Close Major-Merger Pairs Since z=1 ---
Evolution of Merger Rate & SFR Enhancement

Cong K. Xu
NAOC

Collaborators:

D. Domingue, C. Cao, Y.-W. Cheng, P. Zuo, Y.H. Zhao,
U. Lisenfeld, M. Yun, N. Lu, J. Huang, Y. Gao, D. Li, J. Mazzarellar,
R. Cutri, W.-H. Sun, J. Surace, N. Scoville, P. Capak, N. Drory,
D. Shupe, M. Bethermin, T. Jarrett,
Herschel Multi-tiered Extragalactic Survey (HerMES) team,
PACS Evolutionary Probe (PEP) team

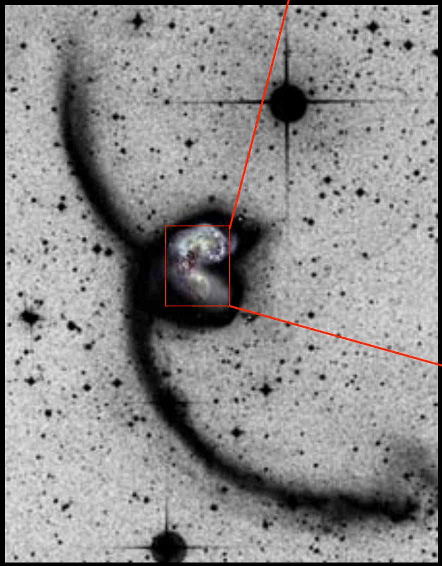
Outline

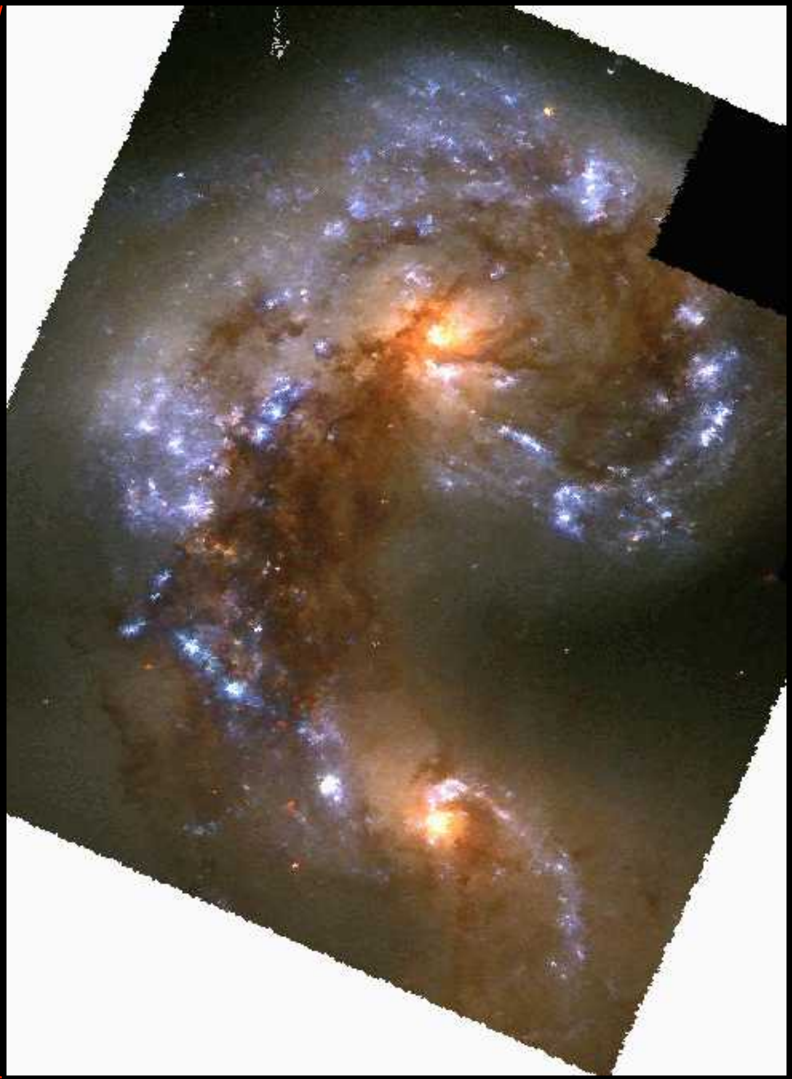
1. What are major mergers? Why are they interesting?
2. Select mergers by identifying close major-merger pairs: pros and cons
3. Our two pair samples:
   1) KPAIR – a local ($z<0.1$) sample of K-band selected pairs
   2) CPAIR – a mid-z ($0.2 < z < 1$) pair sample selected in COSMOS field
4. Merger rate and its cosmic evolution
5. Merger induced star formation and its cosmic evolution

Mergers: Interacting galaxies undergoing merging process.

Major mergers: mergers of nearly equal mass galaxies (mass ratio<3).

Minor mergers: mergers of a massive galaxy ("master") and a low mass galaxy ("satellite)".



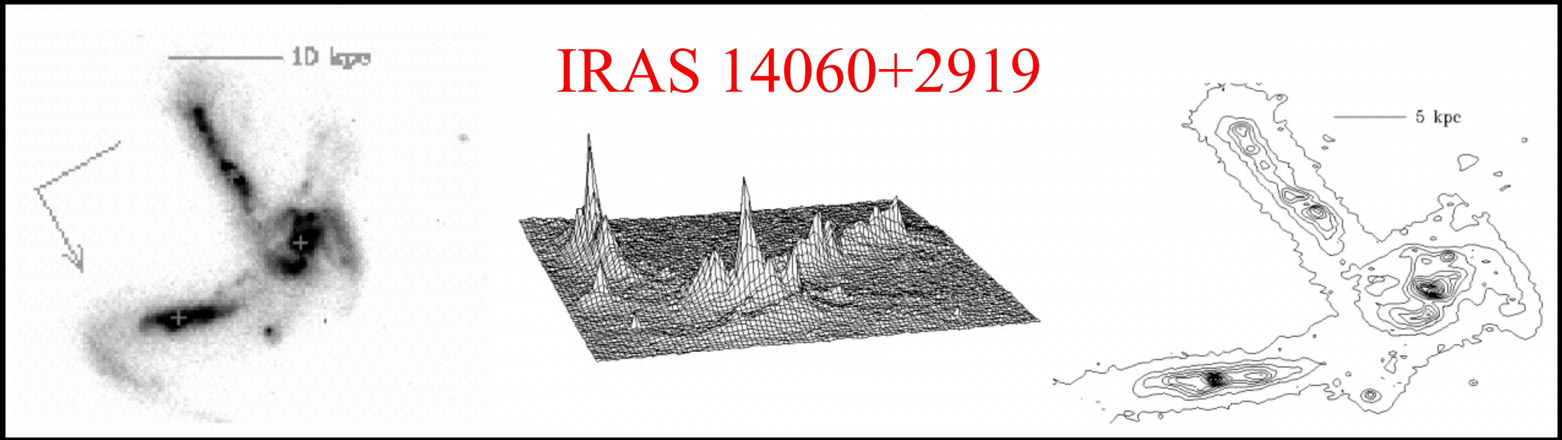


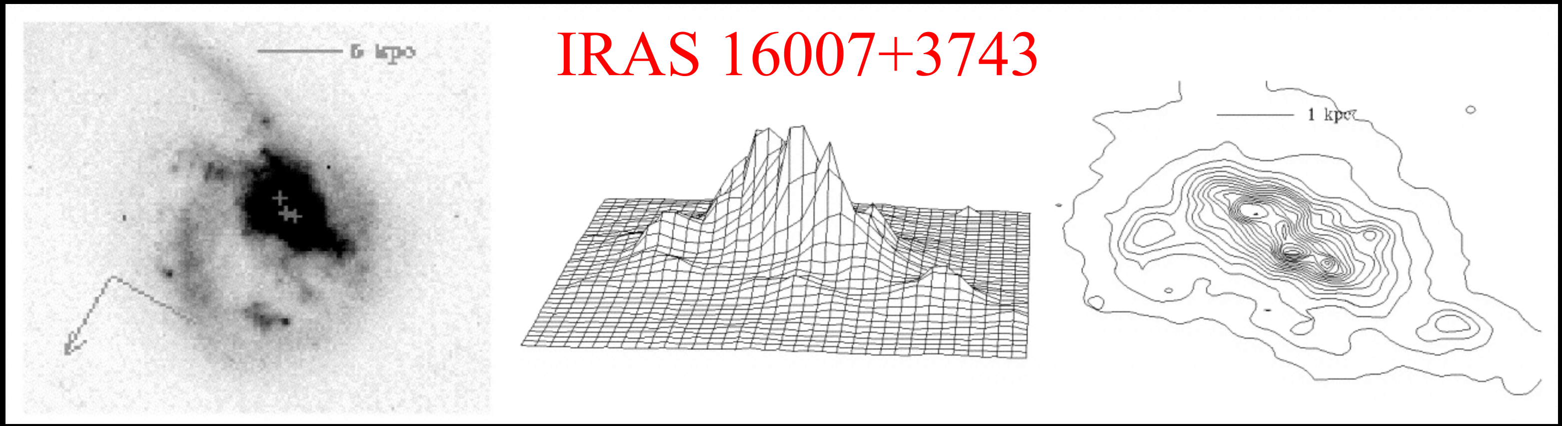
Antennae Galaxies (HST image)

Major Mergers & ULIRGS

Ultra-Luminous Infrared Galaxies (ULIRGs):

- The most luminous (bolometric) galaxies in the local universe.
- $L_{IR} > 10^{12}\ L_{\odot}$ (~ 100 times brighter than the Milky Way).
- > 90% are Major Mergers!

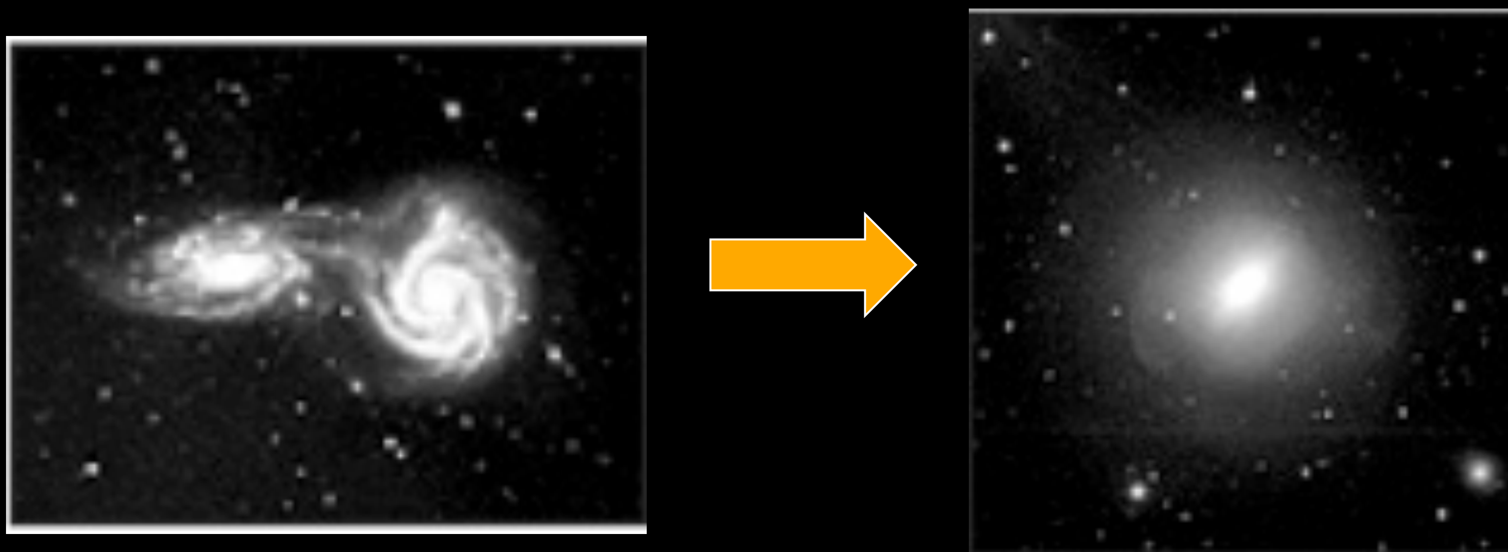




Cui et al. 2001, AJ 122, 63

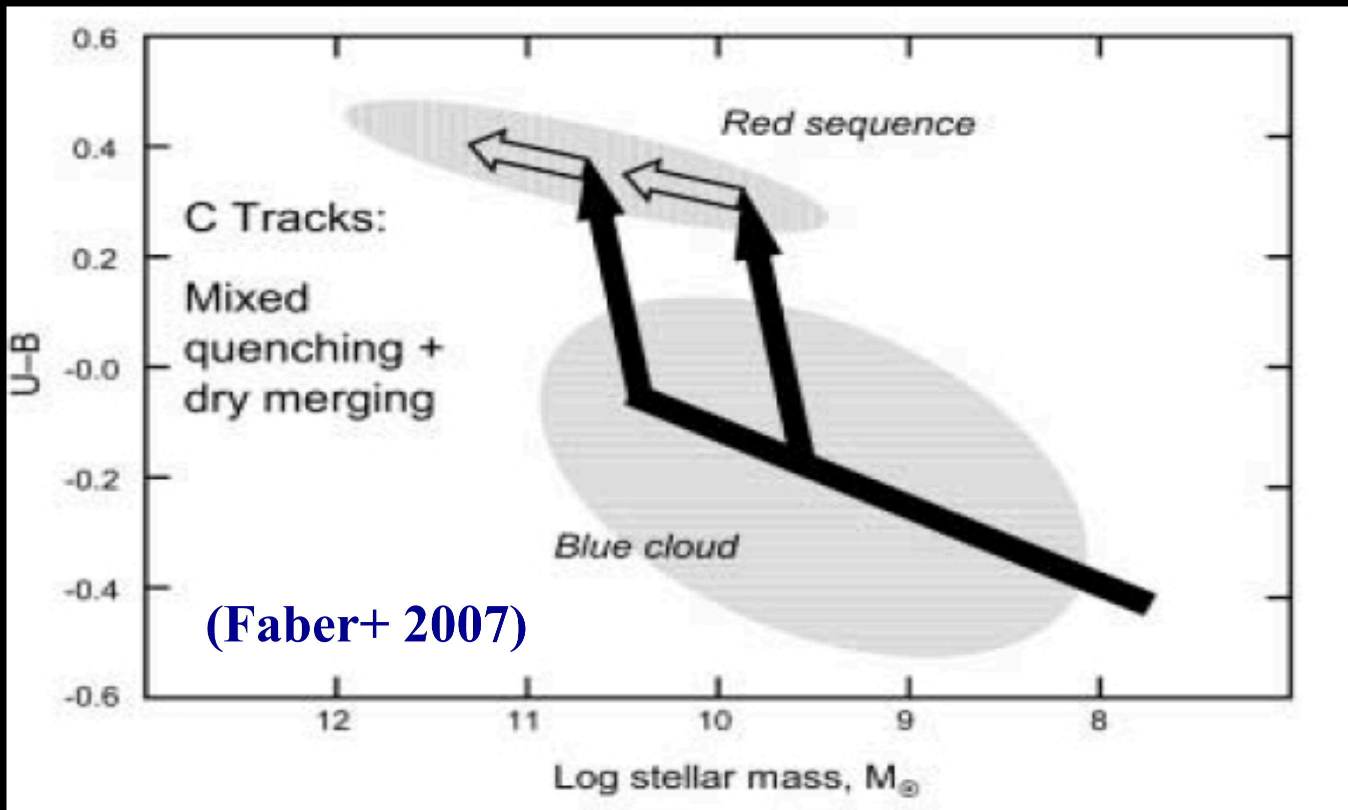
Major Mergers and Galaxy Evolution

- Structure growth: smaller systems merge to form larger systems.



Major Mergers and Galaxy Evolution

- Structure growth: smaller systems merge to form larger systems.
- Formation of Red Sequence (particularly for massive E galaxies):



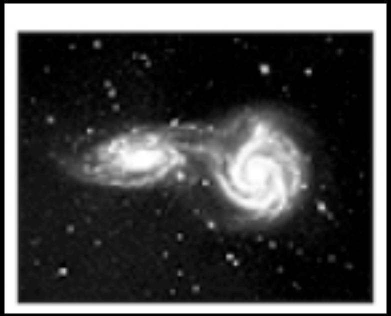
Merger Selection

Two "classical" selection methods:

1. Galaxy pairs: NGC5426/5427, NGC4038/4039 (Antennae)
2. Peculiar galaxies: NGC7252, NGC3670

Merging Sequence:

NGC5426/7



Antennae

NGC7252

NGC3670

Our Pair Samples

1. KPAIR – A local sample of close major-merger pairs:
   - 170 major-merger pairs selected in K-band (2MASS).
   - 85% redshift completeness (SDSS + 60 new).
   - $z < 0.1$; median $z = 0.04$.

2. CPAIR – A sample of close major-merger pairs of $0.2<z<1$
   - 300+ pairs selected in the COSMOS field.
   - Mass selected ($M_{star} \geq M_{limit}$), volume limited sample.
   - Photo-z, 100% complete.

Why Close Major-Merger Pairs:

- Advantages over other selections (e.g. morphology, wide pairs, etc):

1) selection effects are insensitive to z (good for evolution studies).

(In contrast, the morphological selection suffers from cosmic dimming, degradation of spatial resolution, morphological k-correction, and contamination by minor-mergers.)

2) Better defined merging time scale (good for merger rate studies).

(Minor mergers, wide pairs, and morphological selected mergers all have rather uncertain time scales.)

But:

- Pair selections miss final stage mergers (two galaxies too close to be identified as binaries). Therefore pair samples are incomplete representations of the merger population. (This is OK for merger rate calculations because of the division by the time scale.)
- Also, pair samples are not suitable for studies of extreme starbursts (and merger induced QSOs) because most of them are in the final stage mergers.

