Quantifying the (Late) Assembly History of Galaxies

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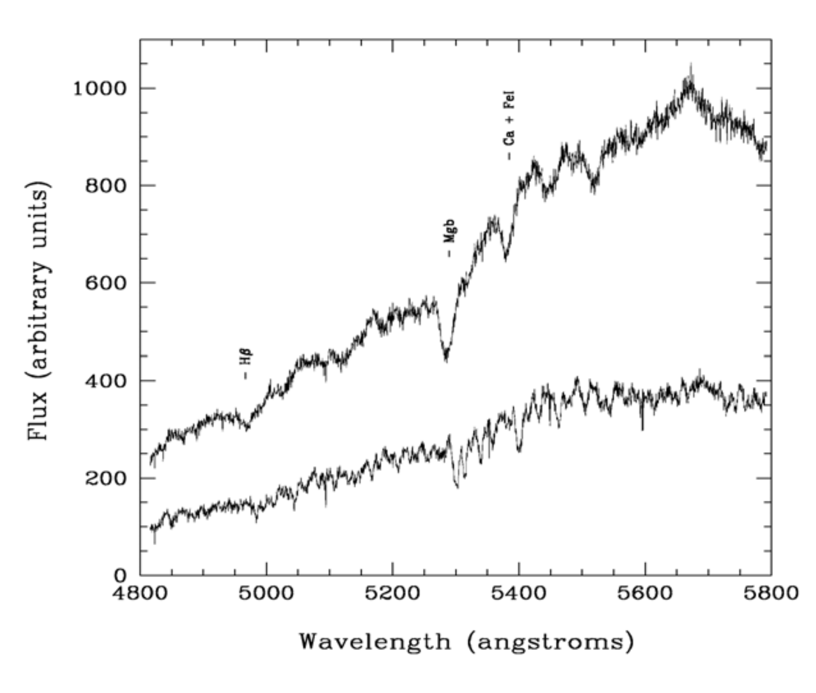
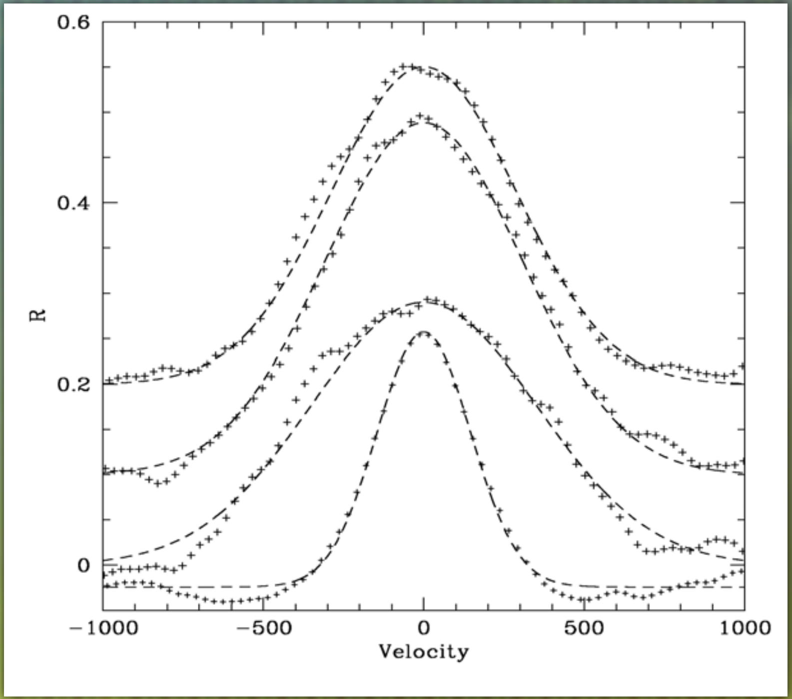
- What I Think We Already Know:
  - Morphology Density Relation (Assembly Depends on Environment) (Dressler 1980)
  - Ratio of Star Forming Galaxies in Clusters Increases with z (Butcher & Oemler 1984; van Dokkum et al. 2000)
  - Peak Epoch of Assembly and Star Formation ($1 < z < 3$) (e.g., Dickinson et al. 2003)
  - For $z < 1$ Familiar Forms but for $z > 1.5$ Chaotic Morphology
  - Structural Scaling Relations (FP and TF) in Place by $z \sim 1$ (van Der Wel et al. 2004; Miller et al. 2011)
  - Ellipticals (L*) Have Grown ~ 2x in Mass for $z < 1$, for 4L* Consistent with Passive Evolution (Brown et al. 2007)
  - Population of Proto-ellipticals Undergoing Mergers Present within Rich Clusters. Two Populations of Ellipticals? (Dressler 1997; van Dokkum et al. 1999)
- What Can the Traditional Scaling Relations at $1 < z < 2$ Tell Us About Assembly History?

