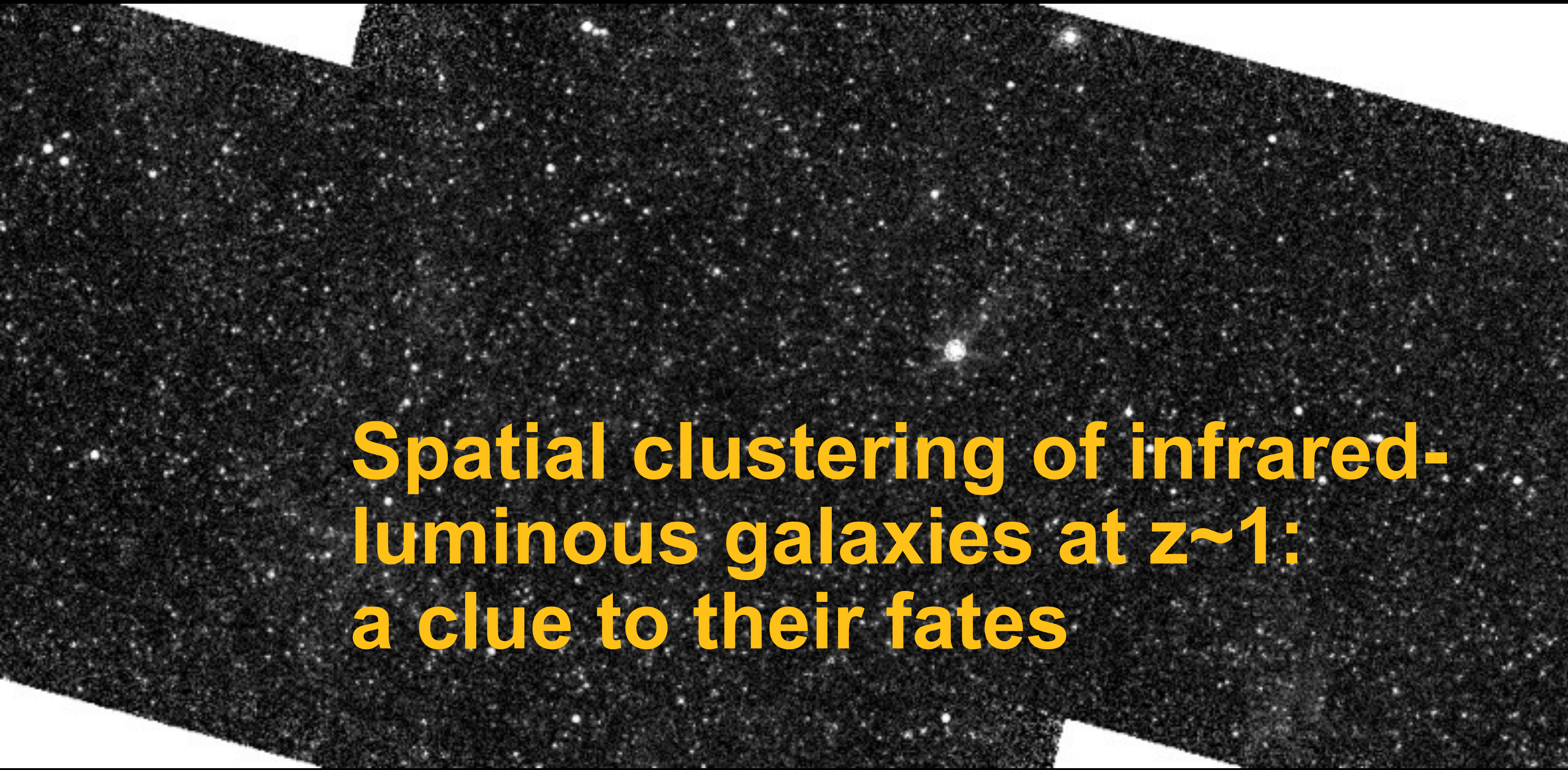
B. Weiner

Spatial clustering of infrared-luminous galaxies, a clue to their fates

The most massive starbursts in both the local and high redshift universe manifest themselves as ultraluminous infrared galaxies. However, it remains controversial what IR-luminous galaxies at z=1 are, and what they will evolve into. Are IR-luminous galaxies at high redshift mostly galaxy mergers, as they are at low redshift? Are ultraluminous IR galaxies strongly clustered, and can we infer whether they must evolve into cluster galaxies today? We measure the spatial clustering of LIRGs and ULIRGs at z=1 using Spitzer/MIPS sources cross-correlated with galaxies from the DEEP2 redshift survey. Because the evolution of clustering strength is well understood, the correlation lengths constrain the galaxy populations that LIRGs and ULIRGs will evolve into, and the classes of AGN to which they may be linked.



Spatial clustering of infrared-luminous galaxies at z~1: a clue to their fates

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+ Jeff Newman, Kai Noeske, Jennifer Lotz, Susan Kassin,
and the MIPS and DEEP2 teams

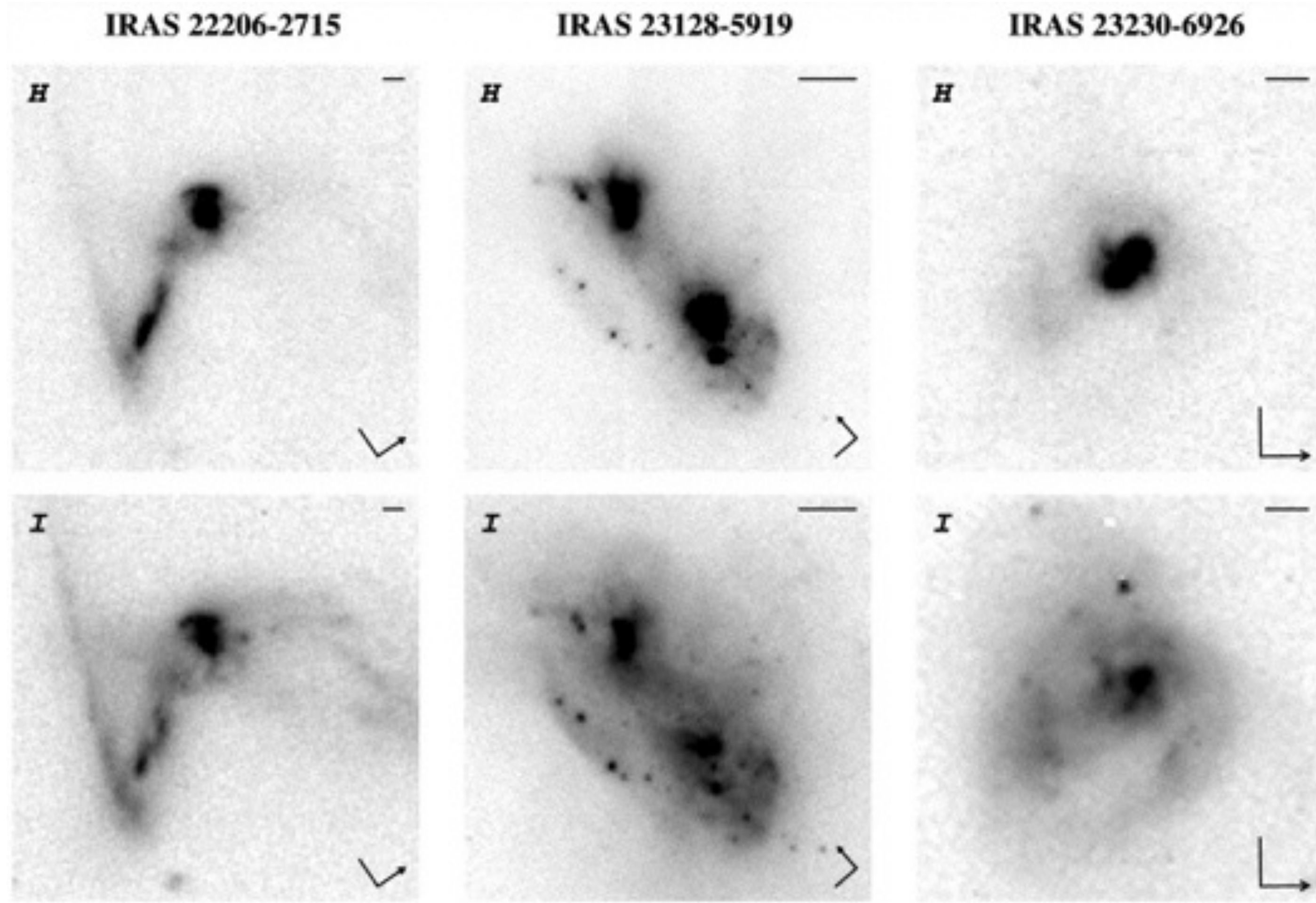
ULIRGs & LIRGs:

