Quantifying the Assembly History of Galaxies Through Velocity Dispersions

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- **What I Think We Already Know:**
  - Morphology Density Relation (Assembly History Depends on Environment, Dressler 1980)
  - Ratio of Star Forming Galaxies in Rich 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 Exist 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)

The Fossil Record of Elliptical Galaxy Assembly

- **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**

Structural Scaling Relations

Virial Theorm plus Assumption of Constant Mass/Light Implies:
<m> ~ σ^2/RG

Elliptical Galaxies Should Populate a 3-parameter Plane

Two Families are Revealed:

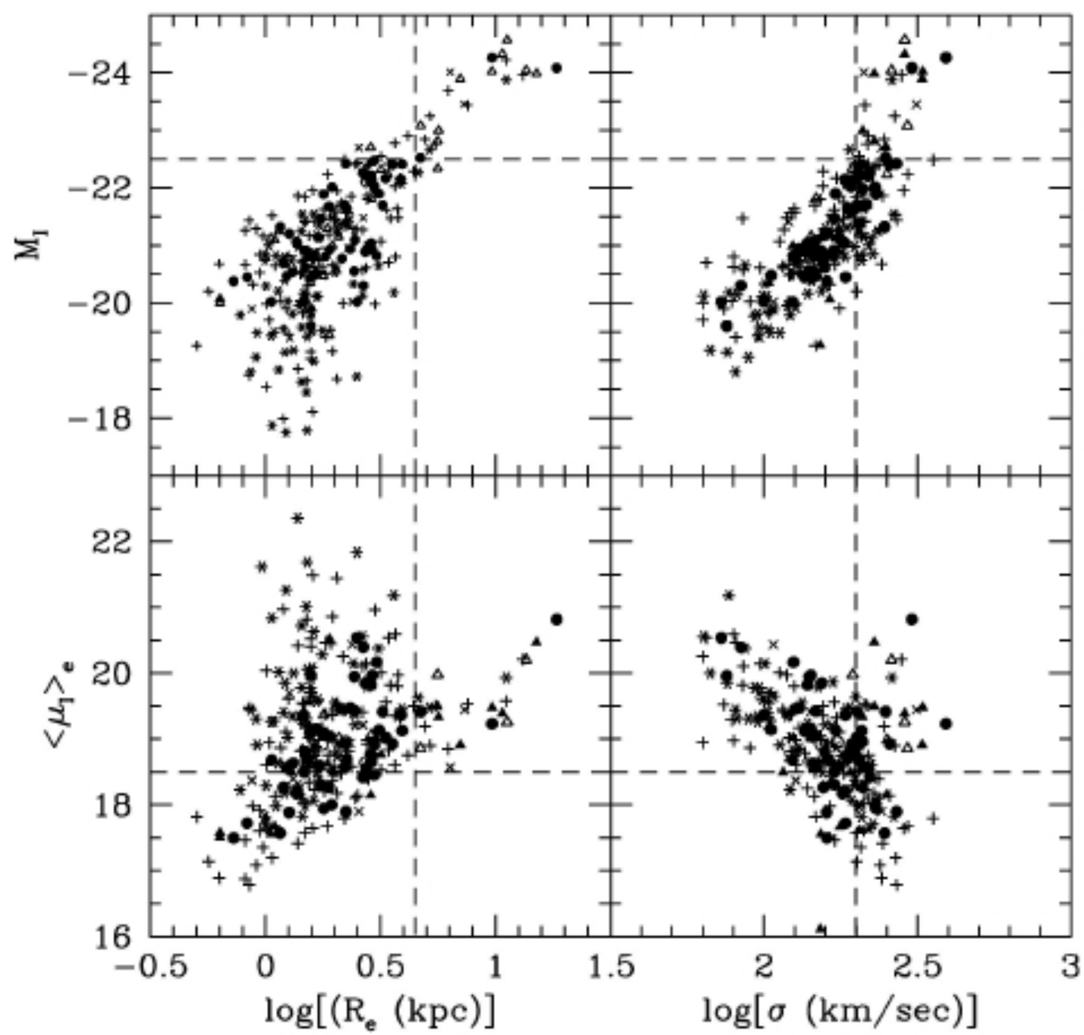
The Brightest, Most Massive Ellipticals Populate a Distinct Region (the Upper Right Region of Each Panel):

