B. Rothberg

The Impact of Star-Formation and Gas Dissipation on Galaxy Kinematics

Mergers in the local universe present a unique opportunity for studying the metamorphoses of galaxies in detail. Yet, many studies and simulations show gas-rich mergers do not contribute significantly to the overall star-formation rate and total mass function of galaxies. The ultimate implication is that Lambda-CDM and our current understanding of galaxy formation and evolution may be completely wrong. I will discuss recent results, based on high-resolution imaging and multi-wavelength spectroscopy, which demonstrate how star-formation and the presence of multiple stellar populations has lead to a serious underestimation of the dynamical masses of star-forming galaxies, in particular, Luminous & Ultraluminous Infrared Galaxies. The presence of Red Supergiants and Asymptotic Giant Branch stars can severely affect the global properties measured in a galaxy, including: mass, age, extinction, and star-formation rate. I will also discuss the impact of these stellar populations on studies of high redshift galaxies.

The Impact of Star-Formation & Gas Dissipation on the Kinematics of IR Luminous Mergers

Barry Rothberg

National Research Council Fellow/Naval Research Labs

Collaboration with Jacqueline Fischer (NRL)

Outline

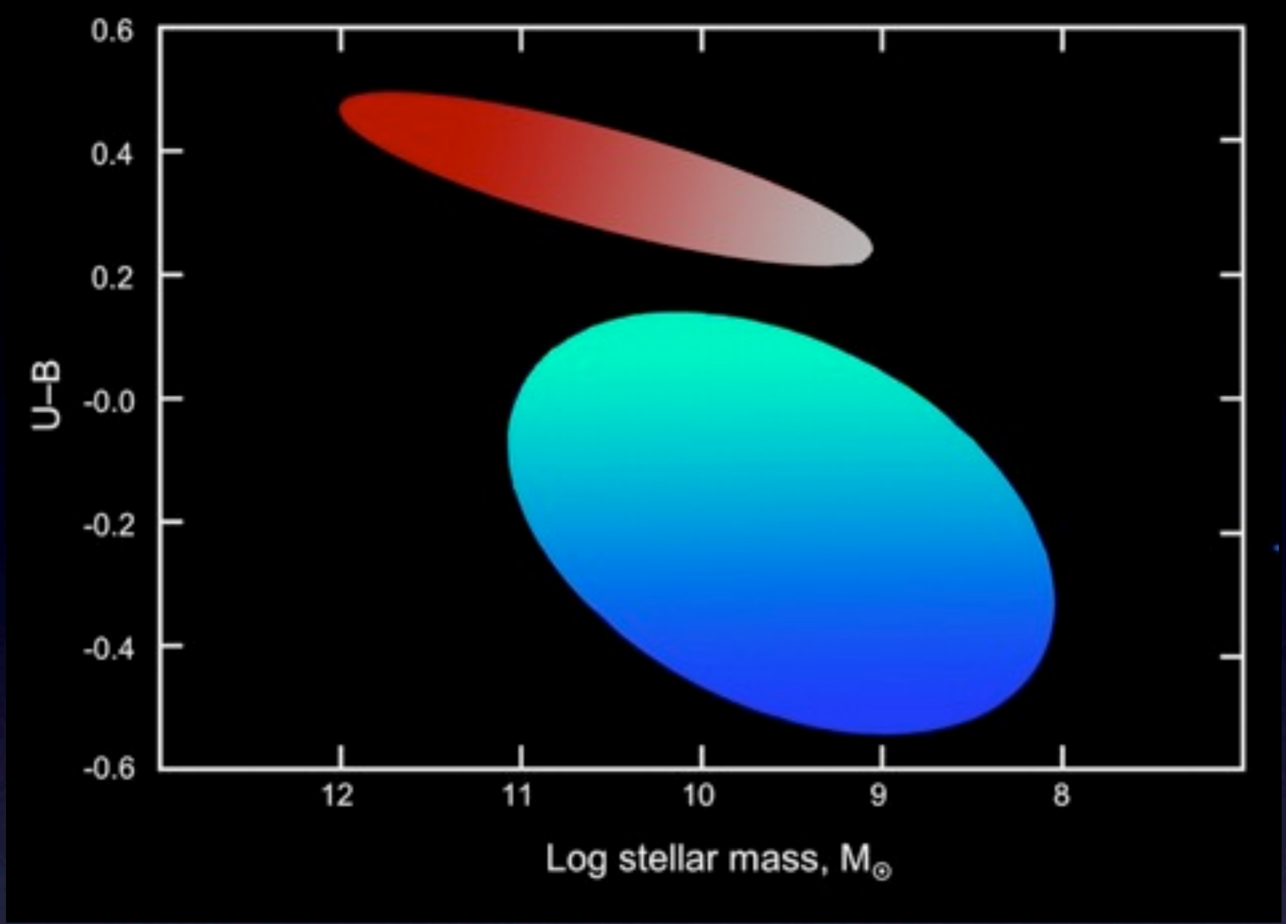
I. Motivation

II. The σ-Discrepancy

III. Dynamical Differences as a function of λ

IV. The Central ~1.5 kpc

Motivation - The BIG picture

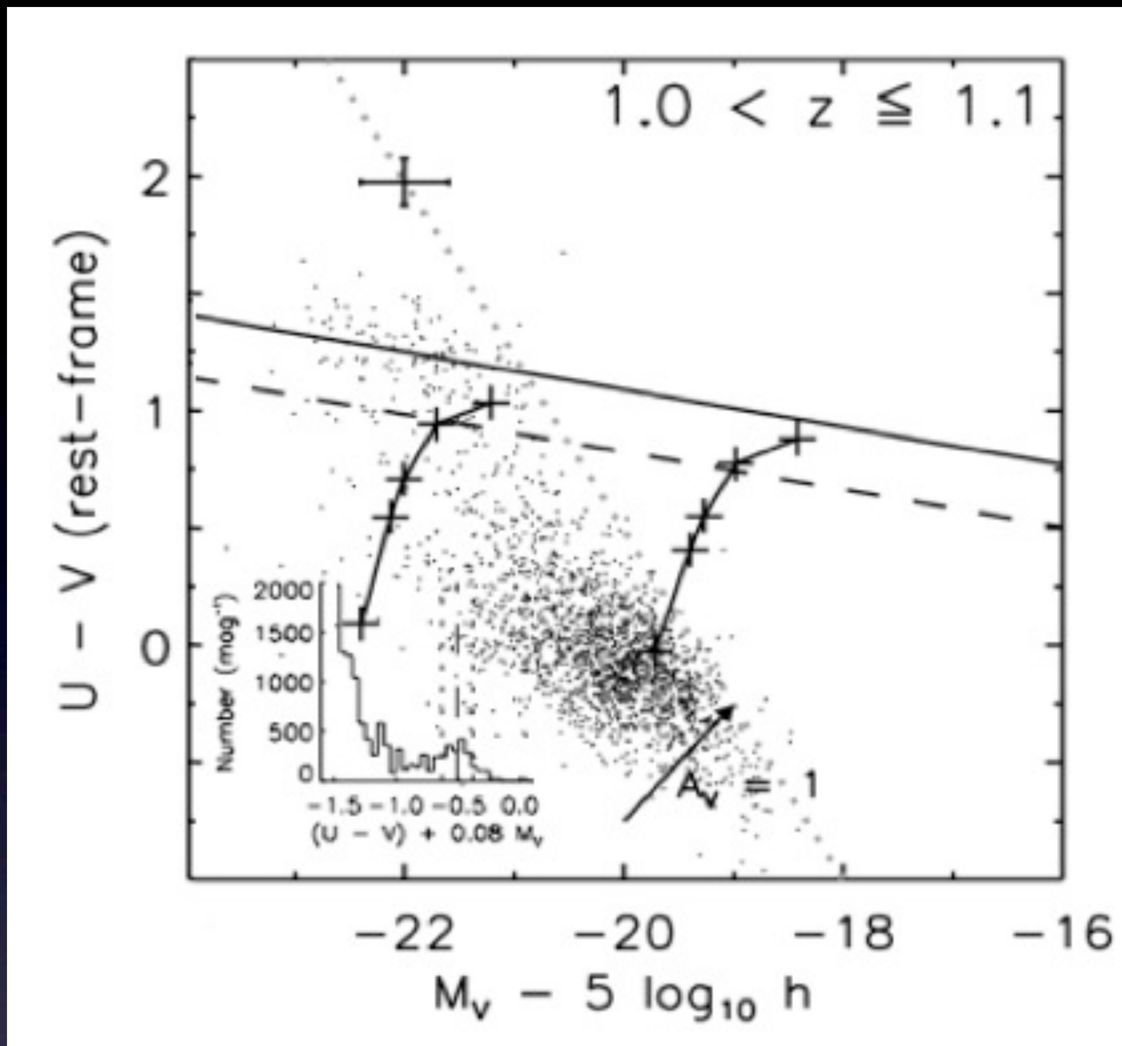


- ΛCDM (cold-dark-matter) cosmology based on merging dark matter halos, therefore merging galaxies
- Galaxies obey a mass-metallicity relationship - ellipticals built up by gas-rich mergers (or are they?)

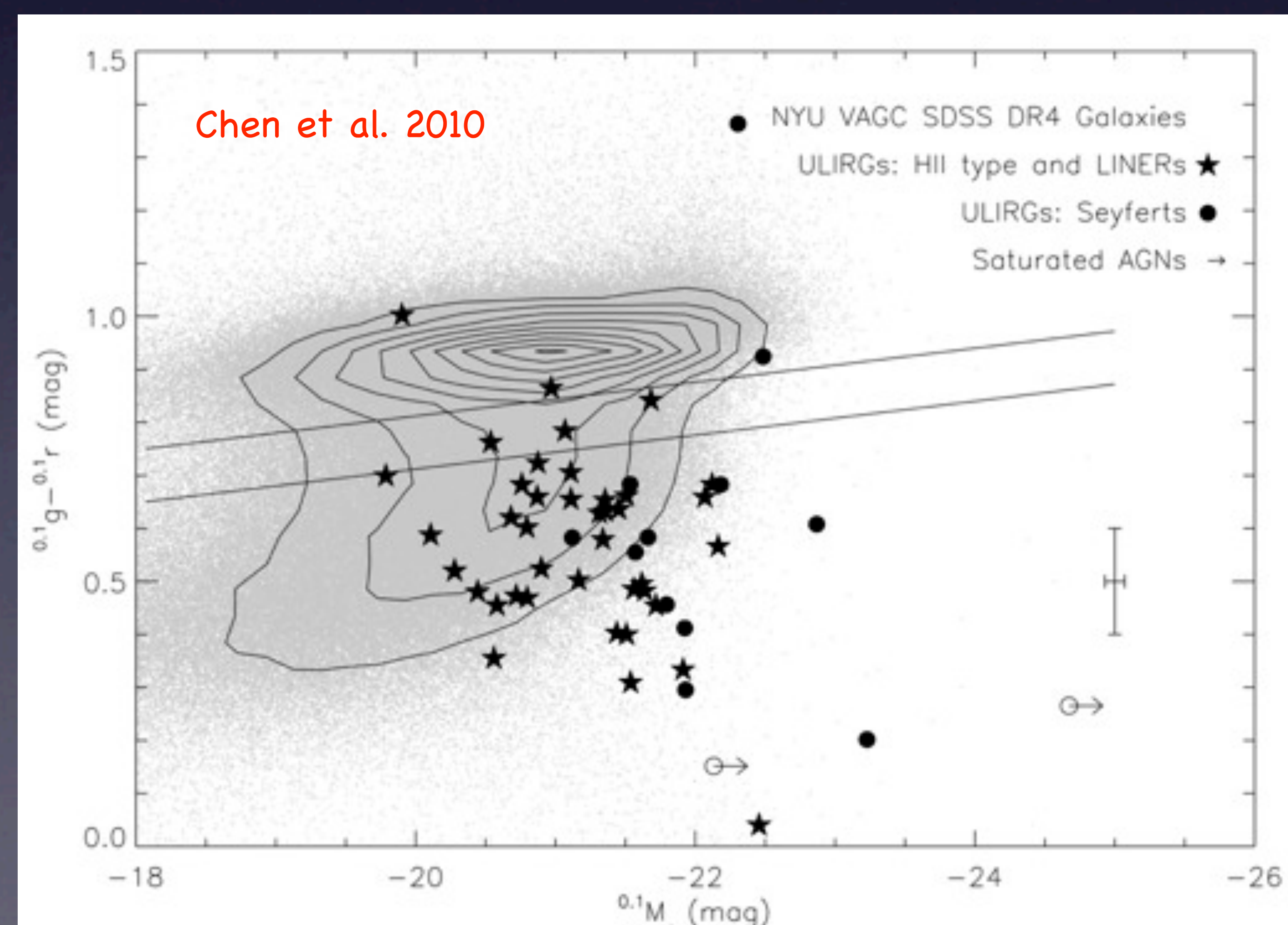
Motivation - The BIG picture

- ΛCDM (cold-dark-matter) cosmology based on merging dark matter halos, therefore merging galaxies
- Galaxies obey a mass-metallicity relationship - ellipticals built up by gas-rich mergers (or are they?)

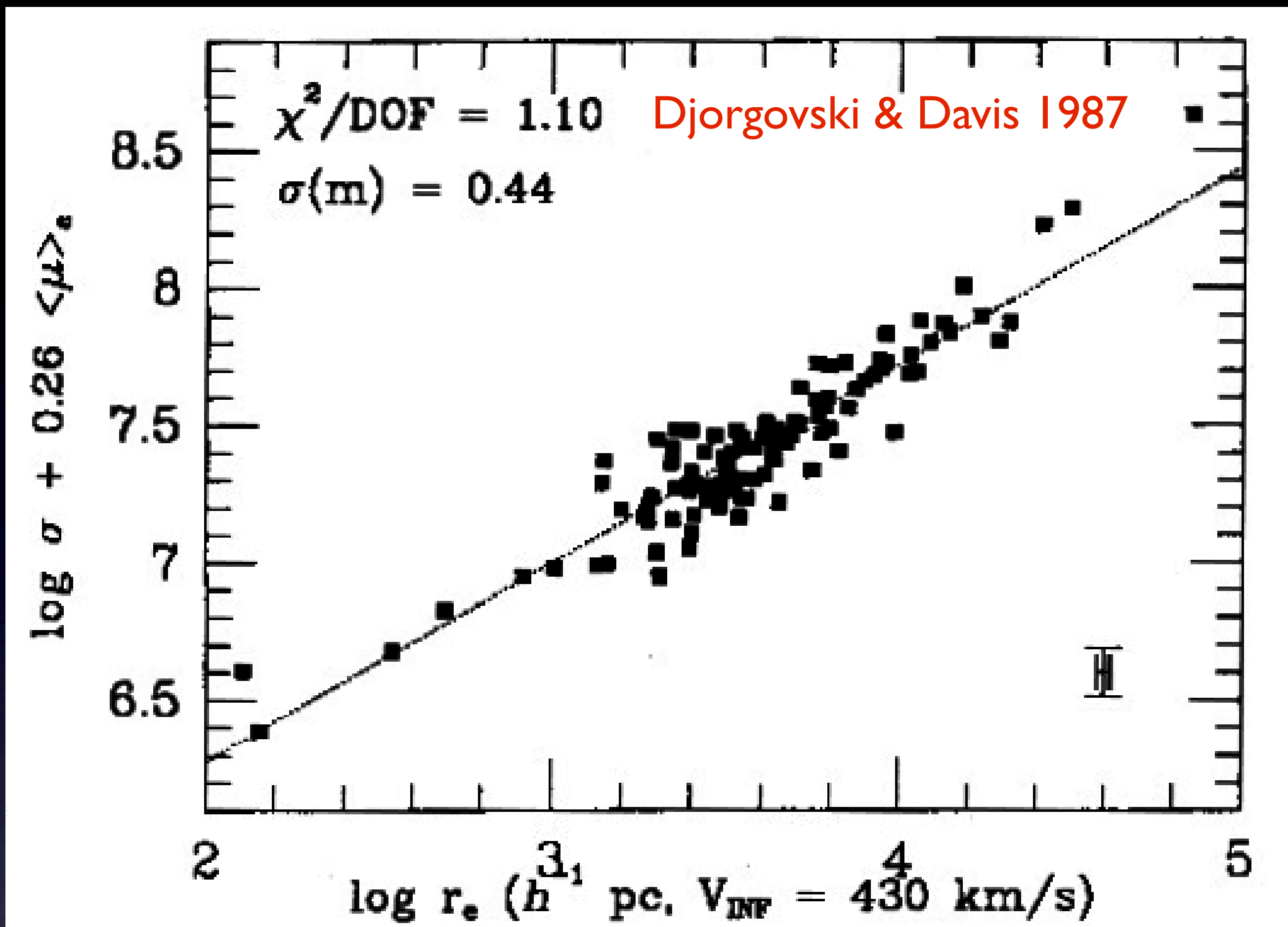
Motivation - The BIG picture



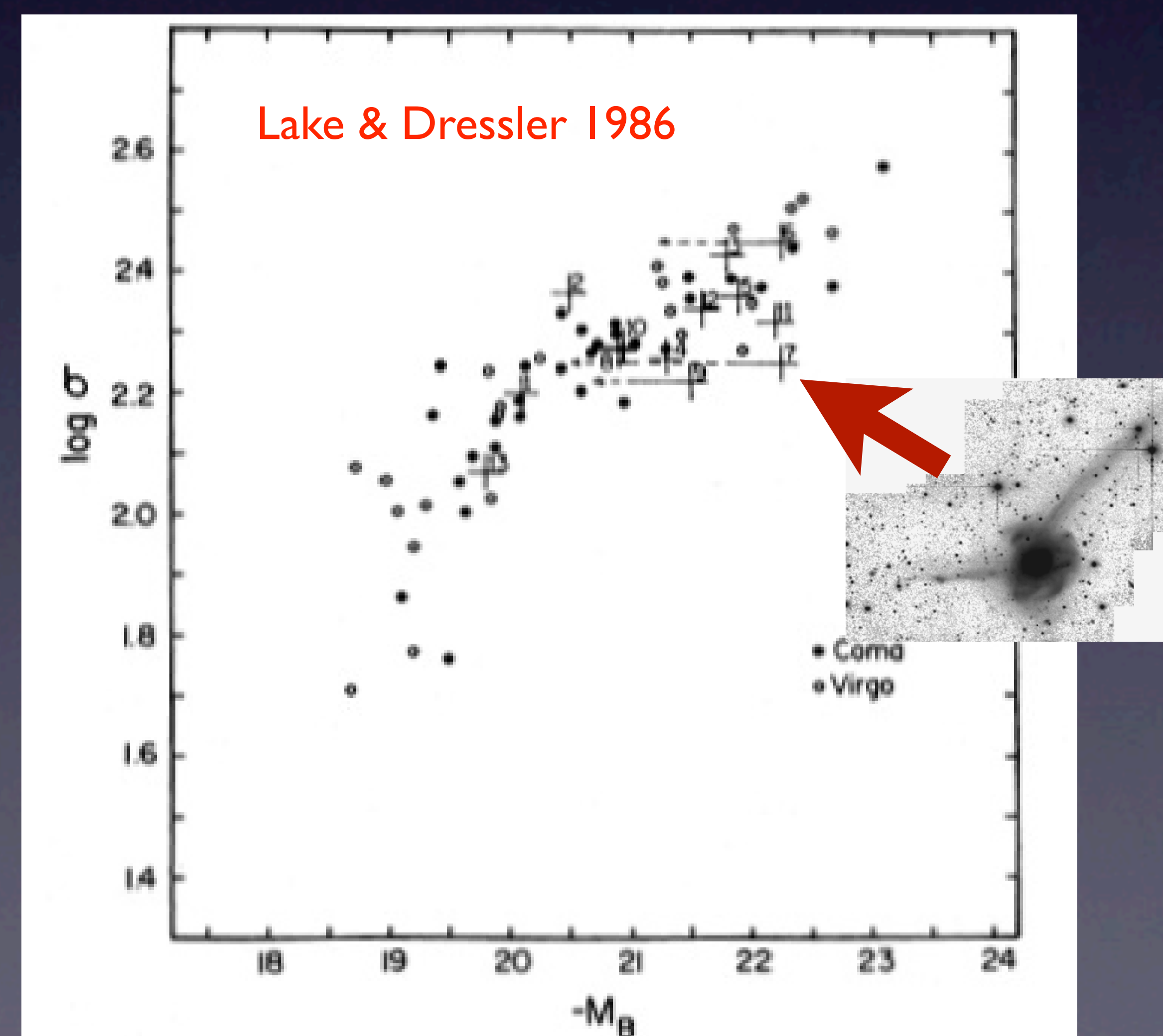
- ΛCDM (cold-dark-matter) cosmology based on merging dark matter halos, therefore merging galaxies
- Galaxies obey a mass-metallicity relationship - ellipticals built up by gas-rich mergers (or are they?)
- Red-Sequence (RS) in place at z~1
- Lack of Bright blue progenitors which passively evolve onto high-end of RS
- ULIRGs passively evolve onto low-mass end of RS?



