Origin of Elliptical Galaxies

- Elliptical Galaxies Form Through Mergers
  - Nearby examples of merging gas-rich systems (e.g. Arp 220)
  - Multiple Nuclei within nearby “red and dead” systems
  - Red galaxies found up to z ~3 but low mass only?
    - Some must form bulk of stars at higher redshift

- Two Broad Classes of Mergers:
  - Dry (Gas-Free) Mergers:
    - Dissipation through violent relaxation
    - No star formation so no enrichment
    - Mass-loss through tides
  - Wet (Gaseous) Mergers:
    - Dissipation though shocks + violent relaxation
    - Associated star formation and AGN activity
    - Mass-loss though both tides and winds

- Both Processes at High and Low Redshifts
  - Down-sizing of Star Formation with time
  - H-β emission common in low-luminosity Es (~ 20% currently)
  - Dust, low-level star formation, AGN activity in some giant Es but relatively rare today
Fundamental Plane of Elliptical Galaxies

- Structural Properties of Elliptical Galaxies form a Fundamental Plane: size, surface brightness, and internal velocity dispersion (Djorgovski & Davis 1987; Dressler et al. 1987)
  - Projection used as a distance indicator for early-type galaxies
  - Alternative projections reflect formation history (e.g., k-space, Bender et al 1992)

- Wyoming Fundamental Plane Survey (Pierce & Berrington)
  - Survey of ~ 2500 Elliptical Galaxies Within 45 Nearby Clusters will be Used to Characterize and Quantify the Merger History of Cluster Environments.
  - Velocity Dispersions Measured from WIYN Spectroscopy
  - Photometric Properties from Imaging at WIYN and WIRO
Internal Velocity Fields of Elliptical Galaxies Reflect Merger History

High Resolution (R ~ 5000) and High Signal-to-Noise (S/N > 20) Spectra of Giant Elliptical Galaxies Reveal Complex Streaming Motions via Broadening Functions (broad profiles right panel). Line-of-sight velocity distribution function as well as 2-d maps (e.g., SAURON)

Moderate-Low Luminosity Ellipticals Have Much More Regular Velocity Fields (narrow profile right panel)

Core Structure within Giant Ellipticals: streaming associated with multiple super-massive black holes (Faber et al 2000)
Structural Scaling Relations Reflect Assembly History

Virial Theorem plus Assumption of Constant Mass/Light Implies:

\[ \langle \mu \rangle \sim \sigma^2/R \]

Elliptical Galaxies Should Populate a 3-parameter Plane

Two Families are Revealed:

The Brightest, Most Massive Ellipticals Populate a Distinct Region (the Upper Right Region of Each Panel):


Fainter, Less Massive Systems Appear to Lie Along a “Dissipational Sequence” (see Lower-Right Panel)

Merger Models Are Just Beginning to Include Gaseous Dissipation. But May Soon Allow Detailed Comparison With Data.

Two families have quite different structural properties: largest systems have cores with complex velocity fields, smaller systems lack cores and have regular velocity fields.
The Velocity Dispersion Distribution Function (VDDF) of Five Nearby Clusters

Parameterized fits to the VDDF (e.g. Schechter) offers promise for quantifying the merger history of galaxies, independent of their morphology or their stellar component (e.g. Sheth et al. 2003).

Accurate fitting requires complete samples to roughly 0.3 dex below $\sigma^*$ ($\sim 3$ mags below $L^*$).

A similar survey at high redshift should reveal evolution in VDDF and enable the assembly history to be parameterized and quantified.
Reliable fits for both $\sigma^*$ and $\alpha$ require good sampling $\sim 3$ mags below $L^*$

- Pushing to highest redshifts ($z > 2$) still possible if $\alpha$ is constrained

- Hierarchical Merging Implies Evolution in VDDF:
  - Expect $\sigma^*$ to increase with time (smaller at high $z$)
  - The “faint end” power law slope ($\alpha$) should steepen with time
Quantifying the Assembly History of Elliptical Galaxies

- Fundamental Plane and VDDF Offer Promise for Quantifying the Assembly History of Ellipticals
- A Corresponding Survey at High Redshift (1 < z < 2) Would Sample the Epoch of Peak Assembly
- Did massive ellipticals undergo early epoch of intense star formation and elemental enrichment (wet) followed by period of hierarchical merging (dry)?
- What is the frequency of low-level star formation in low-luminosity ellipticals. Today its as high as 20% 3-4 mags below L*.
- Early universe holds the key for addressing these issues and characterizing these processes.
- At high redshifts, all the standard diagnostic lines will be found at near-infrared wavelengths (J & H)
Discovering High Redshift Clusters with the Spitzer Space Telescope

The spectral energy distribution peaks in the rest-frame H-band.