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

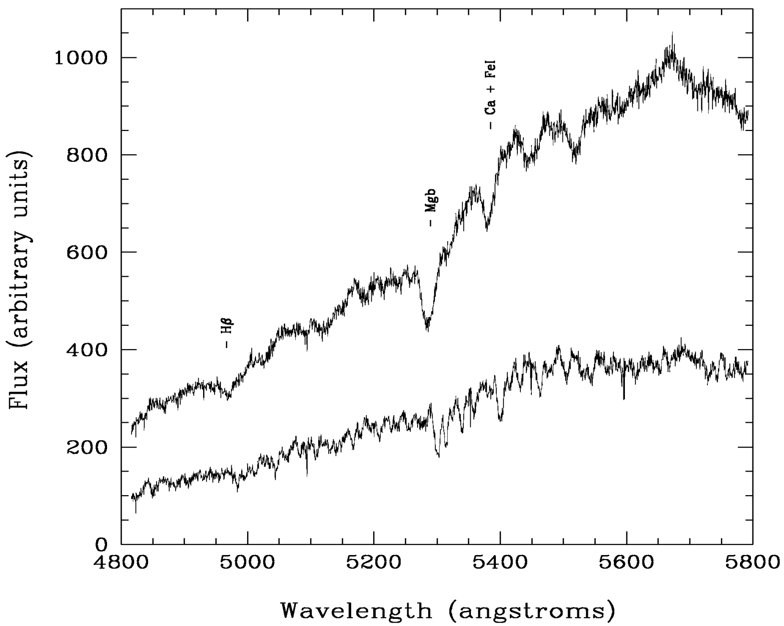
Fainter, Less Massive Systems Appear to Lie Along a "Dissipational Sequence" (see Lower-Right Panel)

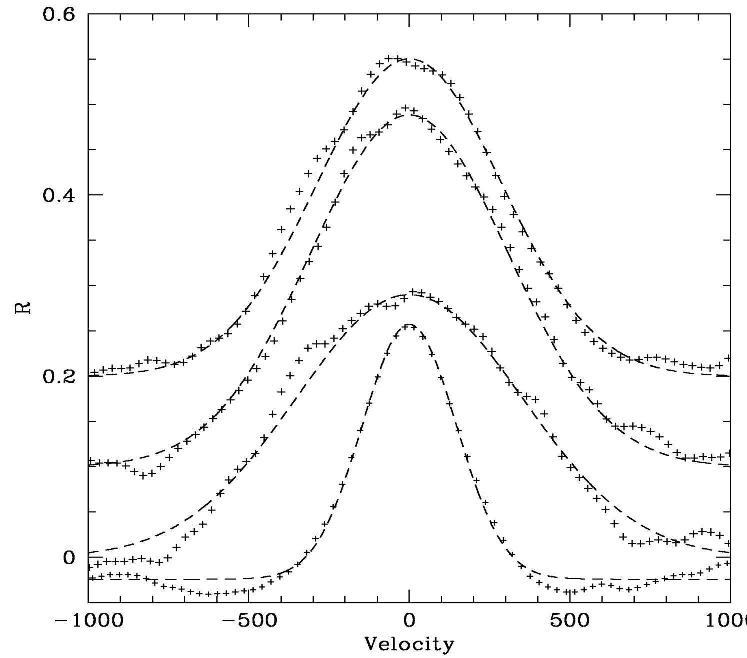
Merger Models Are Beginning to Include Gaseous Dissipation. But May Soon Allow Detailed Comparison With Data.