Selection of KPAIR (Local Sample)

Parent sample:

- 77451 galaxies with $K_s \leq 13.5$ (2MASS)
- redshifts: 86% (mostly from SDSS)
- sky coverage: ~5800 deg^2

Pair Selection Criteria:

1. $5\ h^{-1}$ kpc < r_p < $20\ h^{-1}$ kpc
2. $\delta K_s < 1$ mag (mass ratio < 2.5)
3. the primary has $K_s \leq 12.5$
4. velocity difference between 2 galaxies: $\delta v < 500$ km/sec

close pairs

major mergers

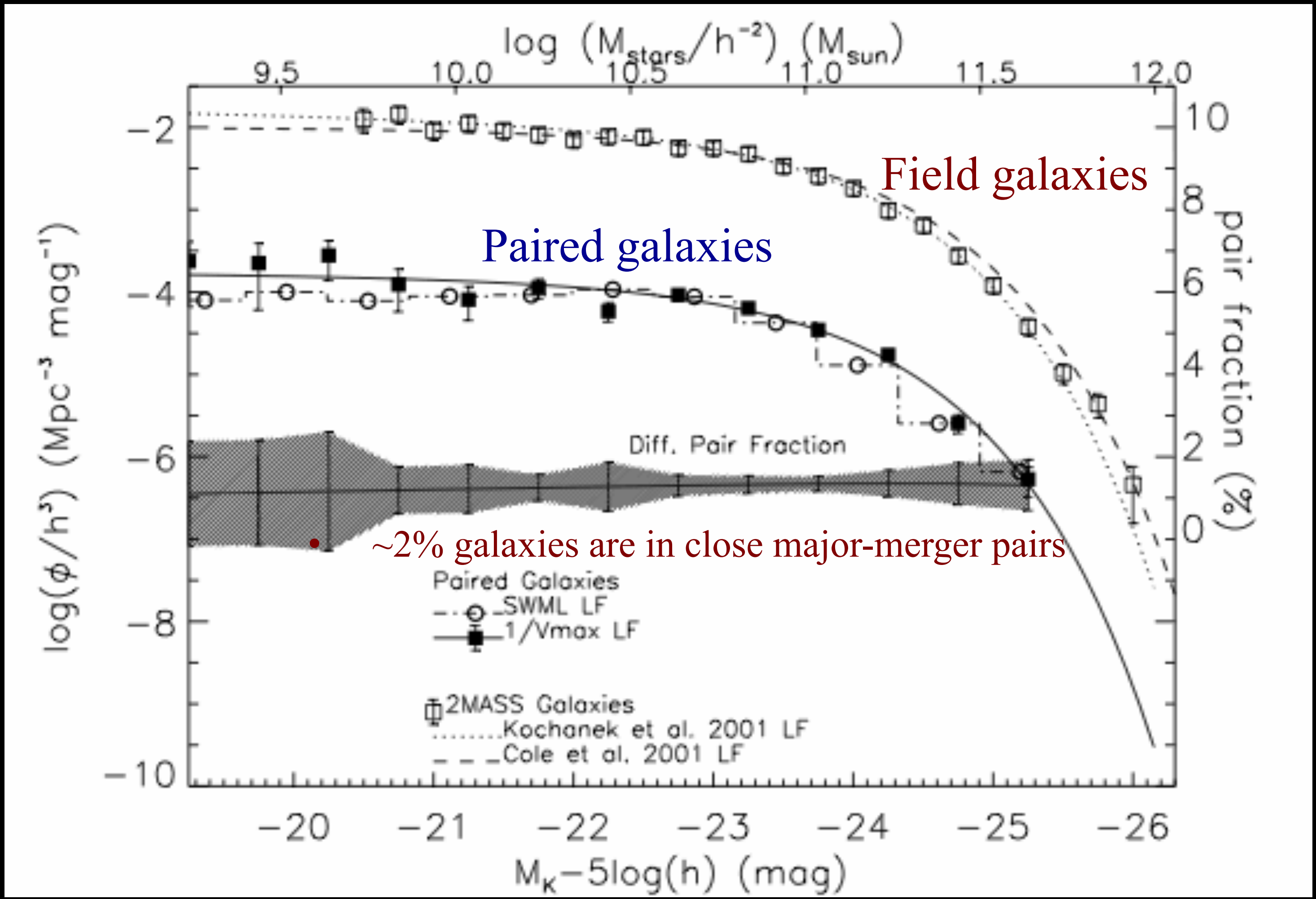
no "missing secondary" bias

reject unphysical false pairs

Total 170 pairs in KPAIR sample

Examples of KPAIRs

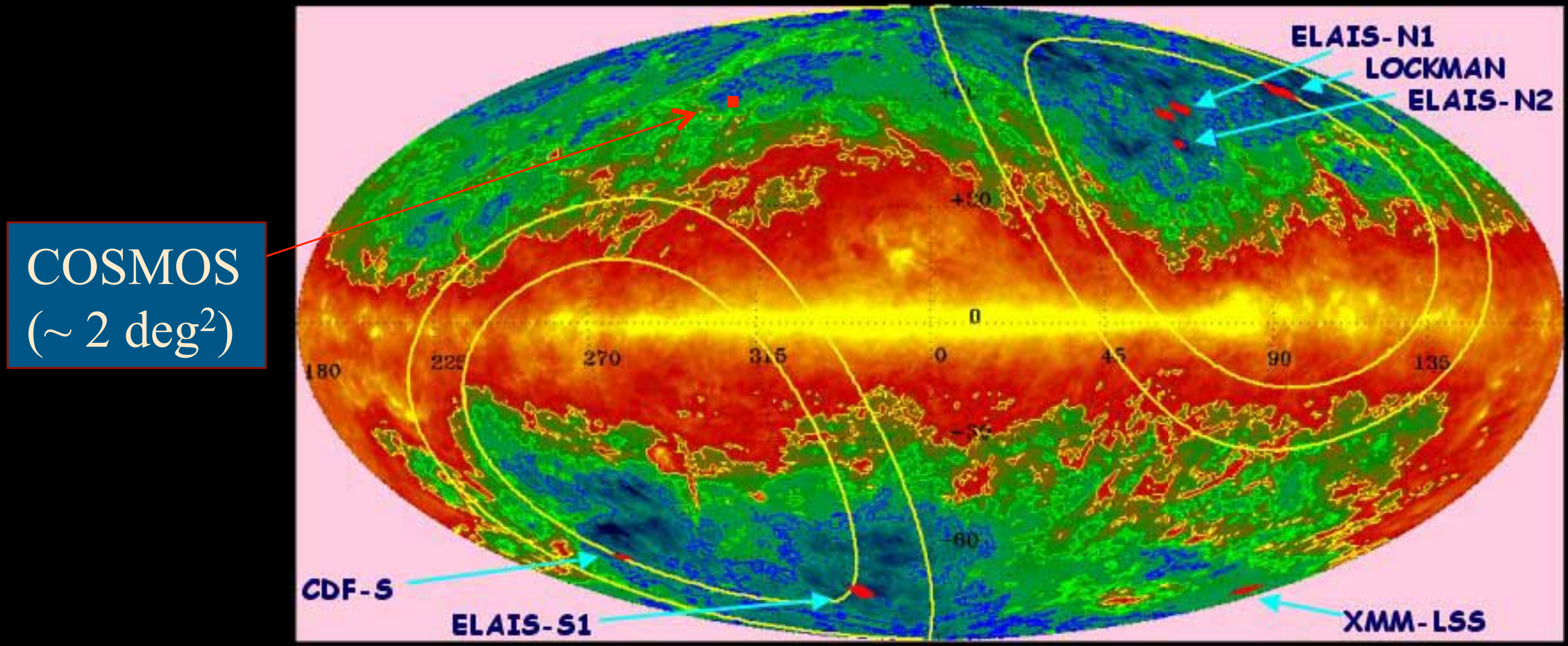
K-band Luminosity Function and Mass Function



(Domingue, Xu, Jarrett & Cheng, 2009)

Selection of CPAIR ($0.2 \le z_{ph} \le 1$)

- Selected in COSMOS field (~2 deg^2; largest HST survey).



- Why in COSMOS?

1. Best photo-z (from >30 bands): $\sigma_{\delta z}/(1+z)=0.7\%$
2. Extensive ancillary data: HST, Herschel, Spitzer, Chandra …

Strengths & limitations of photo-z selected pair samples (compared to spect-z selected pair samples)

Strengths:

- much larger sample size (~10x of zCOSMOS sample of close pairs);
- enable studies of variations between subsamples (diff in M, z, type)
- higher completeness (in particular compared to spect-z samples based on sparsely sampled redshift surveys).

Limitations:

- vulnerable to contaminations of projected unphysical pairs;
- therefore not good for studies of wide pairs and minor mergers;

(for our close major-merger pairs, the contamination is ~10%).

Selection of CPAIR Sample

Parent sample:

- 35,234 galaxies with $M_{star} > M_{limit}$ (Drory+ 2009).
- $0.2 < z_{ph} < 1.0$

Pair Selection Criteria:

1. $5\ h^{-1}$ kpc $< r_p < 20\ h^{-1}$ kpc
2. Mass ratio < 2.5
3. The primary has $M_{star} > 2.5 \times M_{limit}$
4. photo-z difference between 2 galaxies: $\delta z_{ph}/(1+z_{ph}) < 0.03$

very similar to those for KPAIR

exclude most spurious pairs whereas keep the sample reasonably complete

Completeness and Reliability of CPAIR sample

Incompleteness:

- missing very close pairs (sep < 2"): $Incom_{close} = 1$ --- 20 %
- missing pairs due to photo-z errors (error of $z/(1+z) > 0.03$): $Incom_{phz} \sim 20\%$

Completeness:

$$C = (1-Incom_{close}) \times (1-Incom_{phz}) \sim 70\ \%$$

spurious pairs fraction

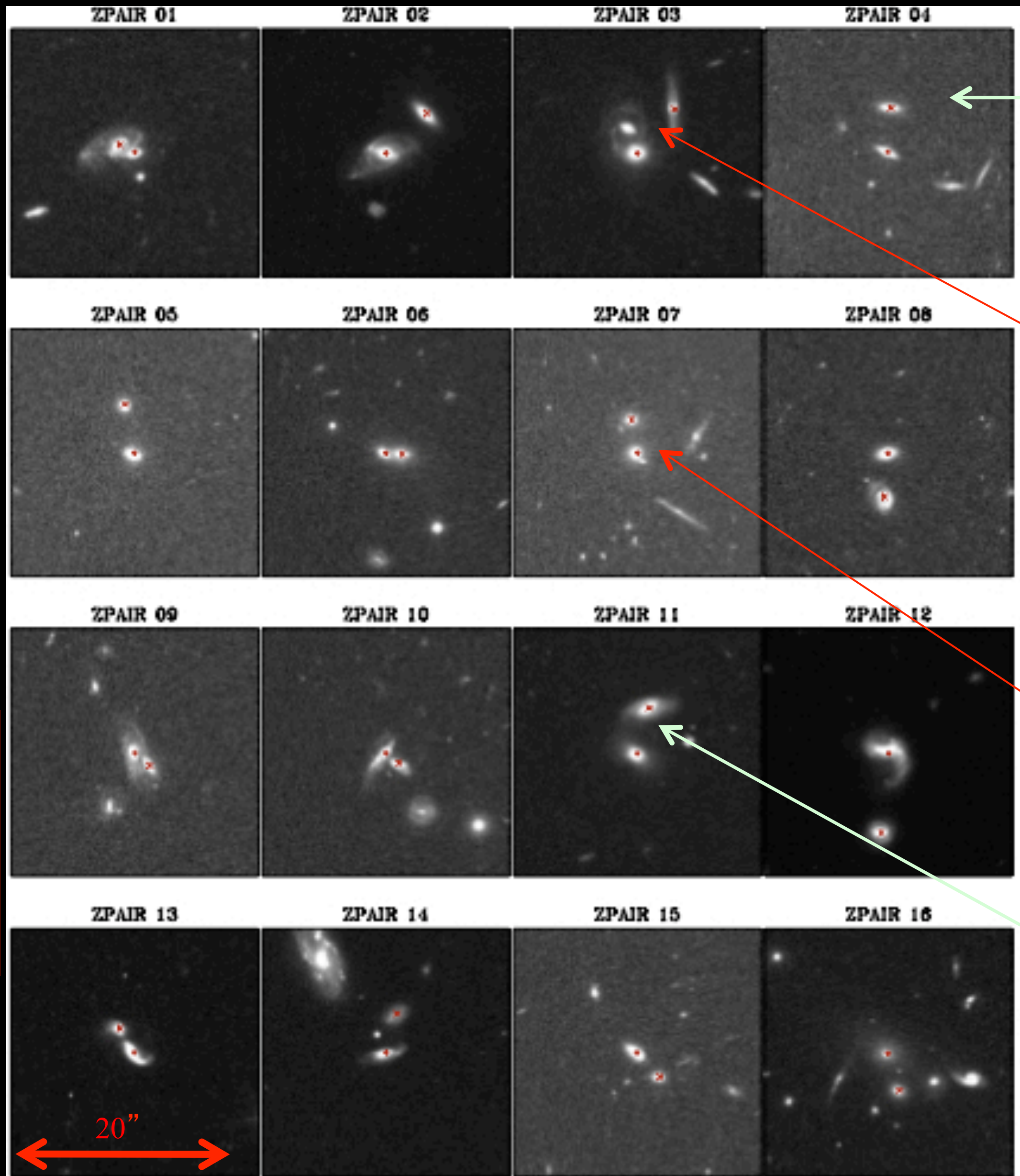
- projected unphysical pairs: $f_{spur,proj} \sim 10\ \%$
- physical pairs with $\delta v > 500$ km/sec: $f_{\delta v > 500} \sim 10\ \%$

Reliability:

$$R = (1-f_{spur,proj}) \times (1-f_{\delta v > 500}) \sim 80\ \%$$

Pairs with photo-z's & spect-z's

HST Images:



missed pairs: ~15% (~2/14)

spurious pairs: ~15% (~2/14)

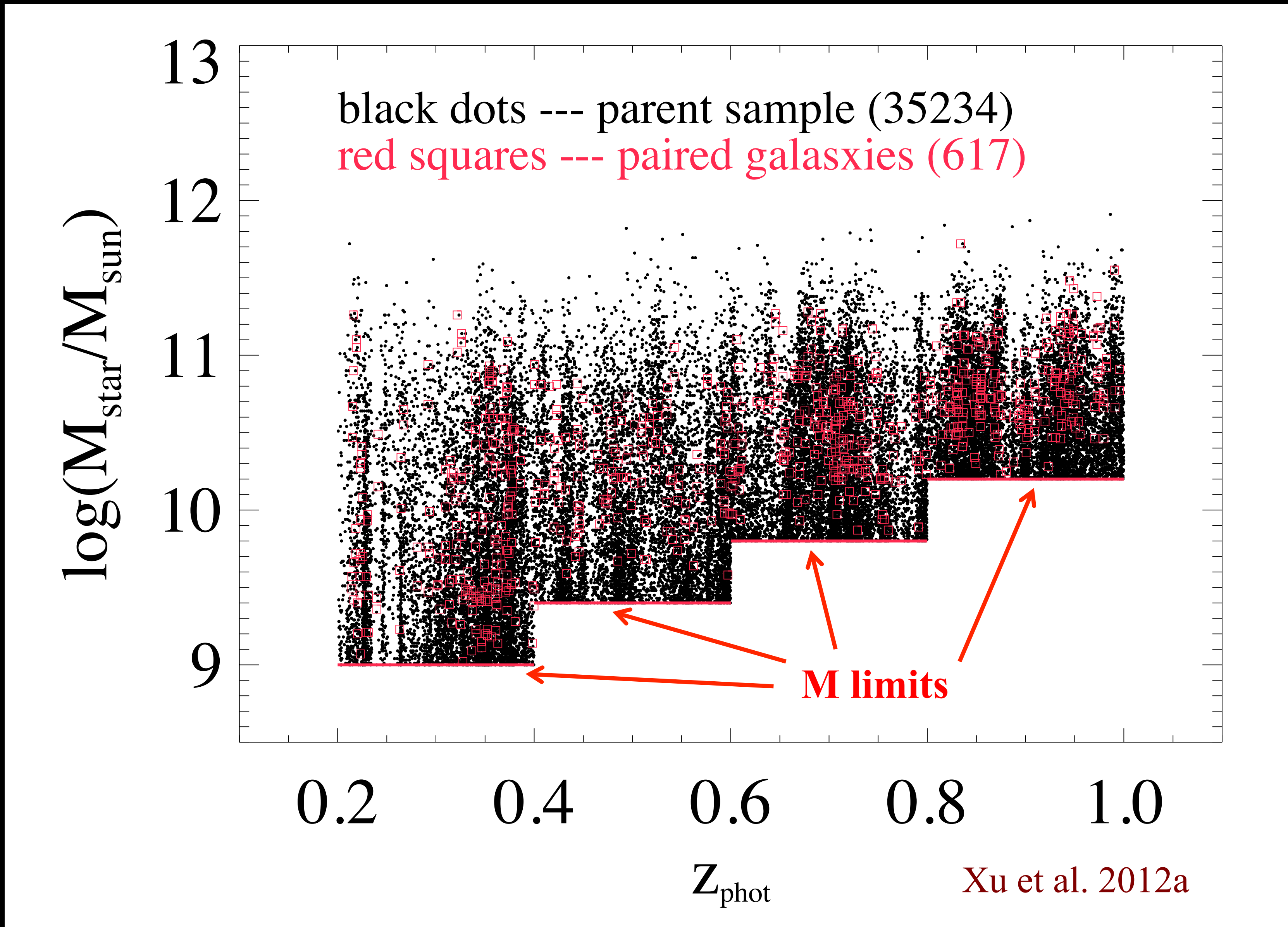
A spurious photo-z pair with $\delta v > 500$ km/sec ($\delta v = 817$ km/sec)

missed by CPAIR sample. One galaxy has a catastrophic photo-z error due to blending.

missed by CPAIR sample: $\delta z/(1+z_{ph}) = 0.0307$ (the criterion is $\delta z/(1+z_{ph}) < 0.03$).

