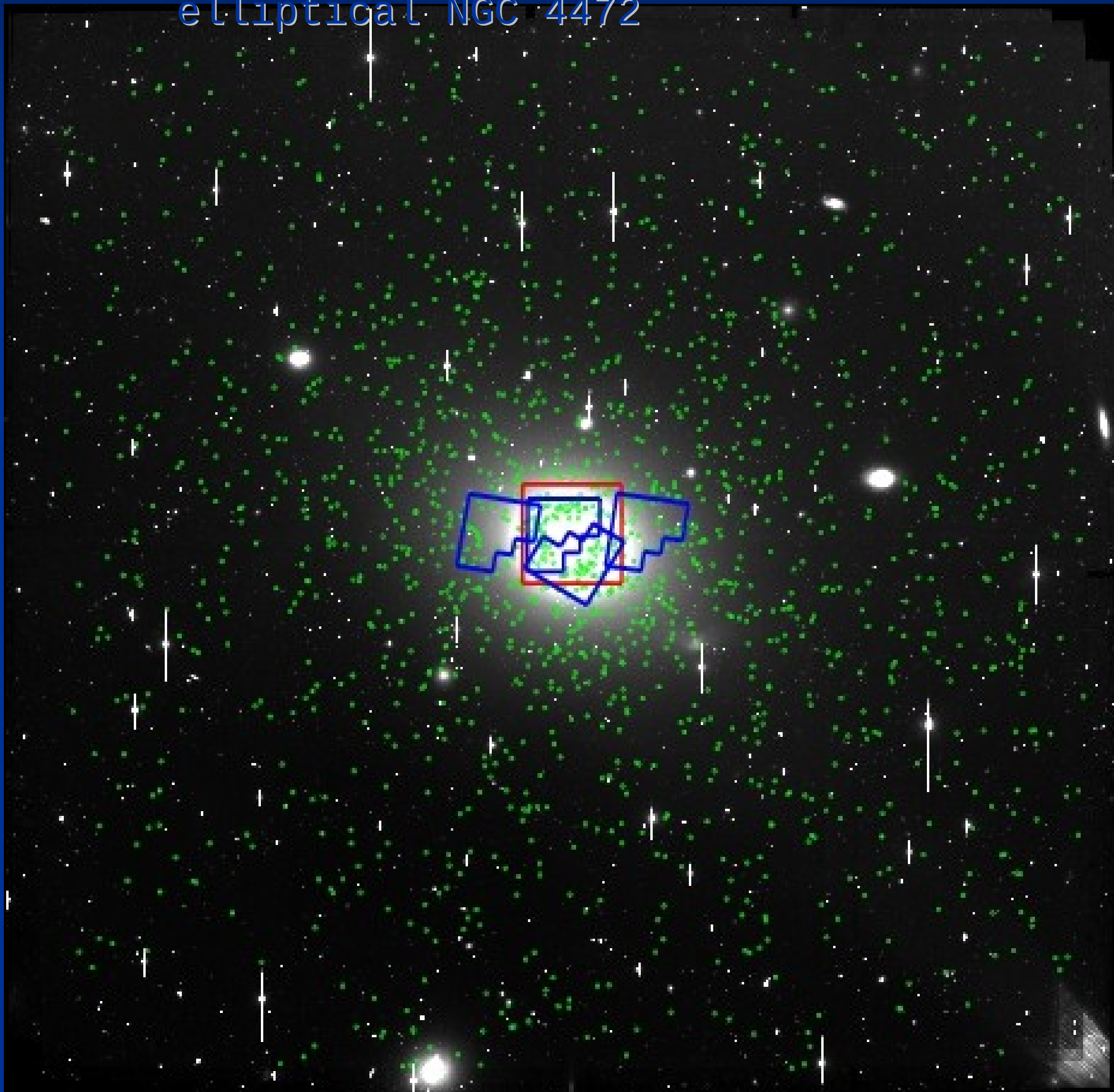
Observations of Globular Cluster Systems of Giant Galaxies

Katherine Rhode

Indiana University



KITP Conference
January 2009

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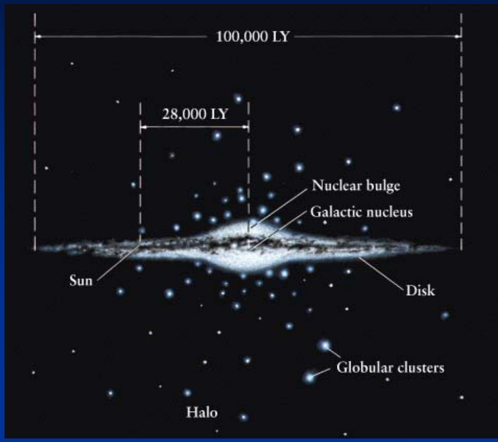
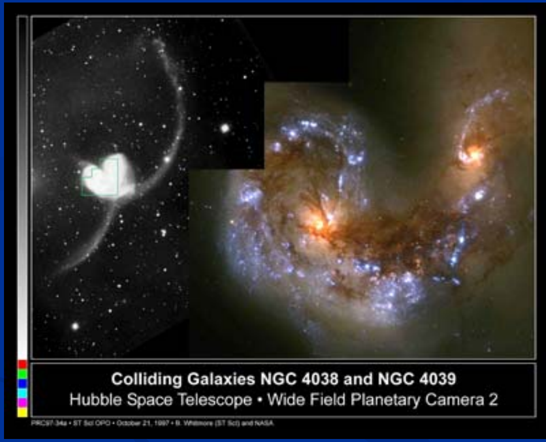
- Background
- Our Wide-field Survey
- Spinoff Science
- The Future

Why Observe Globular Cluster *Systems*?

- Globular clusters make ideal "fossil records" of galaxies:
  - ~~simple stellar populations~~
  - luminous (M_V ~ –11 to –4)
  - old (few – 12+ Gyr)
  - formed in gas-rich mergers; associated with major SF episodes
  - identified in all types of galaxies, at all galactocentric radii





- Quantifying the *ensemble* properties of GC systems helps address fundamental questions:
  - How did galaxies form and evolve?
  - How is the matter in galaxies distributed?

What Do We Want to Observe?

Want to establish fundamental quantities that characterize the GC system of a galaxy:

- Spatial distribution

  Radial profile of GC system,

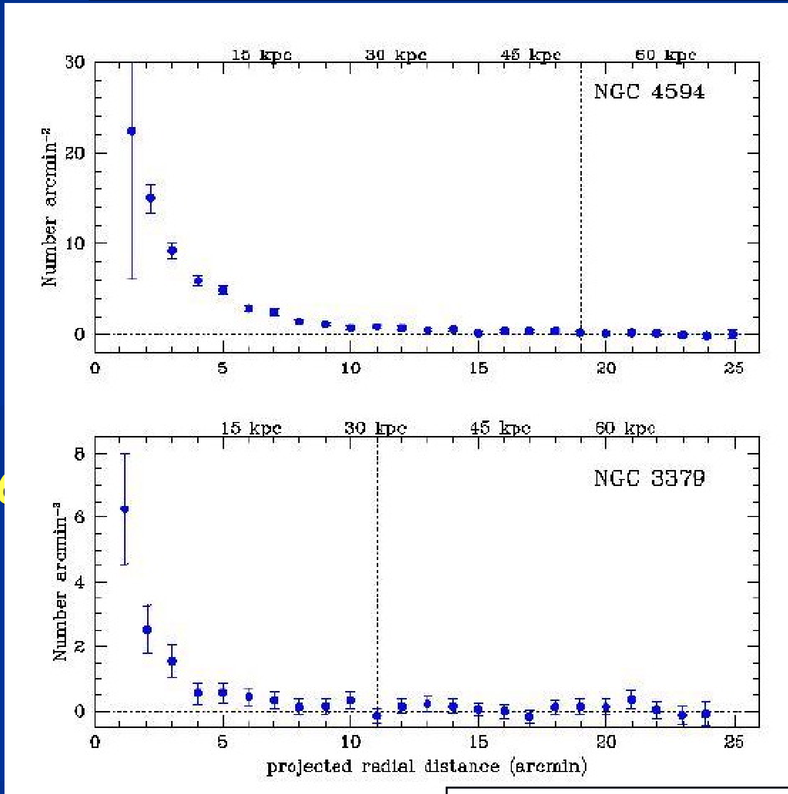
  over its full radial range

- Total number of GCs (N_{GC})

- Specific Frequency

  N_{GC} normalized by host

Spatial distributions of GC
NGC 3379 and NGC 4594



(Rhode & Zepf 2

What Do We Want to Observe? *(continued)*

Want to establish fundamental quantities that characterize the GC system of a galaxy:

