Interacting Galaxies and Binary Quasars:
A Cosmic Rendezvous
Trieste, Italy: 2012 April 4

The Role of Galaxy Mergers and AGN Among High Redshift (U)LIRGs

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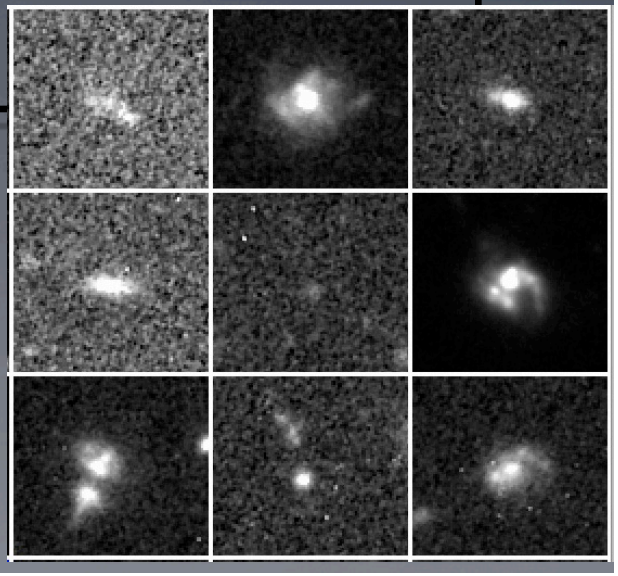
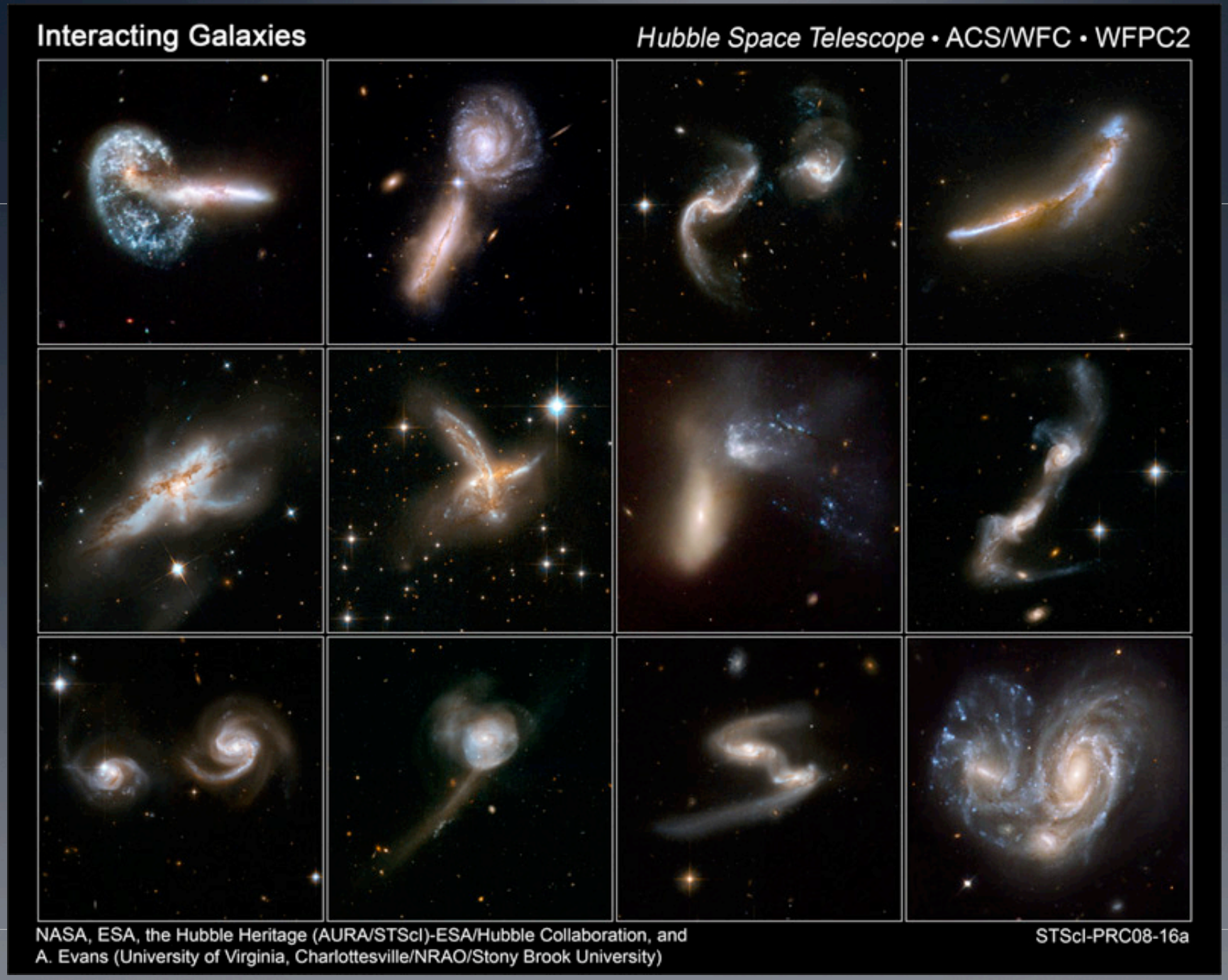
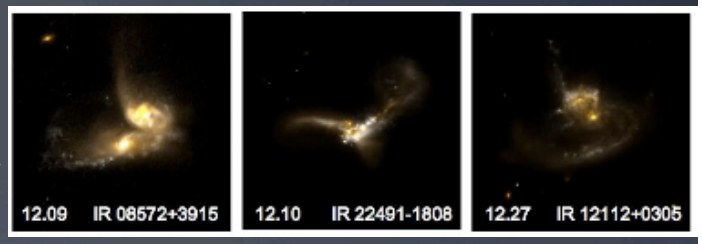
D. Sanders, M. Dickinson, and the
COSMOS, GOODS-Herschel, &
CANDELS Collaborations

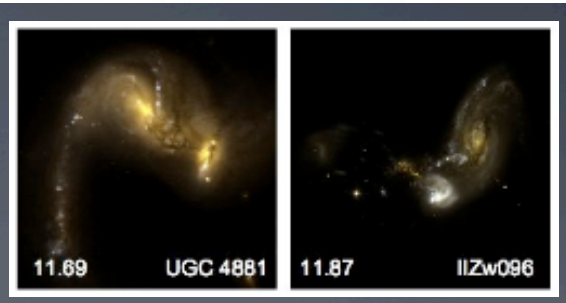


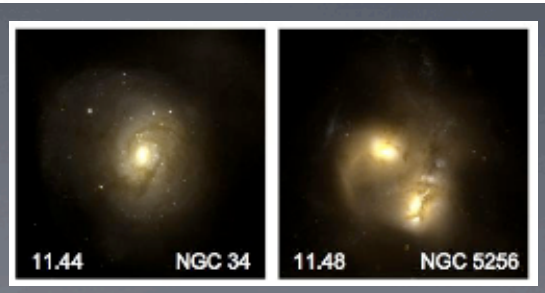

Interacting Galaxies
Hubble Space Telescope • ACS/WFC • WFPC2
NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and
A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)
STScI-PRC08-16a

Properties of Local (U)LIRGs

- **ULIRGs**: IRAS 1 Jy Sample, med(z) = 0.145 (Veilleux, Kim, & Sanders 2002)
  - > 99% are major mergers of gas rich spirals
- **LIRGs**: RBGS, med(z) =0.0082 (Sanders et al 2003, Ishida 2004)
  - **$\log(L_{IR}) > 11.5$**
    - strongly interacting major mergers (65%)
    - doubles (18%)
    - minor interactions (18%)
  - **$\log(L_{IR}) < 11.5$**
    - strongly interacting major mergers (36%)
    - doubles (23%),
    - minor interactions (15%)
    - high luminosity end of normal starforming disks (26%)



