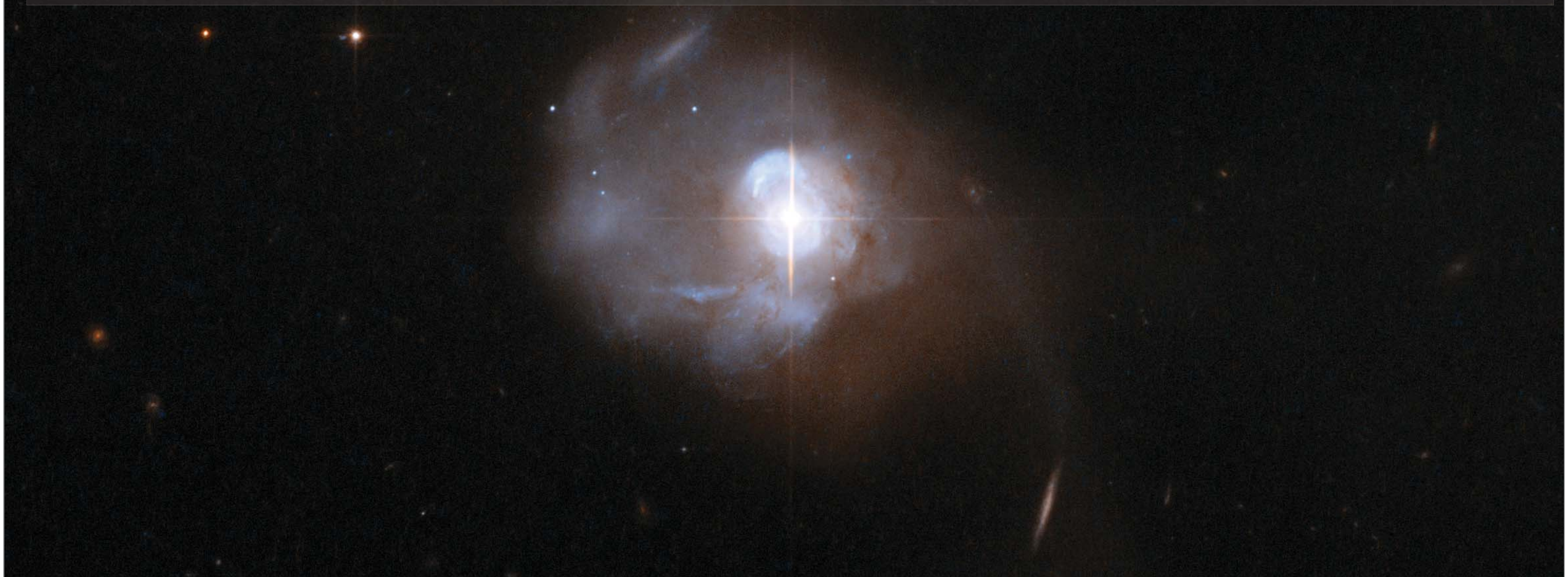
A Monster at any other Epoch:

Are Intermediate Redshift ULIRGs the Progenitors of QSO Host Galaxies?



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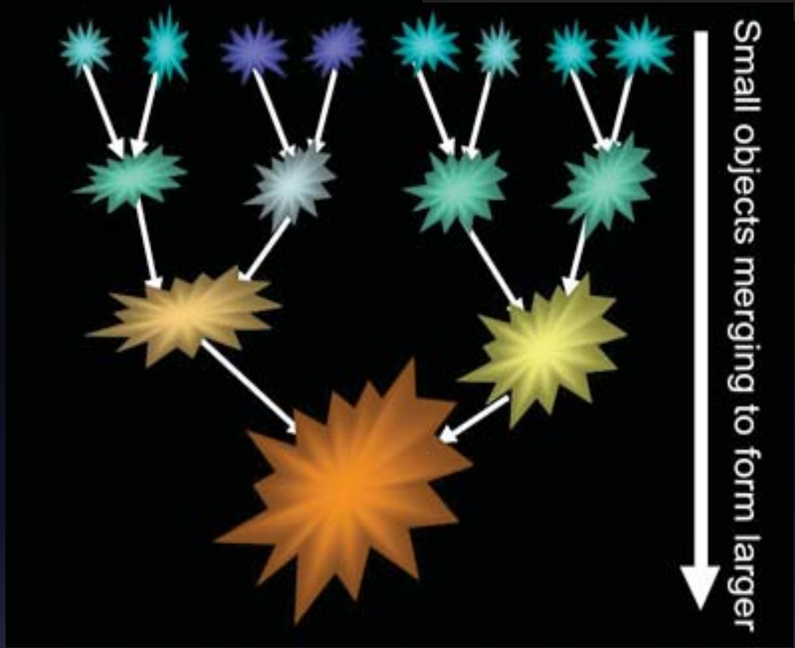
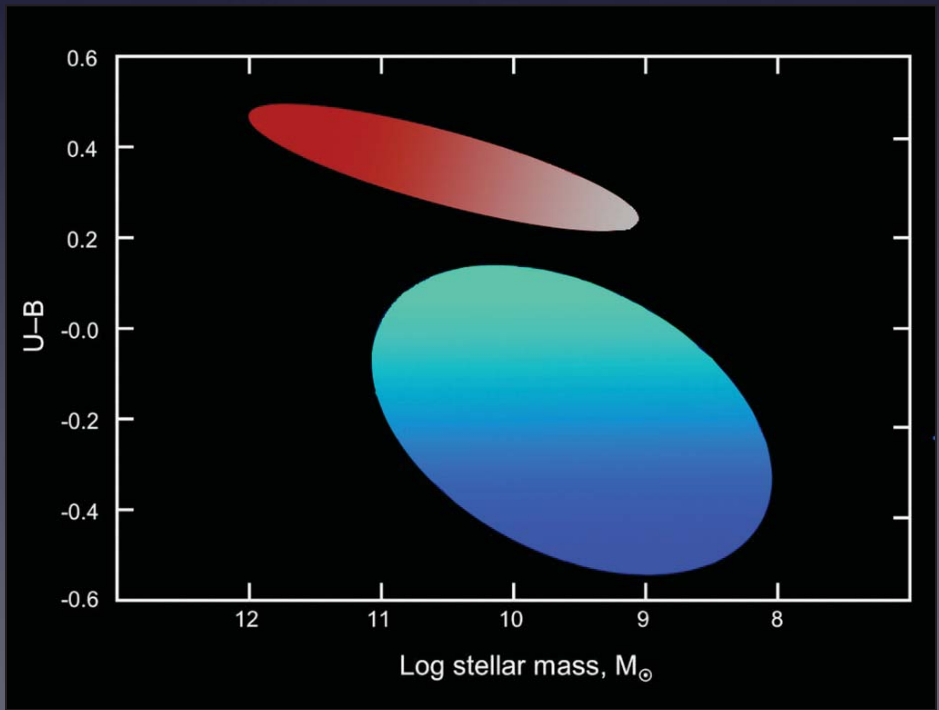
LARGE BINOCULAR TELESCOPE

