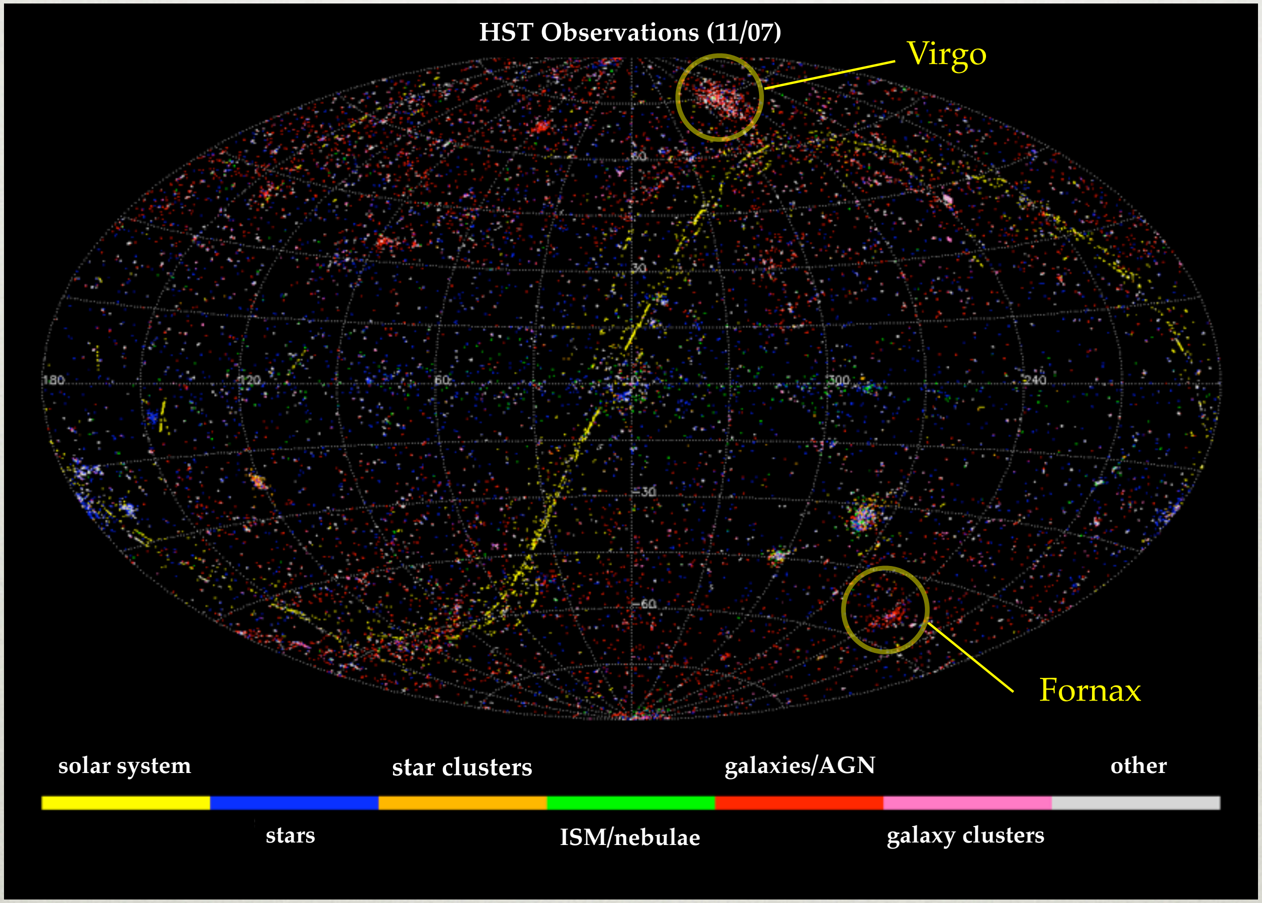
The Properties of Galaxies in the Virgo and Fornax Clusters: What We've Learned

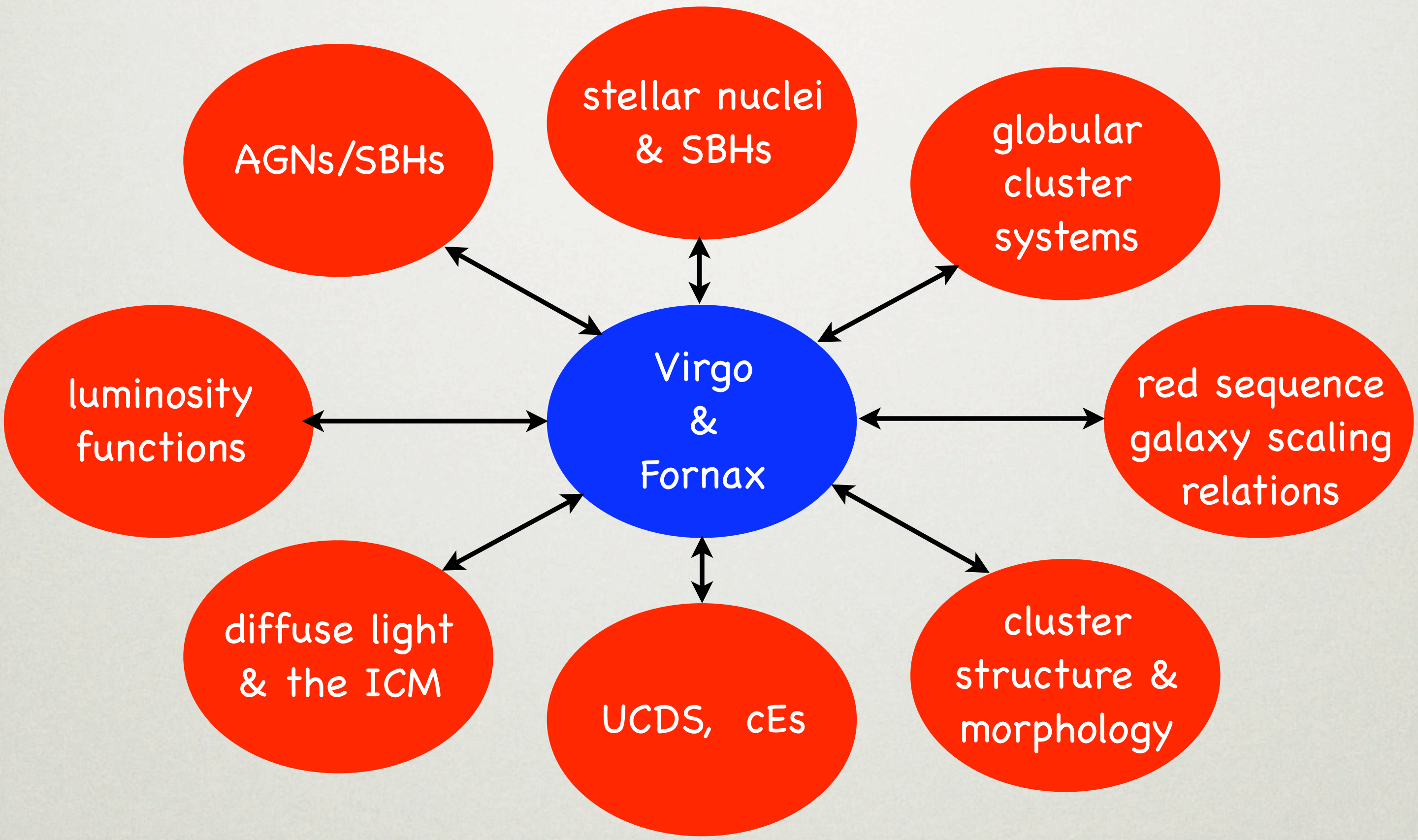
Patrick Côté (HIA)



30 March - 3 April, 2009, "Galaxy Evolution and Environment", Kuala Lumpur, Malaysia

Talk Outline

- The Virgo and Fornax Clusters in Context
- Properties at a Glance



- A Look Ahead: The Next Generation Virgo Cluster Survey
- Summary and Conclusions

Virgo and Fornax at a Glance

	Virgo	Fornax
Richness Class	1	0
Ω	≈ 100 deg^2	≈ 10 deg^2
Distance	16.5 ± 0.1 ± 1.1 Mpc	20.0 ± 0.3 ± 1.4 Mpc
$\sigma(v_r)$	≈ 750 km/s (A), 400 km/s (B)	374 ± 26 km/s
R_{200}	1.55 ± 0.06 Mpc (5.4 ± 0.2 deg)	≈ 0.67 Mpc (1.9 deg):
R_s	0.56 ± 0.18 Mpc (1.9 ± 0.6 deg)	≈ 50 kpc (0.14 deg):
c	2.8 ± 0.7	13.4:
M_{200}	$(4.2 \pm 0.5)\times10^{14}\ M_\odot$	~ $1.3\times10^{13}\ M_\odot$
M_{gas}/M_{tot}	8–14% (A), ≈ 0.5% (B)	~ 8%
M_{gal}/M_{tot}	3–4% (A), ≈ 4% (B)	~ 6%
$\langle kT \rangle_x$	2.58 ± 0.03 keV	1.20 ± 0.04 keV
$\langle Fe \rangle_x$	0.34 ± 0.02 solar	0.23 ± 0.03 solar

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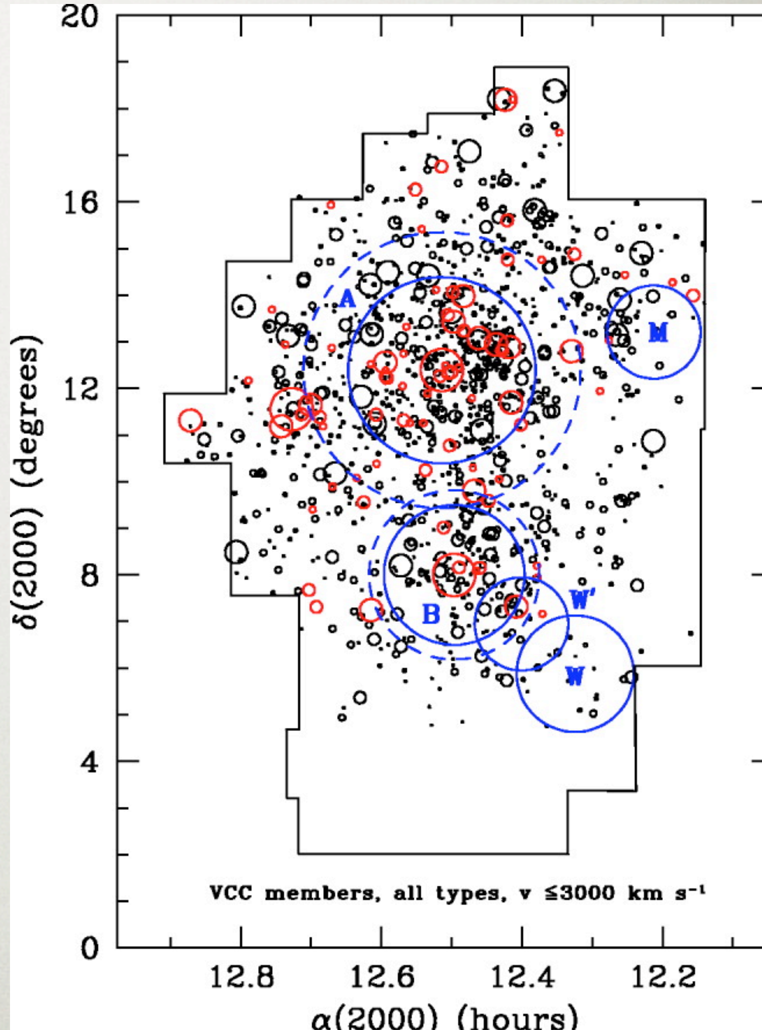
Cluster Morphology: Virgo

- Smith and Shapley (1930s), Reaves (1950s-1980s), de Vaucouleurs et al. (1950s-1970s), Huchra et al. (1980s), and esp. Binggeli, Sandage and Tammann (1980s - Virgo Cluster Catalog = VCC).
- A large, irregular cluster ($\Omega_{VCC} \approx 100$ deg^2), with at least two major substructures centered on M87 ("Virgo A") and M49 ("Virgo B"), plus several other possible smaller groupings around M84/M86, M60 and M100.
- Galaxy centroid falls between M87 and M86, along the so-called "Principal Axis".
- X-ray counts peak up on M87 ⇨ the dynamical center of marginally relaxed cluster.
- d_V = 16.5 Mpc. ⇨ 1" = 80 pc, 0.05" = 4 pc
- The line-of-sight depth of the Virgo Cluster is 2.4±0.4 Mpc.
- The cluster structure is roughly triaxial (1.0:0.7:0.5) .



Mei et al. (2007)

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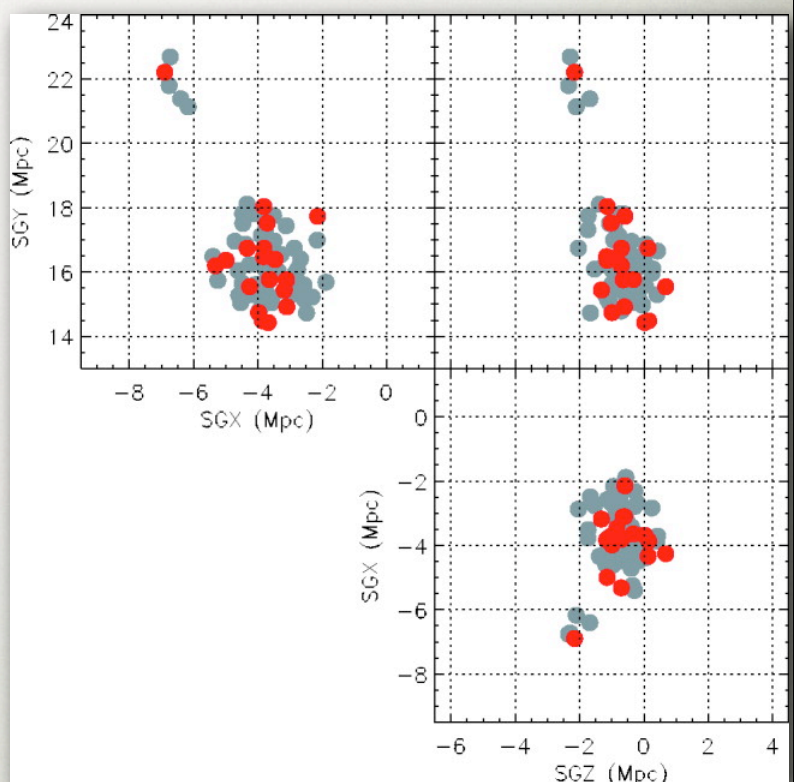


Mei et al. (2007)

Cluster Morphology: Fornax

- Smaller and denser than the Virgo cluster. Definitive optical survey still that of Ferguson (1989).

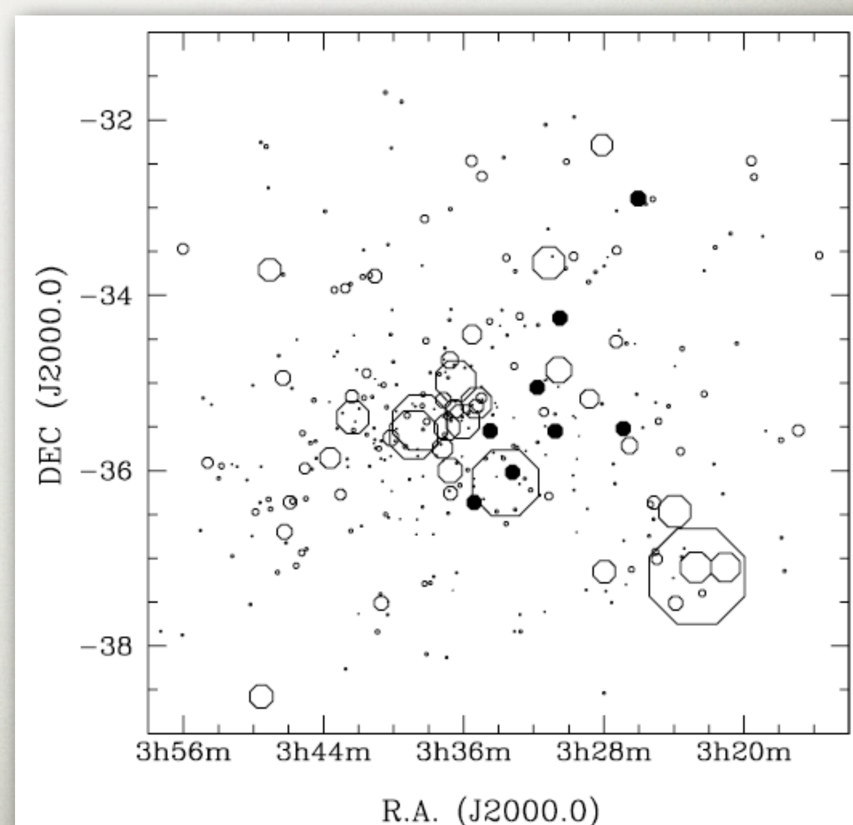
- Main cluster centered on NGC1399, with a secondary group of mainly late-type galaxies associated with NGC1316.

- A precise relative distance with respect to Virgo of $d_F/d_V = 1.214 \pm 0.017$.

  $d_F = 20.0$ Mpc. ⇨ 1″ = 100 pc, 0.05″ = 5 pc

- Cluster depth smaller than the observed "cosmic scatter" in SBF technique: $\sigma_{cos} = 0.06 \pm 0.01$ mag.

- No evidence for systematic trends of the galaxy distances with position or velocity (e.g., no current infall) ⇨ Fornax appears compact (Jerjen 2003) and well virialized.