Star formation or AGN
reprocessed by dust.

Locally, many LIRGs
and nearly all ULIRGs
are interacting galaxies.
Locally, ULIRGs are rare.

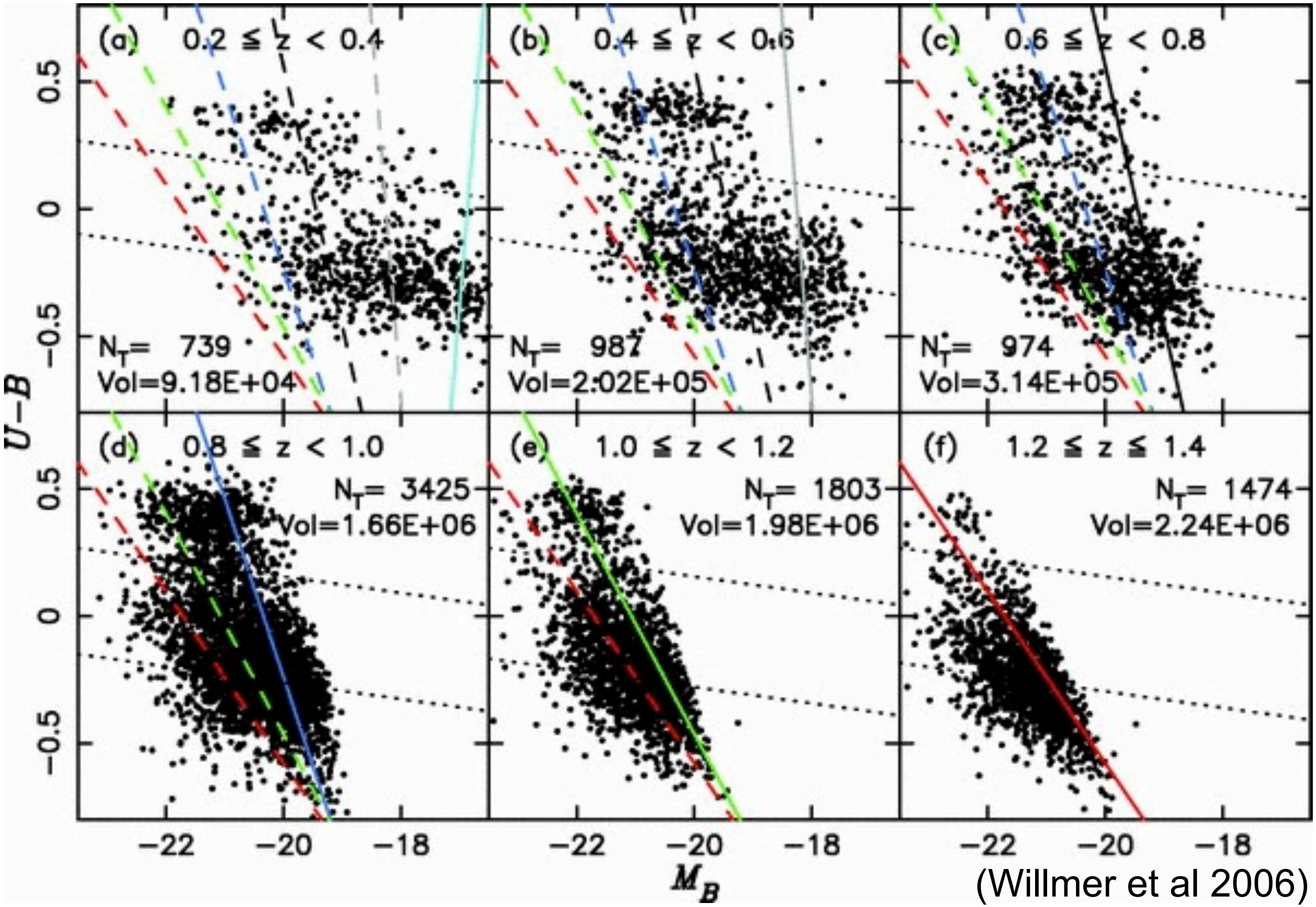
At z~1, high global SFR
means more galaxies
above LIRG threshold.
But are these LIRGs
similar to local LIRGs -
mostly mergers?

Is a z~1 LIRG the ancestor of
a red galaxy, or a Milky Way?
Was the Milky Way a LIRG in the past?