GEORGE MASON UNIVERSITY

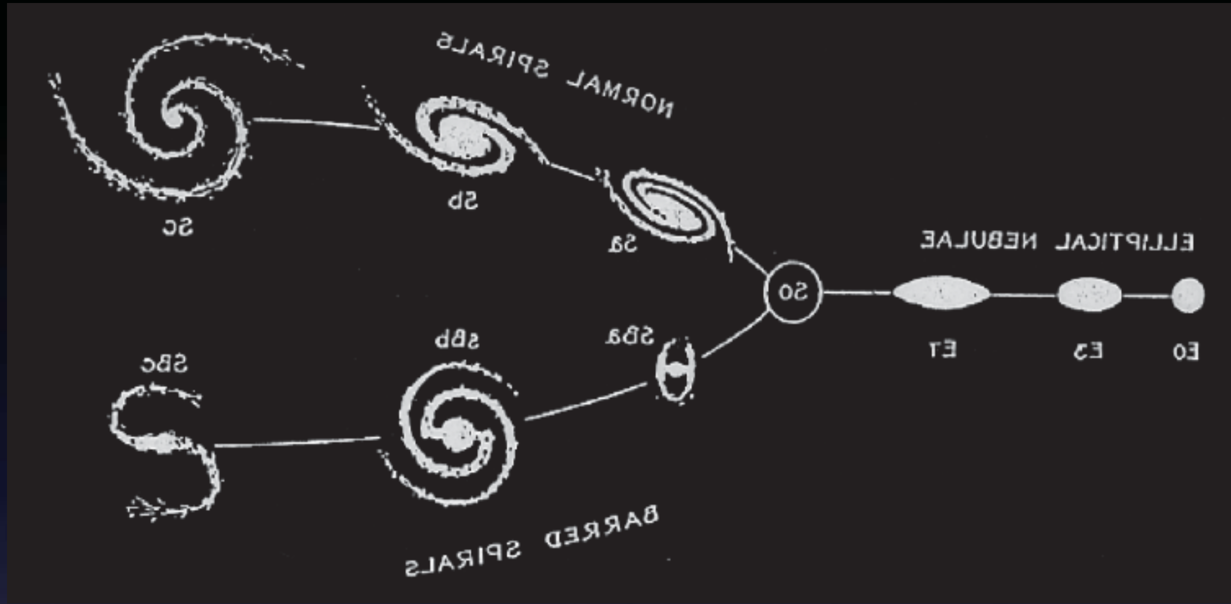
Motivation





- ΛCDM (cold-dark-matter) cosmology based on merging dark matter halos
- Halos contain galaxies which hierarchically merge to form larger and larger (massive) systems
- Galaxies obey a mass-metallicity relationship (known for > 30yrs)
- Only way to increase metallicity over time is via star-formation
- Mergers provide a way to build up galaxies over time, add stars, and increase metallicity

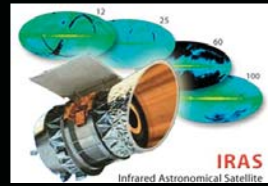
Merger Hypothesis



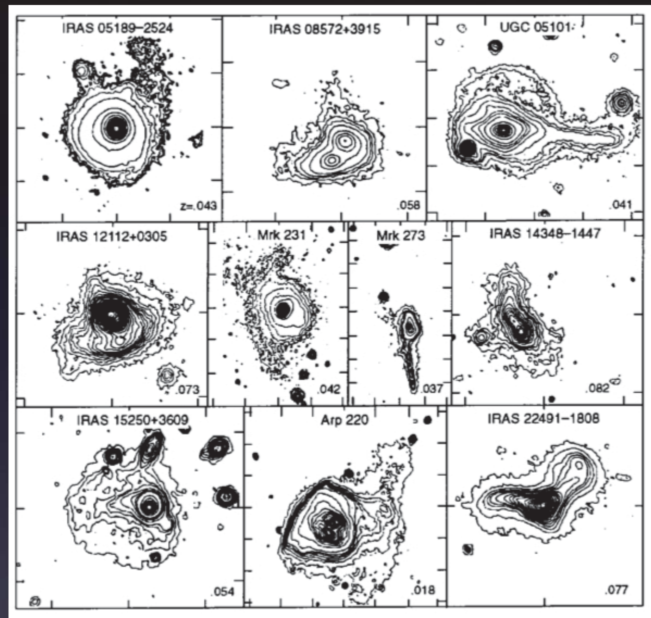
- Tidal Friction: energy transfer from orbits produces tidal features
- Orbital Decay: energy transfer causes braking & orbital decay → merger
- Violent Relaxation: potential changes, stars gain/lose energy → ~r1/4 profile
- Dissipation: gas funneled to barycenter; gas triggers star-formation → m* ↑
- Phase-Mixing: correlated orbits altered; stars with different periods "smooth" out structure (~1 Gyr) → elliptical galaxy
- The number of mergers increases with look-back time

