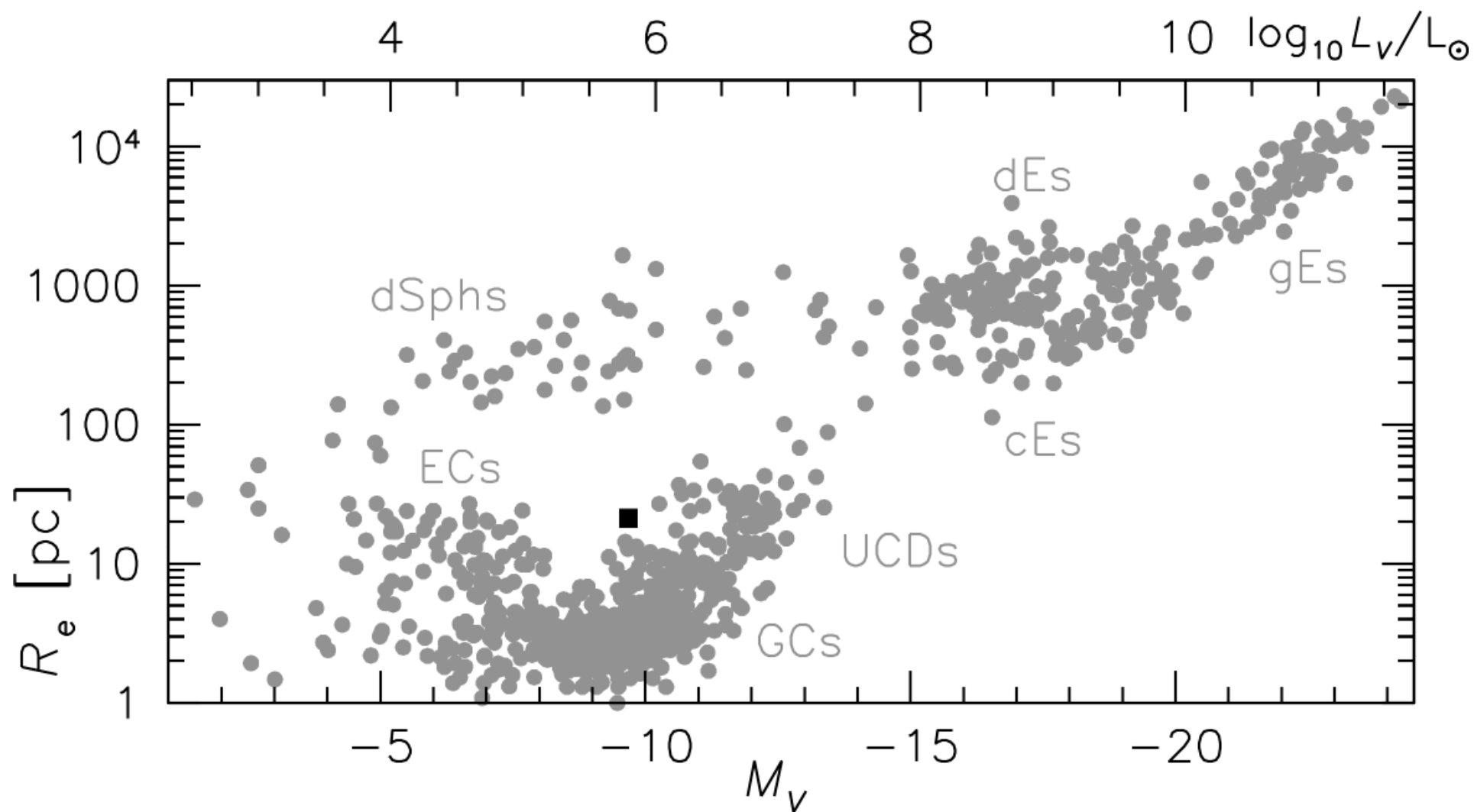
Space between clusters
and galaxies entirely filled
with CSSs