IRAS-selected ULIRGs at z~0.2
(WFPC2/NICMOS, Bushouse et al 2003)

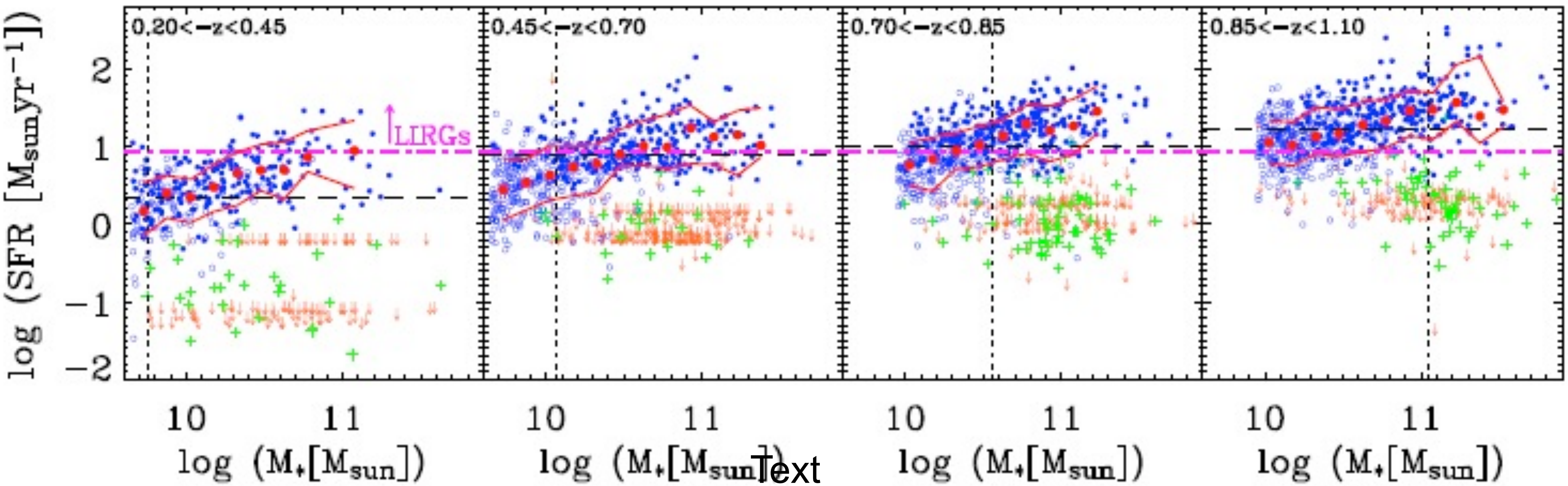
Quenching: ULIRGs may be a stage in:
merger > ULIRG > QSO > elliptical   (e.g. Sanders 1988)



(Willmer et al 2006)

Color-luminosity diagram for galaxies in the DEEP2 redshift survey:
at z>1 there is already a color bimodality: red and blue galaxies.
red = mostly quiescent, E/S0, blue = star-forming. From z=1 to now,
the mass in red galaxies increases and the blue galaxies decline in SFR.
What drives the increase in red galaxy mass?
Mergers, gas exhaustion, AGN feedback, ???

The global decline of SFR with time:



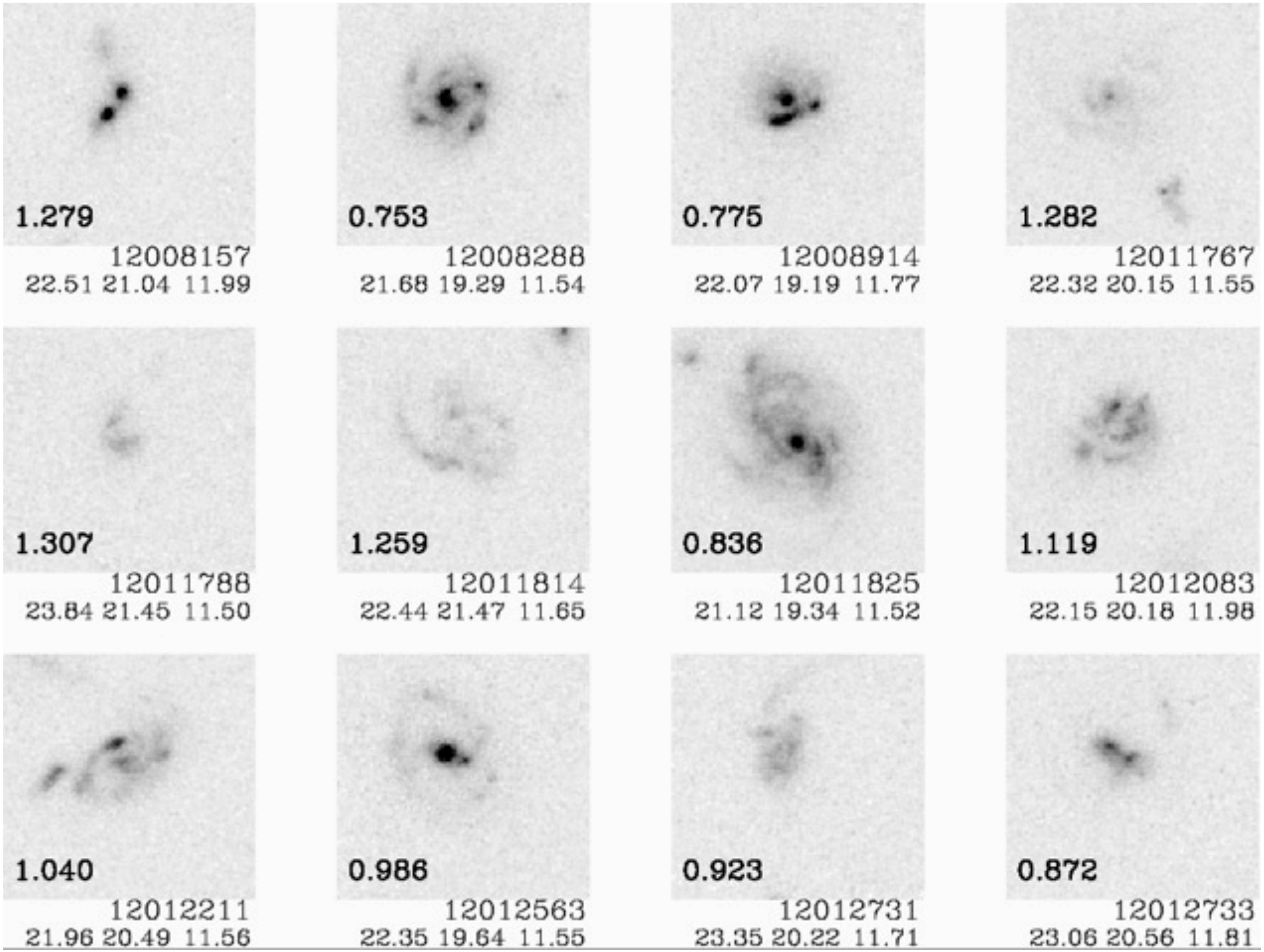
(Kai Noeske, BJW et al 2007)

Dependence of star formation rate on stellar mass in the DEEP2 Groth Strip:
SFR measured with far-IR (Spitzer/MIPS) and nebular emission lines

The scatter in the SFR-mass relation is ~0.3 dex:
implies that extreme bursts are rare.
The overall SFR declines gradually for the entire sample:
implies that the global decline of SFR is due to a decline in individual galaxies.