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

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 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 Theorm plus Assumption of Constant Mass/Light Implies:
$<\mu> \sim \sigma^2/RG$

Elliptical Galaxies Should Populate a 3-parameter Plane

Two Families are Revealed:

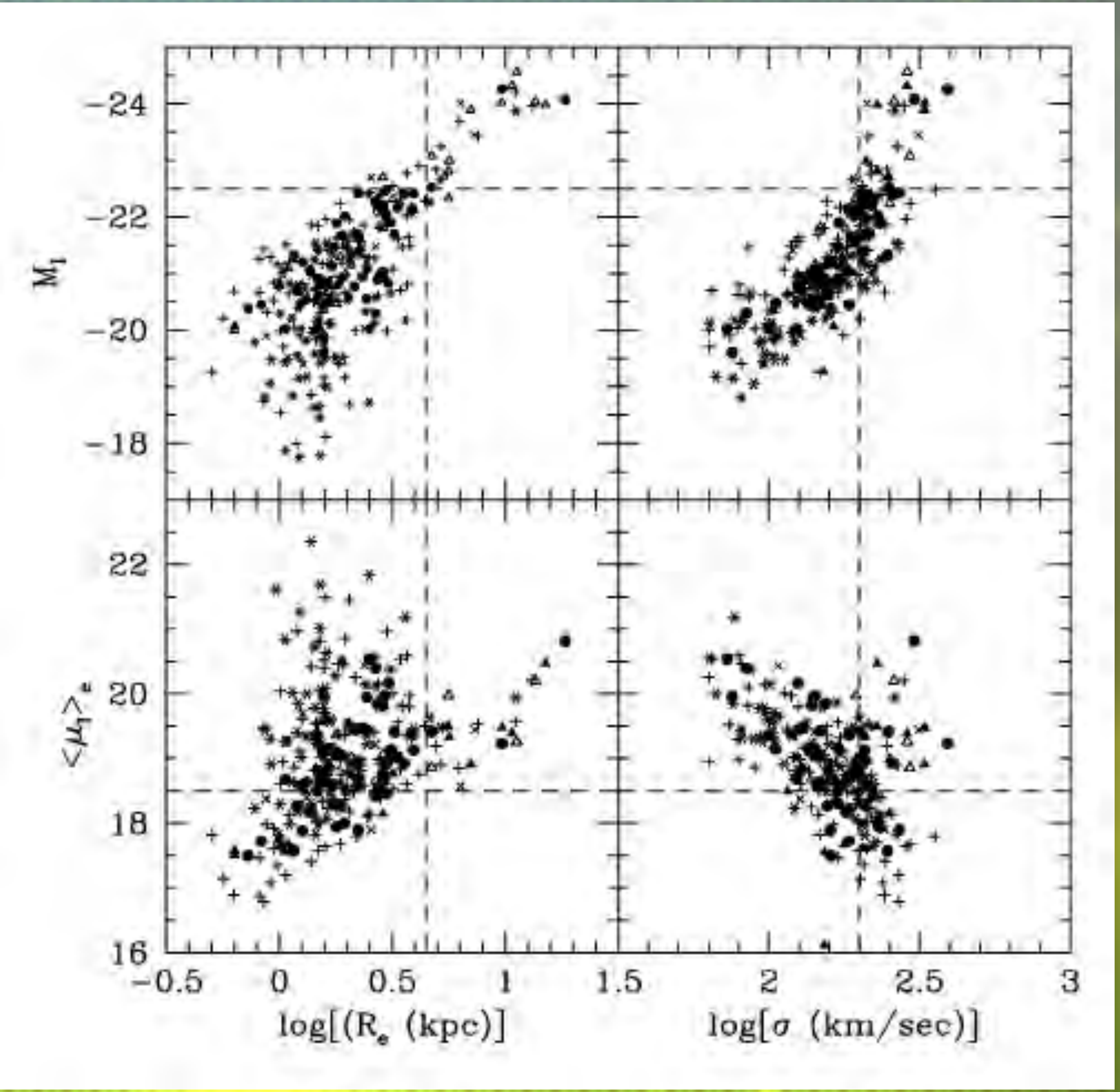
The Brightest, Most Massive Ellipticals Populate a Distinct Region (the Upper Right Region of Each Panel):

Interpreted as Evidence for Dry Merger Growth of Most Massive Systems.