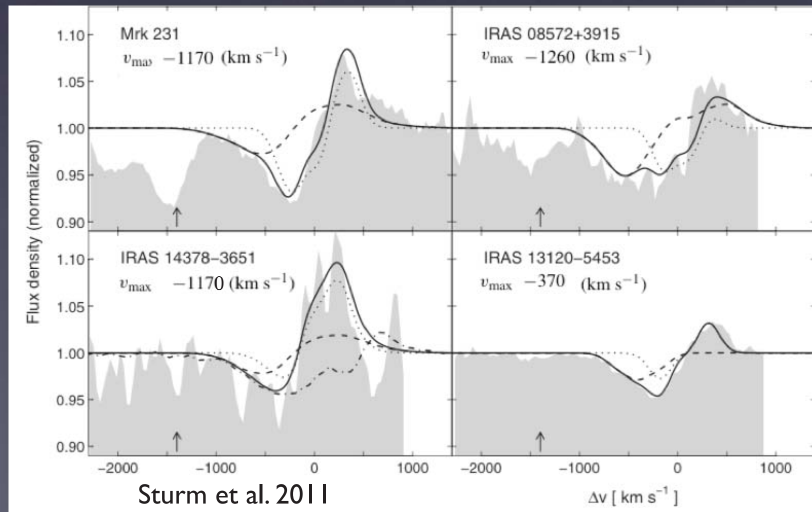
Toomre & Toomre 1972, Toomre 1977

Local ULIRGs

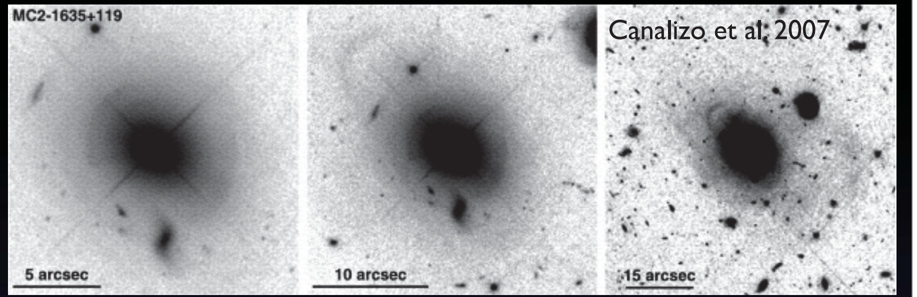


- IRAS discovery of Luminous & Ultraluminous Infrared Galaxies: $L_{IR} \gtrsim 10^{11\&12}\ L_\odot$ (8-1000μm luminosity)
- Some LIRGs, & ***all*** ULIRGs have peculiar morphologies
- For z≲0.4 the Bolometric Luminosity Function of ULIRGs ~ QSOs
- LIRGs/ULIRGs have $\gtrsim 10^{9\text{-}10}\ M_\odot$ of $M(H_2)$(e.g. Downes & Solomon 1998)
- High-speed absorption outflows; mass loss ~100s $M_\odot\ yr^{-1}$; AGN powered (e.g. Fischer et al. 2010; Sturm et al. 2011; Veilleux & Rupke 2012)
- Stellar light profiles of relaxed systems match elliptical galaxies (e.g. Surace 2000; Genzel et al. 2001; Veilleux et al. 2002, 2006; Rothberg et al. 2004, 2013; Kim et al. 2013) *- is this enough?*

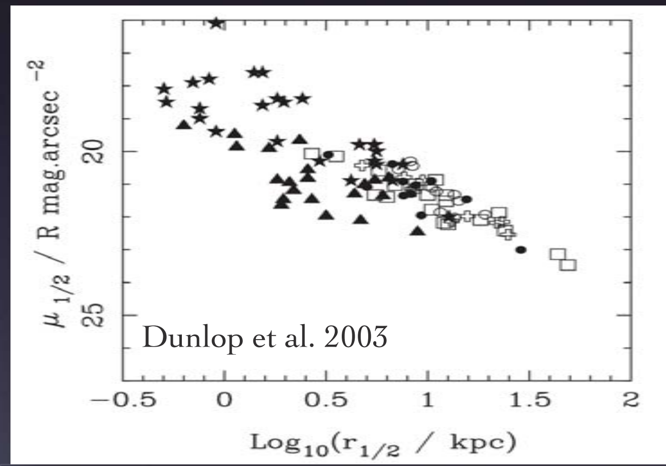


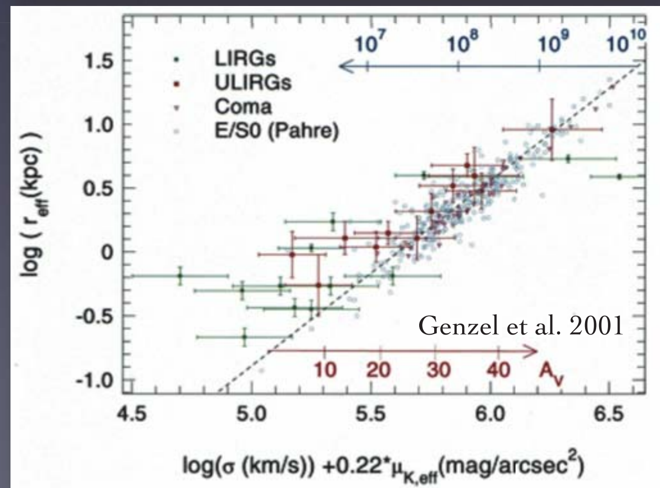


Do Local ULIRGs Beget QSOs?