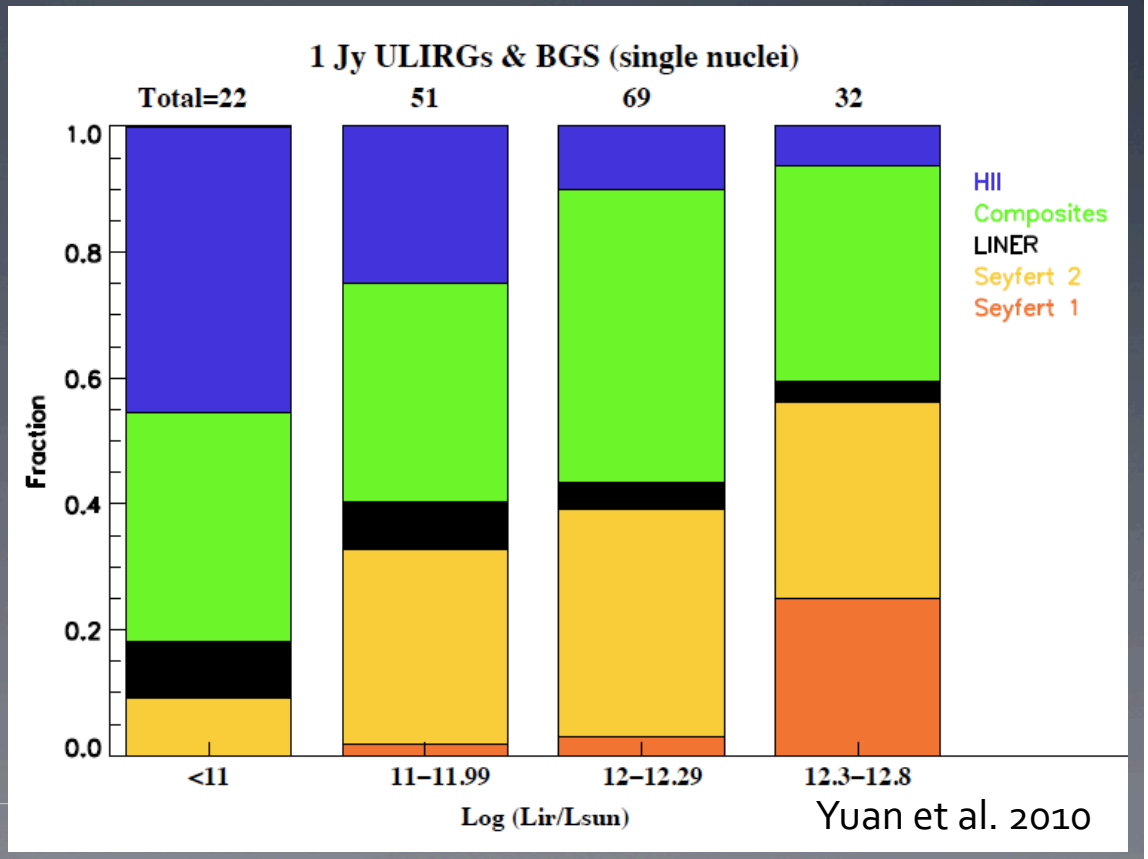




Fraction of mergers increases systematically with L_{IR}!

Properties of Local (U)LIRGs

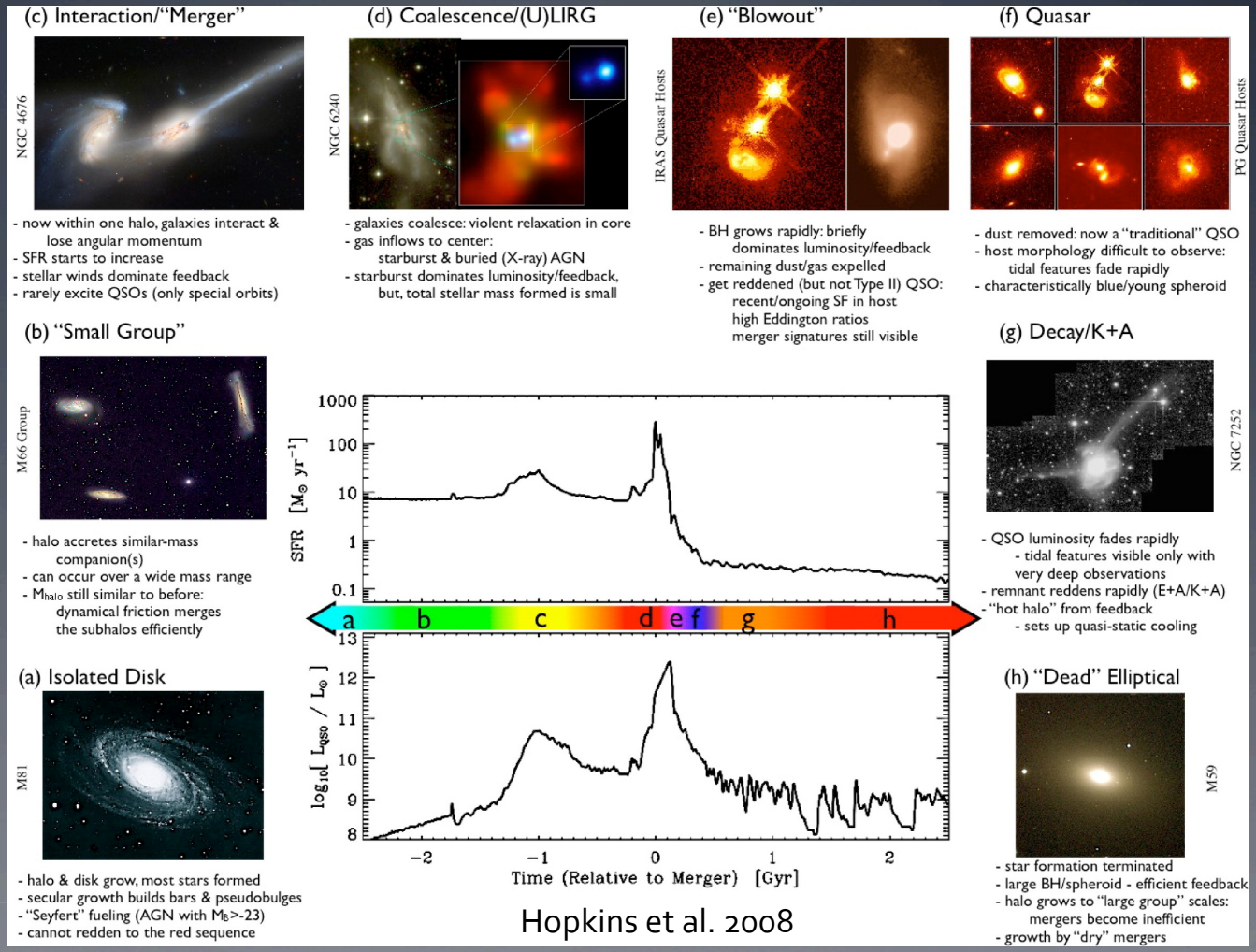
- Fraction of (U)LIRGs with an AGN increases with L_{IR}
  - Veilleux et al. 1995, 1999; Tran et al. 2001; Yuan et al. 2010
- < 20% for $L_{IR} < 10^{11} L_{\odot}$
- > 50% for $L_{IR} > 10^{12.3} L_{\odot}$
- Large fraction of composites
  - Mix of SF, AGN, shocks
  - Difficult to disentangle



Yuan et al. 2010

The Merger Scenario

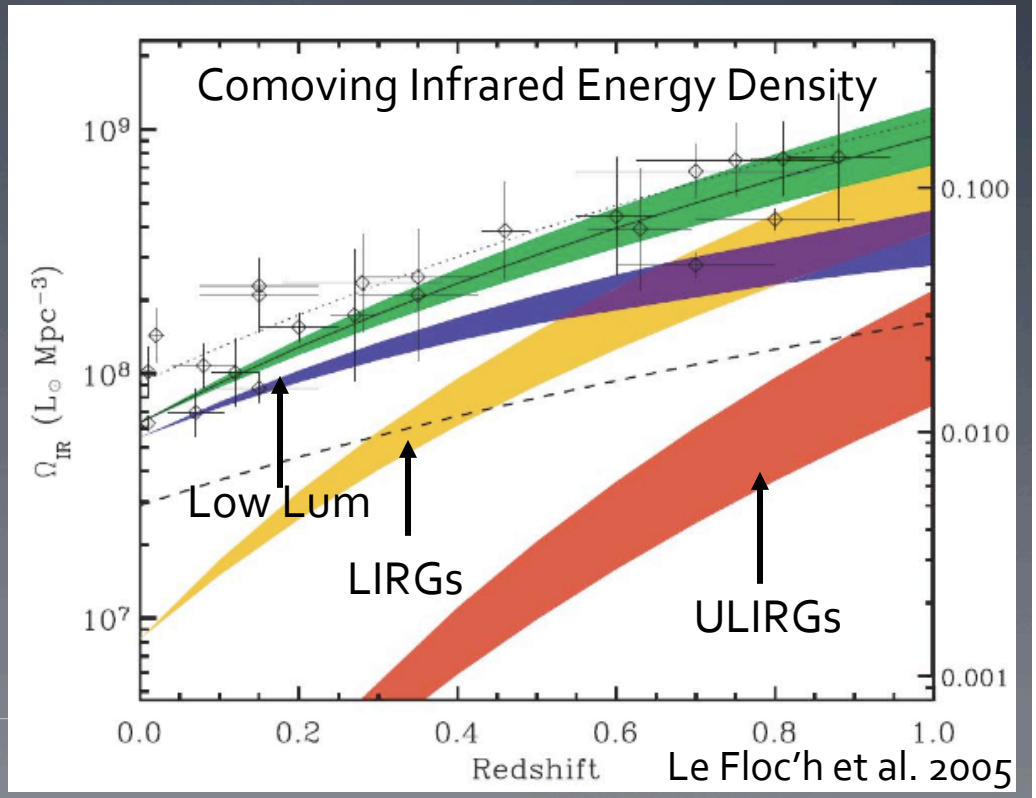
- Mergers among ULIRGs are ubiquitous
- High AGN fraction among ULIRGs
- Leads to the merger scenario (Sanders et al. 1988)
  - Evolutionary connection: Gas-rich mergers → LIRG → ULIRG → QSO
  - Eventually form "red and dead" elliptical