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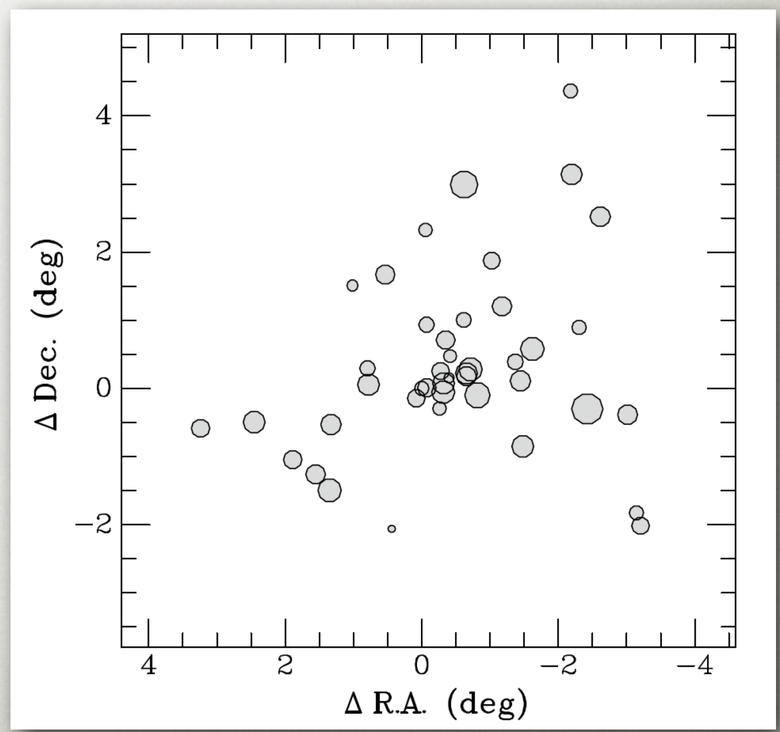


Blakeslee et al. (2009)

Morphological Mix from the VCC and FCC

Cataloged galaxies in the VCC: 2096

- Probable or confirmed members: ≈ 1300
- 850 dwarf ellipticals (65%)
- 130 spirals (10%)
- 90 irregulars (7%)
- 90 dwarfs of intermediate type (Irr-dE) (7%)
- 80 "E" or "S0" galaxies (6%)
- 60 miscellaneous (5%)

FCC: 2678

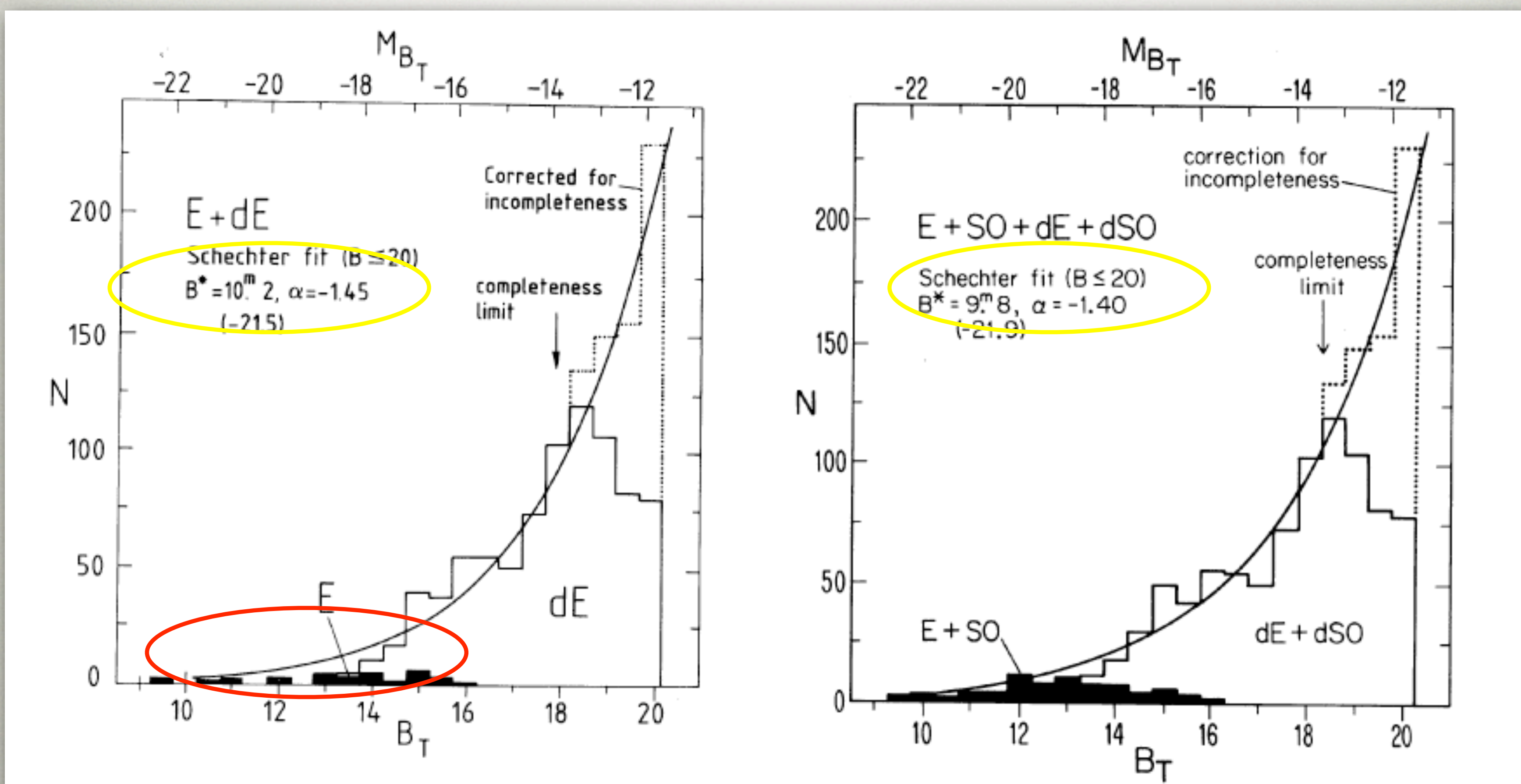
- 235 prob./conf. members
- 170 dwarf ellipticals (72%)
- 17 spirals (7%)
- 13 irregulars (6%)
- 23 "int." dwarfs (10%)
- 23 "E" or "S0" (10%)
- ≈ 15 miscellaneous (6%)

- Low-mass galaxies ("dwarfs") dominate the census in both clusters. Most of these dwarfs are early-type, gas-poor dE/dS0 systems.
- No dramatic differences in the mix of morphological types.

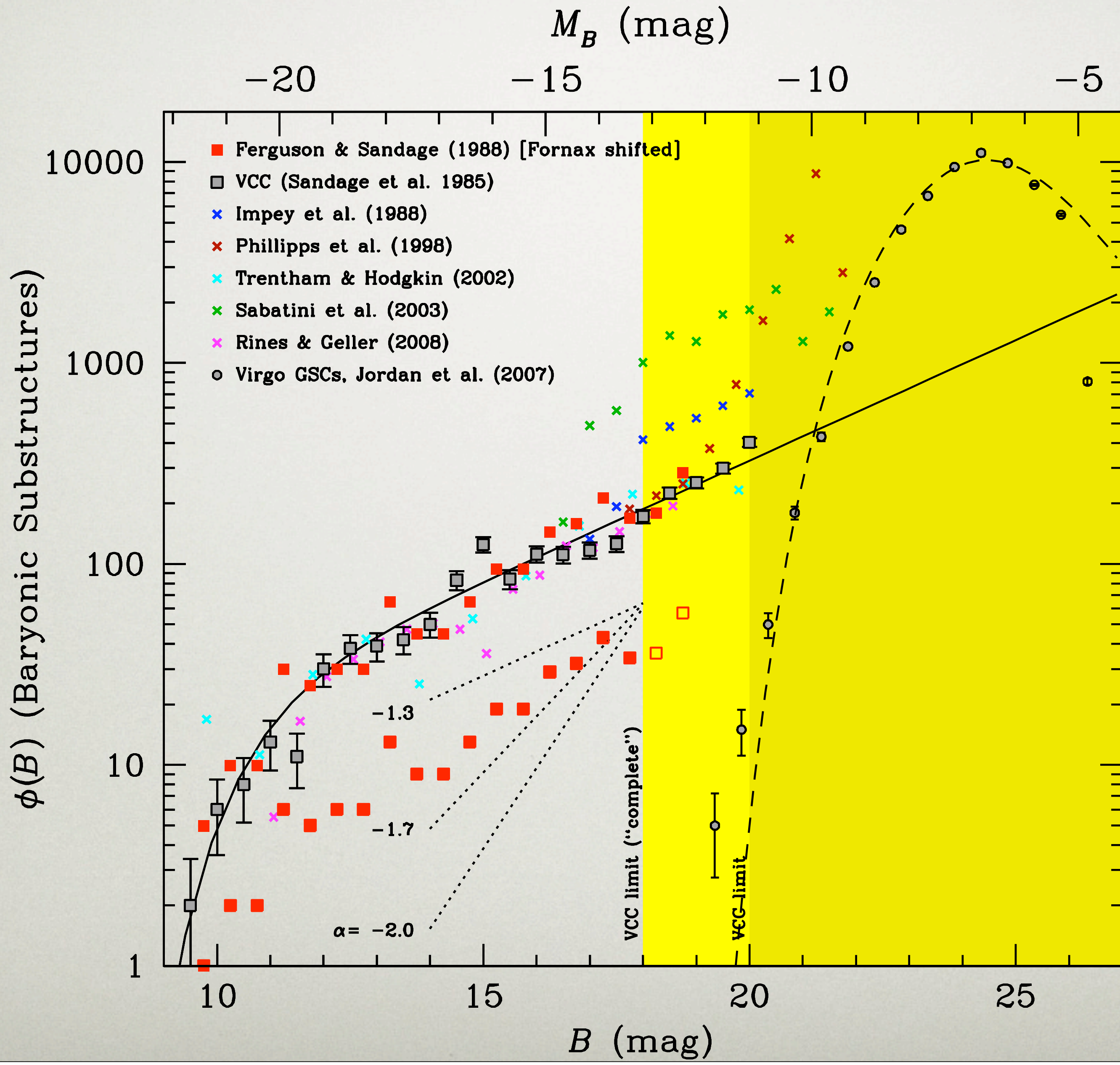
Binggeli et al. (1987), Binggeli & Huchra (2001), Ferguson & Sandage (1988), Ferguson (1989)

The Virgo Luminosity Function

- The Virgo luminosity function studied extensively by Sandage et al. (1985).



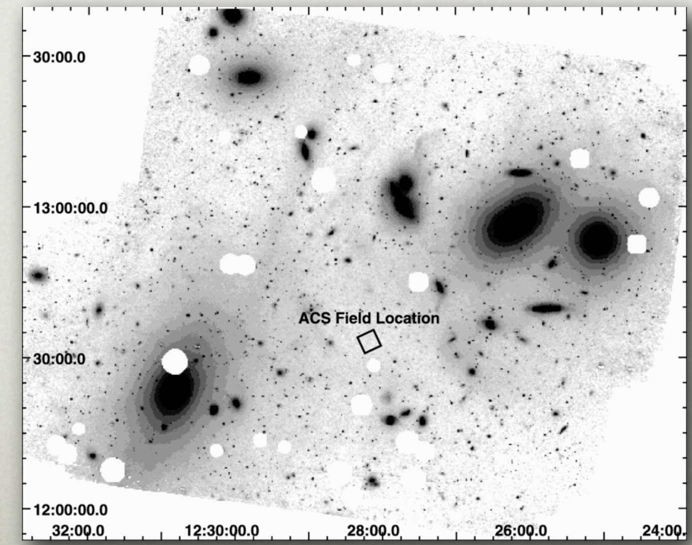
The LF in Virgo and Fornax

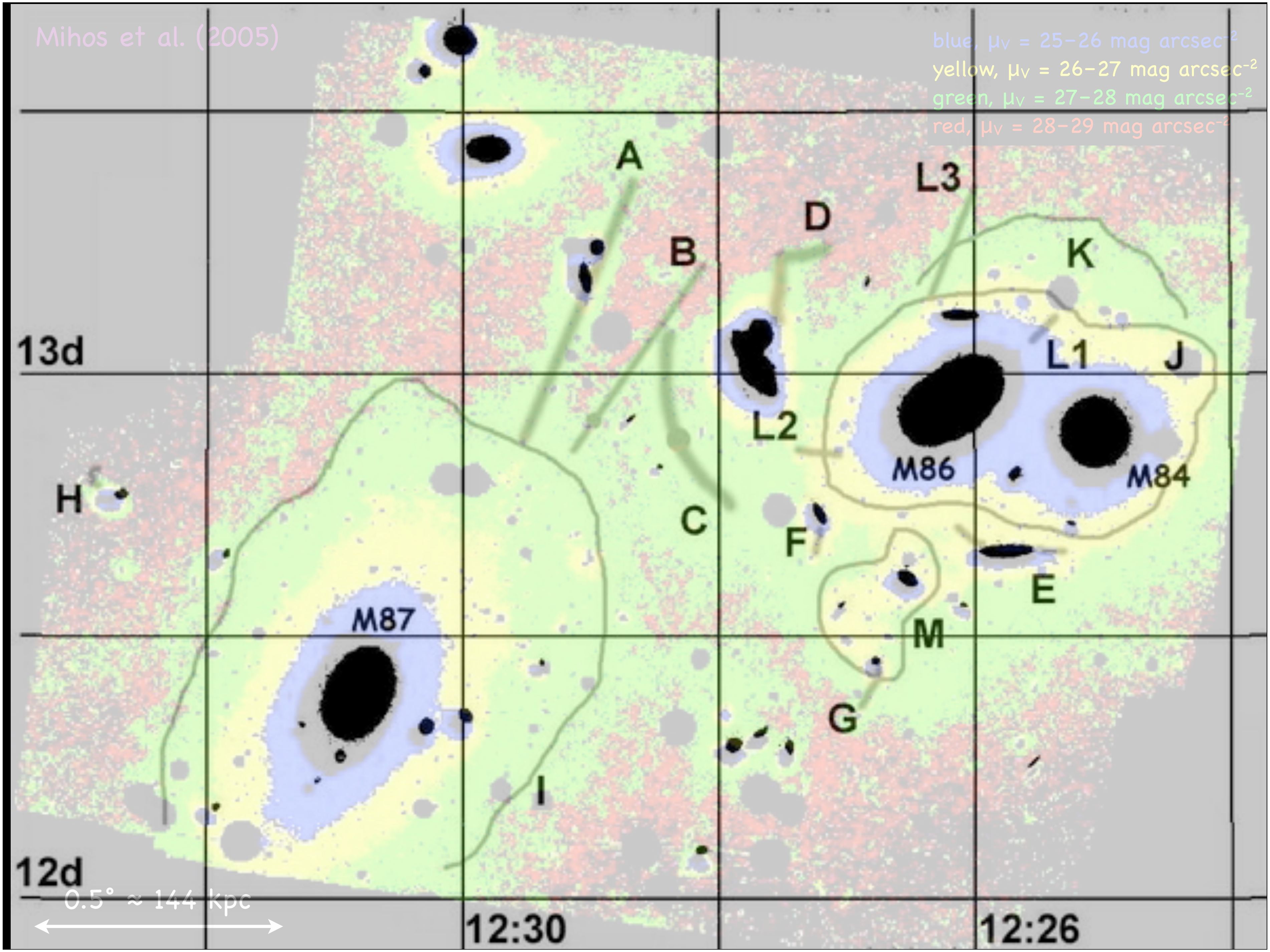


Diffuse Light and the Intracluster Medium

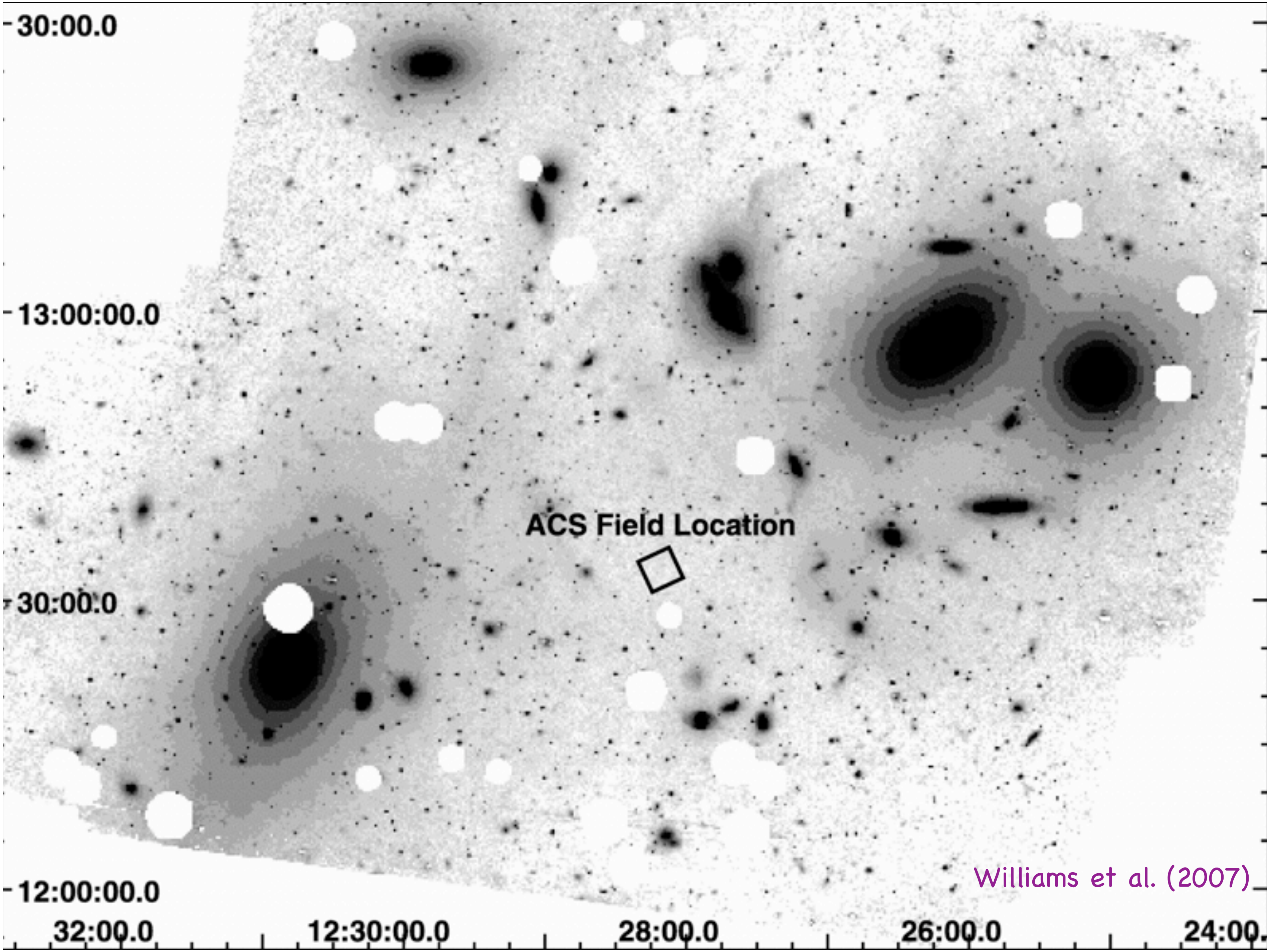
- Direct study of Virgo's diffuse intracluster light (ICL) challenging but feasible using surface photometry (Mihos et al. 2005).
- Observations with the 0.6m Burrell Schmidt telescope ➩ 1.5 mag deeper than previous surveys.