Two families have quite different structural properties: largest systems have cores with complex velocity fields, smaller systems lack cores and have regular velocity fields.



Internal Velocity Fields of Elliptical Galaxies Also Reflect Their Merger History





High Resolution (R ~ 5000) and High Signal-to-Noise (S/N > 30) Spectra of Giant Elliptical Galaxies Reveal Complex Streaming Motions via CCF Broadening Functions (broad profiles right panel). Line-of-sight velocity distribution function as well as 2-d maps (e.g., SAURON)

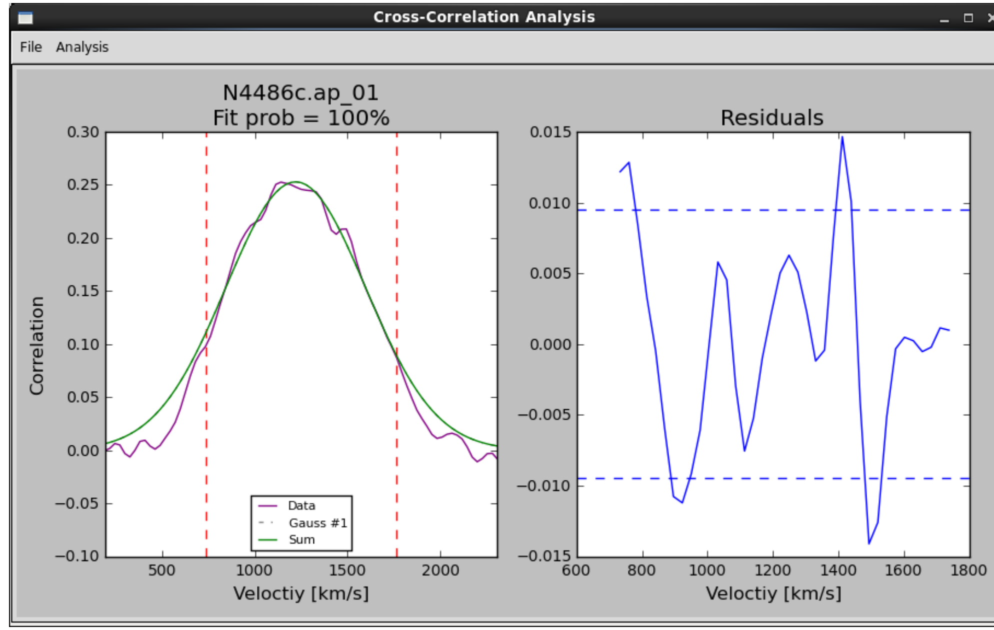
Moderate-Low Luminosity Ellipticals Have More Regular Velocity Fields (narrow profile right panel)

Streaming Appears Significant but How Can We Quantify the Phenomena?

