Luminous infrared galaxies: energetics and evolution with redshift

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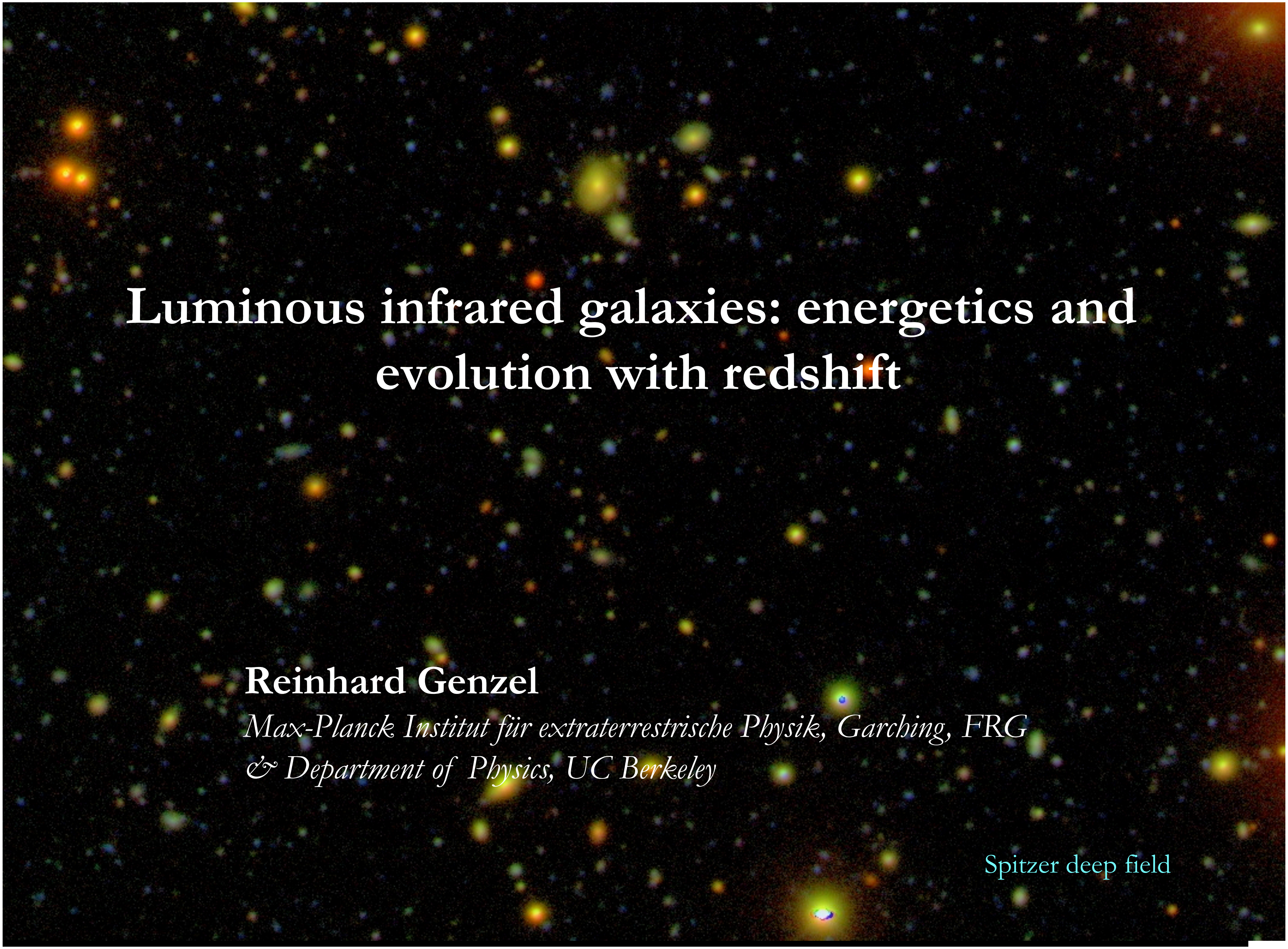


Spitzer deep field

the great leap with Spitzer

- extensive deep surveys of star formation/dusty AGN/stellar masses to z~6, covering cosmic evolution of SMGs, ULIRGs and LIRGs (to z~1.5)
- PAH spectro-photometry to z~3
- line spectral diagnostics in QSOs and extensive samples of (U)LIRGs

M82 Spitzer

the great leap with Spitzer

and a comment:

based on the experience from IRAS/ISO
we have come to call (U)LIRGs 'starbursts',
i.e. $M_{gas}/L_{FIR} << t_{Hubble}$

as a result, (U)LIRGs are rare at z~0
all other galaxies are called 'normal'

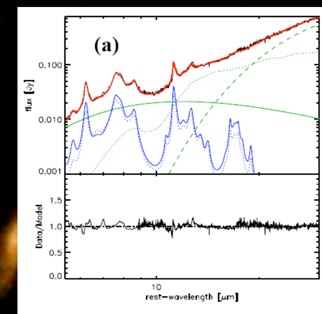
I will show in this talk that this implicit conclusion may not be true anymore at high-z:

then some (U)LIRGs were 'normal' galaxies

M82 Spitzer

infrared diagnostics of (hidden) energy sources

Veilleux et al. (QUEST): agree to within 10-20%



SED decomposition

MIR methods of quantifying the AGN contribution

[Ne V]/[Ne II]

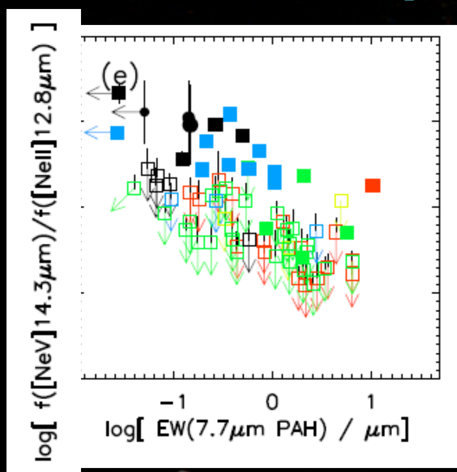
[O IV]/[Ne II]

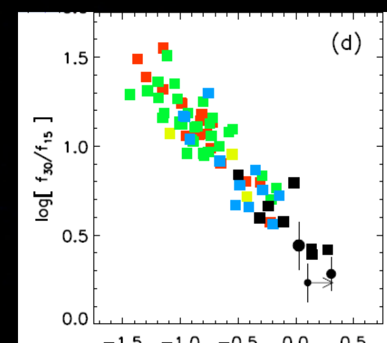
W_{eq}(PAH)

f_{30}/f_{15}

SEDs

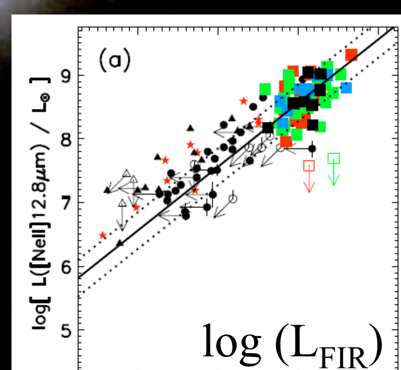
L(MIR)/L(FIR)





log (L_{MIR-BB}/L_{FIR})

- HII-like ULIRG
- LINER ULIRG
- Sy2 ULIRG
- Sy1 ULIRG
- QSO
- Seyfert (ISO)
- Starburst (ISO)



[Ne II] as reference line for L_{FIR}

is the Sanders et al. 1988 scenario correct?

or monsters vs. babies

ULTRALUMINOUS INFRARED GALAXIES AND THE ORIGIN OF QUASARS

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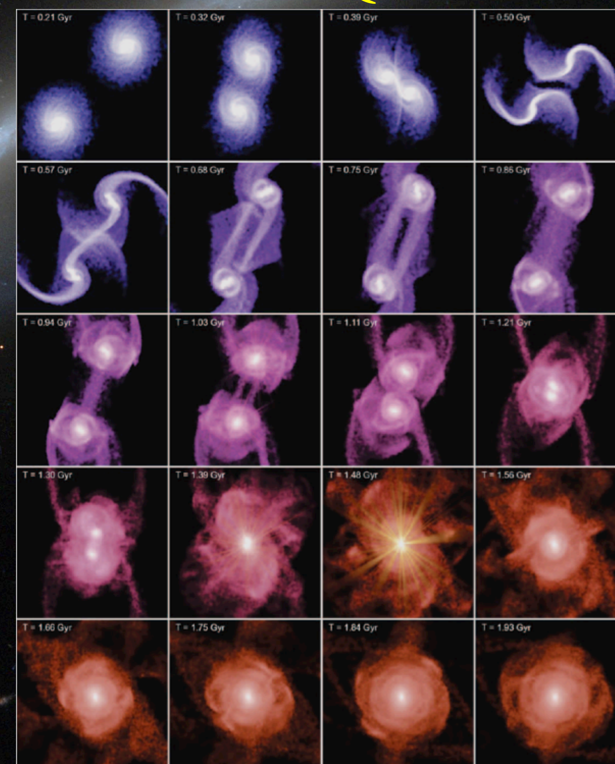
ABSTRACT

An evolutionary connection between ultraluminous infrared galaxies and quasars is deduced from the observations of all 10 infrared galaxies with luminosities $L(8\text{–}1000\ \mu m) \geq 10^{12}\ L_\odot$, taken from a flux-limited sample of infrared bright galaxies. Images of the infrared galaxies show that nearly all are strongly interacting merger systems with exceptionally luminous nuclei. Millimeter-wave CO observations show that these objects typically contain $0.5\text{–}2 \times 10^{10}\ M_\odot$ of H_2. Optical spectra indicate a mixture of starburst and active galactic nucleus (AGN) energy sources, both of which are apparently fueled by the tremendous reservoir of molecular gas. It is proposed that these ultraluminous infrared galaxies represent the initial, dust-enshrouded stages of quasars. Once these nuclei shed their obscuring dust, allowing the AGN to visually dominate the decaying starburst, they become optically selected quasars. The origin of quasars through the merger of molecular gas-rich spiral galaxies can account for both the increased number of high-luminosity quasars at large redshift, when the universe was smaller and gas supplies less depleted, and the observed "redshift-cutoff" of quasars which represents the epoch after galaxy formation when the first collisions occur.

simulations: 'QSO mode'



Springel et al. 2005,
Hopkins et al. 2006

is the Sanders et al. 1988 scenario correct?

or monsters vs. babies

- ULIRGs are mostly <2:1 (major) gas-rich mergers

  (Downes & Solomon 1998, Sakamoto et al. 1998, Scoville et al. 2000, Dasyra et al. 2006a)