Motivation - Local Picture

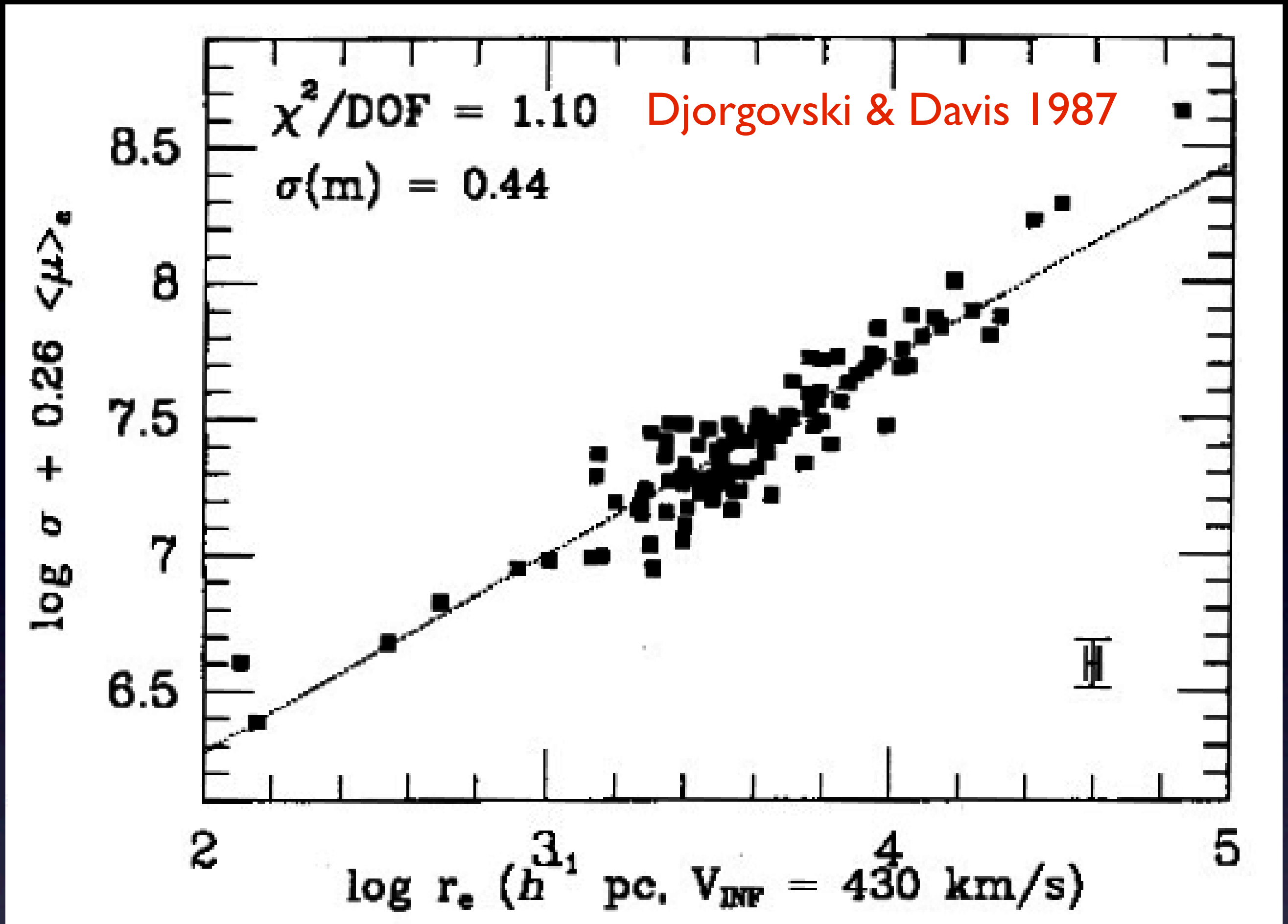


- Ellipticals obey mass & luminosity correlations (Faber-Jackson & Fundamental Plane)
- Toomre Hypothesis: gas-rich mergers obey elliptical correlations & form new, more massive galaxies



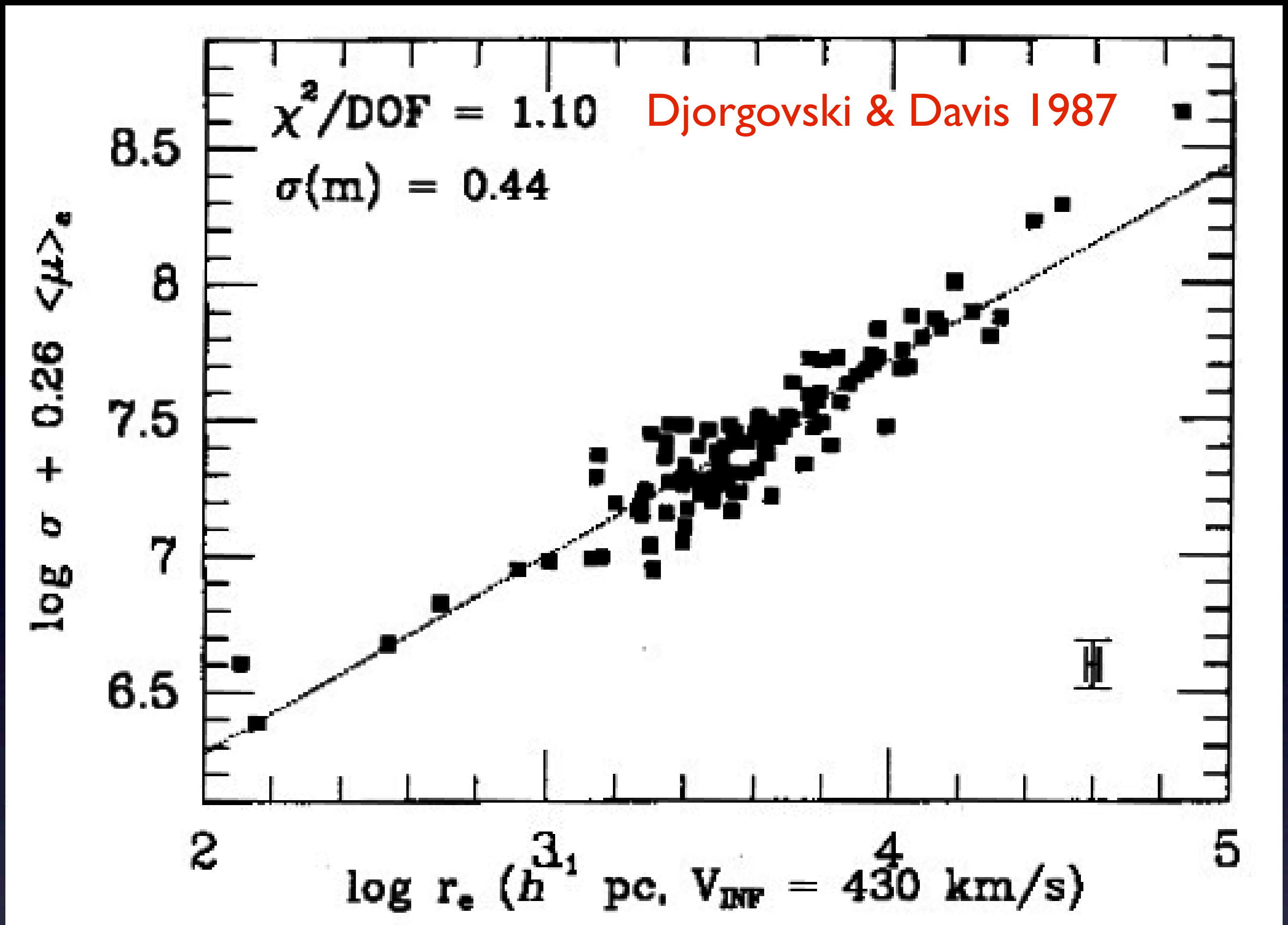
- For an **<u>optically selected</u>** mergers, MgIb & CaT absorption lines, $\sigma_{Merger} \approx \sigma_{Ellip}$
- B-band photometry + MgIb/CaT σ show mergers lie on **high-mass** end of Faber-Jackson

Motivation - Local Picture

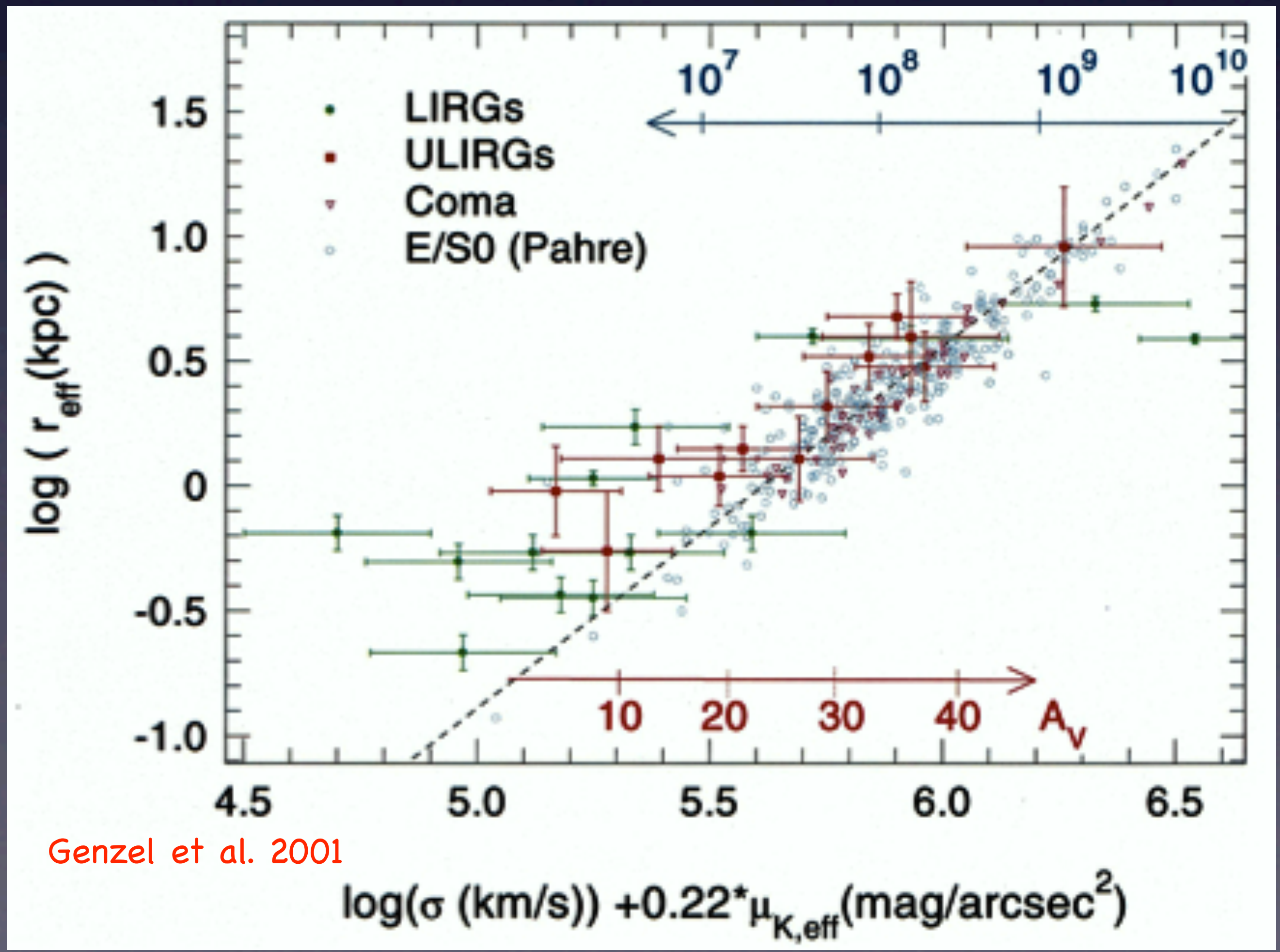


- Ellipticals obey mass & luminosity correlations (Faber-Jackson & Fundamental Plane)
- Toomre Hypothesis: gas-rich mergers obey elliptical correlations & form new, more massive galaxies