Another spurious photo-z pair ($\delta v = 6318$ km/sec)

COSMOS Paired Galaxies (CPAIR) Sample (including triplets)

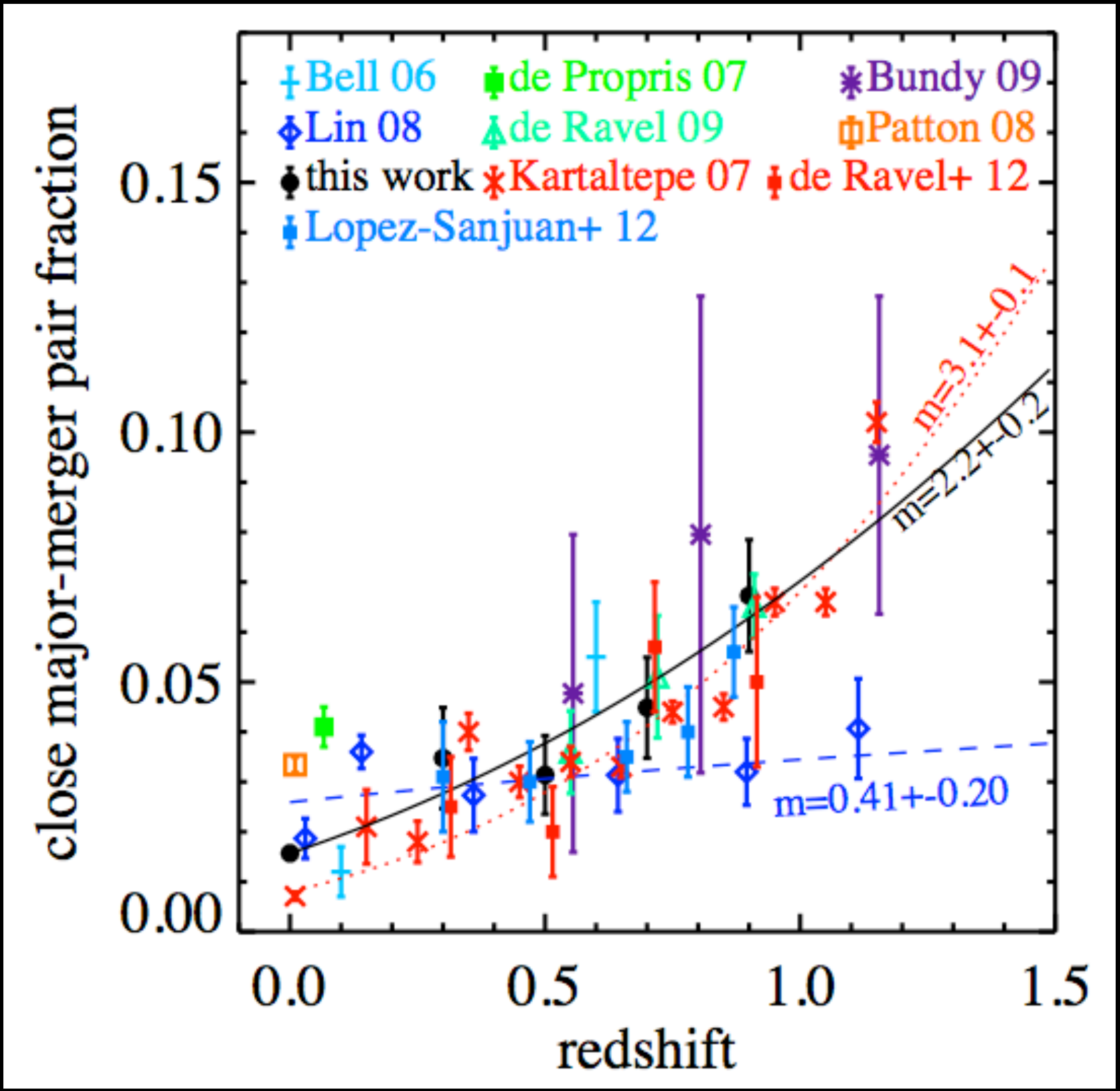


Results on Merger Rate Evolution

pair fraction evol

- $f_{pair} \propto (1+z)^m$
  $m = 2.2 \pm 0.2$

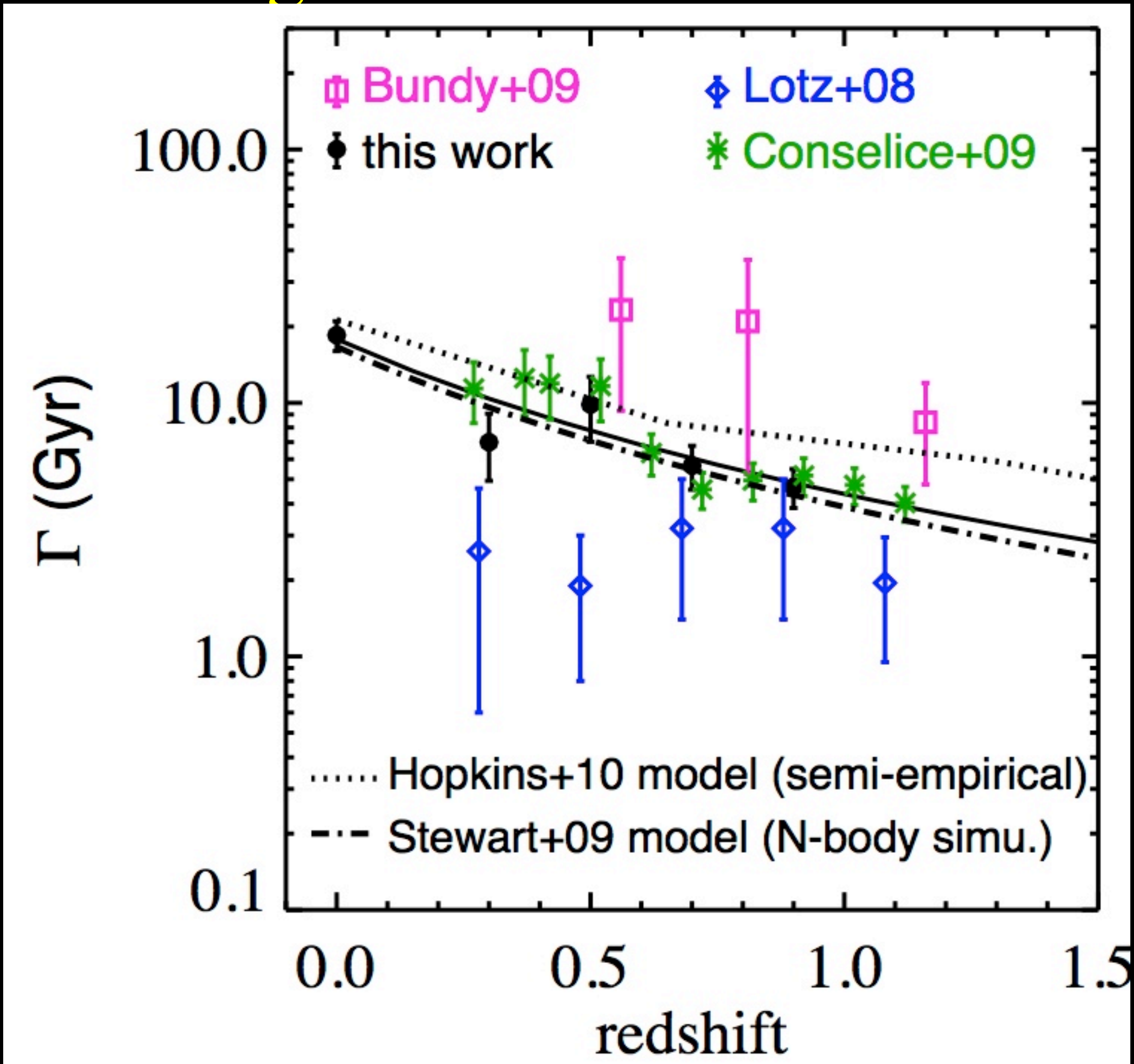
- Intermediate between the strong evolution (Kartaltepe 07) and weak evol (Lin et al. 08).



Xu et al. 2012a

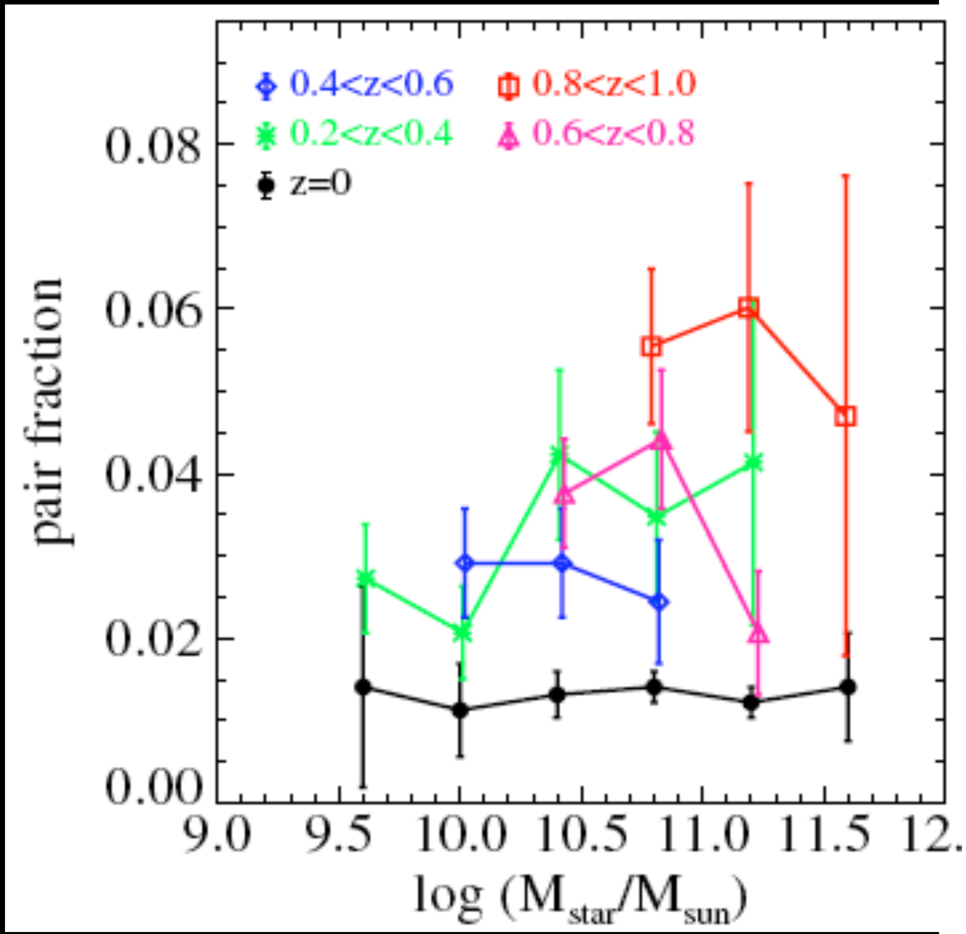
Merger Rate Evolution

- diff. merger rate:
  $R_{mg} = f_{pair}/T_{mg}$
- merger time scale
  $T_{mg} \sim 0.3$ Gyr
- $\Gamma = 1/R_{mg}$

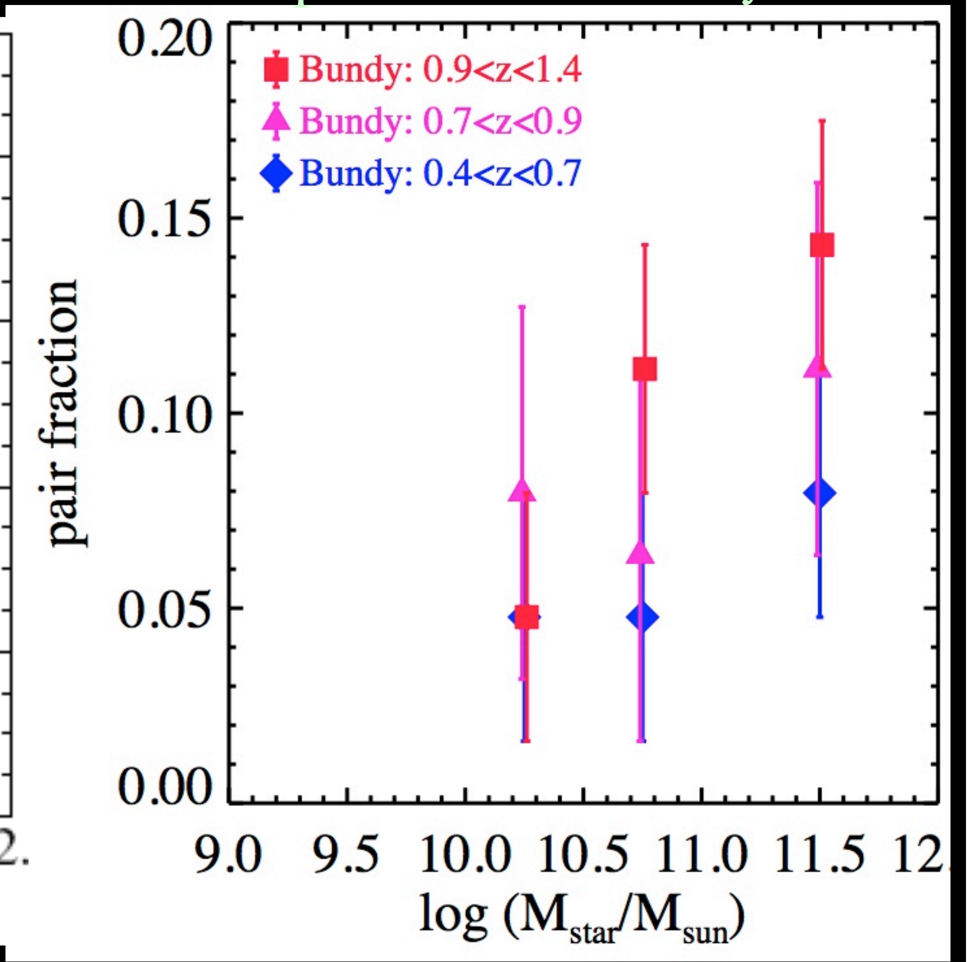


Results:
- very good agreements with simulations;
- good agreements with morphological selected mergers (Consellice+09);
- since z=1, every galaxy has undergone 1 ± 0.5 major mergers.

Mass dependent pair fractions



Comparison with Bundy+09



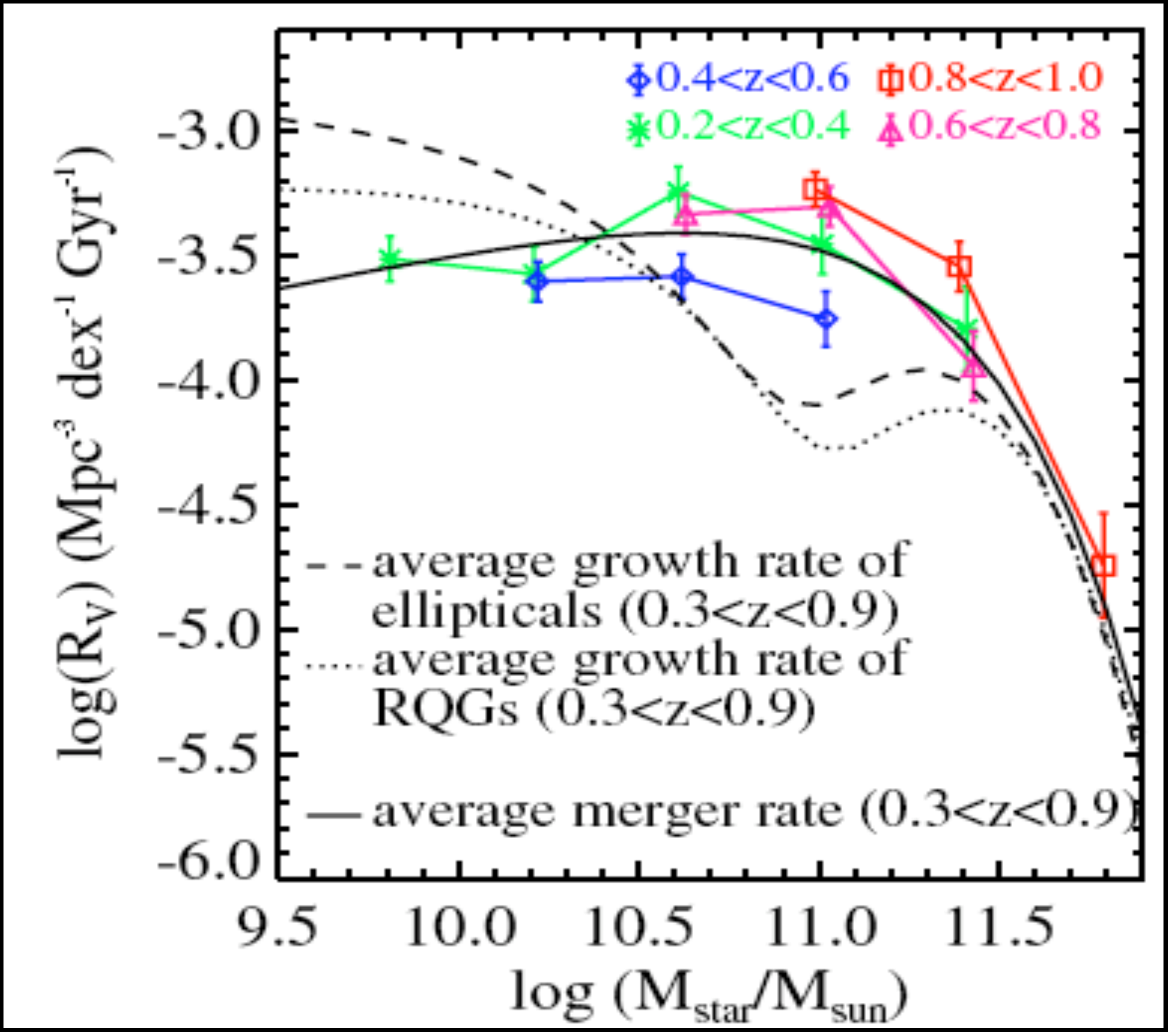
- no mass dependence (contradicting Bundy et al. 2009)

Major Mergers vs. E and Red Galaxies Formation

Our results:

• Massive E & R: major mergers can fully account for the formation.

• Low mass E & R: major mergers are not the major contributors.