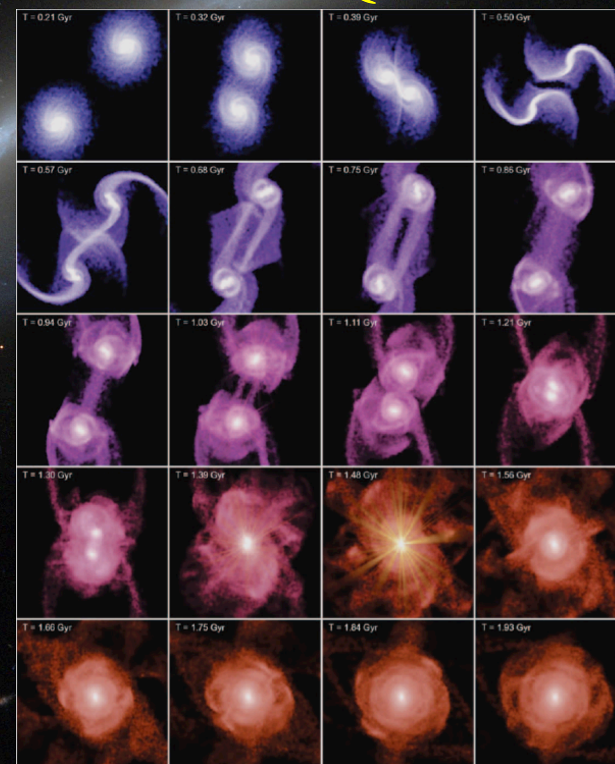
- ULIRG remnants are structurally and kinematically similar to moderate mass, disky ellipticals

  (Doyon et al. 1994, Scoville et al. 2000, Genzel et al. 2001, Tacconi et al. 2002, Dasyra et al. 2006b)

- PG QSO stellar masses similar to ULIRGs

  (Dasyra et al. 2007)

simulations: 'QSO mode'

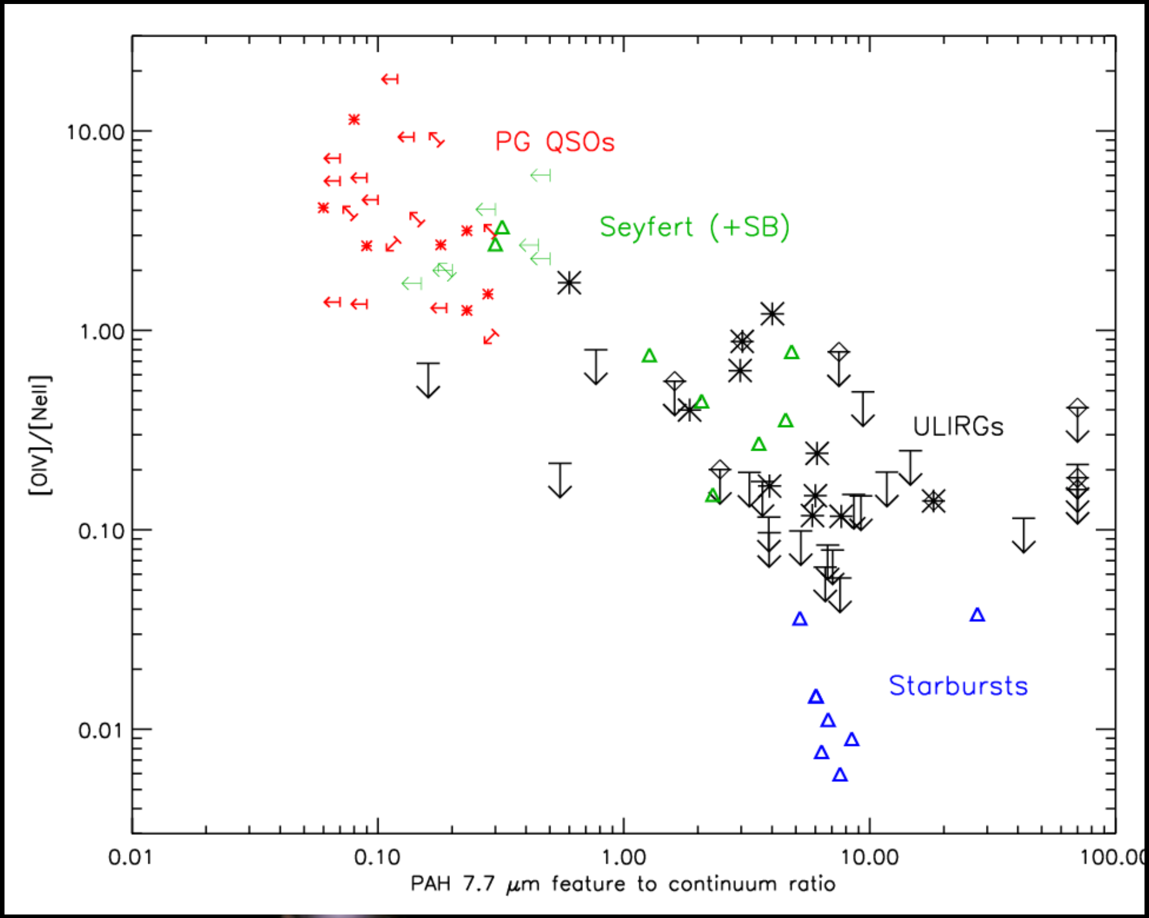


Springel et al. 2005, Hopkins et al. 2006

spectral diagnostic diagrams

Lutz et al. 1996, 1999, Genzel et al. 1998, Veilleux et al. 2006, Armus et al 2007, Dale et al. 2006, Spoon et al. 2007, Desai et al. 2007, Farrah et al. 2007, 2009

spectral diagnostic diagrams



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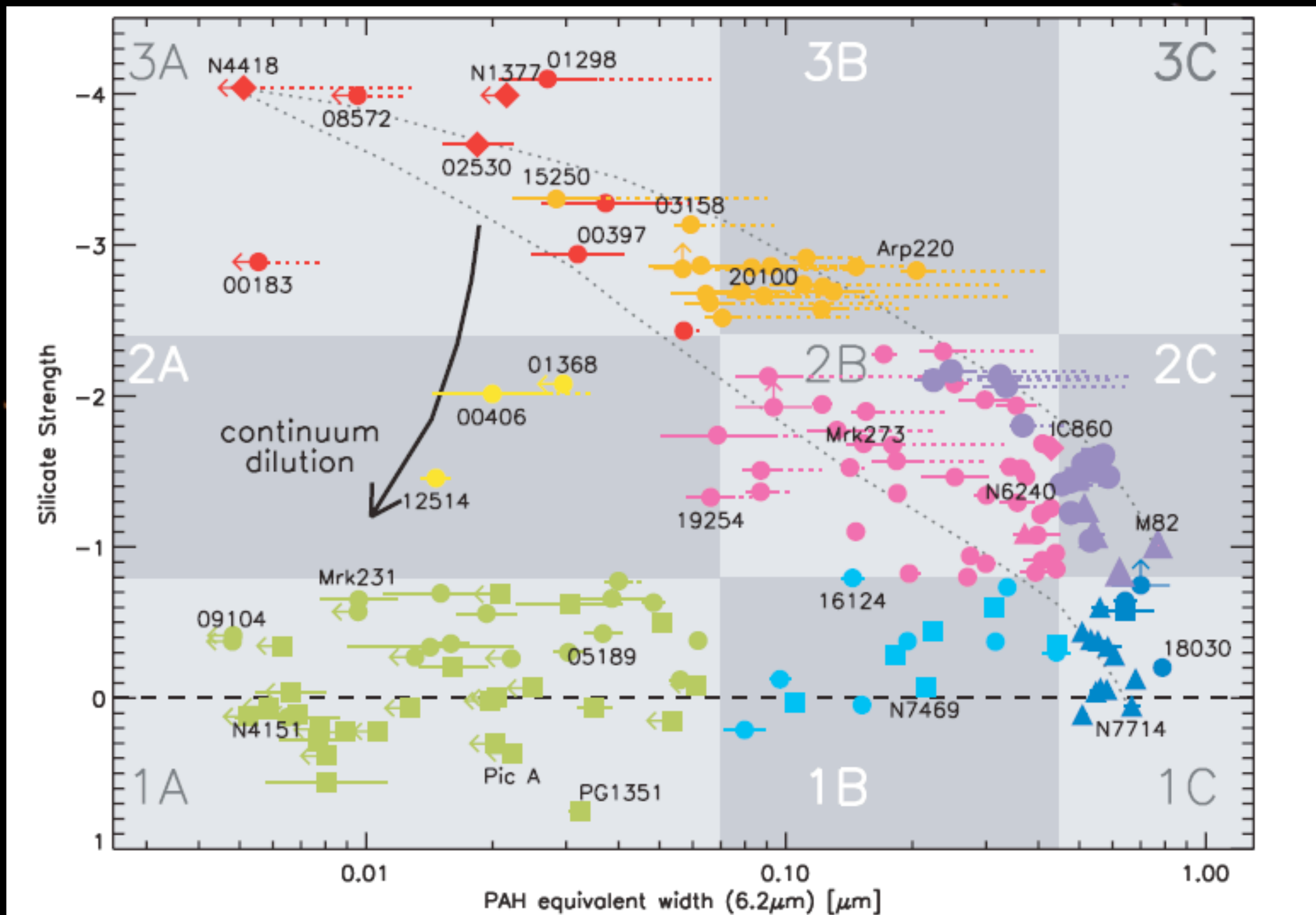
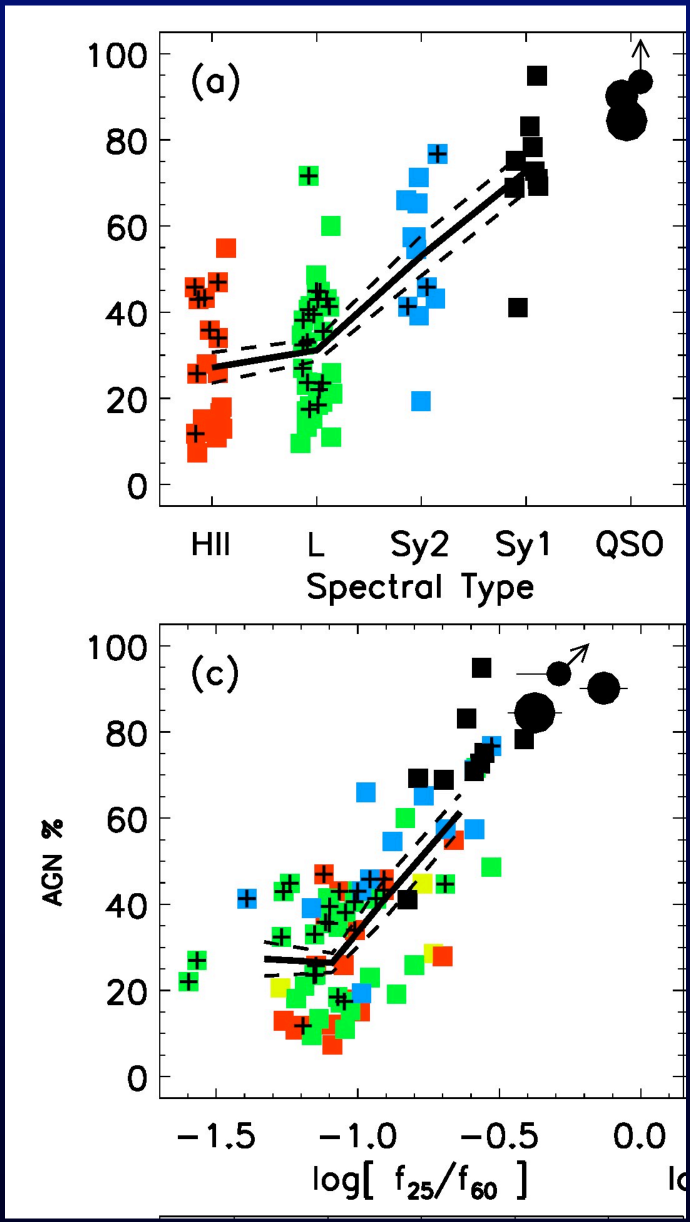
spectral diagnostic diagrams



