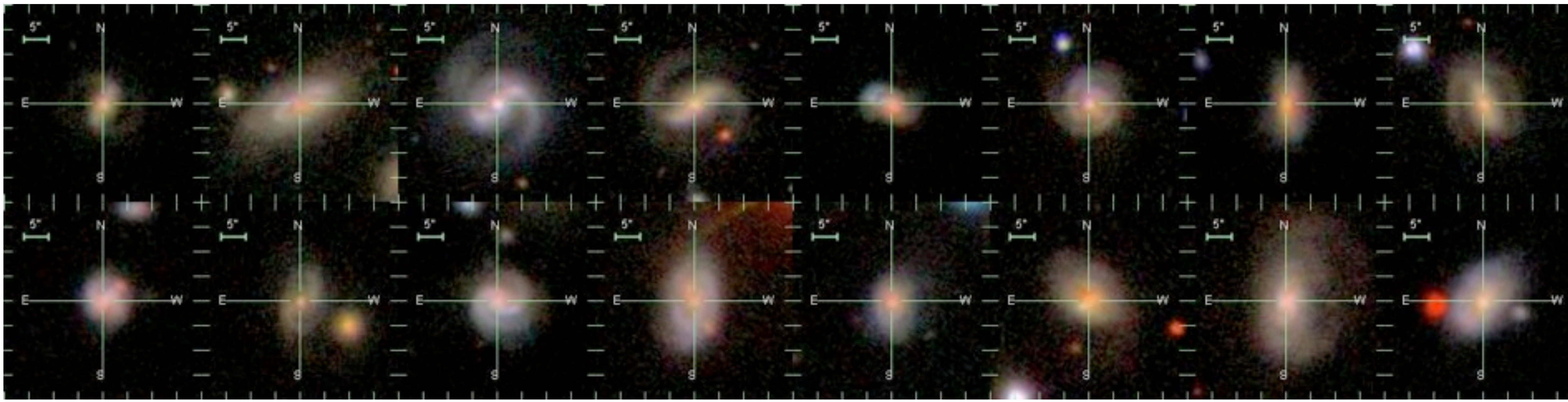
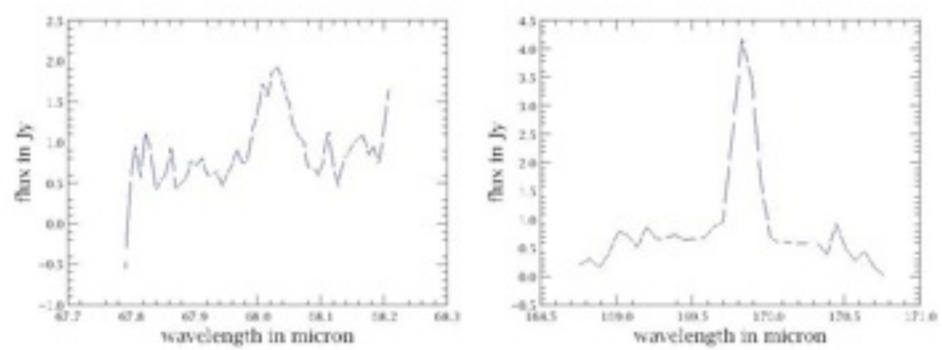
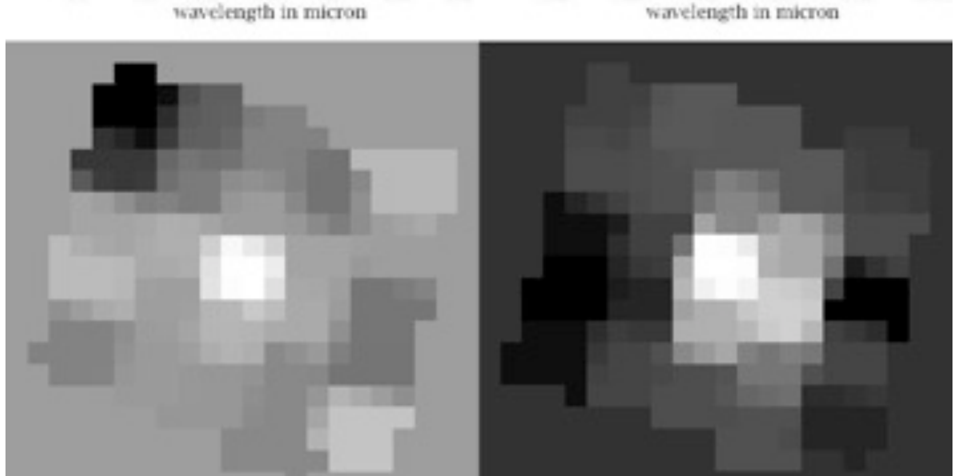
Far-infrared line spectroscopy as a probe of star forming regions in disks, or LIRGs, or disky LIRGs - and the nature of high-z star forming galaxies