Stripping trajectories for
nucleated dwarfs
Pfeffer & Baumgardt 2013

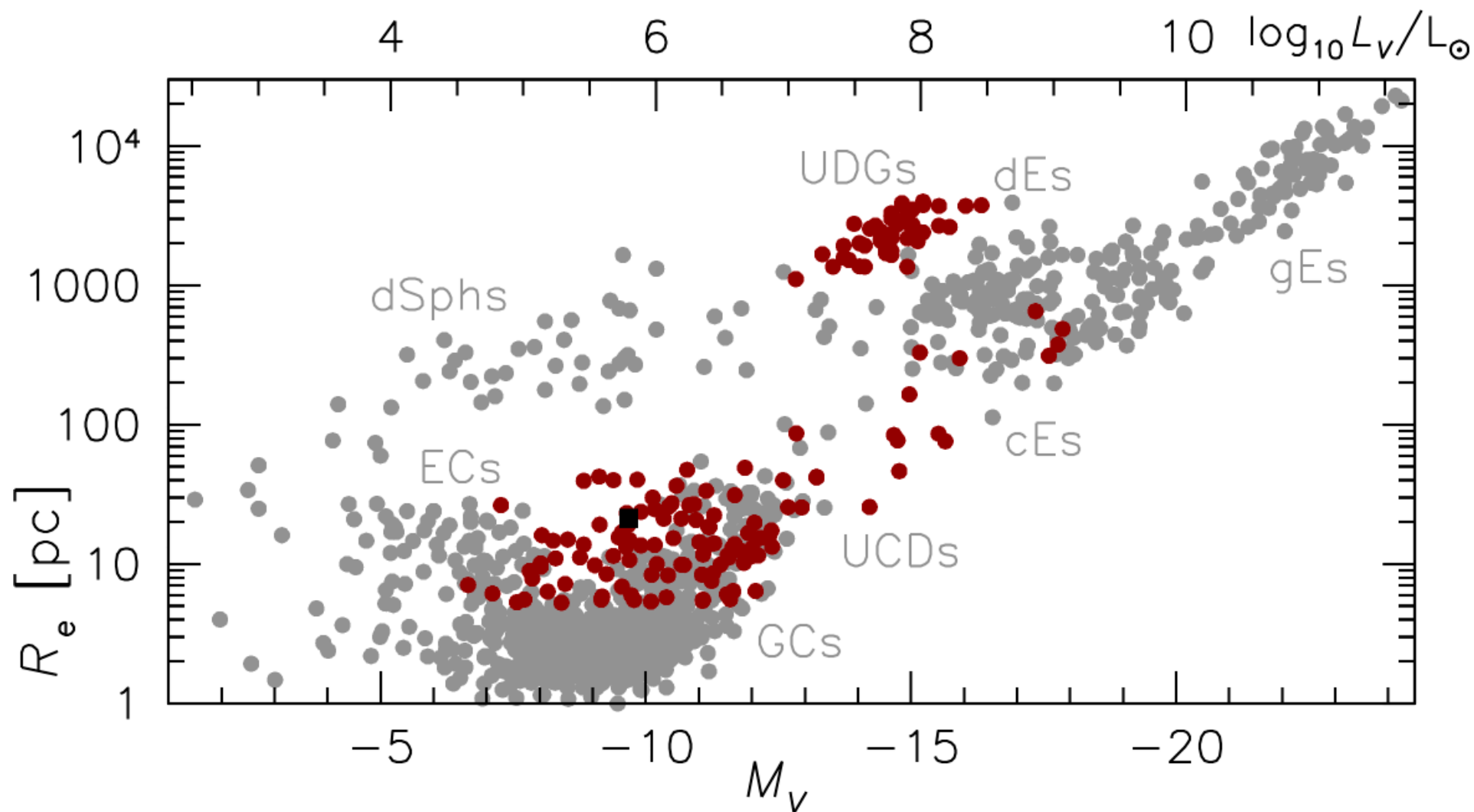
UDGs

- > 100 larger than UCDs
- > 100 fainter than normal elliptical galaxies (at their size)

The Everything Plot circa 2011



The Everything Plot circa 2015



Summary

SLUGGS Chemodynamical survey of 25
(+3) nearby ETGs
Range of M , env , σ , v/σ Globular
clusters to $\sim 10 r_{\text{eff}}$, Starlight to $\sim 3 r_{\text{eff}}$

<http://sluggs.ucolick.org>

The size-L plane is filling up, but no violators
of the “zone of avoidance” → a physical
(density) boundary?

Many UCDs and likely some massive GCs are
stripped galaxy nuclei

Stripped nuclei are easily observable tracers of
minor mergers/accretion

The densest galaxies do not necessarily have
elevated M/L (AO needed to find central BHs)



SAGES in Chile 2011

Open questions:

Are there any “sacred” gaps?

What proportion of UCDs and local “red nuggets” are stripped galaxies?

Affects cosmic accounting and inferences for halo build up

Is there any way to confirm residual dark matter in UCDs?

Is there a genuine distinction between star clusters, UCDs and galaxies? Fe spread? Central BHs?

How did UDGs form?