Lutz et al. 1996, 1999, Genzel et al. 1998, Veilleux et al. 2006, Armus et al 2007, Dale et al. 2006, Spoon et al. 2007, Desai et al. 2007, Farrah et al. 2007, 2009

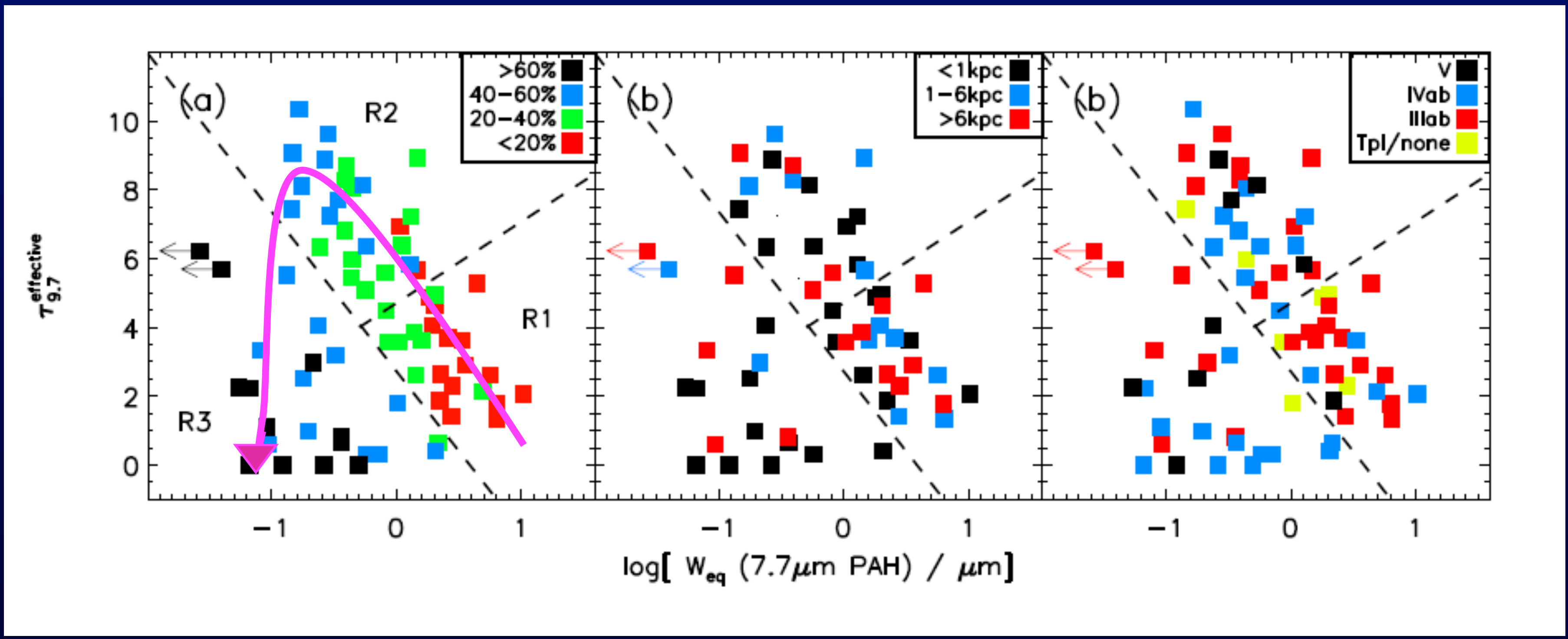


AGN fractions

- <AGN%> ~ 37% in ULIRGs, less in LINER/HII ULIRGs
- Good agreement w/ ISO results (Genzel et al. 1998)
- Strong correlations with optical spectral types and f_{25}/f_{60}
- QSOs fall along these trends

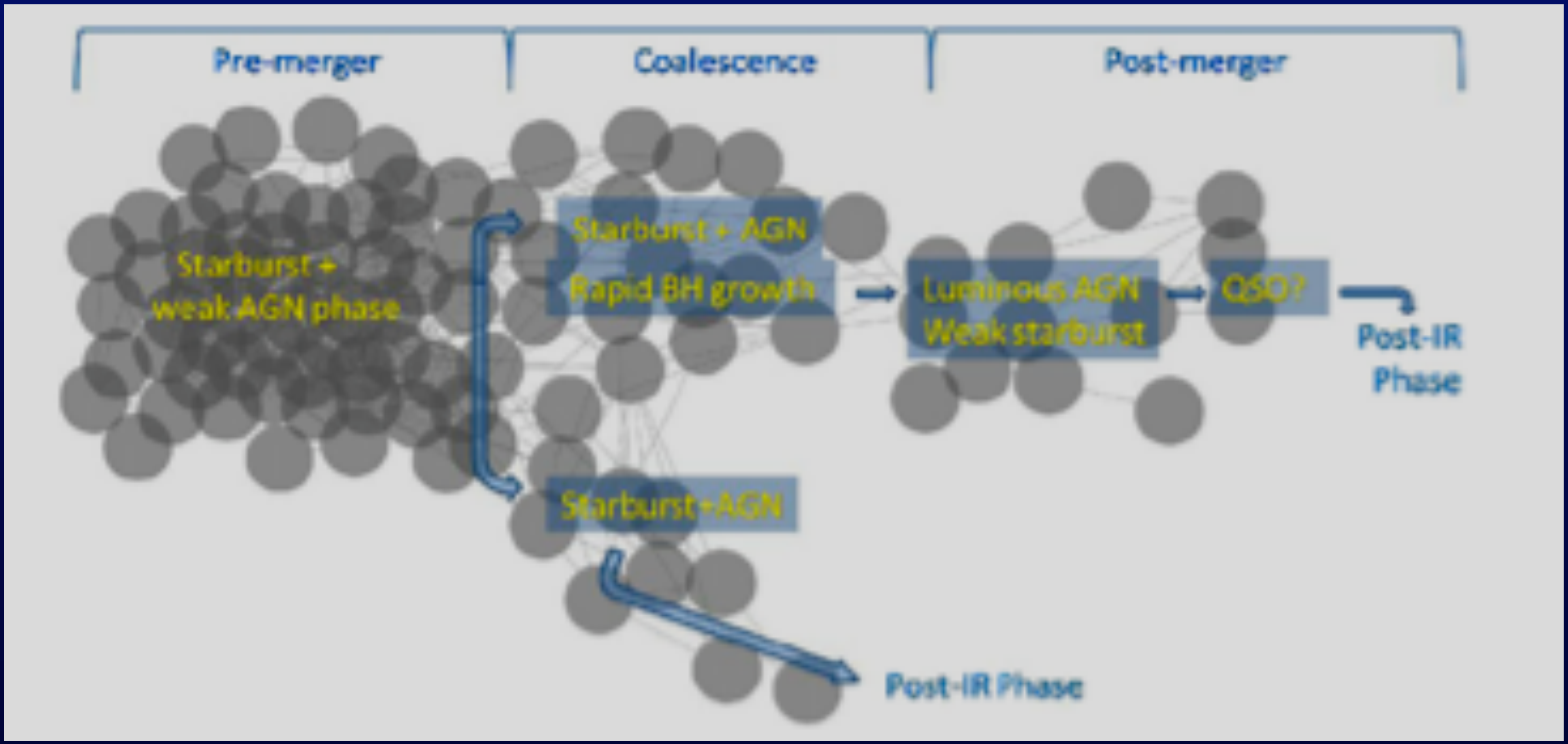
Veilleux et al. 2009, Rupke et al. 2009

evolution of ULIRGs



Veilleux et al. 2009, Spoon et al. 2007

two paths in the evolution?

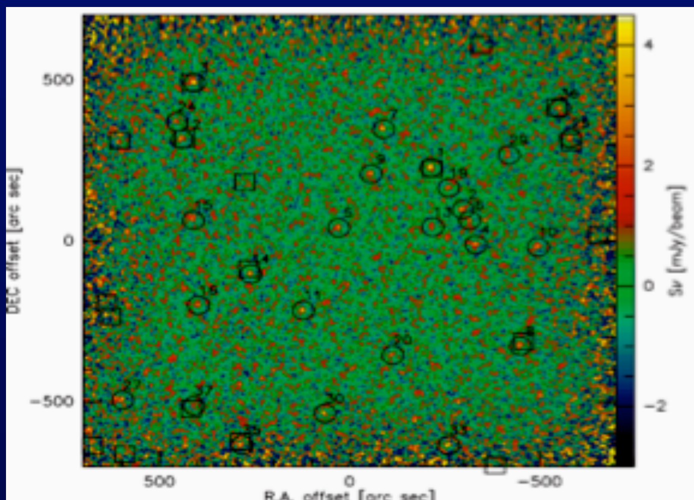


Farrah et al. 2009

Submillimeter galaxies

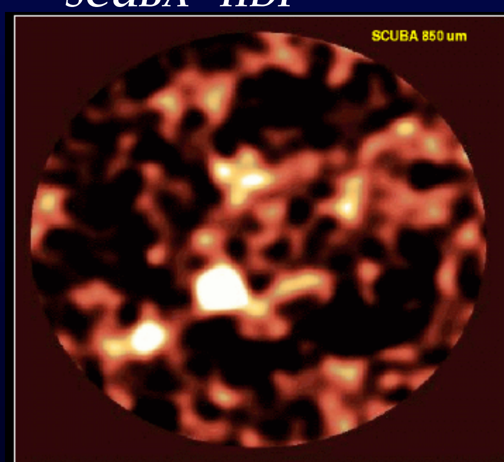
Smail, Blain, Ivison et al. 1997-2002

MAMBO - COSMOS



Bertoldi et al. 2007

SCUBA - HDF



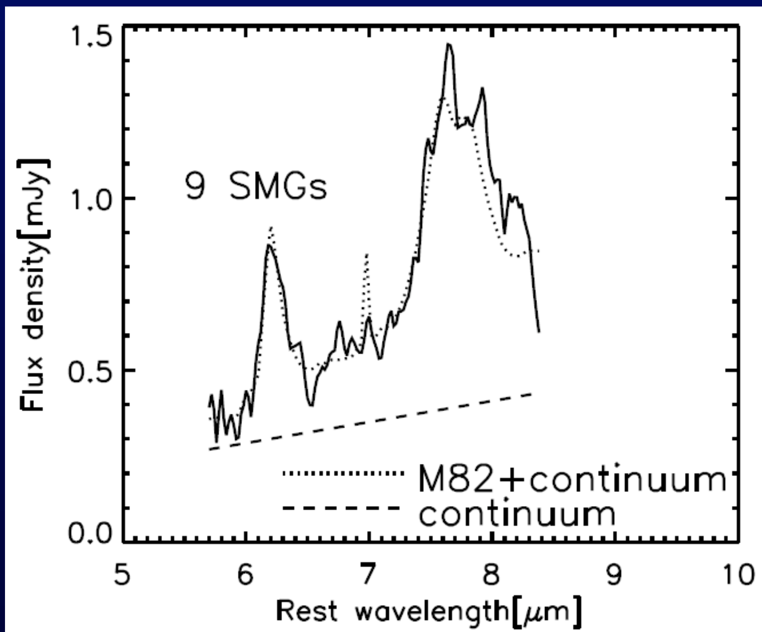
Hughes et al. 1998

- *>1000 well detected sources > few x $10^{12....13.3}$ $L_{\odot}$*
- *volume density: $S_{850\mu m}$≥5 mJy ~ 10^{-5} h_{70}^{-3} Mpc^{-3}*
- *make up a significant fraction of the submm background and energy release at redshift 1-4*