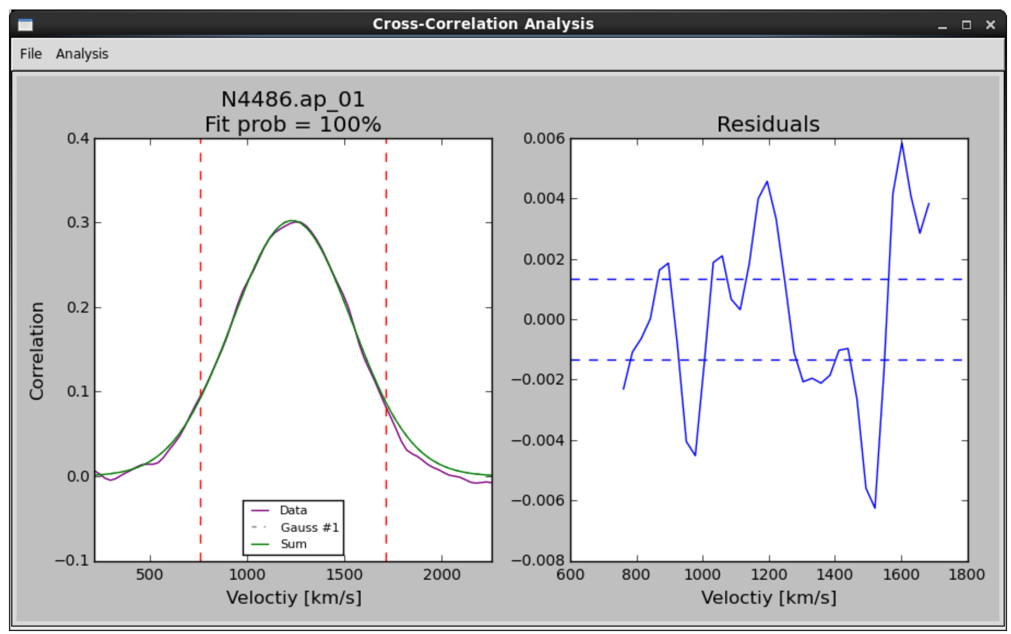
Quantifying Stellar Streaming Within Giant Es

- How Can We Quantify the Phenomena?
- CCF using Super Metal Rich K Giants as Templates (FXCor)
- Model the CCF with Multiple Gaussian Fits (fitGauss: Tyler Ellis)
- Evaluate Significance Using F-test (Ratio of Chi-squares)
- Simulations Are Crucial for Modeling the CCF
  - Provides Procedure for Modeling rms in CCF given S/N in Galaxy Spectra
  - RMS Depends on Both the Spectral S/N and the Single-component Broadening
- F-test: Multiple Gaussian Fits for Giant Es Are Statistically Significant
- Greater Substructure at Smallest Spatial Scales (< 1kpc)

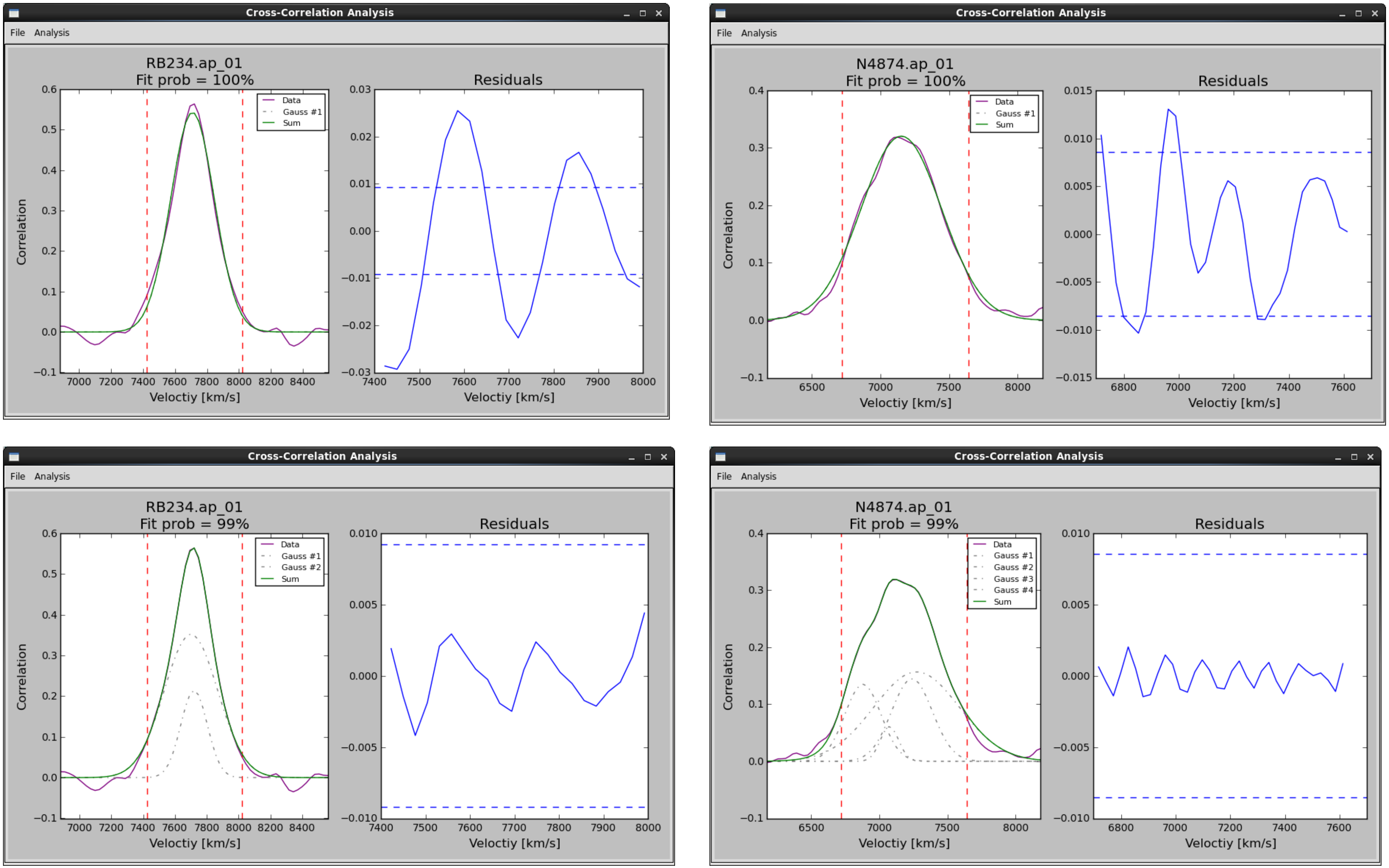
  (see next slide)



