2-Phase Assembly of Galaxies and their GC Systems

Collaborators

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Study Astrophysics of Globular clusters in Extragalactic Systems

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UCO/Lick Observatory
Two-phase early-type galaxy formation

- Motivated by observations of strong size-redshift evolution

**Half-light radius (z=0) versus mass**
(after Oser+2010)
Two-phase early-type galaxy formation

- Motivated by observations of strong size-redshift evolution

- Only ~10% of stars formed in major merger starbursts, even in bulges
  (SAMs: Parry et al 09, High z IR obs: Hopkins & Hernquist 10)
The SLUGGS Survey

SAGES Legacy Unifying Globulars and Galaxies Survey

26 nearby early-type galaxies; range of properties (M, env, ...)

Photometry (Subaru) and spectroscopy (Keck)

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

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

Spectroscopic Mapping of Early-type Galaxies to their Outer Limits
Wide field 2-D stellar kinematics with Keck

Use extra slit light from DEIMOS GC spectra to probe galaxy kinematics and metallicities to $\sim 3 R_{\text{eff}}$ (pseudo IFU)

Norris+'08; Proctor+'08; Foster+’09, 2010; Arnold+’10

“SKiMS”: Stellar Kinematics with Multiple Slits
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“SKiMS”: Stellar Kinematics with Multiple Slits

NGC 2768
Galaxy Kinematic Profiles

Inner profiles do not predict large radius behavior.
Galaxy Kinematic Profiles

Inner profiles do not predict large radius behavior.
NGC 3115
Arnold et al (2011)

Disky elliptical/S0 at ~10 Mpc
GC velocities from Keck+
Arnold et al 2011

N3115 data is not a fit!!

2-phase cosmological simulation
Ceverino et al 2010

Inner regions heated disk material
Outer regions accreted
Need large radii data to test generic merger predictions

Two-component galaxies can **in principle** be produced by major mergers

**BUT**

Low-angular momentum 1:1 merger needed for low halo rotation
  - Rare
  - Predicts kinematic twist - not so far seen

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I:1 Wet Merger Simulation

Hoffman et al. 2010
NGC 1407 GC metallicity profile

Forbes et al 2011
The Relationships between Compact Stellar Systems: A Fresh View of UCDs in M87
Brodie et al 2011

New area of parameter space

- faint UCD
- classic UCD

- faint compact GC
- bright compact “UCD”

![Image of a graph displaying parameter space for M87.](image-url)
The Relationships between Compact Stellar Systems: A Fresh View of UCDs in M87
Brodie et al 2011

New area of parameter space

No size-L relationship!
The Everything Plot

UCDs bright end of a continuous EC sequence
Gap between galaxies and star clusters

2 formation channels for star clusters?
GCs form as compact objects
ECs form with a range of radii that are tidally limited (van den Bergh '96; Da Costa et al '09; Baumgardt et al '10)

Only distance-confirmed objects
UCDs in M87 have the same size as MW ECs when rescaled by the tidal radius even though they have very different mass scales - 3 orders of magnitude!!!

**Prediction:** ECs should have a strong size-mass relation at a given $R$. 

Two populations of Star Clusters

- **ECs/UCDs tidally limited**

<table>
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<th>Color</th>
<th>Description</th>
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<tbody>
<tr>
<td>Orange</td>
<td>MW</td>
</tr>
<tr>
<td>Black</td>
<td>M87</td>
</tr>
<tr>
<td>Teal</td>
<td>Faint Fuzzies</td>
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</tbody>
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$$r_J = \left( \frac{G M_c}{2 V_G^2} \right)^{1/3} R_{GC}^{2/3}$$
SUMMARY

Tests of 2-phase galaxy assembly

26 nearby early-type galaxies

SLUGGS survey: Globular clusters to \( \sim 10 \) r_{eff}

SMEAGOL survey: Field stars to \( \sim 3 \) r_{eff}

Inner profiles \( \Rightarrow \) large radius behavior - wide field observations essential

Evidence for 2 components

Examples in: NGC 3115 GC and stellar kinematics

NGC 1407 Metallicity gradients

Difficult to produce rapid inner + low outer rotation with major mergers

Cosmological simulations of “wild disks” + accretion preferred

UCDs in M87

Faint UCDs discovered in M87

Need spectra and accurate sizes to define UCD samples

No size-luminosity relation

UCDs bright end of a continuous EC sequence

2 formation channels for star clusters?

GCs form as compact objects

ECs form with a range of radii that are tidally limited

*Prediction:* ECs should have a strong size-mass relation at a given R