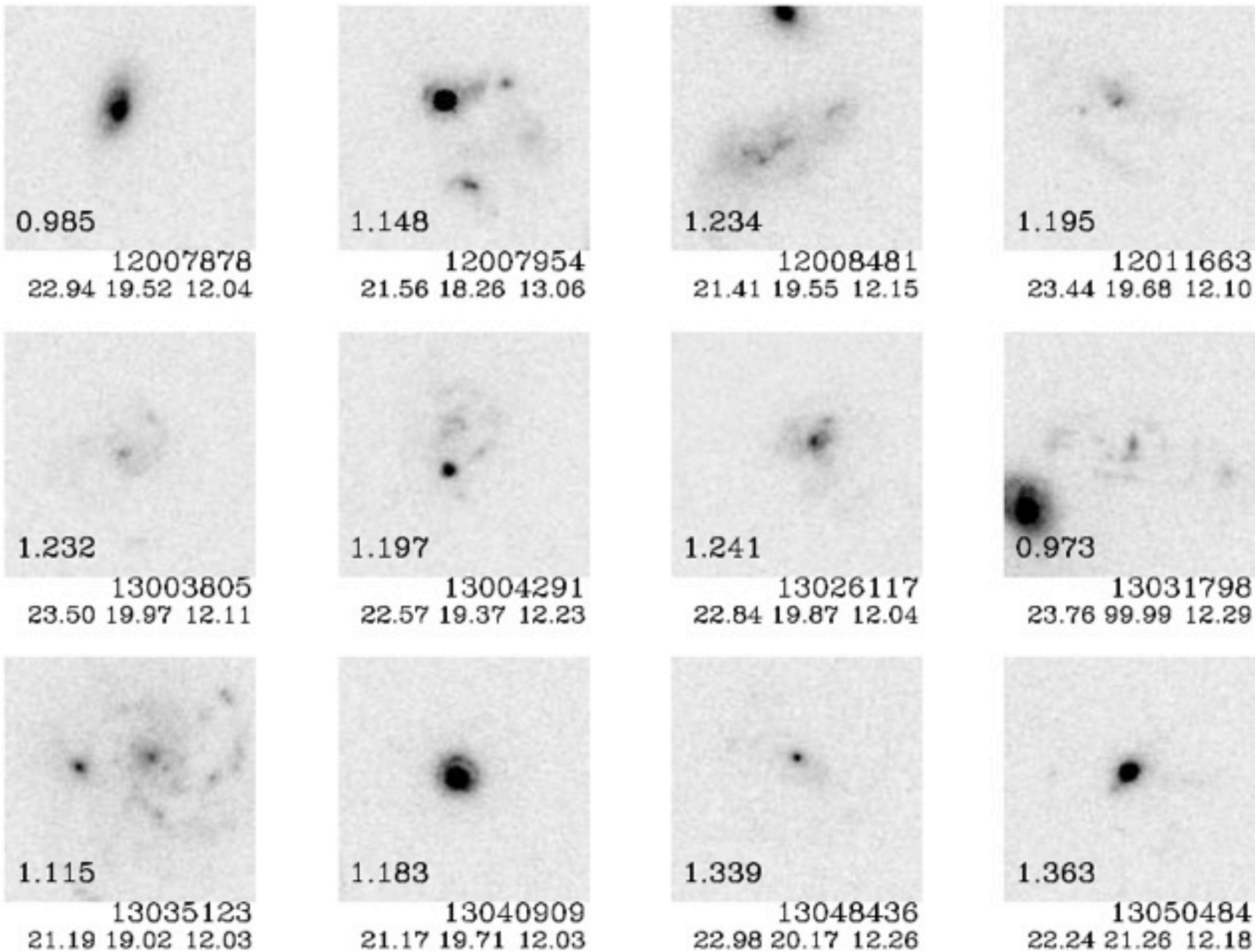
Still want to know how/what type of galaxies turn off SF and redden.

Example bright LIRGs in the Groth Strip: MIPS 24um, HST/ACS I



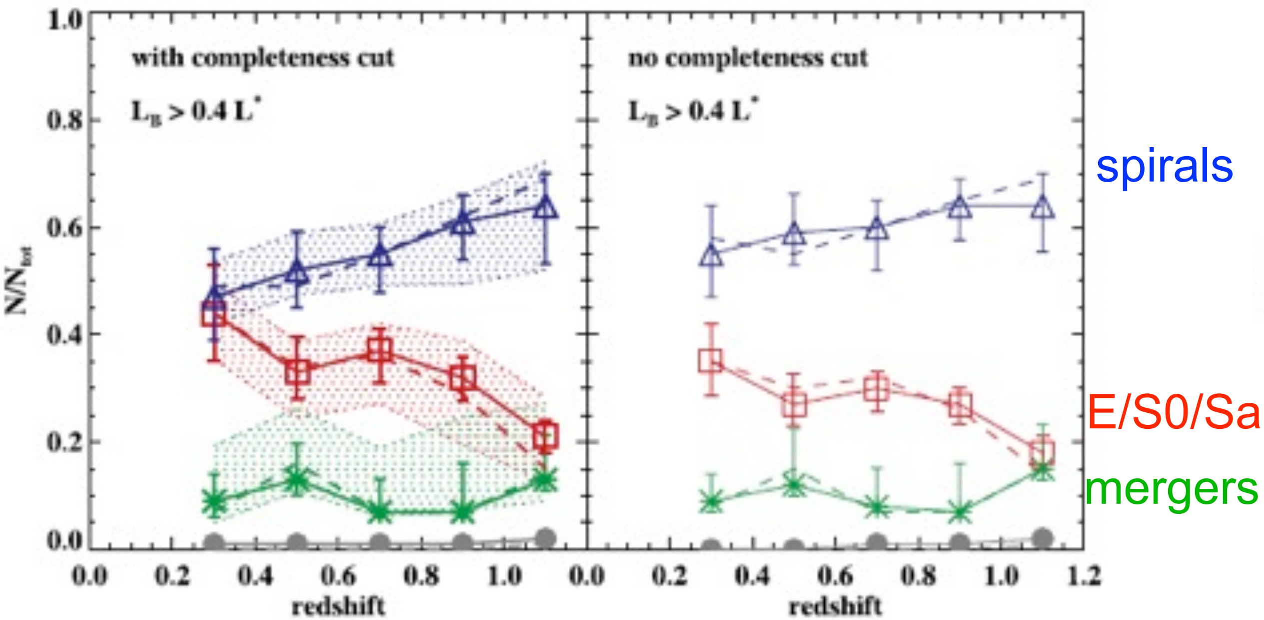
At z=1, IR-luminous galaxies more common; some LIRGs are spirals