"We see several long (>100 kpc) tidal streamers, as well as a myriad of smaller scale tidal tails and bridges between galaxies. The diffuse halo of M87 is traced out to nearly 200 kpc, appearing very irregular on these scales, while significant diffuse light is also detected around the M84/M86 pair. Several galaxies in the core are embedded in common envelopes, suggesting they are true physical subgroups. The complex substructure of Virgo's diffuse ICL reflects the hierarchical nature of cluster assembly, rather than being the product of smooth accretion around a central galaxy."





Mihos et al. (2005)
blue, μV = 25–26 mag arcsec-2
yellow, μV = 26–27 mag arcsec-2
green, μV = 27–28 mag arcsec-2
red, μV = 28–29 mag arcsec-2
A
B
C
D
E
F
G
H
I
J
K
L1
L2
L3
M
M84
M86
M87
13d
12d
12:30
12:26
0.5° ≈ 144 kpc

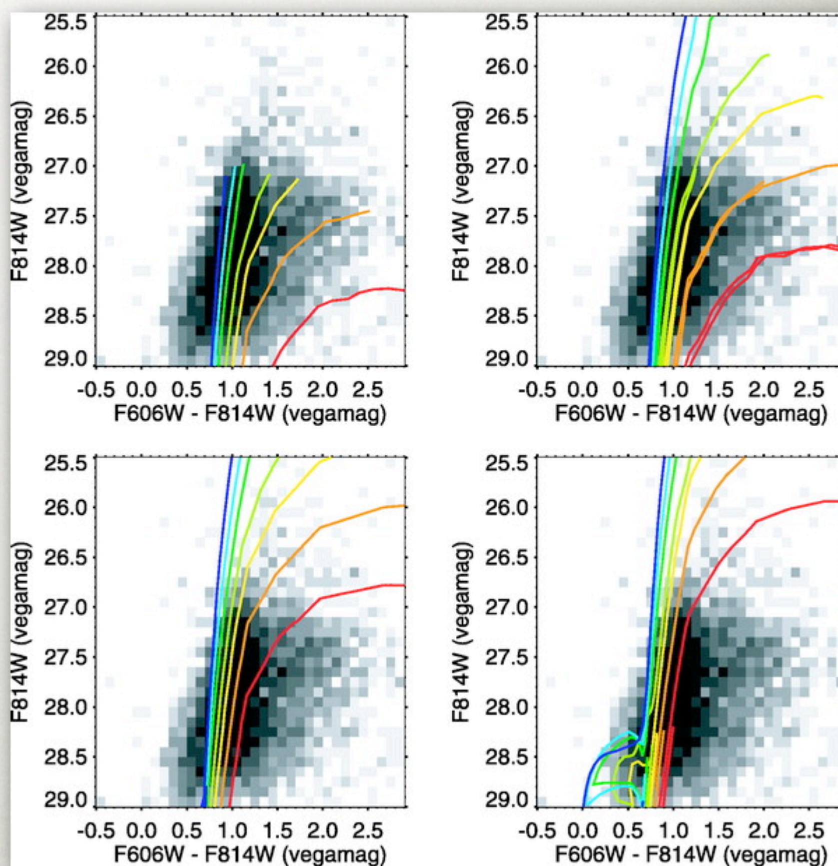


Williams et al. (2007)

Diffuse Light and the Intracluster Medium

- The ICL population contains the full range of metallicities probed: -2.5 ≤ [M/H] ≤ 0.0 (see also Durrell et al. 2002).
- Some evidence that the younger (≲10 Gyr) component of the population is more metal-rich, with [M/H] > -0.5.
- Virgo's ICL population is dominated by old, metal-poor stars. There is, however, some evidence for the existence of a younger, metal-rich component.
- Best-fitting model: 70%−80% of the stars have ages > 10 Gyr, with a mean metallicity of [M/H] ~ -1.0.

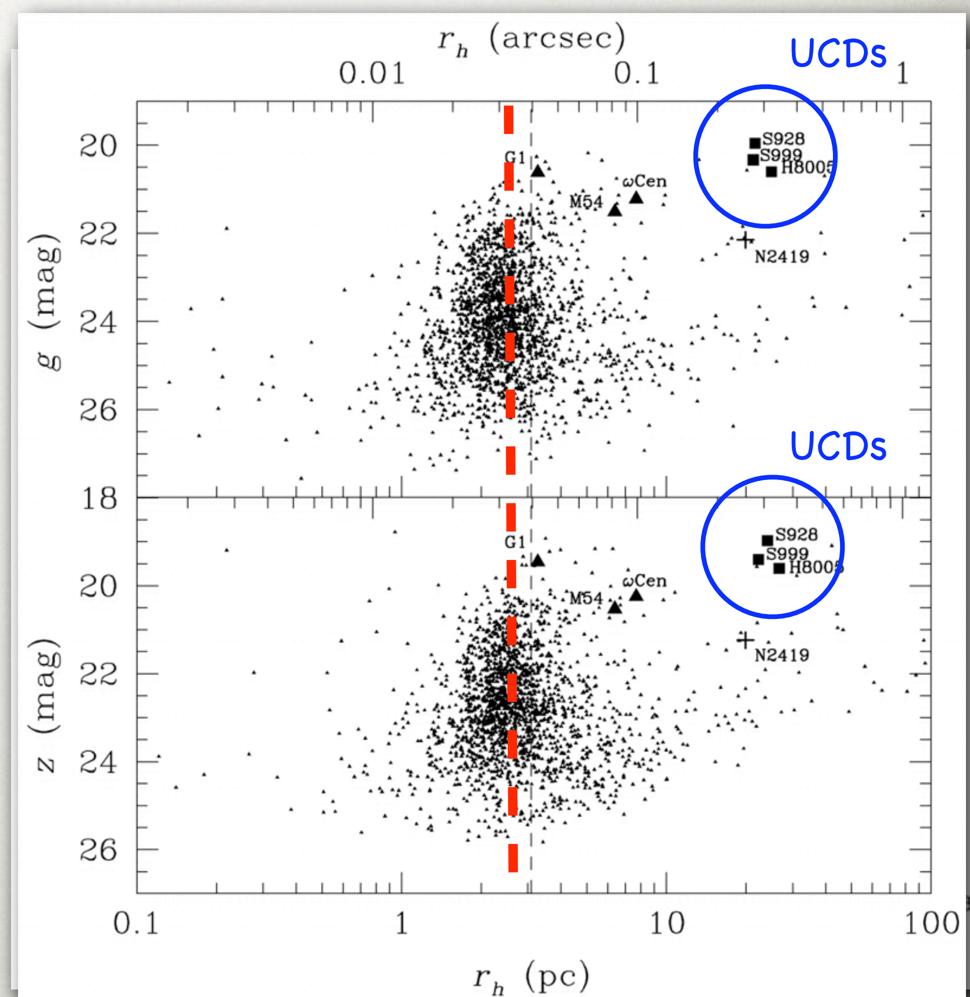
Williams et al. (2007)



Compact Stellar Systems: UCDs, cEs

- Faint, compact stellar systems that appear nearly starlike in ground-based images of Virgo and Fornax.
- Five UCDs identified in the Fornax cluster thanks to the Fornax Cluster Spectroscopic Survey that used the 2dF spectrograph on the AAT (e.g., Drinkwater et al. 2000, 2003; see also Hilker et al. 1999, Phillips et al. 2001, Minniti et al. 1998).
- Approximately nine counterparts in the Virgo cluster identified on the basis of HST imaging in Hasegan et al. (2005).
- Distinct from globular clusters? Related to cEs (compact ellipticals)? Endproducts of harassment/threshing?

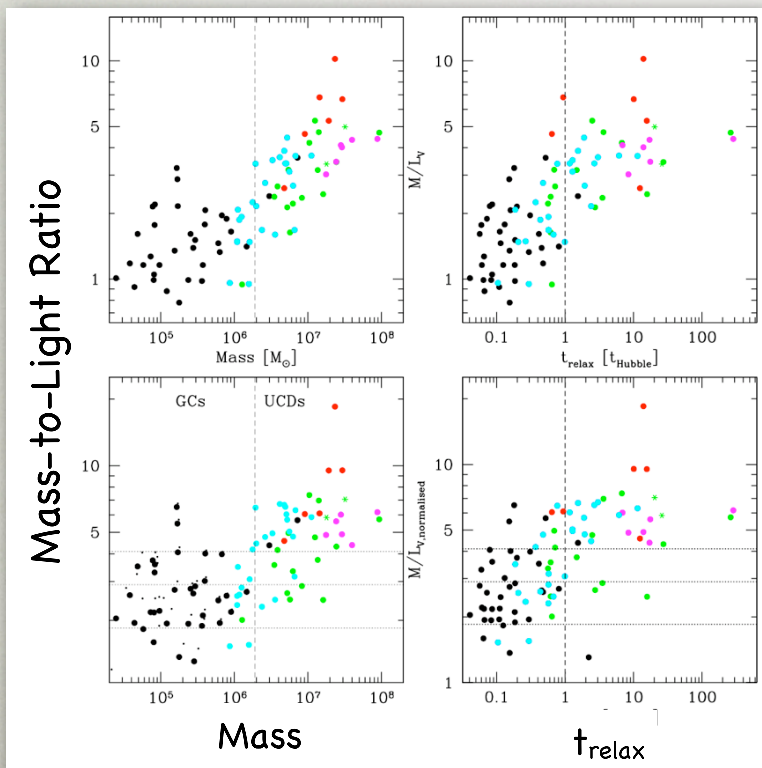
Globular Clusters in Virgo (r_h ~ 2.7 pc)



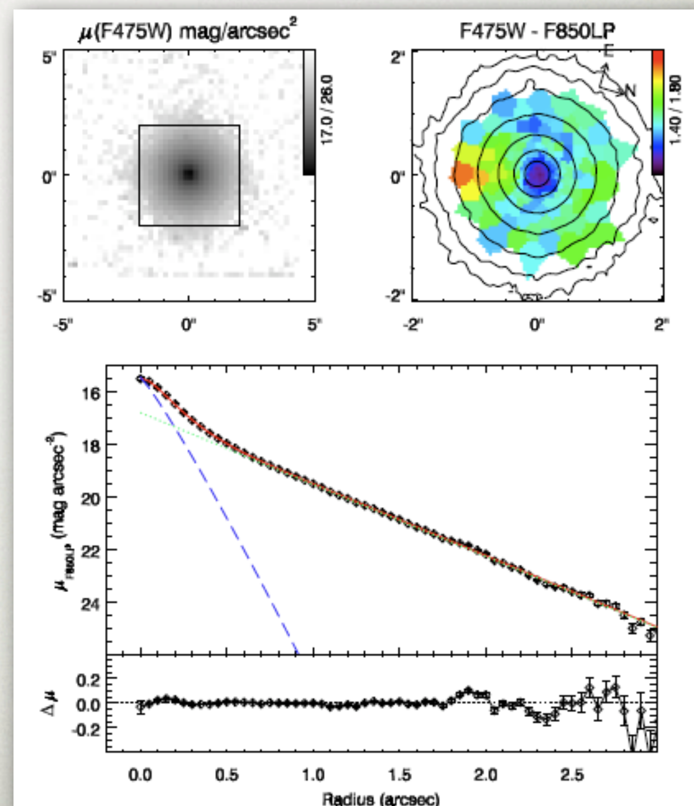
Hasegan et al. (2005)

Compact Stellar Systems: UCDs, cEs

- Some evidence for a two-component structure in a few objects (e.g., Hilker et al. 2007; Chilingarian & Mamon 2008). Stripping of dEs? (e.g., Bekki et al. 2003).
- Some evidence for dark matter in the brightest UCDs, with M/Ls 2-3x higher than population synthesis models predict. But a small effect!
- However, an enhancement in M/L over globular clusters seems clear, at $M \approx (2\text{-}3)\times10^6\ M_\odot$



Mieske et al. (2008)



Chilingarian & Mamon et al. (2008)

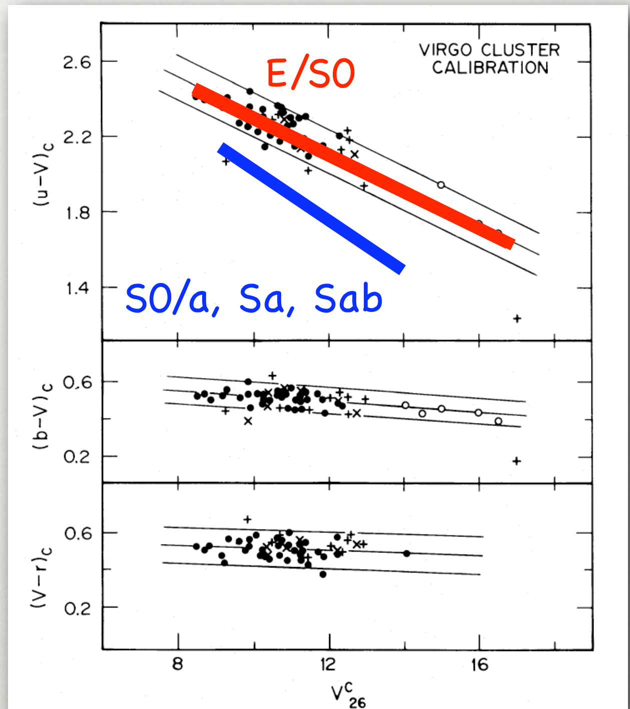
The Red and Blue Sequences in Virgo

- Differences between the colour-magnitude relation for E and S0s compared to spirals first widely recognized and characterized for Virgo cluster galaxies.

- The precursor to the "red sequence" and "blue cloud" formalism used today.

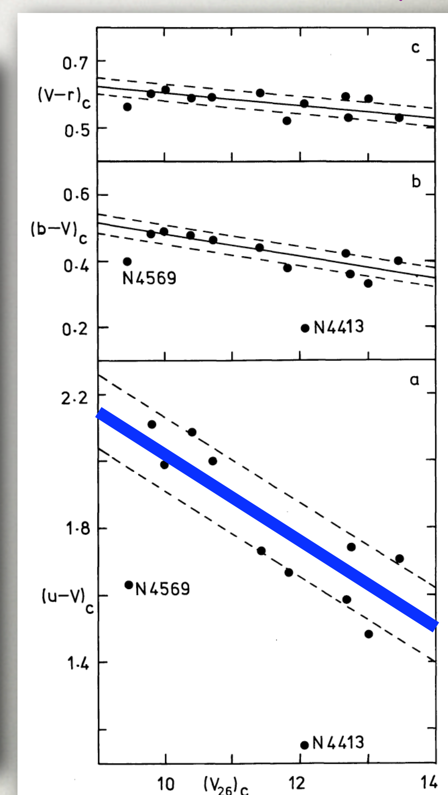
- [Note that E and S0 galaxies were combined into a single class in the earliest studies.]