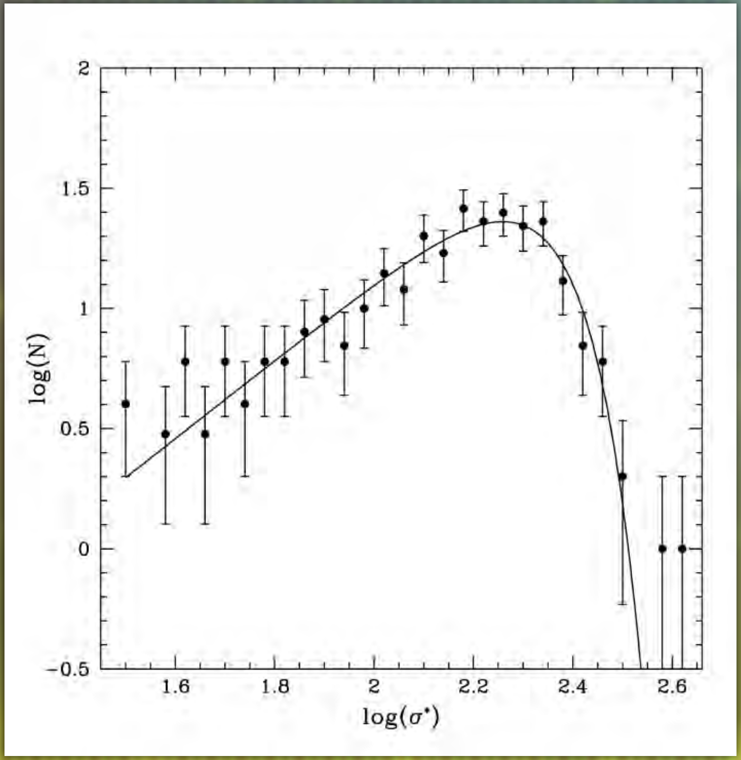
Fainter, Less Massive Systems Appear to Lie Along a "Dissipational Sequence" (see Lower-Right Panel)

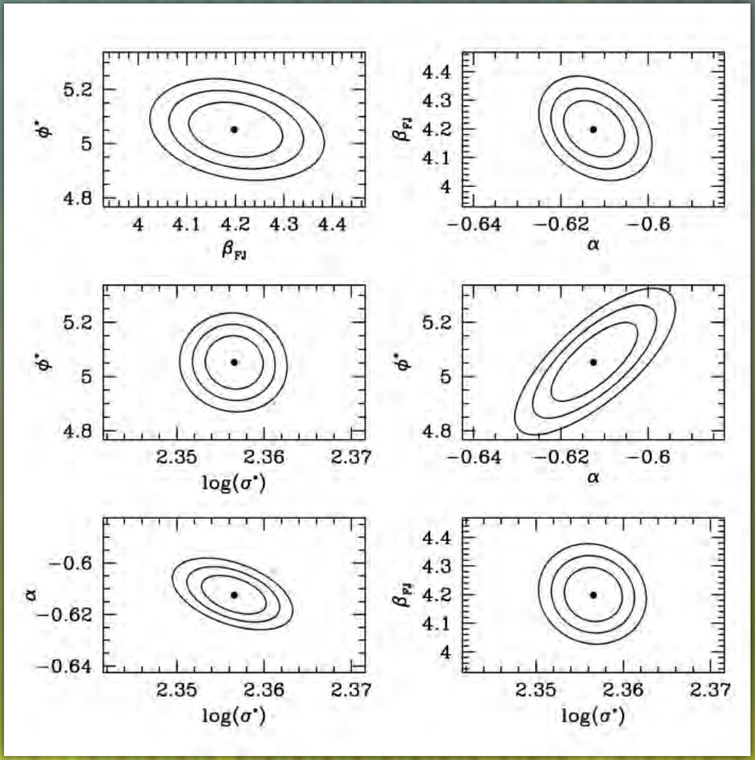
Merger Models Are Beginning to Include Gaseous Dissipation. But May Soon Allow Detailed Comparison With Data.