Hopkins et al. 2008

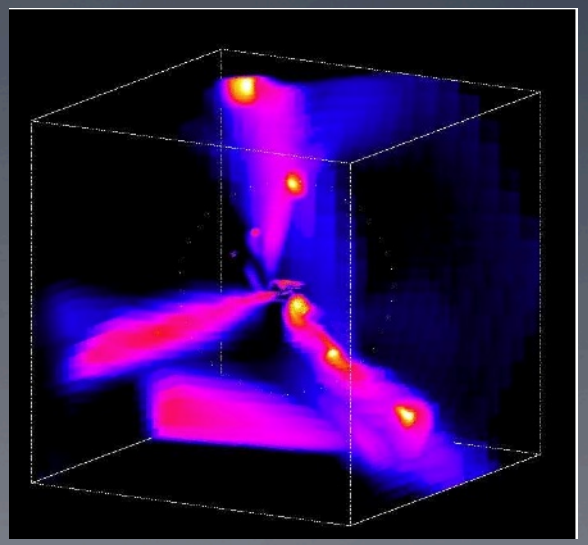
High Redshift (U)LIRGs

- LIRGs dominate IR energy density (and cosmic star formation rate) at z > 0.7
  - Le Floc'h et al. 2005
- ULIRGs as important or dominate by z~2
  - Caputi et al. 2007; Magnelli et al. 2009, 2011; Bethermin et al. 2011; Murphy et al. 2011
- Important role at the peak of galaxy assembly



The Role of Cold Flows

- Some theoretical simulations suggest that the high SFRs of (U)LIRGs can be sustained at high redshift (z~2) by 'cold flows' (e.g., Dekel et al. 2009, Davé et al. 2009)
  - Accretion of cold gas along filaments
  - Minor mergers

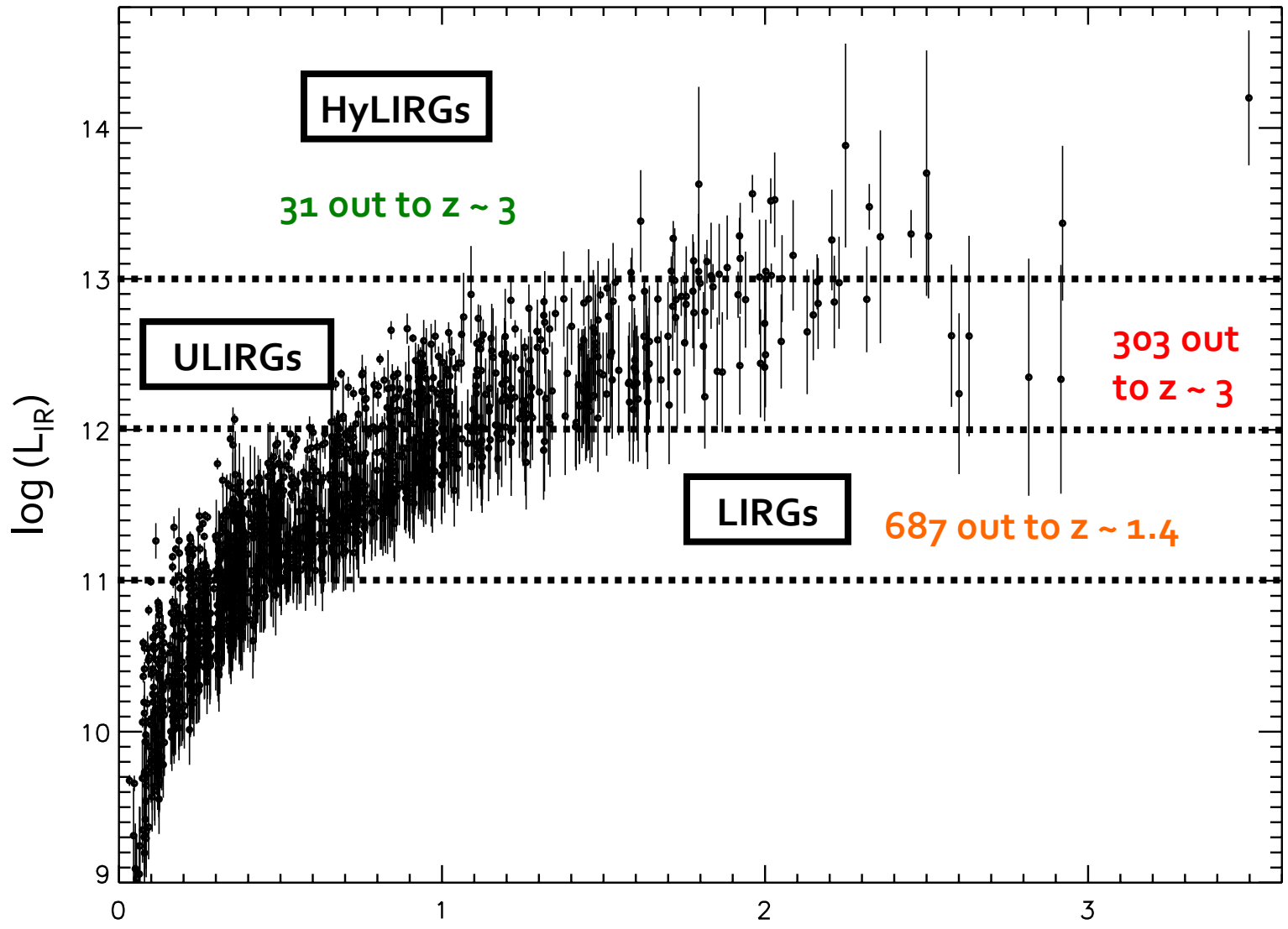


- Observationally supported by apparent *lack* of mergers among high redshift (U)LIRGs (e.g., Genzel et al. 2006; Forster-Schreiber et al. 2009)
  - Mix of results at high redshift so far
  - High redshift mergers are hard to see
  - Cold flows have yet to be observed!

Previous High Redshift (z~2) Studies

- 24 μm / color selected samples
  - e.g., Dasyra et al. 2008; Melbourne et al. 2009; Bussmann et al. 2009, 2011; Zamojski et al. 2010
  - Wide range of results
- Submillimeter Galaxies (SMGs)
  - Morphology (e.g., Conselice et al. 2003; Swinbank et al. 2010)
  - Kinematics (e.g., Tacconi et al. 2008)
  - Tend to find high fractions of mergers
- IFU Kinematics of massive star forming galaxies (SMGs/BzKs, etc.)
  - e.g., Genzel et al. 2008; Forster-Schreiber et al. 2009
  - Mixed results – 1/3 mergers, 1/3 rotation dominated, 1/3 dispersion dominated

COSMOS 70 μm Sample



Kartaltepe et al. 2010a

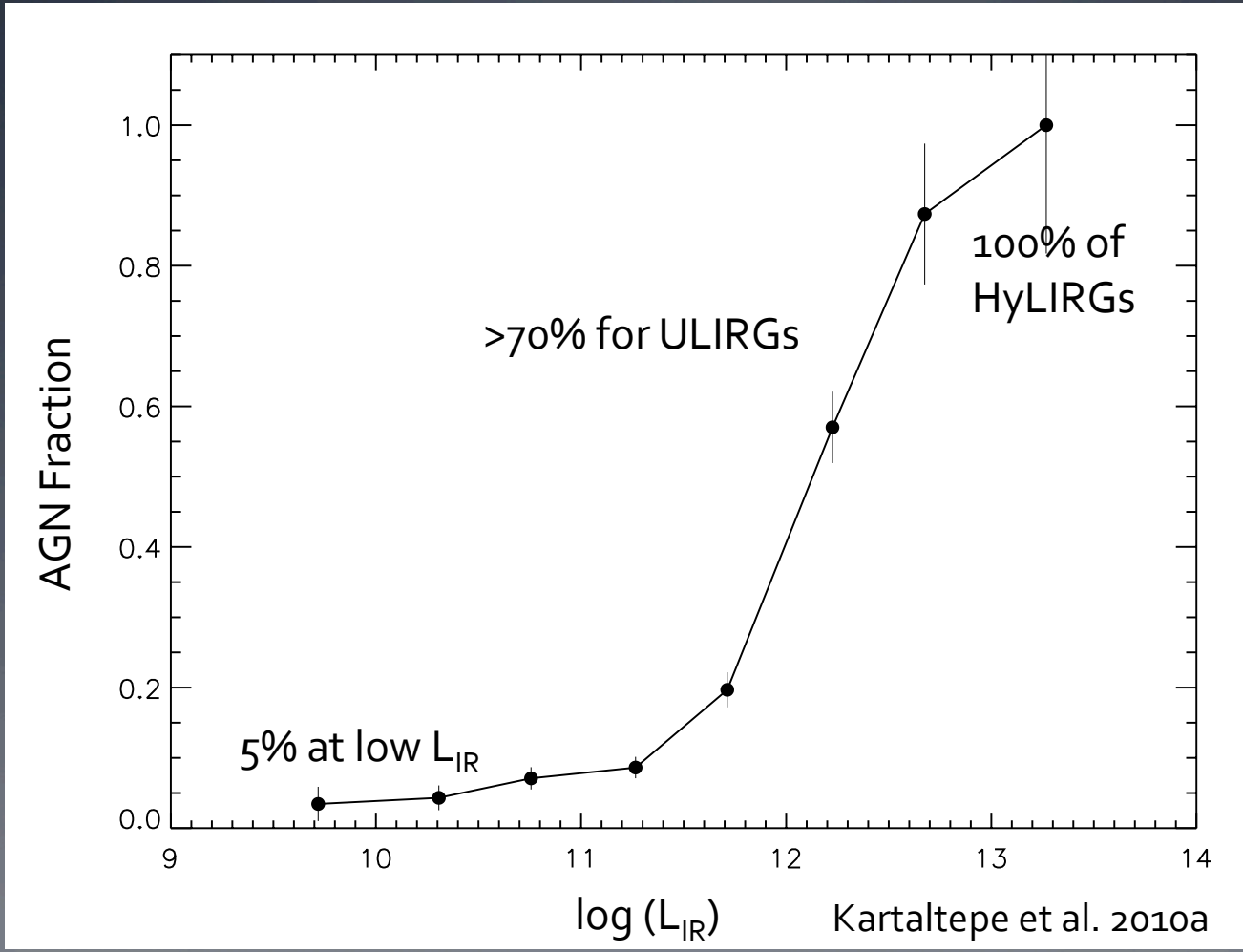
COSMOS 70 μm Sample

Identified AGN using several techniques

- **X-ray luminosity**
- Radio power
- **SED shape (i.e., Power-law)**
- IRAC colors
- Infrared to optical ratio (e.g., Fiore et al. 2008, Dey et al. 2008)
- [Spectroscopic diagnostics]