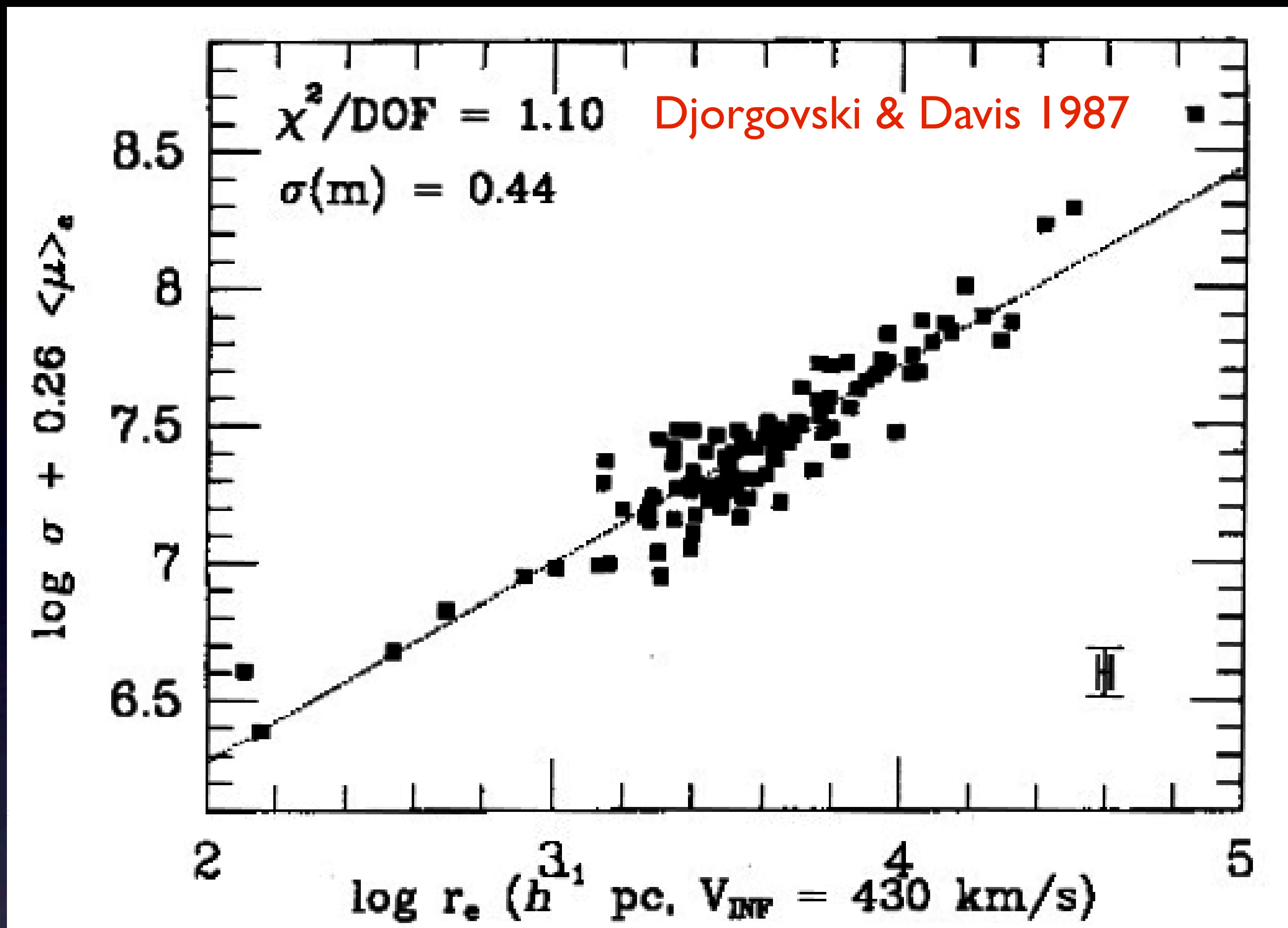
Motivation - Local Picture



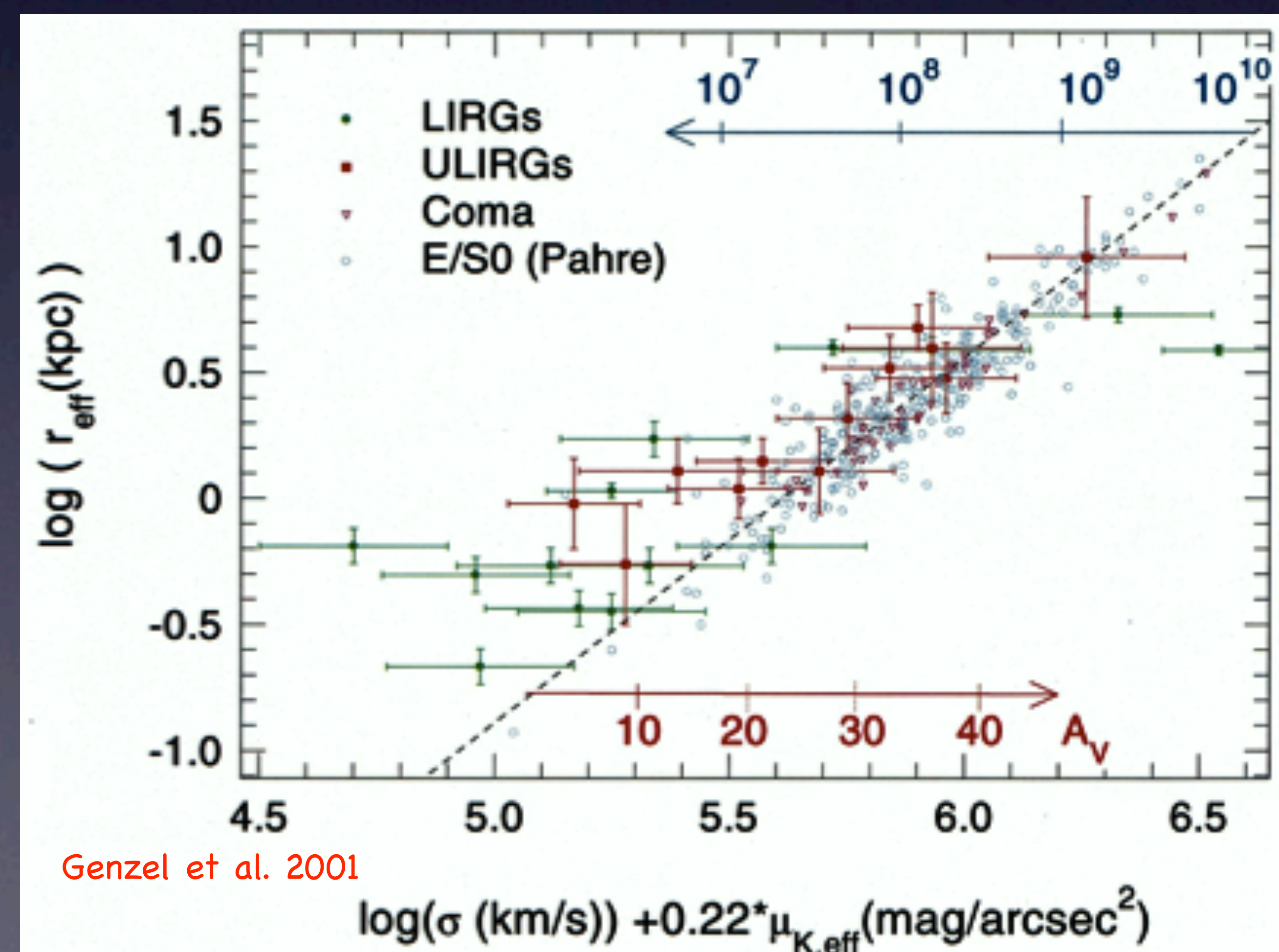
- Ellipticals obey mass & luminosity correlations (Faber-Jackson & Fundamental Plane)
- Toomre Hypothesis: gas-rich mergers obey elliptical correlations & form new, more massive galaxies



Motivation - Local Picture



- Ellipticals obey mass & luminosity correlations (Faber-Jackson & Fundamental Plane)
- Toomre Hypothesis: gas-rich mergers obey elliptical correlations & form new, more massive galaxies



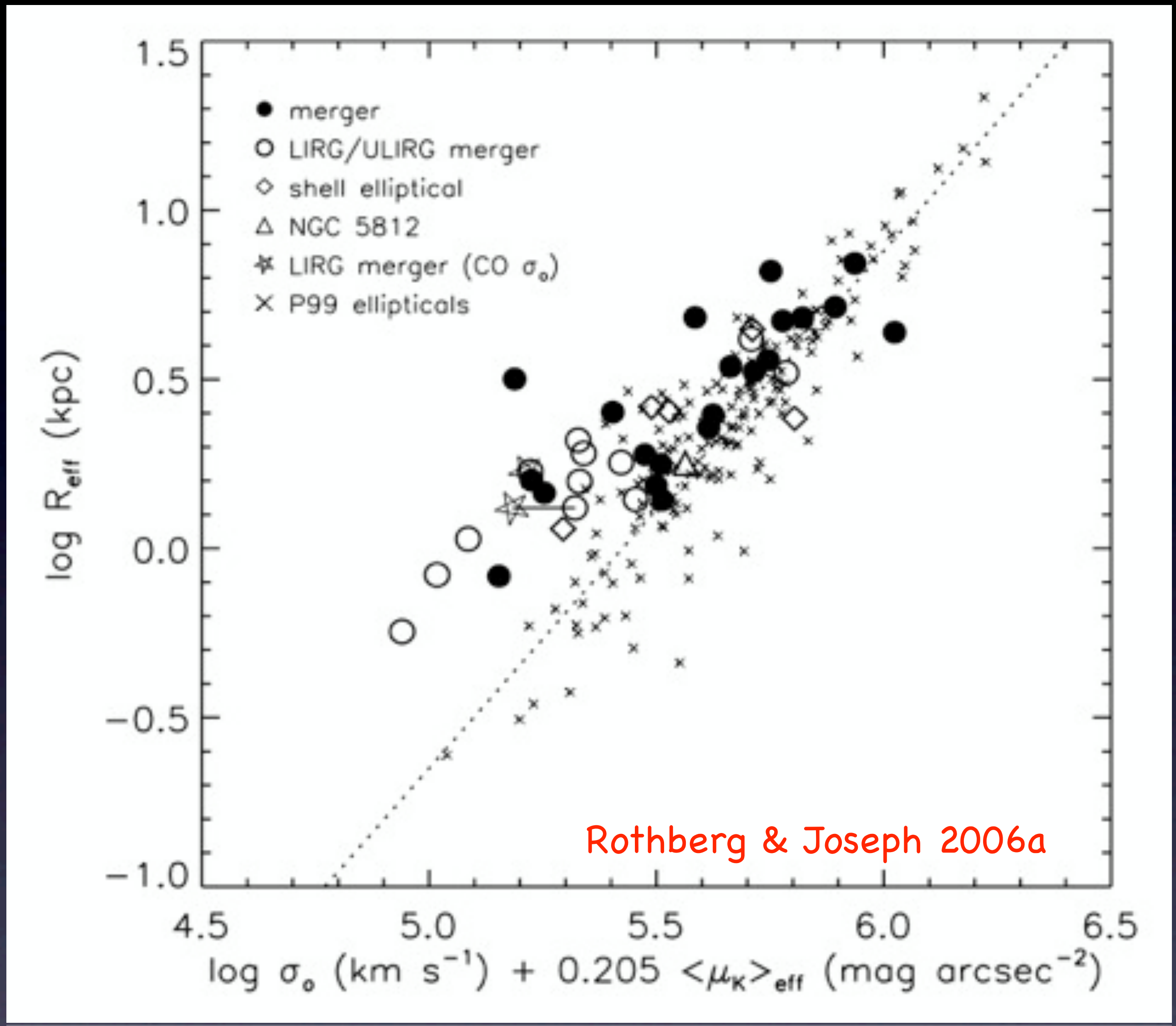
- Subsequent studies focused solely on LIRG/ULIRG samples (near-IR photometry/spectroscopy)

  (e.g Doyon et al. 94; Shier et al. 94, 96, Shier & Fischer 98; James et al. 99; Genzel et al. 01, Tacconi et al. 02; Dasyra et al. 06)

- High surface brightness, low σ

Motivation - Local Picture II

- K-band photometry + CaII triplet (0.85 μm) spectroscopy to measure σ in 51 *optically* selected single nuclei mergers (Rothberg & Joseph 2006a,b)
- Most mergers lie ***on*** FP
- LIRG/ULIRGs lie offset in 1 area
- Offset primarily due to $<\mu_K>_{eff}$ NOT σ
- Same objects show **SYSTEMATICALLY DIFFERENT** σ at CaT and CO wavelengths



- **σ-Discrepancy**

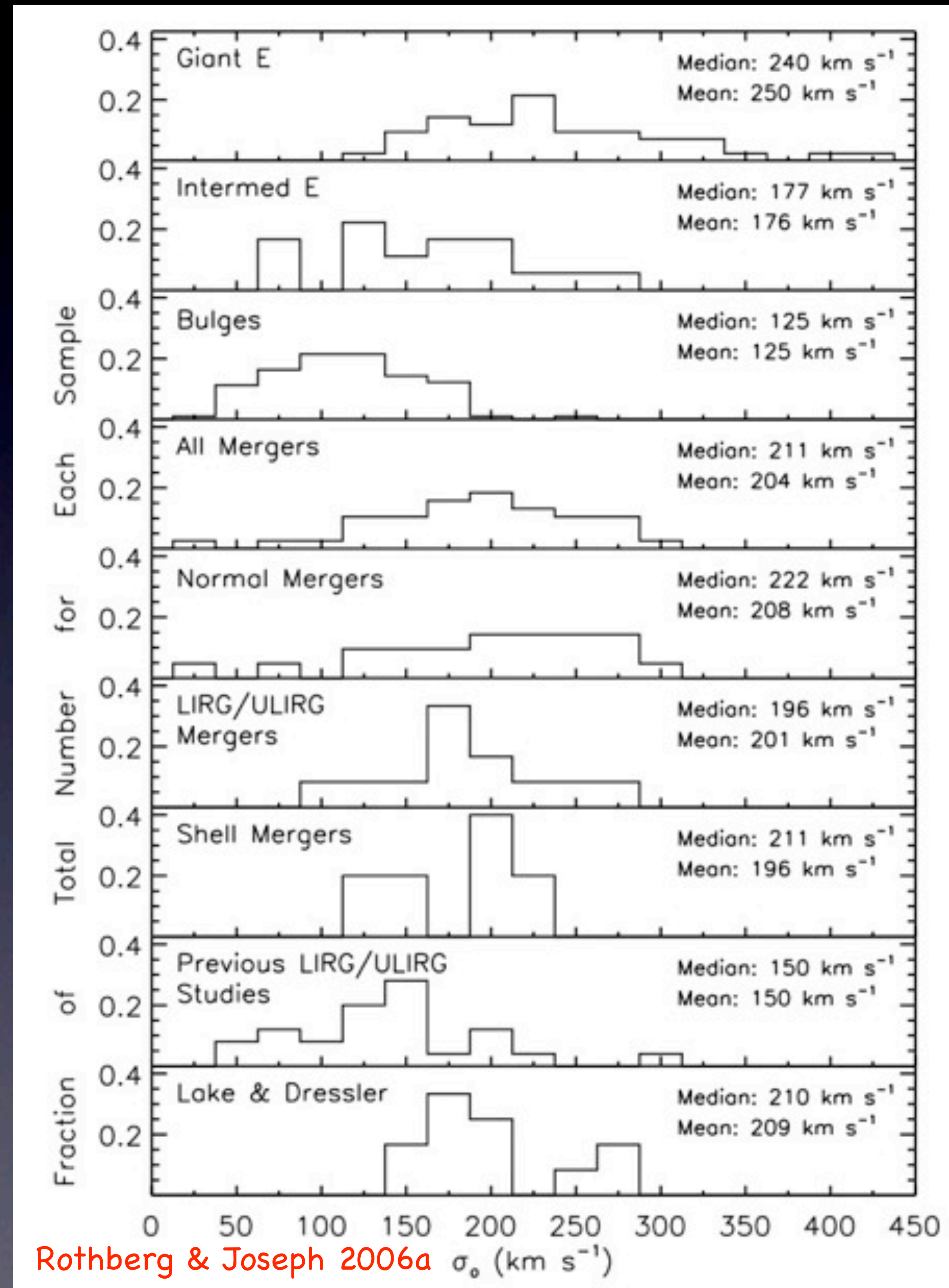
Motivation - Local Picture II

- K-band photometry + CaII triplet (0.85 μm) spectroscopy to measure σ in 51 *optically* selected single nuclei mergers (Rothberg & Joseph 2006a,b)
- Most mergers lie ***on*** FP
- LIRG/ULIRGs lie offset in 1 area
- Offset primarily due to $<\mu_K>_{eff}$ NOT σ
- Same objects show **SYSTEMATICALLY DIFFERENT** σ at CaT and CO wavelengths

- **σ-Discrepancy**

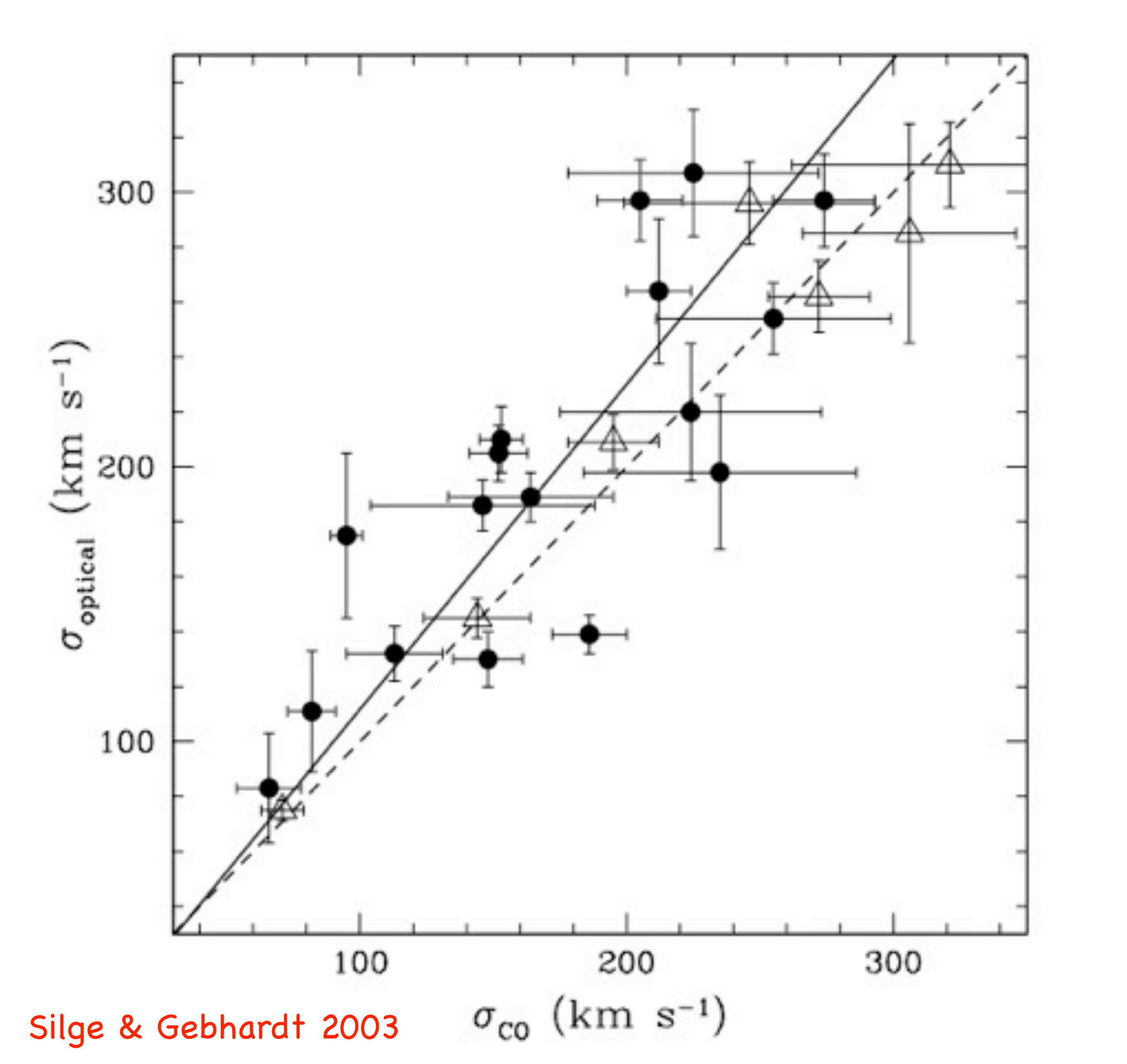
Motivation - Local Picture II

- K-band photometry + CaII triplet (0.85 μm) spectroscopy to measure σ in 51 *optically* selected single nuclei mergers (Rothberg & Joseph 2006a,b)
- Most mergers lie ***on*** FP
- LIRG/ULIRGs lie offset in 1 area
- Offset primarily due to $<\mu_K>_{eff}$ NOT σ
- Same objects show **SYSTEMATICALLY DIFFERENT** σ at CaT and CO wavelengths
- **σ-Discrepancy**



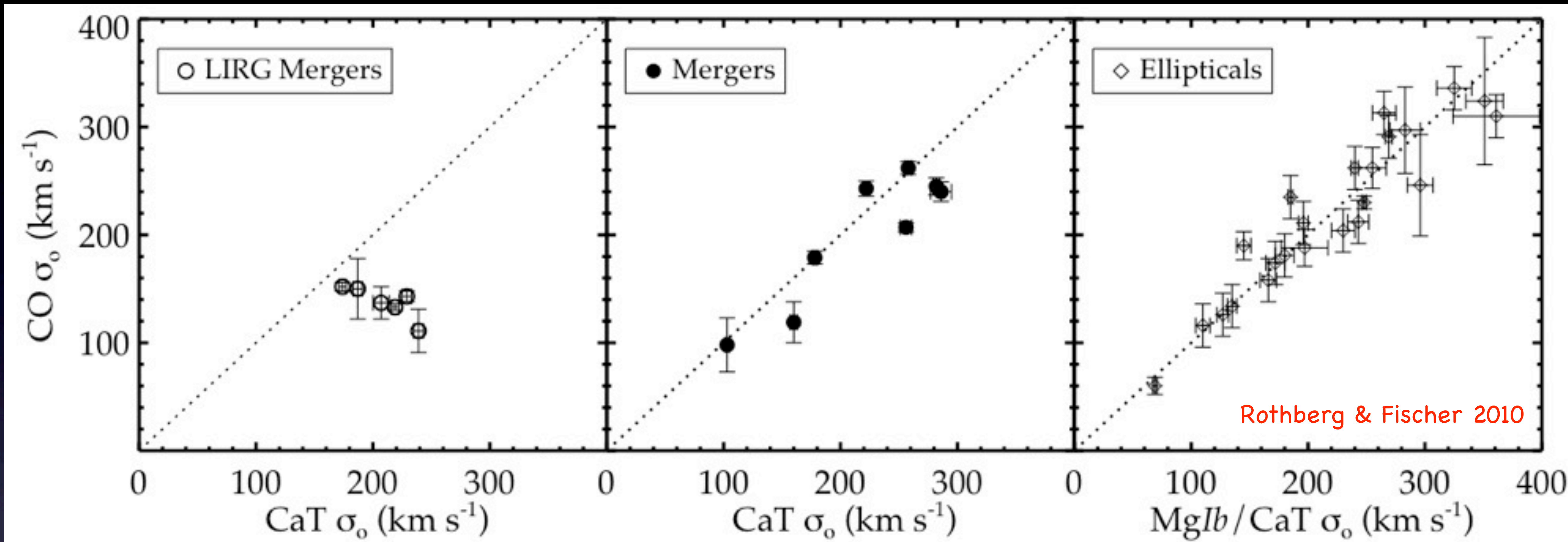
σ-Discrepancy in Early-type Galaxies

- Silge & Gebhardt found CO yields up to 30% smaller σ in 25 nearby early-types (dominated by S0s)
- EWs of CO and Mg_2 did not correlate with each other
- Concluded dust was involved:
    - Cold stellar component with dust dominates CO σ
    - Hot stellar component dominates optical σ