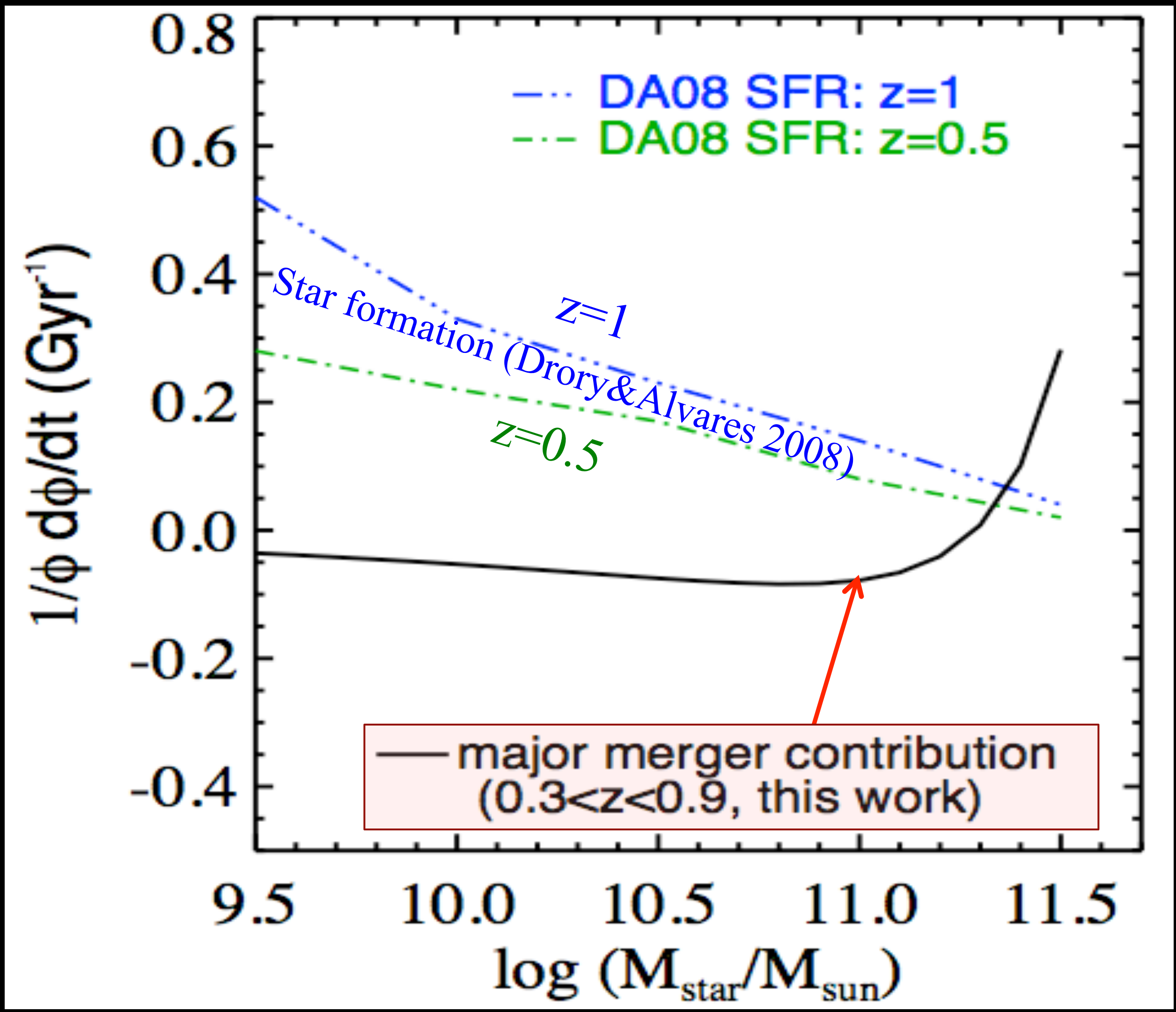


Impacts of Major Mergers to Galaxy Assembly Since z =1

- fractional change rate of galaxy stellar mass function (φ):

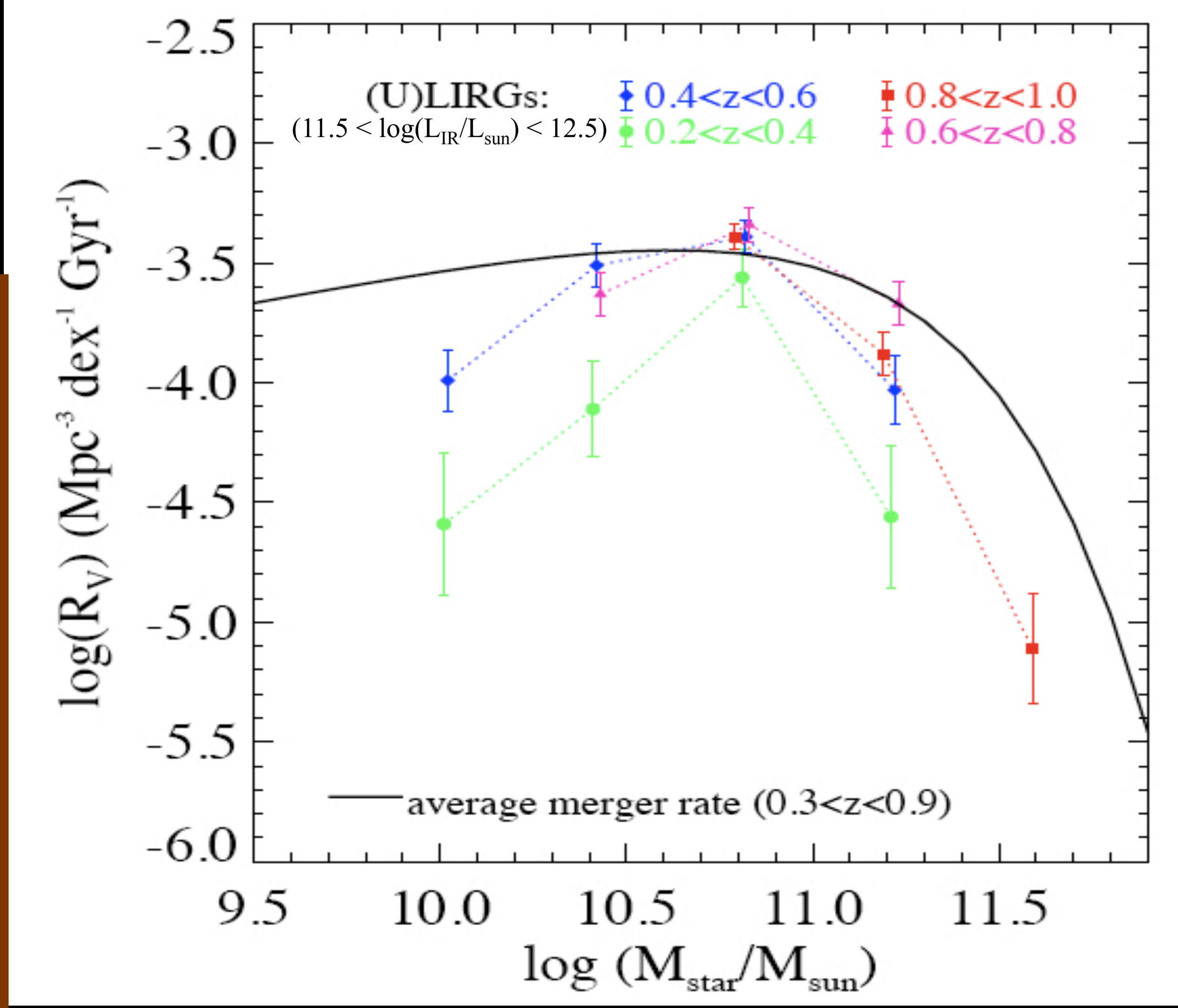
$$\varphi = 1/\varphi\, d\varphi/dt$$

Our result shows:
- dominate assembly of most massive galaxies
- negligible for less massive galaxies.



Major Mergers & (U)LIRGs

(U)LIRG data:
Kartaltepe+ 2010,
S-COSMOS
(MIPS survey,
Sanders+ 2007)

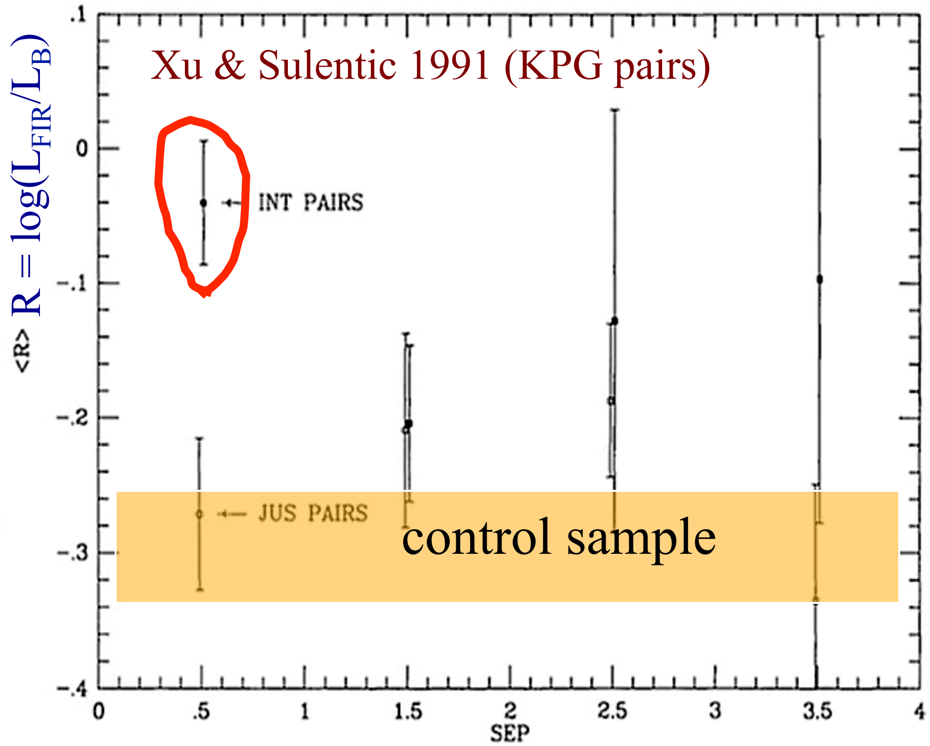


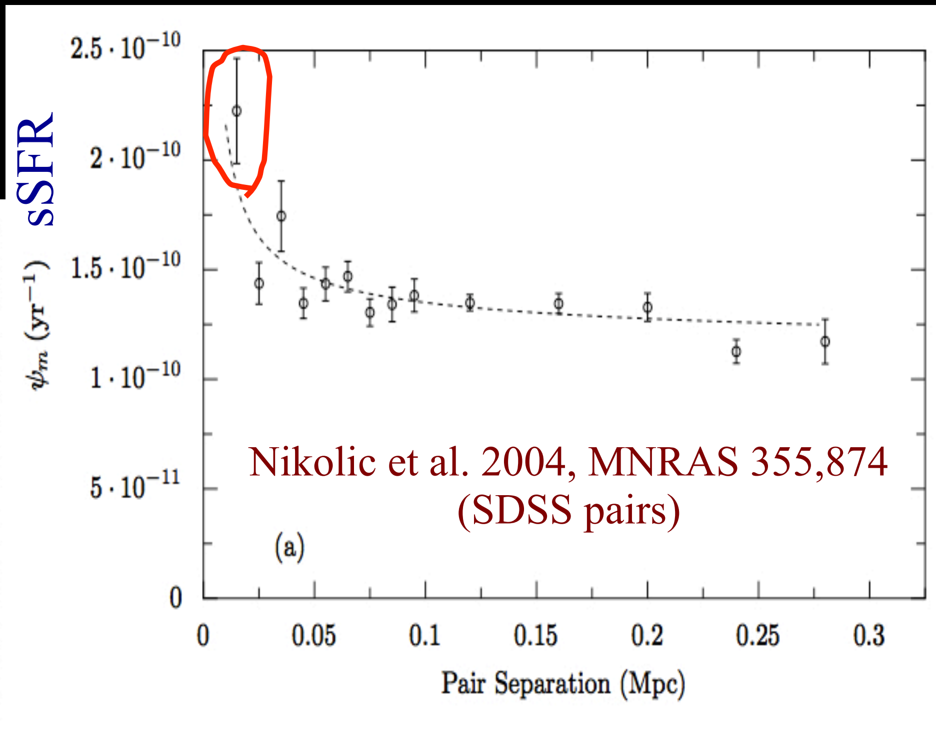
Results:

- Mass distributions of (U)LIRG rates are log-normal functions.
- For **L*** galaxies the major-merger rate and (U)LIRG rate are comparable (1 (U)LIRG per merger??).
- most low mass and very massive major mergers do not become (U)LIRGs.

SFR enhancement in close pairs

- Early studies using IRAS data: Kennicutt et al 1987, Telesco et al. 1988, Xu & Sulentic 1991: close pairs show significant SFR enhancement.





SEP = r (kpc) / size-of-primary (kpc)

Recent results on SFR enhancement:

- Strong enhancement for sep < 20 kpc/h
- Enhancement drops sharply with sep.

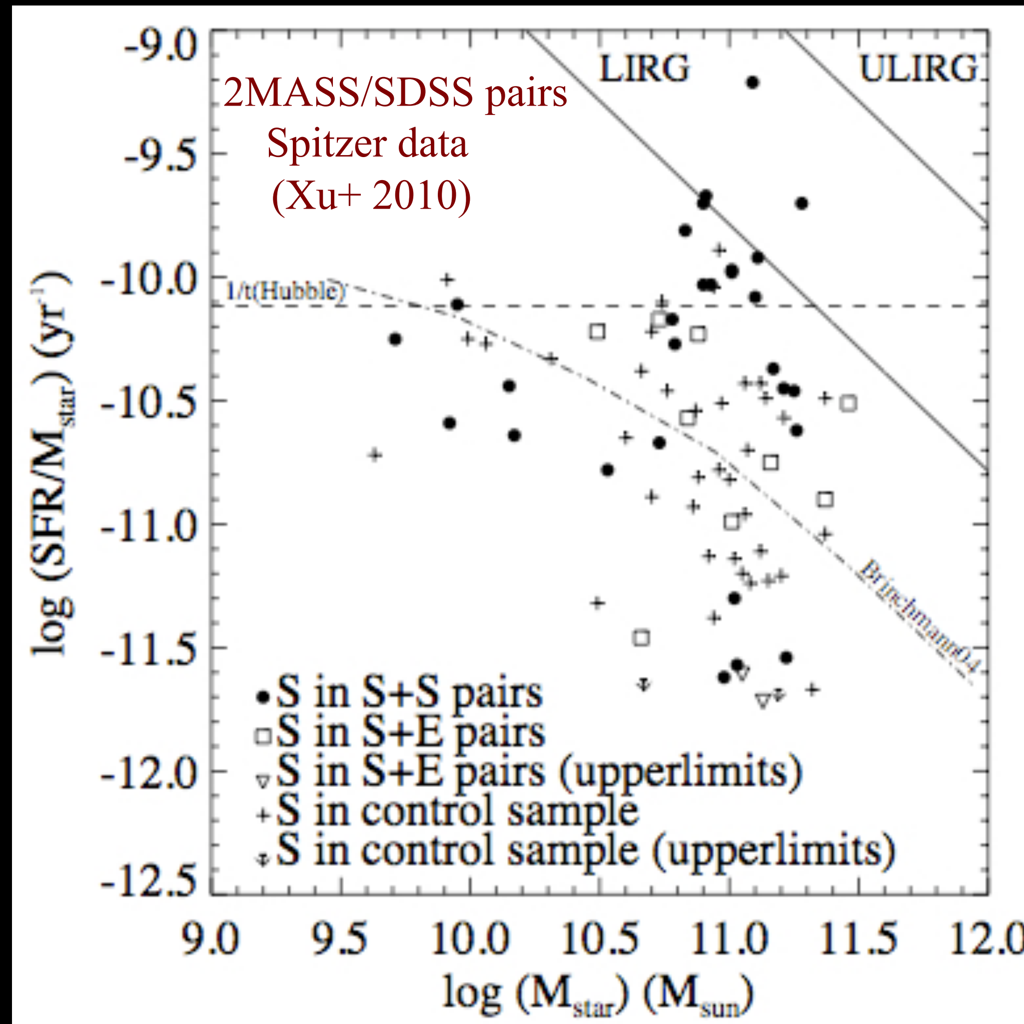
Do all SFGs in close (r < 20 h^{-1} kpc) pairs have enhanced sSFR?

Our Spitzer observations of galaxies in KPAIR:

- Sample: 27 S+S & S+E pairs
- Non-AGN Spirals: 29
- Mapping in 7 bands (3.6, 4.5, 5.8, 8, 24, 70, 160 μm).

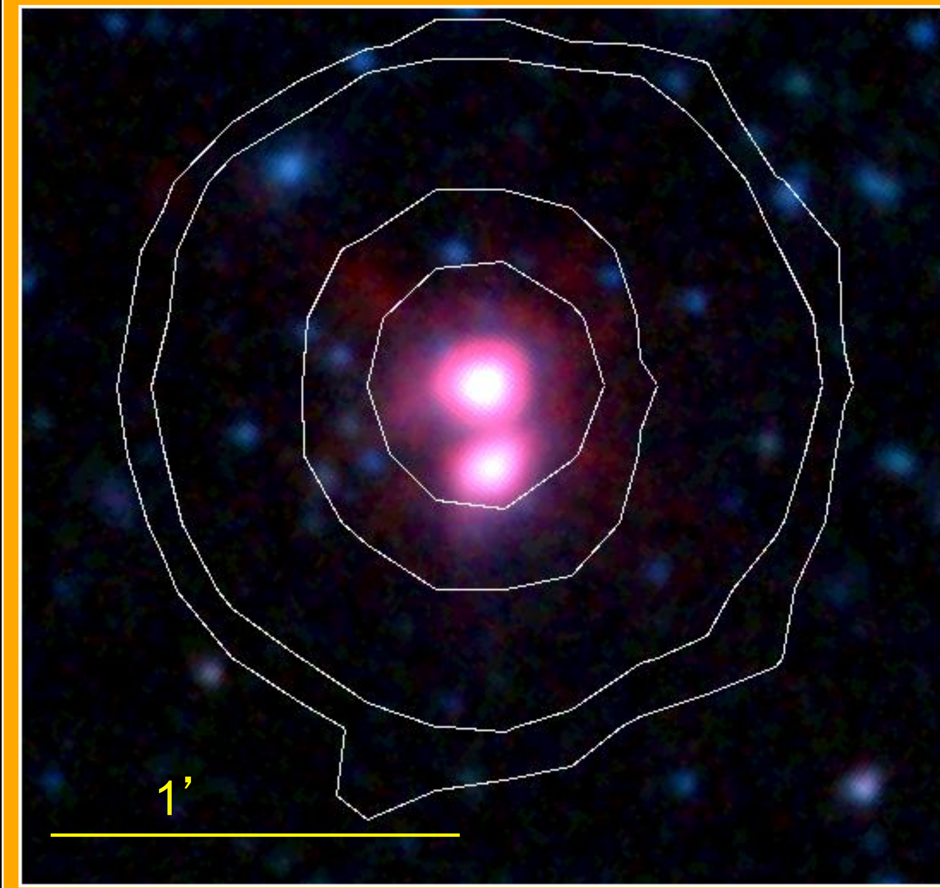
- Control galaxies: one-to-one mass matched to paired galaxies.