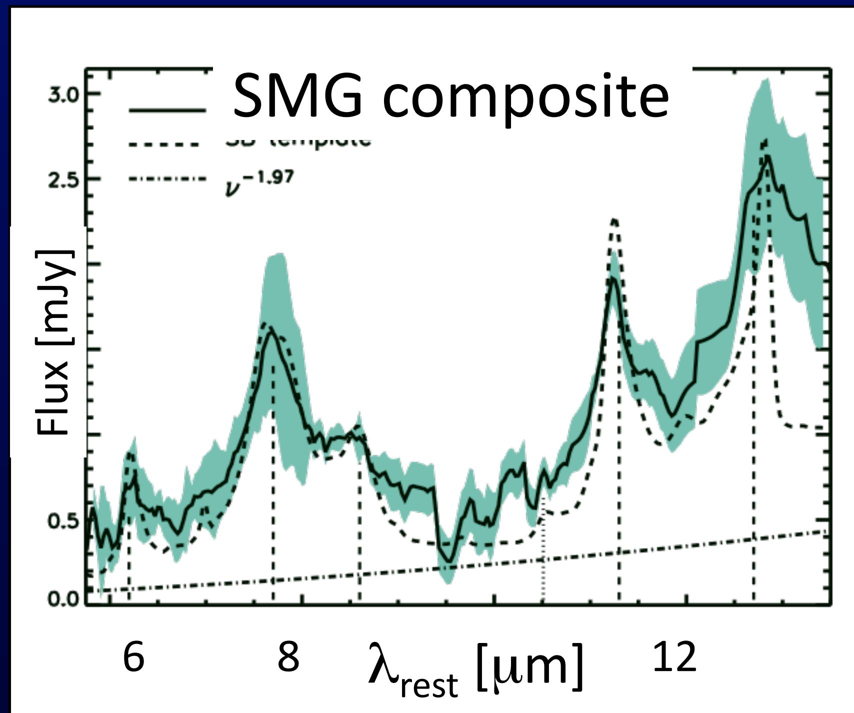
<z>~2.2 (Chapman et al. 2005)

but Spitzer discovered a number of z~3-4 SMGs

Mid-IR spectra of SMGs: star formation dominated



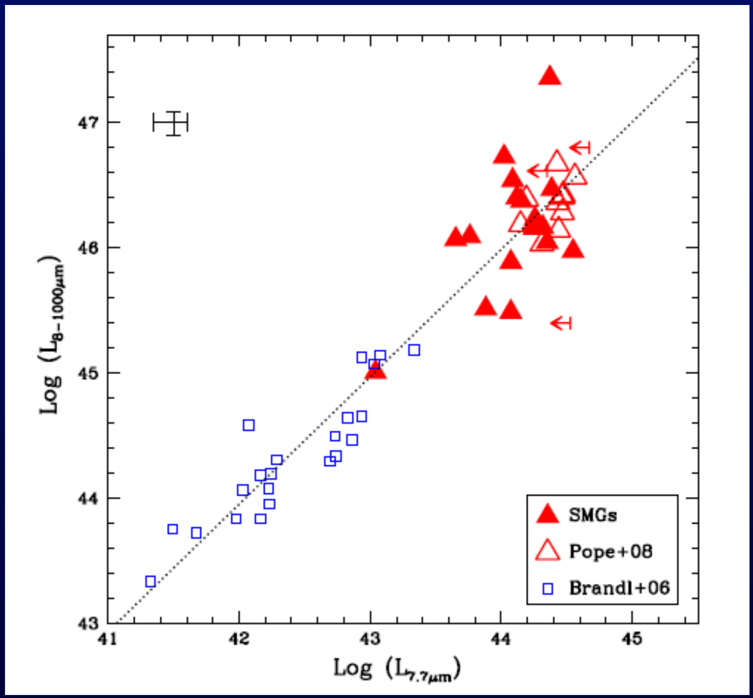
9 SMGs: Valiante et al. 2007



24 SMGs: Menendez-Delmestre et al. 2009: >80% star formation

Lutz et al. 2005. Valiante et al. 2007, Menedez-Delmestre et al. 2007, 2009, Pope et al. 2008

Mid-IR spectra of SMGs: star formation dominated

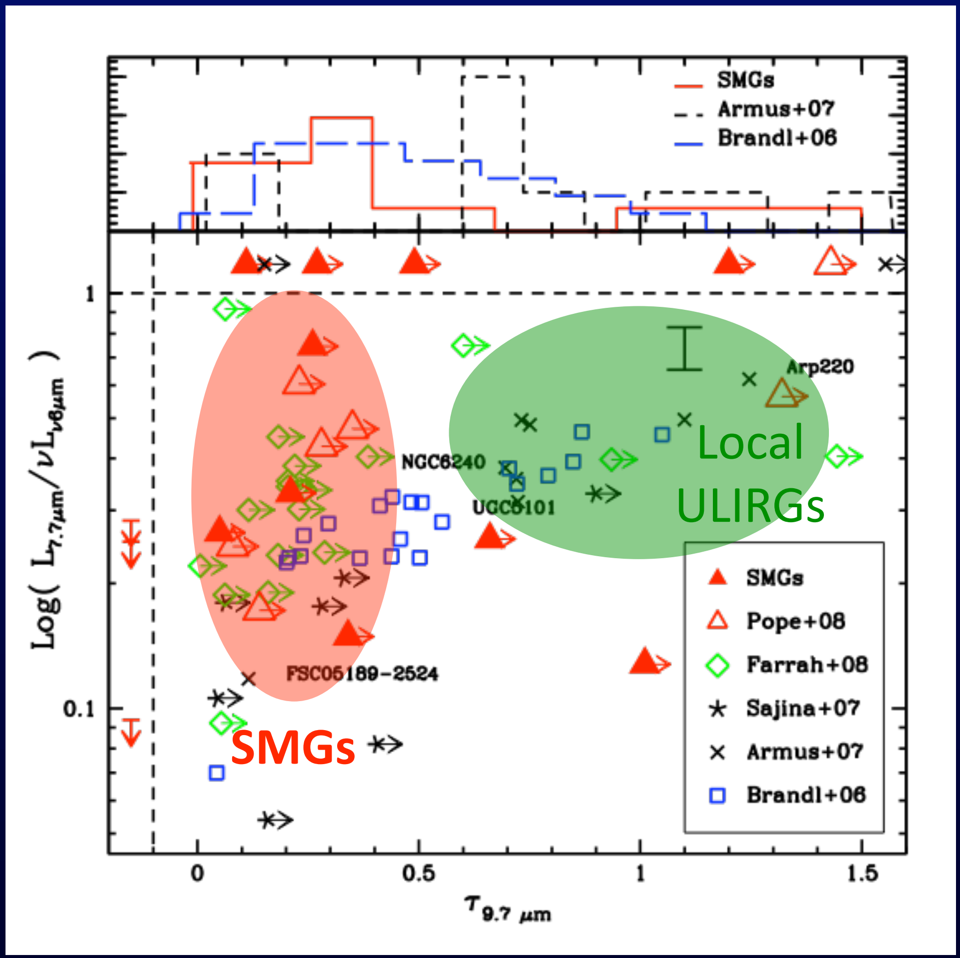


Pope et al.: SMGs on extrapolation of local starbursts

SMGs often have detectable AGNs (X-rays); these contribute ~10-30% to the total luminosity

Lutz et al. 2005, Alexander et al. 2006, 2008, Valiante et al. 2007, Menedez-Delmestre et al. 2007, 2009, Pope et al. 2008

Mid-IR spectra of SMGs: lower silicate extinction than local ULIRGs



star formation activity spatially extended

Menedez-Delmestre et al. 2009

Optically faint Spitzer 24 μ m sources (DOGs)

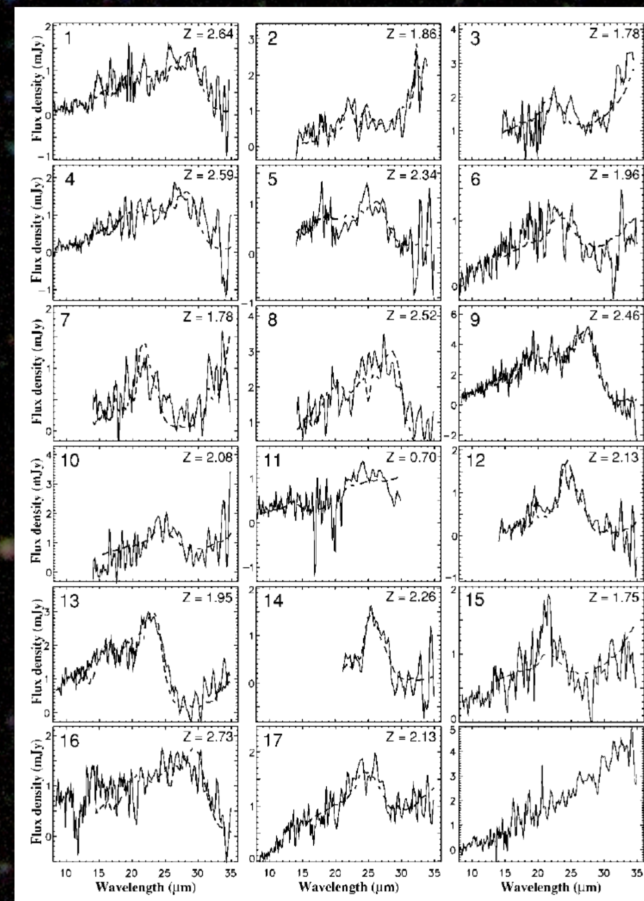
Dusty star formation? Obscured AGN?

Some PAH detections, large fraction of (obscured) continua

faint at submm/mm

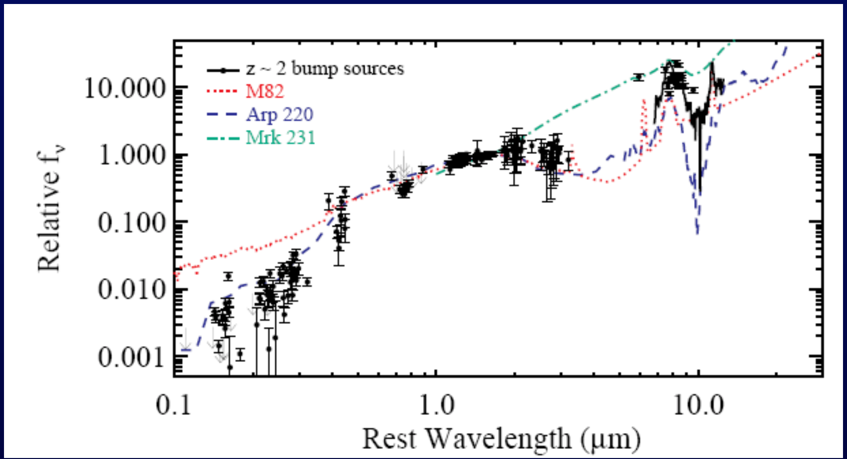
volume densities ~0.2x SMGs

transition objects to QSOs?