- Color distribution

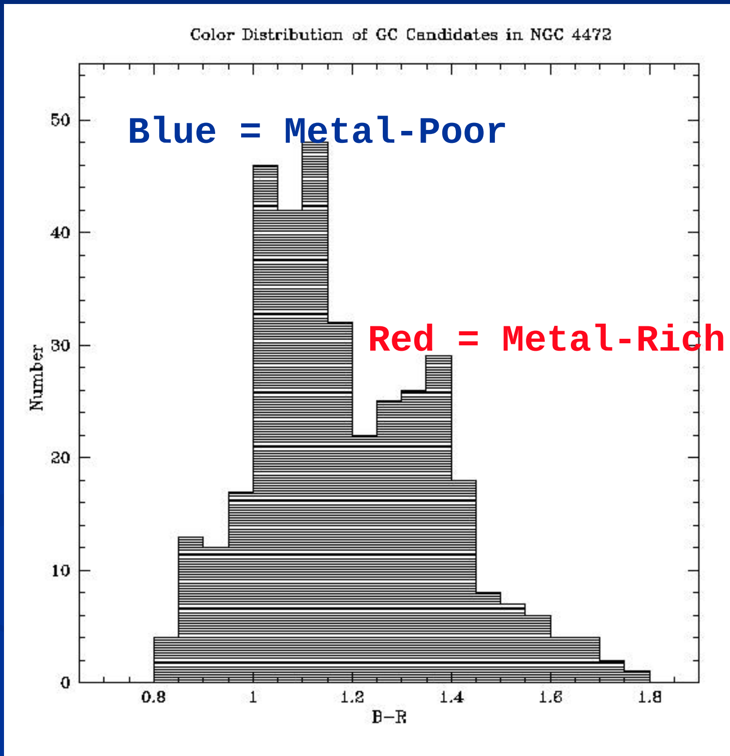
  Number/proportion of blue/red GCs

  (In **old** stellar pops (age ≥ 3 Gyr), optical color primarily traces metallicity)

- Color gradients

  How does mean color (blue/red ratio) change with

B-R colors of GCs in Virgo elli



Rhode & Zepf (2001)

How Can We Use the Data?

- We can use these measurements to test specific galaxy formation models
  - Models (e.g., major mergers, multi-phase collapse, collapse + accretion, hierarchical merging) make predictions for how quantities like S_N, blue/red ratio, color gradient change with host galaxy properties and formation history

- Observed GC system properties help constrain new models/ideas for how galaxies form and evolve

- Knowing the locations and colors of GCs out to large galactocentric radius enables other science:
  - Dynamical studies of galaxies (use GCs as luminous tracers of galaxy

Observational Requirements

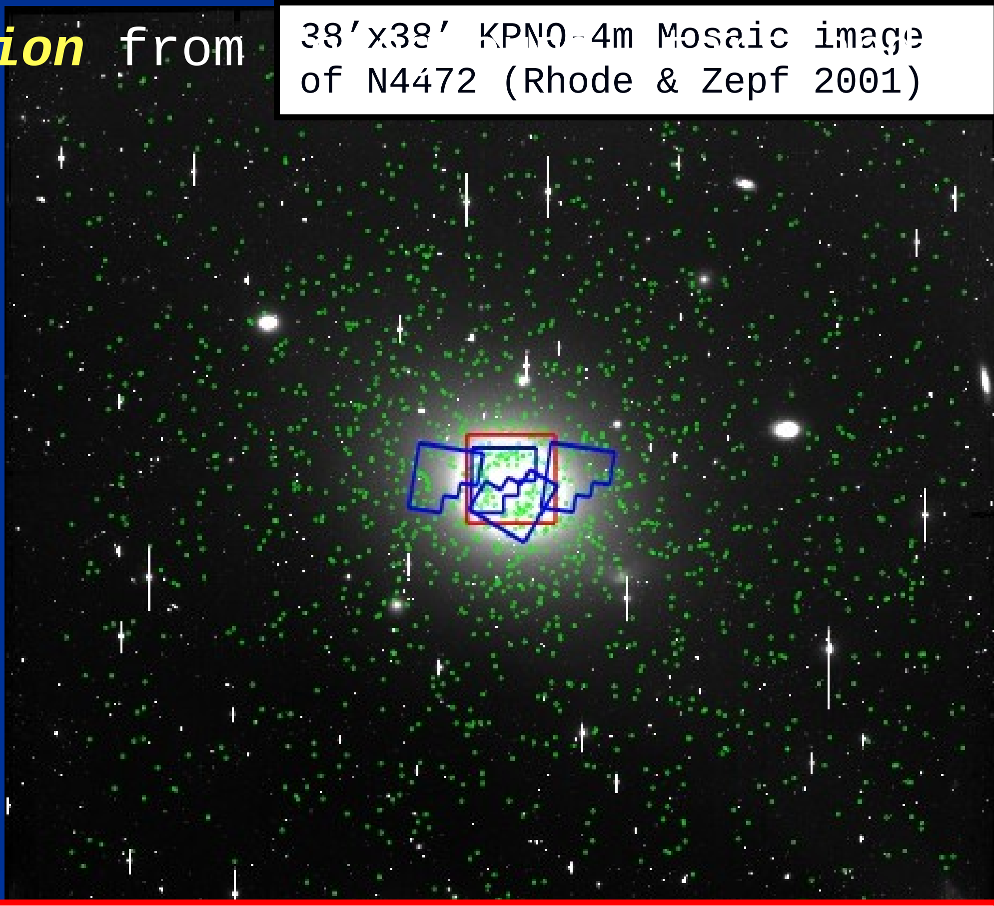
Aim: study globular cluster systems of giant galaxies beyond the Local Group

GCs are ***faint and unresolved*** in ground-based images at these distances; *contamination* from

Ideally, we want:

- large field of view
  GC systems of spirals and ellipticals extend to ~20 kpc to >100 kpc (~5′ to 23′ at 15 Mpc)
- excellent resolution
  to distinguish point-source GCs from background galaxies
- deep, multi-color imaging
  photometry in three filters (e.g., BVR) helps separate GCs from stars

38′x38′ KPNO 4m Mosaic image of N4472 (Rhode & Zepf 2001)

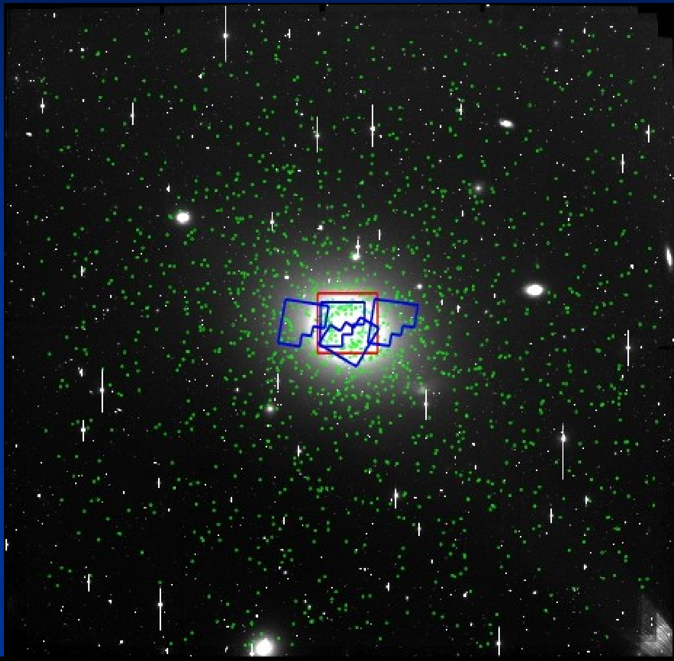


Green = GC candidates Blue, Red =

Two Main Methods Used Today

HST WFPC2 / ACS imaging:

- Superior sensitivity; easy to observe past GCLF peak at Virgo distances (V ~24)
- Distinguishes GCs from most background galaxies
- Very small areal coverage (r ~2.4′, or ~12 kpc at Virgo)
- Extrapolation necessary to get global properties



38′x38′ KP-4m Mosaic image of N4472 (Rhode & Zepf 2001)

Wide-field ground-based CCD imaging:

- Reach peak of GCLF of galaxies to ~25 Mpc with 4m telescope and reasonable exposure times
- Large areal coverage possible with mosaic CCDs

The Wide-Field GC System Survey

(with Steve Zepf, Arunav Kundu, Aaron Larner, Jessica Windschitl, Michael Young)

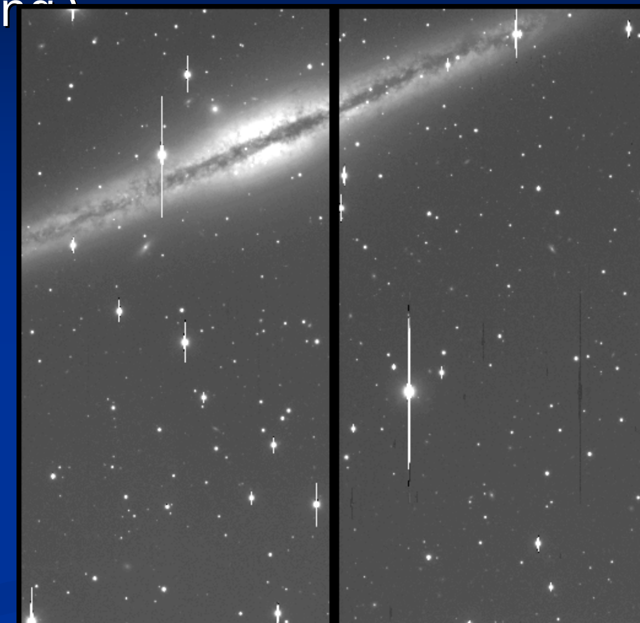
- Use wide-field mosaic imagers on the KP-4m and WIYN 3.5m to systematically study GC systems of Es, S0s, and spirals, 10-20 Mpc away