CCF for M87: Top: 2arcsec, Bottom: 15 arcsec



Substructure vs. Luminosity



Typical L ~ 0.1 L* Elliptical **Typical L ~ 10 L* Elliptical**

Interpretation

- **Stellar Streaming**
  - **Fossil Record of Mergers/Assembly**
  - **However Dynamical Timescale: t ~ R/σ**

    2 arcsec at Coma ~ 1 kpc, so 200 km/sec -> t ~ 5 x 10^6 yrs

    Phase Mixing Should Quickly Wash Out Stellar Streams
- **Evidence for Multiple SMBHs?**
  - **Dry Mergers Within Rich Clusters Unlikely to Result in SMBH Merging (no gas)**
  - **L > L* Es Should Have Multiple SMBHs**
  - **Multiple SMBHs Could Act as Egg Beater to Heat Stars**
    - **Responsible for Both Cores (Nuker Team) and Stellar Streaming?**
  - **Possibly but Sphere of Influence:**

    $r \sim GM/\sigma^2 \sim 7$ pc (for 10^8 M_s)
  - **Streaming Within a 2 arcsec Fiber is About 130x Larger Than the SMBH Sphere of Influence!**
    - **Wakes from SMBHs Seem Unlikely; What About Associated Nuclei?**

Promise of TMT

- **TMT will Enable the FP to Be Characterized to z ~ 1**
  - **Quantify the Relative Role of Wet and Dry Mergers in Assembly of Elliptical Galaxies**
- **TMT can Quantify and Characterize Stellar Streaming within the Cores of Giant Es to z ~ 1**
  - **Quantify Phenomena Over Cosmic Time if Selection Effects Can Be Controlled (Progenitor Bias)**
- **TMT Can Also Resolve the SMBH Sphere of Influence for z < 0.05 Ellipticals**
  - **About 100 Massive Elliptical Galaxies (L > L*) Within This Volume**
  - **If Giant Es Harbor Multiple SMBHs We Will Find Them!**
    - **IRIS + NFIRAOS Can Sample E-cores and Characterize the SMBHs SoI with 4 mas Resolution (3x sampling for 10^8 M_S at 100 Mpc)**
  - **Enables Direct Test of Stellar Streaming – SMBH Hypothesis**
  - **Task for Another ISDT**