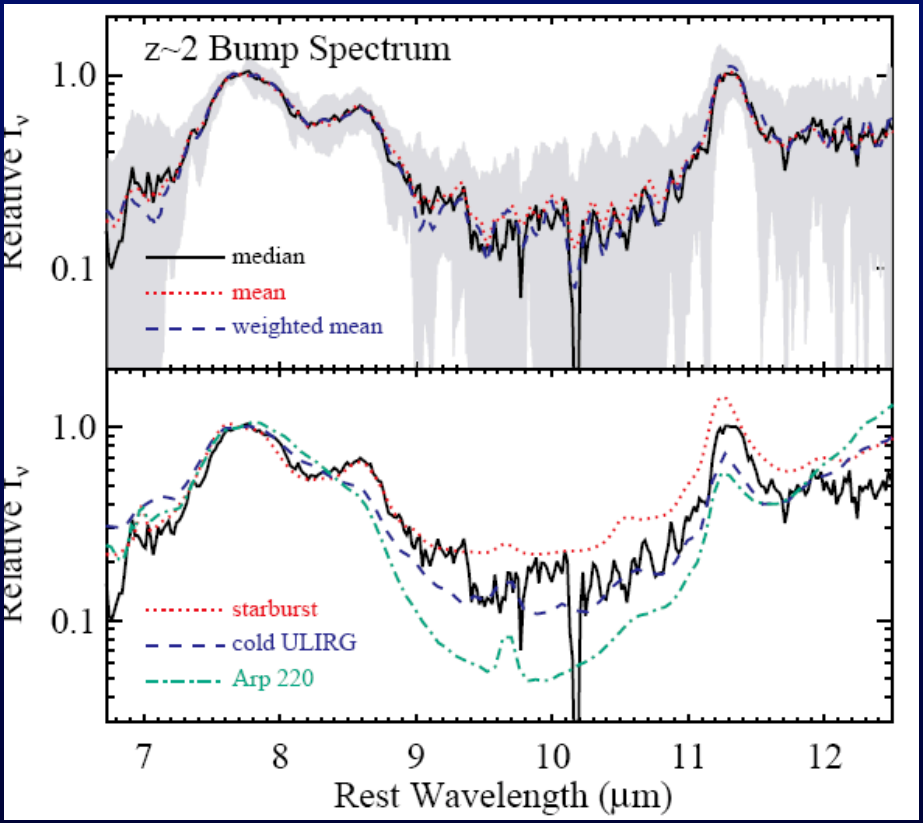


Houck et al. 2005, 2006, Lutz et al. 2005b, Weedman et al. 2006, Yan et al. 2006, Martinez-Sansigre et al. 2005, Donley et al. 2005, 2007, Alonso-Herrero et al. 2006, Daddi et al. 2007, LeFloc'h, Magliocchetti et al. 2008, Dey et al. 2008

High-z ‘bump’ ULIRGs



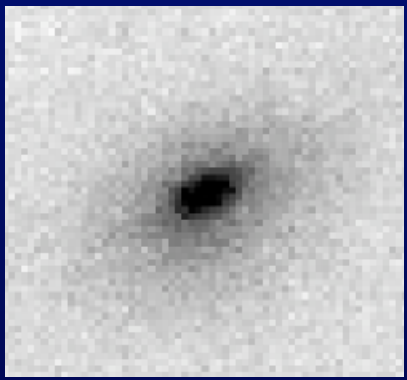
Desai et al. 2009

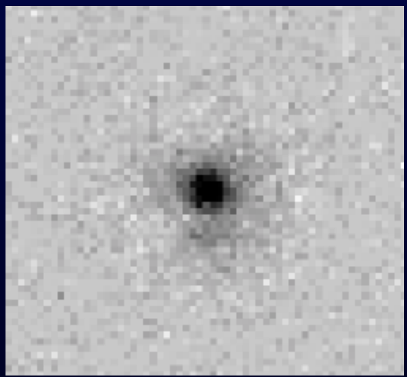


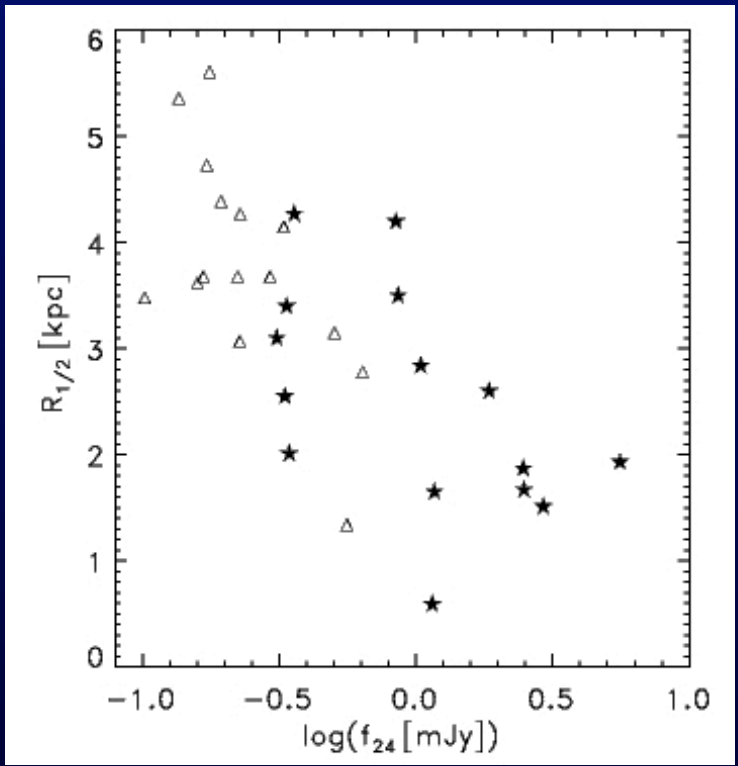
z~2 ULIRGs with 1.6µm stellar bump have strong PAH emission and SED reminiscent of Arp220

Alonso-Herrero et al. 2009, Brandl et al. 2006, Spoon et al.2007, Farrah et al. 2008, Rigby et al. 2008

AGNs do not dominate DOG morphology



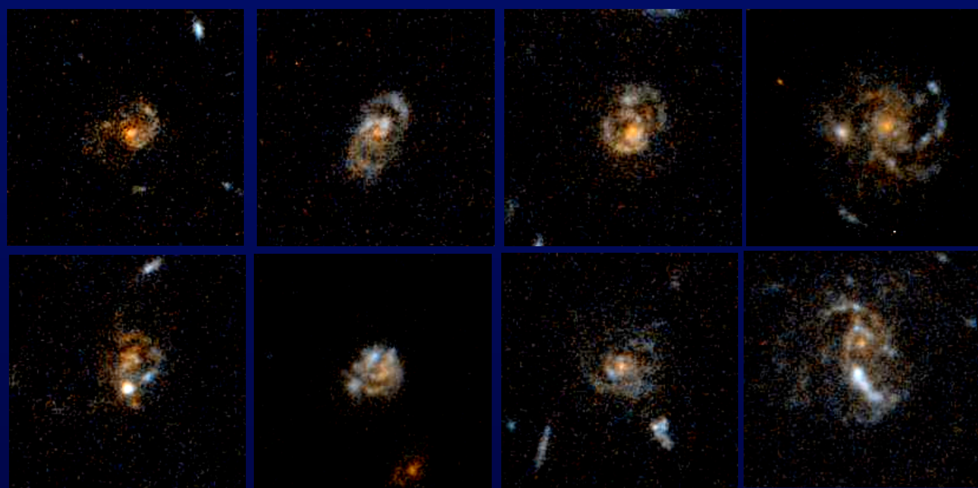




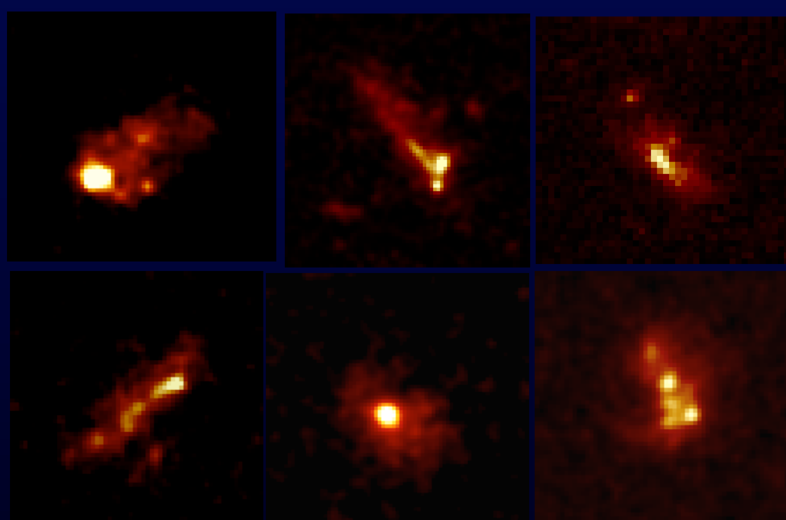
more luminous –
more compact –
more AGN dominated?