- GCs are point sources; select by their

  V magnitudes and BVR colors

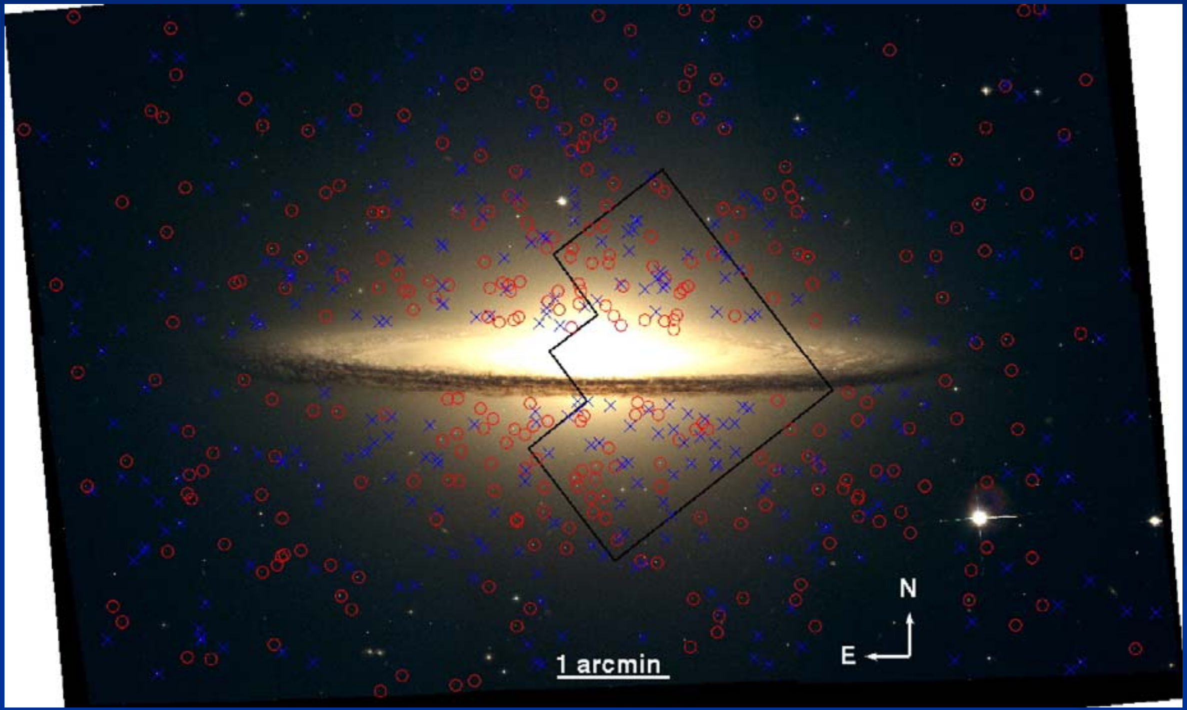
- Minimize and then quantify contamination with 3-color photometry, good image quality, archival HST data

- Derive accurate, ***global*** properties of each galaxy's GC system to constrain



WIYN Minimosaic Image of NGC 891

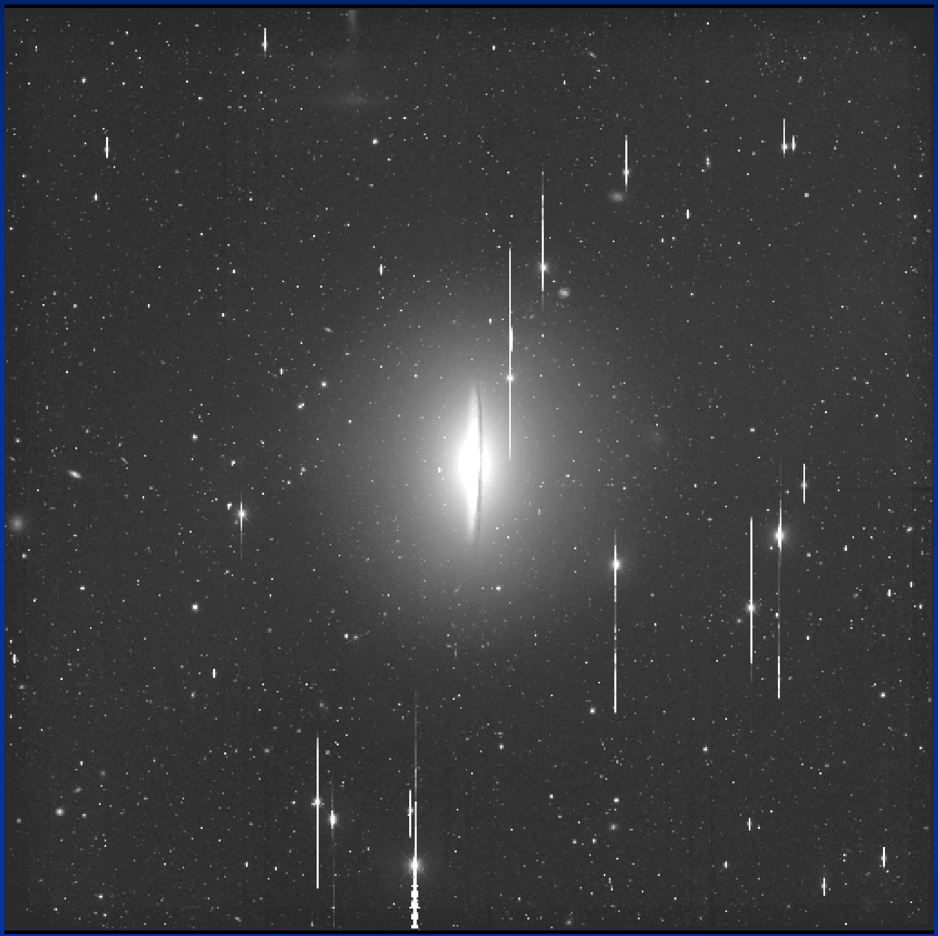
For comparison…



HST ACS **6-pointing mosaic** of the Sombrero galaxy

Circles and crosses = GC candidates identified by Spitler et al. (2006)
WFPC2 footprint = area of GC system studied by Larsen et al. (2001)

For comparison…

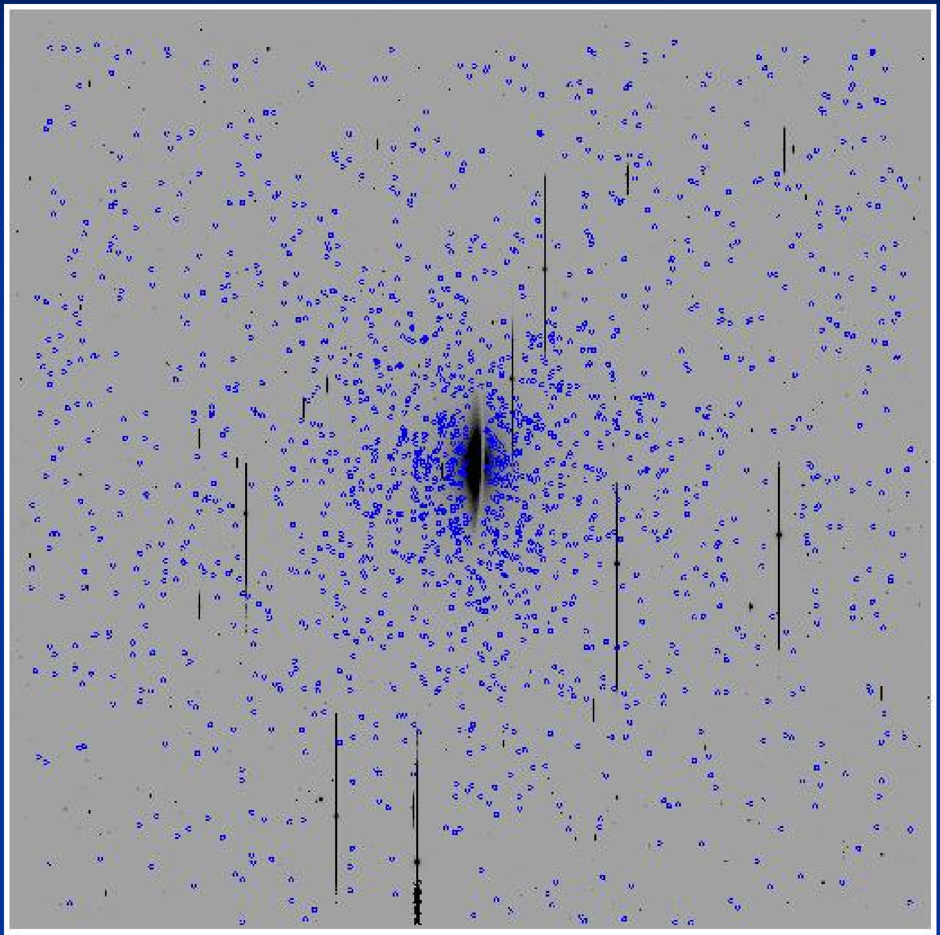


KP-4m Mosaic V image of Sombrero (Rhode & Zepf 2004)