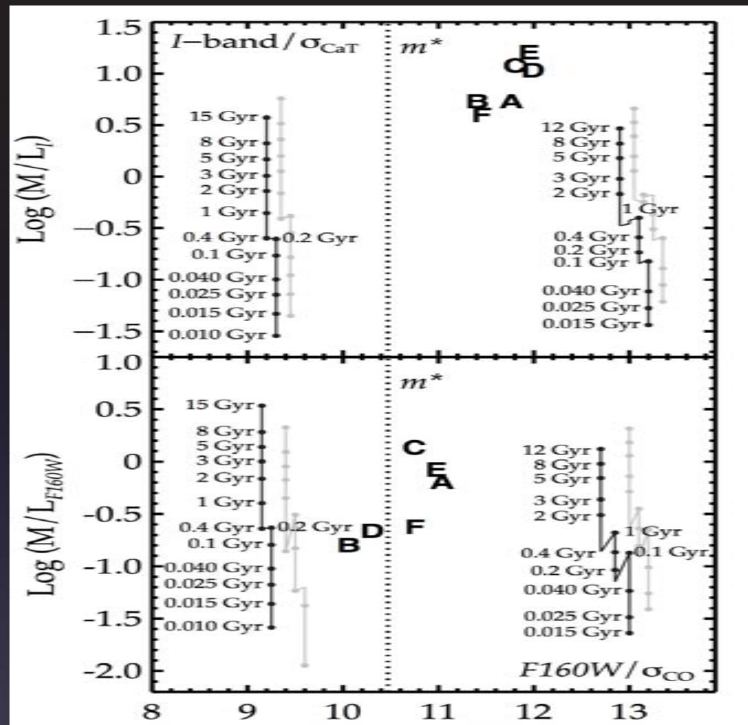
- QSOs are found predominantly in massive ellipticals & show tidal debris & shells in deep imaging.
- Many QSOs are classified as ULIRGs & vice-versa.
- Near-IR observations were first used to measure dynamical masses and suggested ULIRGs did *not* form *m** ellipticals or were the progenitors of QSOs (i.e. Genzel et al. 2001; Dunlop et al. 2003).
- If ULIRGs are dusty, then only the near-IR should give the *correct* answer.



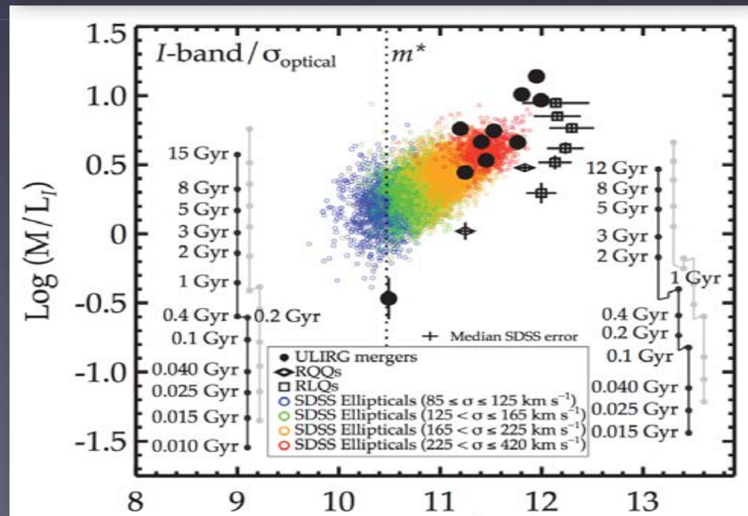


Do Local ULIRGs Beget QSOs?

- The σ-Discrepancy (Rothberg & Fischer 2010; Rothberg et al. 2013) demonstrated that near-IR kinematic observations do *not* reflect random motions.
  - Not seen in ellipticals (Vanderbeke et al. 2011; Kang et al. 2013) nor in spiral bulges (Riffel al. 2015). ellipticals
  - Scales with L_{IR} - weaker effect seen in LIRGs
- ULIRGs host a younger central stellar disk formed after the merging event which dominates near-IR observations.
- Dust blocks this young disk from being seen at shorter wavelengths, but optical σ*'s probe the true random motions of stars
- ***Local ULIRG sizes & dynamical masses are statistically indistinguishable*** from Radio Loud and Radio Quiet QSO Host Galaxies (Rothberg et al. 2013).