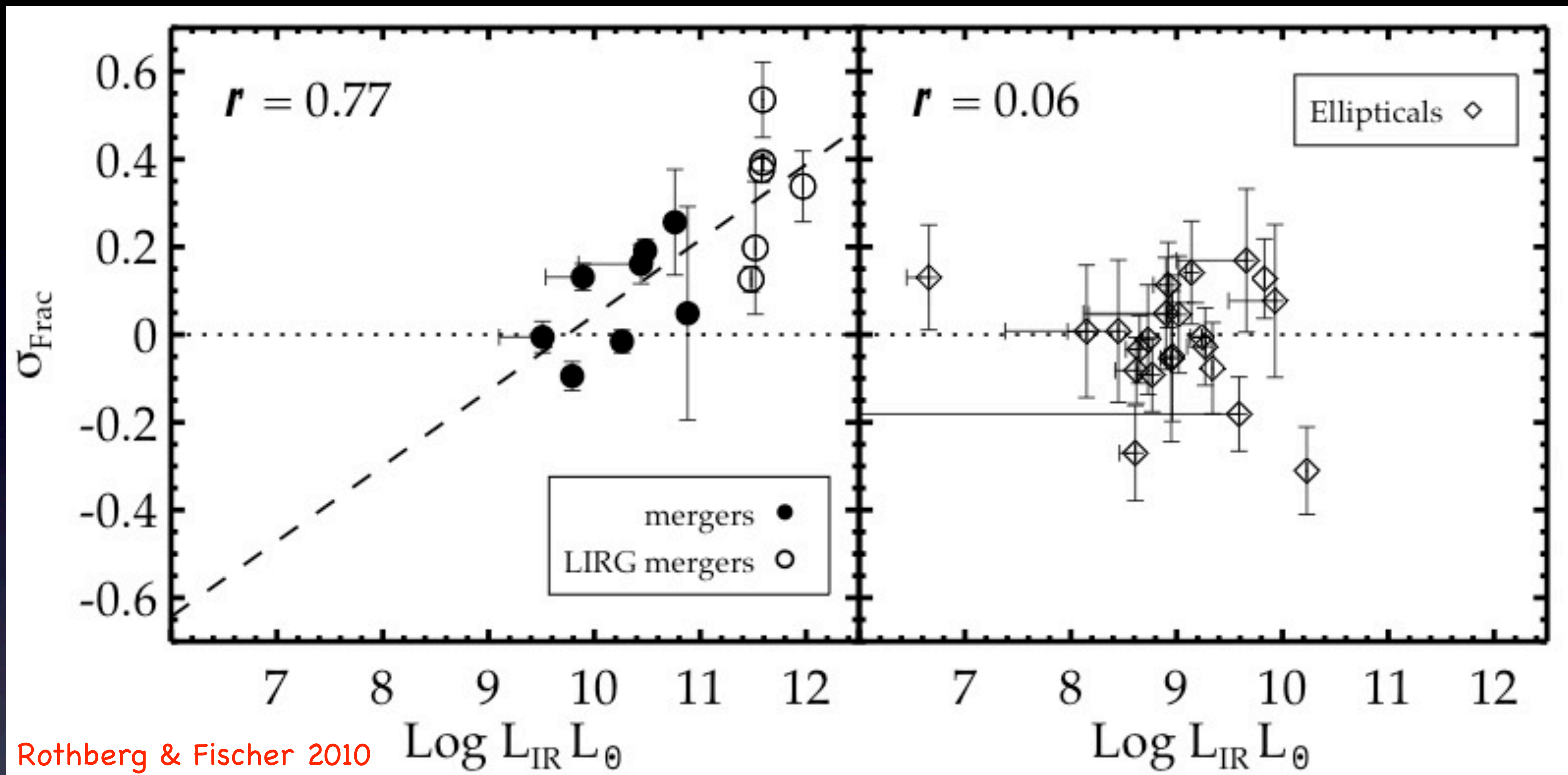
Mergers & Early-type Galaxies show σ-Discrepancy: Is there a problem with either Optical or IR σ?

Test the σ-Discrepancy



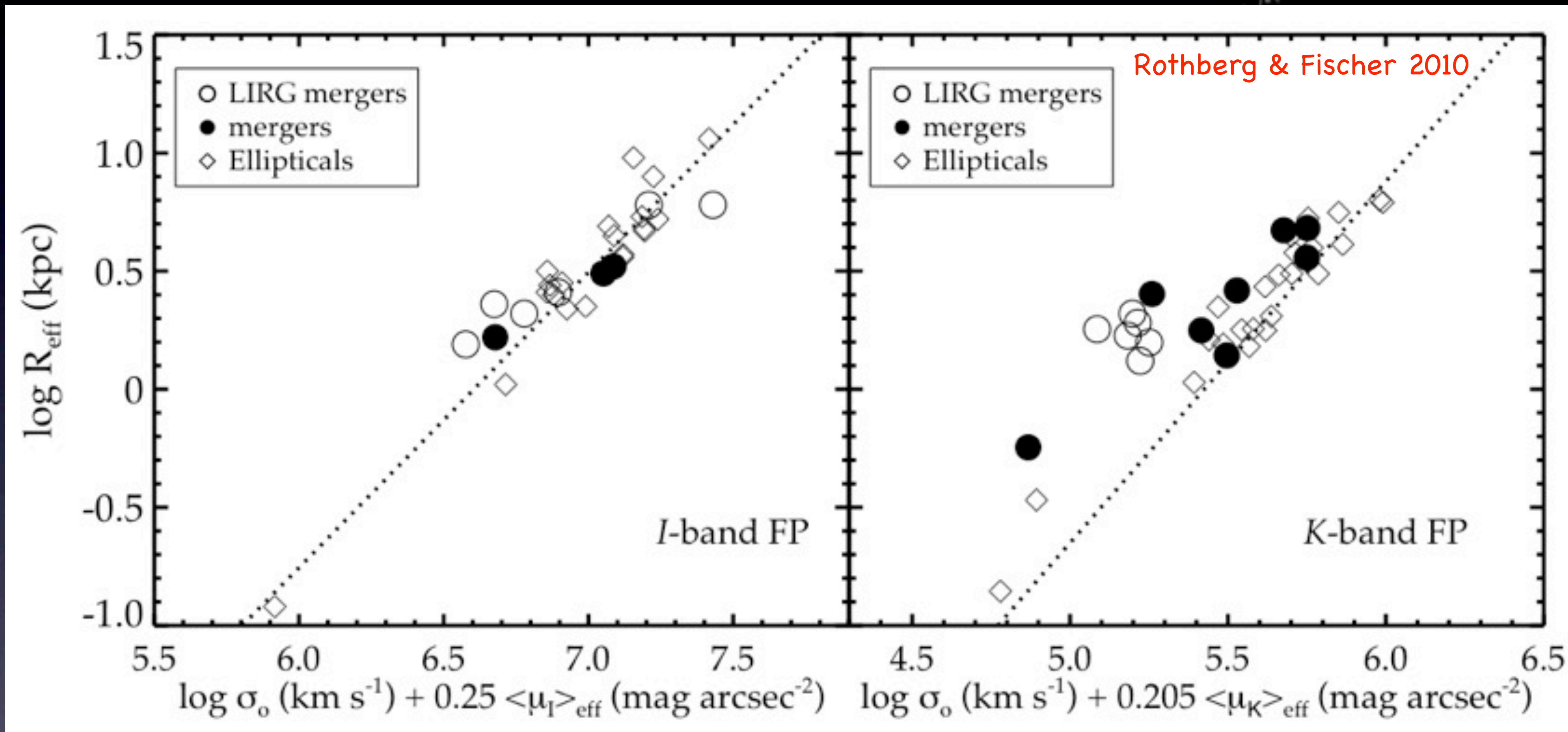
- Comparison of Optical (CaT for Mergers, CaT & MgIb for E's) and near-IR CO bandhead
- Compare 8 non-LIRGs & 23 "Pure" Ellipticals with 6 LIRGs
- Ellipticals within 1σ scatter of unity
- Evolution of slope from LIRGs → non-LIRGs → Ellipticals

σ-Discrepancy and L_{IR}

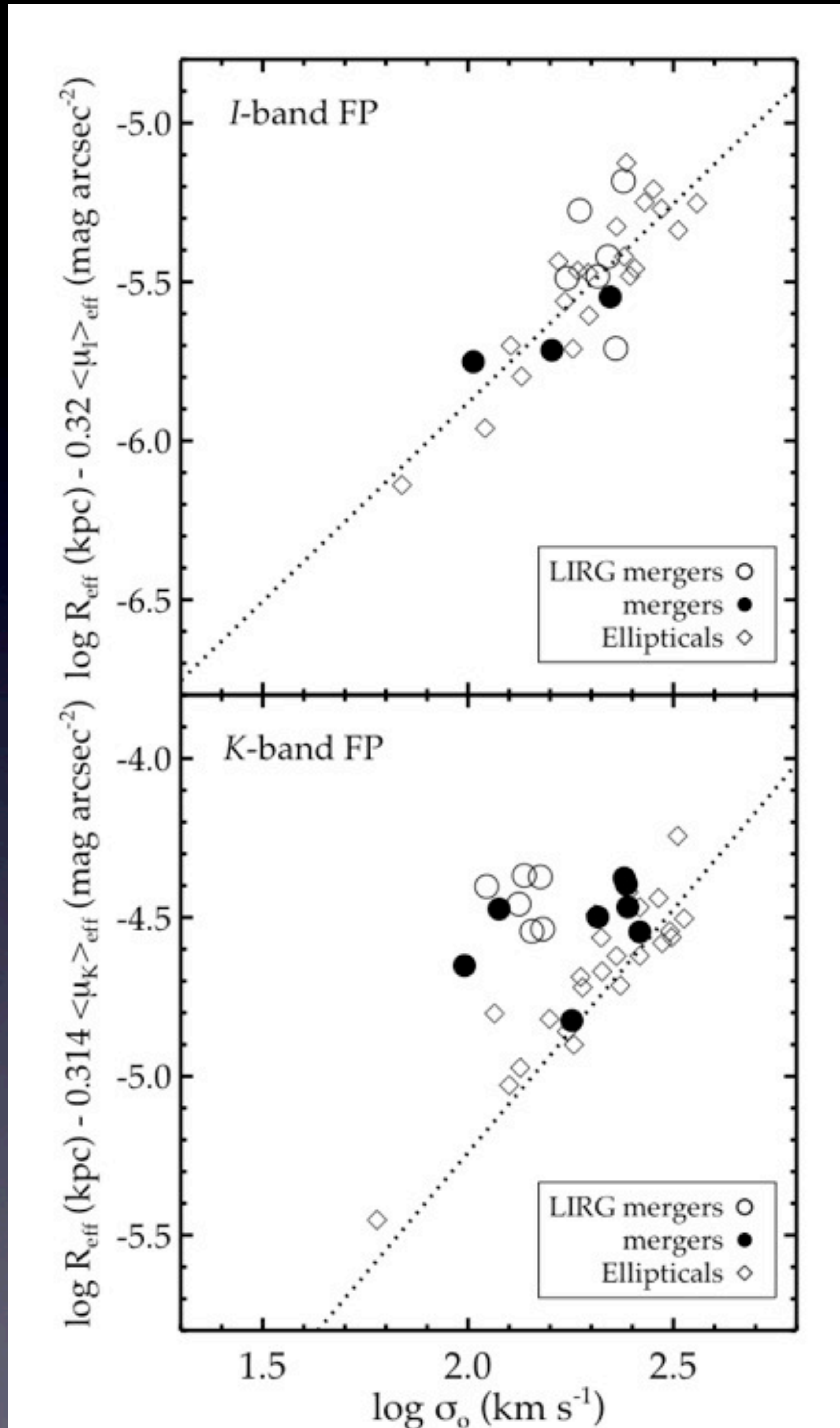


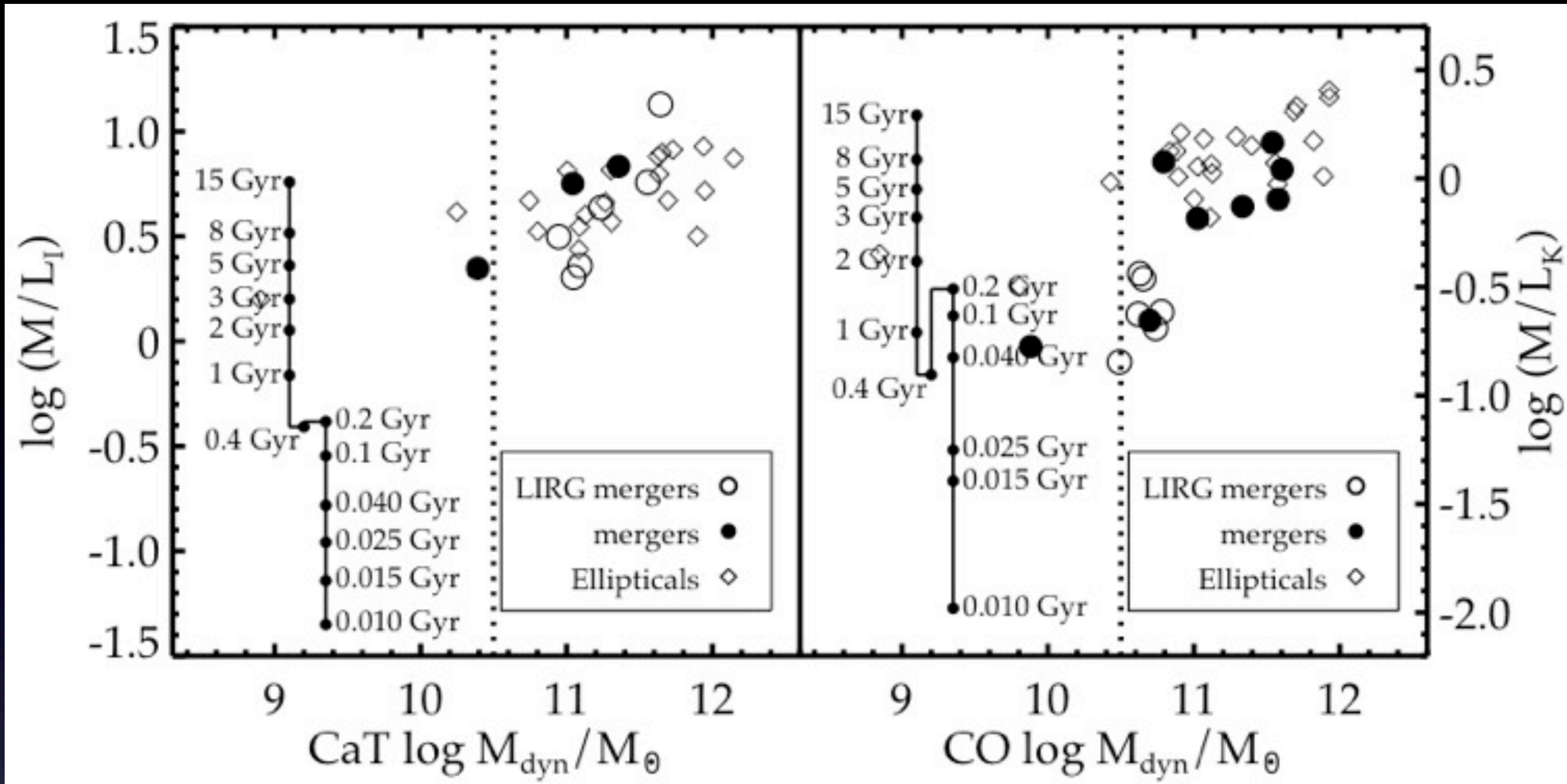
- Introduce the parameter: σ_{frac} to test with other observed properties
- Strong correlation between L_{IR} and σ_{frac}
- Correction for σ: $$\sigma_{\rm frac} = 0.17^{\pm 0.04} \log L_{\rm IR} - 1.67^{\pm 0.44} \quad (\log L_{\rm IR} \geqslant 9.5). \quad (7)$$

Head to Head: Optical vs near-IR

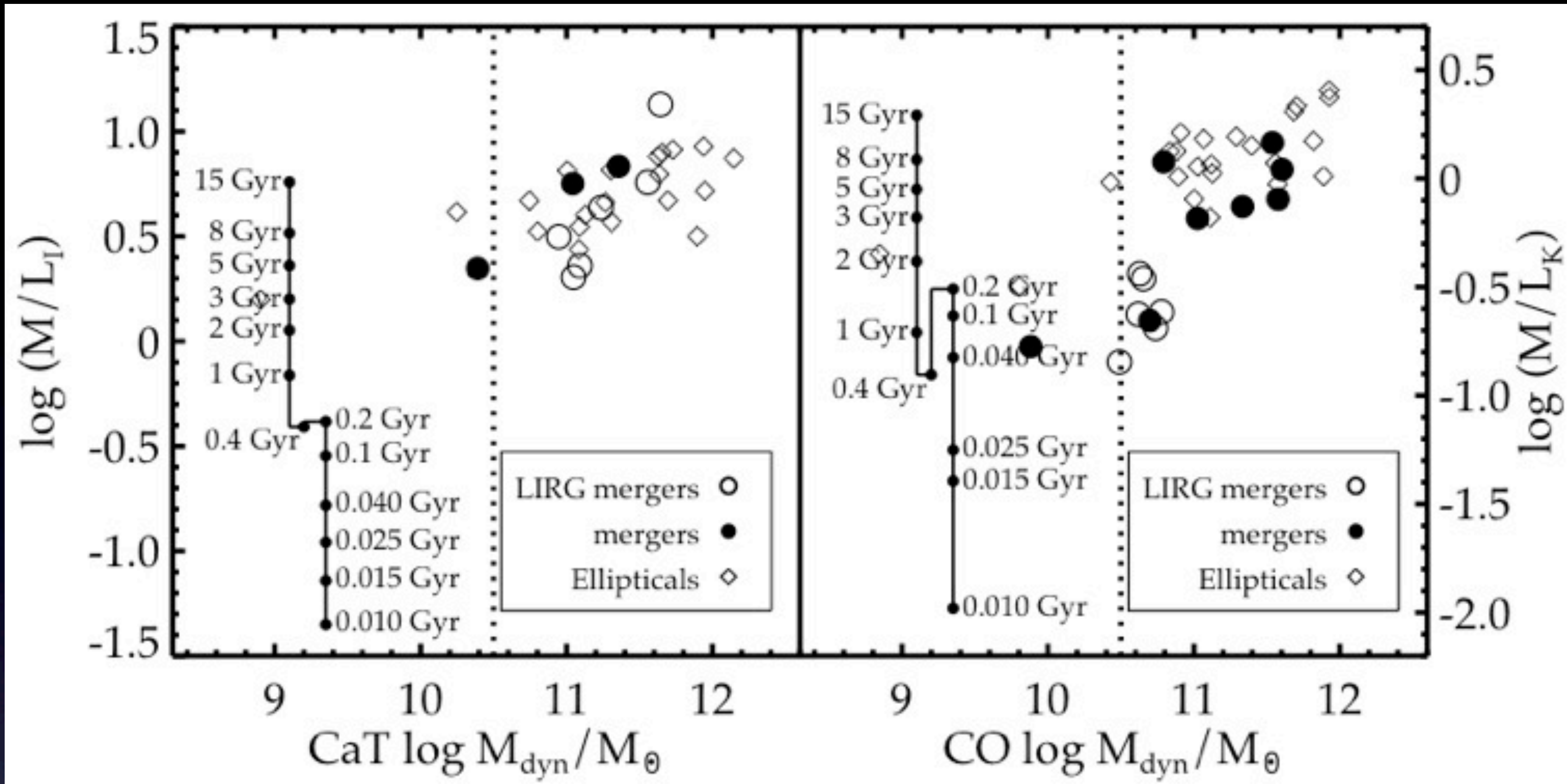


- *I*-band: merger-remnants ≈ Elliptical Galaxies
- *K*-band: LIRG merger remnants clustered together
- These results are consistent with **BOTH** older LIRG/ULIRG studies and LD86,RJ06a