Benjamin Weiner
Steward Observatory

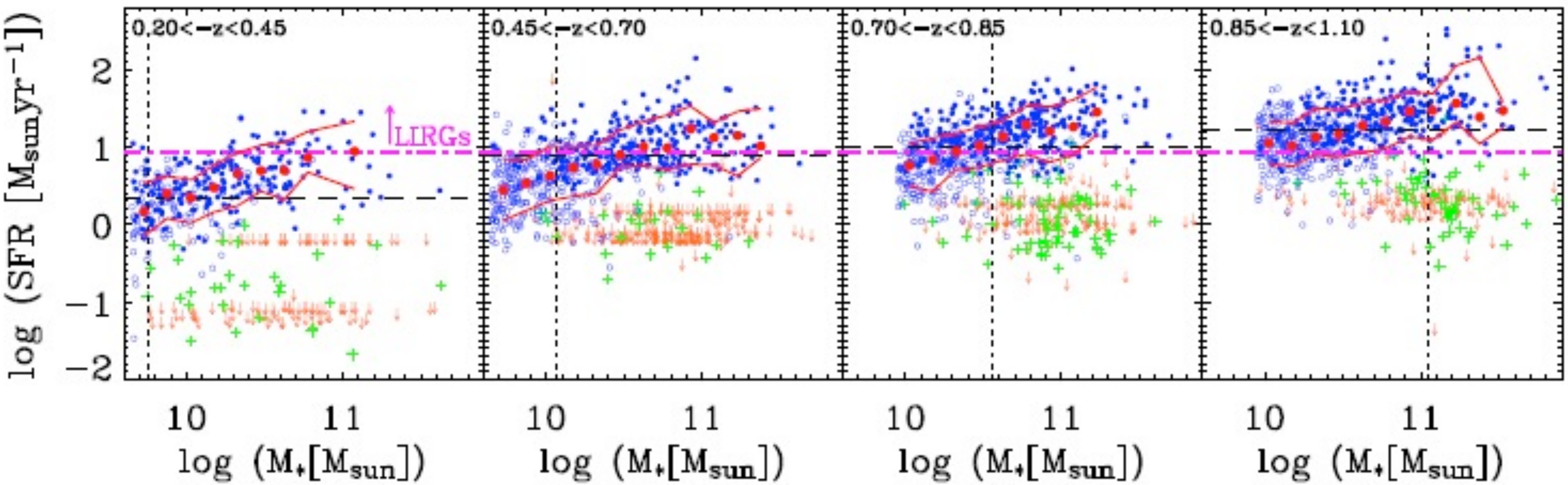
with Almudena Alonso-Herrero
Wiphu Rujopakarn
George Rieke
Eiichi Egami

In the local universe, IR luminosity is tied to galaxy properties such as SED shape and merger stage. How will this change when we try to understand galaxy evolution across redshift?

What can we use as local analogs for high-z galaxies?
Is a distant LIRG or ULIRG (L>10^11, 10^12 Lsun) similar to a local LIRG or ULIRG?

Far-IR line emission is a probe of galactic star formation: use it to address these questions, with Herschel and sub-mm telescopes.