The answer is NO!

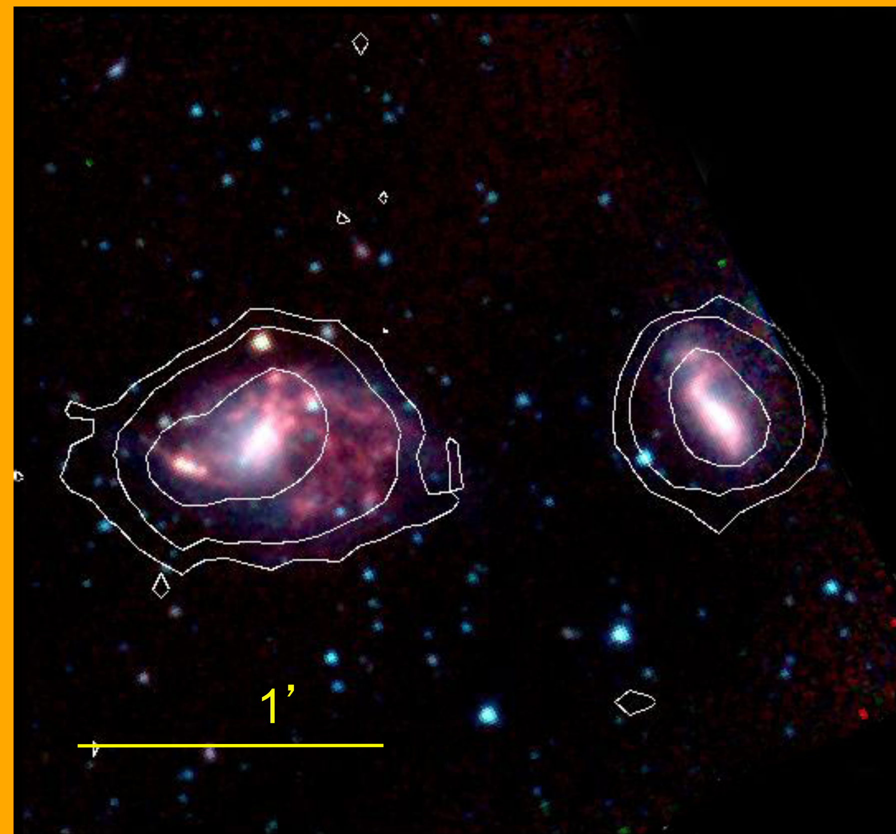


Examples of S+S pairs

IRAC image +70μm contours



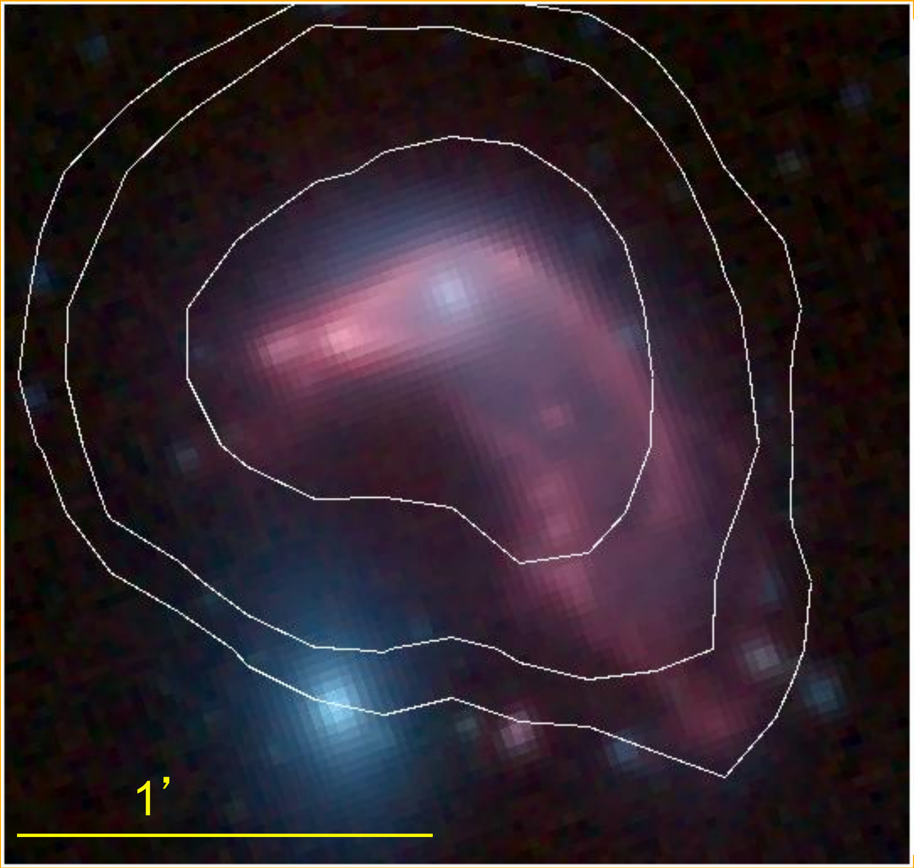
KPAIR J1704+3448 (high mass)

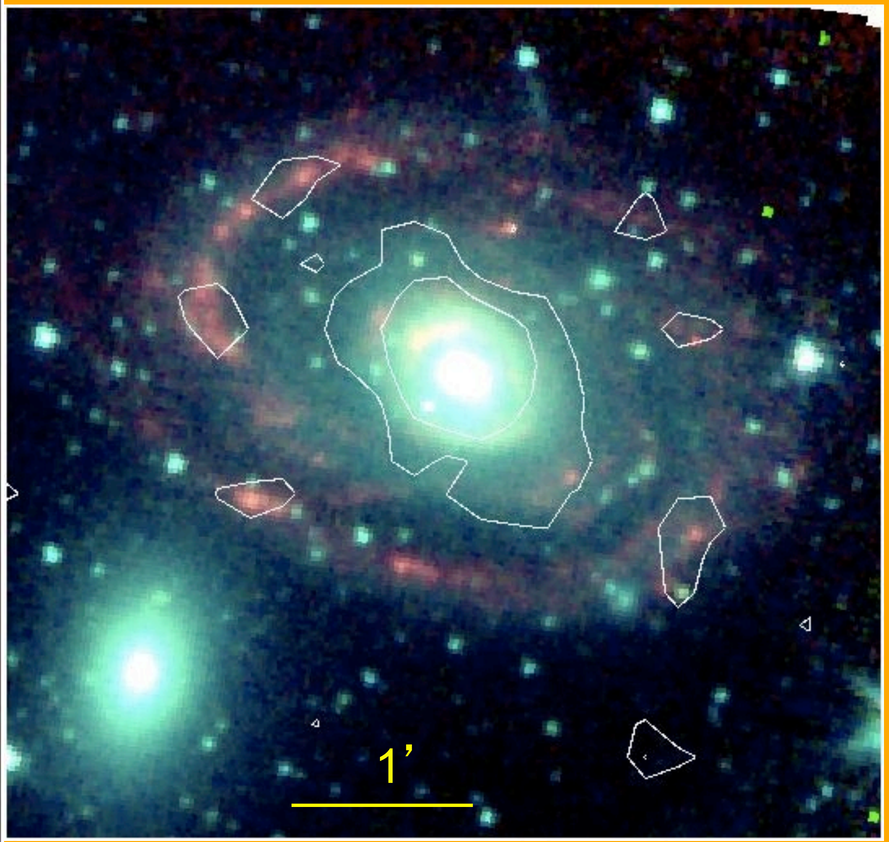


KPAIR J0949+0037 (low mass)

Examples of S+E Pairs

IRAC image +70μm contours





KPAIR J0937+0245 (Arp 142)

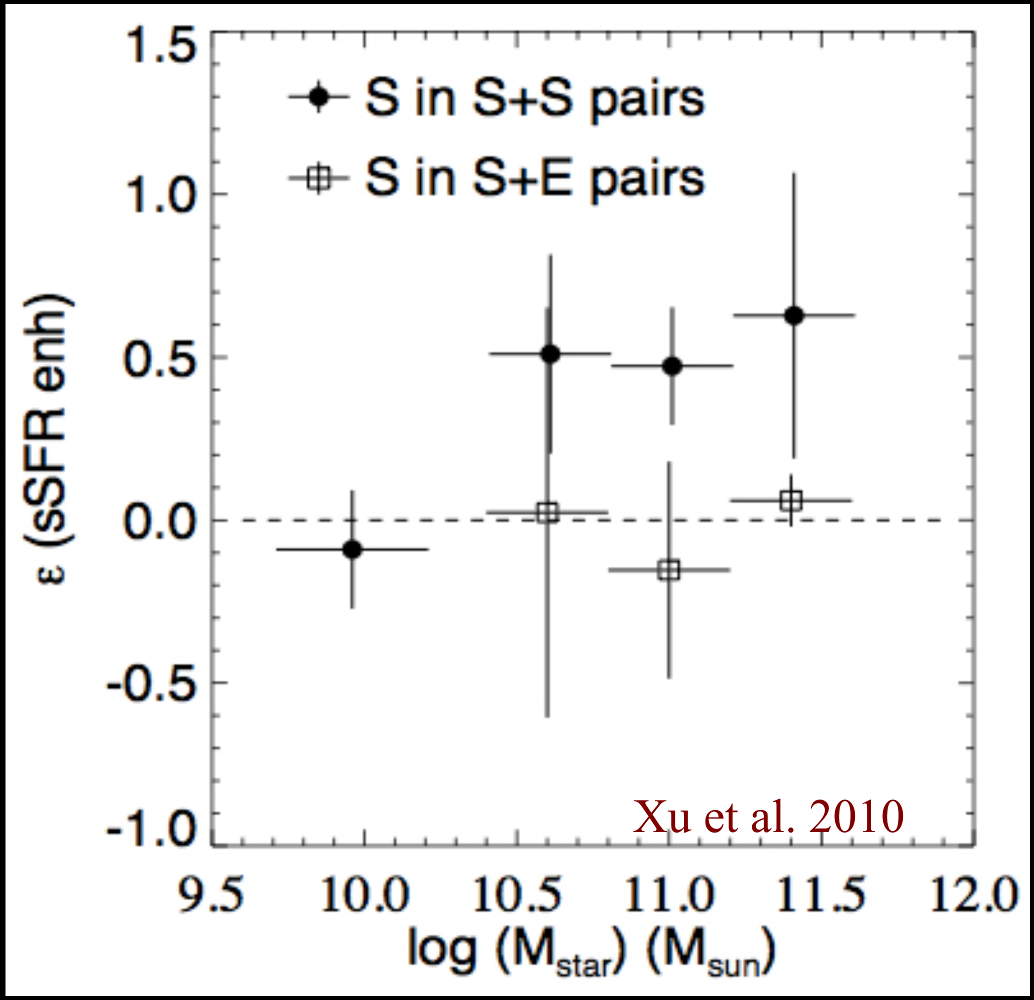
KPAIR J2047+0019

Spitzer Observations -- Statistical Results

$$\varepsilon = \log(SFR/M)_{PAIR} - \log(SFR/M)_{control}$$

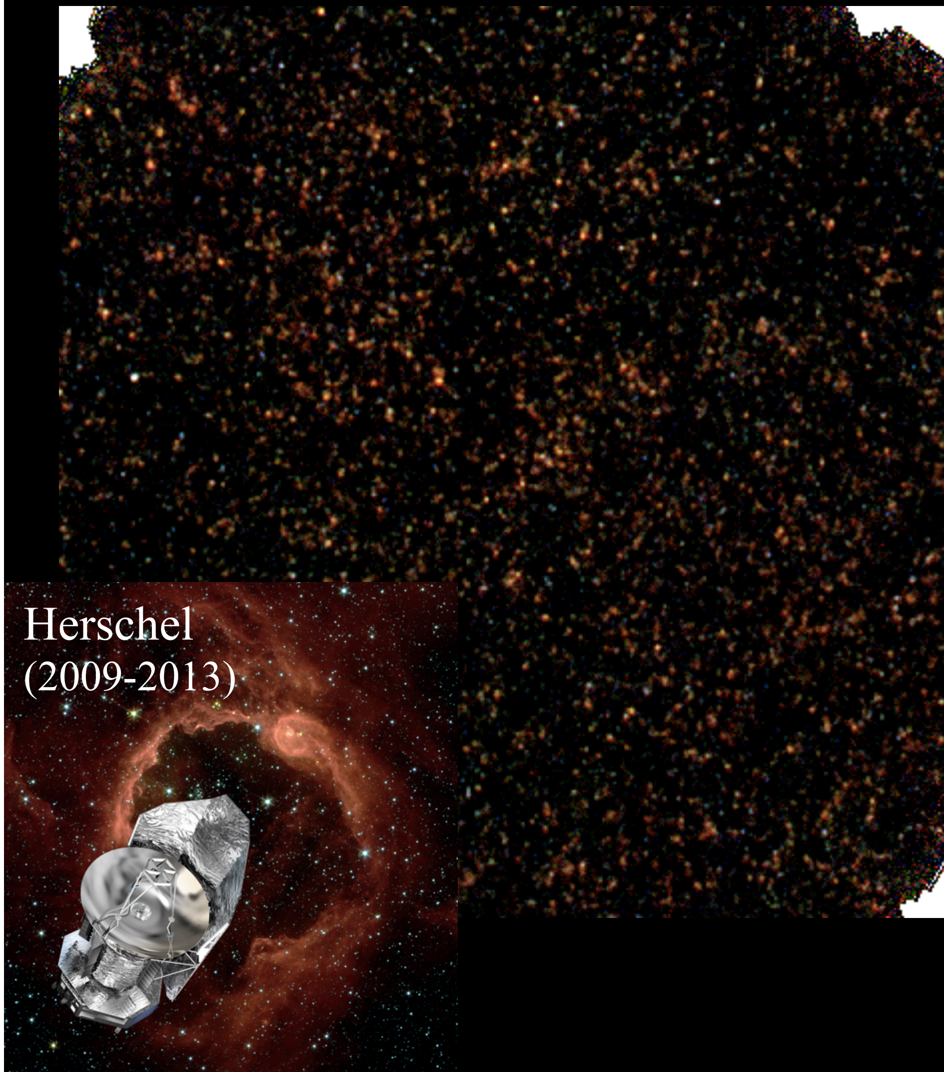
SFR enhancement (ε):

- massive S in SS pairs: enhanced!
- low mass S in SS pairs: No!
- S in S+E pairs: No!