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



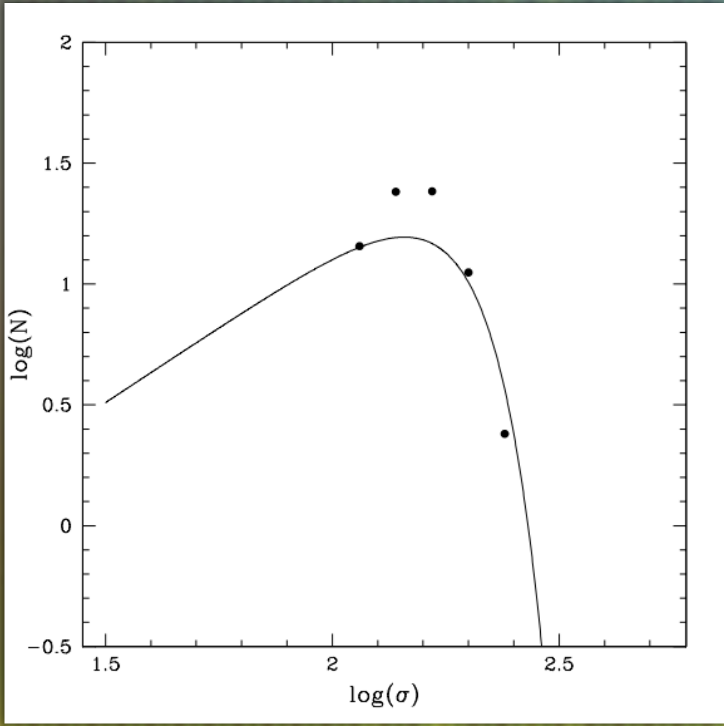


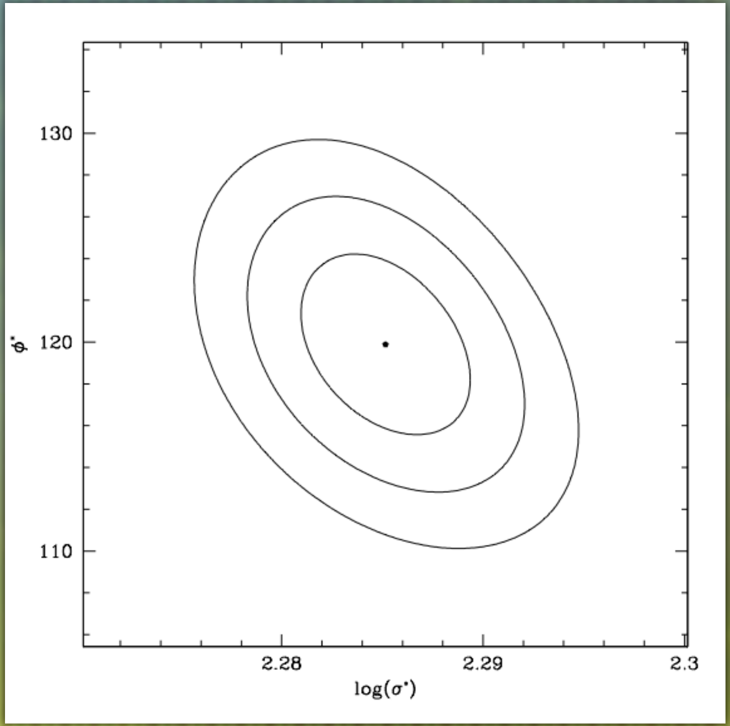
Parameterized fits to the VDDF (e.g. Schechter) offers promise for quantifying the merger history of galaxies, independent of their morphology or their stellar component (e.g Sheth et al. 2003).

Accurate fitting requires complete samples to roughly 0.3 dex below σ* (~ 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.

Incompleteness Effects VDDF Fits





- Reliable fits for both σ* and α require good sampling ~ 3 mags below L*
- Pushing to highest redshifts (z > 2) still possible if α is constrained
- Hierachical Merging Implies Evolution in VDDF:
  - Expect σ* to increase with time (smaller at higher z)
  - The "faint end" power law slope (α) should steepen with time

Spectroscopic Survey of Elliptical Galaxies

- Fundamental Plane and VDDF Offer Promise for Quantifying the Assembly History of Ellipticals (wet vs. dry mergers)
- Survey of Cluster & Field Ellipticals 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 star formation in lower-luminosity ellipticals (downsizing)? Today its as high as 20% 3-4 mags below L*.
- At high redshifts, all the standard diagnostic lines will be found at near-infrared wavelengths (J & H) and would also provide metallicities.