- Classified morphology
  - Used ACS images
  - Spirals, ellipticals, mergers (minor and major), QSOs, & unknown

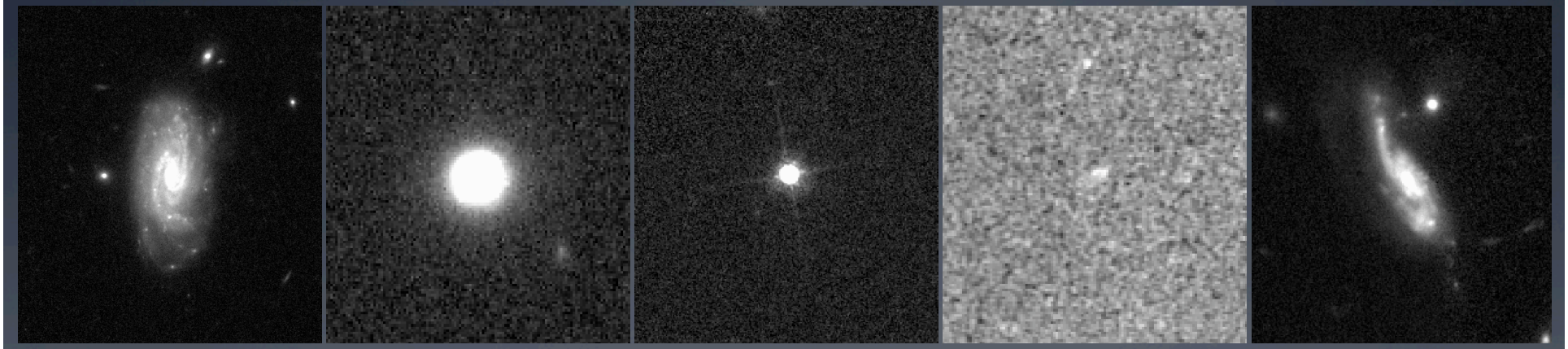
AGN Fraction



AGN Fraction increases systematically with L_{IR} (as it does locally)!