Keck/AO
Melbourne et al. 2008, 2009

HST imaging of z~1-2 UV/optically selected (U)LIRGS

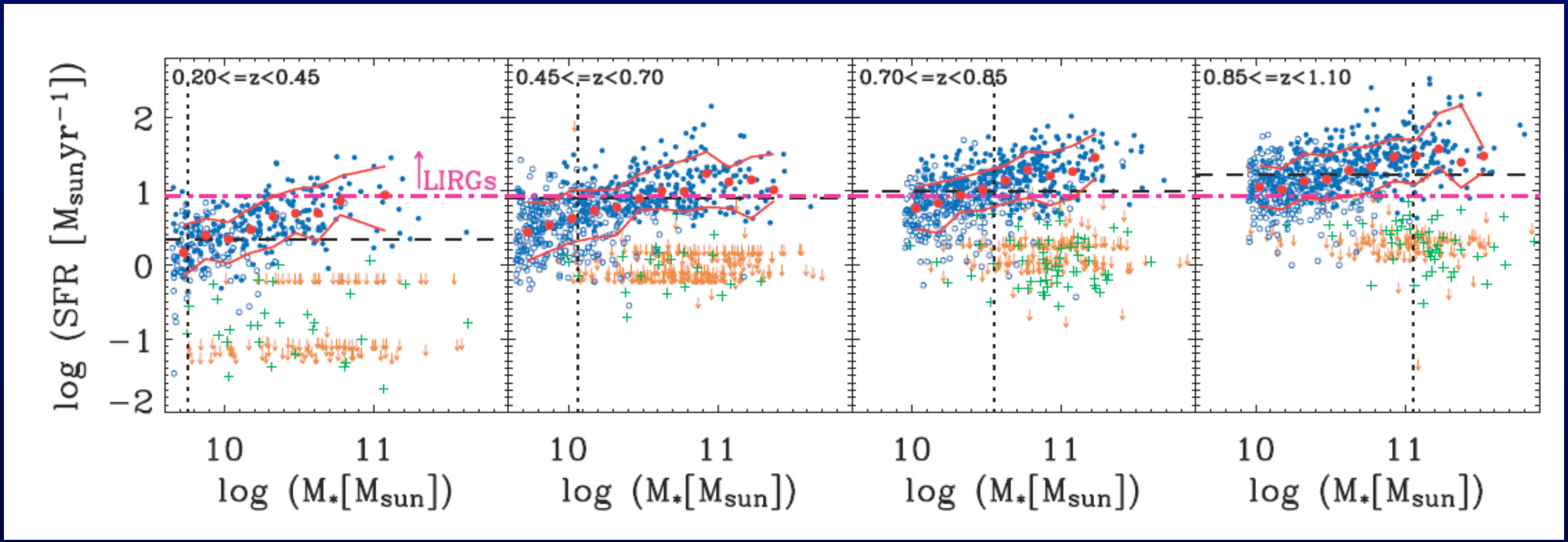


z~1 (AEGIS)
Noeske et al. 2007
Cooper et al. 2009



z~2 (BX/BM/BzK/DRG)
Förster Schreiber et al. 2009b
Kriek et al. 2009

high-z star forming galaxies form a SFR-M$_*$ 'main sequence'

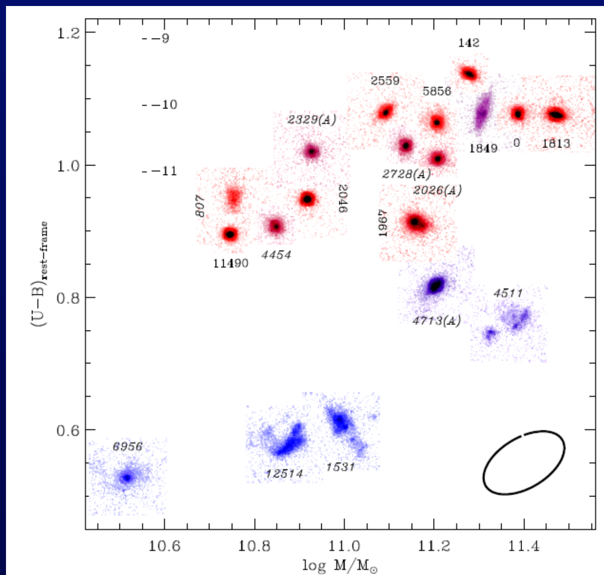


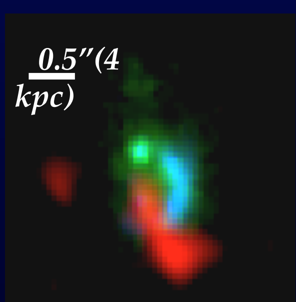
SFR-M$_*$ 'main sequence' and high duty cycle

$$SFR = 150\, M_{*,11}^{0.8} \left(\frac{1+z}{3.2} \right)^{2.7} \quad M_\odot\, yr^{-1}, \quad \eta_{SF} \geq 0.4$$

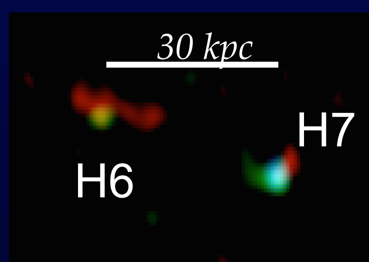
Noeske et al. 2007, Daddi et al. 2007, Elbaz et al. 2007

SMGs and the formation of red spheroids

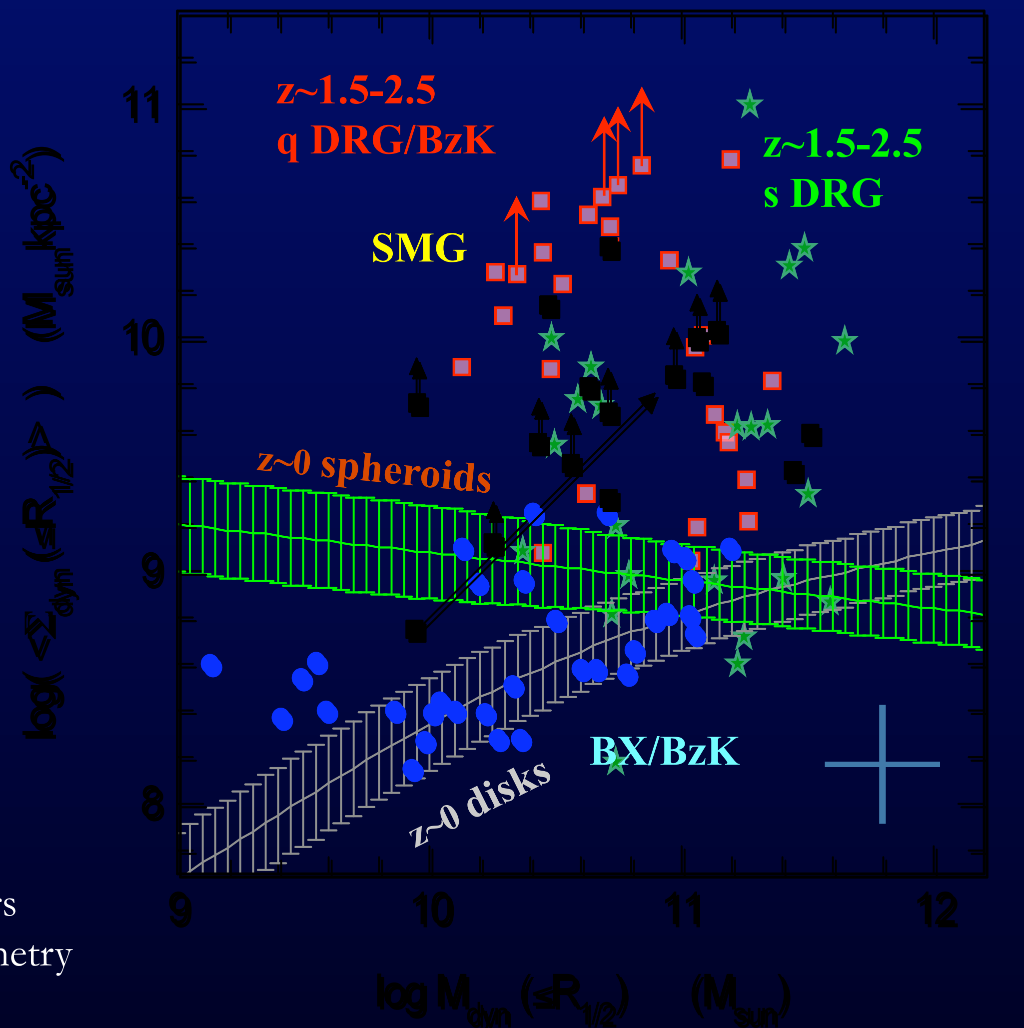




CO 7-6 (red) on ACS (blue) & NICMOS (green)

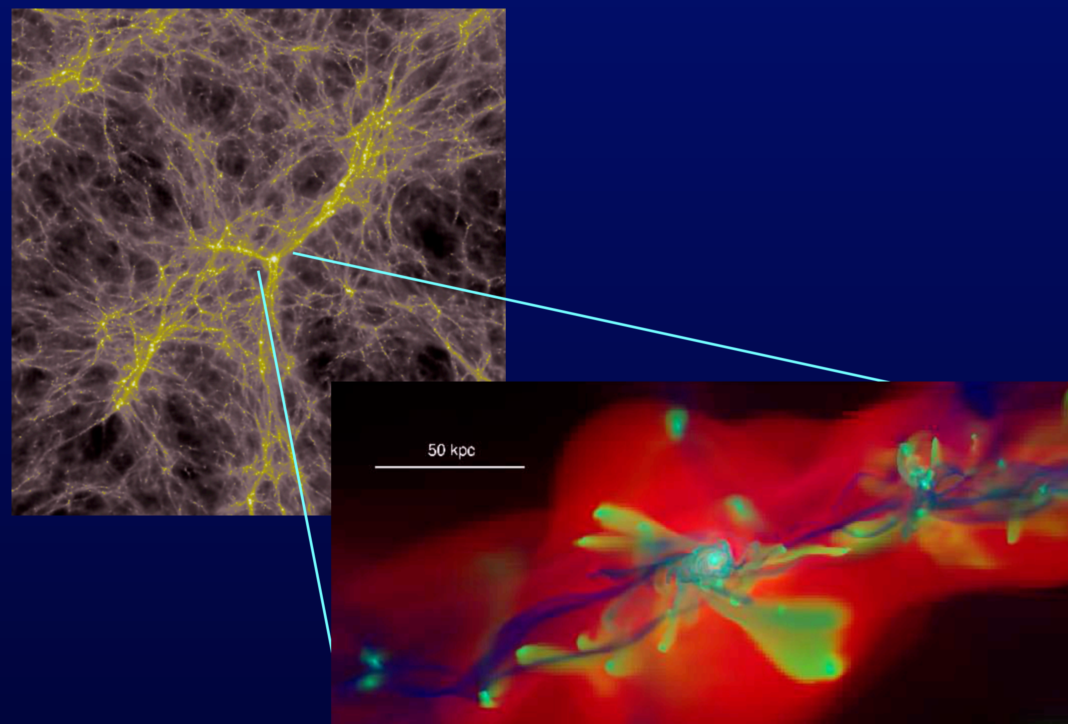


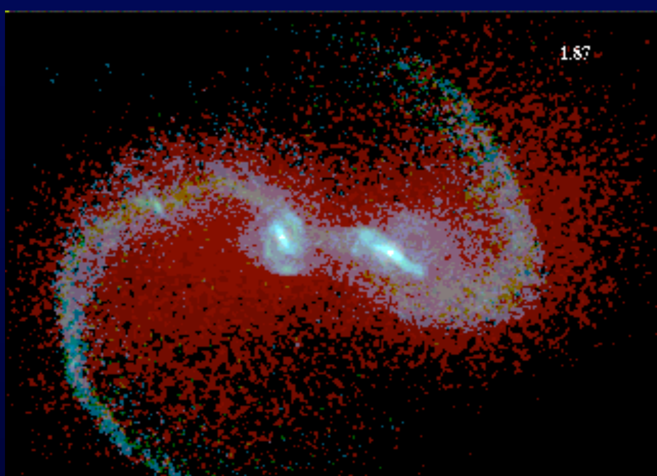
evidence for major mergers from PdBI mm-interferometry (Tacconi et al. 2006, 2008)



Daddi, Toft, Franx, van Dokkum, Kriek, Cimatti et al. 2004-2009, Tacconi et al. 2008

relation to theory of galaxy evolution: what drives star formation over cosmic epochs?