FOV = 38′ x 37′ (Radial coverage ~75 kpc)

For comparison…

Blue = GC candidates (point sources with BVR mags and colors like GCs)



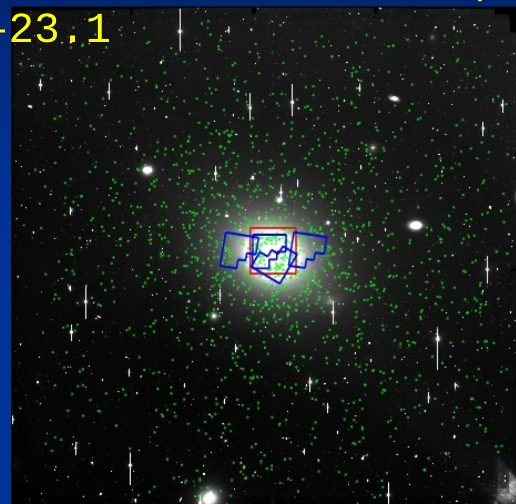
KP-4m Mosaic V image of Sombrero (Rhode & Zepf 2004)

FOV = 38′ x 37′ (Radial coverage ~75 kpc)

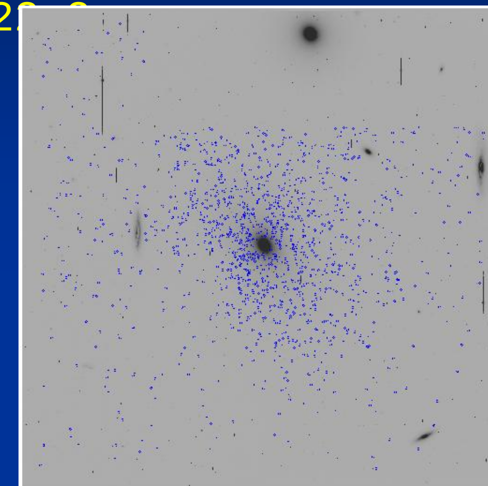
Elliptical & S0 Galaxies

Virgo Cluster Es

NGC 4472 (M49) M_V = −23.1

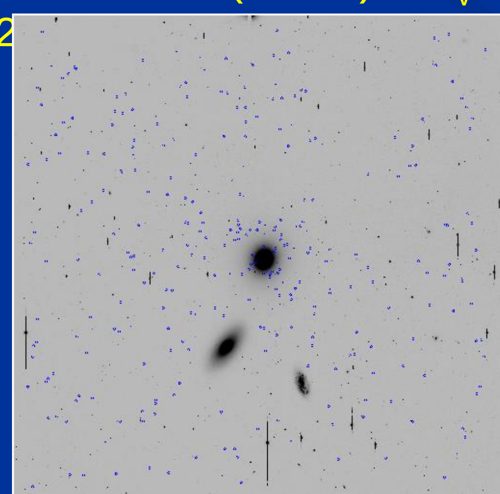


NGC 4406 (M86) M_V = −2

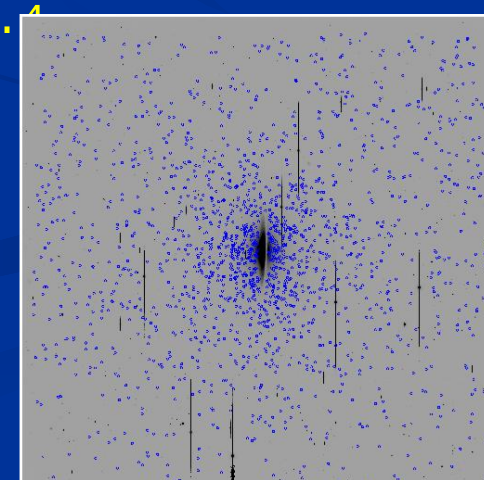


Field E/S0s

NGC 3379 (M105) M_V = −2



NGC 4594 (M104) M_V = − 22.