Visvanathan & Sandage (1977)



Es and S0s

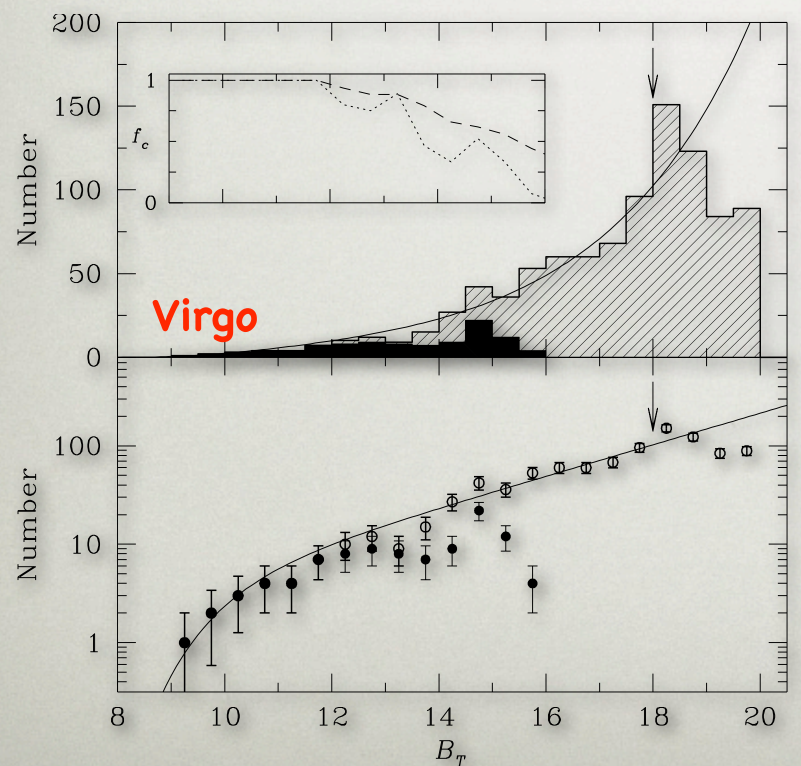
Visvanathan & Griersmith (1977)

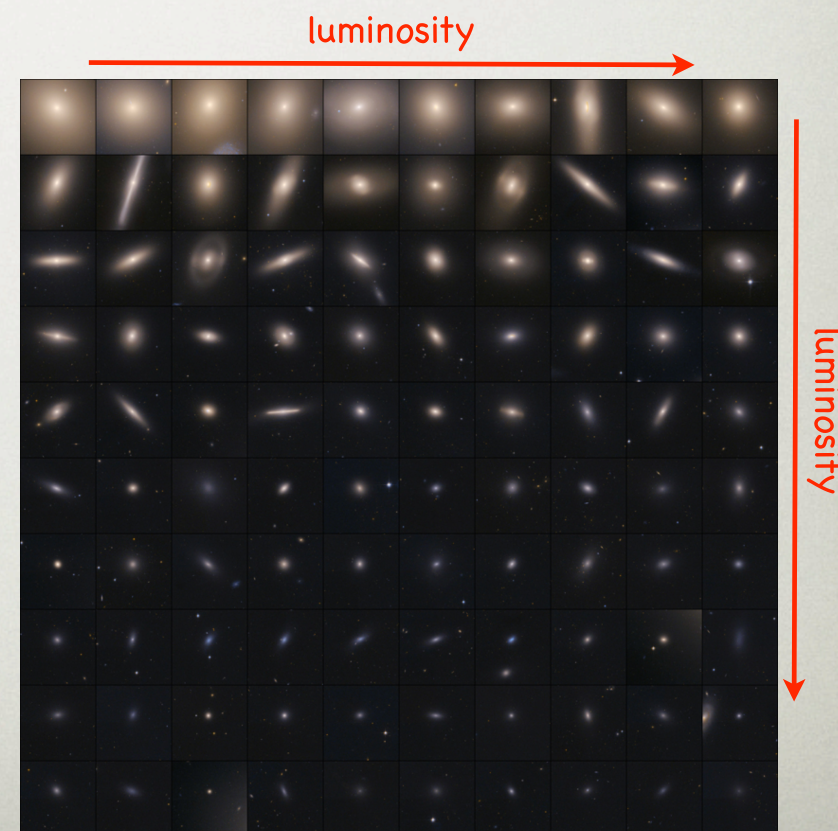


Early-Type Spirals

The ACS Virgo and Fornax Cluster Surveys

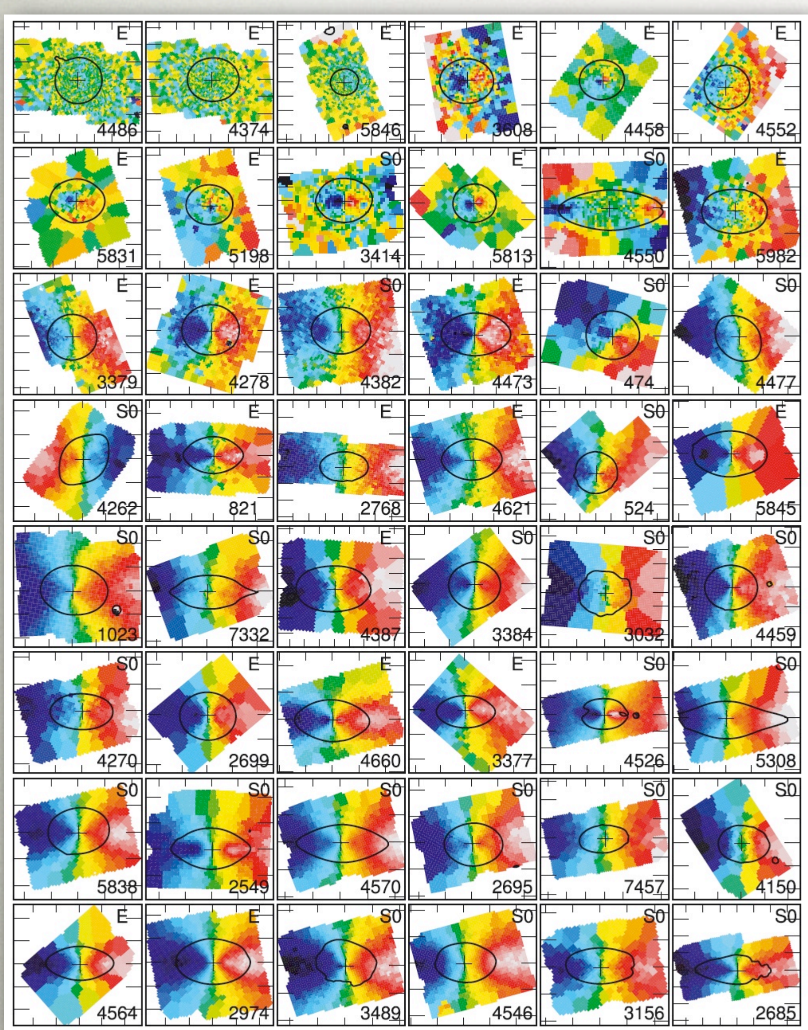
- Imaging survey of 100/43 early-type galaxies in the Virgo/Fornax Clusters with ACS on HST.
  ⇒ **ACSVCS** (Cycle 11; Côté et al. 2004) and **ACSFCS** (Cycle 13; Jordán et al. 2007)
- (100 + 43 = 143) galaxies spanning ranges in L_B of 545x (V), 345x (F), 720x (combined)
- $-22.26 < M_B < -15.12$
- E, S0, dE, dE,N, dS0.
- Each galaxy observed with HST/ACS in g & z bands.
- Virgo sample 61% complete to limit, Fornax 100% complete.





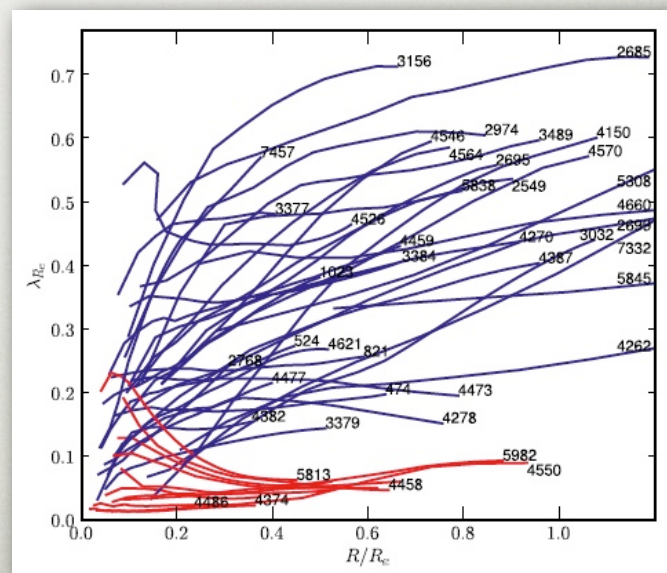
Kinematics and Dynamics: SAURON Results

2D stellar velocity fields



- A representative sample of 72 nearby (cz < 3000 km s^{-1}) early-type galaxies (24 E, 24 S0 and 24 Sa), half of which are in a cluster (mostly Virgo) environment and half in the field.
- No immediate correspondence with morphological structure, core/power-law classification.
- "E/S0 classification destined to extinction".

"angular momentum" profiles



Emsellem et al. (2007)

An Early-Type Sample that is Blind to Previous Classification Schemes

ID (1)		VCC (2)	B_T (3)	C83 (4)	R83 (5)	BST85 (6)	T (7)	NED (8)	vdB08 (9)	Notes (10)
49	✗	698	13.60	...	...	$S0_1(8)$	S	SA0: sp	E4/S0	
50	✓	1422	13.64	...	...	E1,N:	E	E1,N:	E3,N	
51	✗	2048	13.81	...	...	d:S0(9)	D	d:S0(9)	E4	
52	✓	1871	13.86	...	...	E3	E	E3	E1	
53	✓	9	13.93	...	E III	dE1,N	D	E	dE0	
54	✓	575	14.14	...	...	E4	E	E?	E4	
55	✗	1910	14.17	...	...	dE1,N	D	E	E2,N	
56	✗	1049	14.20	N4472 DW6	...	S0(4)	S	S0(4)	E1	
57	✗	856	14.25	...	...	dE1,N	D	dE,N	Sa?	
58	✗	140	14.30	...	...	$SO_{1/2}(4)$	S	S0?	E3	
59	✓	1355	14.31	...	E II	dE2,N	D	E0:	dE1,N	
60	✓	1087	14.31	...	...	dE3,N	D	dE,N	dE2,N	
61	✓	1297	14.33	...	...	E1 (†)	E	cE0	E1	
62	✗	1861	14.37	...	...	dE0,N	D	E	dE0,N	
63	✗	543	14.39	...	...	dE5	D	dE5	S(B)0:	
64	✗	1431	14.51	...	...	E?	D	E?	dE0/E0	
65	✗	1528	14.51	...	...	d:E1	D	d:E1	E2	
66	✗	1695	14.53	...	E II	dS0:	D	dS0:	E2	
67	✗	1833	14.54	...	...	$RSB0_{1/2}$	S	$S0_1(6)$	E3	
68	✗	437	14.54	...	...	dE5,N	D	dE5,N	E3/S0(3)	
69	✓	2019	14.55	...	...	dE4,N	D	E?	dE2,N	
70	✓	33	14.67	...	...	d:E2,N:	D	E?	dE0,N	
71	✓	200	14.69	...	...	dE2,N	D	dE2,N	d?E1	
72	✓	571	14.74	...	...	$SB0_1(6)$	S	$SB0_1(6)$	S0(5)	
73	✗	21	14.75	...	...	dS0(4)	D	S0?	dE4/S)(4),N	
74	✗	1488	14.76	...	...	E6:	E	dE	S0(4)	
75	✗	1779	14.83	...	E II	dS0(6):	D	dS0:	S0(5)	
76	✗	1895	14.91	...	...	d:E6	D	d:E6	S0(6)	
77	✗	1499	14.94	...	...	E3pec or S0	E	E?	E5 pec	
78	✓	1545	14.96	...	...	E4 (†)	E	E4	E1	
79	✓	1192	15.04	...	...	E3 (†)	E	E2	cE1	
80	✓	1857	15.07	...	E III	dE4:,N?	D	dE	dE5/S0(5)	
81	✓	1075	15.08	M87 DW22	E II	dE4,N	D	dE4,N	dE1,N	
82	✓	1948	15.10	...	E II	dE3	D	dE3	dE2	
83	✓	1627	15.16	...	...	E0 (†)	E	E0	cE1	
84	✓	1440	15.20	...	...	E0 (†)	E	E0	cE0	
85	✓	230	15.20	...	...	dE4:,N:	D	dE4:,N:	dE1,N	
86	✓	2050	15.20	...	E II	dE5:,N	D	dE5:,N	E5,N	
87	✓	1993	15.30	...	...	E0 (†)	E	E0	cE0	
88	✗	751	15.30	...	...	dS0	D	dS0	E5	
89	✓	1828	15.33	...	I: III	dE2,N	D	dE,N	dE2,N	
90	✓	538	15.40	...	...	E0	E	E0	cE0	
91	✓	1407	15.49	M87 DW1	...	dE2,N	D	dE,N	dE2,N	
92	✓	1886	15.49	...	...	dE5,N	D	dE5,N	dE5,N?	
93	✓	1199	15.50	...	...	E2 (†)	E	E2	cE1	
94	✗	1743	15.50	...	E II	dE6	D	dE6	S0/dE6,N?	
95	✓	1539	15.68	M87 DW31	...	dE0,N	D	dE0,N	dE0,N	
96	✓	1185	15.68	M87 DW7	E II	dE1,N	D	dE1	dE0,N	

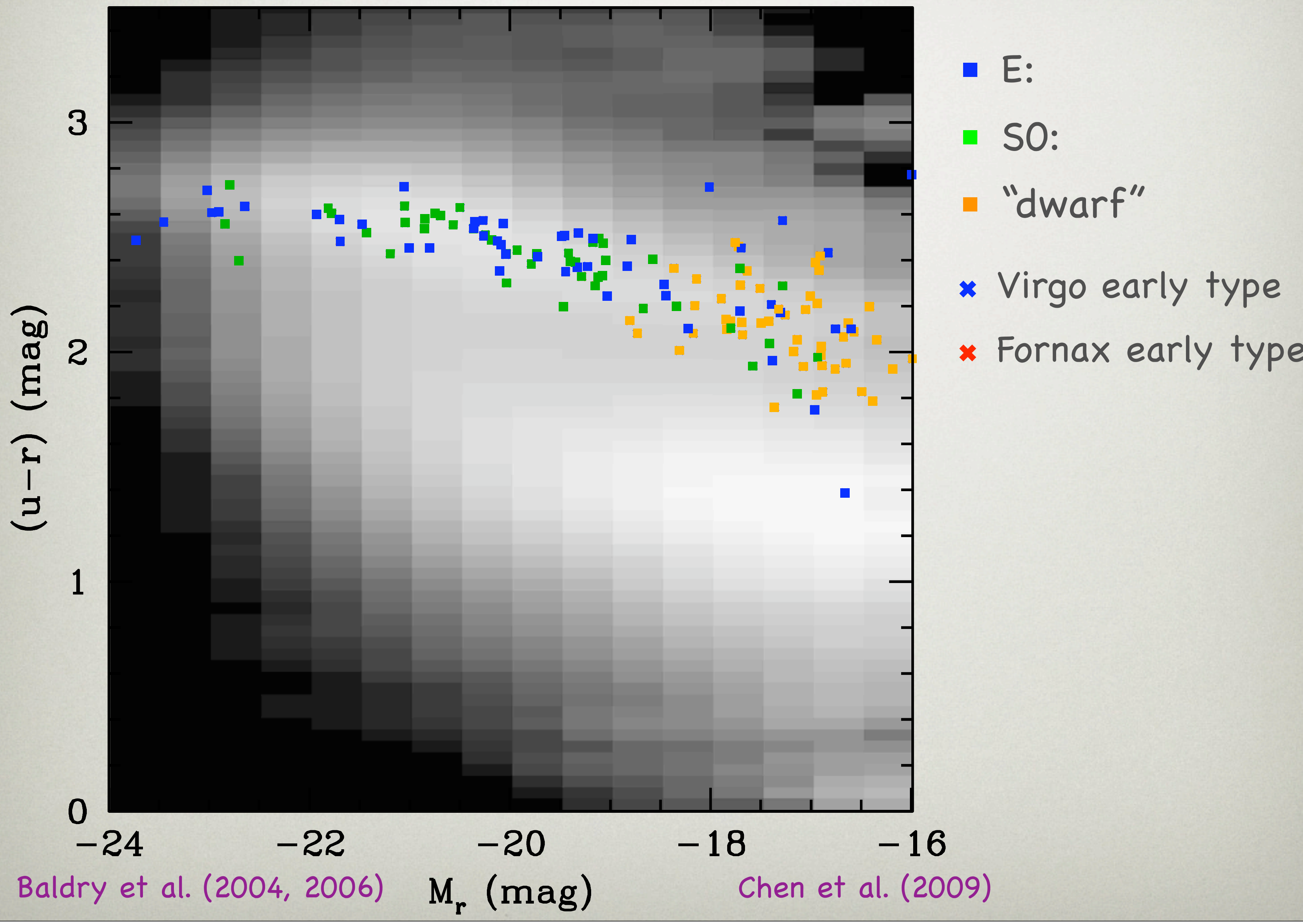
BST85 = Binggeli, Sandage & Tammann (1985)

NED = RC3, BST85, etc

vdB08 = van den Bergh (2008)

- Percentage of galaxies with consistent and unambiguous classifications (E vs. S0, E vs. dE, etc): 58%.
- If agreement between E and cE classes is also required, 44%.

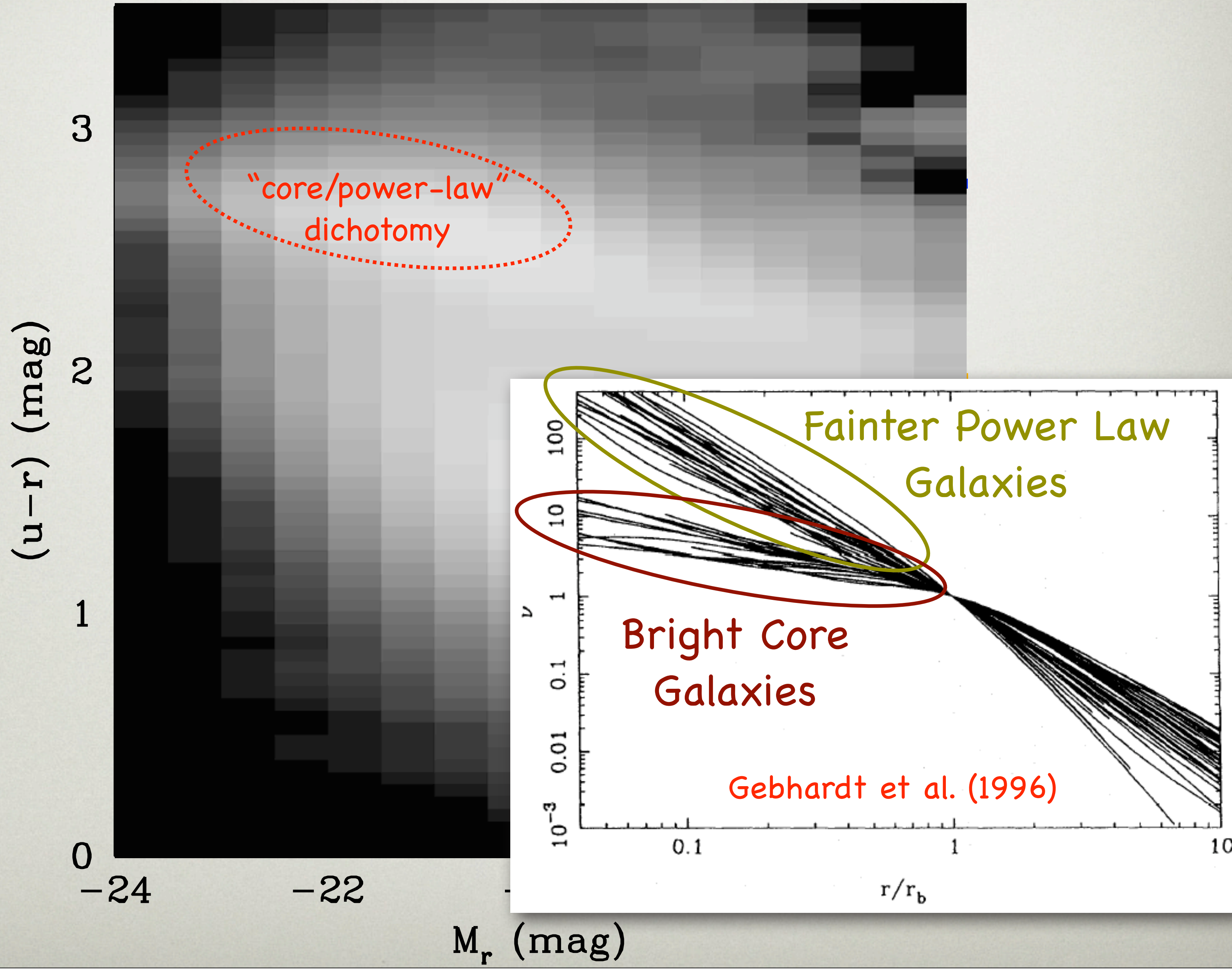
A Red Sequence Survey in Virgo and Fornax



Baldry et al. (2004, 2006)

Chen et al. (2009)

Dichotomies Along the Red Sequence?