Fundamental Plane at $z > 1$: Survey Requirements

- Survey should span peak epoch of assembly ($1 < z < 2$)
- Familiar Optical Features found in J-band at $z > 1$
- High Resolution (R ~ 5000) and High Signal-to-Noise (S/N > 20) Near-IR Spectra (Y, J, H bands)
- Complete Sample to M* + 2-3 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

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)
- **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's History Likely Different (e.g. Cosmic Variance)
  - Ground Truth May Require Redshift Surveys of the Environment of Each Cluster (Photo-z Probably not Sufficient)

Straw-man FP Survey: TMT + WFOS & IRMS

- Apparent mags: Absolute Mags of Nearby Gals + DM (D_L) + (1+z)-corr.+ 1/(1+z) Mag evol. for z < 1.5 then constant.
- Mulit-object Spectroscopy of Clusters over 5-7 arcmin field
- TMT + WFOS Assumptions:
  - R = 5000, Slit: 0.5 arcsec (TMT spectroscopic ETC)
  - Exposure Times to Reach S/N = 50 (minimum for good vel. disp.)

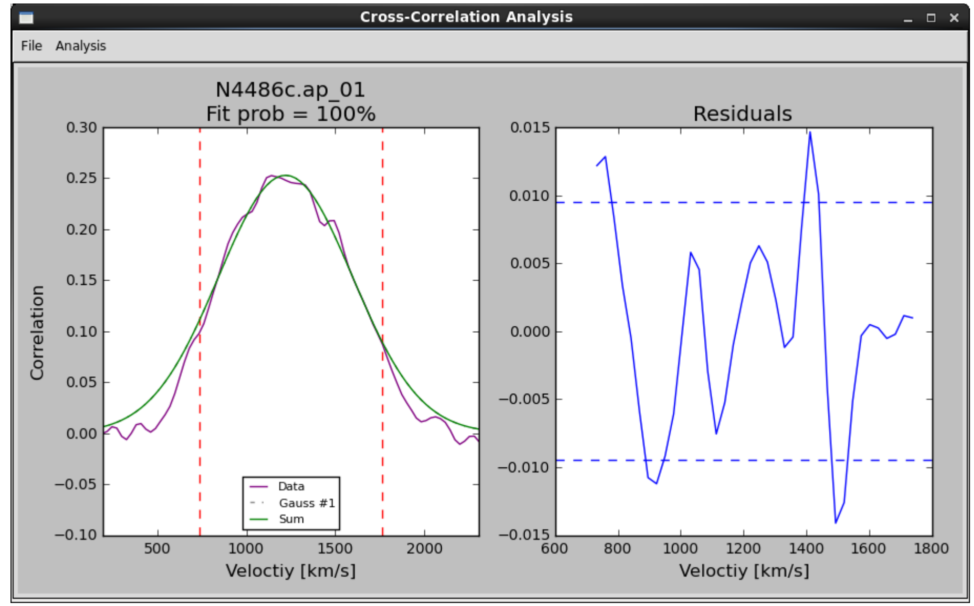
Z	Band	M* - 1 (exp)	M* +2 (exp.)	M* + 3 (exp.)
0.75	I	16.7 (min)	19.7 (3 min)	20.7 (min)
1.00	Y	17.6 (min)	20.6 (min)	21.6 (min)
1.25	J	18.5 (min)	21.5 (30 min)	22.5 (2 hrs)
1.50	J	19.2 (min)	22.2 (1 hr)	23.2 (6 hrs)
1.75	---	19.9 (30 min)	22.9 (3 hrs)	23.9 (20 hrs)
2.00	H	20.7 (1 hr)	24.9 (16 hrs)	24.7 (50 hrs)
2.25	H	21.6 (2 hrs)	24.6 (80 hrs)	25.6 (500 hr)