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 ~ 3000) 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 (~ 50 spectra per 5 arcmin Field)
- Require Several Clusters in Order to Sample Range of Environments
- 20 Hours/Cluster (2 Nights/cluster)
- Sample of ~ 3000 Galaxies (Cluster + Field)
- Full Survey: 60 nights

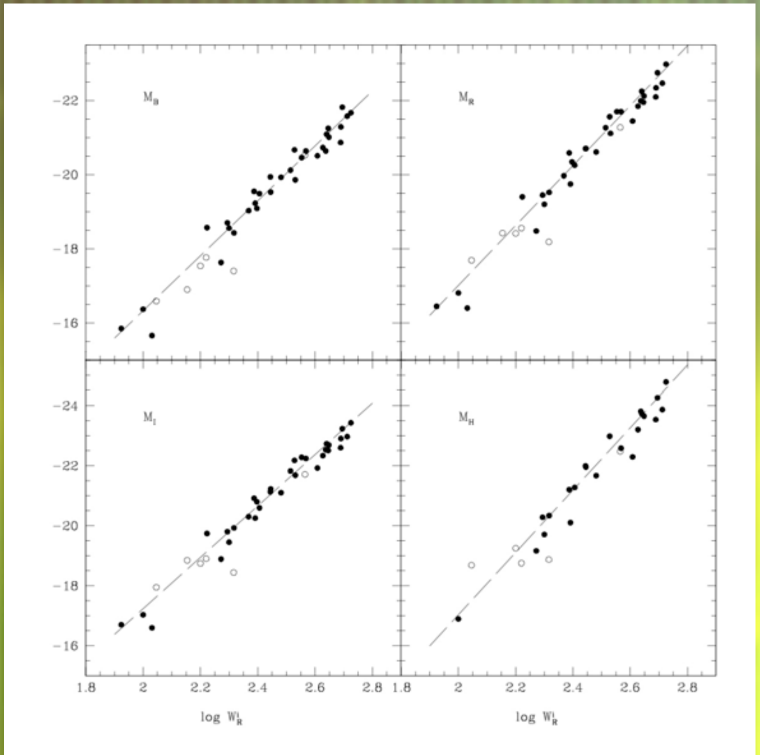
Straw-man FP Survey: GMT + GMACS & NIRMOS

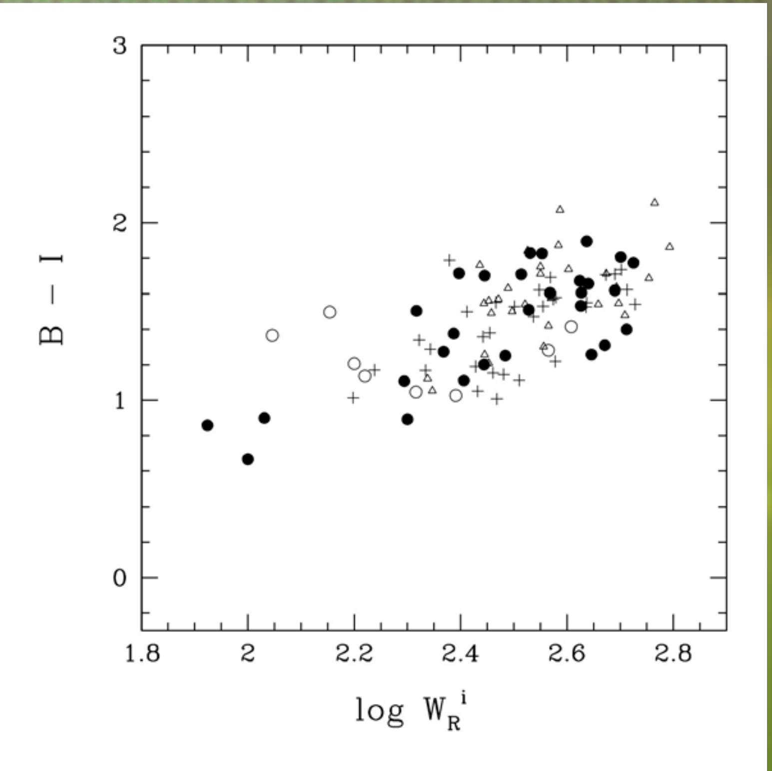
- Apparent mags: Absolute Mags of Nearby Gals + DM (D_L) + K-corr.+ 1 Mag evol.
- Mulit-object Spectroscopy over 5-7 arcmin field
- GMT + NIRMOS Assumptions (from TMT Detailed Science Case Table 5-1):
  - R = 3000, Slit: 0.3 arcsec, Sensitivity as Given
  - Exposure Times to Reach S/N = 20 (minimum for good vel. disp.)
  - (Caution: slit losses only roughly estimated)

Z	Band	M* - 1 (exp)	M* + 2 (exp.)	M* + 3 (exp.)
0.75	I	16.7 (min)	19.7 (min)	20.7 (min)
1.00	Y	17.6 (min)	20.6 (min)	21.6 (min)
1.25	J	18.5 (min)	21.5 (30 min)	22.5 (2 hrs)
1.50	J	19.2 (min)	22.2 (1 hr)	23.2 (6 hrs)
1.75	---	19.9 (30 min)	22.9 (3 hrs)	23.9 (20 hrs)
2.00	H	20.7 (1 hr)	23.7 (16 hrs)	24.7 (80 hrs)
2.25	H	21.6 (2 hrs)	24.6 (80 hrs)	25.6 (500 hr)

What About Disk Galaxies?