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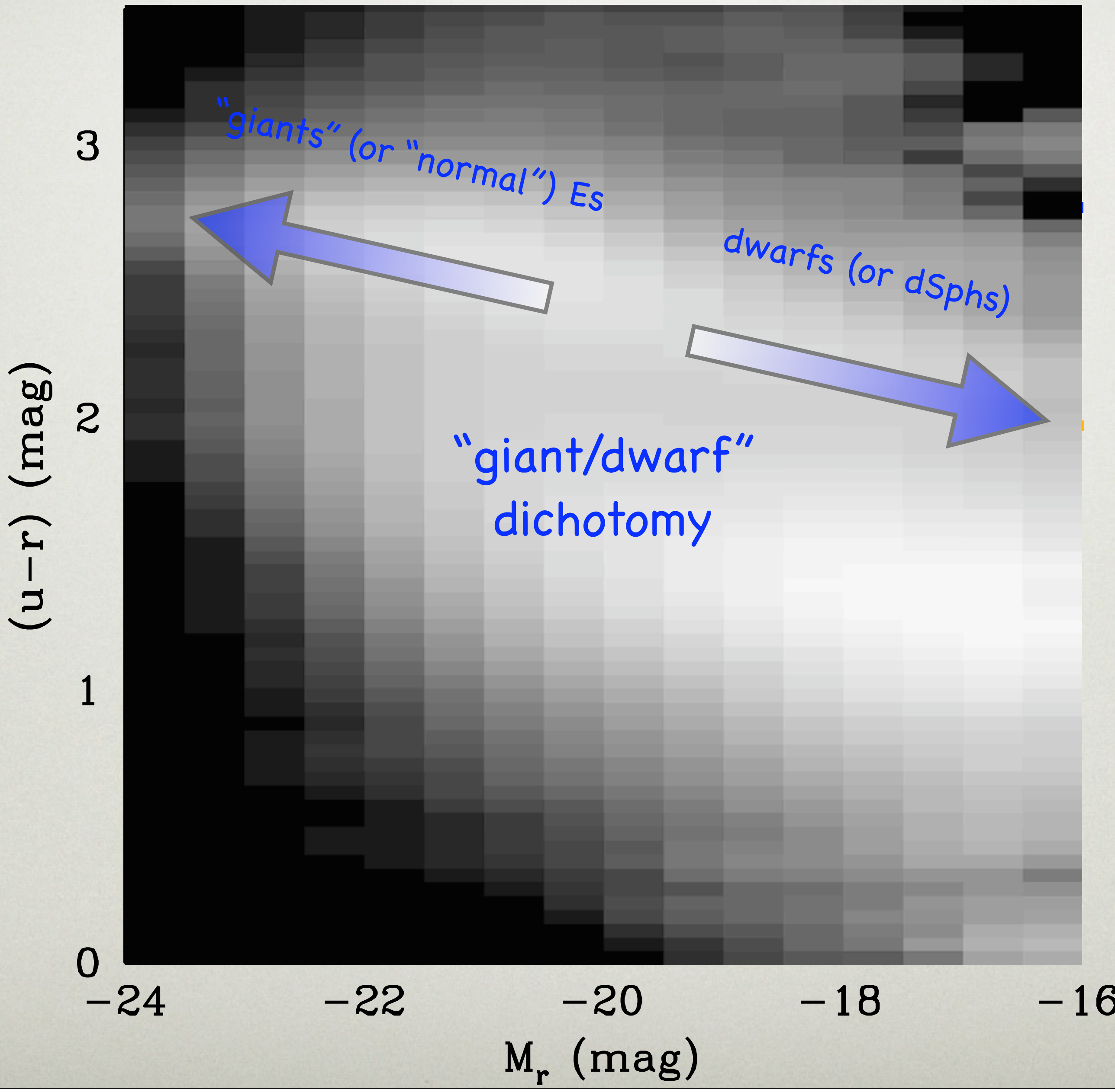
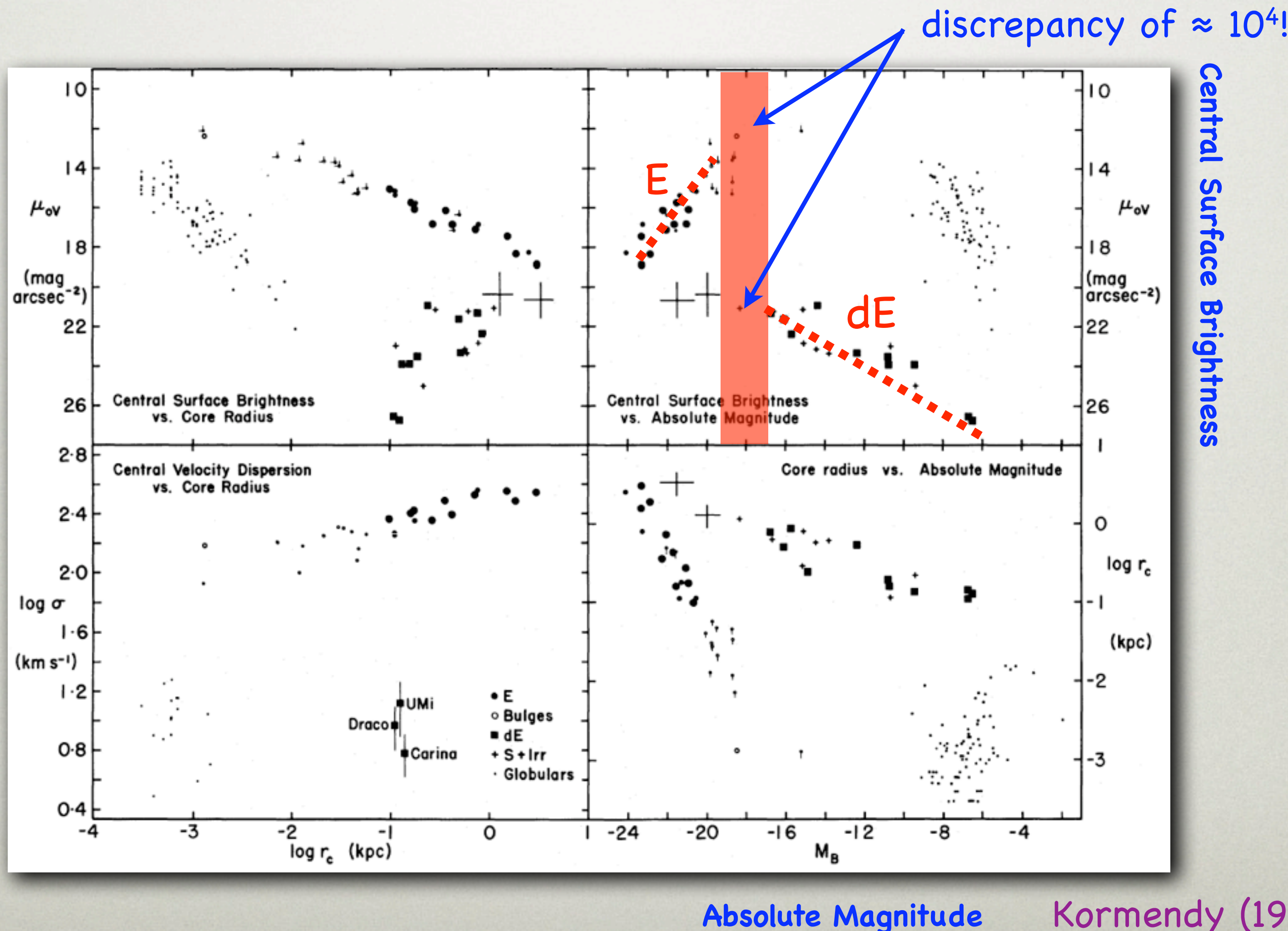


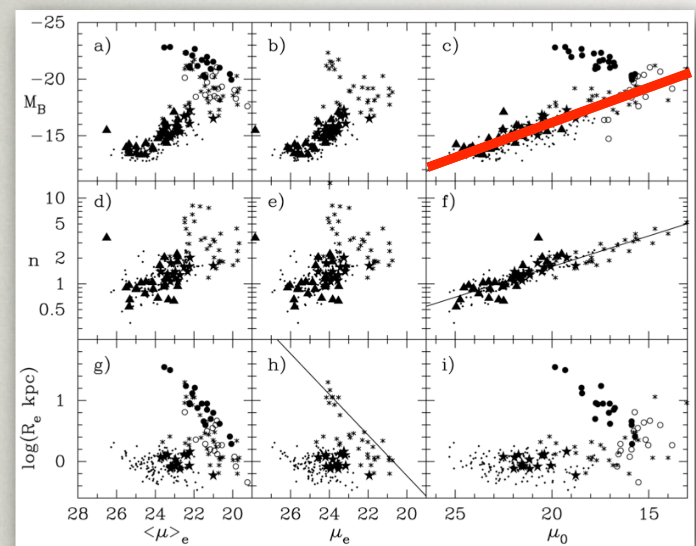
Giants vs. Dwarfs/dSphs

- "Normal" ("ordinary" or "giant") ellipticals have nearly orthogonal scaling relations in some of their central properties:

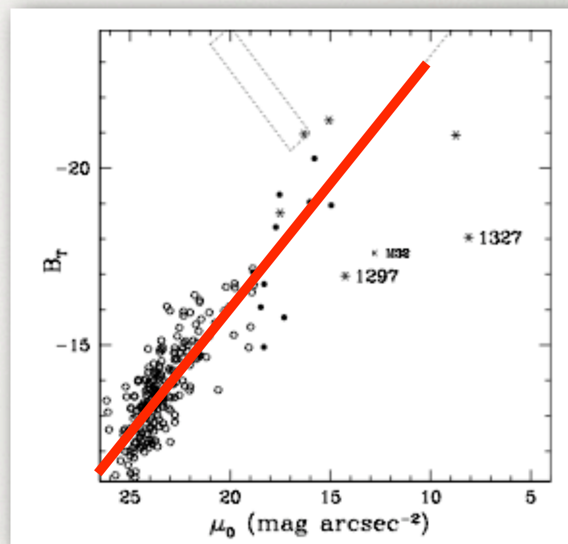


Kormendy (1985)

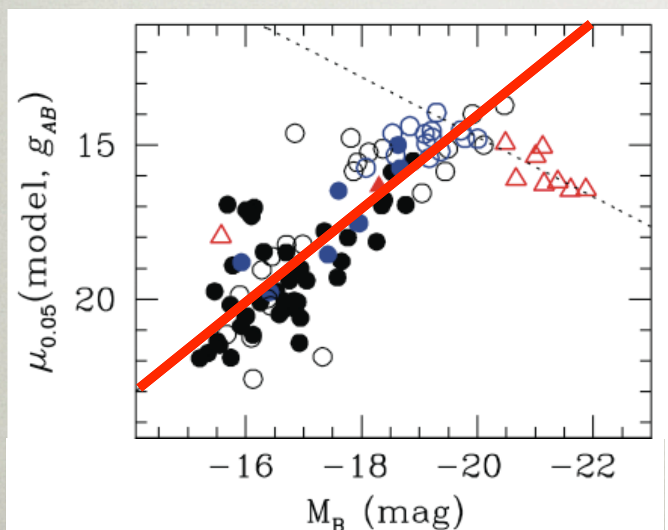
No Giant/Dwarf Dichotomy?



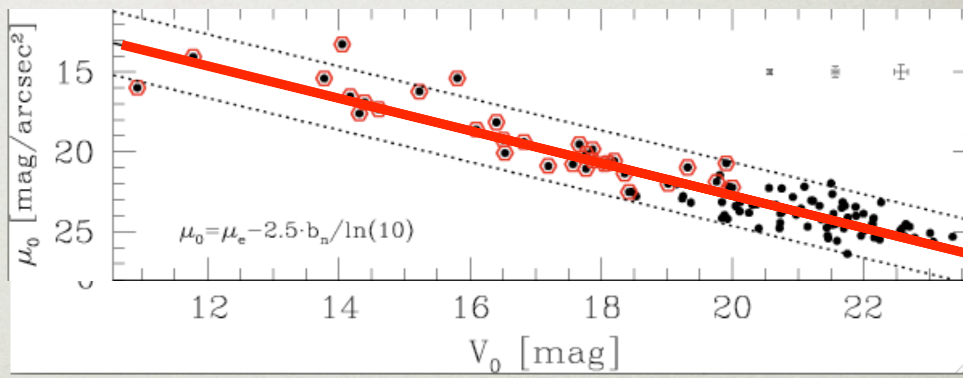
Graham & Guzmán (2003)



Gavazzi et al. (2005)

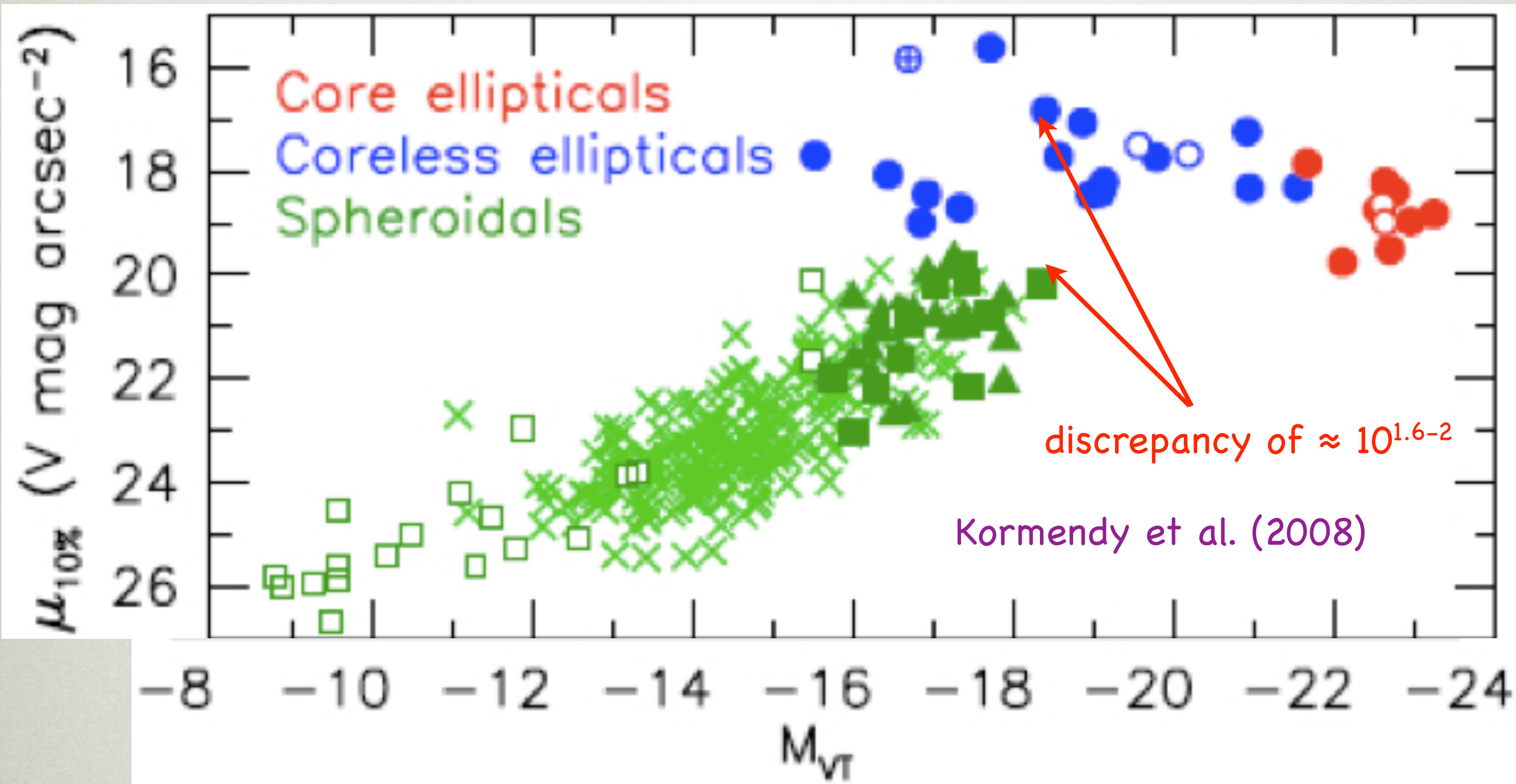


Ferrarese et al. (2006)