Context: High SFR in all blue galaxies at z=1: not just in mergers



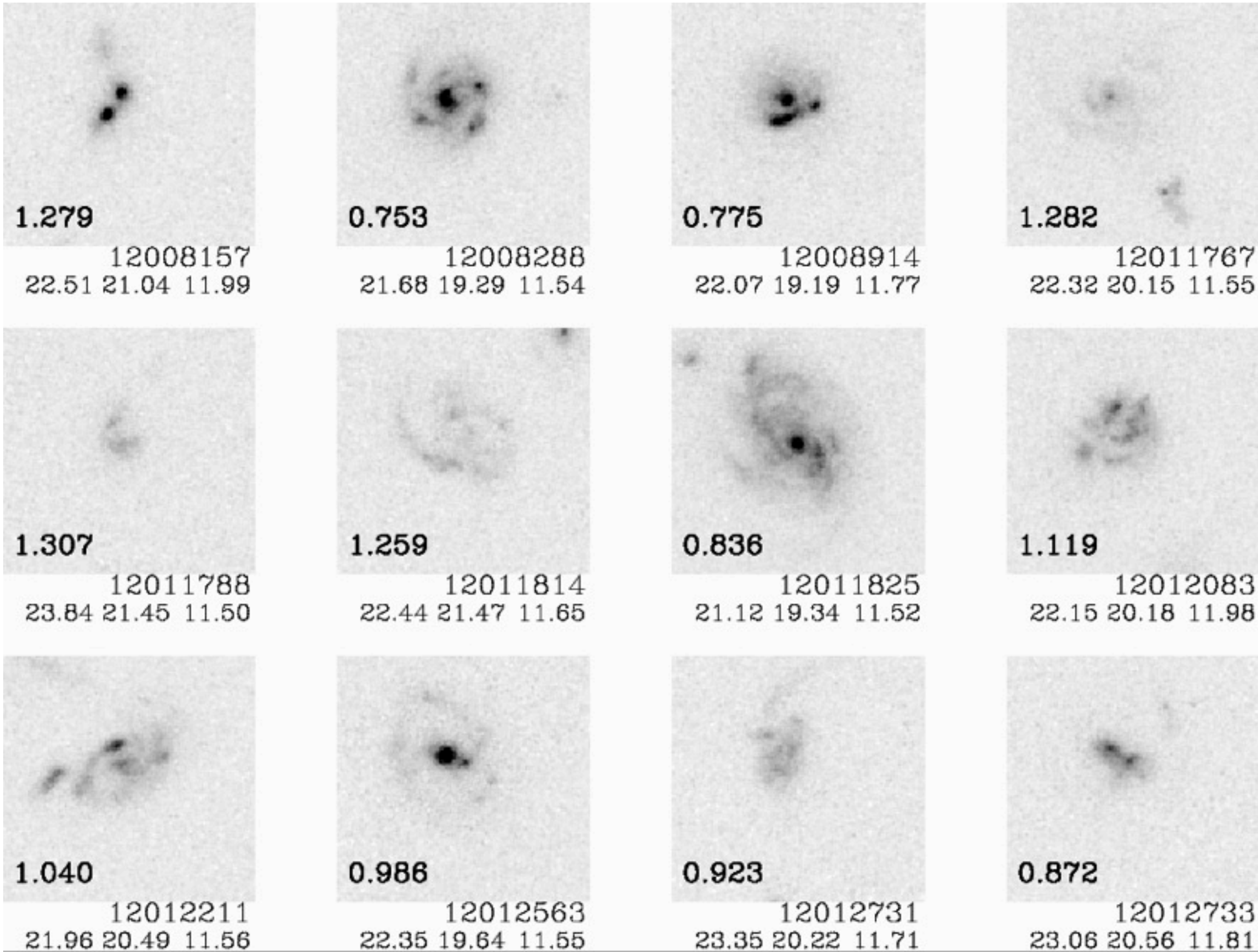
(from Kai Noeske, BJW et al 2007; also X. Zheng et al 2007)

At z=1, the global SFR is 10x higher than today – in what galaxies does this occur?

DEEP2 sample, using SFR from both far-IR (Spitzer/MIPS) and nebular emission lines.
The scatter in the SFR-stellar mass relation is ~0.3 dex:
"main sequence," 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 all SF galaxies.