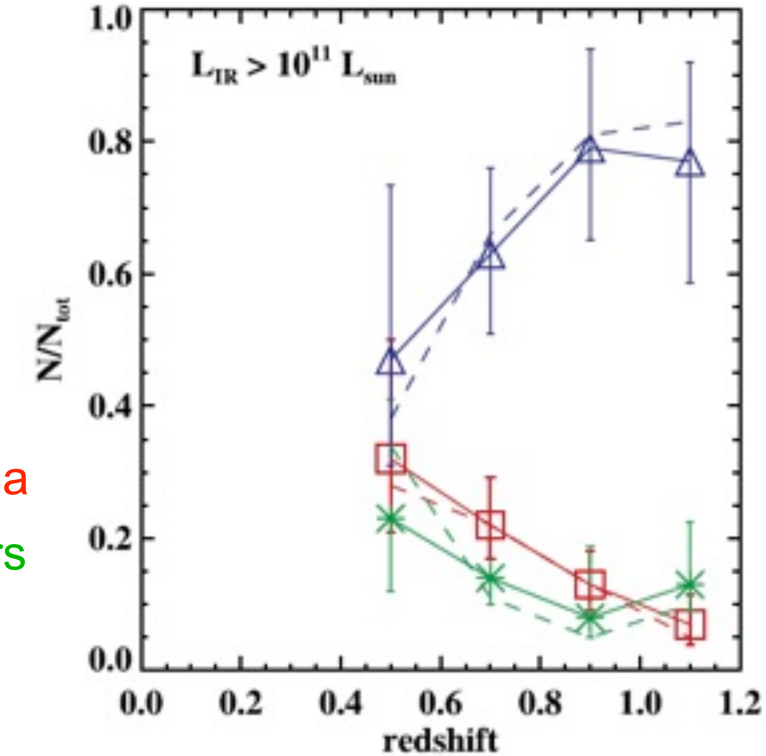
A few ULIRGs in the Groth Strip: MIPS 24um, HST/ACS I



At z=1, ULIRGs mostly look peculiar/merger, but highly extincted

Morphological type fractions from HST





(Lotz et al 2008,
from DEEP2 EGS field)

Quantitative classification of galaxy structure from HST images shows that ~10% of galaxies > 0.4 L* are mergers and the rate does not increase strongly with redshift.

At z~1, most LIRGs are spirals.
There might be evolution in the sense of lower fraction of spiral-LIRGs at low z (as expected if they are depleting their gas?) but the statistics are not strong.

This leaves open questions: Where do ULIRGs and LIRGs occur? What do they evolve into?

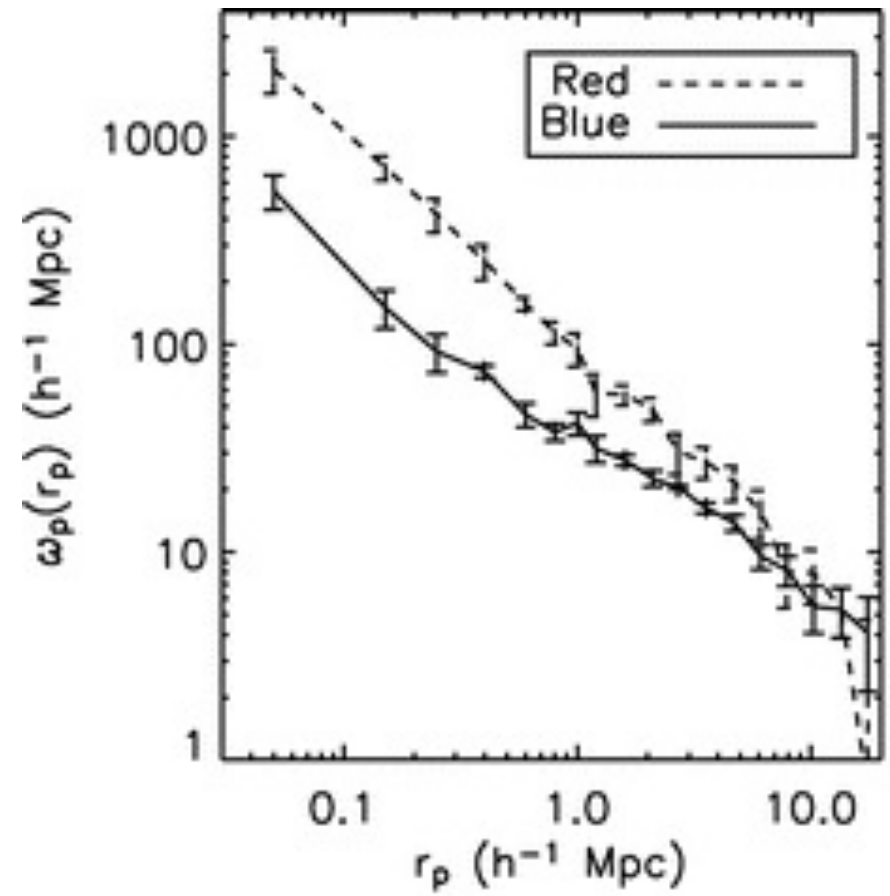
Clustering as History:

Understanding galaxy clustering is a major success of modern cosmology and is based on physics in the linear regime.

Clustering measurements allow linking populations across time – the evolution of dark matter halo clustering is well understood.

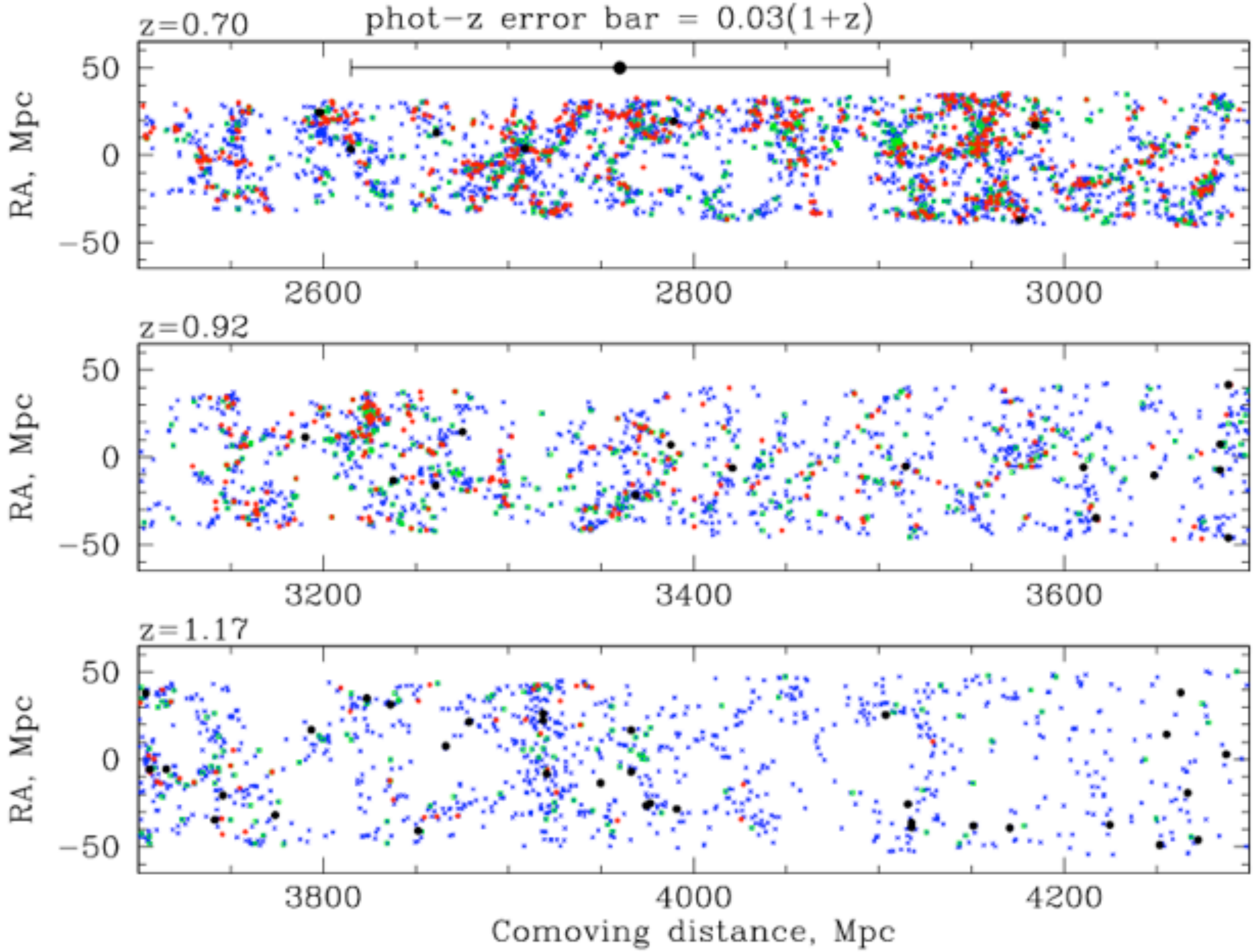
Massive objects are more strongly clustered.