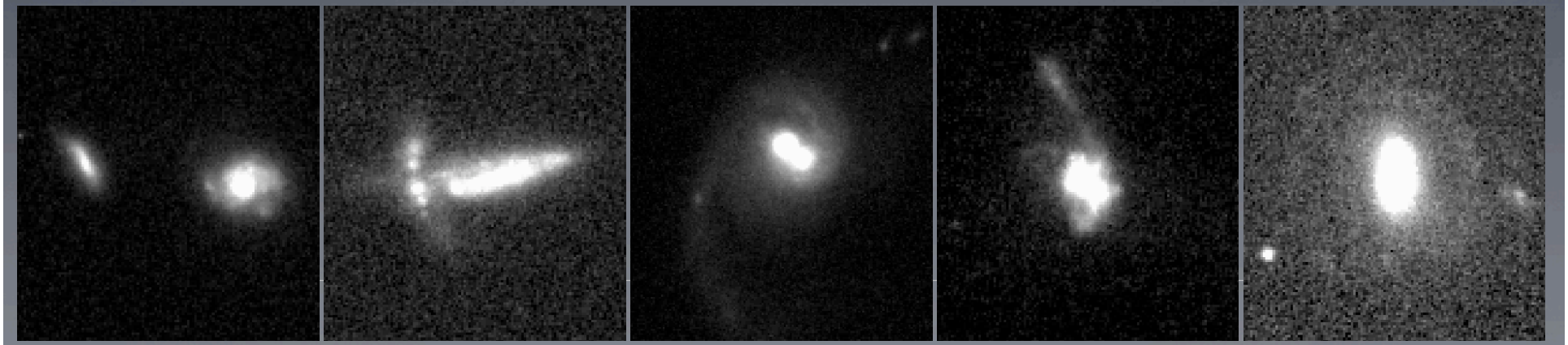
Morphological Classification

Spiral Elliptical QSO Unknown Minor Merger

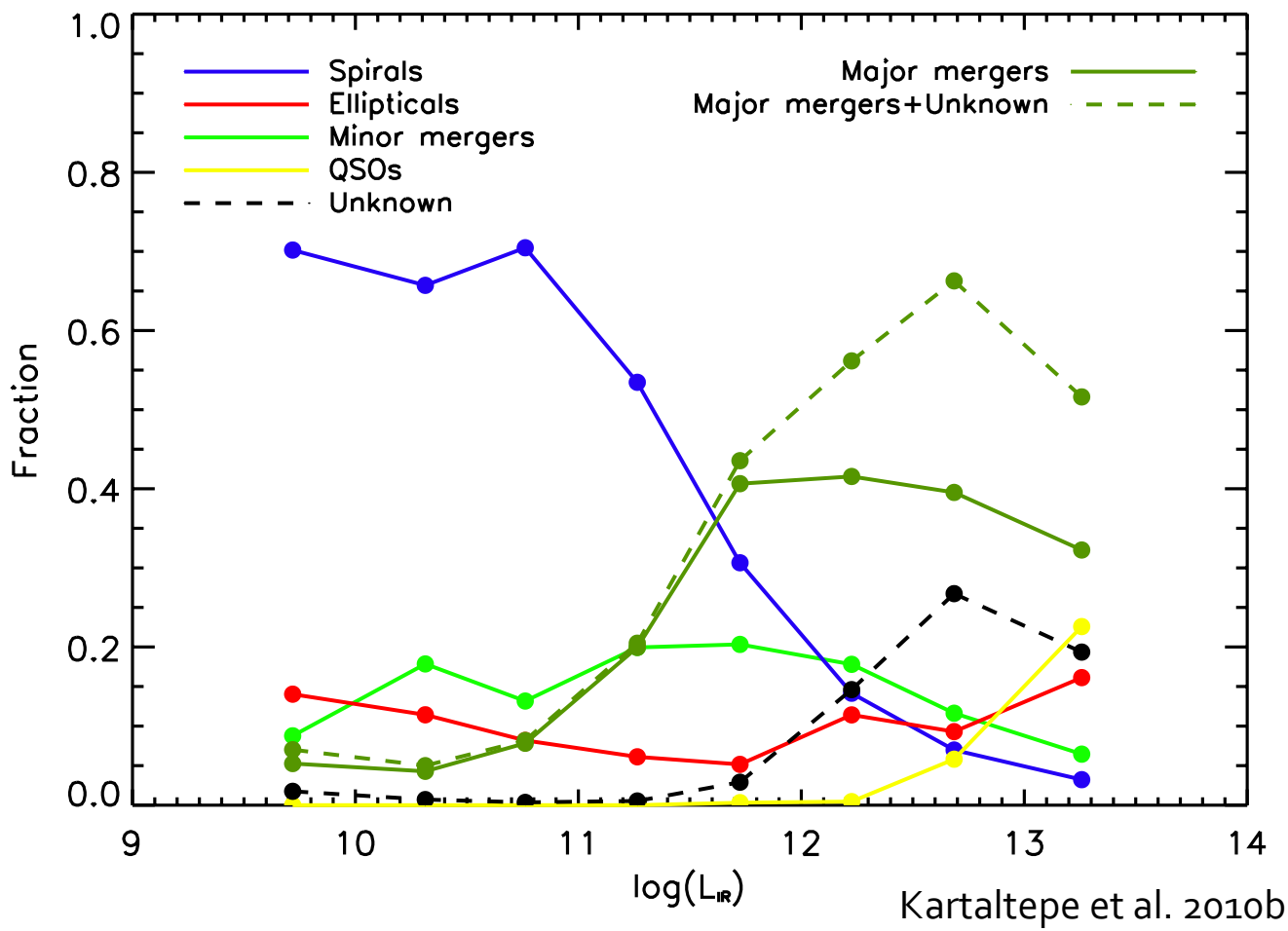


Major Mergers

I II III IV V

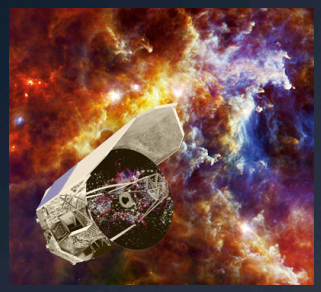


Merger Fraction



Kartaltepe et al. 2010b

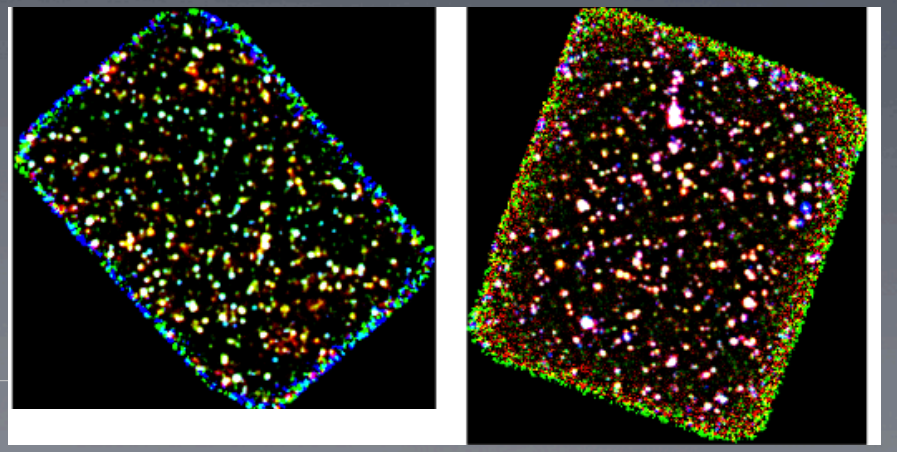
- Fraction of spirals drops
- Major mergers increase to ~40%
- Unknowns make up additional ~20%
- Minor mergers have an effect only at log (L_{IR})<11.5
- Significant contribution from 'QSO' class at high L_{IR}
- Consistent with previous studies over corresponding z and L_{IR} ranges

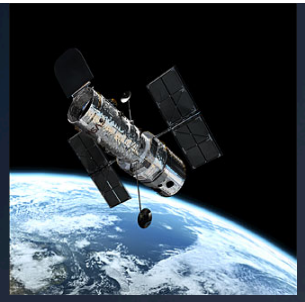


GOODS-*Herschel*

- *Herschel* coverage of both GOODS fields (PI: D. Elbaz)
  - Deepest *Herschel* data taken!
  - Full GOODS-N field: 1.6 mJy (@ 100 μm)
  - Central part of GOODS-S: 0.6 mJy (@ 100 μm)
- Small area coverage but very deep
- Well suited for identifying high redshift ($z > 1$) sources
- 100-500 μm coverage is closer to the peak of emission
  - Better for constraining L_{IR} and T_{dust}

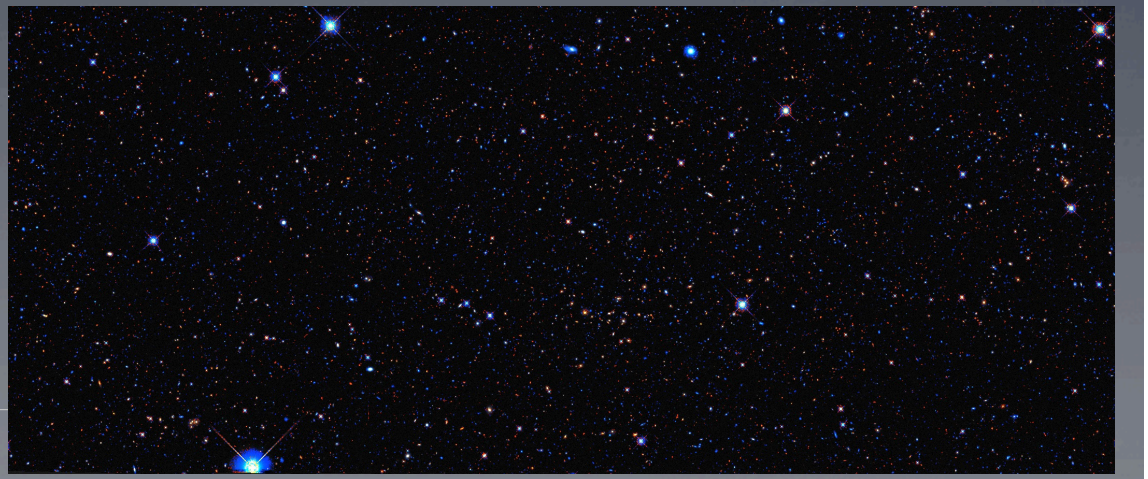
GOODS-N GOODS-S





CANDELS

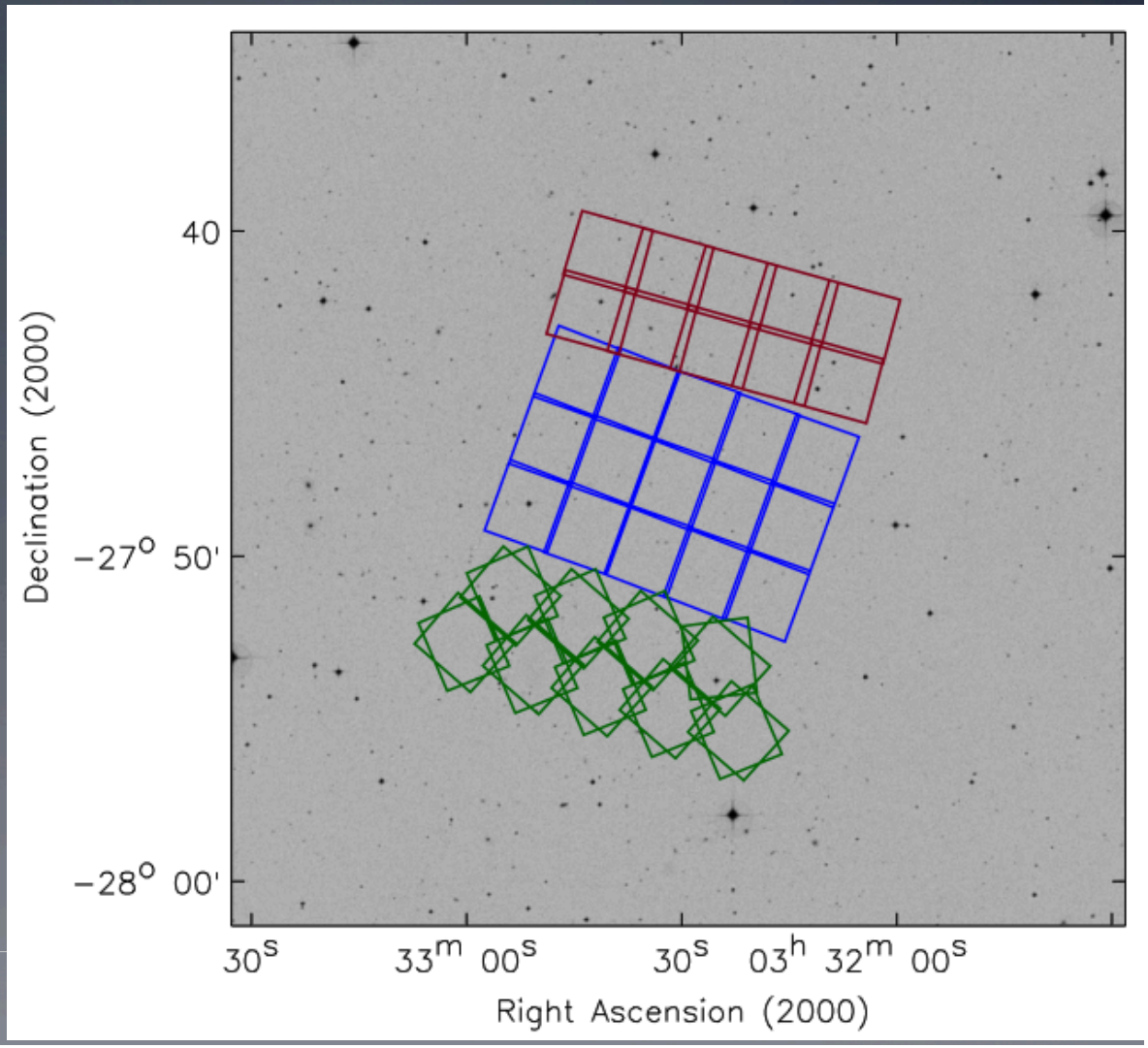
- Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (PIs: S. Faber & H. Ferguson)
- Multi-cycle HST Treasury Program
- WFC3 NIR imaging of portions of 5 deep fields
  - GOODS-N, GOODS-S, UDS, COSMOS, EGS