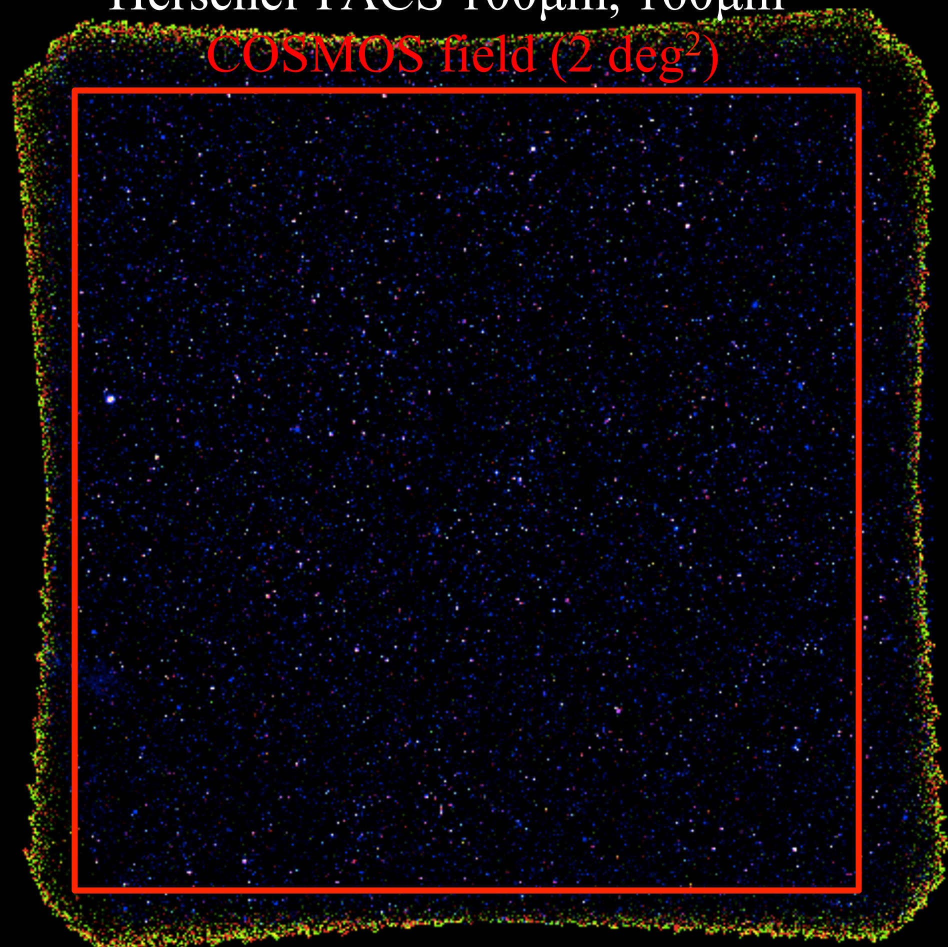


Cosmic Evolution of SFR Enhancement

Herschel-SPIRE 250μm, 350μm, 500μm



Spitzer 24μm &
Herschel-PACS 100μm, 160μm

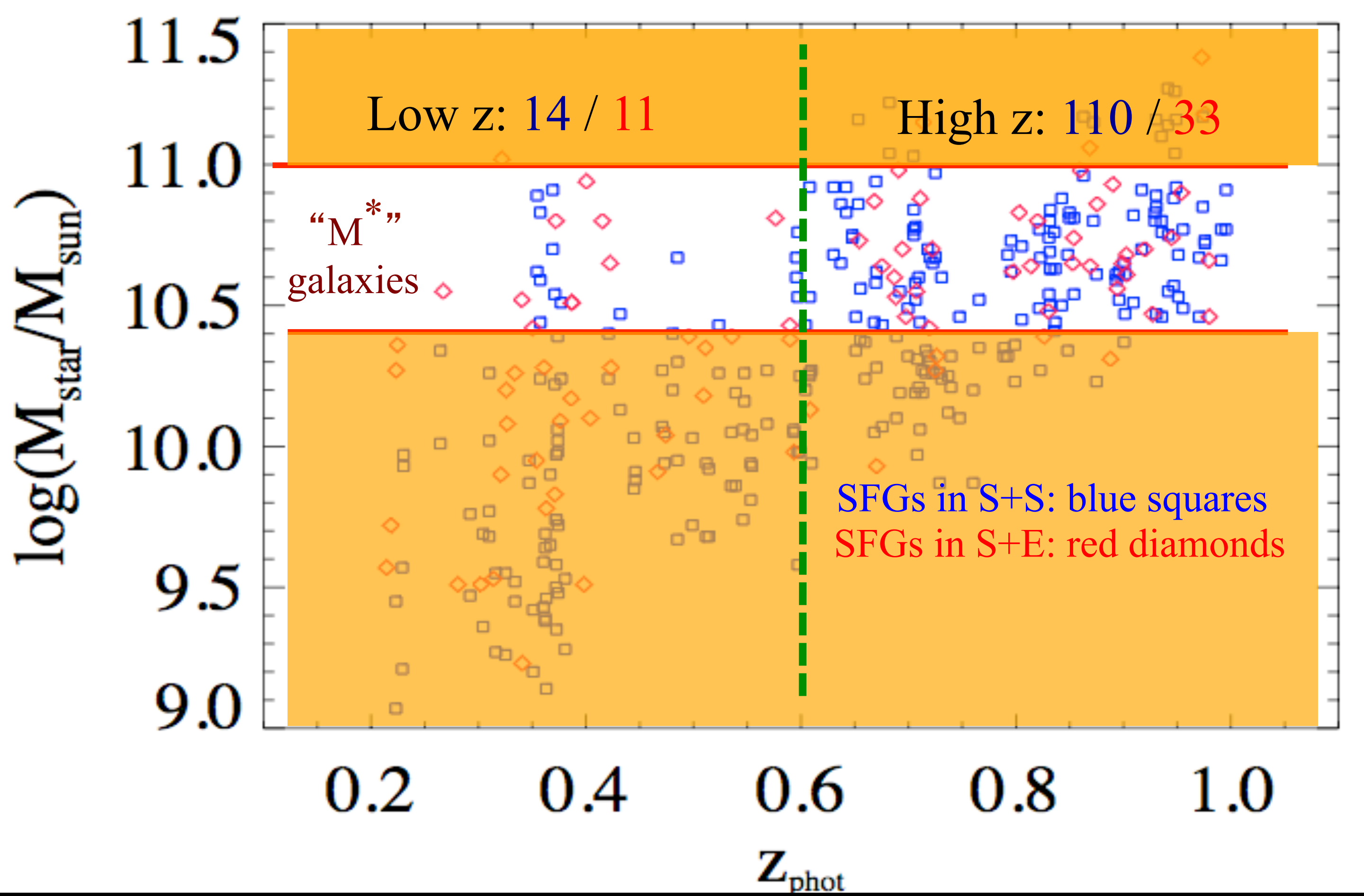


Samples of Paired Star Forming Galaxies (SFGs)

Two samples:
- 62 S+S pairs (124 SFGs)
- 44 S+E pairs (44 SFGs)

2 z_{phot}-bins:
- 0.2 <z< 0.6: 7 S+S pairs (14 SFGs) 11 S+E pairs
- 0.6<z<1.0: 55 S+S pairs (110 SFGs) 33 S+E pairs

Star Forming Galaxies (SFGs) in CPAIRs

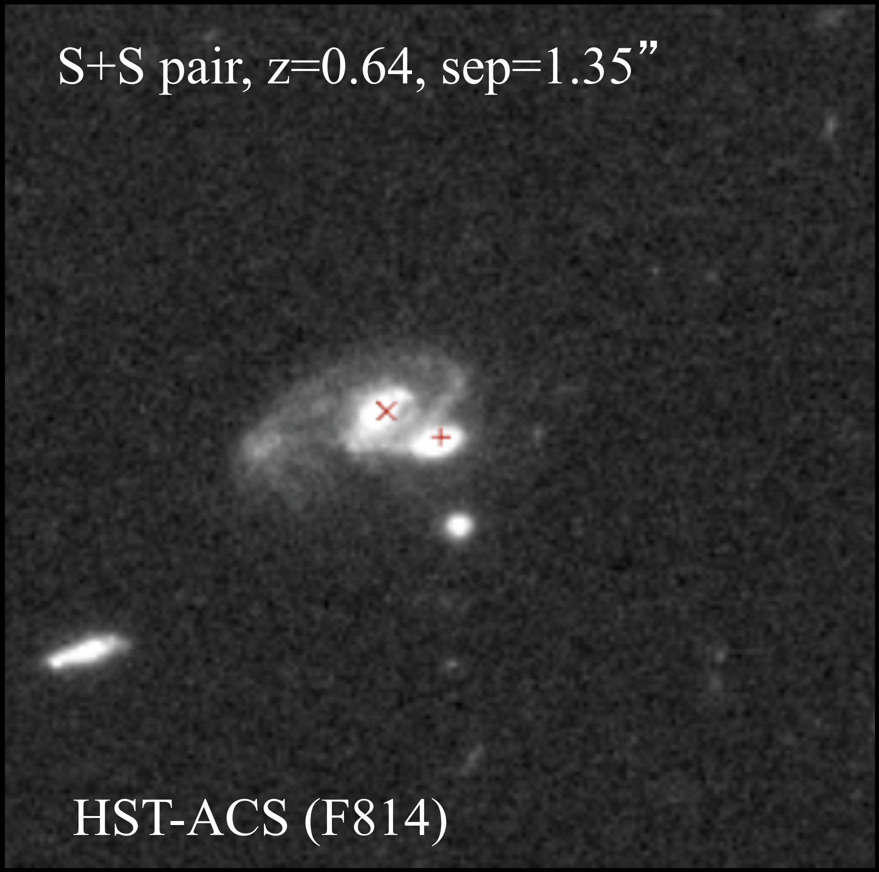


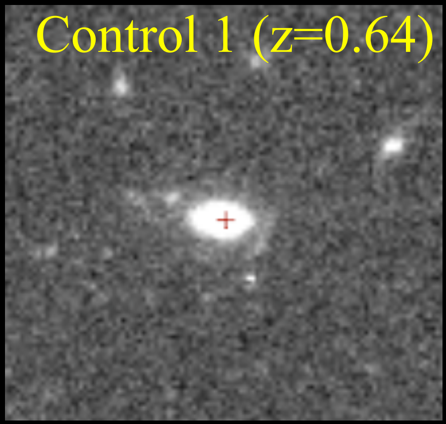
Wide z and M range within each bin: importance of well matched controls!!

The Control Samples

- Also selected from the photo-z catalog of the COSMOS survey.
- Every paired galaxy matched by 10 galaxies in z, mass, ρ_{local} & type.
- Peculiar (A> 0.35 & G+0.4×A>0.66) & paired galaxies excluded.

Example:

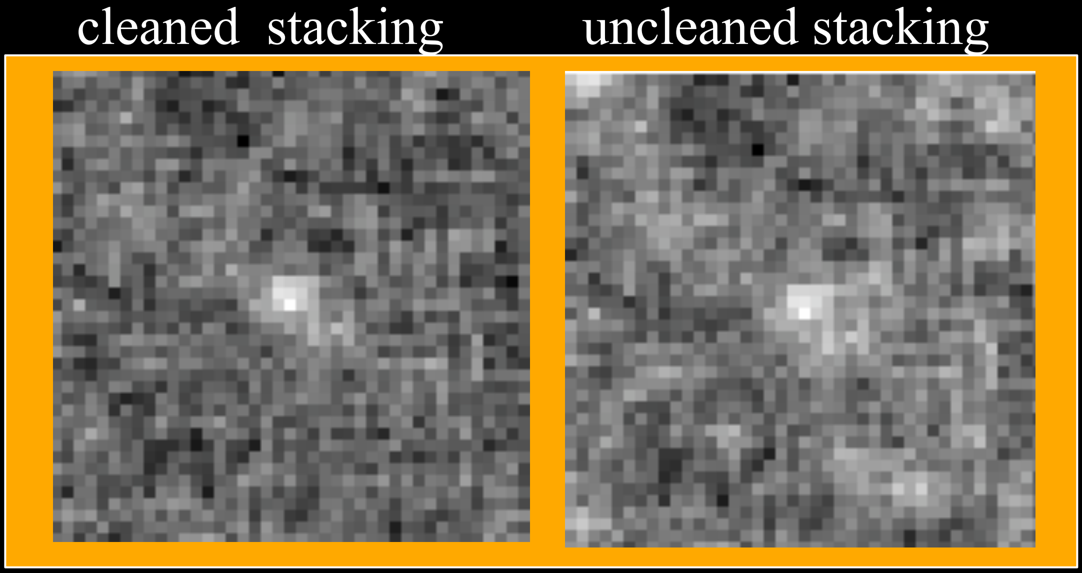




Stacking of IR images

- Need stacking because of the low detection rates (<30%)

▪ MIPS-24, PACS-100, PACS-160 Bands: Cleaned Stacking (Zheng et al. 2007)

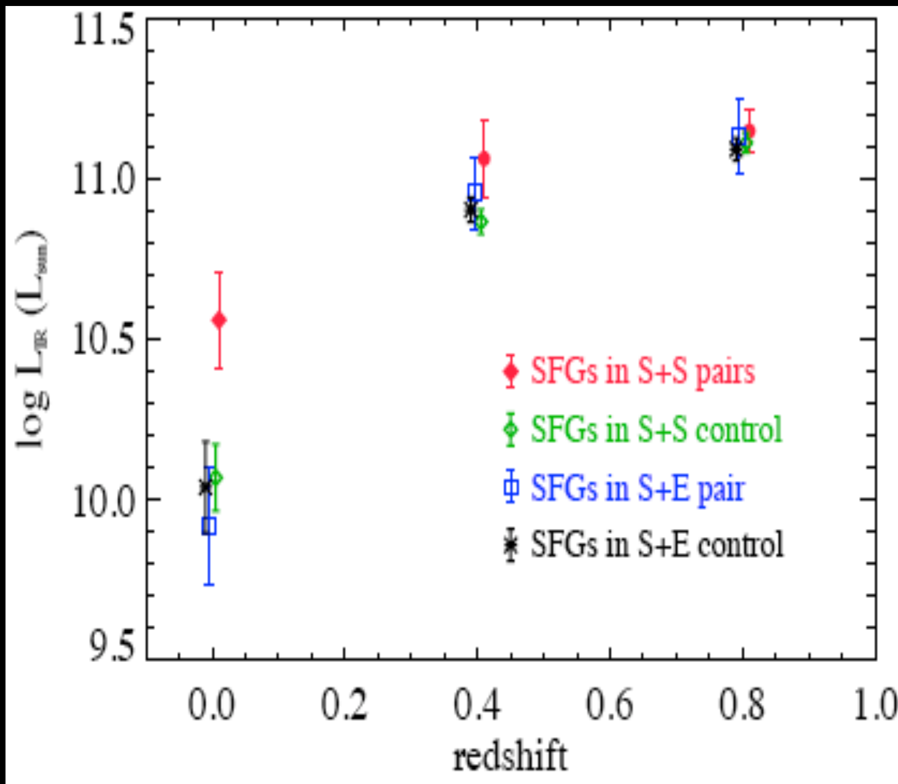


▪ SPIRE 250, 350, 500 μm bands: Covariance method (Marsden et al. 2009)

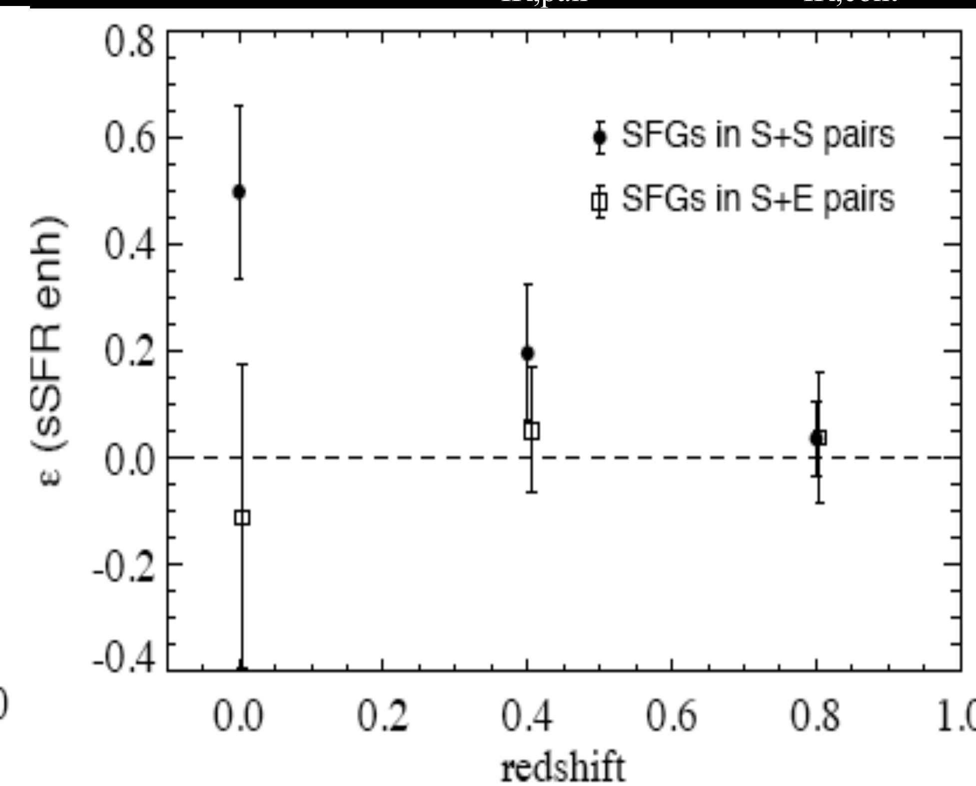
- good for confusion limited maps (giving smaller errors).
- not good when pairs are resolved (not applicable to S+S in 24 and 100 μm maps).

evolution of SFR enhancement

Mean L_{IR} (fitting 100,160, 250, 350 μm)



sSFR enh. (ε =<log $L_{IR,pair}$ > – <log $L_{IR,cont}$>)



Xu et al. 2012b

- S+S pairs: enhancement decreases from z=0 (ε=0.50±0.16, corresponding to an enhancement of a factor of ~3) to z=0.8 (consistent with no enhencement).
- S+E pairs: no enhancement at any redshift.

S+S pairs: decreasing sSFR enhancement with increasing z

A plausible interpretation:

- negative dependence of strength of merger induced nuclear starburst on gas fraction $f_{burst} \propto (1 - f_{gas})$ (Hopkins+ 2009): gas infall is cause by a torque imposed by the stellar disc that rotates slower than gas disc (so gas loses angular momentum to stars). When gas fraction is high (stellar fraction low), this effect is weak.
- consistent with higher f_{gas} in z ~ 1 galaxies;
- also consistent with no enhancement in z=0 low mass paired SFGs ($f_{gas} \sim 30\%$).

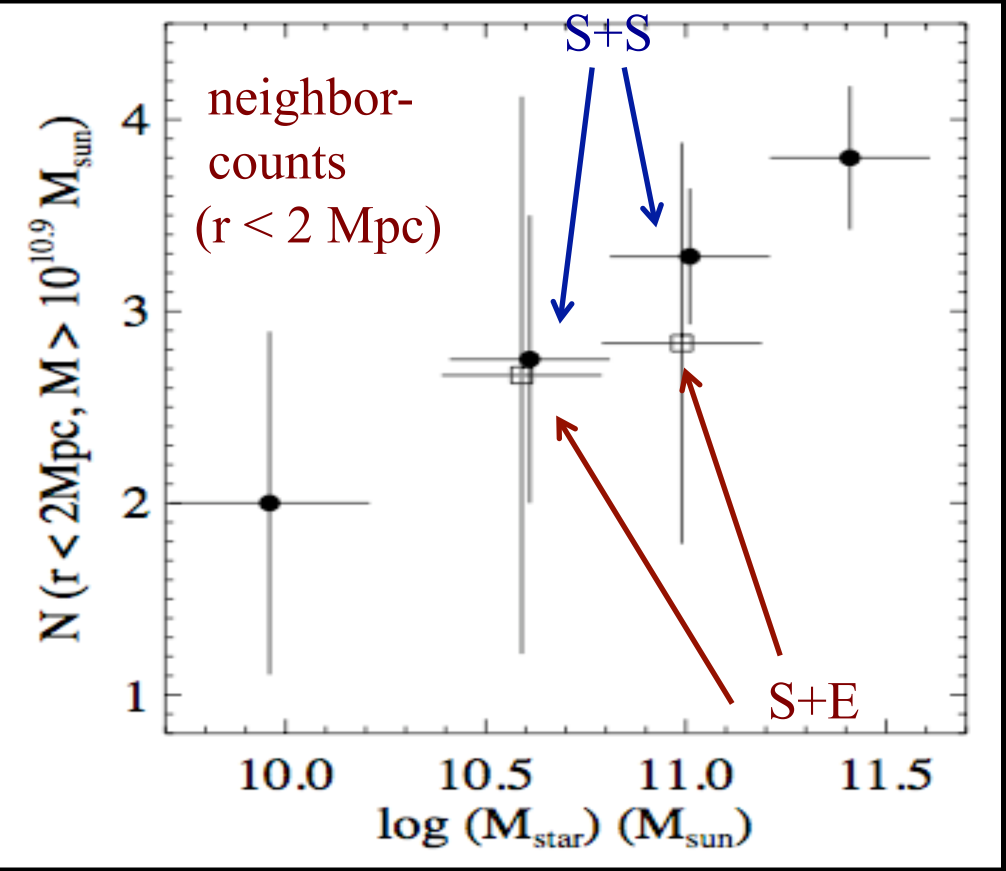
SFGs in S+E pairs: No sSFR enhancement !?

- Puzzle: How can an SFG know the type of its companion?