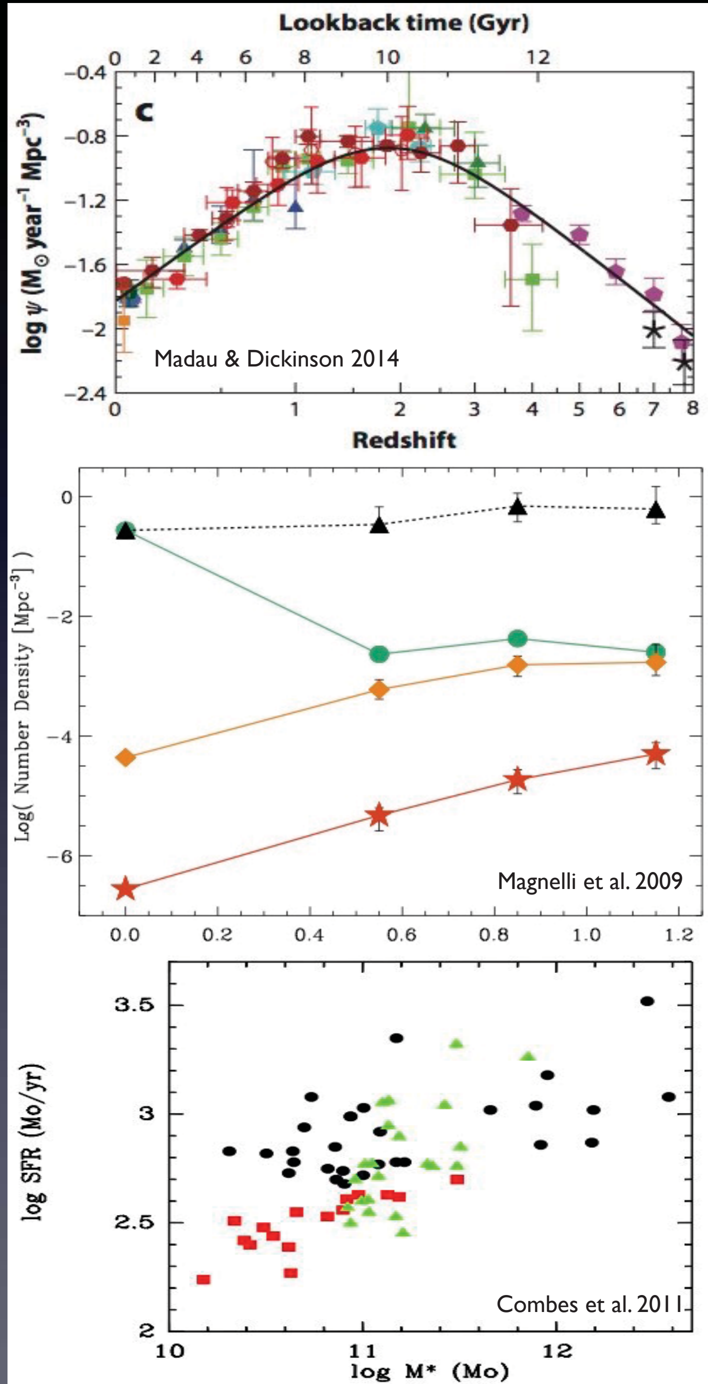
Rothberg et al. 2013



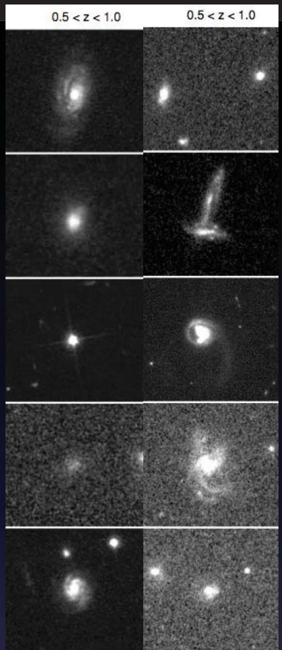
Rothberg et al. 2013

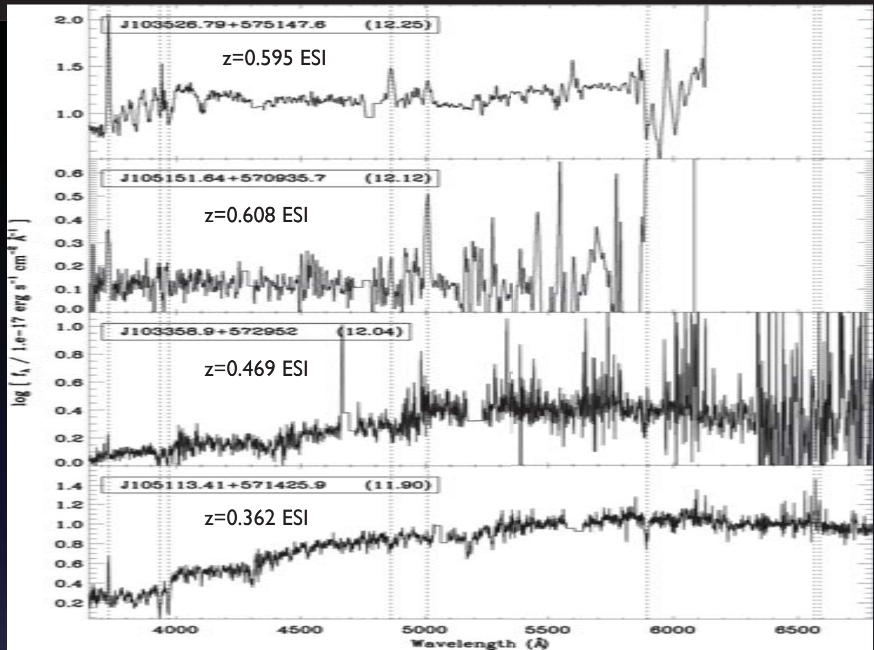
A Transition Epoch

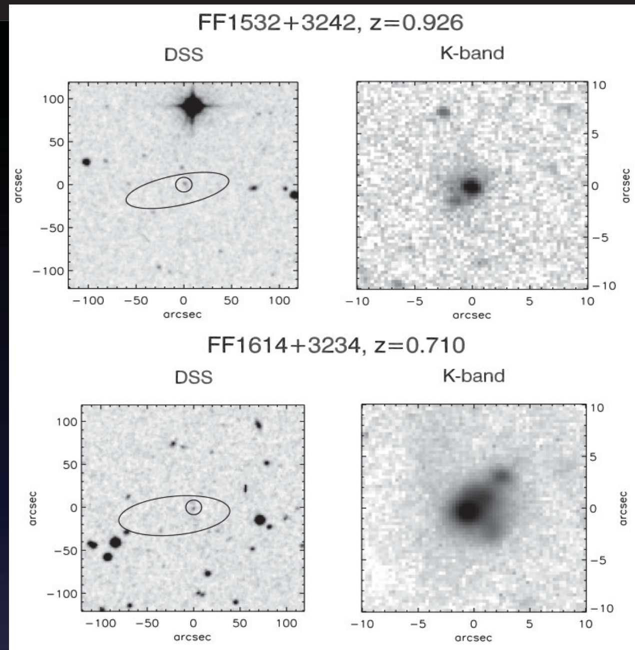
- At 0.4 < z < 1.0 Star Formation peaks up significantly (e.g. Madau et al. 1998).
- The ULIRG number density is 100x greater at z~1 compared to the local Universe (e.g. Le Floc'h et al. 2005; Magnelli et al. 2009).
- At z~0.7 ULIRGs begin to dominate the star-forming activity in the Universe (Le Floc'h et al. 2005).
- Stellar and Dynamical masses (from CO emission) of ULIRGs at 0.3 < z < 0.6 in the $10^{11\text{-}12}$ $M_\odot$ range (Filled black circles - Combes et al. 2011).



What are ULIRGs at z~1?







- Many z~1 ULIRG samples are selected from 24μm fluxes scaled to estimate L_{IR} via local SED templates (e.g. GOODS, CANDELS, COSMO); BzK techniques; MIPS 70 & 160 μm fluxes; or color-selected Dust Obscured Galaxies (*f*24/R flux).