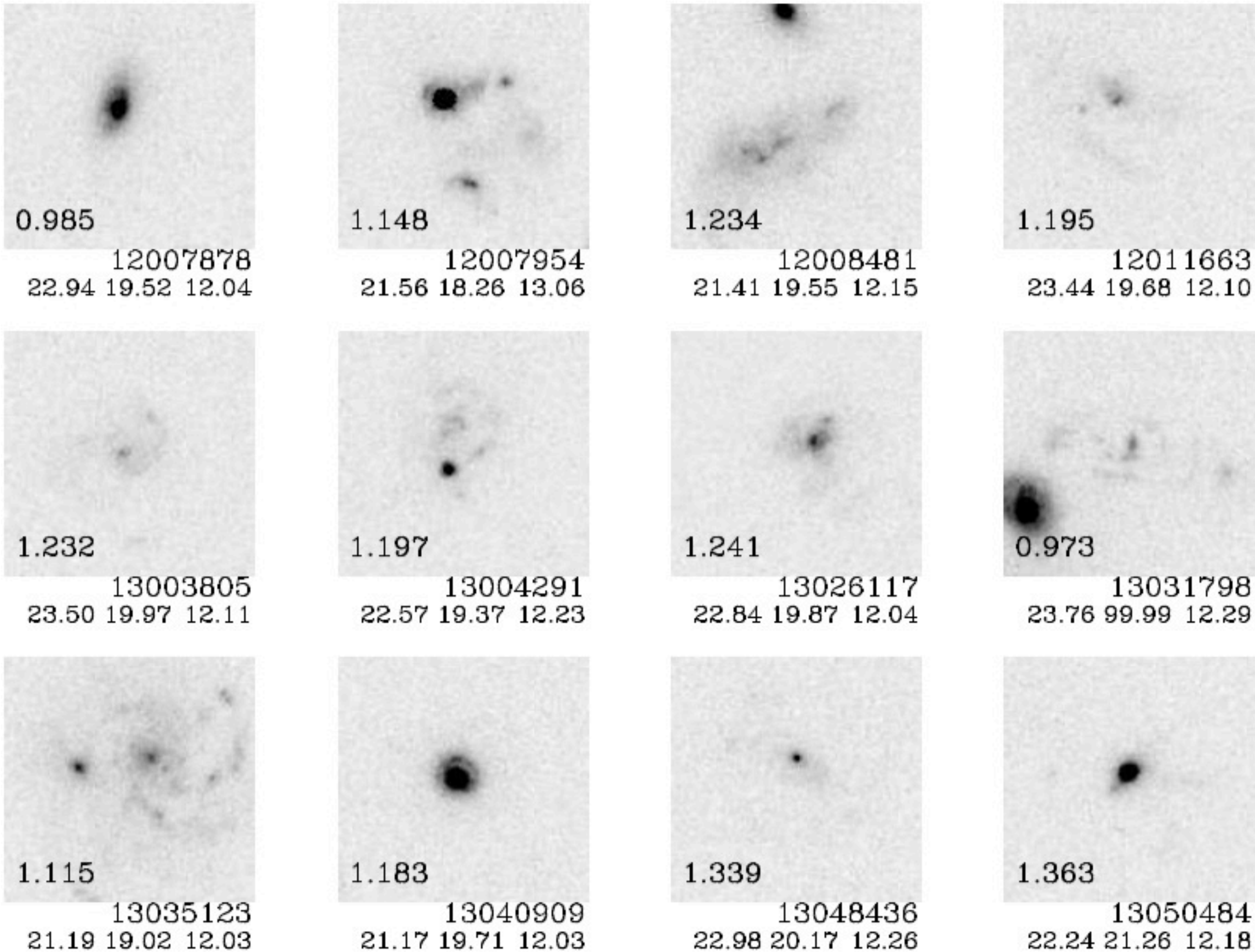
Locally, LIRGs are unusual and LIRG/ULIRGs are typically major mergers,
but at z=1, most star forming galaxies at M*>1e10 are LIRGs, SFR > 10 Msun/yr.
Local IR-luminous galaxies may not be good predictor of high-z properties.