I-band FP
K-band FP
LIRG mergers
mergers
Ellipticals
log R_eff (kpc) - 0.32 <μ_I>_eff (mag arcsec^-2)
log R_eff (kpc) - 0.314 <μ_K>_eff (mag arcsec^-2)
log σ_o (km s^-1)
-5.0
-5.5
-6.0
-6.5
-4.0
-4.5
-5.0
-5.5
1.5
2.0
2.5

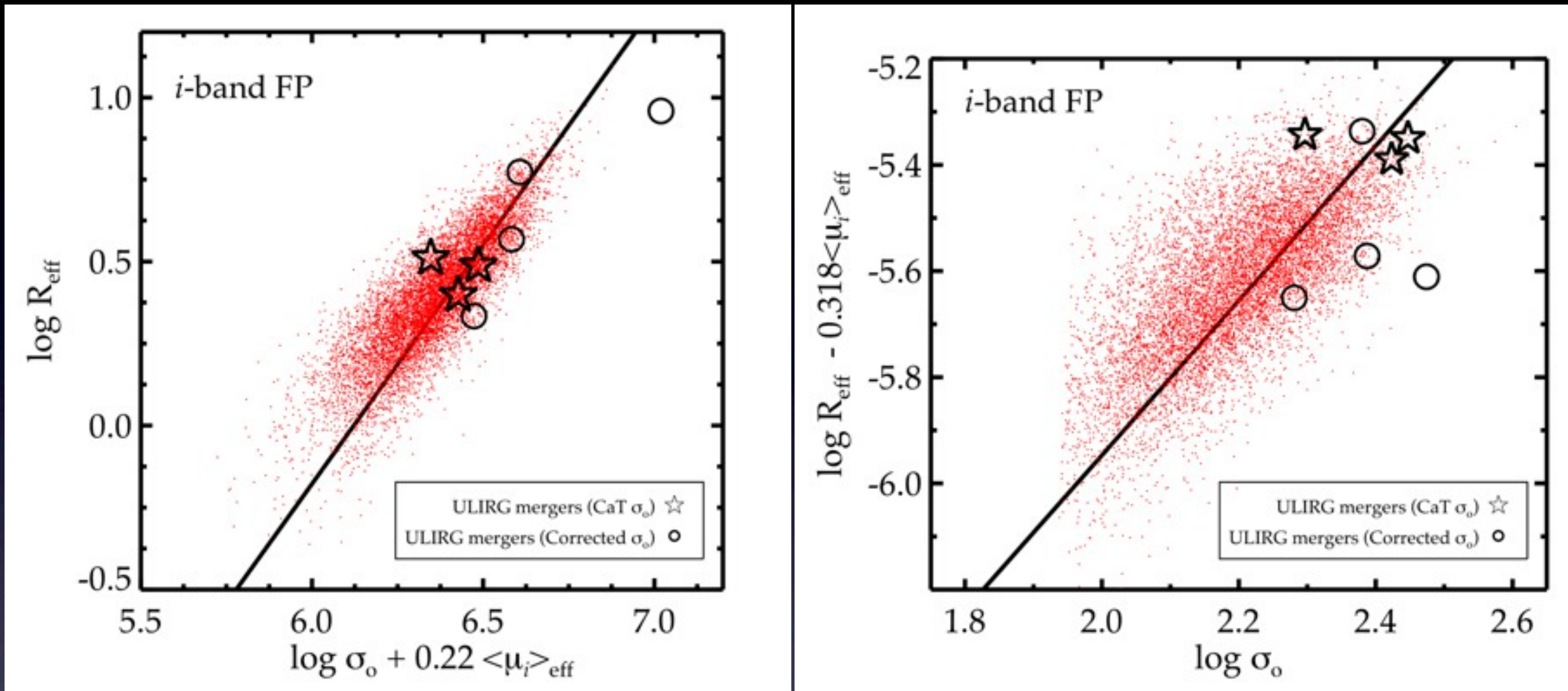


log (M/L$_I$)
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
15 Gyr
8 Gyr
5 Gyr
3 Gyr
2 Gyr
1 Gyr
0.4 Gyr
0.2 Gyr
0.1 Gyr
0.040 Gyr
0.025 Gyr
0.015 Gyr
0.010 Gyr
LIRG mergers
mergers
Ellipticals
9
10
11
12
CaT log M$_{dyn}$/M$_\odot$
CO log M$_{dyn}$/M$_\odot$
log (M/L$_K$)
0.5
0
-0.5
-1.0
-1.5
-2.0



- Compare *M/L* of galaxies with evolution of a burst population (from Maraston 2005, Salpeter IMF, Solar Metallicity)
- Two **Different** ages for the *I*-band and *K*-band observations
- Mass ranges in the *I*-band clearly show LIRGs with $m > m^*$
- Once again, little variation between *I*-band and *K*-band observations of ellipticals
- M/L_K strongly correlated with σ_{frac}

Testing the Predictions for ULIRGs



- Comparison with ~9300 ellipticals from SDSS ($0.02 < z < 0.15$)
- 7 ULIRGs:
  - 3 - measured CaT σ (Keck-2 ESI)
  - 4 - corrected CO σ using Eq. 7 (RF10)

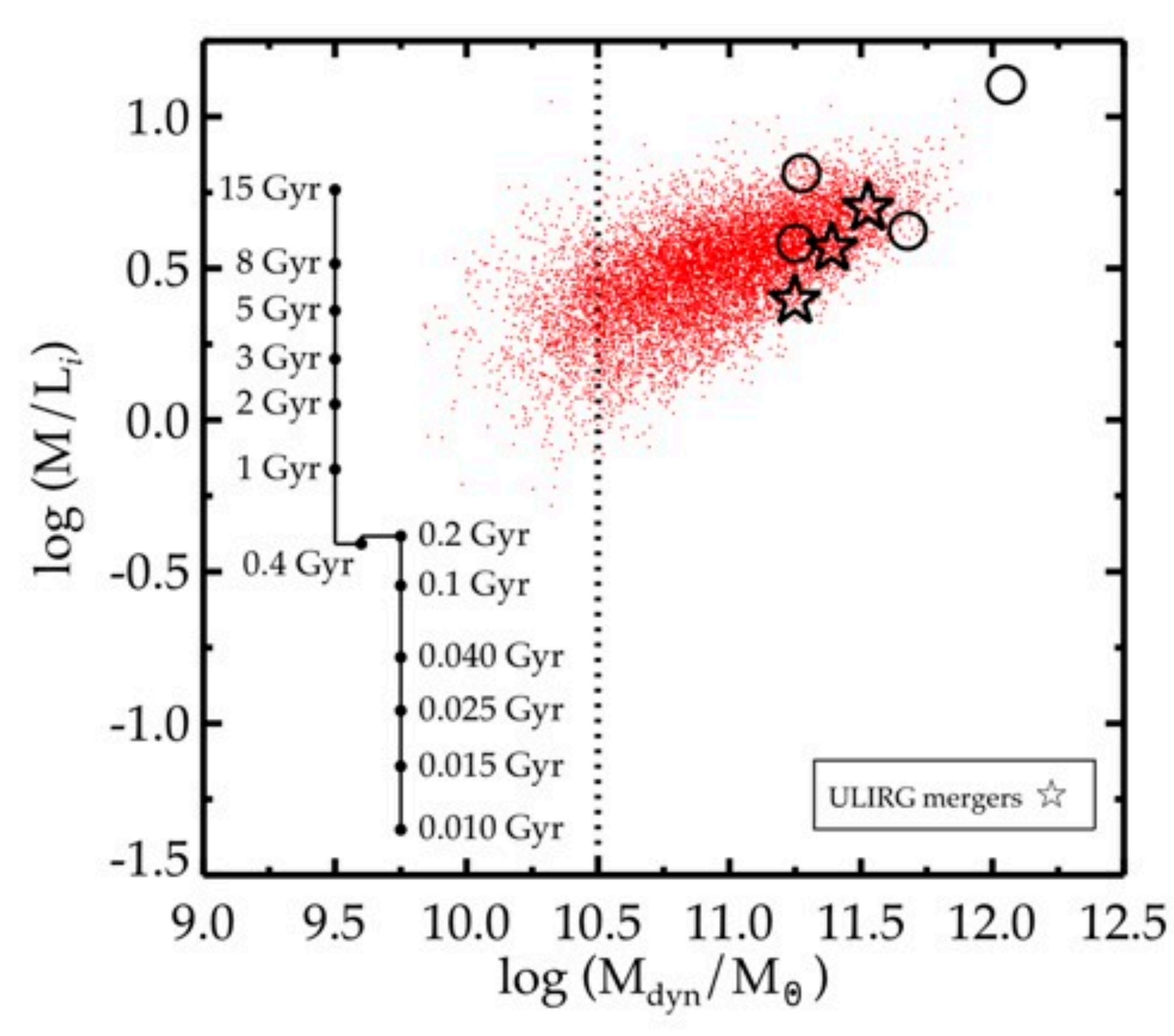
Testing the Predictions for ULIRGs

- Comparison with ~9300 ellipticals from SDSS ($0.02 < z < 0.15$)
- 7 ULIRGs:

  3 - measured CaT σ (Keck-2 ESI)

  4 - corrected CO σ using Eq. 7 (RF10)

Testing the Predictions for ULIRGs

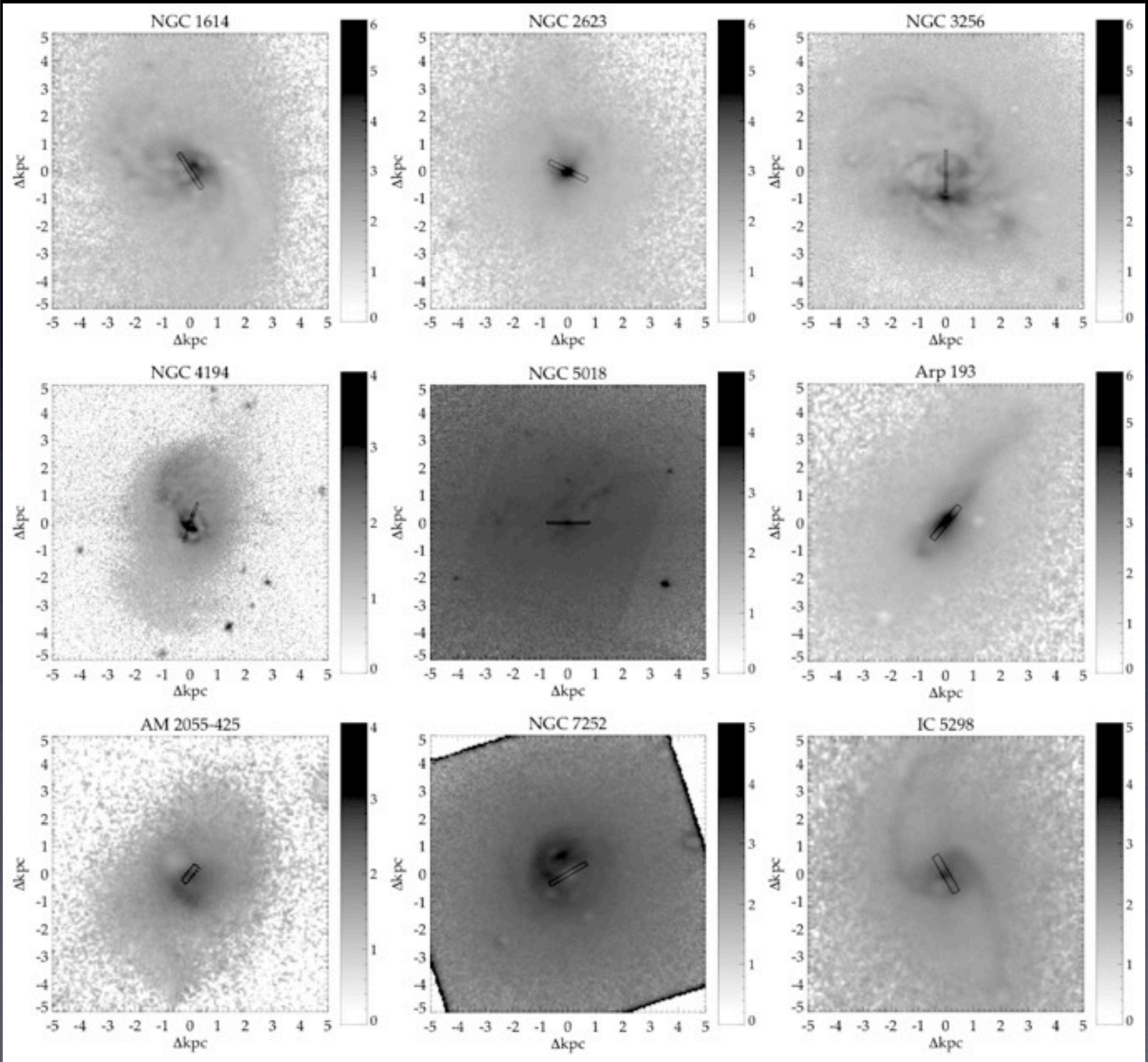


- Comparison with ~9300 ellipticals from SDSS (0.02 < z < 0.15)
- 7 ULIRGs:

  3 - measured CaT σ (Keck-2 ESI)

  4 - corrected CO σ using Eq. 7 (RF10)

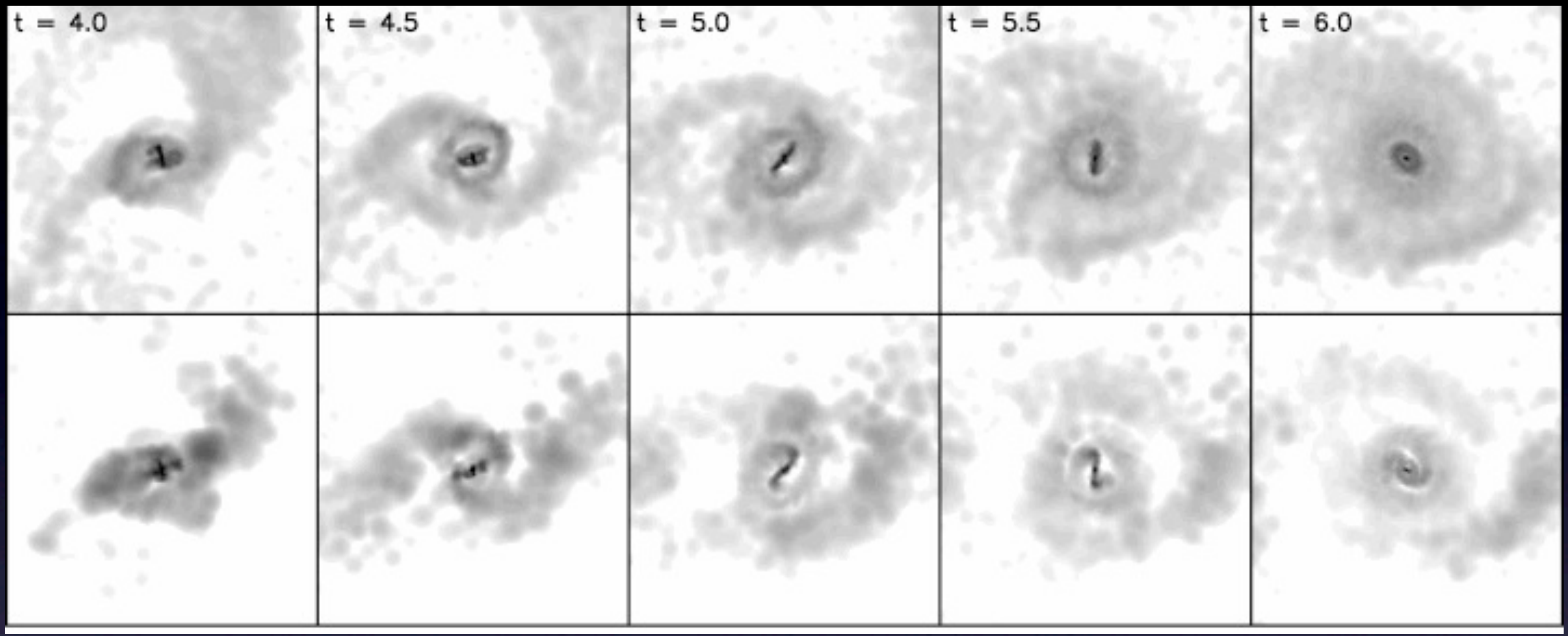
What is the Spatial Extent of the *I* vs. *K* Difference?