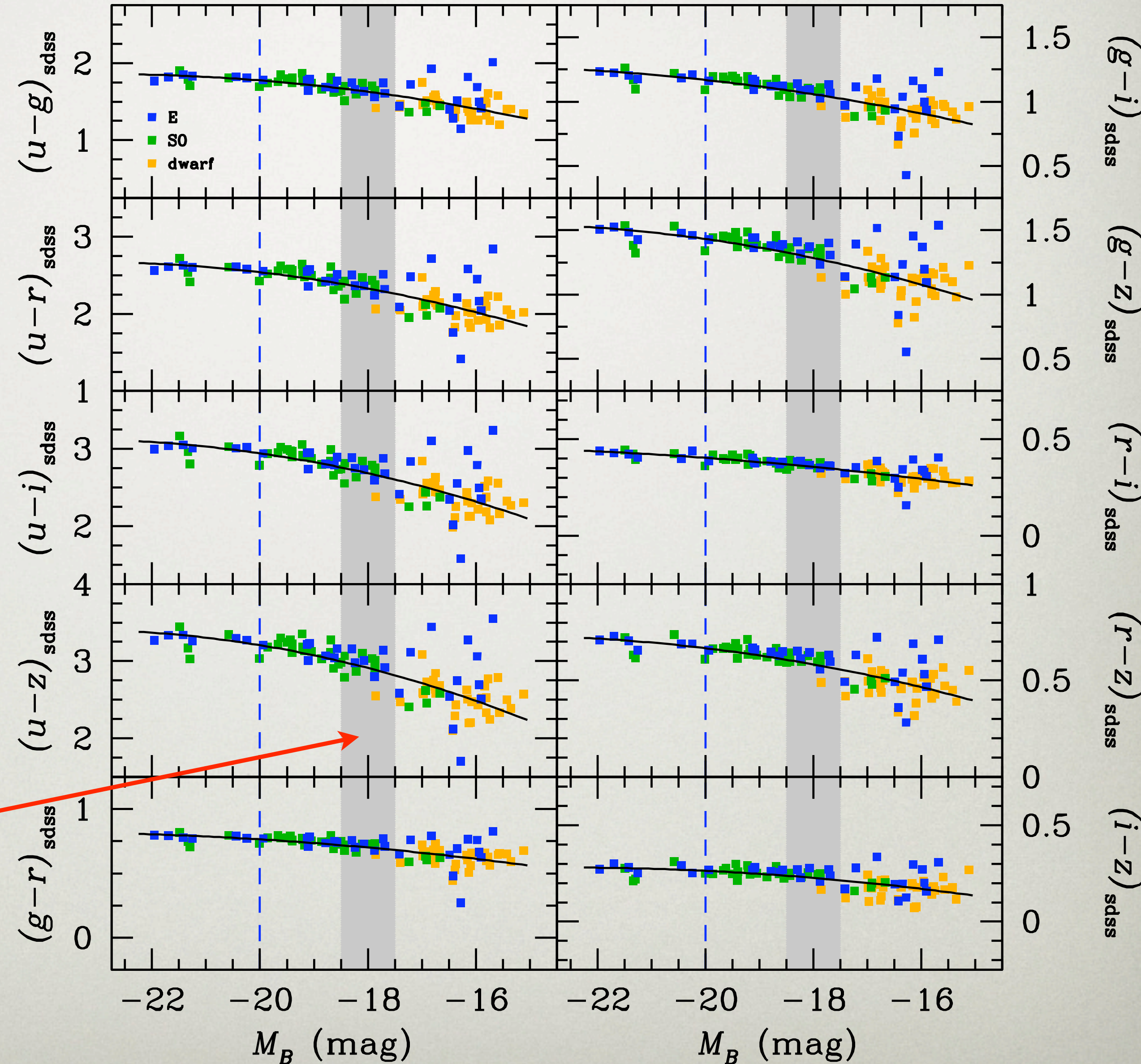
Misgeld et al. (2008)

No Giant/Dwarf Dichotomy?



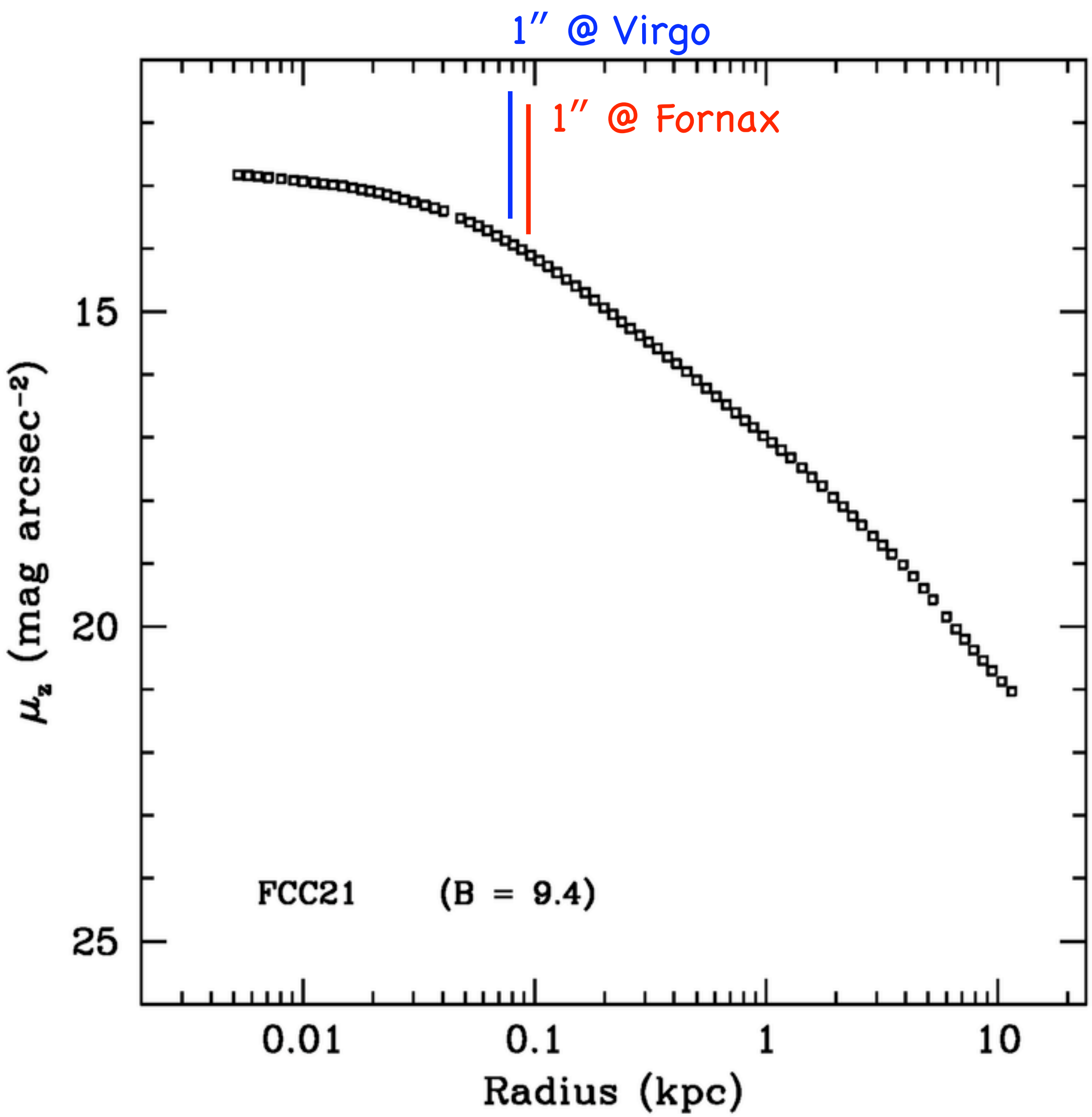
Global Parameters: Colour-Magnitude Diagrams

- Curve-of-growth photometry performed on SDSS mosaics of 100 ACSVCS program galaxies ➔ aperture colours within $R_e/2$ (Chen et al. 2009).



Transition from "Giants" to "Dwarfs":
$M_B \approx -18.0 \pm 0.5$

Surface Brightness Profiles

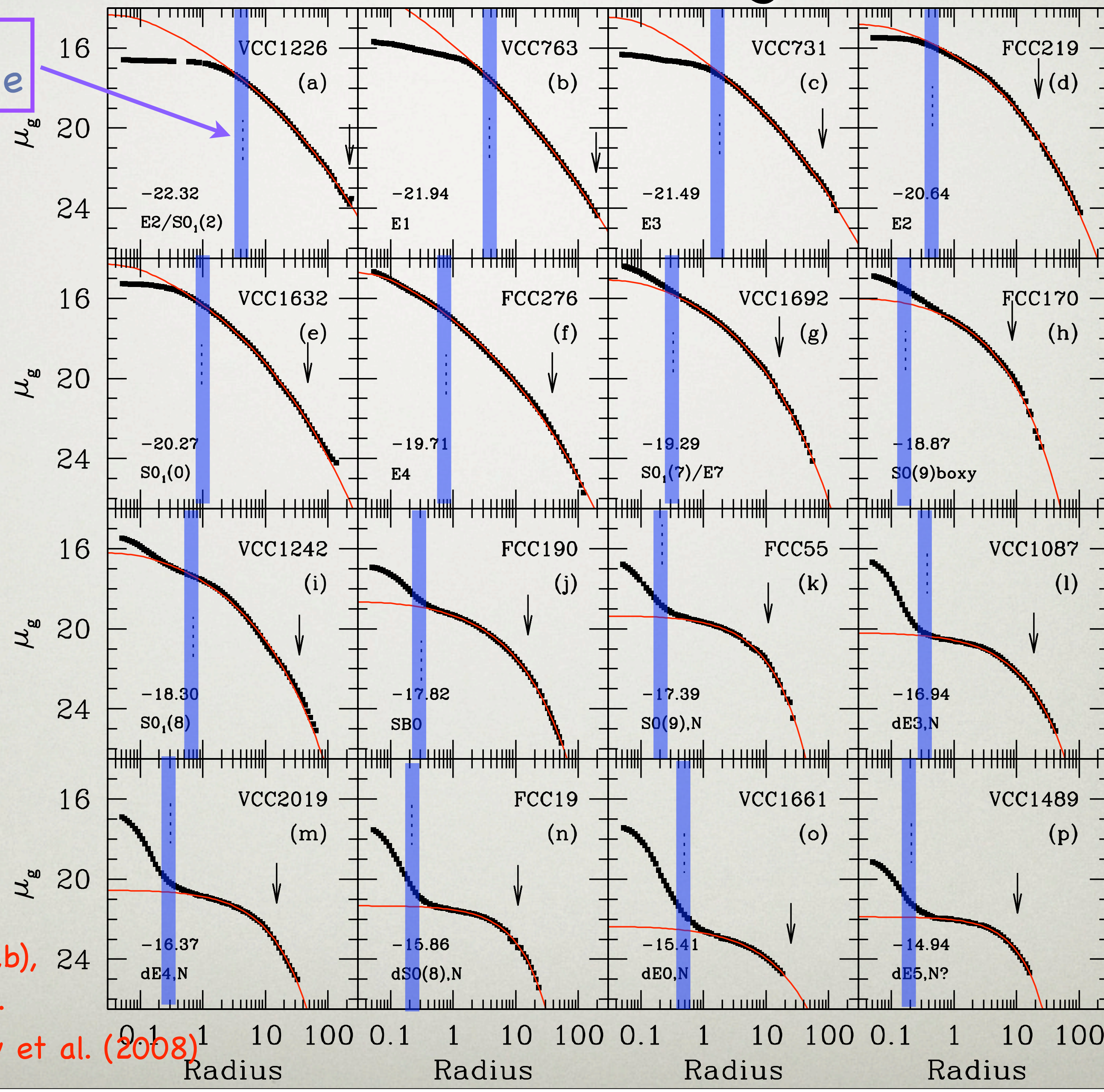


Systematic Behavior of the HST Brightness Profiles

2%Re

Luminosity "Deficit"

Luminosity "Excess"



A "Core" and "Power-law" Dichotomy?

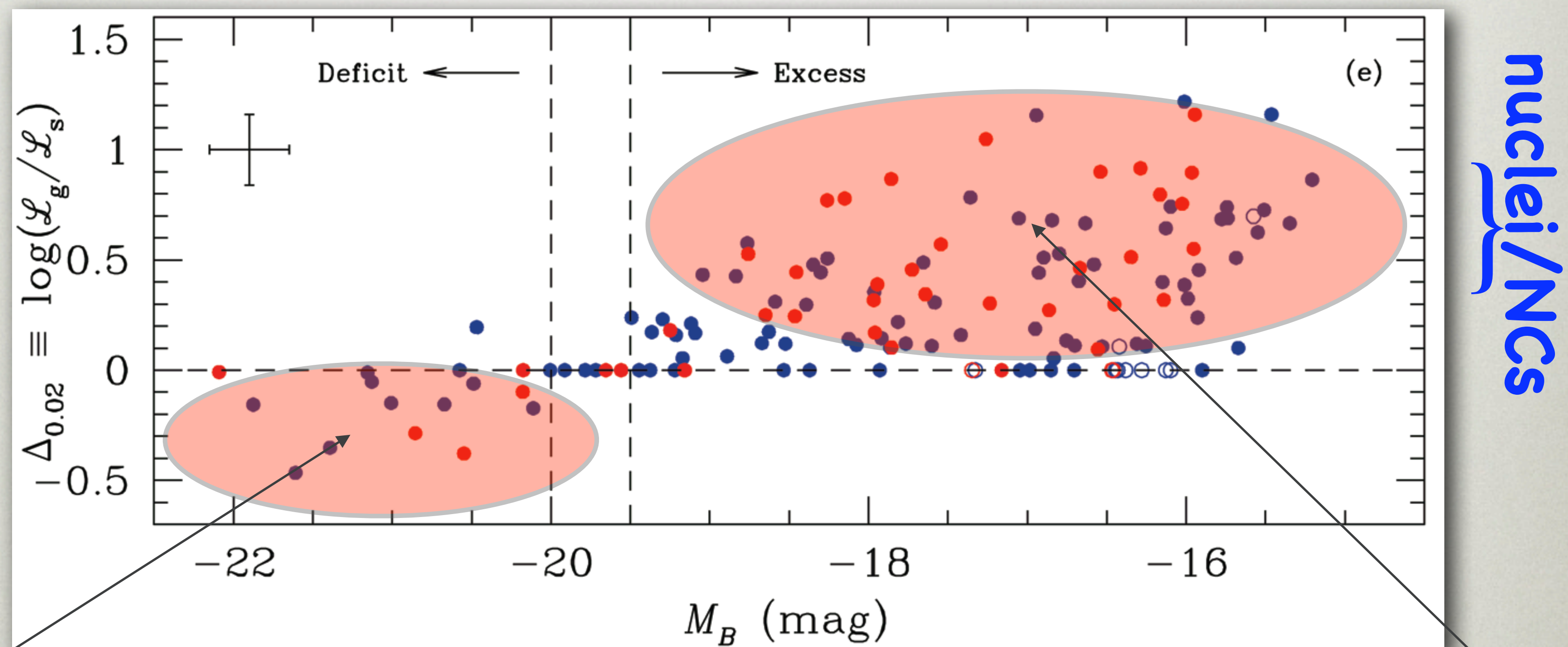
Ferrarese et al. (2006a,b), Côté et al. (2006,2007).

Confirmed by Kormendy et al. (2008)

Central Profiles: From Deficit to Excess

- Define a parameter, $\Delta_{0.02}$, that measures the net luminosity deviation from the inward extrapolation of the outer Sersic component:

$\Delta_{0.02} \equiv \log(L_{galaxy}/L_{sersic})$ $\quad 0 < R < 0.02R_e$

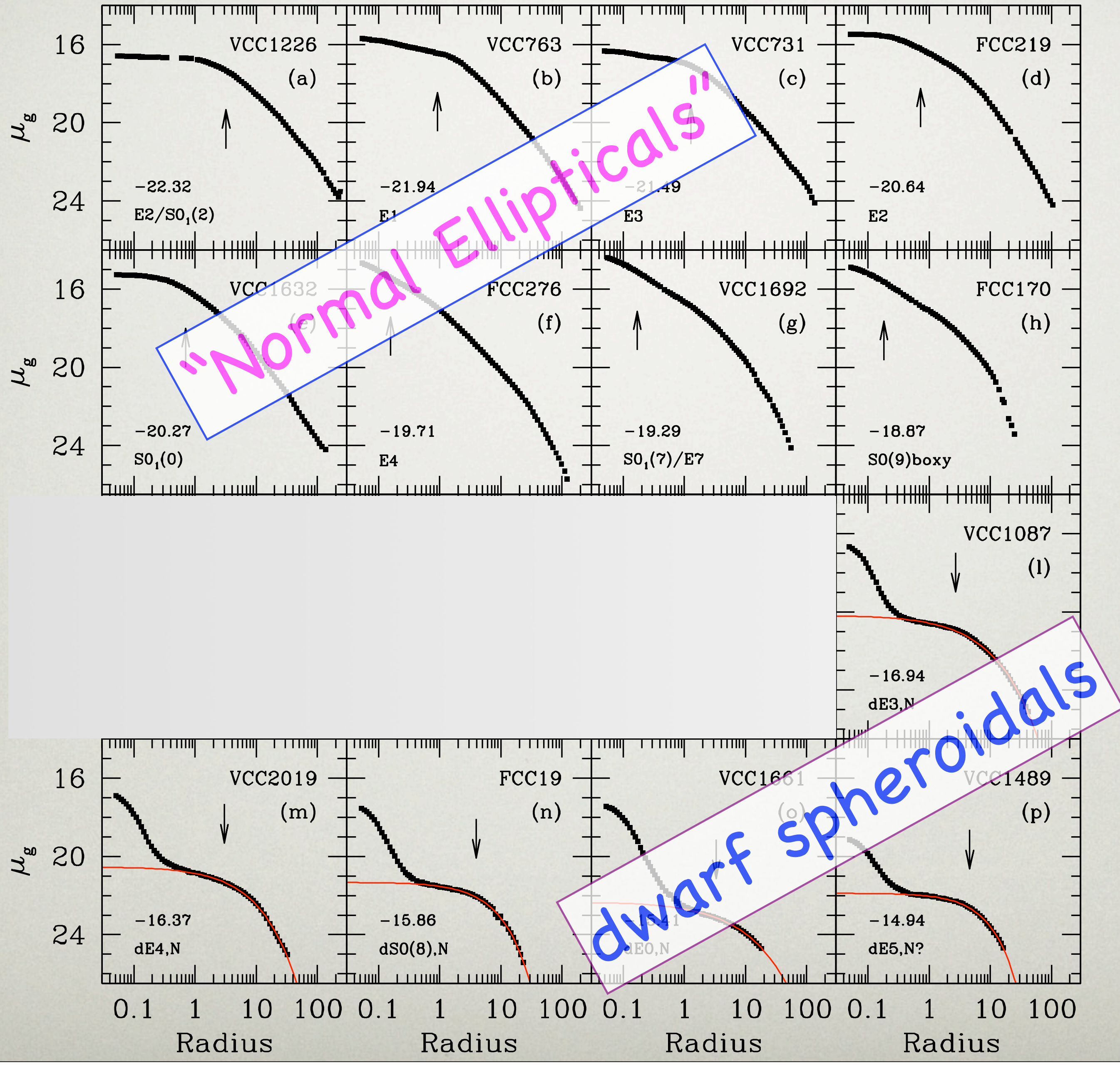


Côté et al. (2007), ApJ, 671, 1456

Core depletion by Supermassive Black Hole Binaries (Ebisuzaki et al. 1991, Faber et al. 1997, Milosavljevic & Merritt 2001)?