- These techniques often overestimate L_{IR}, producing samples contaminated by non-ULIRGs and/or producing widely disparate morphological distributions (e.g. Papovich 2007; Kartaltepe 2010). Some techniques bias selection in favor of AGNs.

- Addition of WISE and Herschel fluxes have improved ULIRG selection at z~1

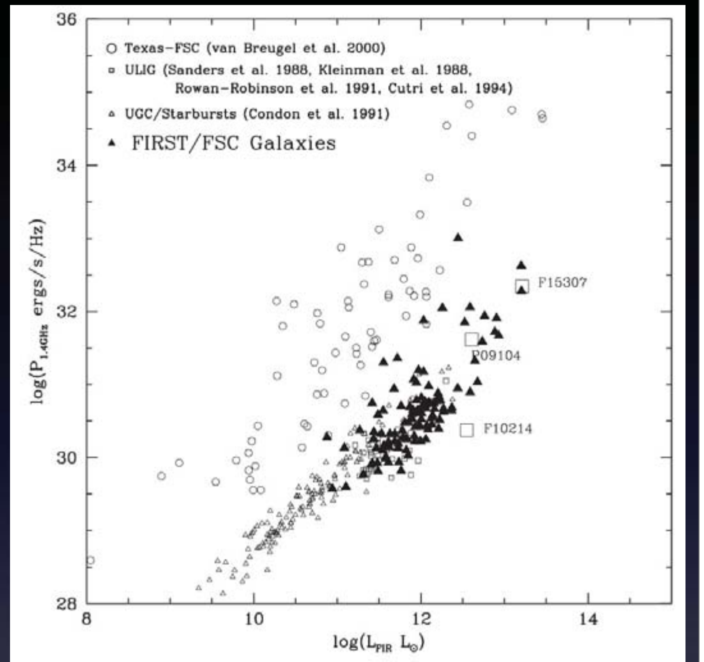
A "Classic" Pilot ULIRG Sample

<u>Parent sample (Stanford et al. 2000):</u>

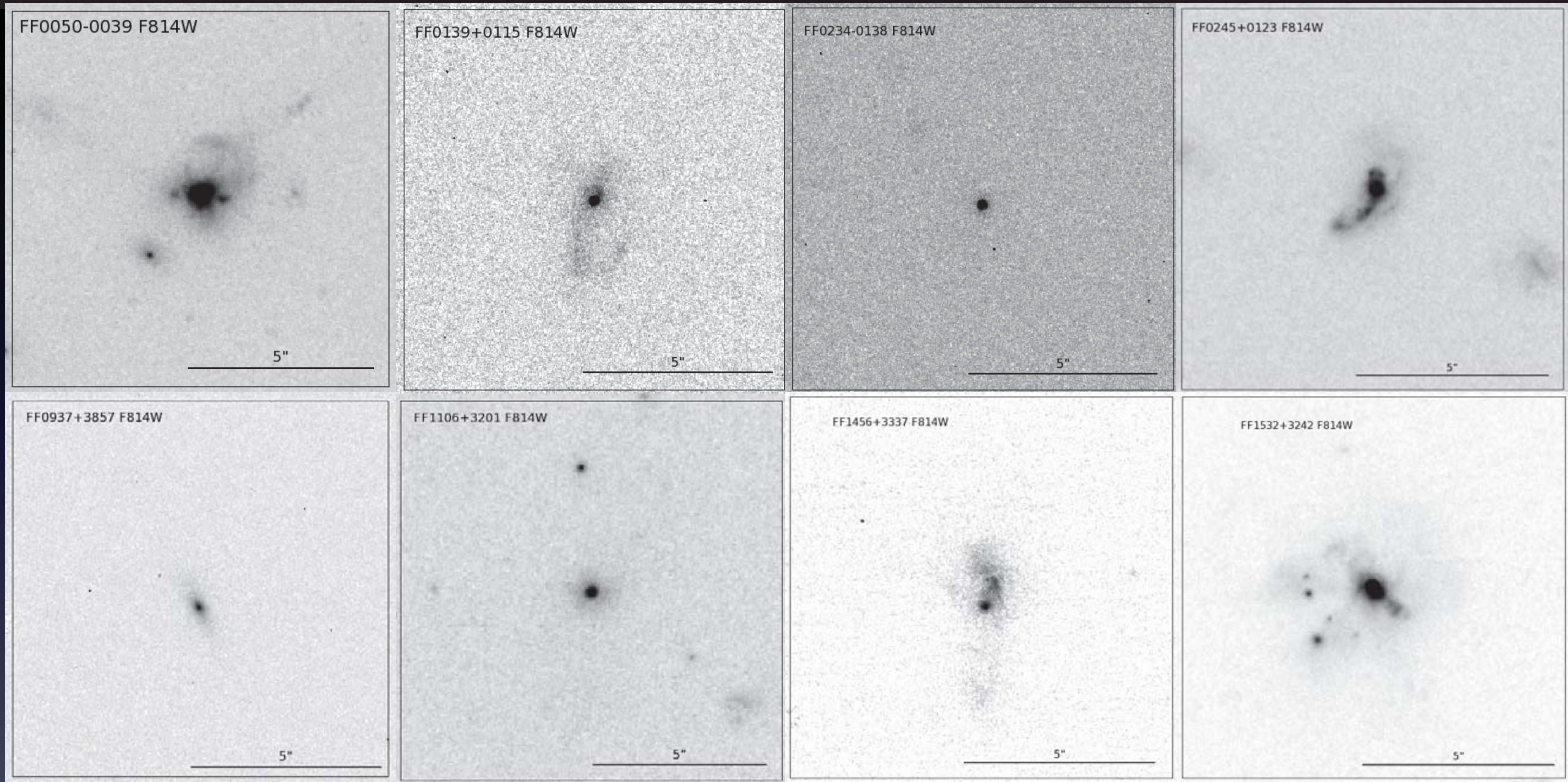
- cross-correlation (~ 0".1)of the *IRAS* Faint Source Catalog (FSC) & Faint Images of the Radio Sky at Twenty cm (FIRST).
- Spectroscopically confirmed $0.1 < z < 1.0$