- Median value for Ellipticals is (I-K) ≈ 2
- (I-K) values are larger than colors predicted by stellar population models
- Highest (I-K) colors are concentrated on small scales in the central regions

Gaseous Dissipation:

(Central few kpc)



- Simulations from Barnes (2002)
- Top row gas particles, bottom row particles weighted by local dissipation rate
- Gas disk forms in the center from dissipation
- Strong star-formation occurs → forms a disk of young stars

Gaseous Dissipation:

(Central few kpc)

Gaseous Dissipation:

(Central few kpc)

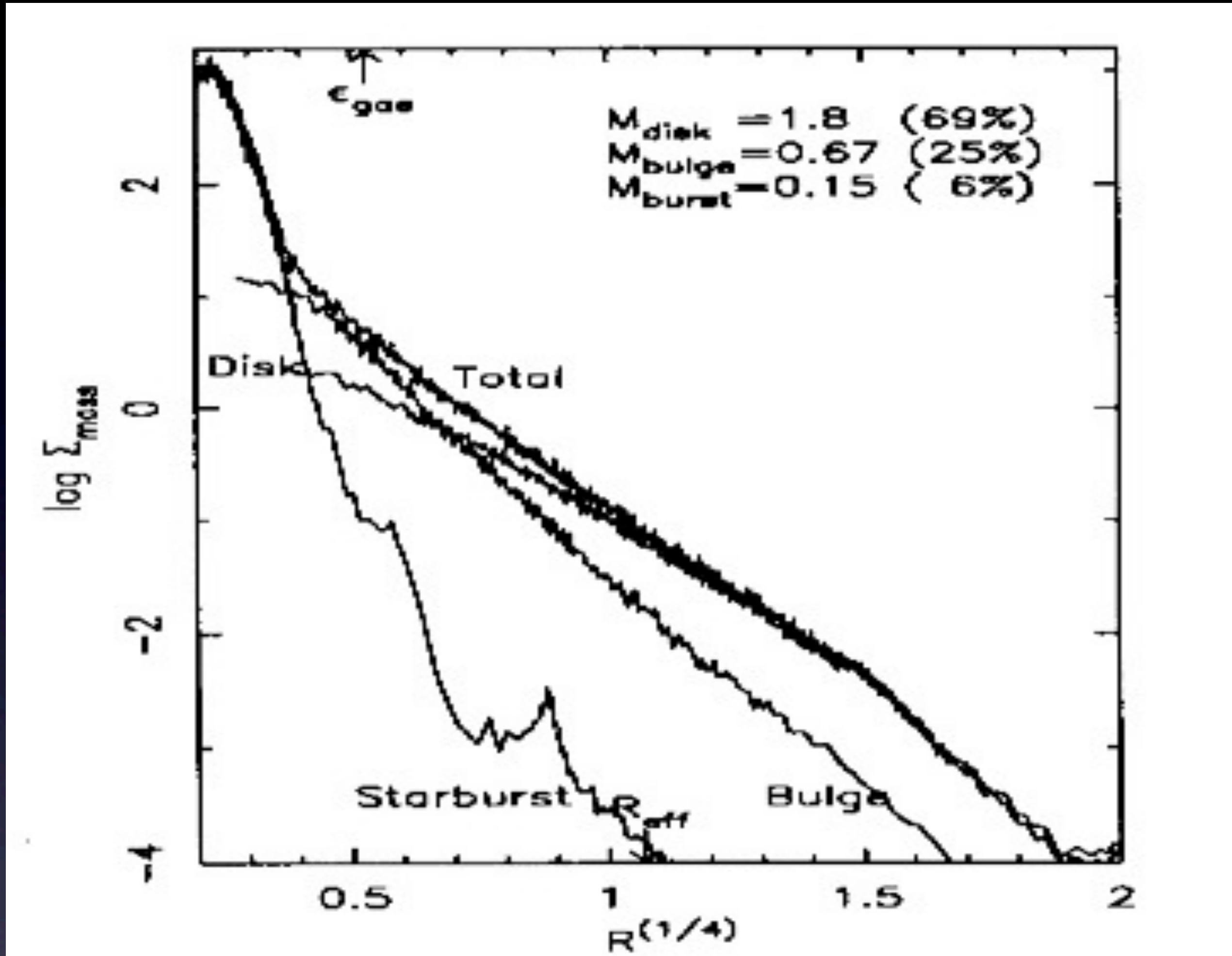


FIG. 1b

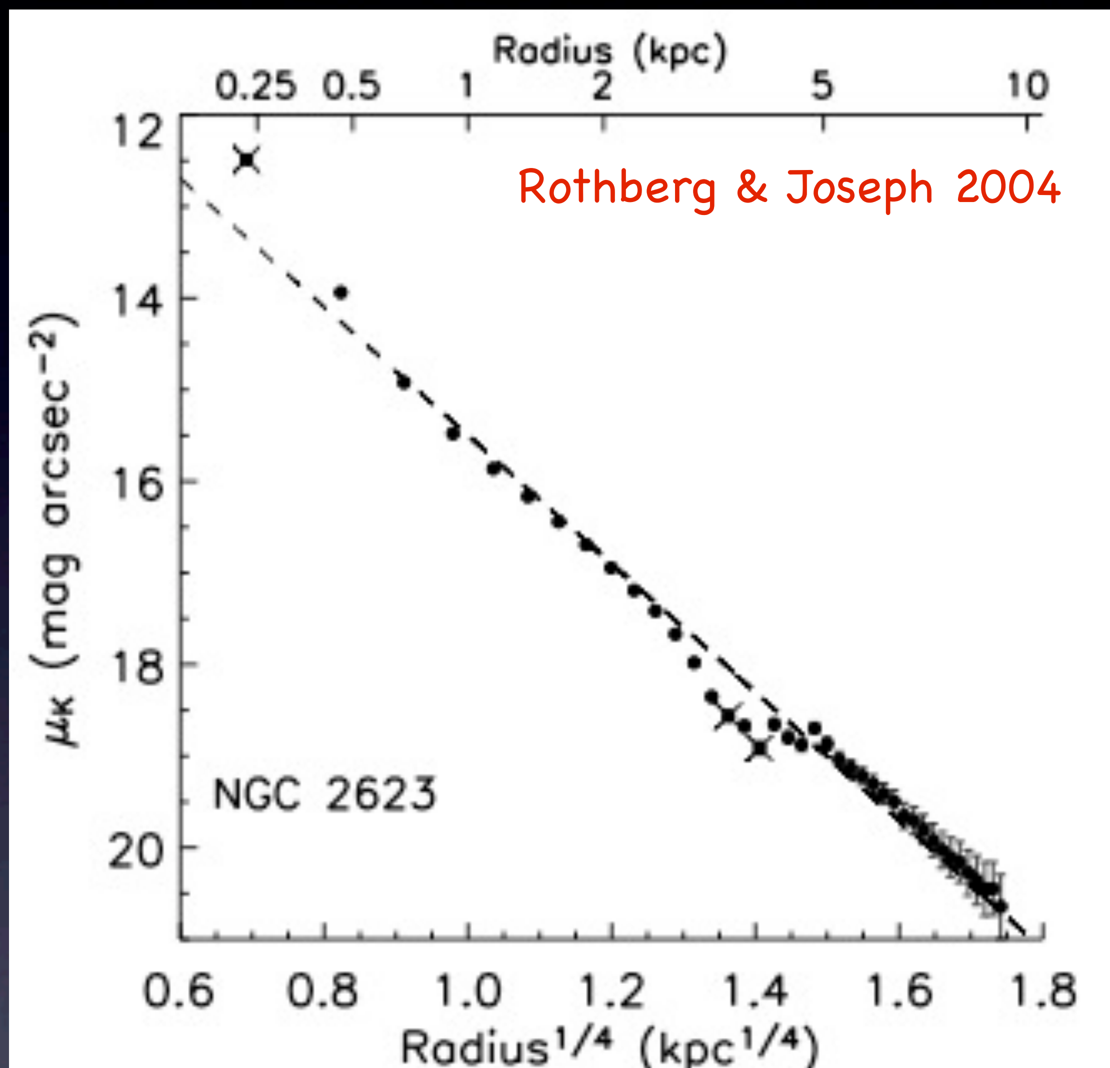
- Gaseous dissipation produces a strong starburst which creates a dense stellar core
- **Prediction:**
    - **Should** Observe an upturn in stellar luminosity profile (MH94, S00)

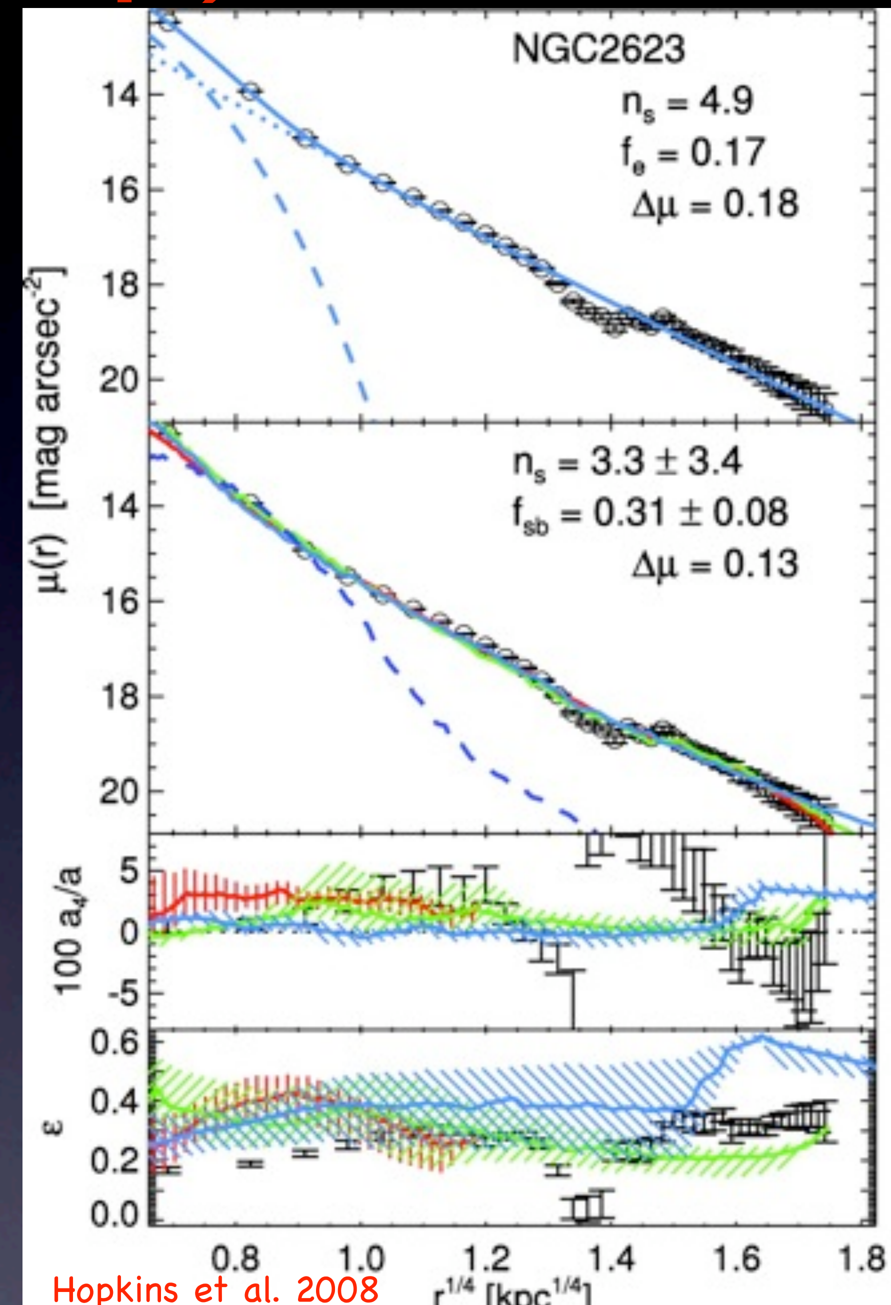
Gaseous Dissipation:

(Central few kpc)

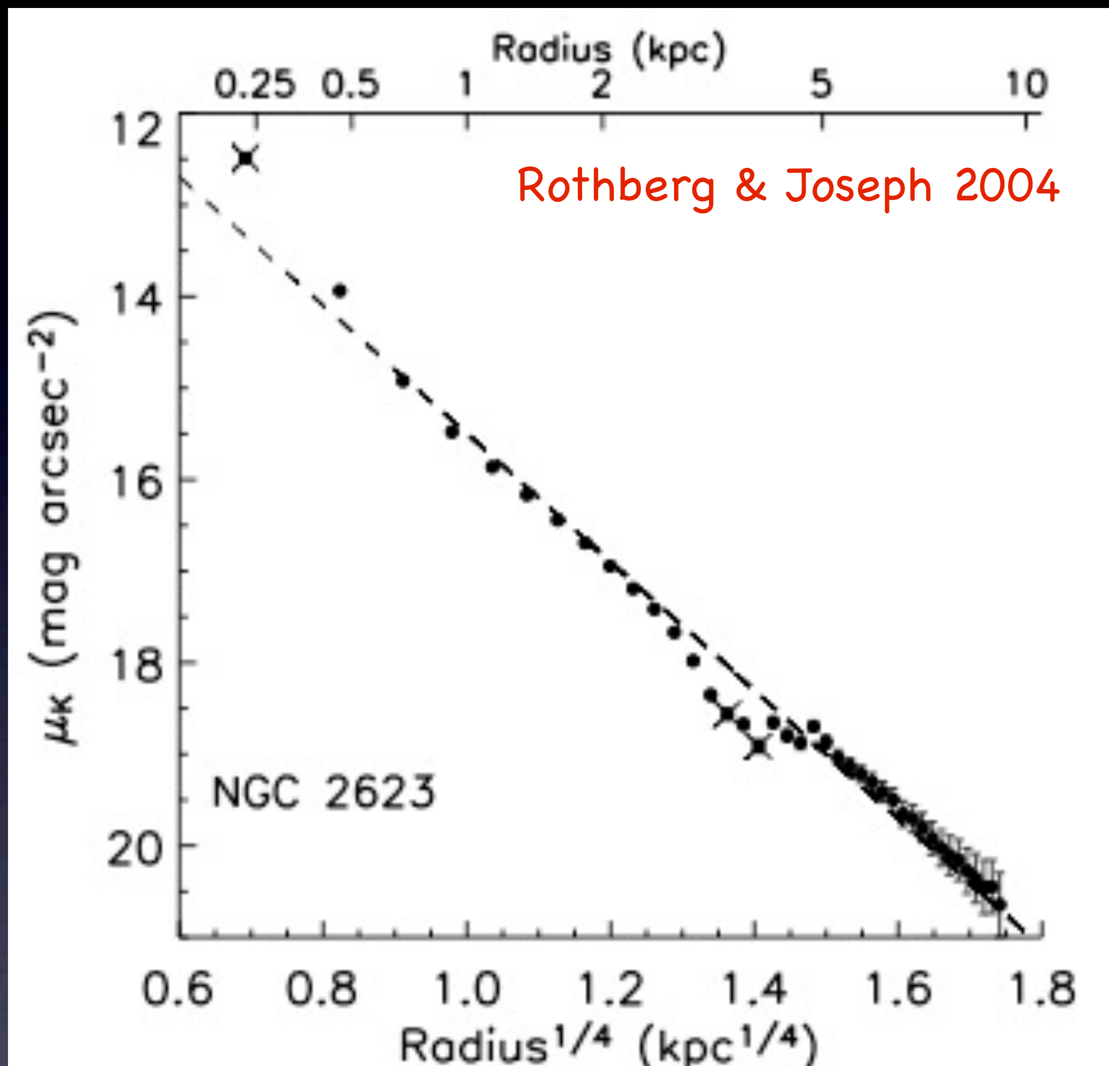
Gaseous Dissipation:

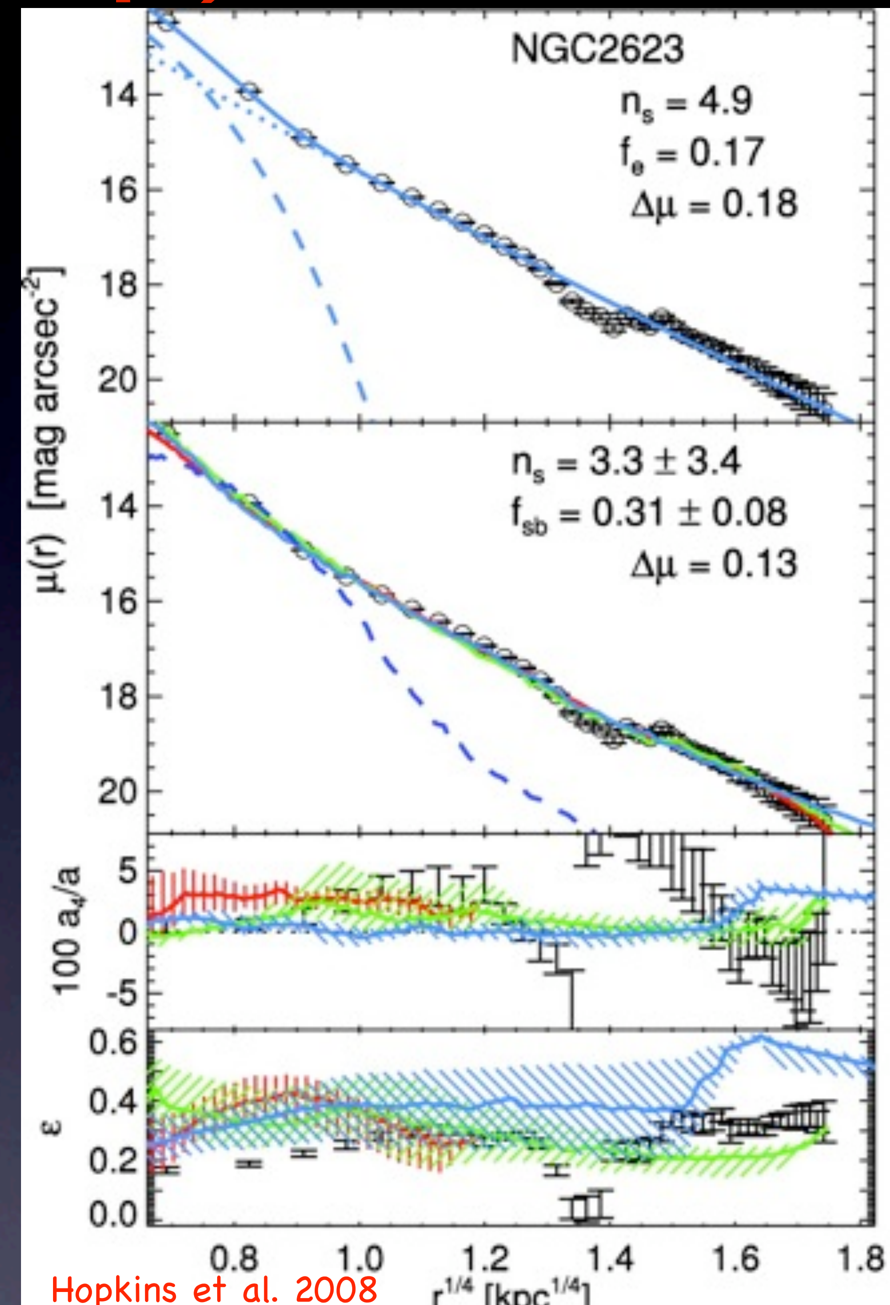
(Central few kpc)





Gaseous Dissipation:
(Central few kpc)