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



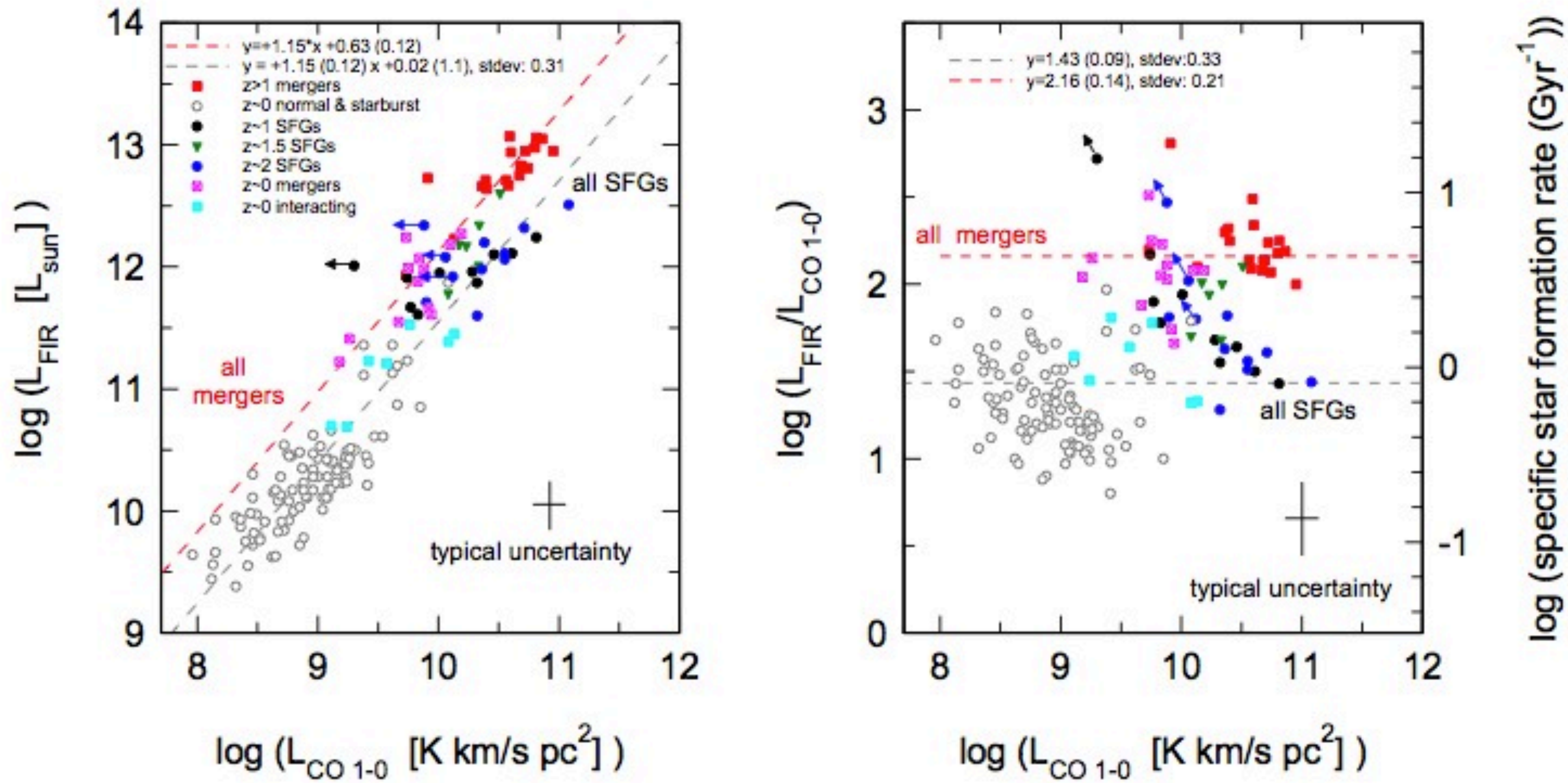
At z=1, IR-luminous galaxies more common; some LIRGs are spirals

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