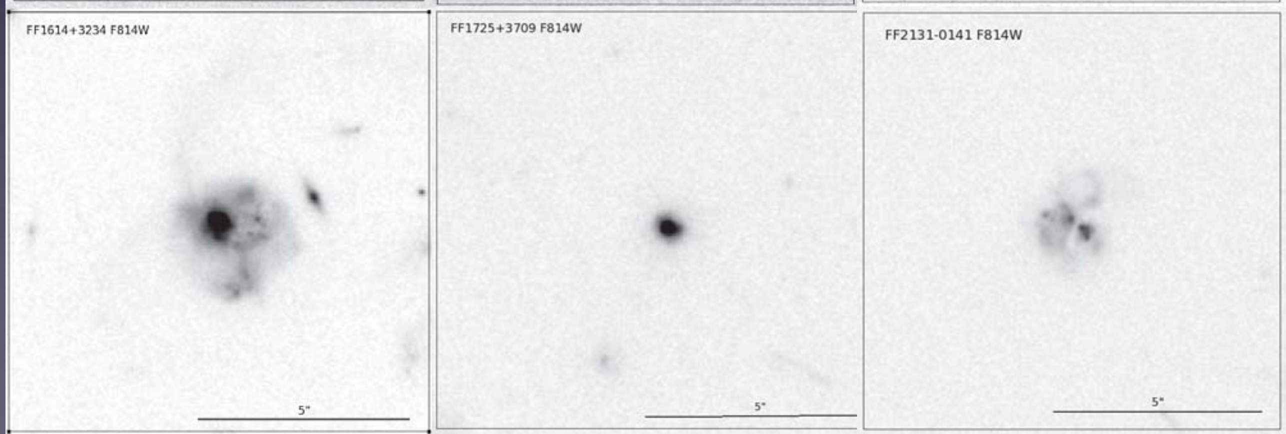
<u>ULIRG sub-sample:</u>

- Restricted to $0.4 < z < 1.0$
- 3σ or better detections at 60 and 100 μm (supplemented by WISE @ 12 and 25 μm)
- Relaxed systems selected to measure kinematic properties
- Final Sample Size: 13 ULIRGs (Log L_{IR} 12.3-13.5)
  - Archival Data:
    - *HST* F814W (ACS or HRC); F160W (NIC2)
    - Rest-frame Hα (6/13) from NIRSPEC/Keck-2
    - SDSS Spectra (2/13 - low S/N)
  - First attempt was to measure σ_{CaT} using NIRSPEC/Keck-2
  - Now - MODS-1 on the Large Binocular Telescope
    - rest-frame UV-optical spectra (0.16-0.54μm ~ 0.21-0.72μm)
    - *R*~1500-2500
    - High S/N spectra for 8/13 (3600sec-8400sec)