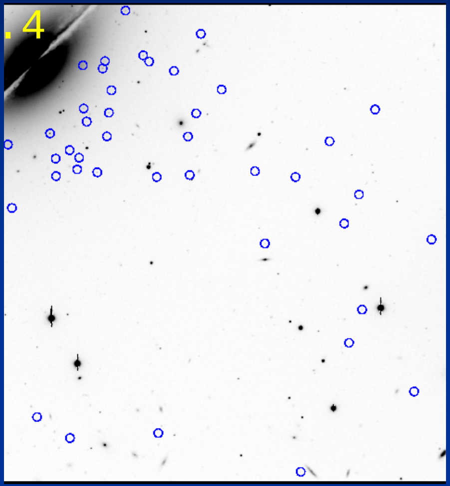


Spiral Galaxies

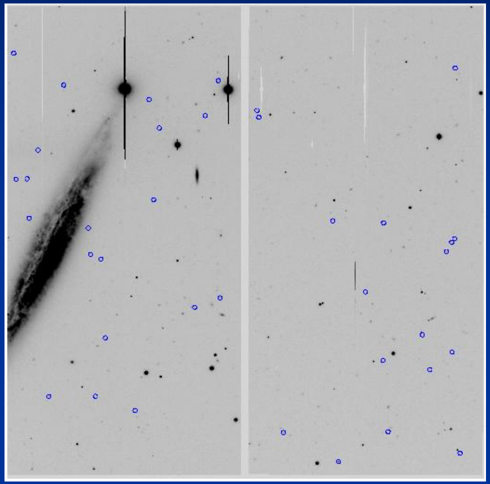
Inclination ~ 75 - 90 deg

Radial coverage ~ 20 - 40 kpc

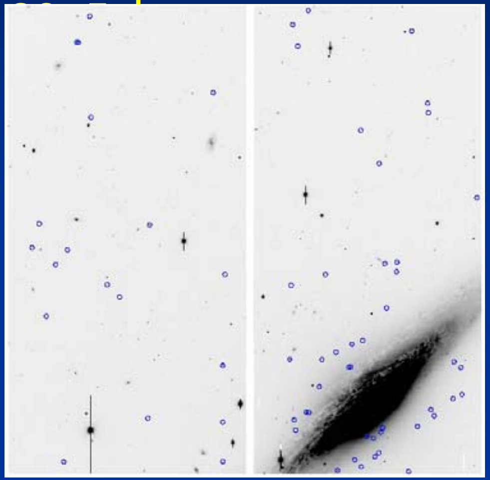
NGC 7814 Sab $M_V = -20.4$



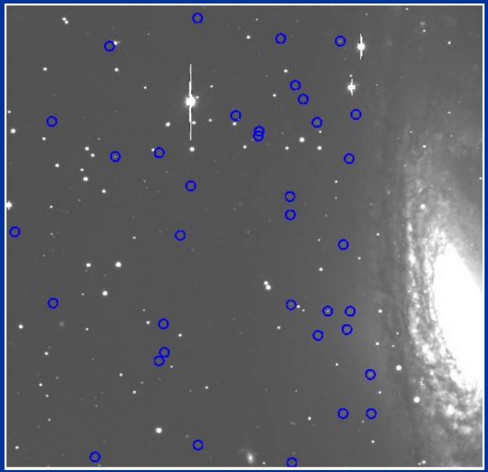
NGC 4157 Sb $M_V = -$



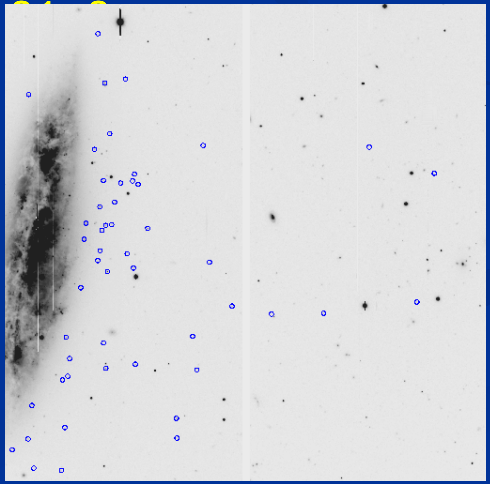
NGC 2683 Sb $M_V = -$



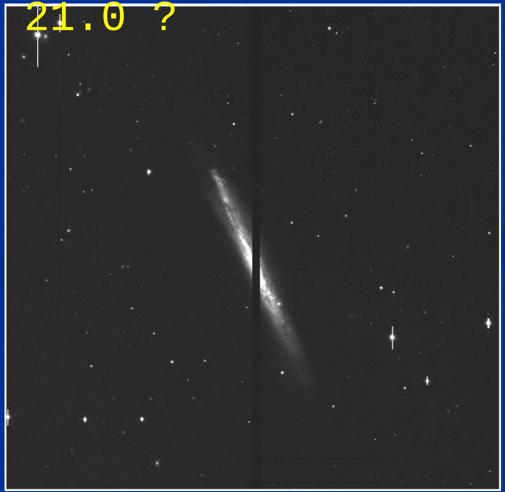
NGC 7331 Sb $M_V = -21.7$



NGC 3556 Sc $M_V = -$

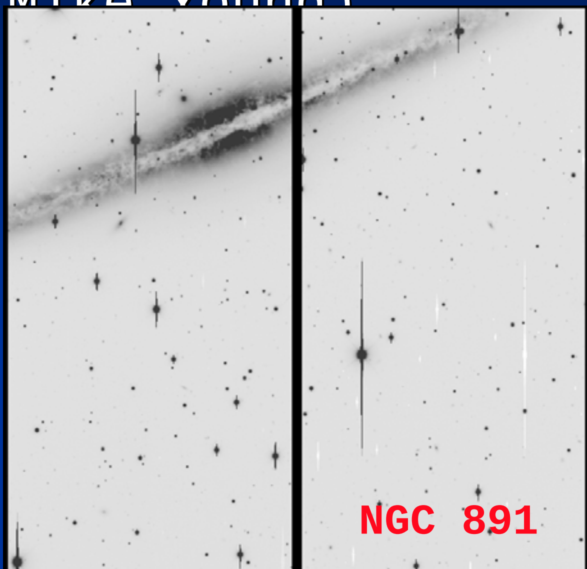


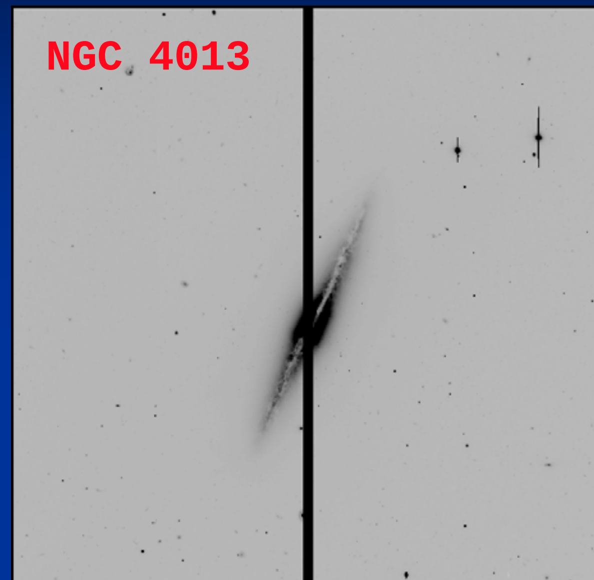
NGC 3044 Sc $M_V = -21.0$?

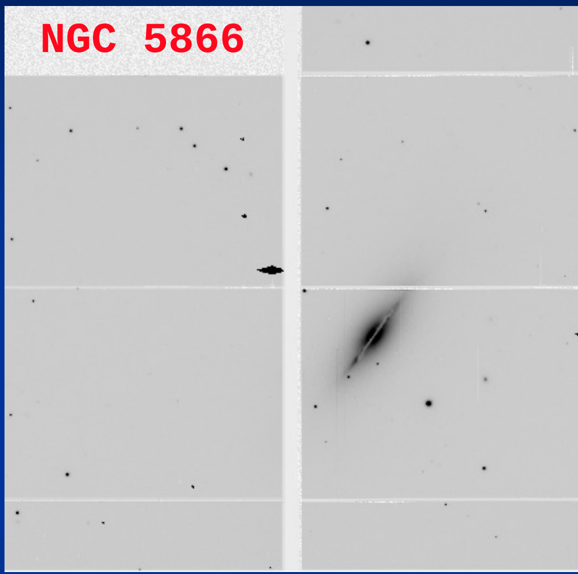


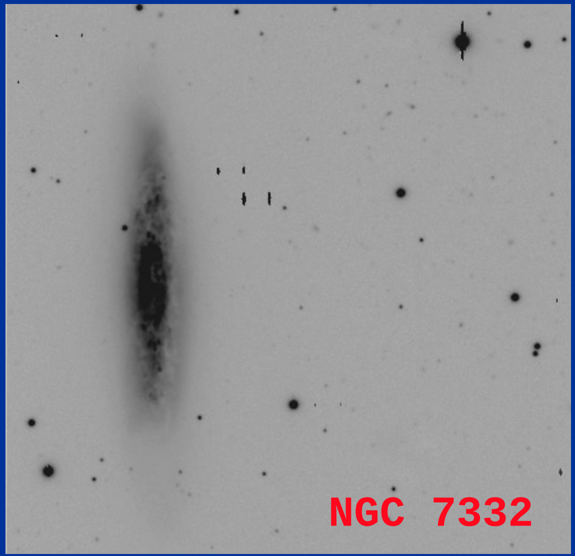
Spiral and S0 Galaxies in Progress

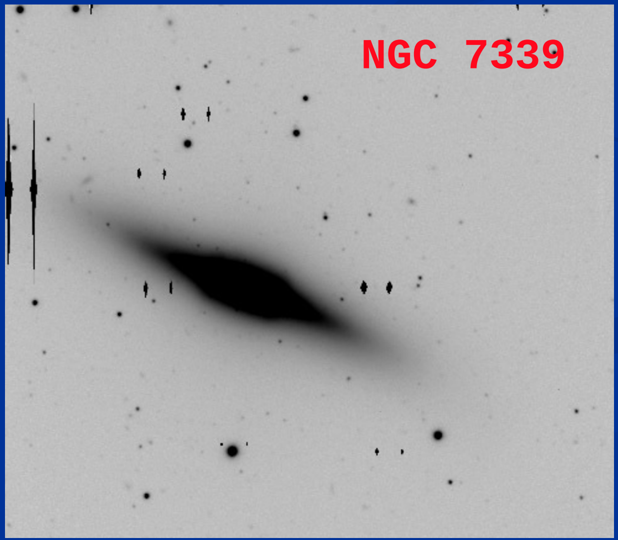
(with Indiana U. grad students Jessica Windschitl and Mike Young)

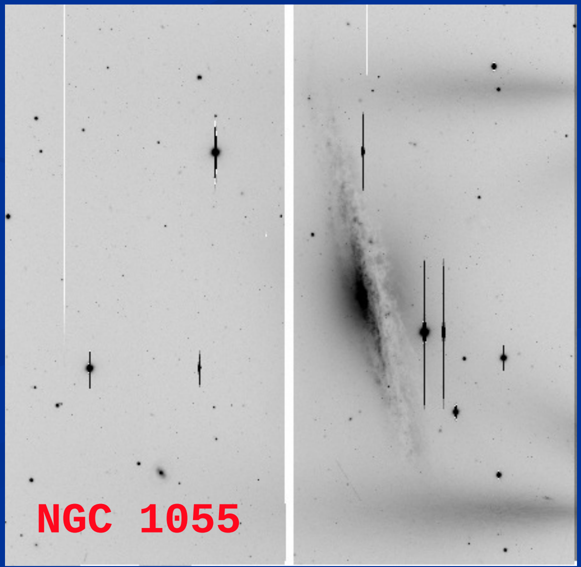












The Survey - Results So Far

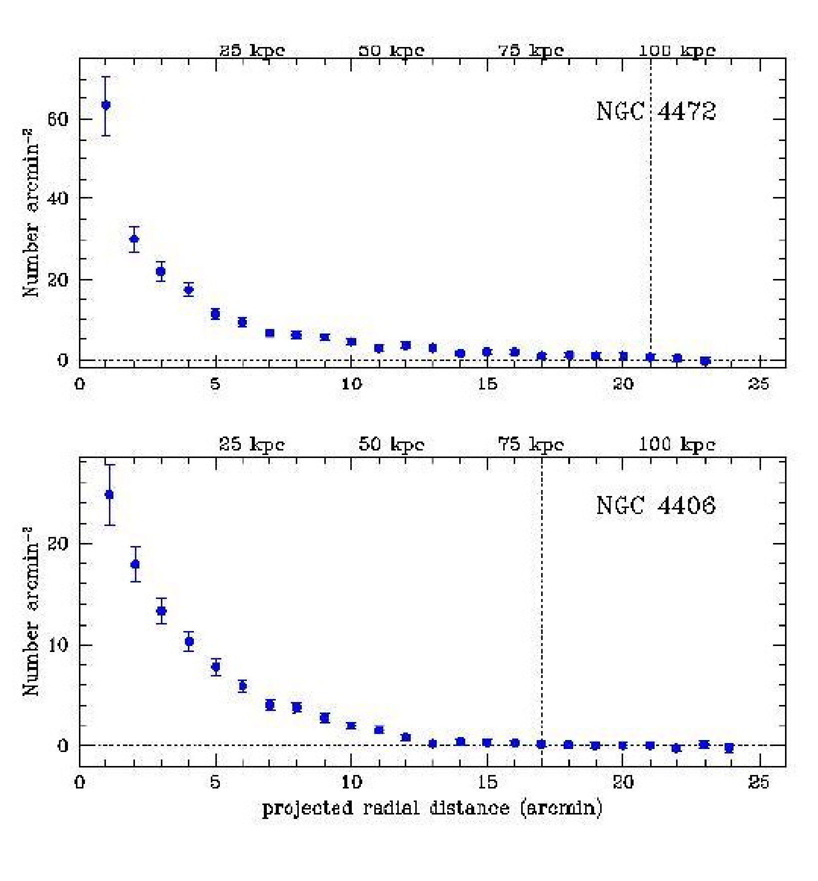
(Rhode & Zepf 2001, 2003, 2004; Rhode, Zepf, & Santos 2005; Rhode et al. 2007)