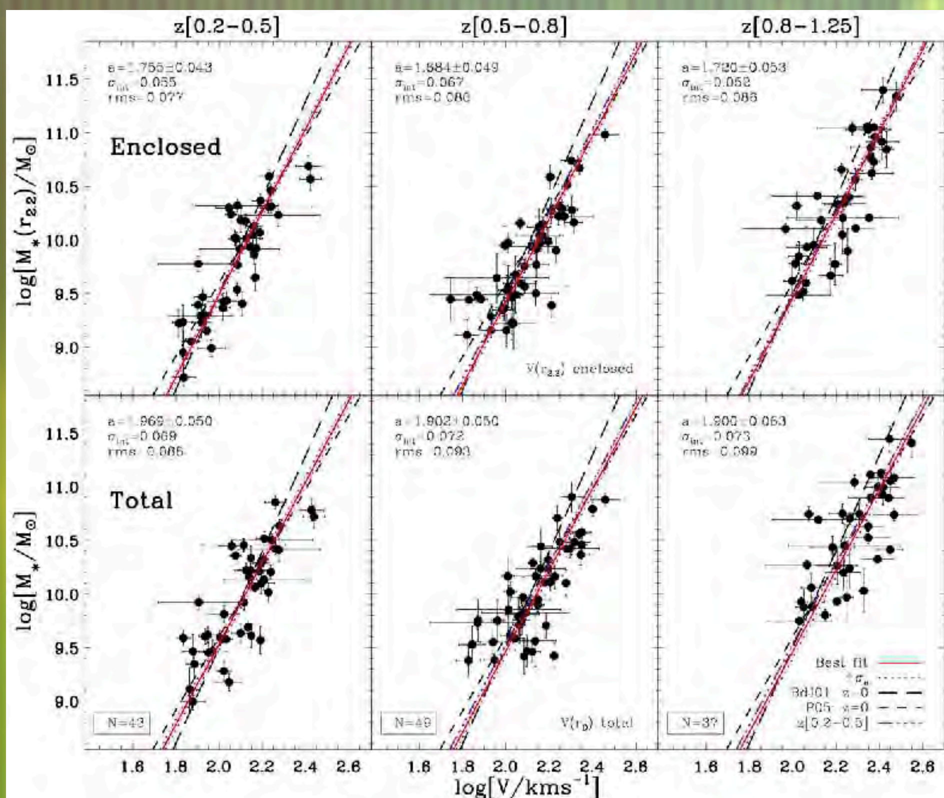
- Tully Fisher Relation for Spiral Galaxies (Pierce & Tully 1992; 2013)
  - Baryons Scale with Dark Matter Halo Depth
- Color vs. Rotational Velocity
  - Star Formation History Correlates with Potential Well Depth (color vs. rotational velocity)
  - Downsizing of Star Formation