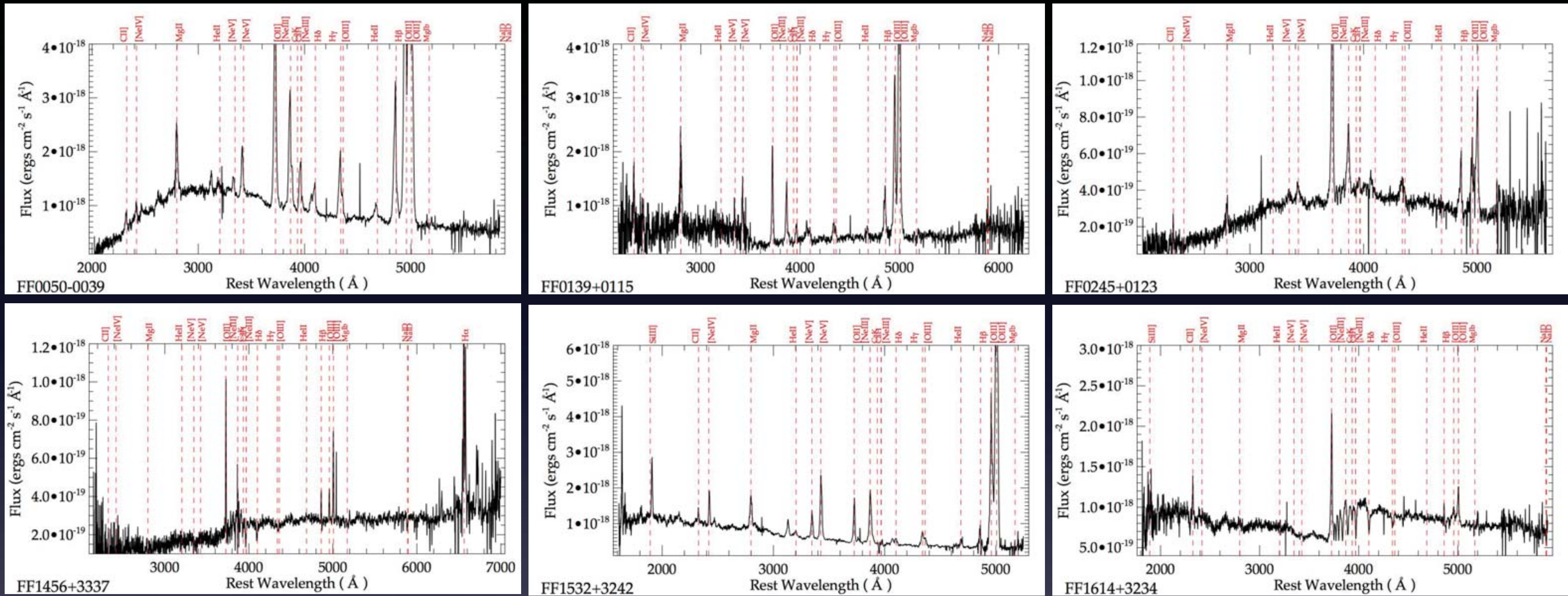
A "Classic" Pilot ULIRG Sample

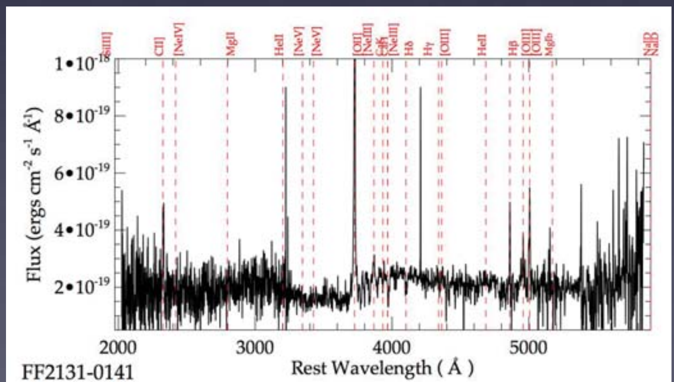




- Archival rest-frame *B* or *V*-band *HST* ACS imaging
- Archival rest-frame *I*, z, or *J*-band *HST* NIC2 imaging (not shown here)

First Results

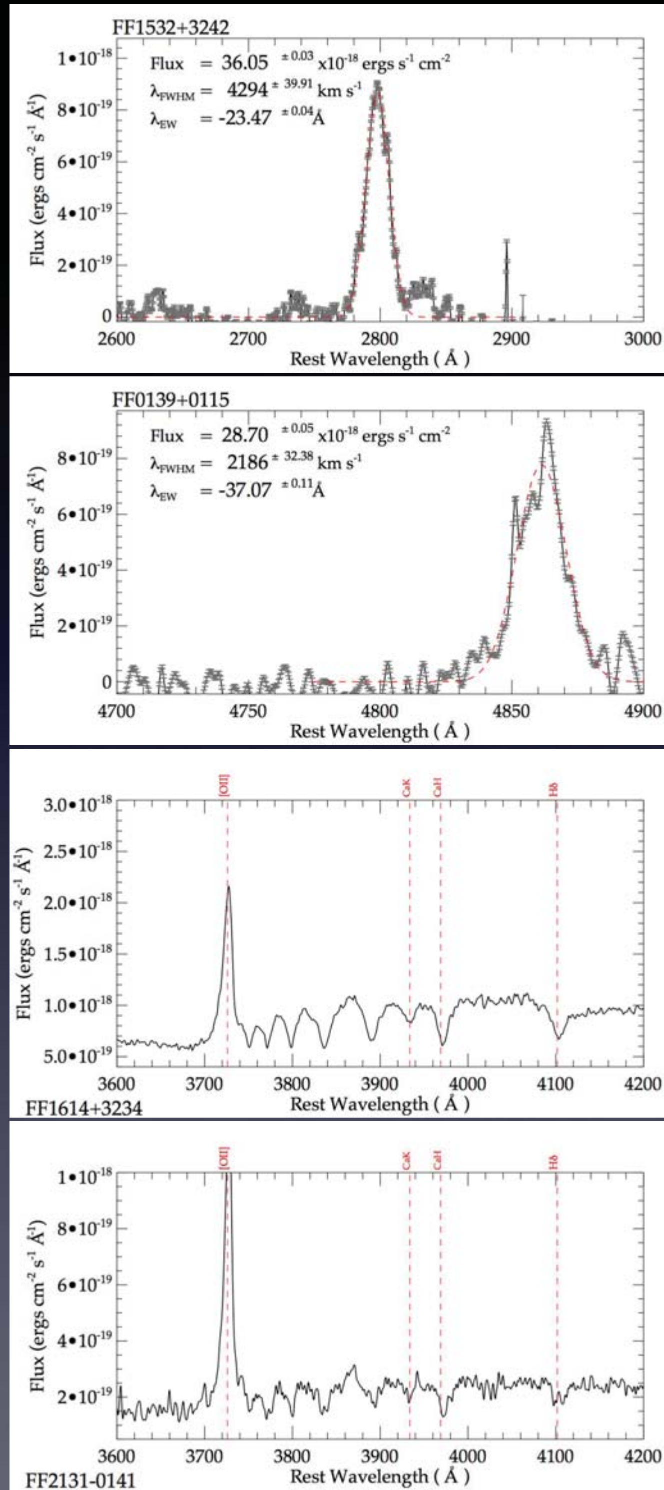




- Shown 7/8 observed with MODS-1
- Complete ULIRG sample will be observed by end of next semester (weather willing)
- Absorption lines in several objects have S/N and resolution sufficient to measure velocity dispersions
- Hβ shows multi-component complexity in several objects
- Clear indications of AGN (QSO) activity

First Results

- H-β widths of ~500-2500 km/s
- Very large MgII velocity widths
- Directly measure M_{BH} for 4/7 ULIRGs
  - Range $7.7 < \text{Log } M_{BH} < 8.4$
  - MgII usually produces slightly higher M_{BH} (~0.2 dex)
  - Mrk 231 Log M_{BH} = 7.9 (Kawakatu et al. 2007).
  - PG QSOs Log M_{BH} = 8.3 Kawakatu et al. 2007)
- Ca H&K absorption features well defined in 3/7 ULIRGs
- High excitation lines present consistent with AGN & QSO activity



Conclusions & Future Work

- Very early (hot off the press) results indicate that relaxed ULIRGs at intermediate redshift are consistent with QSOs
- Deep spectroscopy with MODS-1 on LBT has provided unprecedented S/N and coverage of rest-frame UV & Optical wavelengths
- Next steps:
  - 1) measure σ^* using Ca H&K
  - 2) measure light profiles and luminosities using HST imaging
  - 3) Directly constrain dynamical masses and M_{BH}-σ for z~1 ULIRGs
    - a) Compare MgII & Hβ with Hα, [OII], [OIII] and other M_{BH} tools
    - b) Directly compare dynamics of mid-z ULIRGs with local ULIRGs
  - 4) Measure gas metallicities and stellar population parameters