- Positions and BVR photometry of 10s - 1000s of GC candidates in nine giant galaxies, out to the full radial extent of the GC systems

- We have global GC system properties to compare to model predictions (see, e.g., Rhode & Zepf 2004)

- S_N 20-75% lower for 4 of 6 galaxies studied previously; errors ***2-4 times smaller*** for all

- Reasons: GC selection in three colors; good



Surface density vs. projected radius for GC systems of Virgo Ellipticals

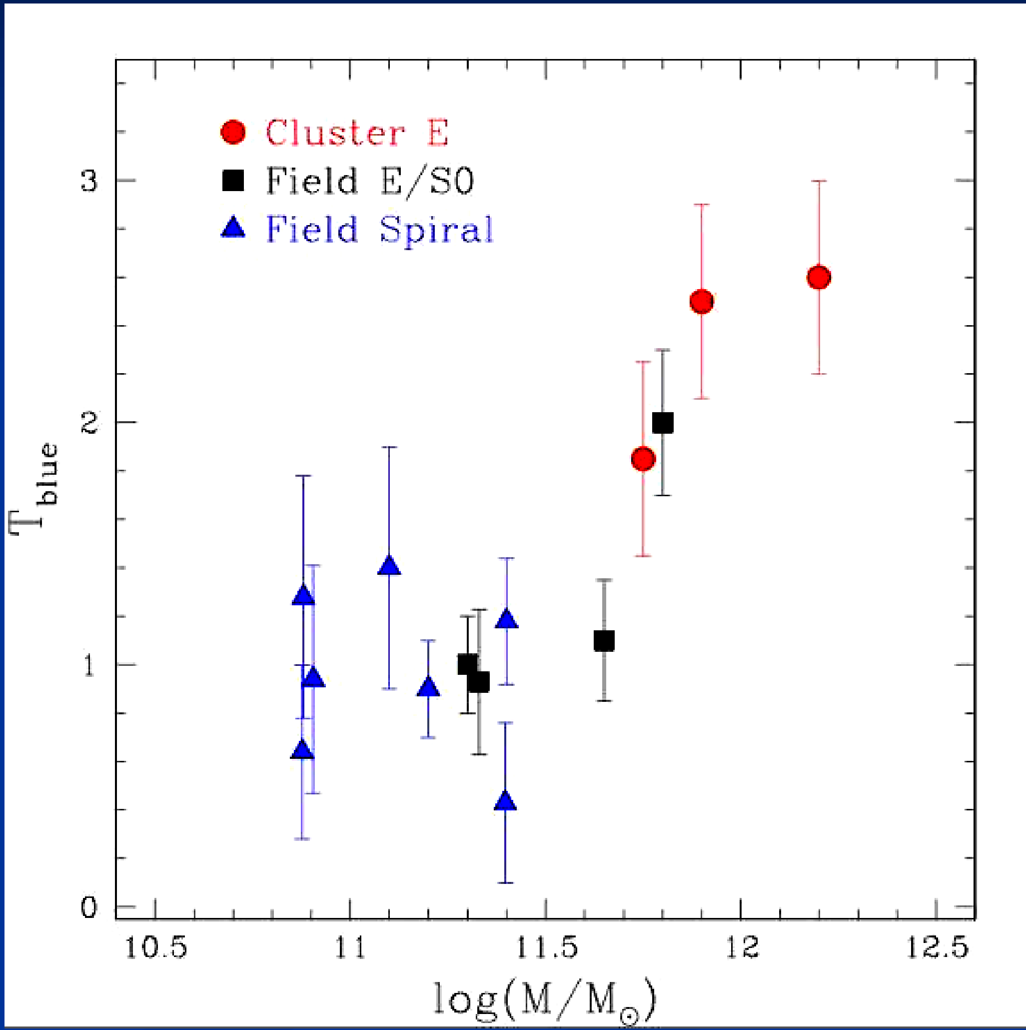
Mass-Normalized Number of Blue GCs (

(Rhode, Zepf, & Santos 2005; Rhode et al. 2007)

- Spiral-spiral merger model for the formation of ellipticals (Ashman & Zepf 1992) predicts that blue GCs in ellipticals come from progenitor spirals; red GCs formed in merger. Spirals and Es should have similar numbers of metal-poor (blue) GCs per host galaxy stellar mass

$T_{blue} = N_{GC(blue)} \, (M_{Galaxy} \, / \, 10^9 \, M_\odot)^{-1}$

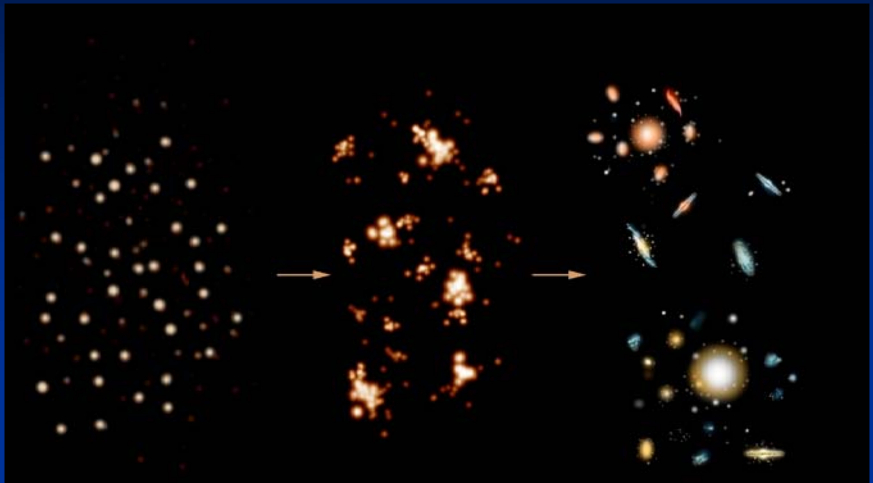
- T_{blue} in spirals is too small to account for blue GC populations of massive cluster ellipticals; simple spiral merger model cannot explain their formation



Nine survey galaxies, + Milky Way, M31, three from literature

Globular Clusters & Hierarchical Gala

(e.g., Beasley et al. 2002, Santos 2003, Rhode, Zepf & Santos



Gemini Observatory illustration

• In hierarchical galaxy formation scenarios, protogalactic fragments merge to form larger structures

• Metal-poor GCs form *during a finite period* in the early Universe, when these gas-rich fragments merge

•"Biasing": Massive galaxies in high-density regions of the Universe begin assembling first

•GC and baryonic structure formation suppressed at high *z* (due to reionization?)

•The more massive the final galaxy, the larger fraction of its total baryonic mass has

•Stellar evolution continues to enrich the intergalactic medium during the break from structure formation

•When baryonic structure formation resumes (~1 Gyr later), new GCs are more metal-rich

•Metal-rich GC populations are

Globular Clusters & Hierarchical Gala

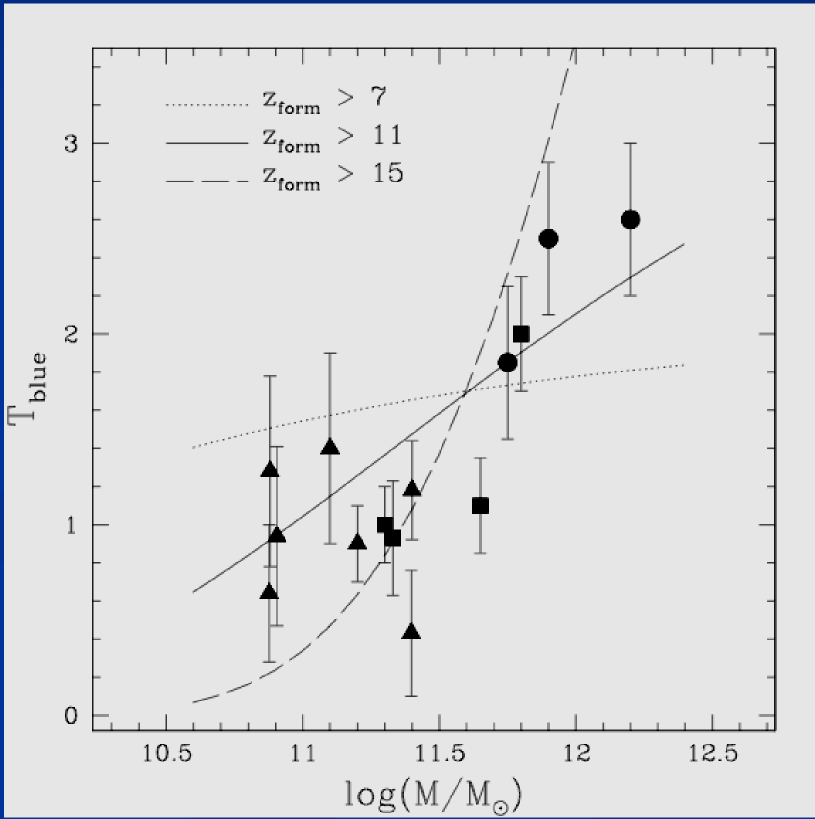
• Extended Press-Schechter calculation by Greg Bryan:

Assume T_{blue} proportional to fraction of galaxy mass collapsed into halos of $\geq 10^8\ M_{sun}$ by given redshift

Dotted line: metal-poor GCs formed before **z = 7**

Solid line: metal-poor GCs formed before **z = 11**

Dashed line: metal-poor GCs formed before **z = 15**



Rhode et al.