Optical surveys have revealed clusters with $z < 1$ (e.g. Gladders et al. 2007).

The Spitzer 3.5m – 4.5m color becomes very red for $z > 1$ ellipticals (e.g. Eisenhardt et al. 2007, Stanford et al. 2005).

A Warm Spitzer Survey of 500 sq. deg. could reveal $\sim 1500$ $z > 1$ clusters (McCarthy 2007; van Dokkum et al. 2007)
Fundamental Plane at $z > 1$: Survey Requirements-I

- Survey should span peak epoch of assembly ($1 < z < 2$)
- Familiar Optical Features found in J-band at $z > 1$
- High Resolution ($R \sim 3500$) and High Signal-to-Noise ($S/N > 20$) Near-IR Spectra (Y, J, H bands)
- Complete Sample to $M^* + 3$ mags (to sample VDDF)
- Multi-object Spectroscopy ($\sim 50$ spectra per 5 arcmin Field)
- Require Several Clusters in Order to Sample Range of Environments
Straw-man Example: TMT + IRMS

- Apparent mags: Absolute Mags of Nearby Gals + DM (D_L) + K-corr. + 1 Mag evol.
- Multi-object Spectroscopy over 5-7 arcmin field (GMT+NIRMOS or TMT+IRMS)
- TMT + IRMS Assumptions (from TMT Detailed Science Case Table 5-1):
  - R = 3270, Slit: 0.23 arcsec, Sensitivity as Given
  - Exposure Times to Reach S/N = 20 (minimum for good vel. disp.)
  - (Caution: slit losses only roughly estimated)

<table>
<thead>
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<th>Z</th>
<th>Band</th>
<th>M* - 1 (exp)</th>
<th>M* + 2 (exp.)</th>
<th>M* + 3 (exp.)</th>
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<td>16.7 (min)</td>
<td>19.7 (min)</td>
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<tr>
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<td>Y</td>
<td>17.6 (min)</td>
<td>20.6 (min)</td>
<td>21.6 (min)</td>
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<tr>
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<td>18.5 (min)</td>
<td>21.5 (30 min)</td>
<td>22.5 (2 hrs)</td>
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<tr>
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<td>J</td>
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<td>22.2 (1 hr)</td>
<td>23.2 (6 hrs)</td>
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<tr>
<td>1.75</td>
<td>---</td>
<td>19.9 (30 min)</td>
<td>22.9 (3 hrs)</td>
<td>23.9 (20 hrs)</td>
</tr>
<tr>
<td>2.00</td>
<td>H</td>
<td>20.7 (1 hr)</td>
<td>23.7 (16 hrs)</td>
<td>24.7 (80 hrs)</td>
</tr>
<tr>
<td>2.25</td>
<td>H</td>
<td>21.6 (2 hrs)</td>
<td>24.6 (80 hrs)</td>
<td>25.6 (500 hr)</td>
</tr>
</tbody>
</table>
Survey Requirements-II

- Assume 3 Broad Redshift Bins:
  - $(0.5 < z < 1.0, 1.0 < z < 1.5, 1.5 < z < 2.0)$
- Assume 10 Clusters/Bin (range of environments)
- 2 Setups/Cluster (100 galaxies: members + field)
- 20 Hours/Cluster (2 Nights/cluster)
- Sample of ~ 3000 Galaxies (Cluster + Field)
- Full Survey: 60 nights
- Minimum Survey (fewer clusters): 30 nights
- Impact of Depth vs. # Clusters: TBD
Summary

- **Survey of Fundamental Plane (1 < z < 2)**
  - Would Reveal the Assembly History of Elliptical Galaxies
    - Characterize the Assembly Process
    - Relative Role of Wet vs. Dry Mergers
    - Characterize the Down-sizing of Star Formation within Early-type Galaxies

- **The Velocity Dispersion Distribution Function (VDDF)**
  - Enables more direct comparison with numerical models
  - Enables comparison of formation histories of ellipticals and spirals
Atmospheric $\text{H}_2\text{O}$ defines the near-infrared windows ($Y$, $J$, $H$, $K$).

Collisional excitation of the upper atmosphere results in strong emission lines (mostly OH).

Thermal emission from atmosphere dominates for $\lambda > 2.3 \, \mu$. The infrared night sky is very bright, approximately $10^4$ times brighter than the background in space. High resolution: work between the lines. Beware scattered light in spectrograph!