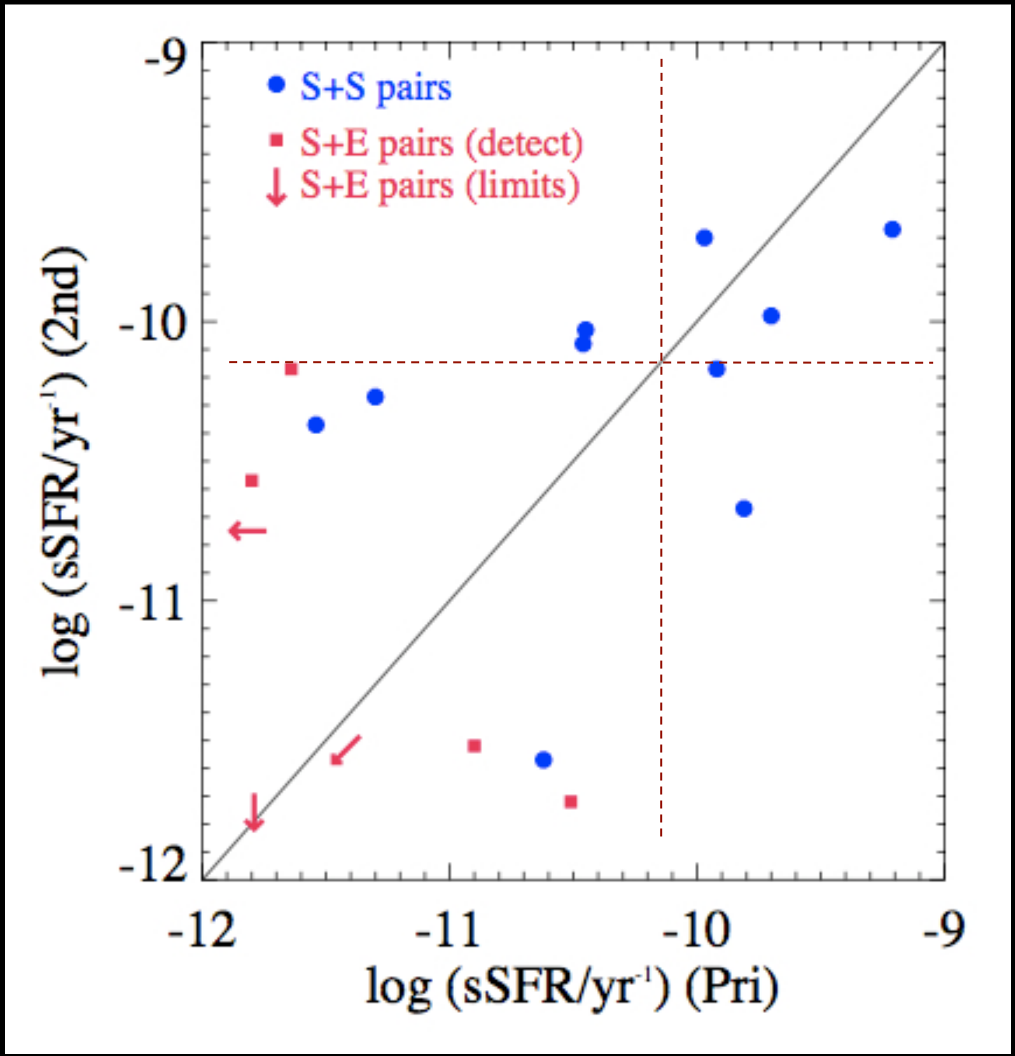
An E companion should induce same tidal effect as an S companion does. So, why massive SFGs in (z=0) S+S pairs have enhancement, while those in S+E pairs don't?)

Due to different large-scale environments around S+E and S+S?

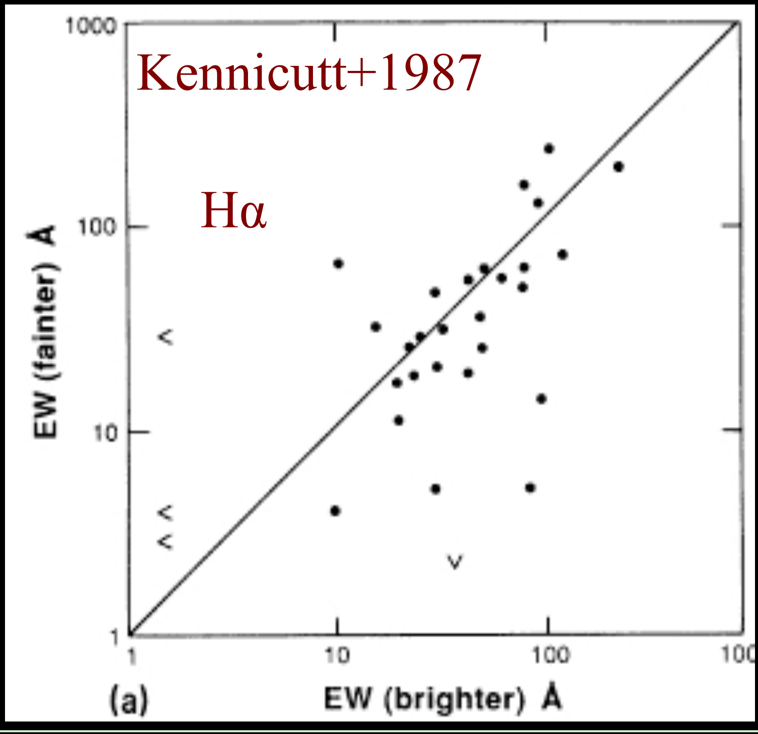
S+E pairs & S+S pairs have similar local (2Mpc) densities →



"Holmberg effect": correlation between the sSFR of two companions



(Xu+ 2010, ApJ 213, 330)



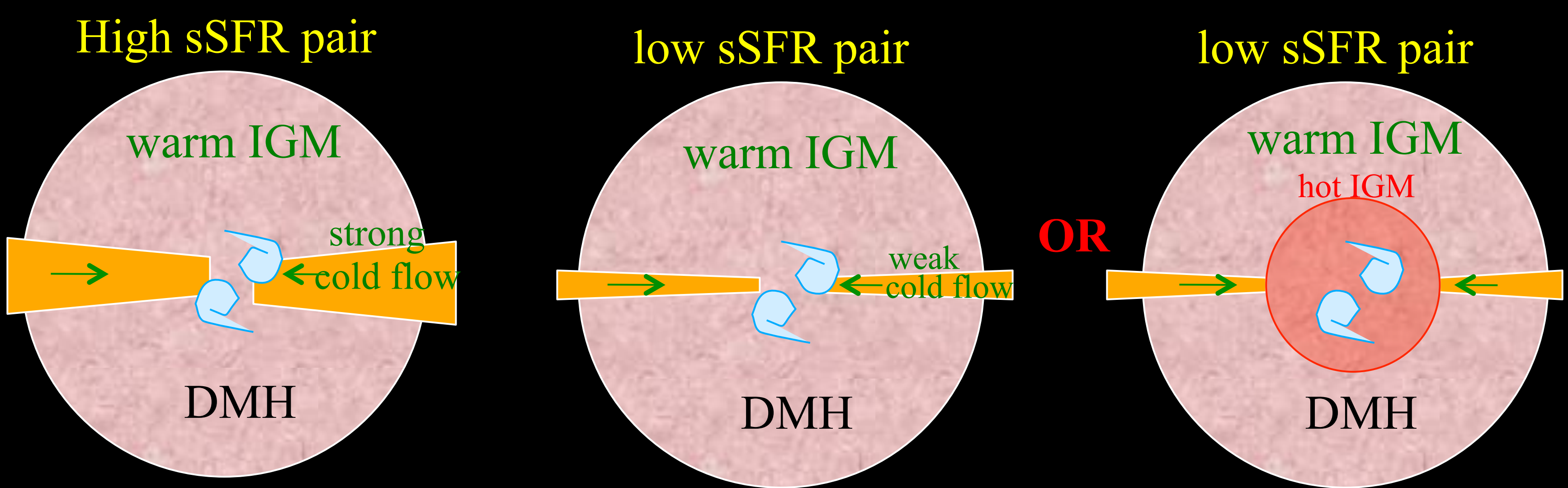
Kennicutt et al. (1987):

- In later stage, both galaxies in an S+S pair may have stronger merger-induced star formation.

BUT: why SFGs in S+E pairs, even when in late stage, do not show strong SFR enhancement?

Can sSFR of galaxies be modulated by IGM in DMH?

- The "Holmberg effect" in S+S pairs and the non-enhancement of S galaxies with E companions reveal a link between the sSFR of two galaxies in a pair.
- My hypothesis: **this is due to the modulation of the sSFR by the IGM in the dark matter halo (DMH) that the two galaxies share.**



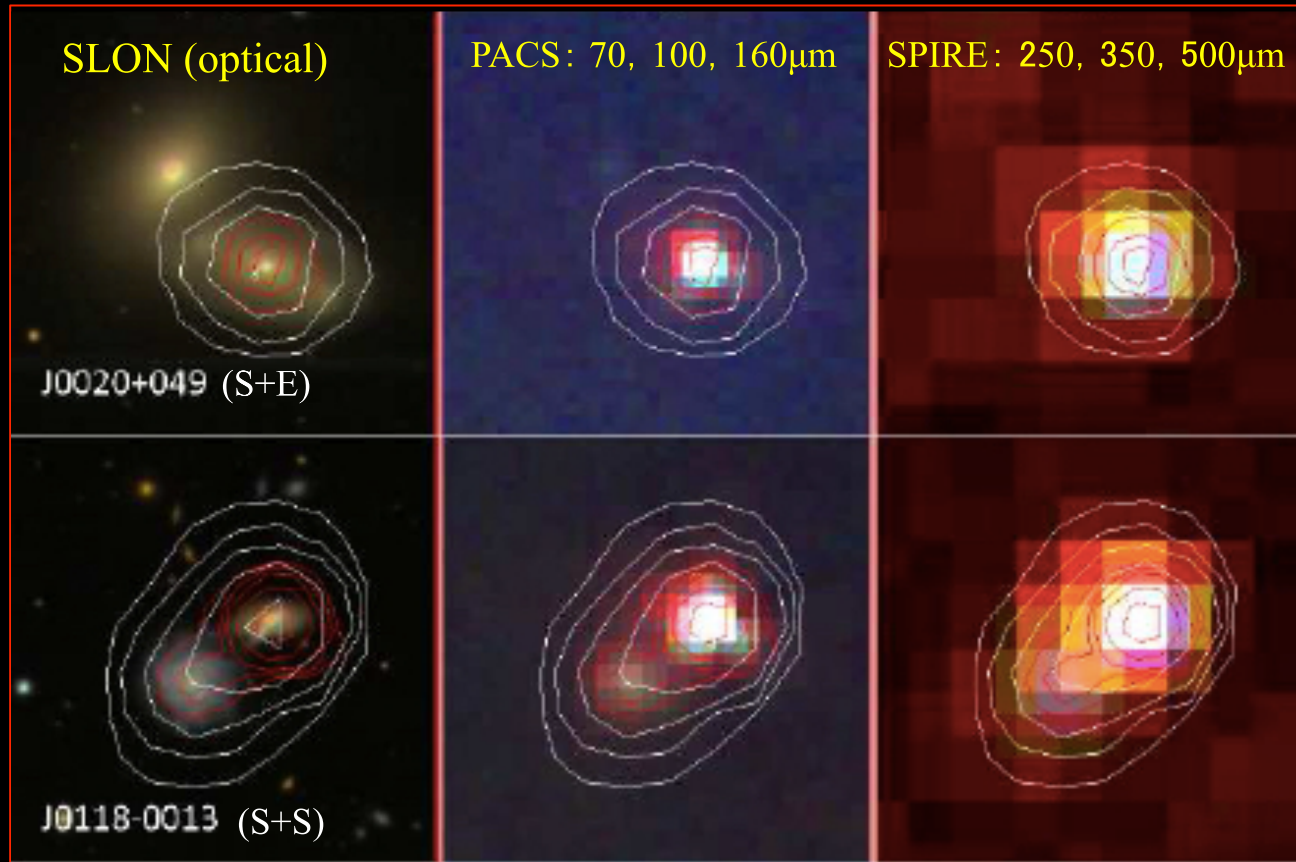
A Prediction: spiral galaxies in S+E pairs shall have lower cold gas content than those in S+S pairs.

Herschel Observations :

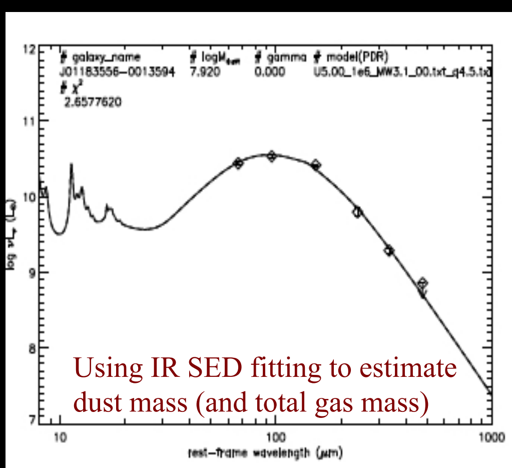
Dust (Gas) Content & Star-formation Efficiency in Pairs

Sample: 88 pairs
(44 S+S, 44 S+E)

FIR imaging
in 6 bands:
70, 100, 160,
250, 350, 500μm

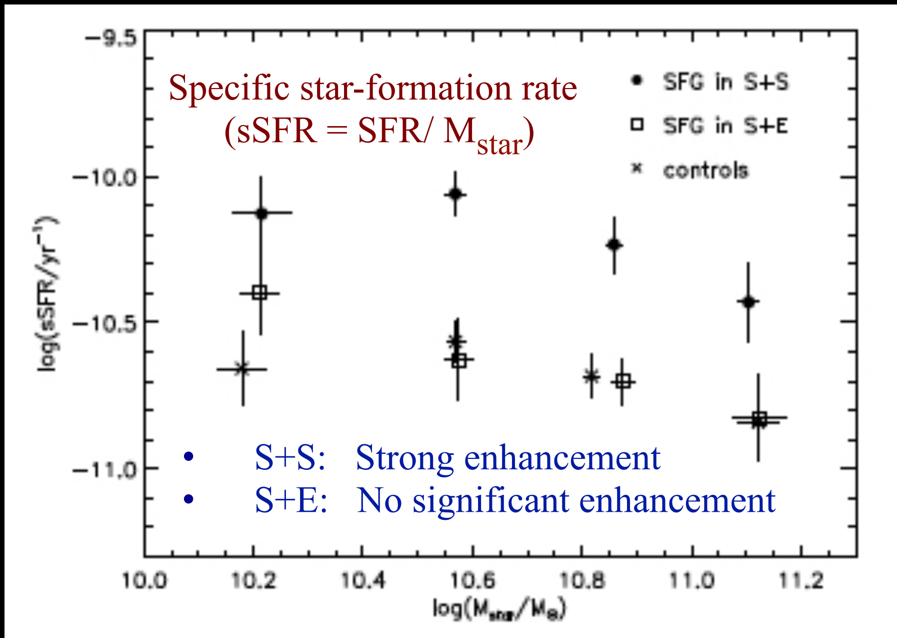


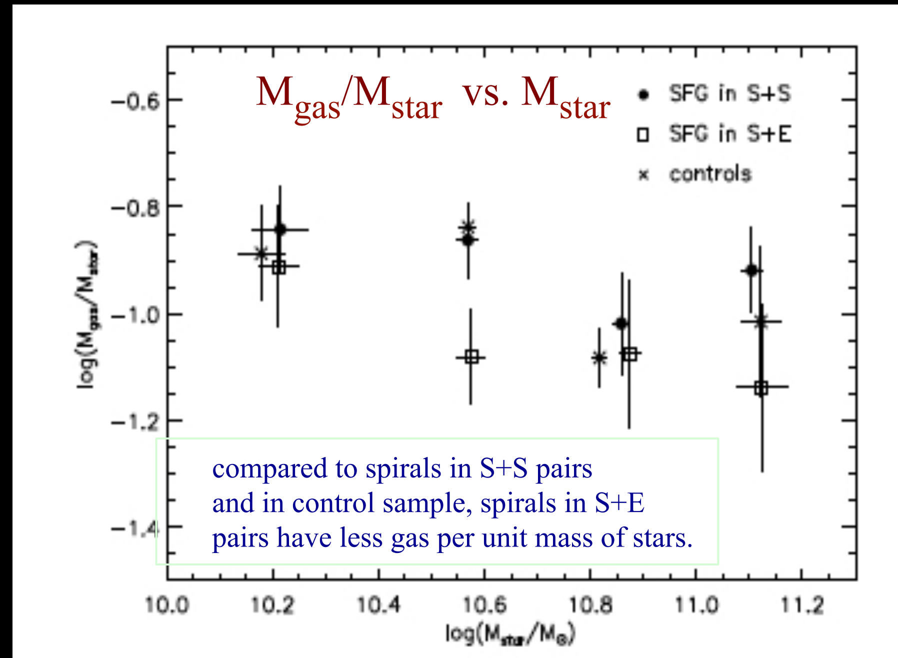
red contours — 70μm, white contours — 250μm (Cao, Xu, et al. 2016)



250, 350, 500μm are new windows opened by Herschel, optimal for studies of dust mass and gas mass (exploiting the tight correlation between dust and gas).

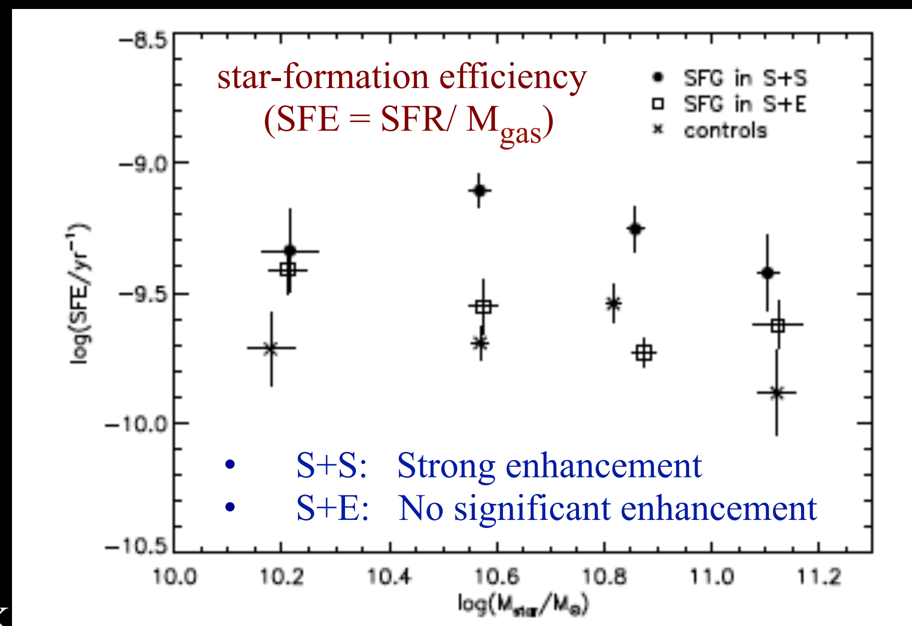
Herschel results:





Cao, Xu, et al. 2016

- Spirals in S+E pairs show no significant SFR enhancement compared to control sample.
- They have slightly lower gas content compared to spirals in S+S pairs and in control sample.
- Their average SFE is significantly (~3x) lower than that of spirals in S+S pairs.