- The biased, hierarchical formation scenario is generally consistent with the data, but we need more predictions to fully test it!

Spectroscopy of GCs from the Survey

(with S. Zepf, A. Romanowsky, G. Bergond, R. Sharples, T. Bridges, K. Fr
J. Brodie, J. Strader, M. Beasley, D. Forbes, B. Chaboyer)

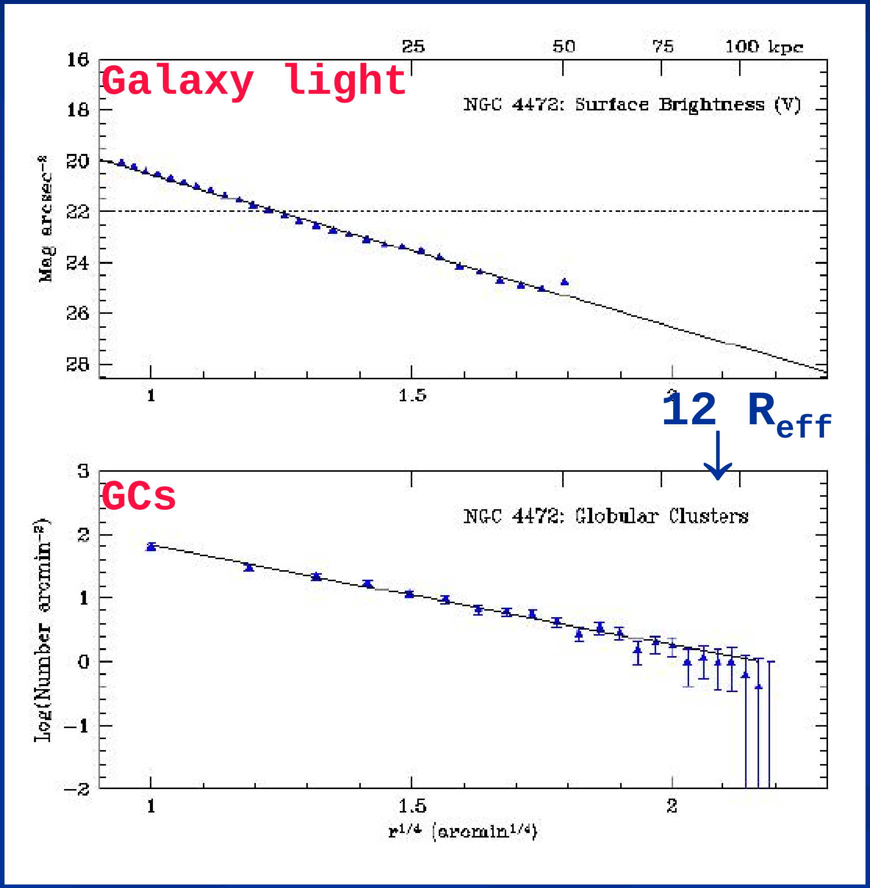
- Why do spectroscopy?
  - radial velocities
  - metallicities, ages of brightest GCs

- Dynamics: derive mass profiles of the galaxy halos, to 10-15 R_{eff}

- Kinematics of blue and red GCs should be different for different galaxy formation scenarios

- Spectroscopy from Keck, VLT, WIYN, AAT, WHT for 3 E/S0 galaxies from the survey; plans for SALT and

GCs and galaxy light in Virgo Elll



Rhode & Zepf (2001

Spectroscopy Results for NGC 4594

(Bridges, Rhode, Zepf, & Freeman 2007)

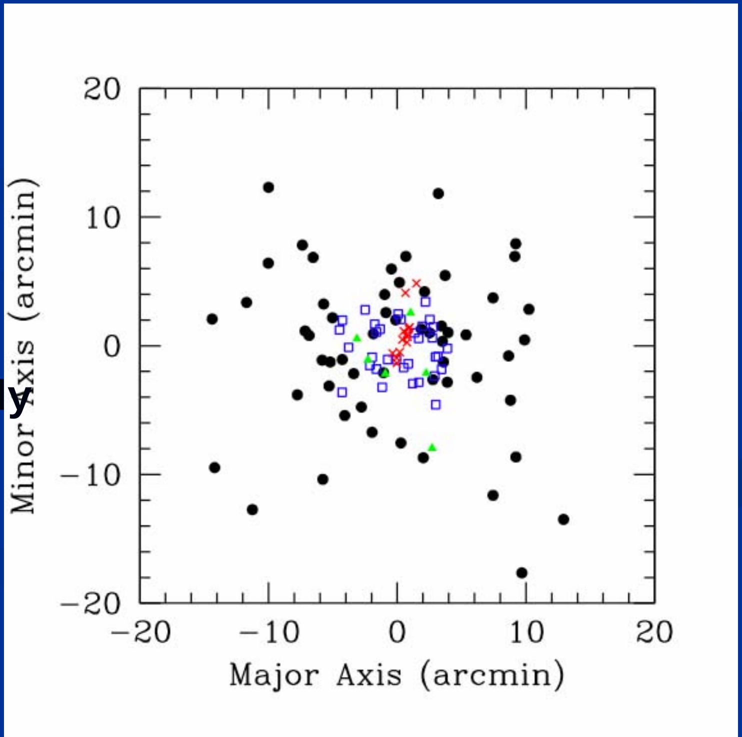
- NGC 4594 (M104) = the Sombrero Galaxy;
M_V = -22.4 field Sa/S0 with ~1900 GCs

- 62 GC velocities from AAT/2dF and WIYN/Hydra, <50 from literature

  ⇒ 108 GC velocities in M104

- Our data increase radial coverage by 4x to ~60 kpc

KP-4m Mosaic image of N4594

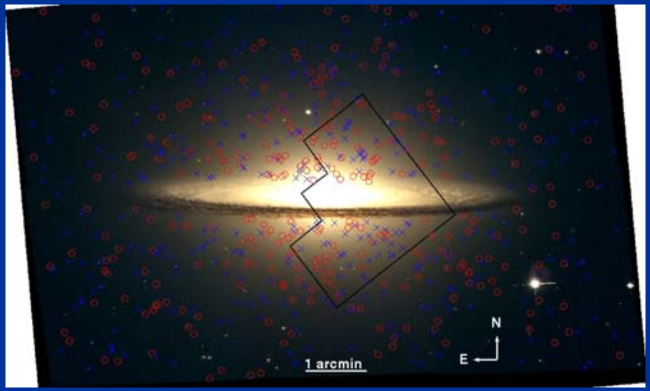


Black, green = GCs in our study
Red, blue = previous work

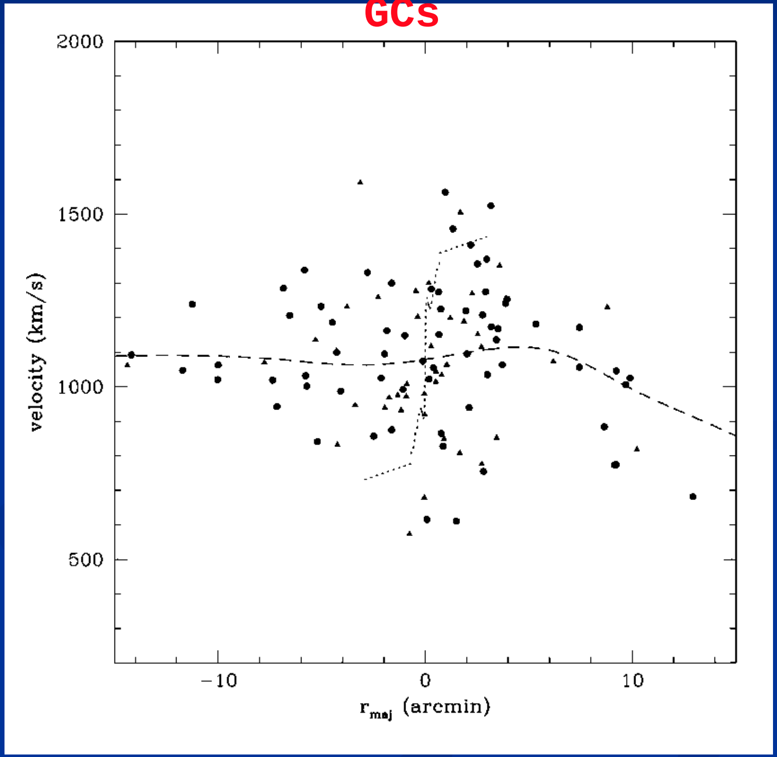
Spectroscopy Results for NGC 4594

(Bridges, Rhode, Zepf, & Freeman 2007)

- No significant rotation in the GC system
  - Angular momentum transferred outward by merger(s)?