UDS Mosaic

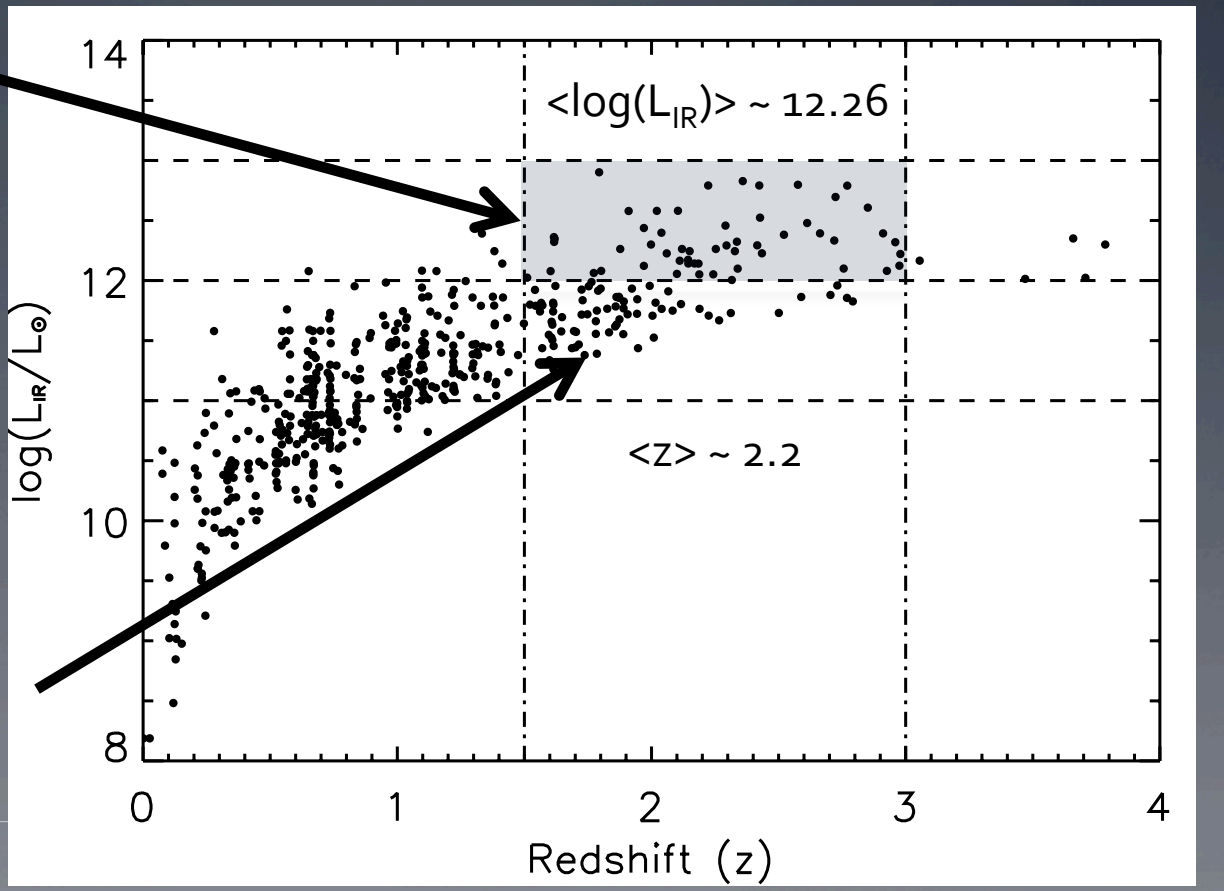
GOODS-*Herschel* & CANDELS

- A match made in heaven!
- Rest-frame optical imaging for z~2 galaxies
- Ideal for probing structure of z~2 ULIRGs



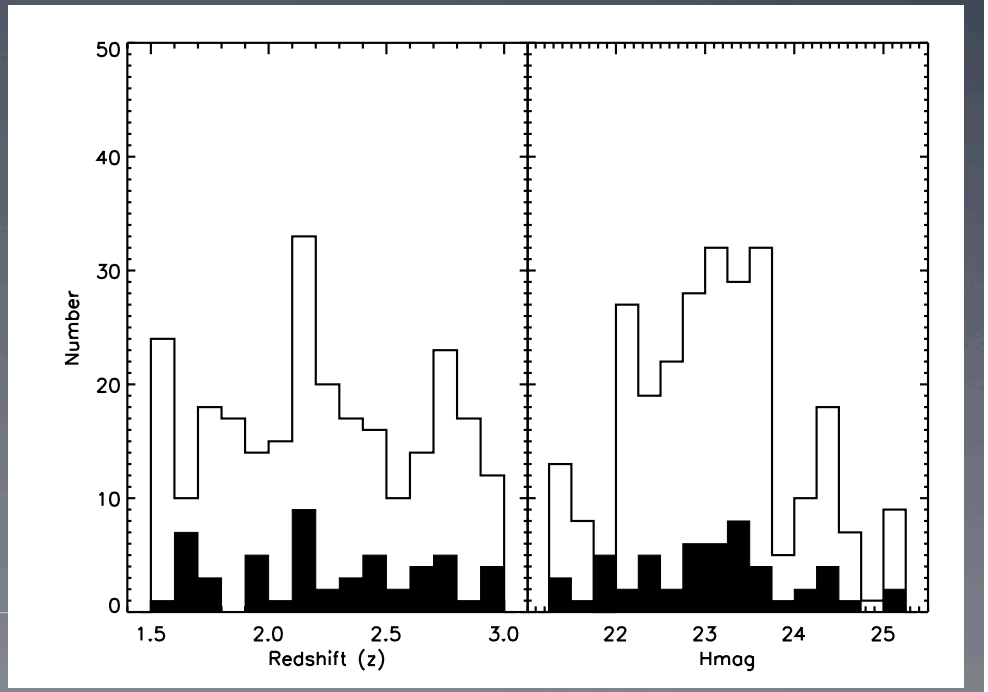
GOODS-*Herschel* ULIRG Sample

- Focus on all ULIRGs with z = 1.5 - 3.0 in GOODS-S
- 52 ULIRGs with CANDELS imaging
  - *First complete, FIR selected sample of ULIRGs at z~2!*
- Additional 70 LIRGs over this z range



Comparison Sample

- Selected 260 comparison galaxies (5 for each ULIRG)
  - Not *Herschel* detected → less luminous z~2 population
- Matched to redshift and H band magnitude
- Randomized and classified ULIRGs + comparison
  - Visual classification scheme
  - Classified by me + 3-5 other classifiers
  - Analyzed agreement
  - Eventually compare to quantitative merger selections



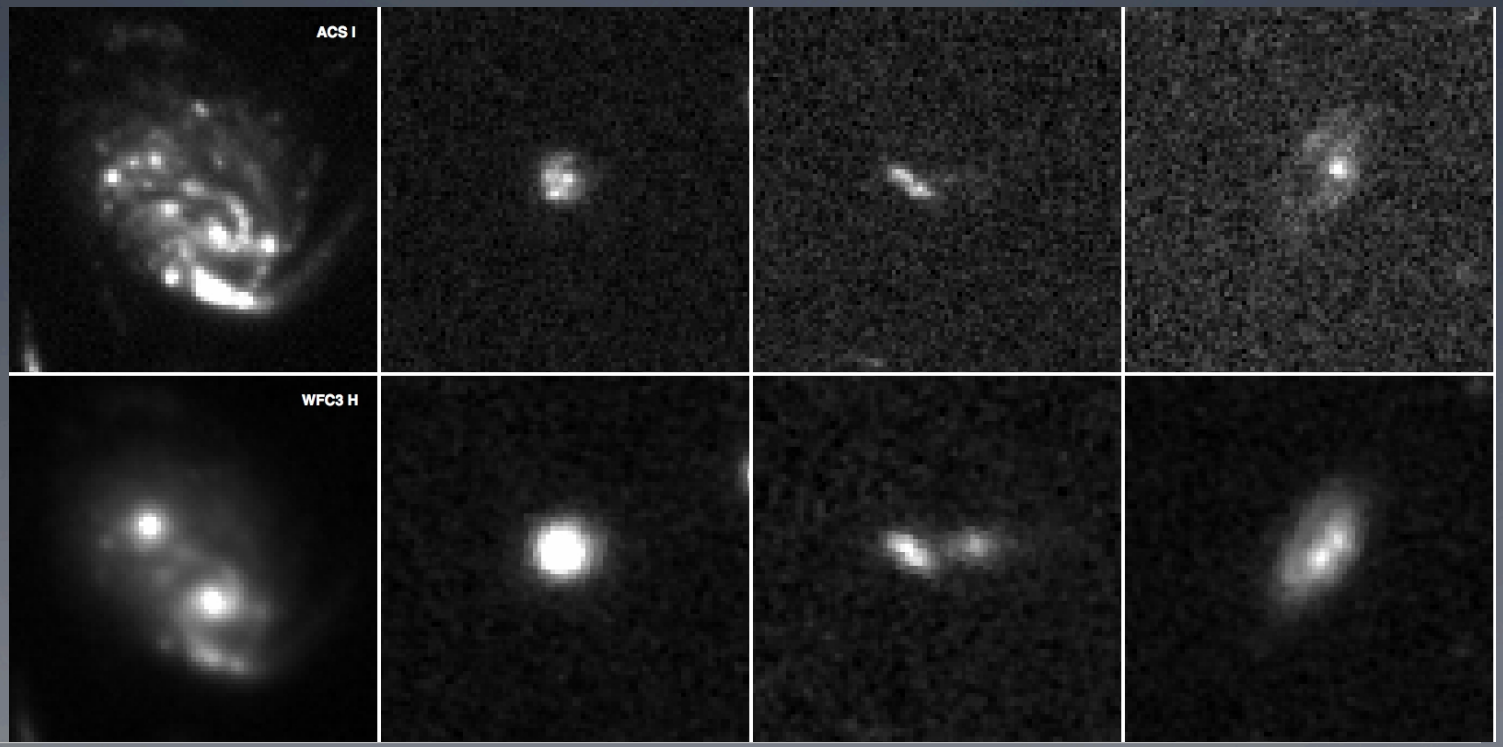
Power of HST/WFC3

- At high-z band shifting becomes important!