Formation of dense stellar cores via gas inflows (Barnes & Hernquist 1991, Mihos & Hernquist 1994, 1996)?

Is there a Dichotomy in Central Parameters with HST?



Compact Stellar Nuclei and SBHs

- Most (all?) massive galaxies are thought to contain supermassive BHs.
- Faint galaxies contain a "compact stellar nucleus" or "nuclear star cluster".

M60

M(B) = -21.4

Deficit $\simeq 2.2 \times 10^9$ $M_\odot$

M (SBH) = $(2 \pm 0.5)10^9$ $M_\odot$

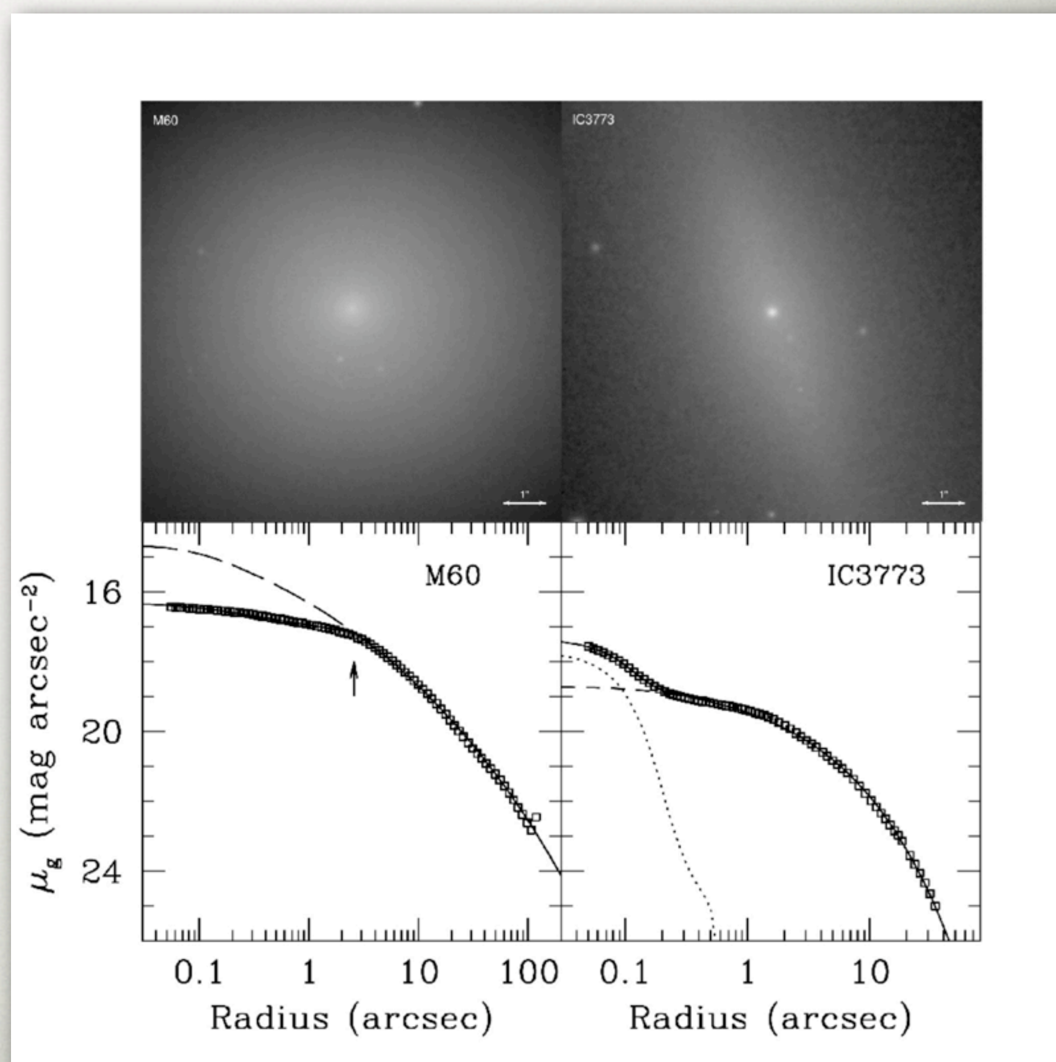
(Gebhardt et al. 2003)

IC3773

M(B) = -17.3

M (nuc) $\simeq (1.3 \pm 0.5)10^6$ $M_\odot$

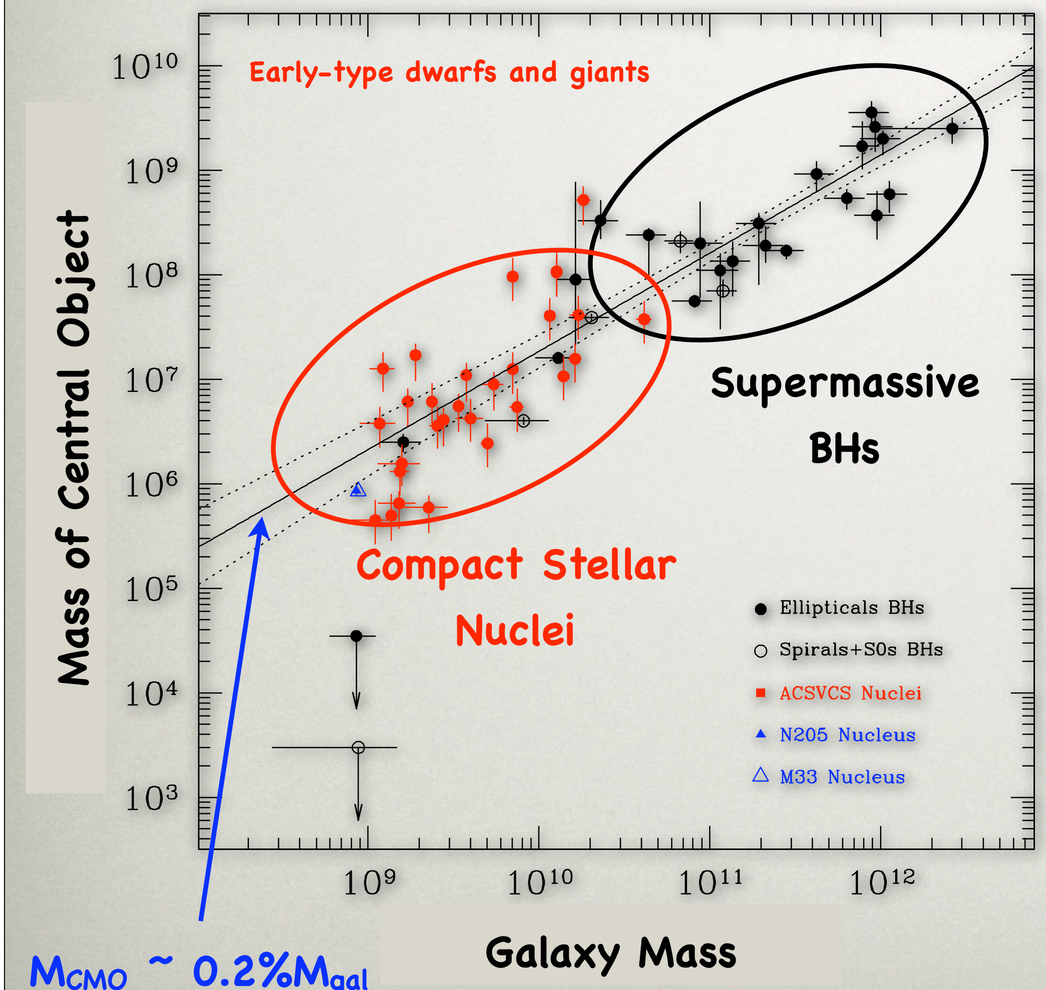
(Côté et al. 2006)



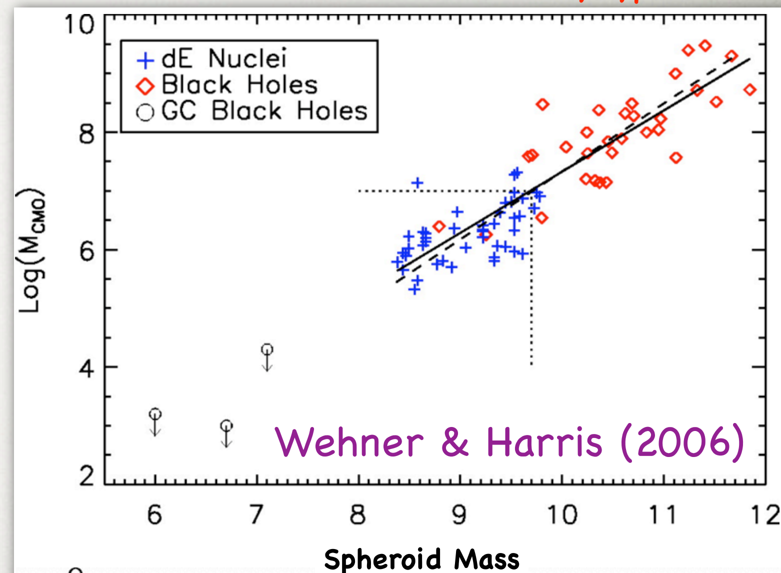
Ferrarese et al. (2006)

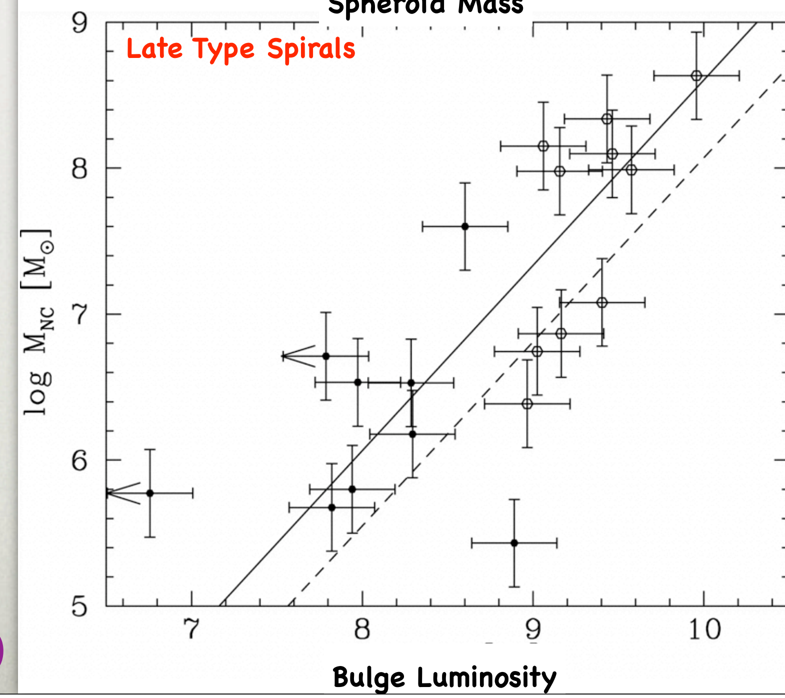
Compact Stellar Nuclei and SBHs

Ferrarese et al. (2006)



Early Type Dwarfs

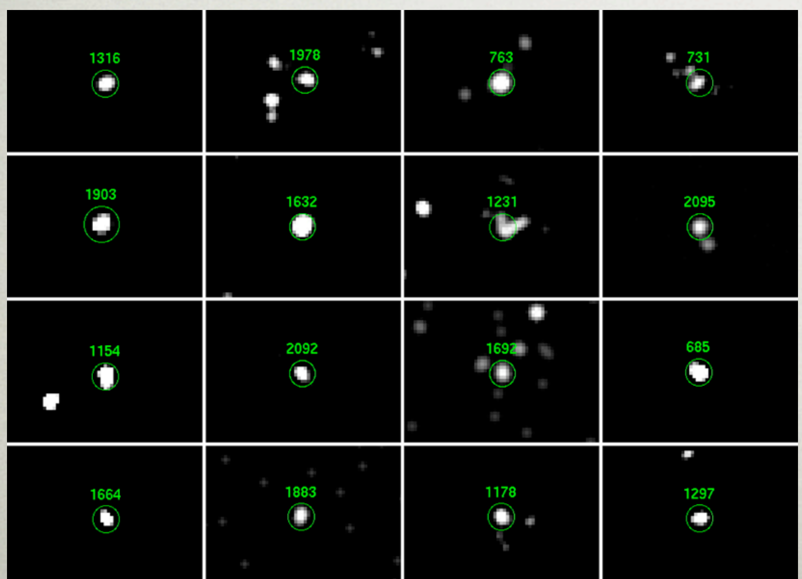




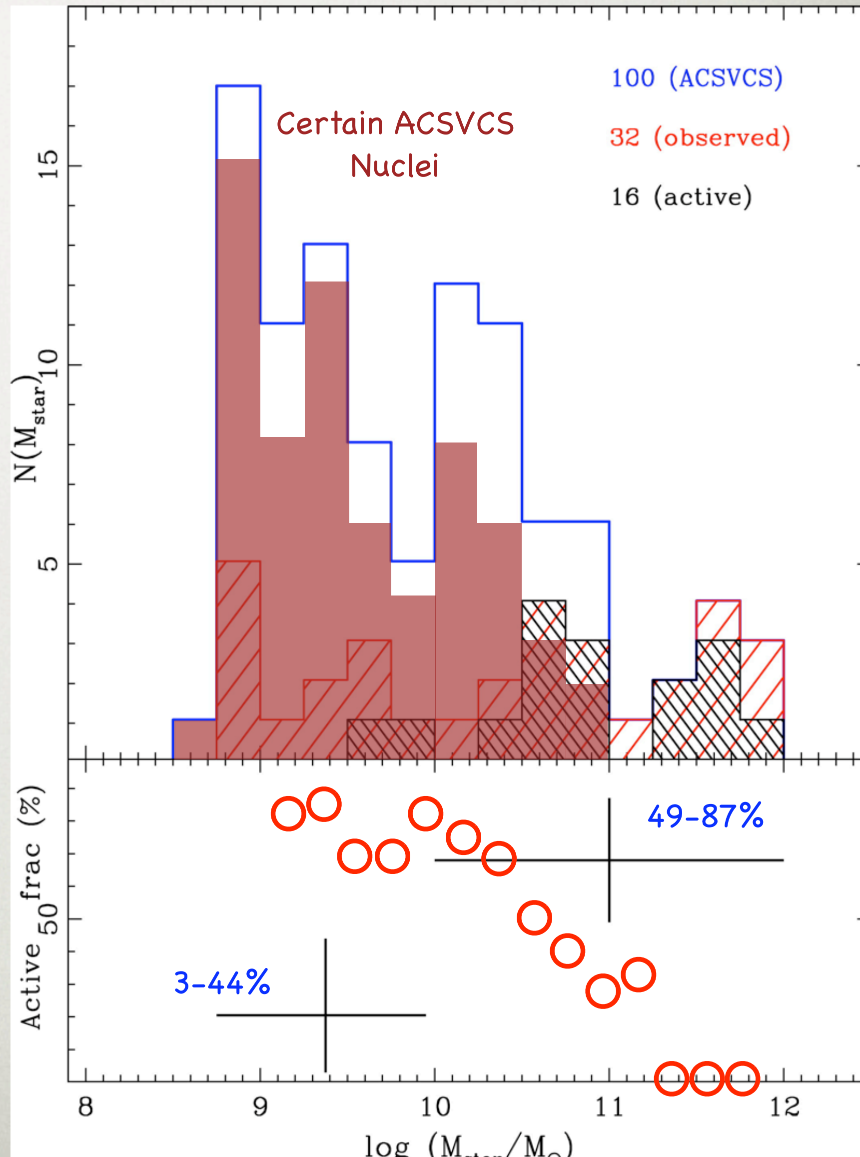
Rossa et al. (2006)

AGNs and Supermassive BHs

- AGN Multiwavelength Survey of Early-Type Galaxies in the Virgo Cluster (AMUSE-Virgo).
- Chandra (+Spitzer) observations for 100 ACSVCS galaxies, to search for low-level supermassive BHs ($L_X \gtrsim 4\times10^{38}$ erg s^{-1}).
- Based on first 32 targets: point-like X-ray emission from 1/2 the objects, but in only two objects fainter than $M_B \approx -18$ ($M \approx 10^{10}$ $M_\odot$).