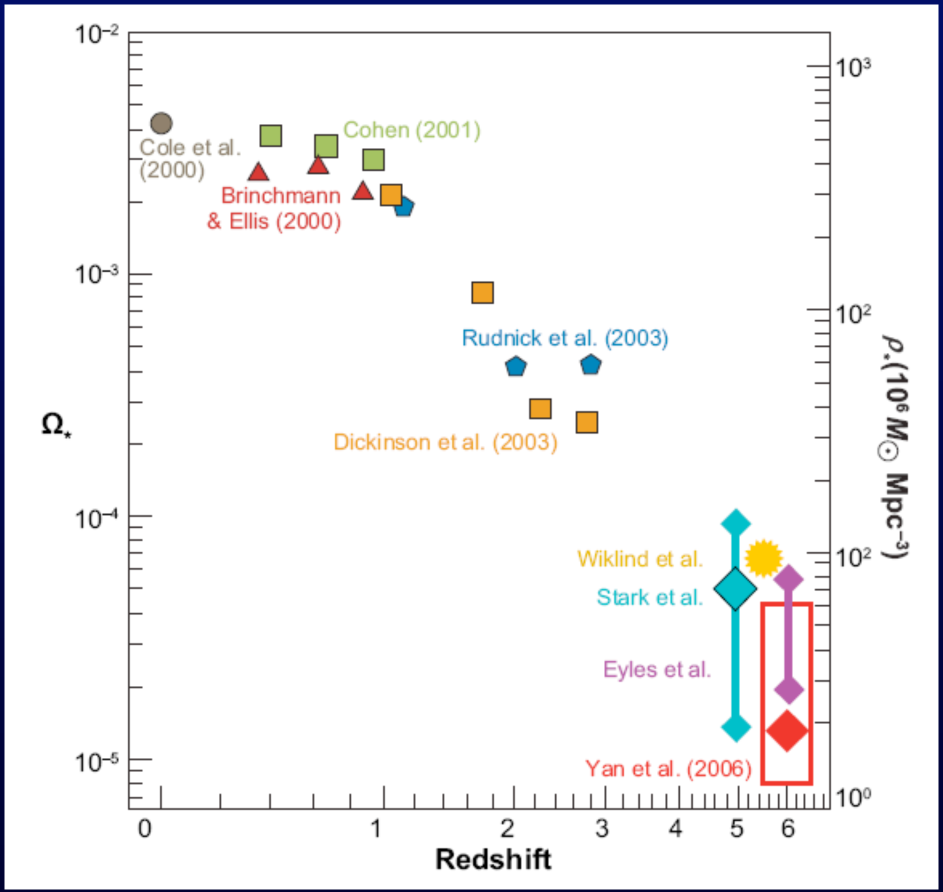
cold flows/streams:

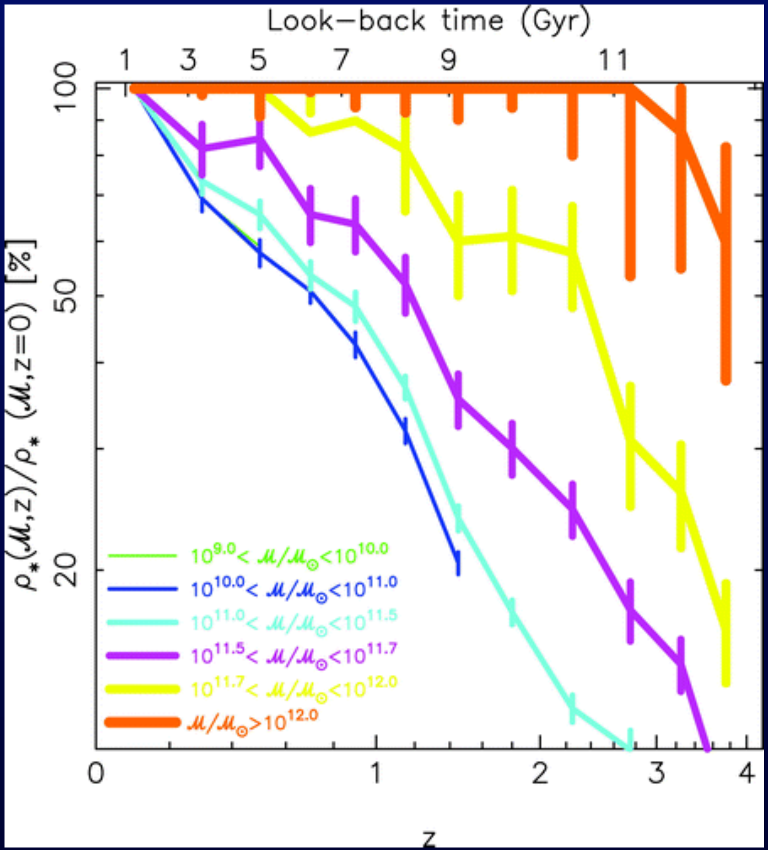
Dekel & Birnboim 2003,2006, Keres et al. 2005, Nagamine et al. 2005, Davé 2007, Kitzbichler & White 2007, Naab et al. 2007, Governato et al. 2008, Ocvirk et al. 2008, Dekel et al. 2009, Agertz et al. 2009

major & minor mergers

Kauffmann et al. 1993, Steinmetz & Navarro 2003, Hernquist, Springel, di Matteo, Hopkins et al. 2003-2006, Robertson & Bullock 2008

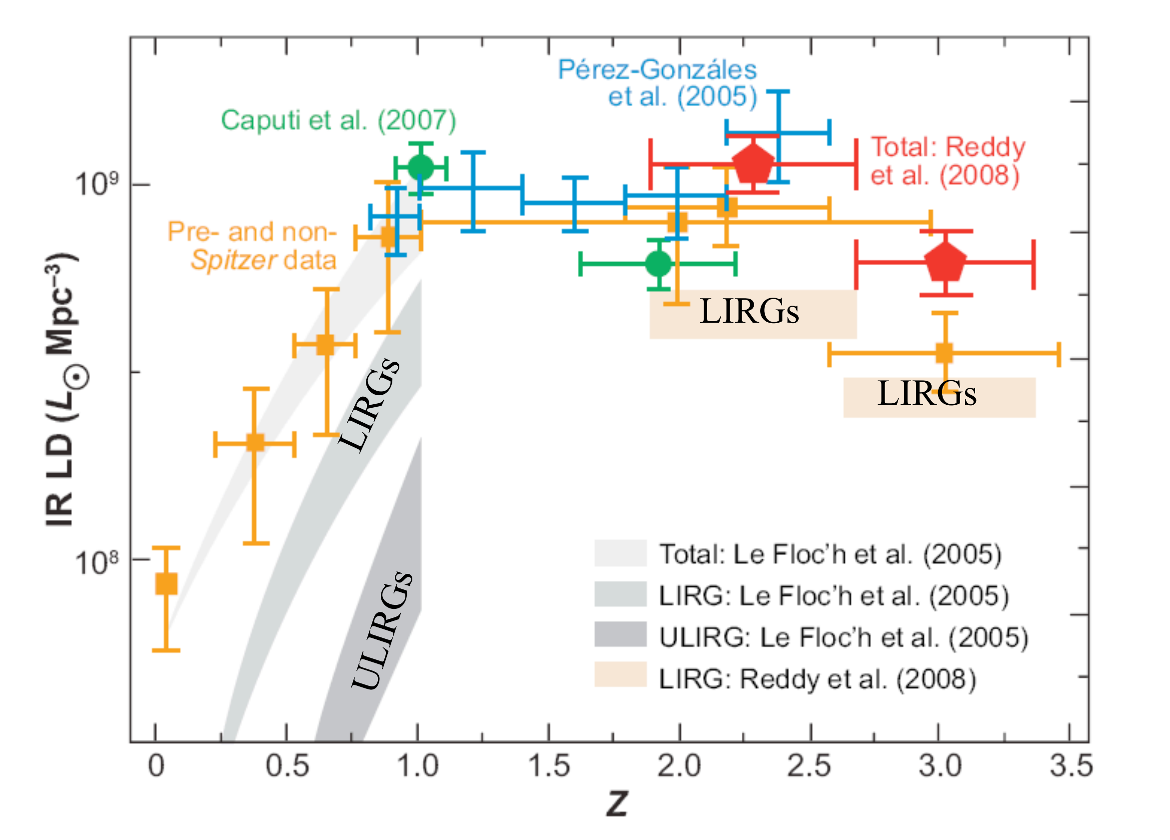
stellar mass assembly: 'downsizing'





Eyles et al. 2005, 2007, Yan et al. 2006, Stark et al. 2007, Perez Gonzalez et al. 2008, Soifer, Helou & Werner 2008

cosmological evolution: the era of LIRGs /ULIRGs



'…at z≥1 IR-luminous galaxies …dominate star formation activity….'

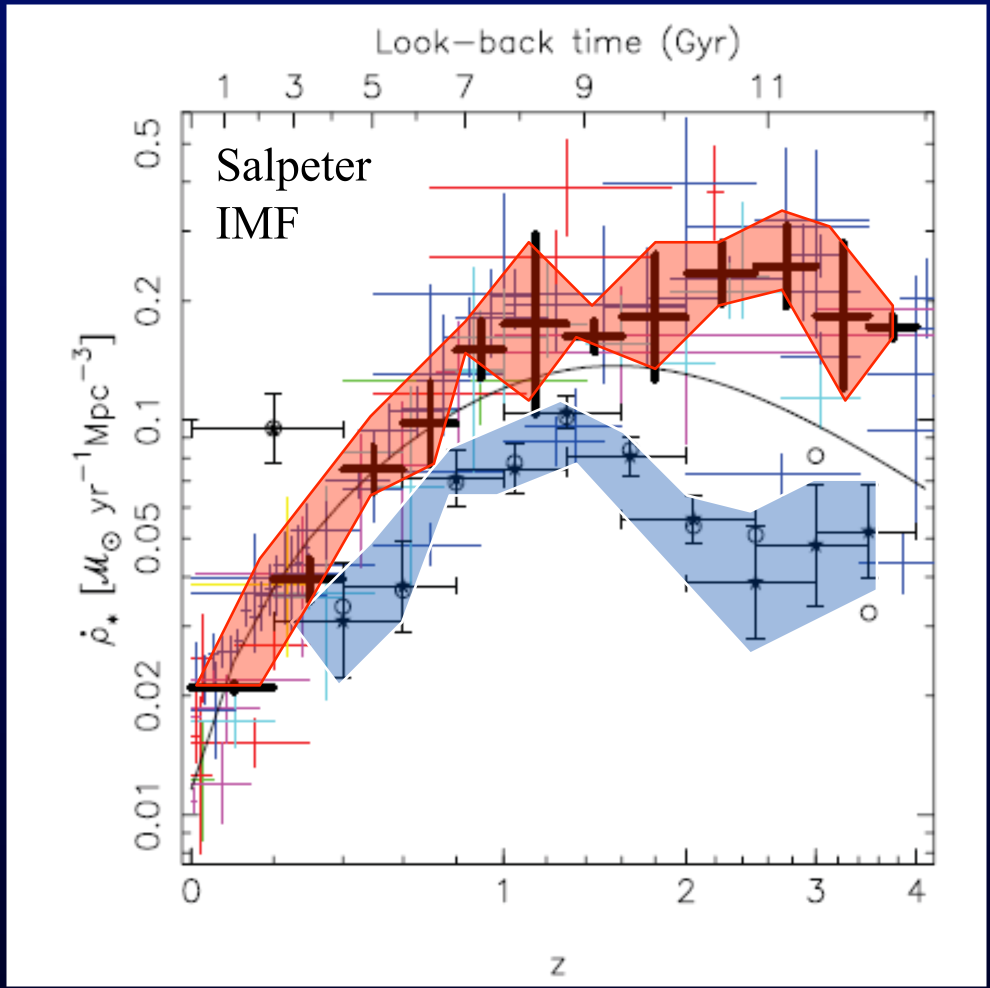
Soifer, Helou & Werner 2008

is there a problem ?