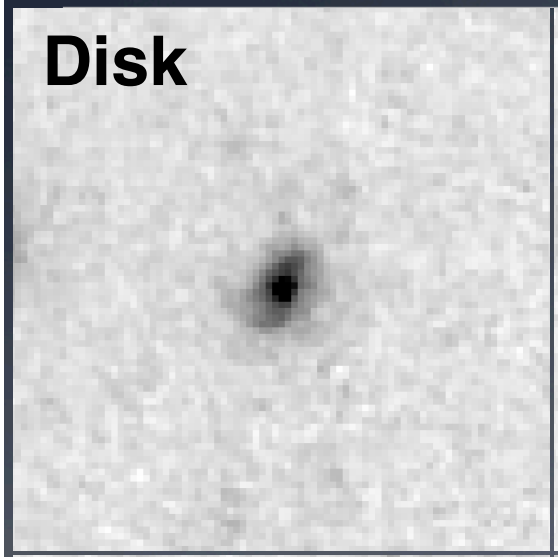
Rest-frame UV versus Rest-frame optical

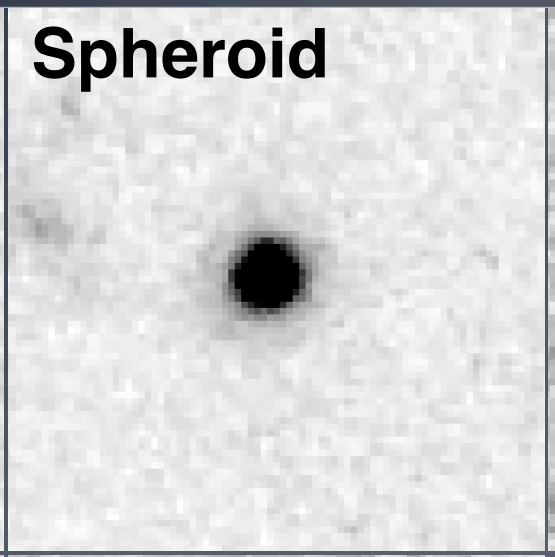
ACS I band

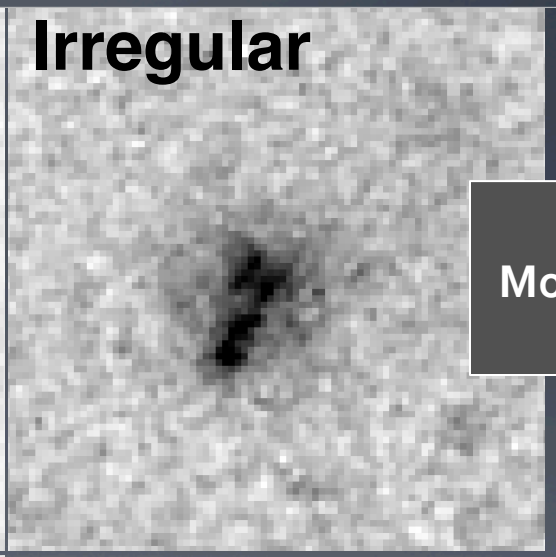
WFC3 H band



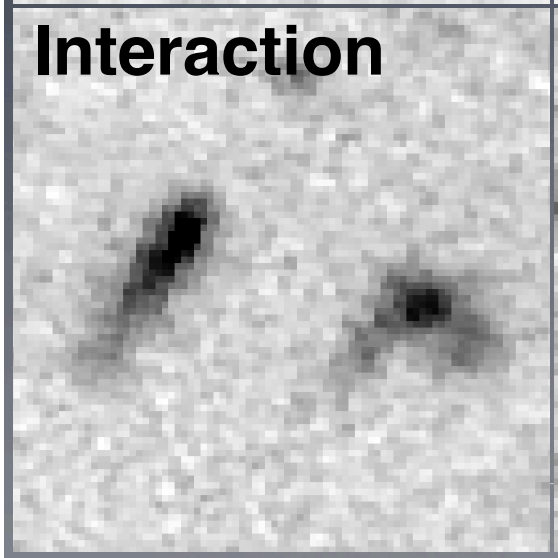
Visual Classification Scheme

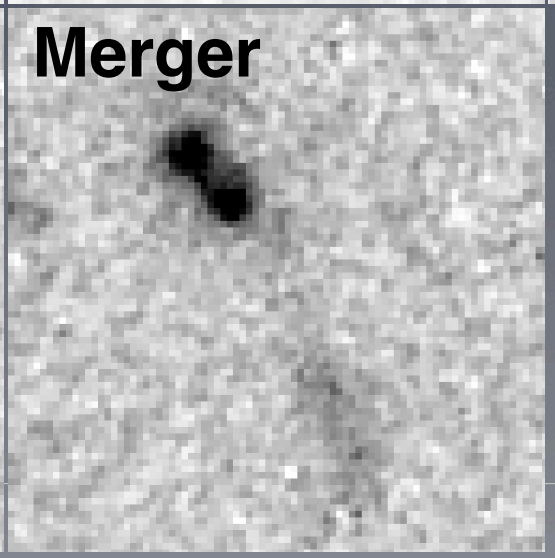






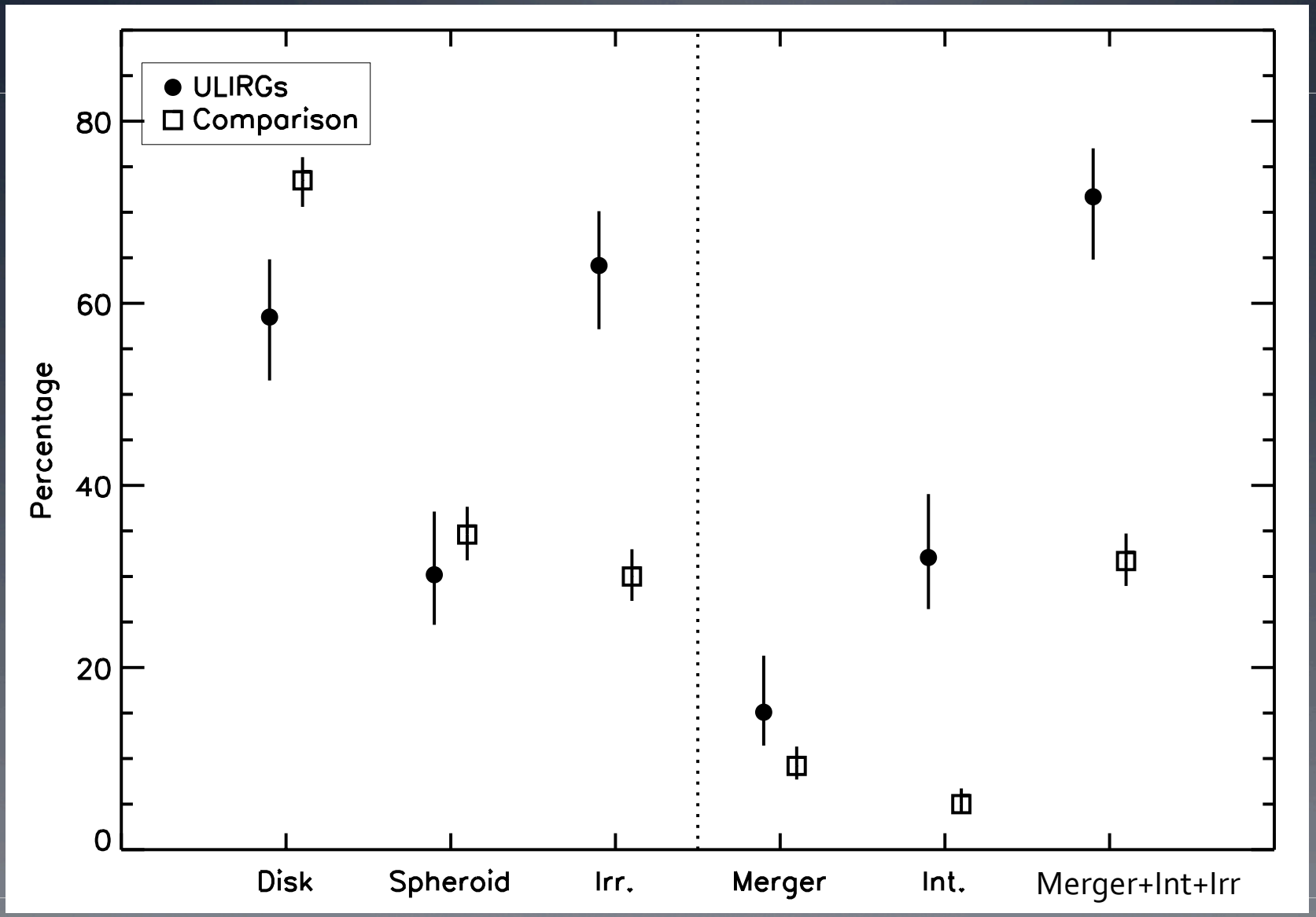
Main Morphological Class





Interaction Class

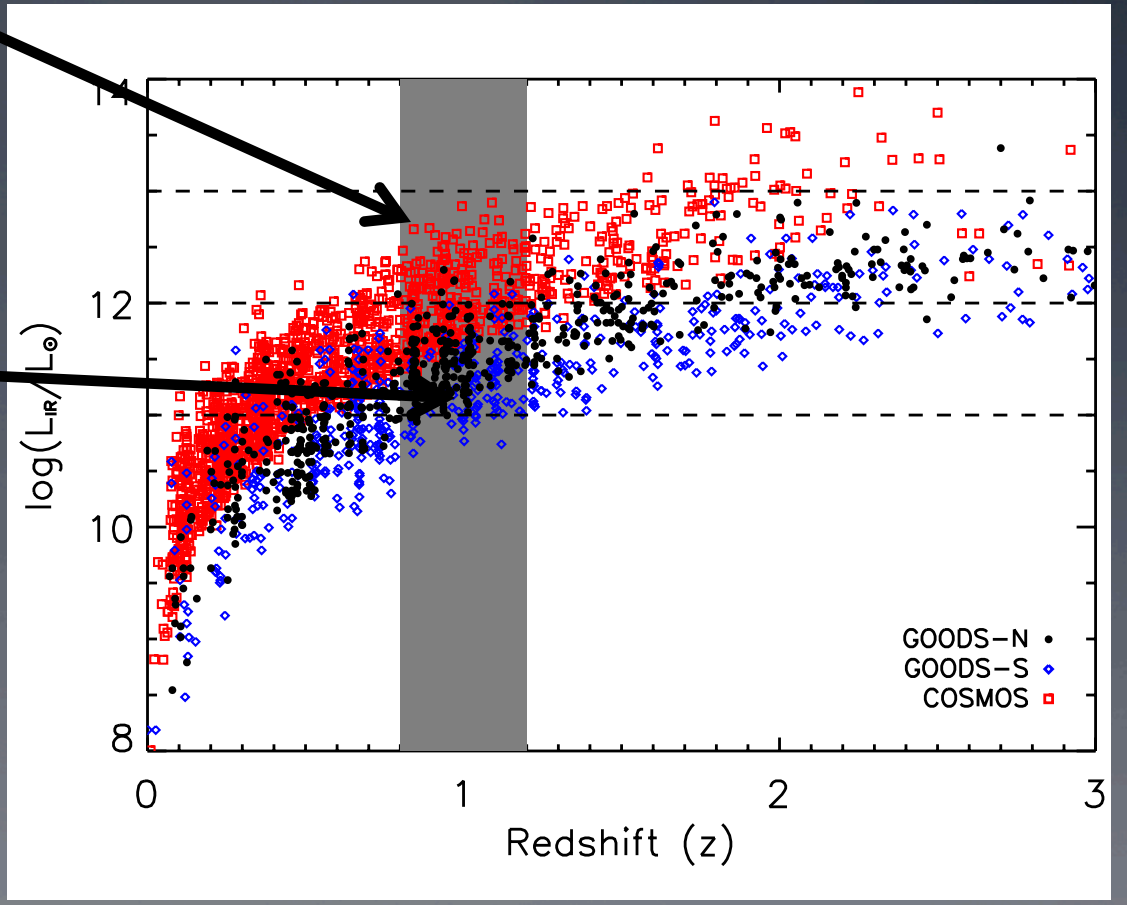
Results

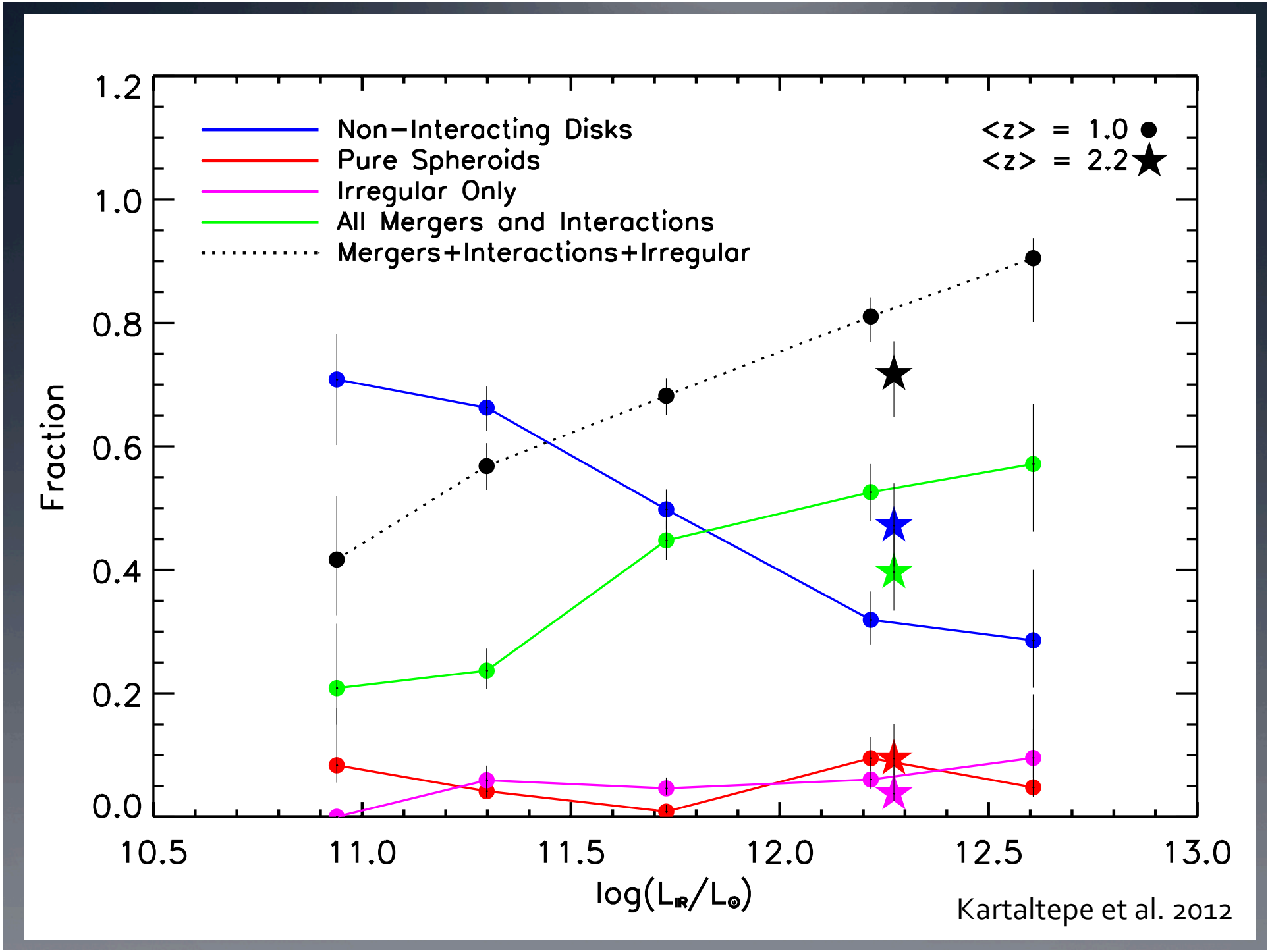


Kartaltepe et al. 2012

Comparison with z ~ 1

- **COSMOS 70 μm**
  - 277 sources 0.8 < z < 1.2
  - Relatively shallow, but large area coverage
  - $\log(L_{IR}) = 11.3 - 12.9$
- **GOODS-*Herschel***
  - North+South
  - 100/160 μm
  - Smaller area, significantly deeper
  - 293 sources w/ 0.8 < z < 1.2
  - $\mathrm{Log}(L_{IR}) = 10.6 - 12.4$
- Classified using ACS imaging and same scheme




Non−Interacting Disks
Pure Spheroids
Irregular Only
All Mergers and Interactions
Mergers+Interactions+Irregular
<z> = 1.0
<z> = 2.2
Fraction
log(L_IR/L_⊙)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10.5
11.0
11.5
12.0
12.5
13.0
Kartaltepe et al. 2012

z~2 ULIRGs

- SFR Enhancement
  - Median(SSFR[(U)LIRGs)] / SSFR['main sequence'])
  - For (U)LIRG non interacting disks: 2.4