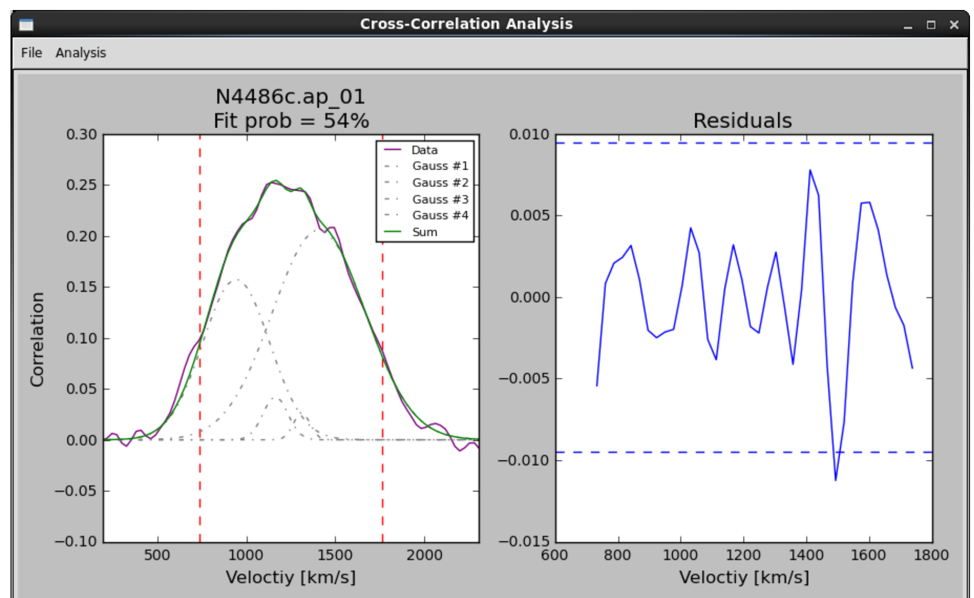
Summary

- **Scaling Relations (Projections of FP) Can Constrain the Assembly History of Elliptical Galaxies**
  - **Quantify the Relative Role of Wet vs. Dry Mergers in Ellipticals in a Given Environment (Cluster) but Selection Effects Are Significant**
- **LOSV Distribution Functions (CCFs) Can Quantify the Degree of Stellar Streaming Within Individual Es**
- **Both Phenomena Sample the Fossil Record of Galaxy Assembly**
  - **TMT will Enable Assembly History to Be Characterized and Quantified to z > 1**
- **TMT Survey of FP at z > 1.5 is Feasible**
  - **Sample Selection is Crucial**
  - **Requires About 2 Nights per Cluster with TMT at Highest z**
- **Hypothesis That Stellar Streaming Within Massive Ellipticals is Associated with Multiple SMBHs is Directly Testable in Nearby (D < 100 Mpc) Clusters (job for another ISDT)**

Remaining Issues with fitGauss

- Convergence and Uniqueness Issues
  - Are Gaussians the Best Basis Set?
  - Software Modifications for Constraining Parameters
  - Better Address Numerical Issues with Gaussian Models
- Develop More Detailed Simulations to Better Model Broad CCFs
  - Insure rms Model is Accurate
  - Enable Users to Create Simulated Spectra Based on the Fitting Results





TMT Spectroscopic Survey of Elliptical Galaxies

- Fundamental Plane and VDDF Offer Promise for Quantifying the Assembly History of Ellipticals (wet vs. dry mergers: Faber et al.2007)
- 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 mags below L*?
- At high redshifts, all the standard diagnostic lines will be found at near-infrared wavelengths (J & H) and would also constrain metallicities and enrichment histories.