Radial velocity vs. major axis distance for N4594 GCs



Circles = Blue GCs, Triangles = Red GCs

Dotted line = Stellar & gas rotation curve

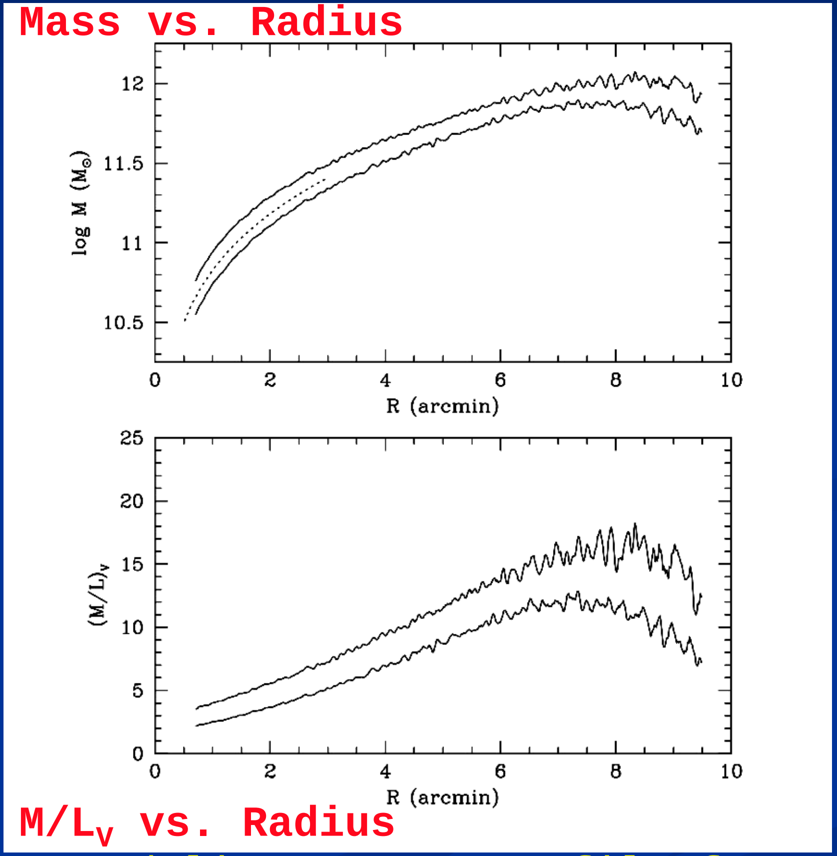
Dashed line = smoothed velocity

Spectroscopy Results for NGC 4594

(Bridges, Rhode, Zepf, & Freeman 2007)

- M/L_V goes from 3 near galaxy center to 14 at 7′ (20 kpc, or 4 Reff)
    - Evidence for dark matter halo in N4594

⇒Also have ~270 GC velocities to 60 kpc from Keck/DEIMOS with Jean Brodie's SAGES group

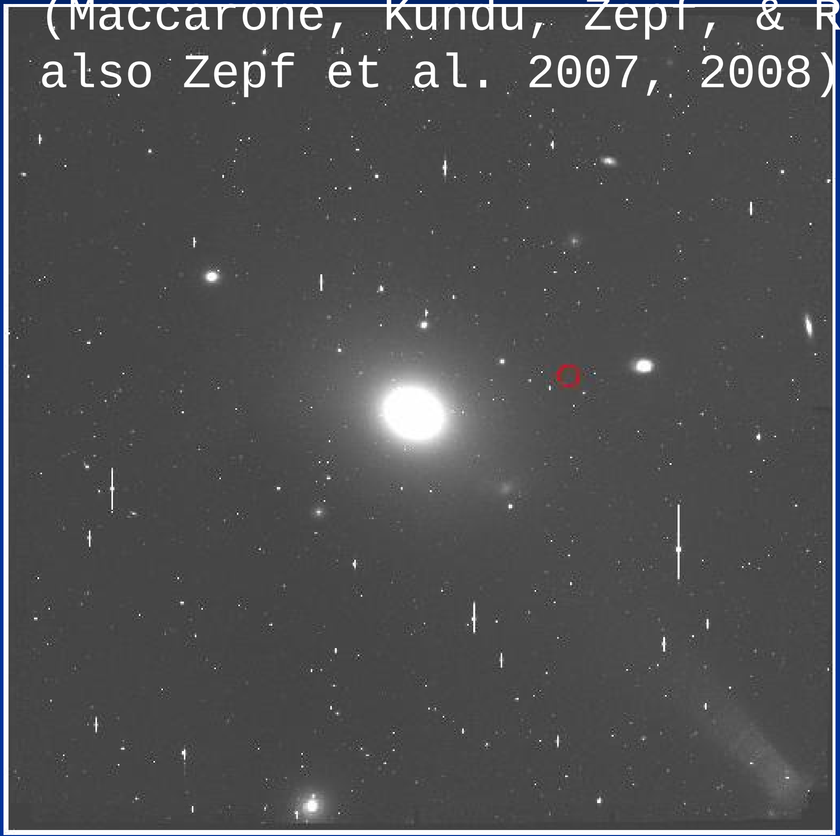


Dotted line = mass profile from stellar rotation curve (Kormendy & Westpfahl 1989)

Solid lines = 1-sigma bounds from GCs

A Black Hole in a Globular Cluster

(Maccarone, Kundu, Zepf, & Rhode 2007, *Nature*; also Zepf et al. 2007, 2008)

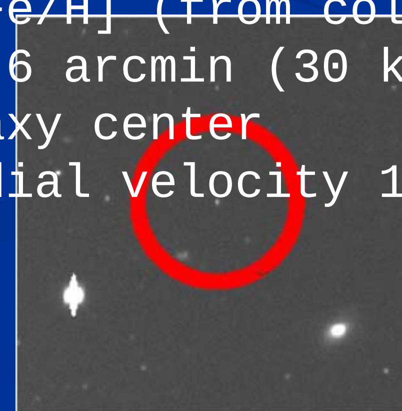


KP-4m Mosaic V image of N4472 FOV = 38′ x 38′, FWHM ~ 1″

- Matching XMM sources to locations of GCs in survey images of NGC 4472

  ⇒ X-ray signature of accreting black hole in one of our GCs

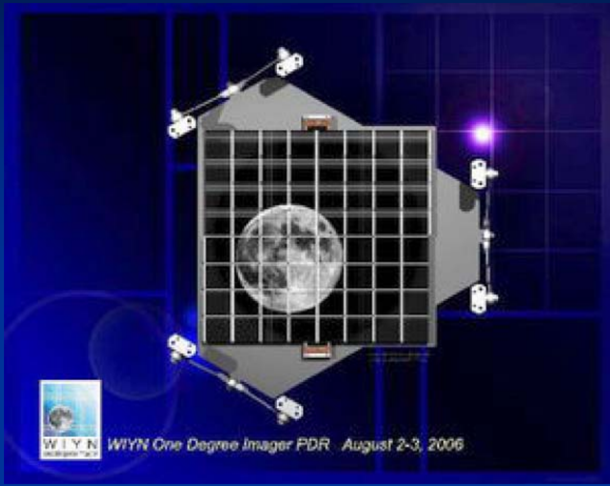
- The Globular Cluster:
  - RZ 2109 in NGC 4472 (Rhode & Zepf 2001)
  - V = 21.0 B-V = 0.7 V-R = 0.4
  - ~7.5 x 10^5 L_{SUN}
  - [Fe/H] (from colors) ~ -1.7
  - 6.6 arcmin (30 kpc) from galaxy center
  - Radial velocity 1477+/-7 km/s



See Tom Maccarone's talk on Friday, Matthew Steele's poster on WHT spectrum

The WIYN One Degree Imager GC System Survey

- ***Next step:*** Multi-year wide-field survey of ~30 galaxies in a range of environments with WIYN 3.5m + ODI



The ideal instrument for GC system studies: WIYN One Degree Imager

1-degree field, **1 Billion** 0.1″ pixels, <0.5″ resolution, high sensitivity in u′g′r′i′z′

Uses **Orthogonal Transfer CCD Arrays** to correct for atmospheric blurring + telescope motion at ~10-100 Hz

First Light Jan 2010; NOAO has 40% of WIYN time