Galaxies are discrete, so Poisson noise means you need many galaxies to measure a correlation function (pair counts as function of separation).



Coil et al 2008
At z=1, DEEP2 red galaxies are more clustered than blue galaxies, as is true locally. r0 ~ 3-4 h^-1 Mpc

$$\xi(r)=(r/r0)^{\gamma}$$



Cone diagram of DEEP2 field 2: rich clustering structure

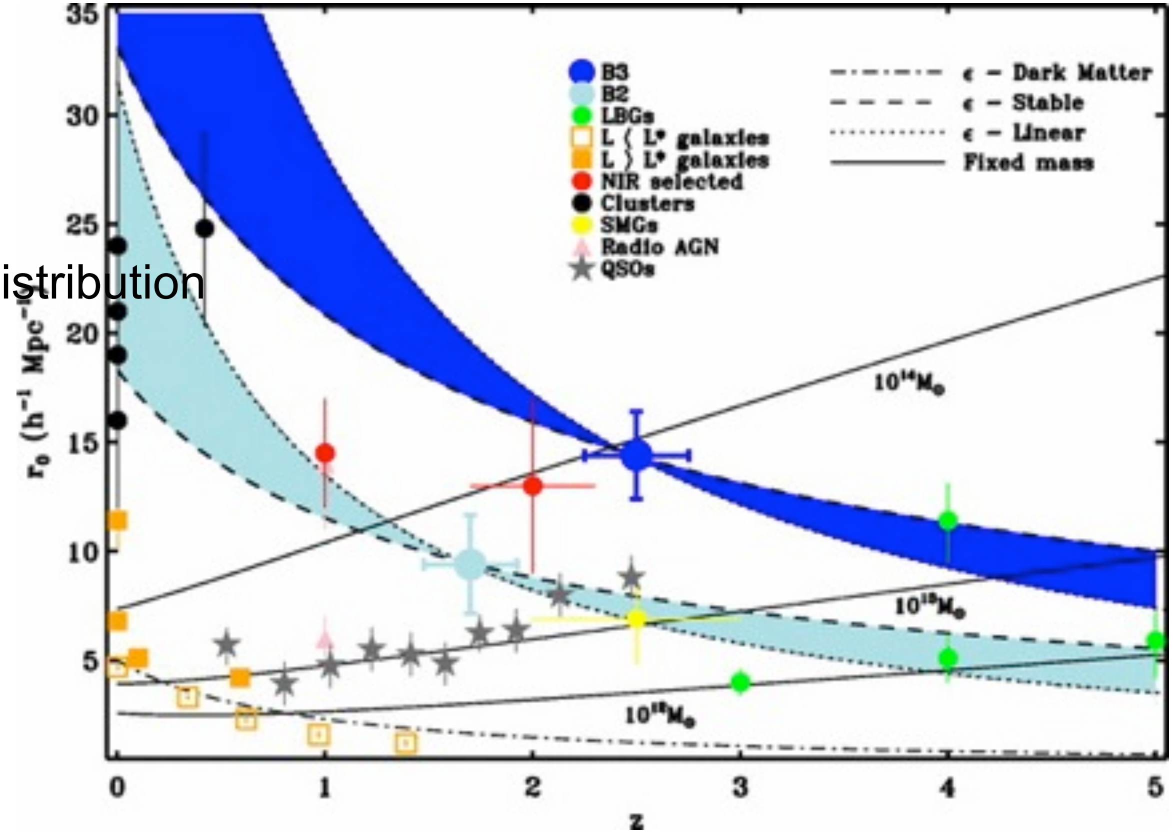
Measurements of angular clustering for z=1-2 ULIRGs

In principle, angular correlation can be inverted to get the spatial CF, but this is critically dependent on knowing the redshift distribution of your sources and its width Δz.

Select galaxies from MIPS24 flux and some kind of photometric cut, and hope you know your redshift distribution.

$$w(\theta)=A\,\theta^{1-\gamma}$$
$$\xi(r)=(r/r0)^{\gamma}$$
$$r0\sim(stuff\times A\,\Delta z)^{1/\gamma}$$

(Limber's equation, Limber 1954)