for Chabrier IMF at z>1.5:

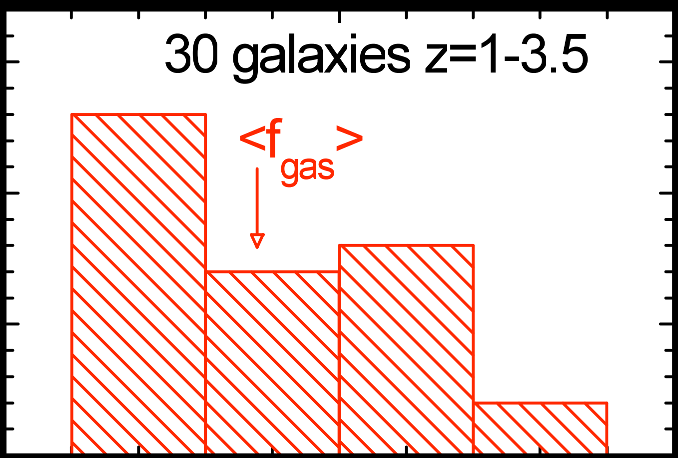
SFR~1.5-3 dM*/dt
similar discrepancy with models

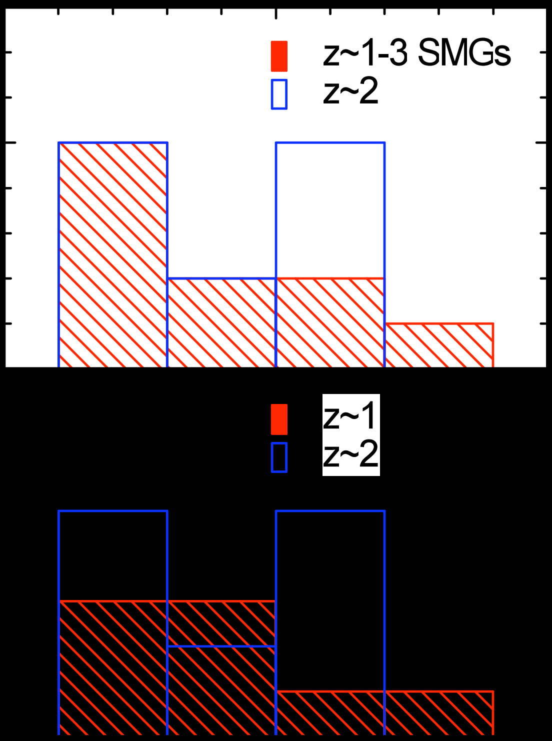
→ IMF top heavy (Baugh et al. 2005, Dave 2008, van Dokkum 2008)
→ SFR-indicator calibration off (Herschel)
→ AGNs affecting mid-IR indicators (Daddi et al. 2007)



Perez-Gonzalez et al. 2008, Hopkins & Beacom 2006

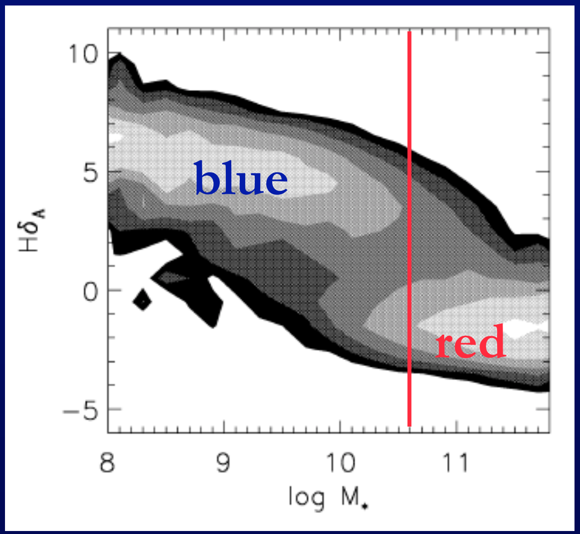
high-z galaxies are gas rich





Tacconi et al. 2008, 2009, Daddi et al. 2008

is there a simple explanation ?



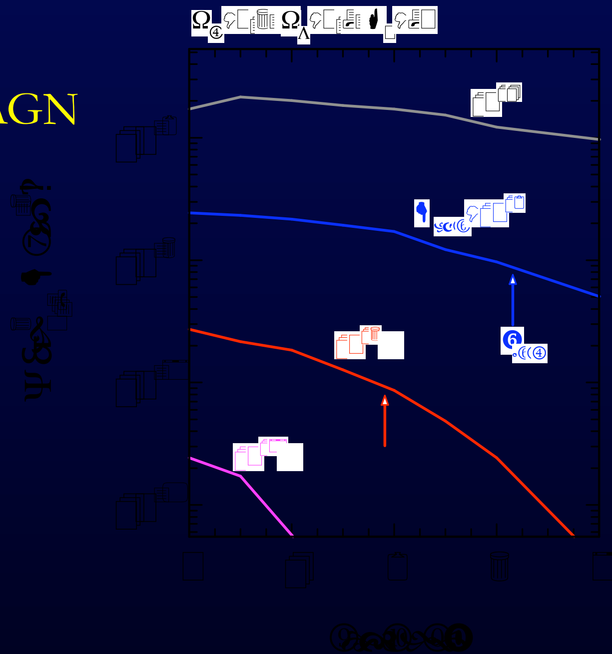
Kauffmann et al. 2003

$$SFR = \varepsilon \frac{f_{H2} M_{baryon}}{\tau_{dyn}} = 0.24 \varepsilon_{0.02} f_{0.1} M_{10}^{3/2} R_{eff,4}^{-3/2} \quad [\mathrm{M}_\odot\, yr^{-1}]$$

$z=0 \;\; M_{\max,10}=10, f_{0.1}=1: \;\; SFR_{\max} \sim 10\ \mathrm{M}_\odot\, yr^{-1}, \mathrm{L}_{\max} \sim 10^{11}\ \mathrm{L}_\odot$ (MW)

$\mathrm{L}=10^{12}, M=5\mathrm{x}10^{10}, SFR=10^{2}: \;\; R_{eff} \sim 600\ pc$ (ULIRG merger)

the same argument also suggests that L~10^{13} HYLIRGs must be AGN



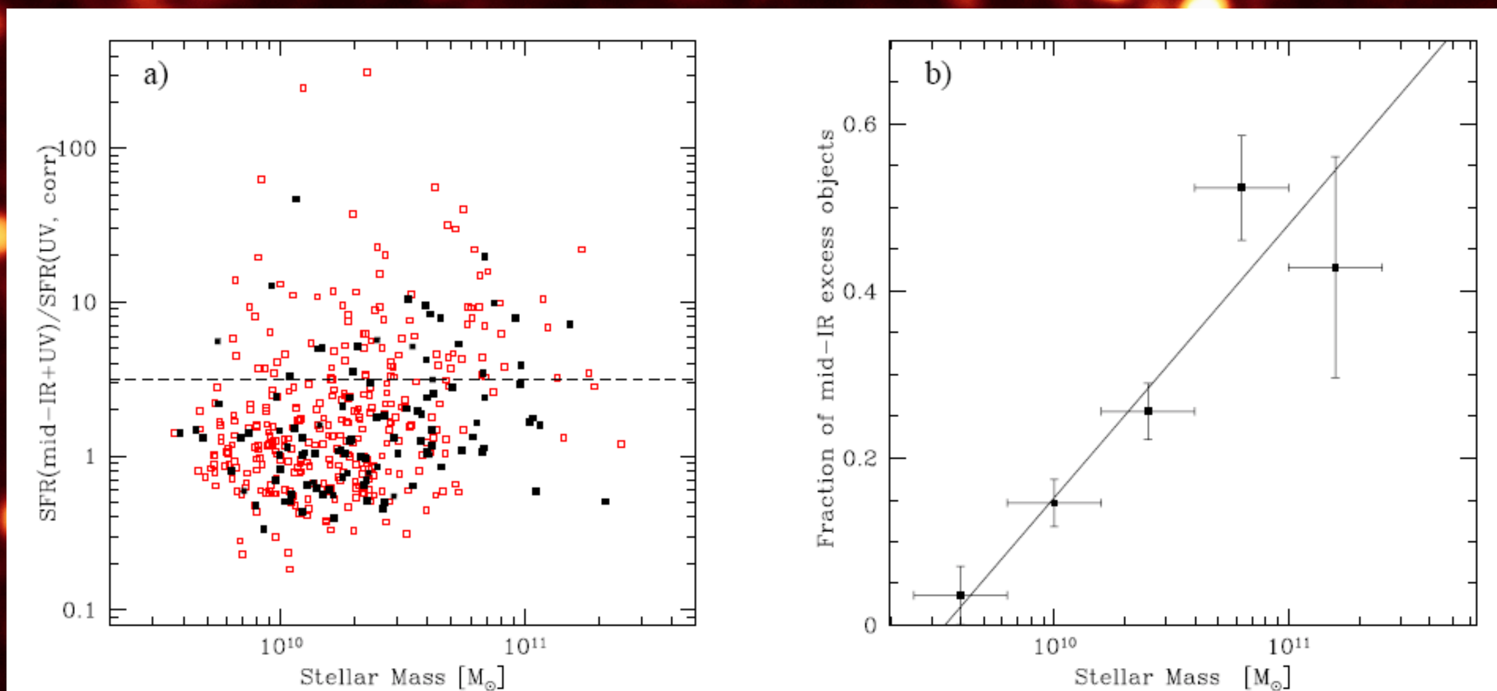
$z=2 \; M_{\max,10}=30, f_{0.1}=5: \;\; SFR_{\max} \sim 150\ \mathrm{M}_\odot\, yr^{-1}, \mathrm{L}_{\max} \sim 10^{12.2}\ \mathrm{L}_\odot(\, BzK)$

$\mathrm{L}=10^{13}, M=2x10^{11}, SFR=10^{3}: \;\; R_{eff} \sim 800\ pc$ (SMG merger)

$z>3 \; M_{\max,10}=5, f_{0.1}=5: \;\; SFR_{\max} \sim 10\ \mathrm{M}_\odot\, yr^{-1}, \mathrm{L}_{\max} \sim 10^{11}\ \mathrm{L}_\odot$ (LBG)

AGN contribution iin high-z ULIRGs

average AGN contribution to FIRB ~10-16% but what about massive end ?



Compton thick, dust obscured AGN contributing to L_{24} in most z~2 massive galaxies?

Lutz et al. 2005, Treister et al.2006, Papovich et al. 2007, Daddi et al. 2007b, Donley et al. 2008

the great leap with Spitzer

- **Spitzer has made ground-breaking contributions to the understanding of the cosmic evolution of star formation in galaxies and the relation between AGN and star formation**