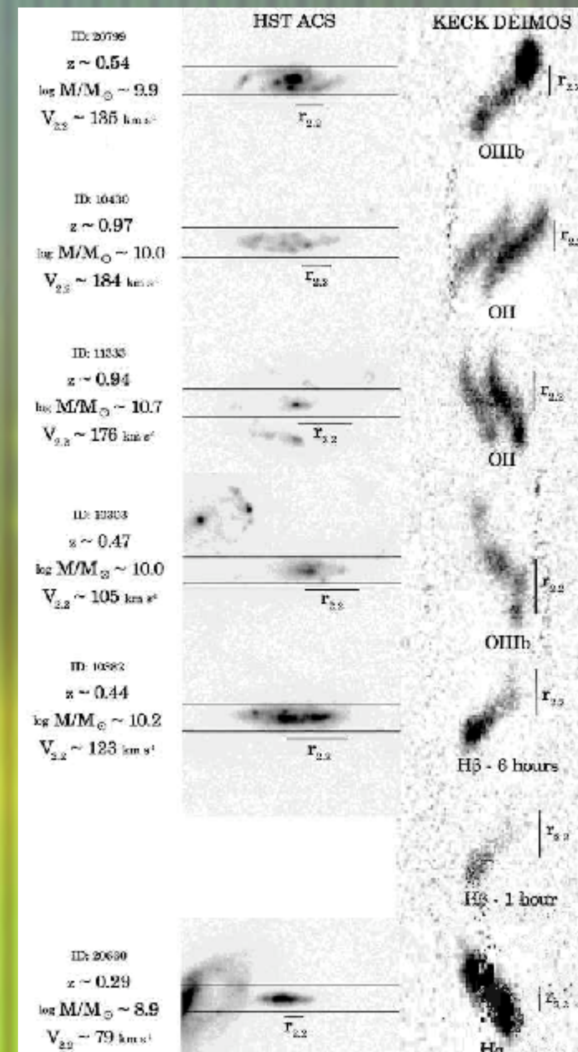




Tully-Fisher Relation at z ~ 1

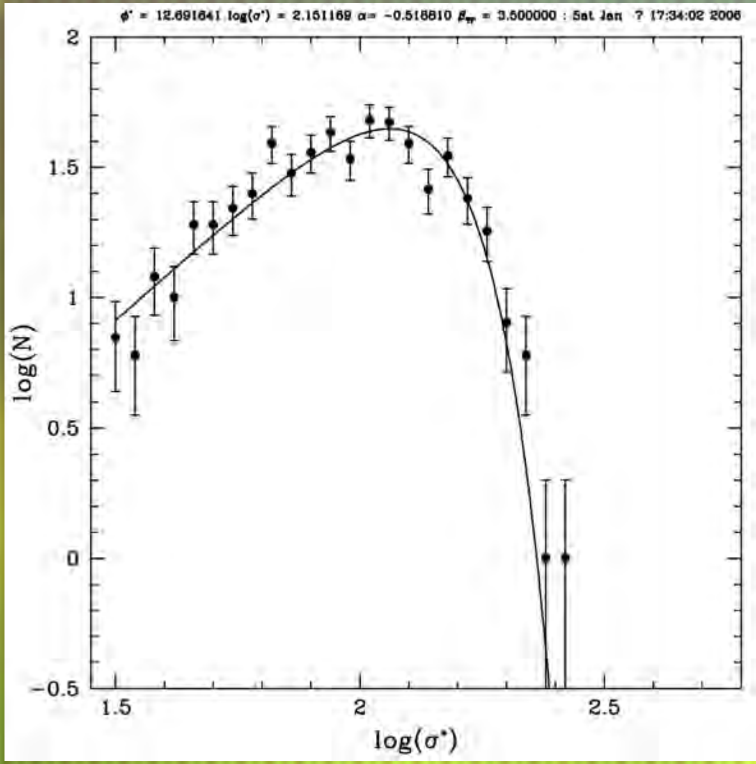
- Rotational Velocities via Optical Spectroscopy
- Numerous Studies via Keck & VLT
  - Conflicting Results on Zero-point Offsets and Scatter
- Recent Ultra-deep Keck Spectroscopy (6-8 hours!) (Miller et al. 2011)
- Unambiguous Rotational Velocities
- Beautiful TF Relations in Place at z ~ 1!



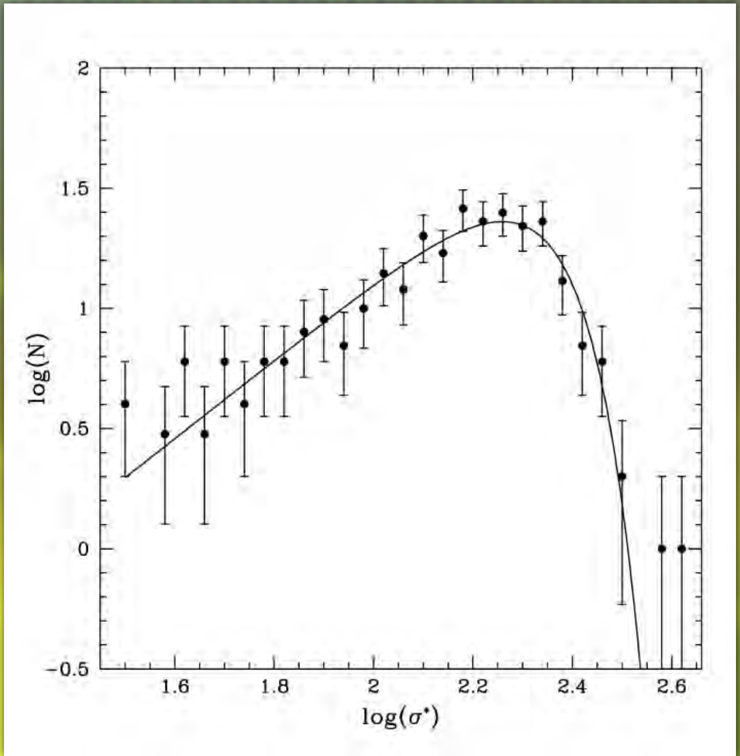


Can We Separate Mass and Luminosity Evolution?