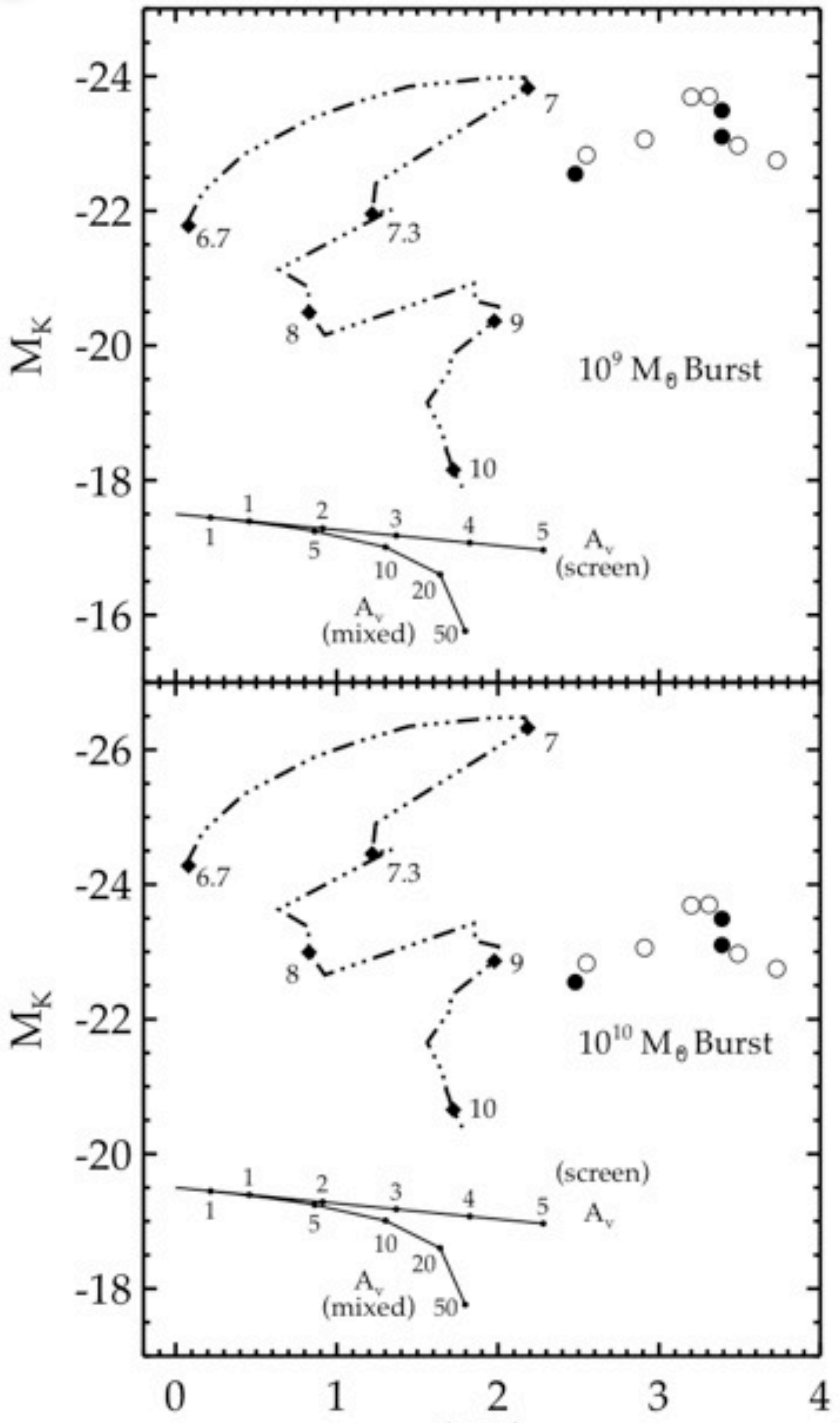




- First confirmation at *K*-band of "excess light" from young population
- Surface Brightness profiles decomposed into old & young components
- Used models to estimate fractional contribution

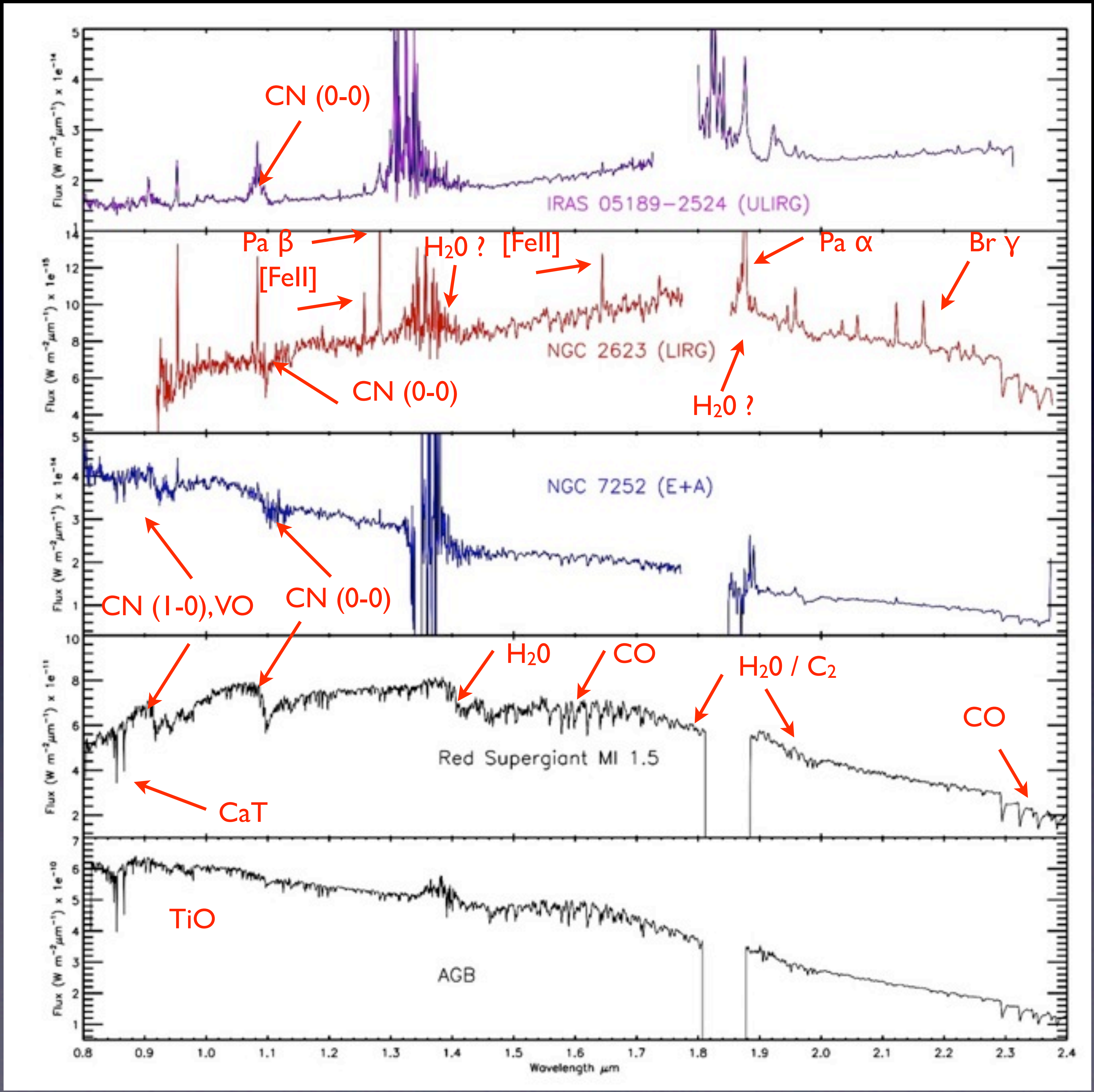
Central ~1.5 Kiloparsec: What colors and shapes tell us

- Can constrain properties of central region:
  - M_K constrains lower mass & age of central population (too bright for mass to be < $10^9 M_\odot$)
  - Total M_{Dyn} from CaT σ constrains upper mass of central population (total mass budget at 1.53 kpc ~ $10^{10} M_\odot$)
  - Mass limits ages of the populations to: t < 20 Myr or 20 Myr < t < 0.9 Gyr
  - (I-K) colors too red to come ONLY from young stars, dust is critical
  - *K*-band central shapes are disky (+a_4/a) and correlate with σ_{frac}



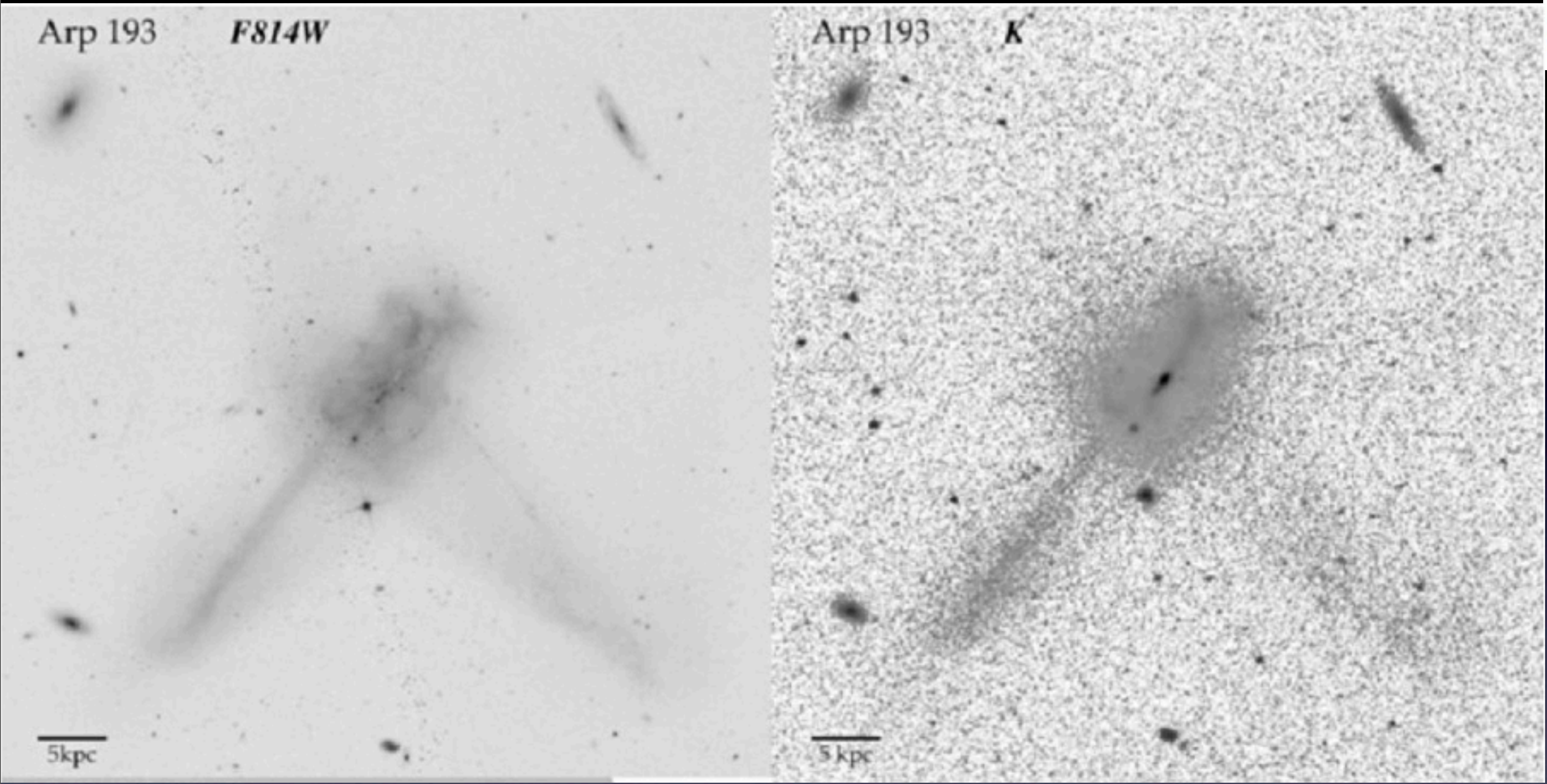
Rothberg & Fischer 2010

Central 1.5 kpc: Stellar Populations



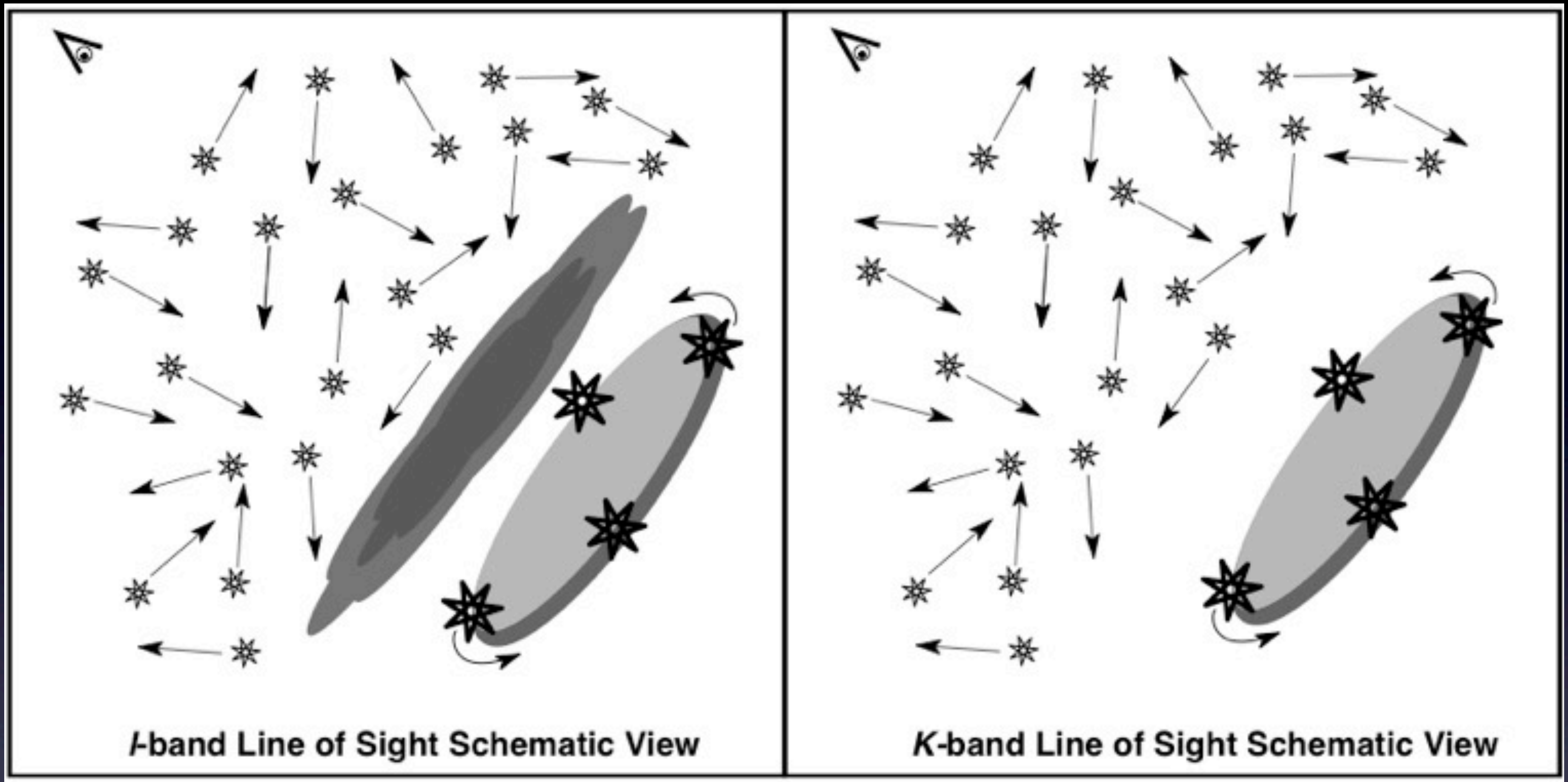
- Equivalent widths of CaT match RGB stars, NOT RSG or AGB stars
- CaT wavelength range shows no evidence of RSG or AGB stars
- Near-IR (1-2.5μm) shows strong features associated with RSG and/or AGB stars

The Picture



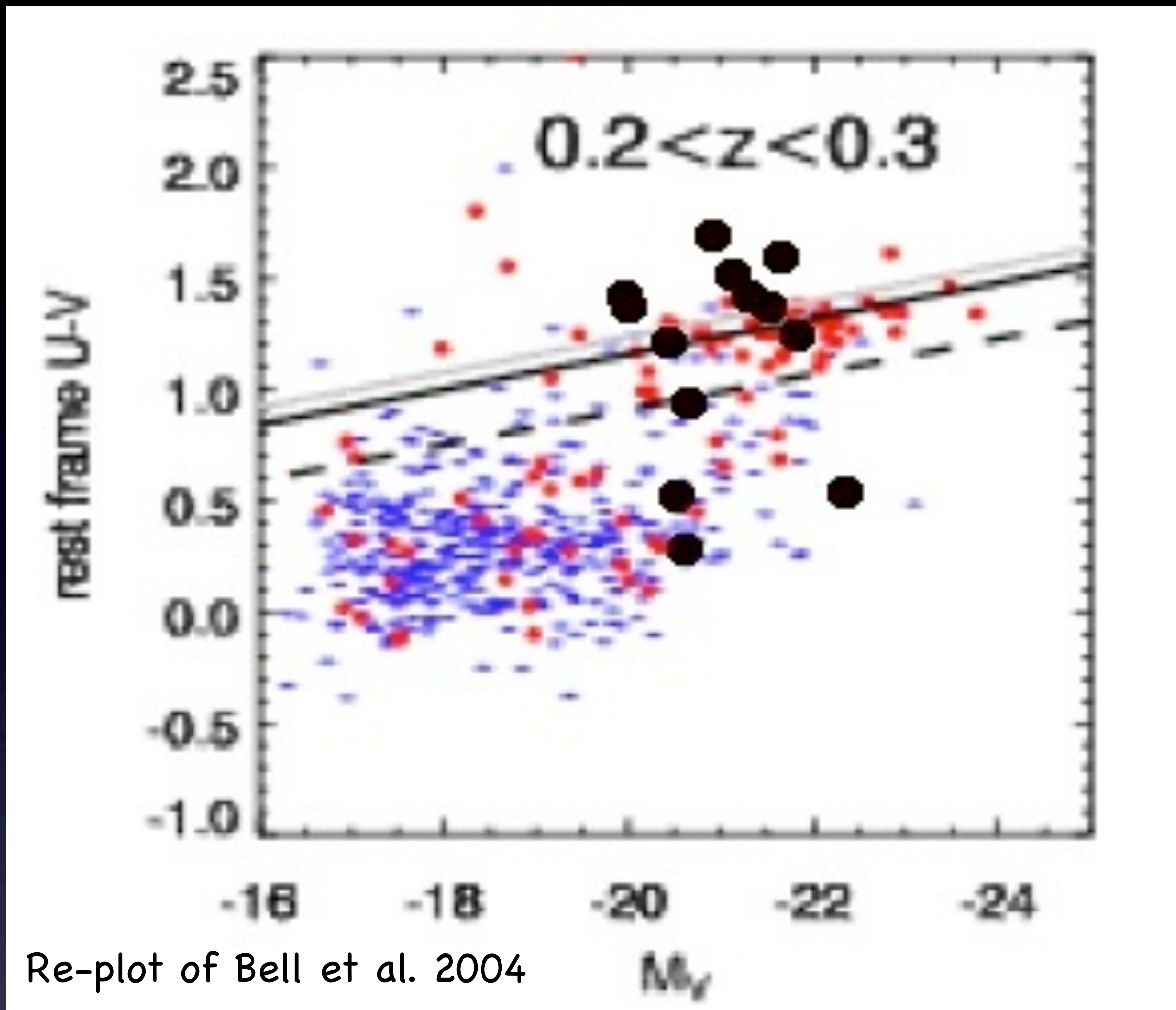
- σ measured in the IR is dominated by young stars (RSGs or AGBs) rotating in a central stellar disk in the ULIRG/LIRG phase
- The central stellar disk is enshrouded by dust, acting as a coronagraph at $\lambda < 1\,\mu m$
- CaT σ measurements are dominated by old, late-type stars from the progenitor spirals, and probes the *true* mass of the galaxy