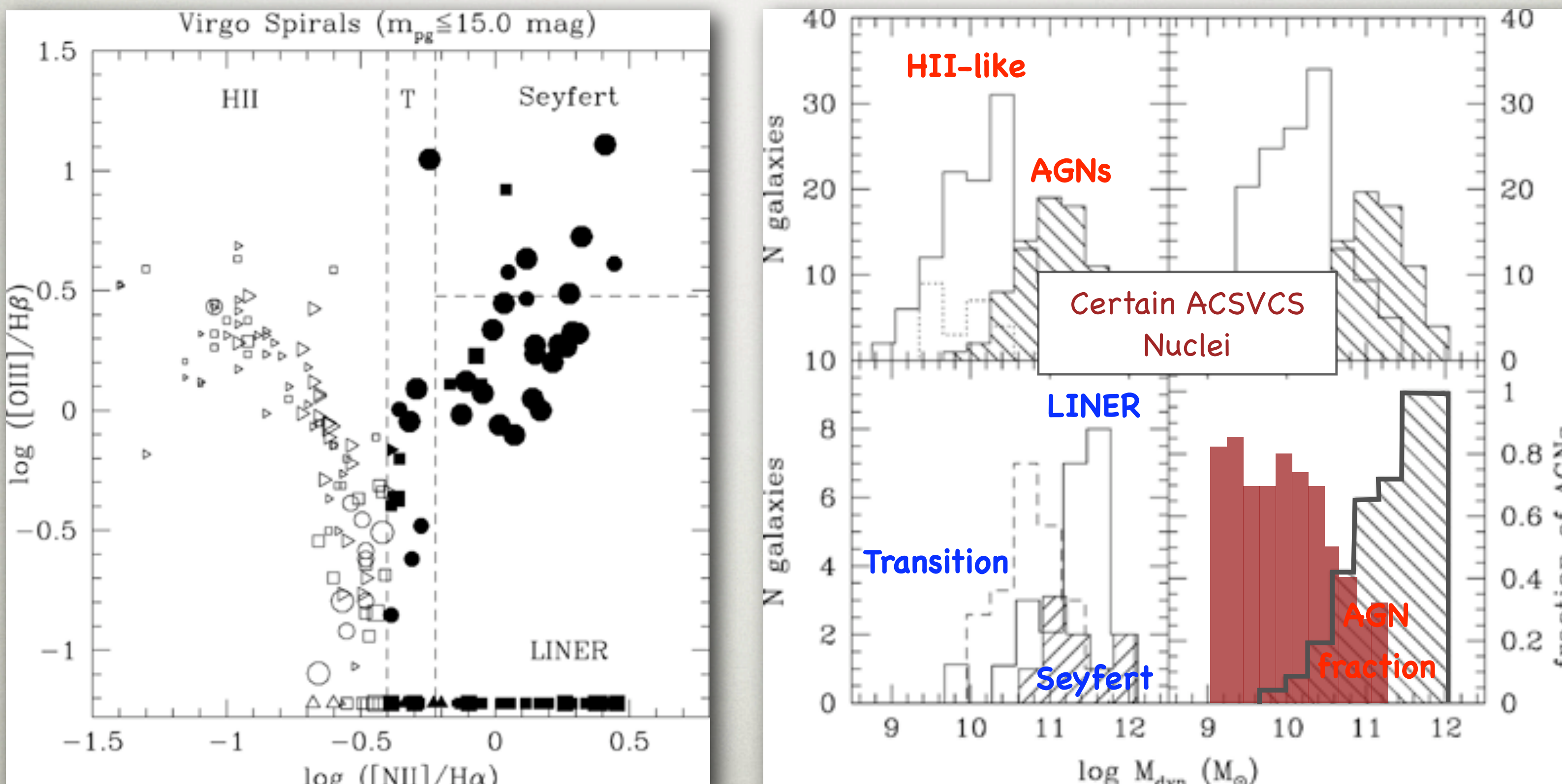


Gallo et al. (2008)



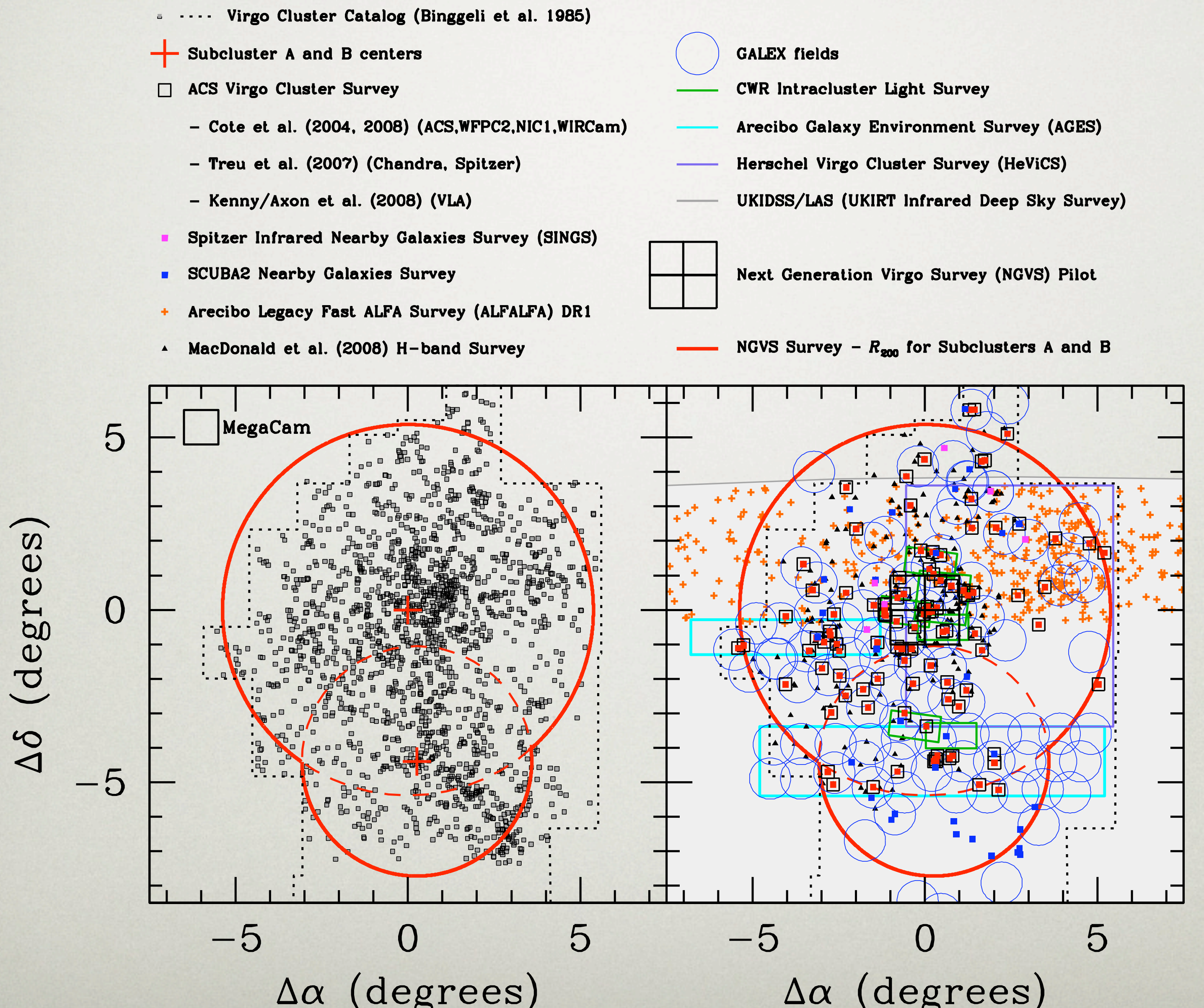
AGNs and Supermassive BHs

- Spectroscopic census (SDSS, Loiano, literature, etc) of AGNs associated with late-type galaxies in the Virgo cluster.
- Observed 213 out of a complete set of 237 galaxies more massive than $M_{dyn} > 10^{8.5}\ M_{\odot}$.
- "It is found that AGNs are hosted exclusively in massive galaxies: i.e. $M_{dyn} \gtrsim 10^{10}\ M_{\odot}$."



Decarli et al. (2007)

Ongoing and Upcoming Programs



The NGVS Team

Laura Ferrarese (PI)
Chantal Balkowski
Michael Balogh
John Blakeslee
Samuel Boissier
Alessandro Boselli
Frederic Bournaud
Claude Carignan
Ray Carlberg
Scott Chapman
Patrick Côté
Stephane Courteau
Tim Davidge
Serge Demers
Pierre-Alain Duc
Pat Durrell
Eric Emsellem
Giuseppe Gavazzi
Raphael Gavazzi
Stephen Gwyn

Henk Hoekstra
Andrés Jordán
Ariane Lancon
Alan McConnachie
Dean McLaughlin
Simona Mei
Yannick Mellier
Chris Mihos
Chien Peng
Eric Peng
Thomas Puzia
Marcin Sawicki
Luc Simard
James Taylor
John Tonry
R. Brent Tully
Wim van Driel
Ludo van Waerbeke
Bernd Vollmer
Christine Wilson

The Next Generation Virgo Cluster Survey

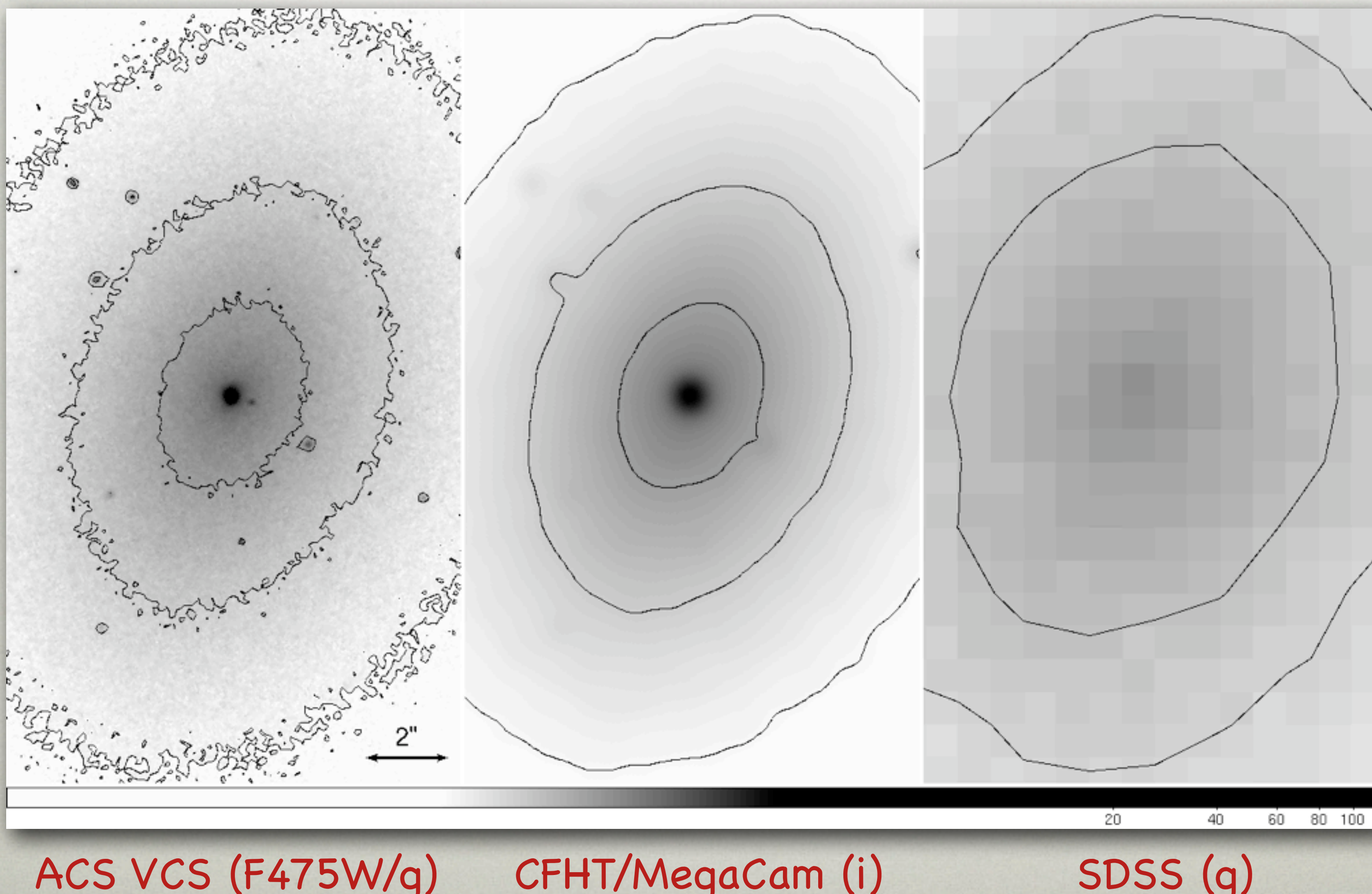
- The (photographic) VCC survey of Binggeli, Sandage & Tammann is now ≈ a quarter century old (1983-1987). Yet it remains the best existing optical survey of Virgo, which is arguably the most important single target in extragalactic astronomy.
- Perhaps surprisingly, SDSS did not significantly improve upon the VCC's point-source and surface brightness detection limits:

	B_{LIM} (mag)	$\mu(B)_{LIM}$ (mag arcsec^{-2})
VCC	22–23	25.3
SDSS	~22.7	25.9

- The SDSS is a based on imaging from a 2.5m telescope, in which each pixel is exposed for 54 sec and the median seeing is 1.4."
- NGVS = an approved CFHT/MegaCam Large Programme (PI = Ferrarese) that will survey the Virgo Cluster out to its virial radii (100 deg^2 in total), in u*g′r′i′z′, to g′ ≈ 25.7 mag (10σ) and $\mu_g{}'$ ≈ 27.7 mag arcsec^{-2} (2σ).
- Awarded 771 hours (~140 nights) over four years (2009A - 2012A).

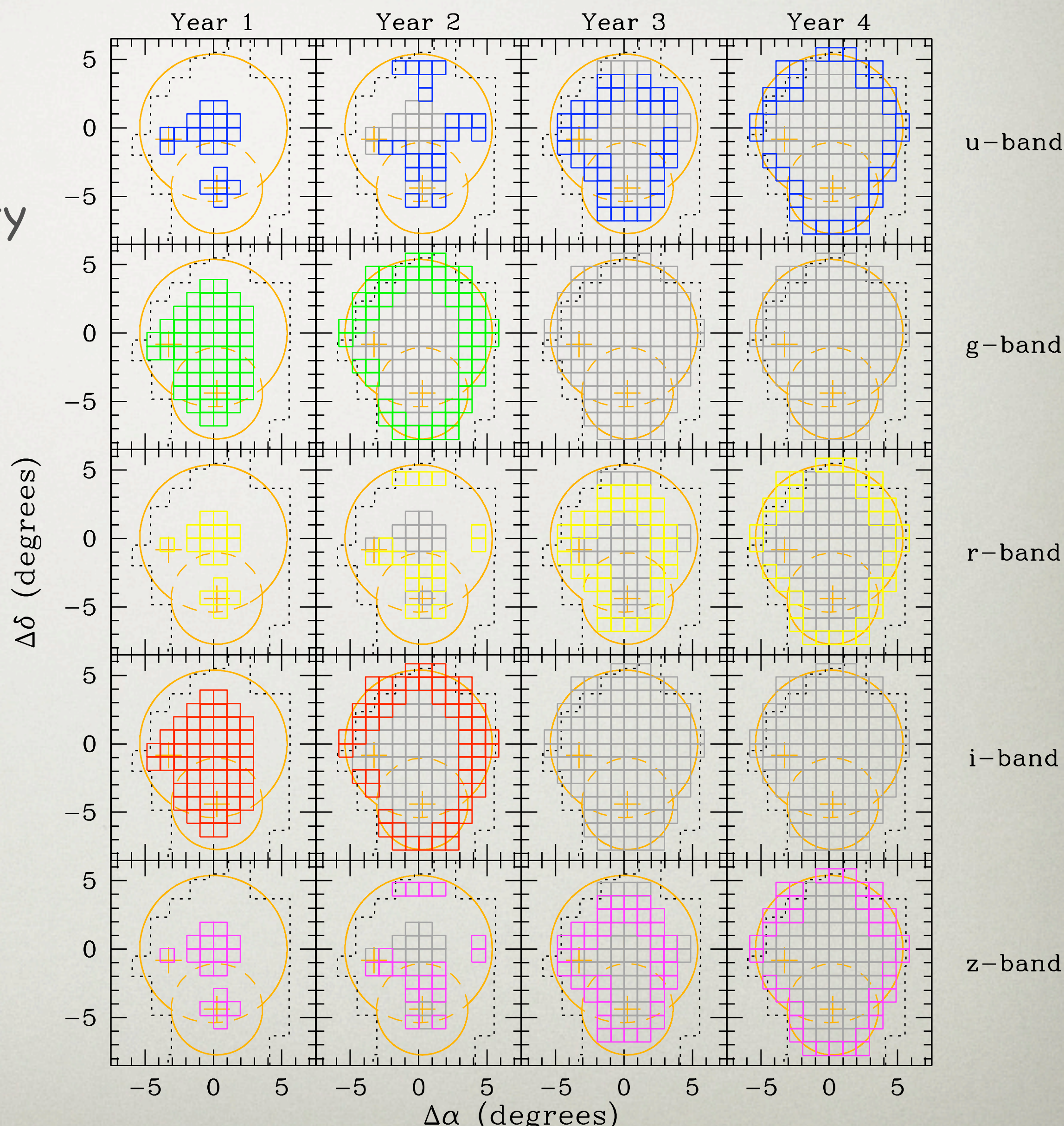
The Next Generation Virgo Cluster Survey

- Compared to the VCC:
  - 100× improvement in depth • >10× in surface brightness • ≈2-3× in FWHM
  - 5× in SED coverage.
- Plus synergistic opportunities with surveys at non-optical wavelengths.



The Next Generation Virgo Cluster Survey

- Virgo Science
  - faint end of the luminosity function.
  - galaxy scaling relations
  - environmental effects
  - the galaxy-ICM connection
  - star clusters, nuclei, compact objects, AGNs
- Background Science:
  - cosmic shear
  - intrinsic alignment
  - high-z clusters
- Foreground Science
  - Milky Way halo (VOD)
  - Kuiper Belt




NGVS
Credit: CFHT, CEA, NRC/HIA, CADC and the NGVS Team