- Circular Velocity Distribution (CVDF) Transformed to VDDF
  (assumes spherical, isothermal halos, Pierce et al. 2013)
- Characterization of Halo Mass Growth in Disk Galaxies
- Allows Comparison with Ellipticals and with Simulations
  (σ^* for spirals about 0.2 dex lower than for ellipticals)



Spirals



Ellipticals

TF Survey at z >1: Survey Requirements

- Survey should span peak epoch of assembly ($1 < z < 2$)
- Photo-z Selection
- Hα found in J-band at $z > 1$
- High Resolution ($R \sim 3000$) and High Signal-to-Noise ($S/N > 10$) Near-IR Spectra (J, H, K bands)
- Complete Sample to log V ~ 1.8 (to sample CDDF)
- Multi-object Spectroscopy (~ 50 spectra per 5 arcmin Field)
- Need Several Fields to Populate CVDF
- 20 Hours/Field (2 Nights/Field)
- Sample of ~ 600 Galaxies (50% Success)
- Full Survey: 25 nights

Straw-man TF Survey: GMT + NIRMOS & GMTIFS

- Scale the Deep Keck Specroscopy for GMT (Hα ~ 3x [OIII] or Hβ)
- Mulit-object Spectroscopy over 5-7 arcmin field or Single Objects with IFS
- GMT + NIRMOS Assumptions:
  - R = 3000, Slit: 0.3 arcsec, Sensitivity as Given (Beware Scattered Light)
  - Exposure Times to Reach S/N = 20 (minimum for good vel. disp.)
    (Gain from GLAO in Spatial Resolution is Significant)

Z	Hα	Log V = 1.8 (exp.)	Log V = 2.0 (exp.)
0.50	1.15 µm	0.8 (hrs)	0.2 (hrs)
0.75	1.31 µm	2.2 (hrs)	0.6 (hrs)
1.00	1.48 µm	4.5 (hrs)	1.3 (hrs)
1.25	1.64 µm	7.9 (hrs)	2.2 (hrs)
1.50	1.80 µm	12 (hrs)	3.5 (hrs)
1.75	1.97 µm	18 (hrs)	5.2 (hrs)
2.00	2.13 µm	25 (hrs)	7.2 (hrs)

Summary

- Scaling Relations (FP & TF) Can Constrain the Assembly History of Elliptical & Spiral Galaxies
  - Relative Role of Wet vs. Dry Mergers in Ellipticals
  - Halo and Disk Growth in Spirals
  - Characterize the Down-sizing of Star Formation within Early-type Galaxies and the Star Formation Rate vs. Halo Depth in Spirals
- The Velocity Dispersion & Circular Velocity Distribution Functions (VDDF, CVDF)
  - Enables More Direct Comparison with Numerical Models for Both Ellipticals & Spirals
  - Enables Comparison of Assembly of Ellipticals and Spirals
- Breakdown in Scaling Relations Expected ($z \sim 2$)
  - Just What We Hope to Characterize with GMT!

GMT FP 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

Cluster Sample Selection is Critical

- Recent Surveys Have Revealed Numerous Clusters
  - Red-sequence Cluster Survey (Optical, NIR colors)
    (z < 1, Gilbank et al. 2011)
    SpARCS (Spitzer high-z survey)
    (z ~ 1, Wilson et al. 2012)
  - Spitzer Deep, Wide-Field Survey (SDWFS)
    (z < 1.5, but see Shallow IRAC Eisenhardt et al. 2008)

- Lots of Clusters so How do We Choose?
- Progenitor Bias for Clusters?
  - Massive DM Halos Present by z ~ 6
    (ΛCDM Simulations: Gao et al. 2004)
  - Significant Evolution Due to Major Merging of Substructure
    (Note: There May Be Significant Differences for L > L* and L < L*
  - How Do We Characterize Cluster Growth with z?
  - Simulations Can Help but Each Cluster is Different (Cosmic Variance)
  - Ground Truth for Each Cluster (Photo-z not sufficient)?