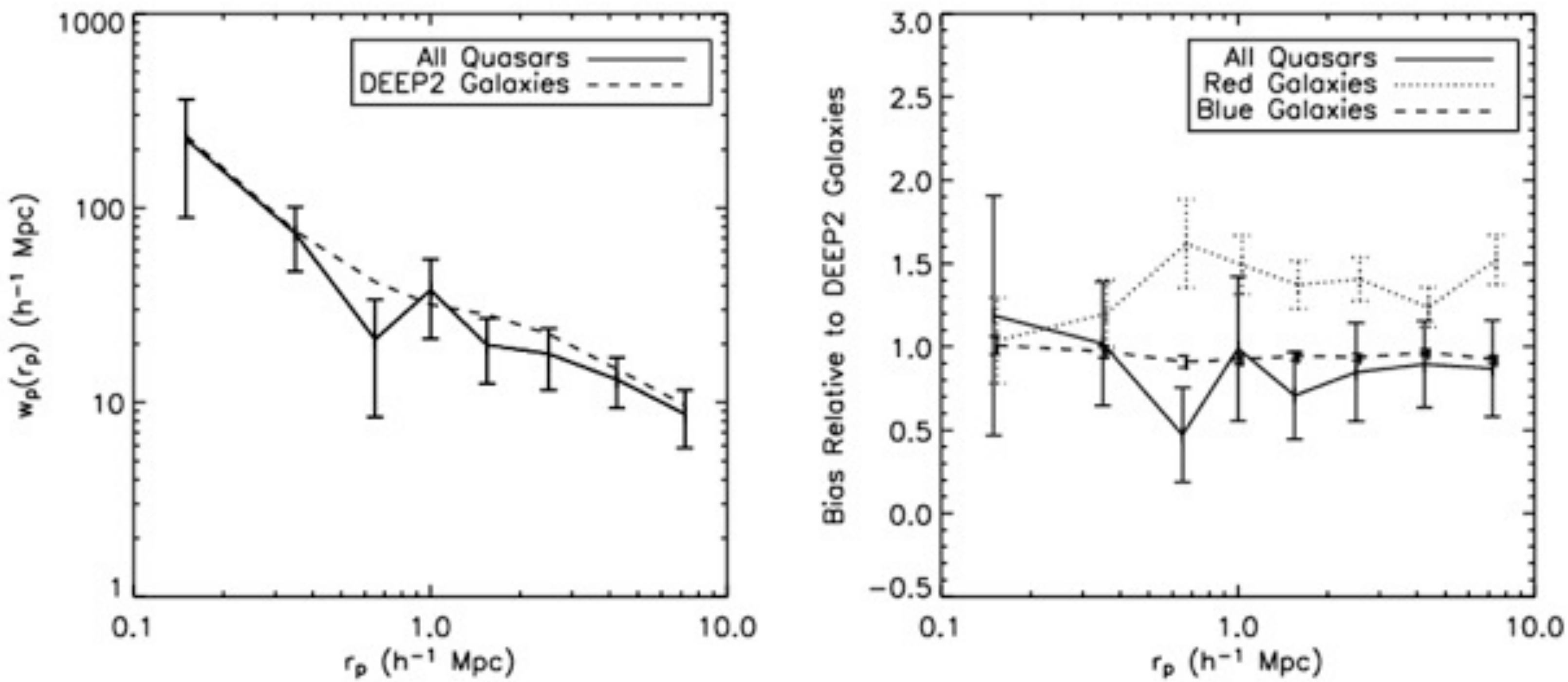


(Farrah et al 2006; wrong Δz)

Galaxies at z=2 with r0=10 h^-1 Mpc were claimed to be already clustered like very massive galaxies today. Growth of clustering brings these up to massive clusters. Galaxies at z=2 with r0=15 h^-1 Mpc have nowhere plausible to grow into. Should this worry you? Probably.

Spatial clustering: beating the Poisson noise with cross correlation

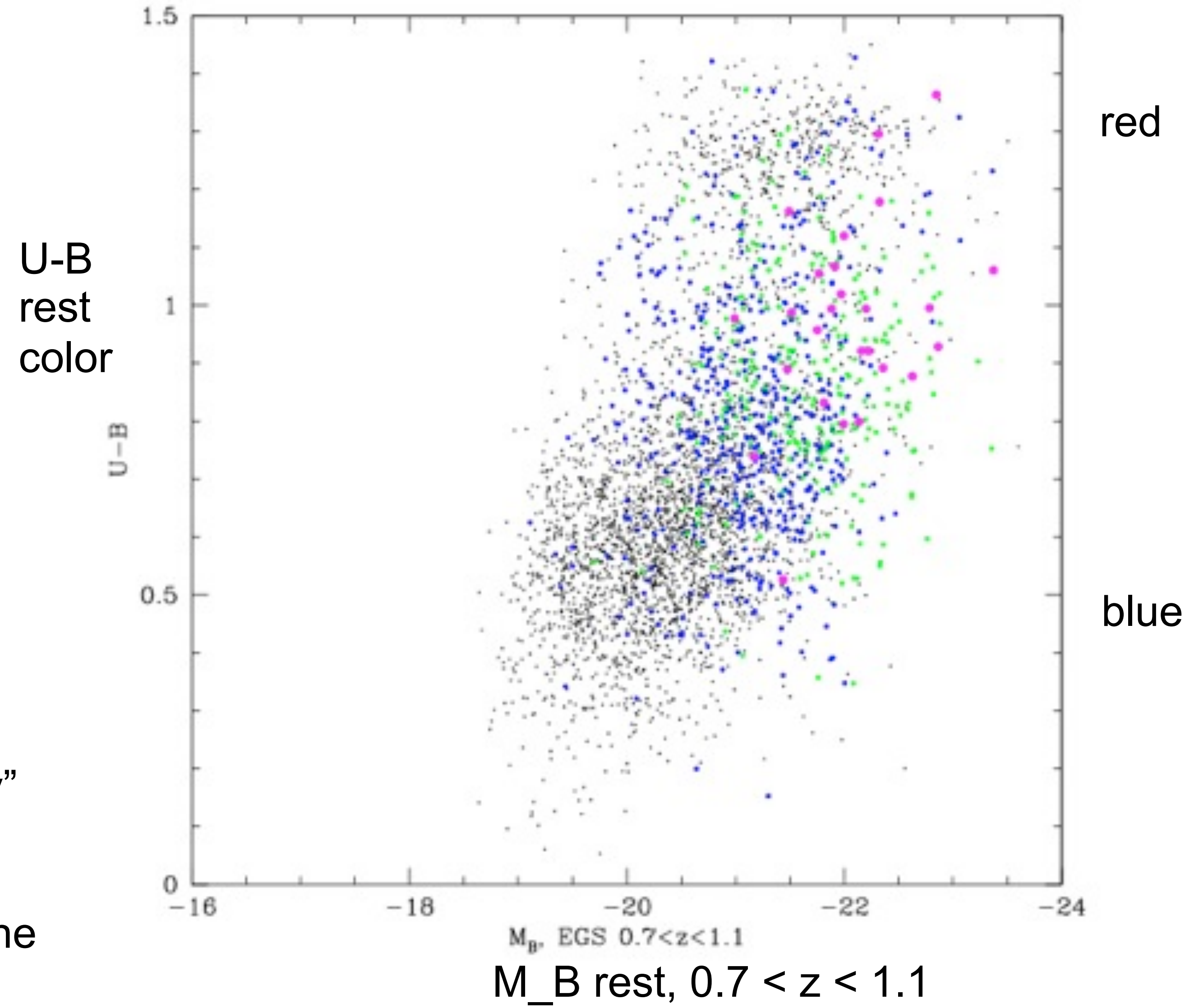
We can't measure spatial autocorrelation of rare objects: ULIRGs, QSOs, without huge samples. But given a large sample of galaxies, we can cross-correlate the ULIRGs to the galaxies.
(For example, imagine cross-correlating positions of museums with people.)