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

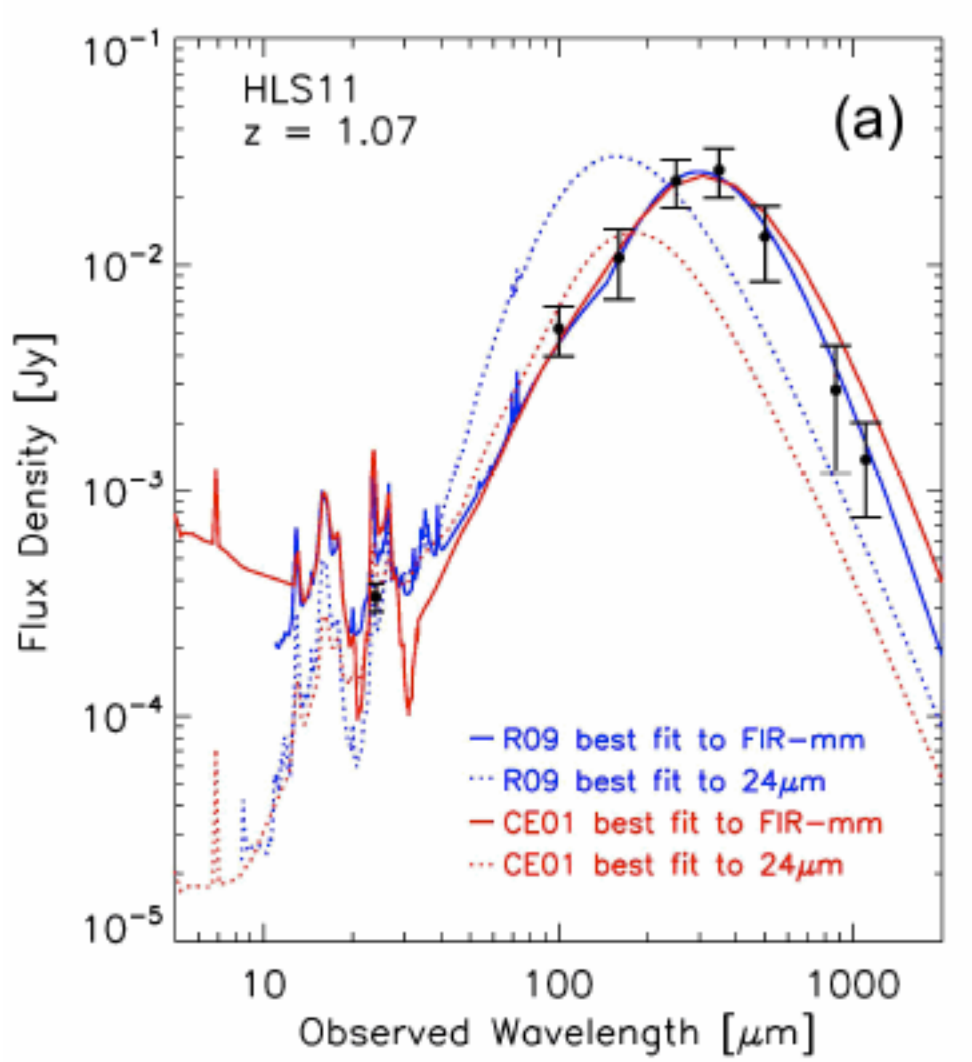
Are there two “modes” or density regimes of SF - mergers and disks? Related to spatial extent of star formation?