The Picture

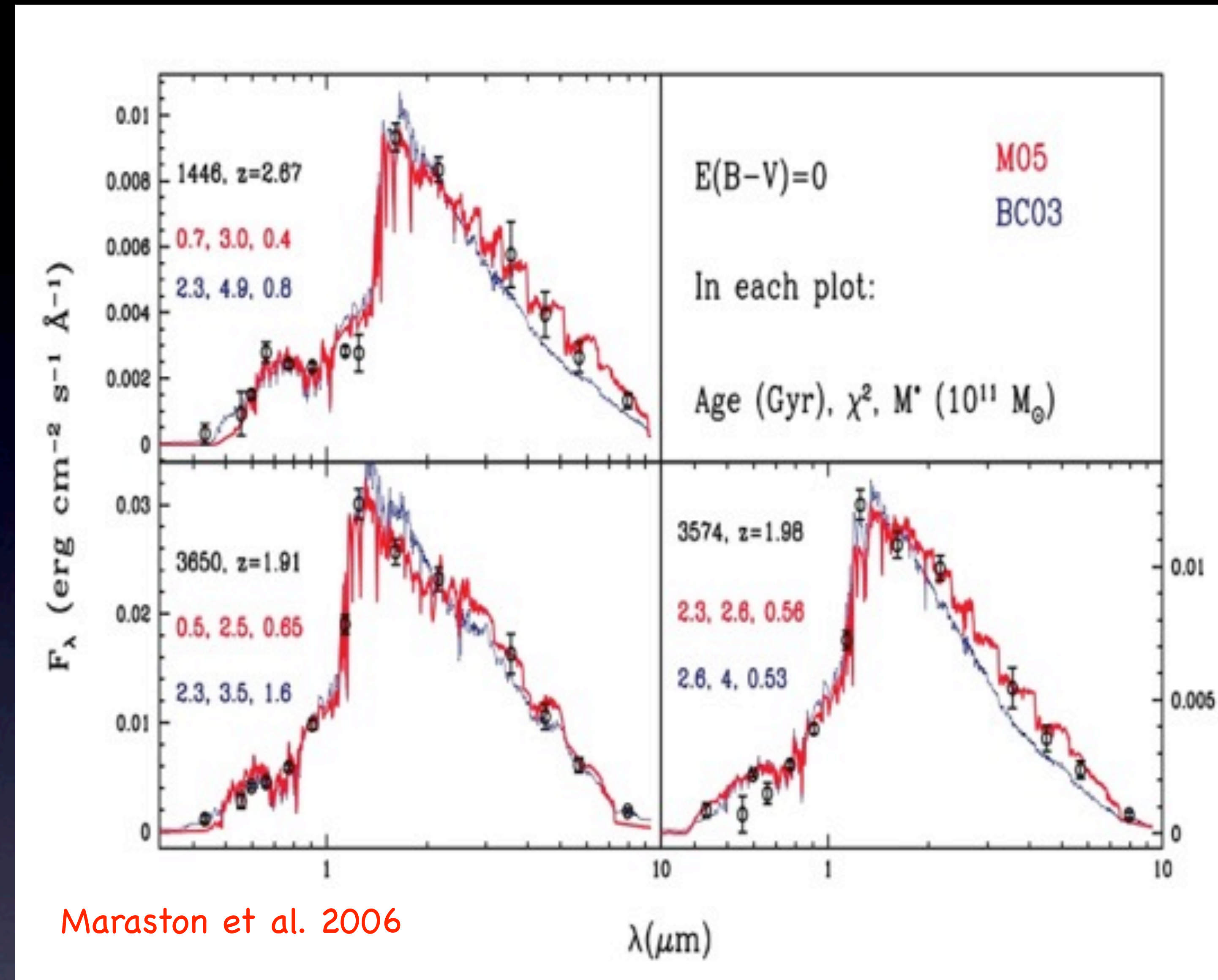


- σ measured in the IR is dominated by young stars (RSGs or AGBs) rotating in a central stellar disk in the ULIRG/LIRG phase
- The central stellar disk is enshrouded by dust, acting as a coronagraph at $\lambda < 1\,\mu m$
- CaT σ measurements are dominated by old, late-type stars from the progenitor spirals, and probes the *true* mass of the galaxy

Closing the Loop - The Big Picture



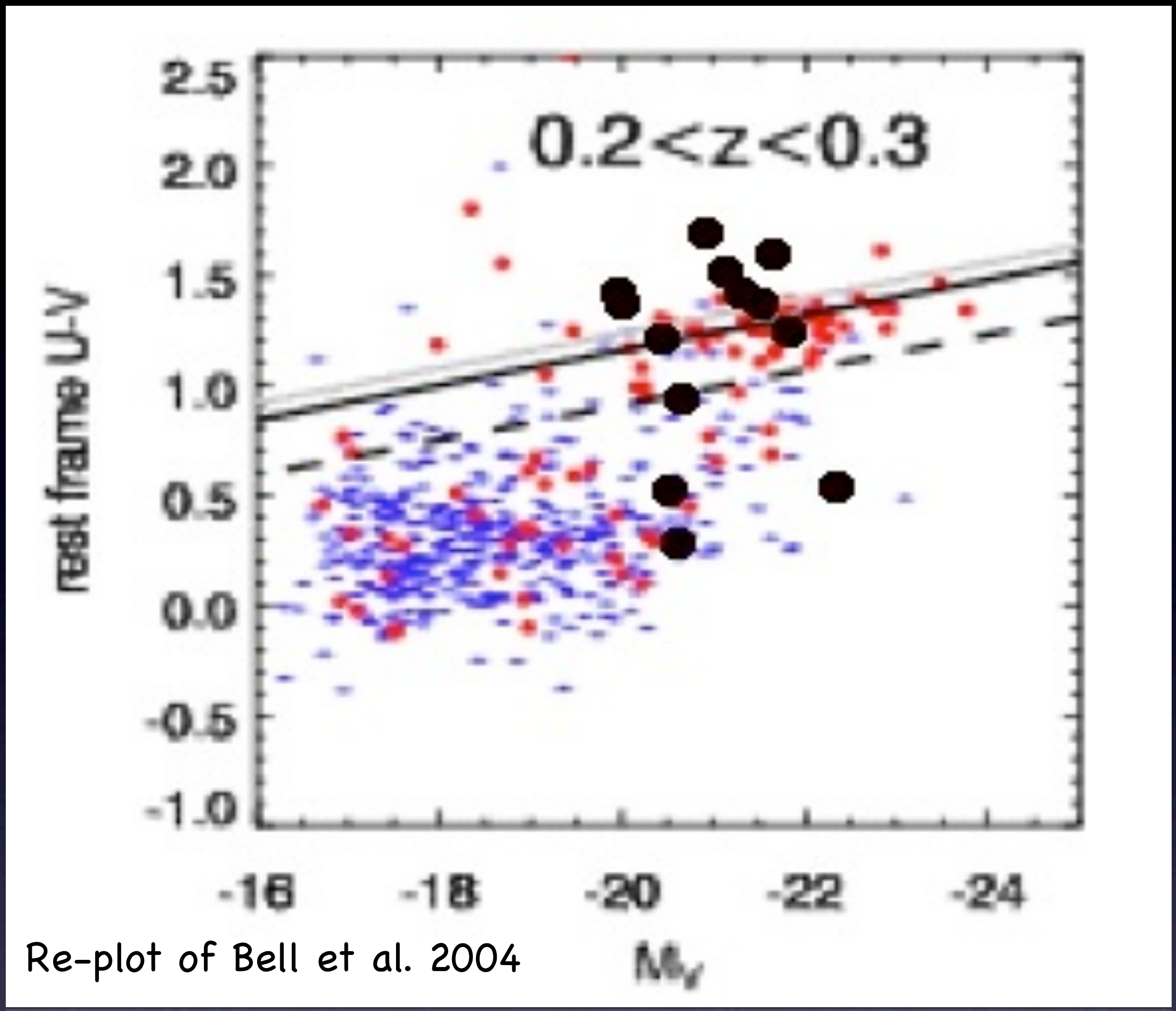
Re-plot of Bell et al. 2004



Maraston et al. 2006

- Different λ's probe different stellar populations (kinematically & photometrically)
- Relying solely on one regime may skew the "truth"
- Stellar populations models need to carefully account for old & young if spectra are unavailable to measure kinematics or age-related features

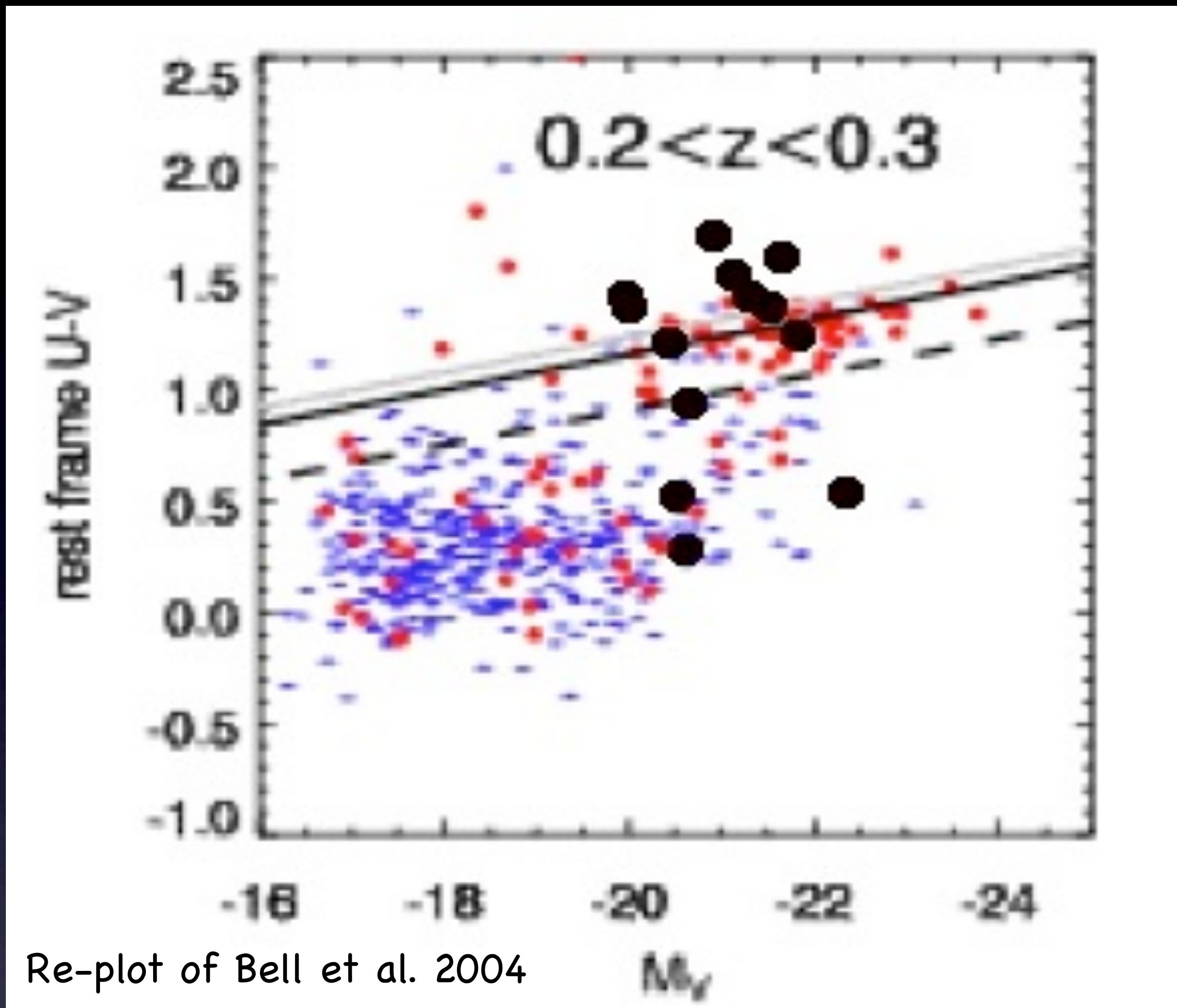
Closing the Loop - The Big Picture



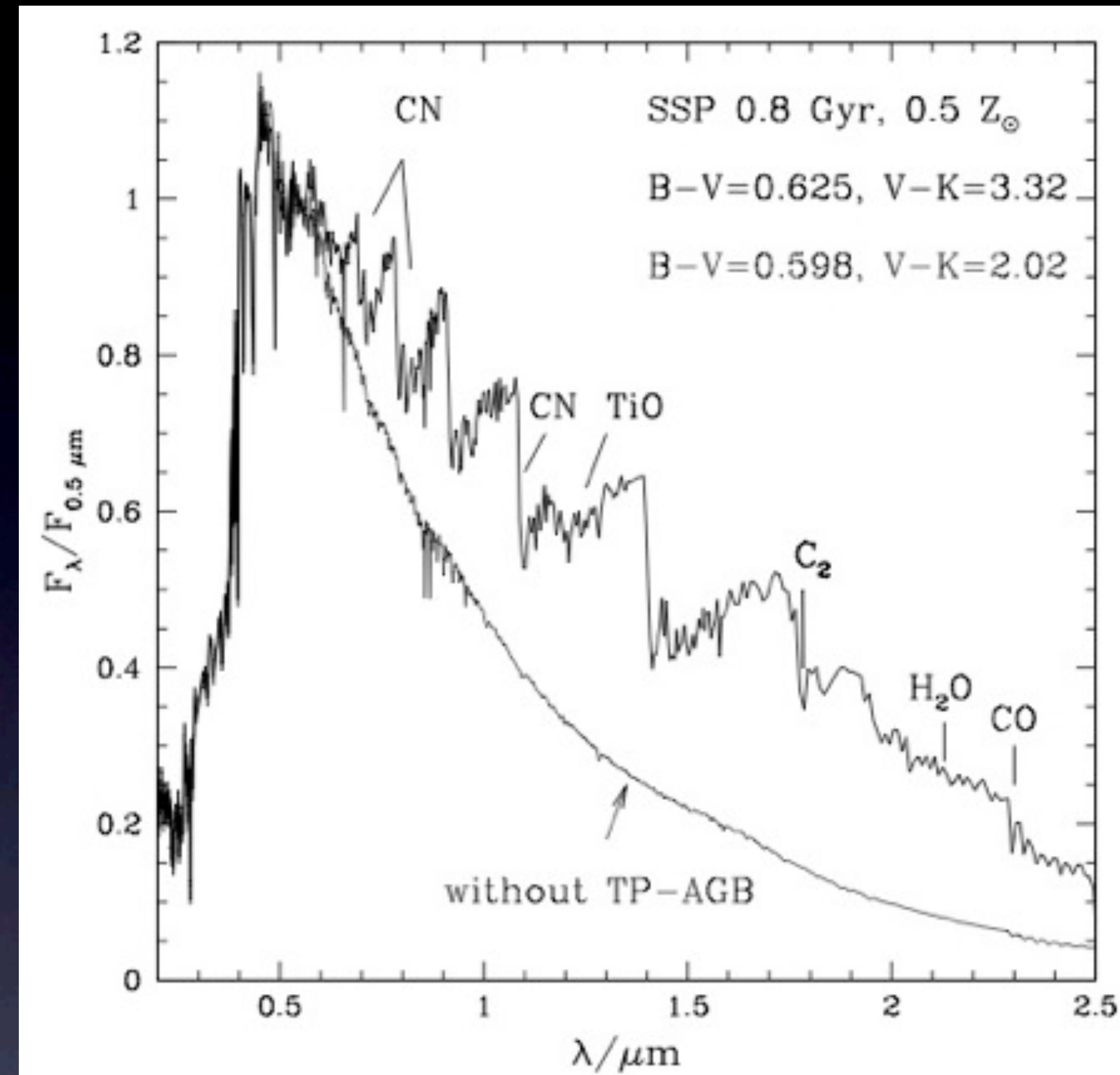
Re-plot of Bell et al. 2004

- Different λ's probe different stellar populations (kinematically & photometrically)
- Relying solely on one regime may skew the "truth"
- Stellar populations models need to carefully account for old & young if spectra are unavailable to measure kinematics or age-related features

Closing the Loop - The Big Picture



Re-plot of Bell et al. 2004



- Different λ's probe different stellar populations (kinematically & photometrically)
- Relying solely on one regime may skew the "truth"
- Stellar populations models need to carefully account for old & young if spectra are unavailable to measure kinematics or age-related features

Conclusions

1. σ-Mismatch is a real phenomenon and correlates with other observed properties (L_{IR}, Dust, Shape, *M*/*L*, Radio Power)

2. IR-luminous mergers present two different faces to us depending on λ

   a) Optical λ = old stellar populations dominate stellar absorption lines. Young population hidden by dust.

   b) IR λ = young burst population

3. RF10 ULIRG predictions: CaT/CO corrected σ show m >> m*

4. Presence of TWO populations complicates kinematics, mass, and age estimates as a function of λ

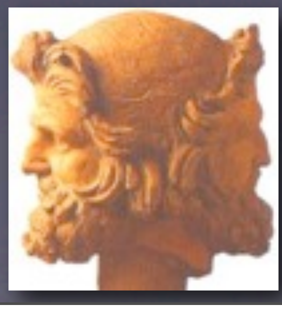
Future Work (ULIRGs)

- ULIRGs: IFU & simultaneous *H*-band imaging and spectroscopy of central few hundred pc (OSIRIS/ LGSAO Keck-2)

- Directly measure size, inclination, mass, & rotation of young central stellar disk

- CaT σ for complete sample of ULIRGs

- Use IFU data and CaT σ as two independent methods to estimate BH masses



Questions, Comments, Complaints: barry.rothberg@nrl.navy.mil