Coil et al 2006: 52 QSOs crossed with 5000 DEEP2 galaxies:
z=1 QSOs are clustered like all galaxies, not like red galaxies.
Coil et al 2009: X-ray AGN are clustered like red galaxies.

We took MIPS data to 200 μJy in DEEP2 field 2, to do this for ULIRGs.

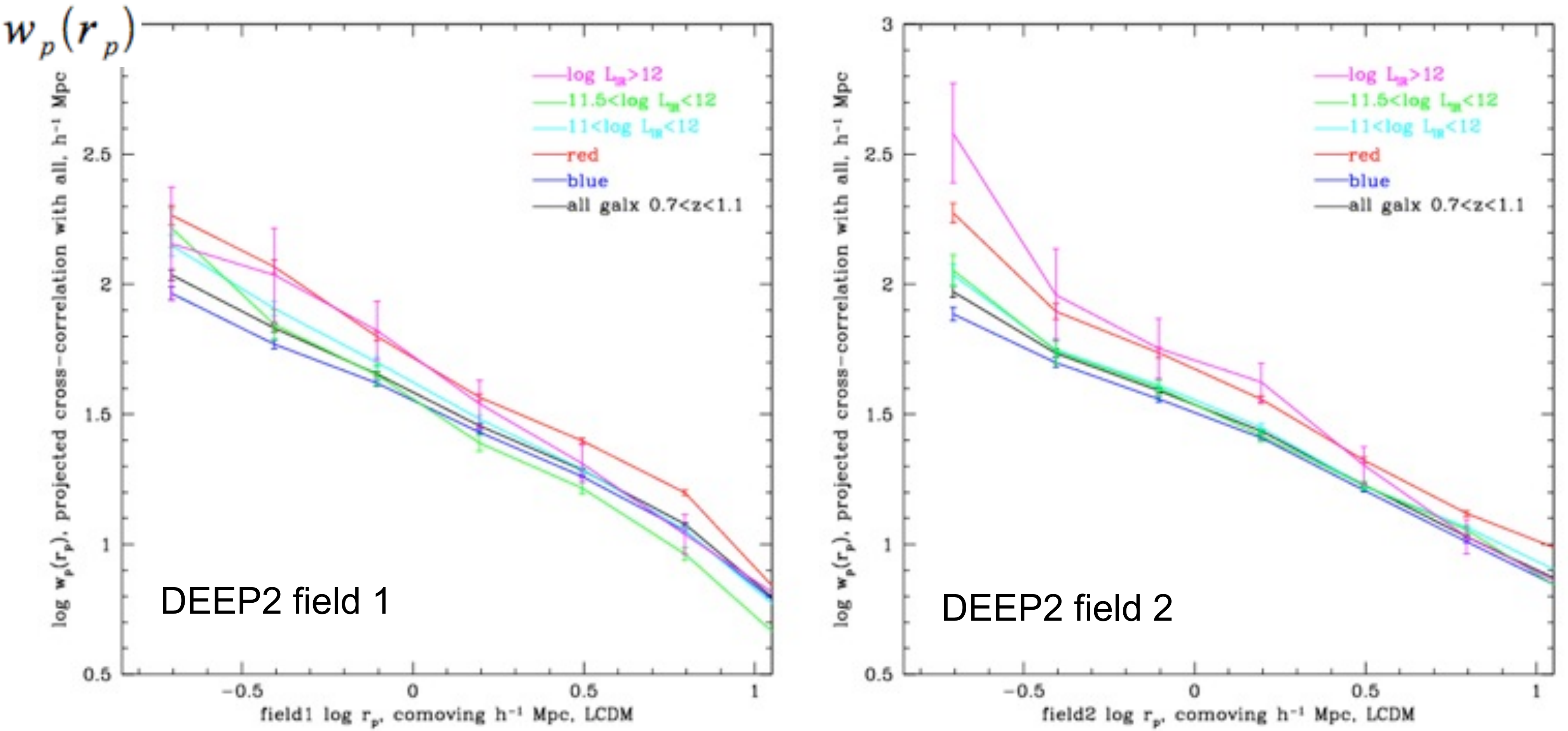
Where do the z~1 ULIRGs and LIRGs sit in color-luminosity?



LIRGs, L_IR > 10^11 Lsun
and brighter LIRGs,
L_IR > 3 x 10^11
are the brighter end of
the blue galaxy population,
edging into the “green valley”

ULIRGs, L_IR > 10^12,
are among the brightest of the
blue or green valley.
Despite being very dusty, they
do not live on the red sequence.

Cross-correlation measurements at 0.7<z<1.1   (two fields)



LIRGs are very similar to blue/intermediate galaxies
ULIRGs are as clustered as red galaxies at few Mpc
ULIRGs may show a steeper correlation fn. slope than red galaxies

ULIRGs => probably occurring in groups (no rich clusters in DEEP2)
Strong clustering, but r_0 is not large (not ~10 Mpc!)
Beware inferring halo mass directly from r_0 or angular clustering.

Some conclusions:

Cross-correlation with galaxy redshift surveys is an efficient method for measuring clustering.

LIRGs (L_IR>10^11) at z=1 are intermediate color galaxies and are clustered like them; many look like spirals; they are less clustered than if they were to mostly evolve into massive ellipticals.

ULIRGs at z=1 are clustered like massive red galaxies, which will give them r0 ~ 4-6 h^-1 Mpc. They mostly look like mergers. They will most likely evolve into red galaxies, but do not have to be a cluster population.

ULIRGs at z=1 are more clustered than the z=1 QSOs, suggesting the ULIRG -> QSO -> elliptical scenario is oversimplified.

ULIRGs at z=1 are not as extreme as the ULIRG at z=2 samples. But the assumptions underlying the z=2 angular clustering measurements may have problems.

Looking toward the future:

To get large samples of rare objects, need wide and fairly deep surveys. It is very helpful to have lots of galaxy redshifts in the same volume.

Before Spitzer warmed up, the Spitzer/MIPS MAGES project surveyed the Bootes field to about the same 24 micron depth as our field 2 observations, but 9 sq degrees. This will yield many IR-luminous galaxies, although the existing redshift survey in Bootes (AGES) is mostly $z < 0.5$ to 1.

The Herschel satellite will measure many objects at longer wavelengths than Spitzer, but does not go much deeper.

Redshift = 2 objects are really interesting; large redshift surveys at $z=2$ will be time-consuming or worse; many groups are planning these with multi-object near-IR spectrographs.

Our last all-sky far-IR imaging survey was IRAS, and the newly-launched WISE satellite will provide a much needed step forward, a survey which can be crossed with e.g. SDSS and SDSS-3.

ALMA will be able to measure molecular gas masses and redshifts for many $z \sim 2$ galaxies. Even with current mm telescopes (IRAM) we are beginning to measure gas masses for galaxies at $z=1$-2.