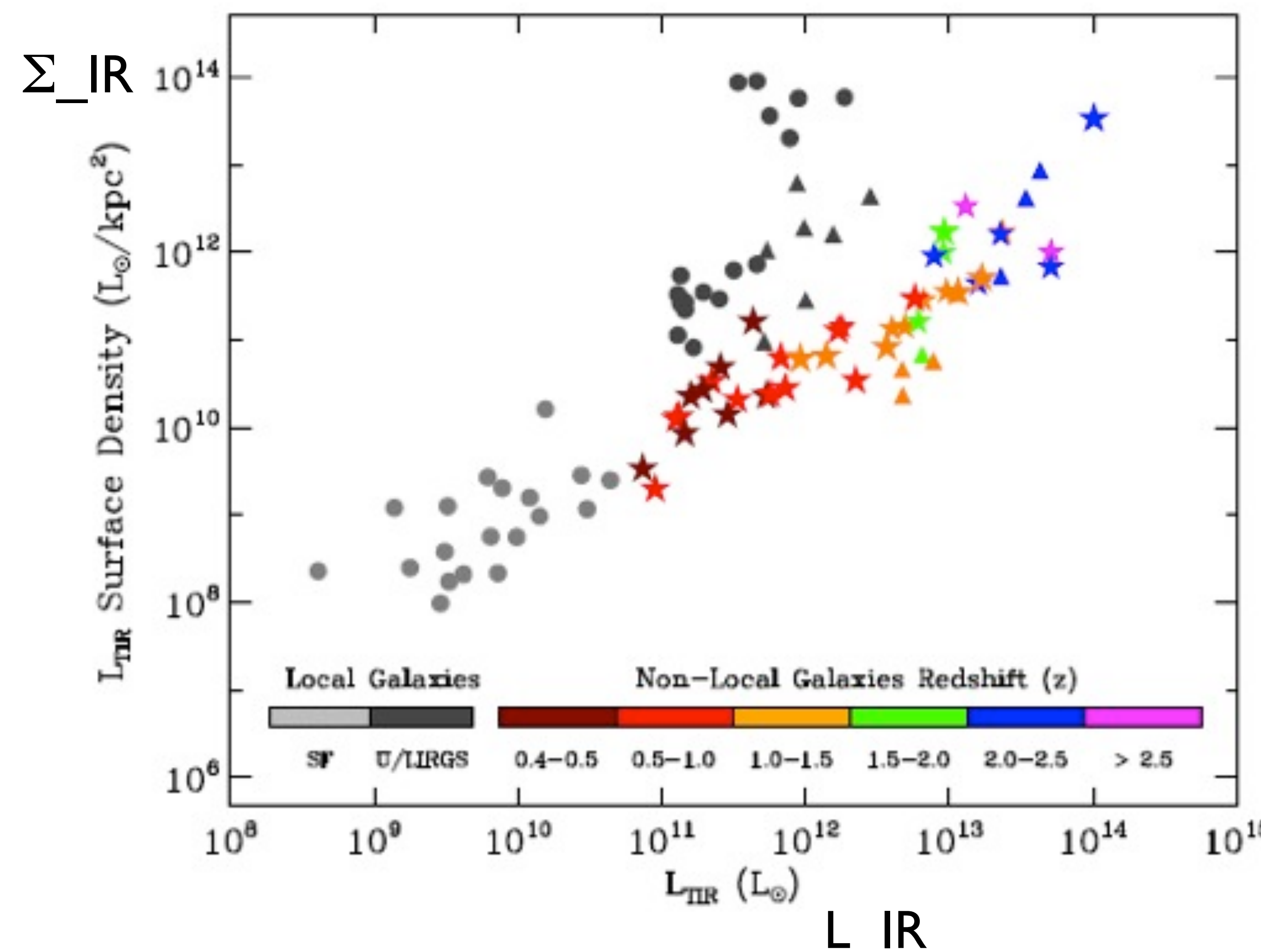


(Tacconi et al 2010; Genzel et al 2010)

Mergers and ULIRGs are at higher L(FIR)/L(CO), while high-z star forming galaxies are at similar value of SF efficiency to low-z SFGs.
Limited size information suggests high-z SFGs are on a Kennicutt-Schmidt relation.
Existence of separate relations is controversial.
Note that high-z SFGs can have modest SF efficiency, at an L_IR that is very high in low-redshift terms.

Evolution in properties of IR-luminous galaxies: surface density?





Rex et al 2010:

SED shapes of IR galaxies at z=1-2 match the shapes of lower-luminosity local galaxies: luminosity to SED relation is shifted. Causes overestimates of L_IR from observed flux at z>1. (also Papovich+ 2007; Rigby+ 2007; Elbaz+ 2011; Nordon+ 2011)

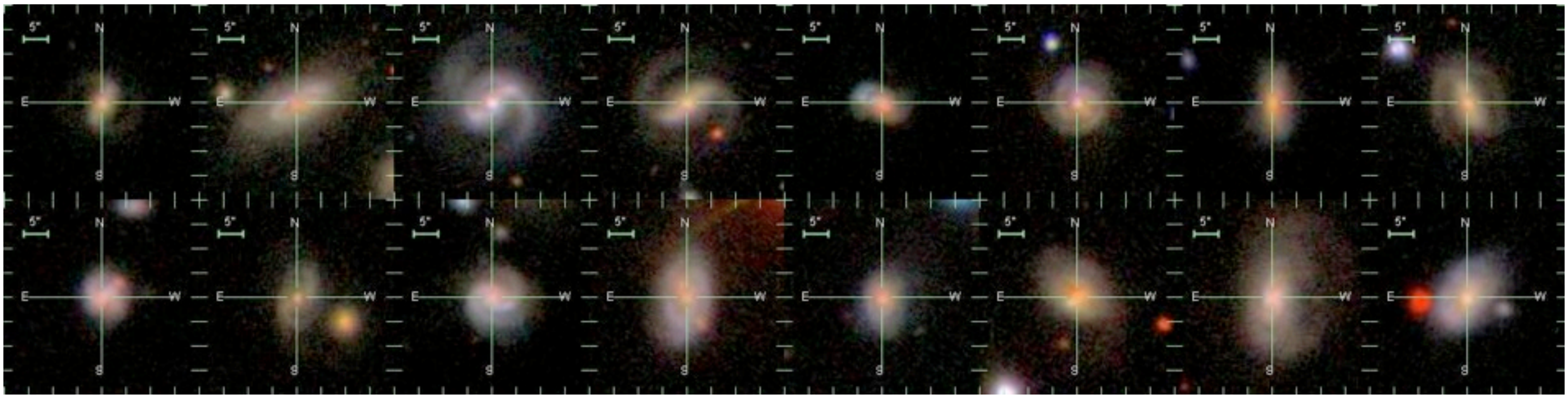
Rujopakarn et al 2010:

high-z very IR-luminous galaxies have larger star-forming radius (in radio or CO) than do local ULIRGs, so there is a difference in L_IR surface density. May explain evolution in IR spectral shapes. Could be related to SF efficiency. But, these sizes are *difficult* to measure.

A sample of disky U/LIRGs at low redshift

Low-redshift ULIRGs and bright LIRGs (L_IR > 3e11 Lsun) are almost always mergers.