  - Spheroid only: 1.4
  - Irregular only: 1.3
  - **Mergers and Interactions: 3.8**

  → SSFR significantly enhanced in mergers and interactions
- AGN Fraction
  - 20 (38%) are X-ray detected AGN (4 Ms CDFS data)
  - 15 (29%) are Power-law AGN
  - **23 unique AGN (44%)**

Summary

- Morphology and AGN content correlated with L_{IR} at all z
  - Difficult with ACS images beyond z~1
- Morphologies of z~2 ULIRGs span a wide range
  - 'Disks' make up a significant fraction (many irregular)
    - 40% non-interacting, 60% total
  - ~45% are clear mergers or interactions
  - Additional ~25% are irregular (minor mergers?)
  - Comparable to fractions at z~1, slightly lower
  - More likely to be interacting pairs than advanced mergers
- SFR of z~2 ULIRGs significantly enhanced (factor of ~3.8)
- 44% of z~2 ULIRGs have an AGN (through X-rays or PL slope)

Future Directions

- The results presented were small numbers!
  - Need rest of CANDELS fields + expanded *Herschel* coverage for firm conclusions/statistics
  - *Herschel*+CANDELS – PI: M. Dickinson (OT2)
  - Coming soon!
- NIR spectroscopic follow-up
  - Starburst-AGN emission line diagnostics
  - What is the role/contribution of the AGN?
  - Large international Subaru FMOS program of COSMOS