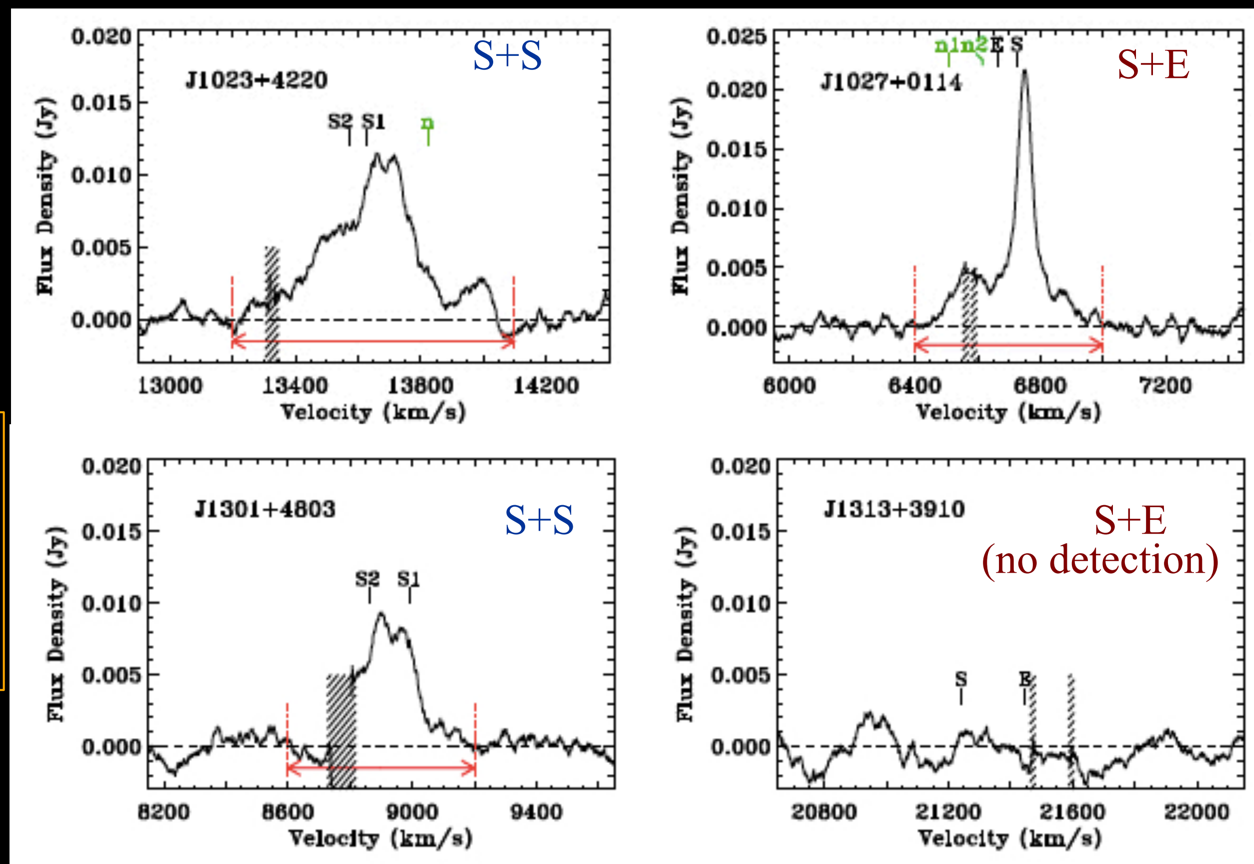


GBT Observations -- HI Gas Content in KPAIR

GBT Observations:
67 pairs = 41 detections
+ 16 upper-limits
+ 10 failed

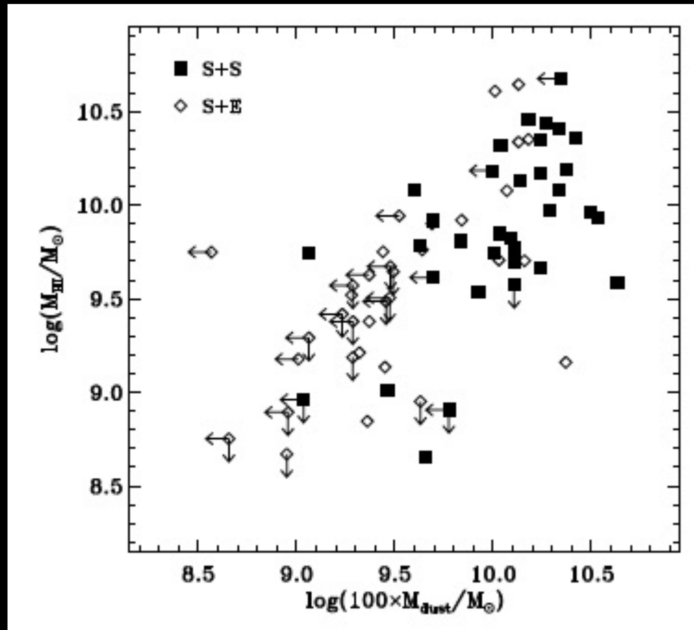
HI flux from literature:
21 pairs (detections)

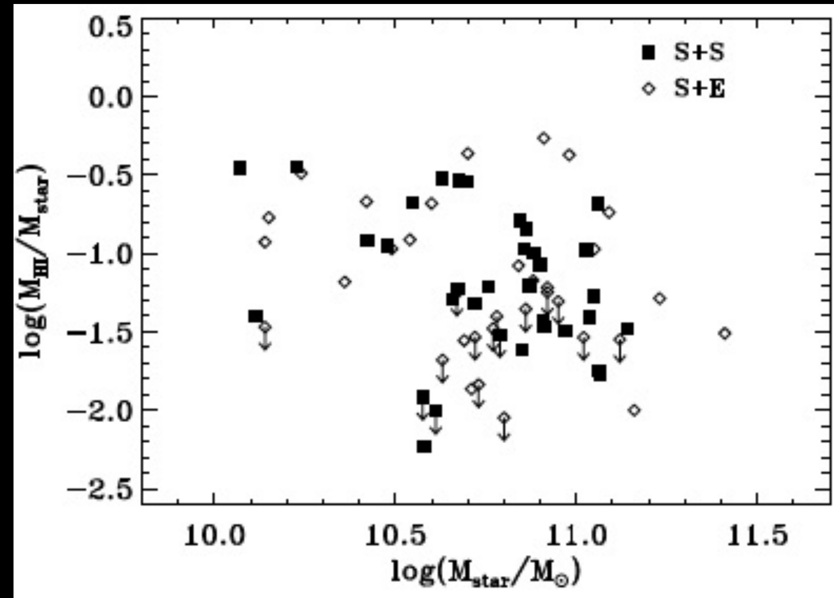
Examples: HI Spectra



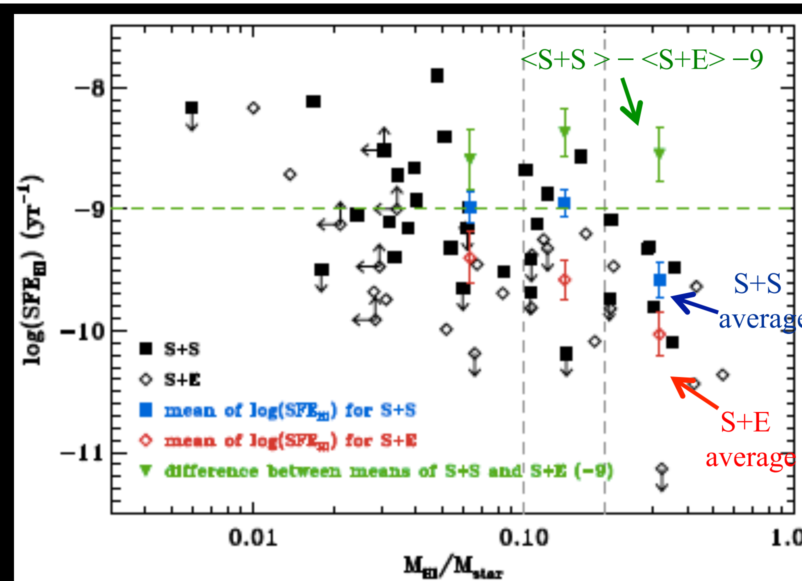
(Zuo, Xu, et al. 2017, submitted)

GBT Results:



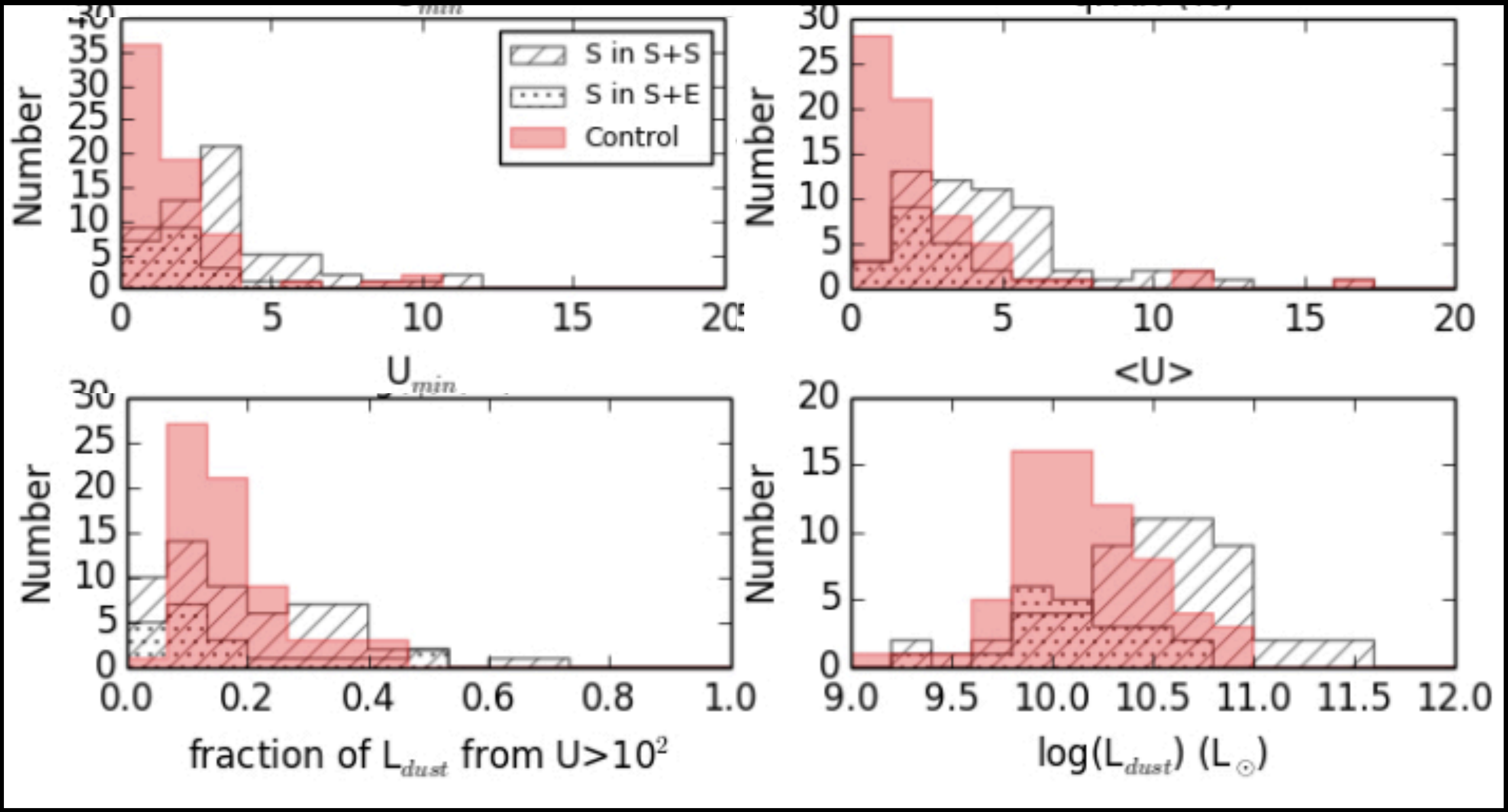


- There is a good correspondence between M_{HI} and $100\times M_{dust}$.
- The average HI fraction of paired spirals is M_{HI}/M_{star}=5±1%, with no significant difference between spirals in S+S and S+E pairs.
- The average SFR/M_{HI} (=SFE_{HI}) of spirals in S+S pairs is ~3× higher than that of spirals in S+E pairs.



(Zuo, Xu, et al. 2017, submitted)

CIGALE model fitting: (using WISE & Herschel data):

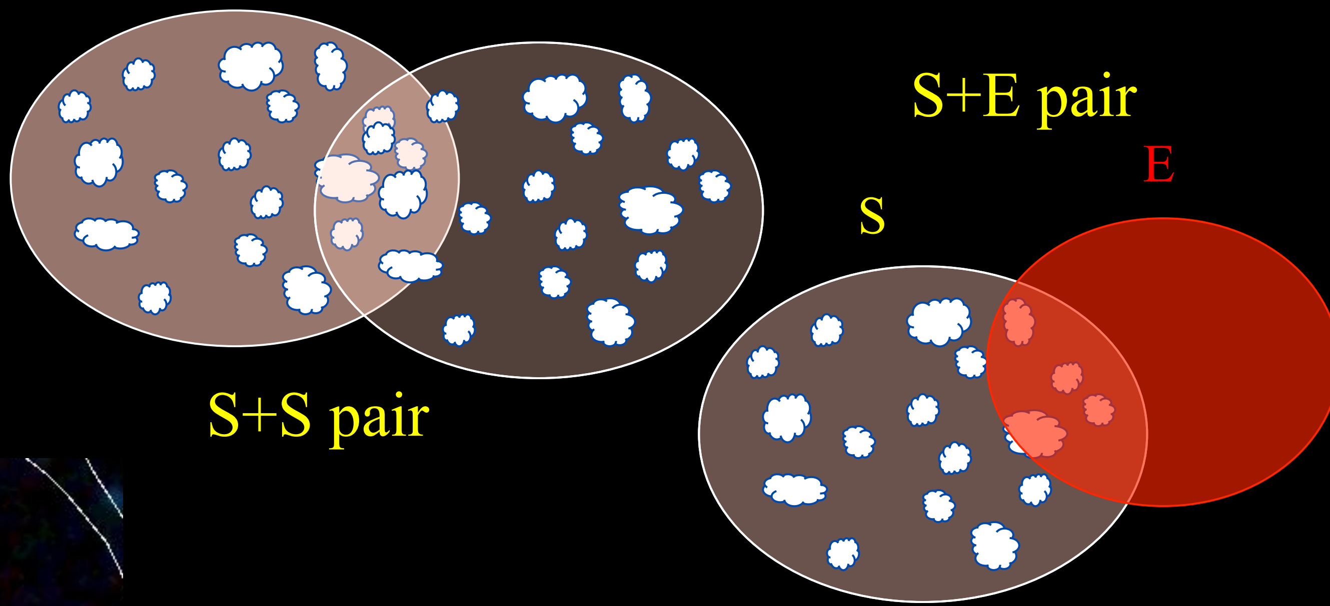


(Domingue, Cao, Xu, et al. 2016)

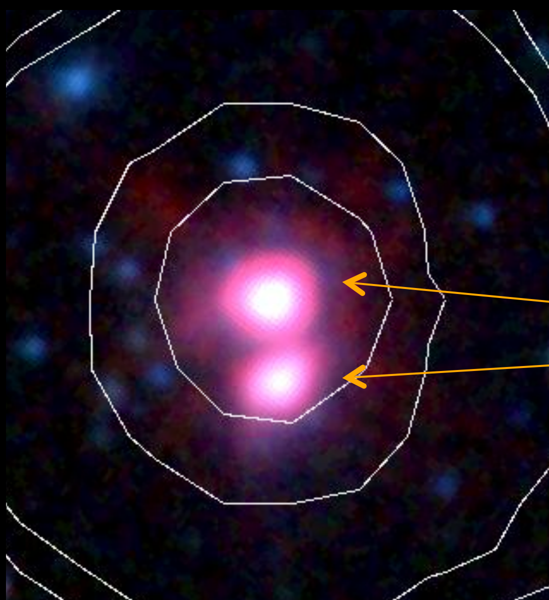
- In S+S pairs, SFR related variables such as Umin（intensity of diffuse ISRF), <U>,
- Ldust, & contribution of SF regions (with U>100）to Ldust，are significantly enhanced.
- But in spirals in S+E pairs，these variables show no enhancement.

Why do S galaxies in S+S have higher SFE than those in S+E???

Proposition: disk-disk collision plays an important role?



But:



In this example of S+S pair with strong sSFR enhancement, the SF regions in two galaxies are well separated: not directly linked to collision.

Summary

1) We studied two large close major-merger pair samples, one has 170 local ($z<0.1$) pairs (KPAIR), another has >300 pairs with $0.2 < z < 1.0$ (CPAIR).
2) We found a moderately strong evolutionary rate for the pair fraction, with the evolutionary index $m = 2.2\pm0.2$. The corresponding merger rate, as a function of redshift, agrees very well with predictions of ΛCDM N-body simulations.
3) The pair fraction shows no significant dependence on stellar mass.
4) Major merger rate can fully account for the formation rates of both massive Es and RQGs since z~1, but not for that of the low mass Es and red galaxies.
5) Major mergers have significant impact on the stellar mass assembly of the most massive galaxies, but for less massive galaxies the stellar mass assembly is dominated by the star formation.
6) Major merger rates (since z~1) are comparable to or higher than (U)LIRG rates.
7) Our results, based on Herschel and Spitzer data, revealed a significant trend for the star formation enhancement in S+S pairs to decrease with increasing redshift. Between z=0 and z=1, this trend occurs in parallel with the dramatic increase (by a factor of ~10) of the sSFR of normal SFGs, both can be explained by the higher gas fraction in higher z disks.
8) SFGs in mixed pairs (S+E pairs) do not show any significant star-formation enhancement at any redshift. Their SFE is ~3× lower than SFGs in S+S pairs.