But not always! We selected a sample from IRAS + SDSS at L_IR = 3e11 - 1e12 L_sun that are large radius, disky non-mergers, non-AGN. These are z ~ 0.1 and bright, so Herschel/PACS spectra are possible.

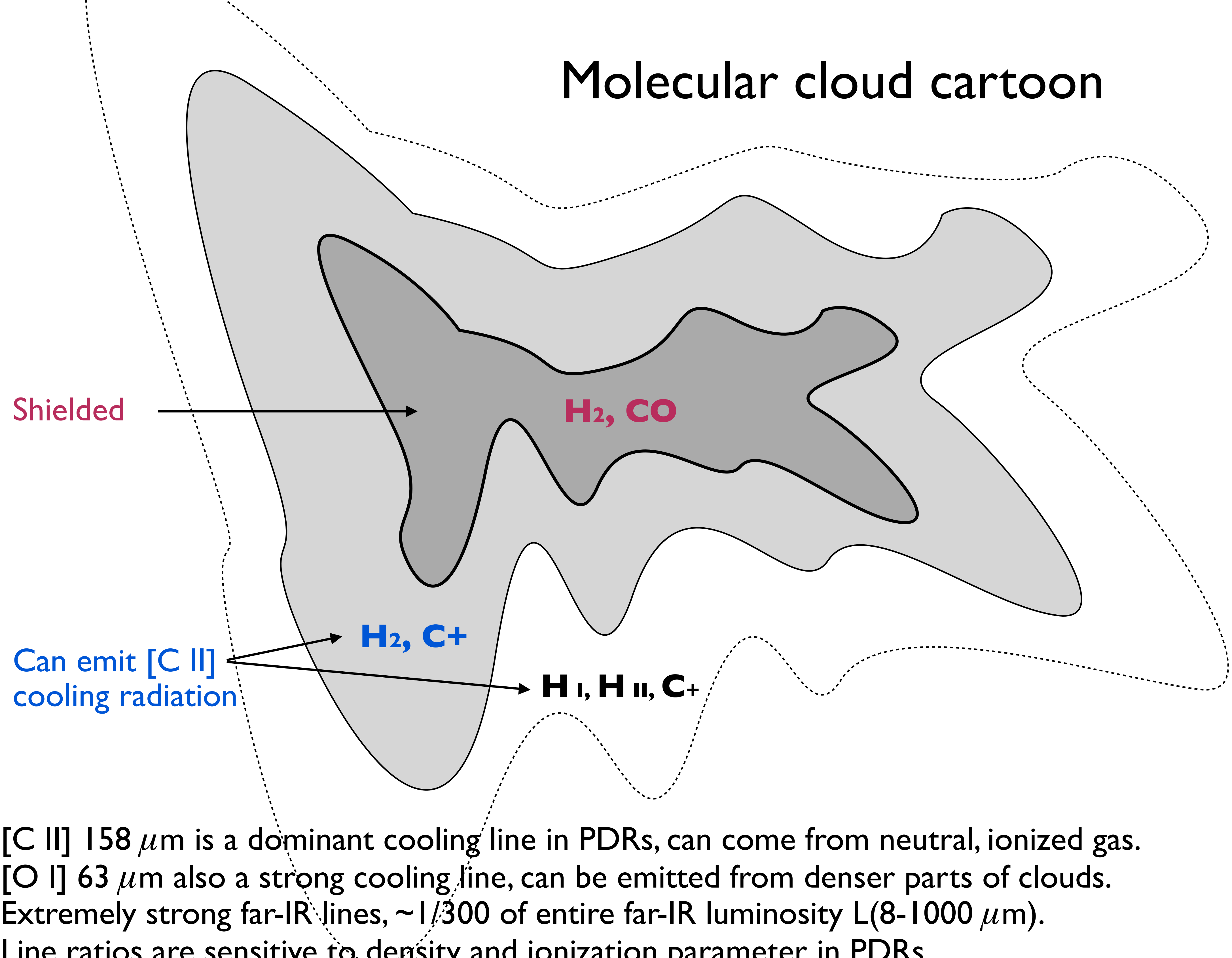


Even after a large-optical-diameter selection, these galaxies were only about 5% of the ULIRG/ bright LIRG population in IRAS + SDSS.

They are big disk galaxies, with strong nebular lines (Hβ, [O III], Hα) and likely high gas mass.

Far-IR spectra probe physical conditions in star forming regions, and can test whether these are analogs of high-z star forming galaxies with high gas mass and L_IR.

Molecular cloud cartoon

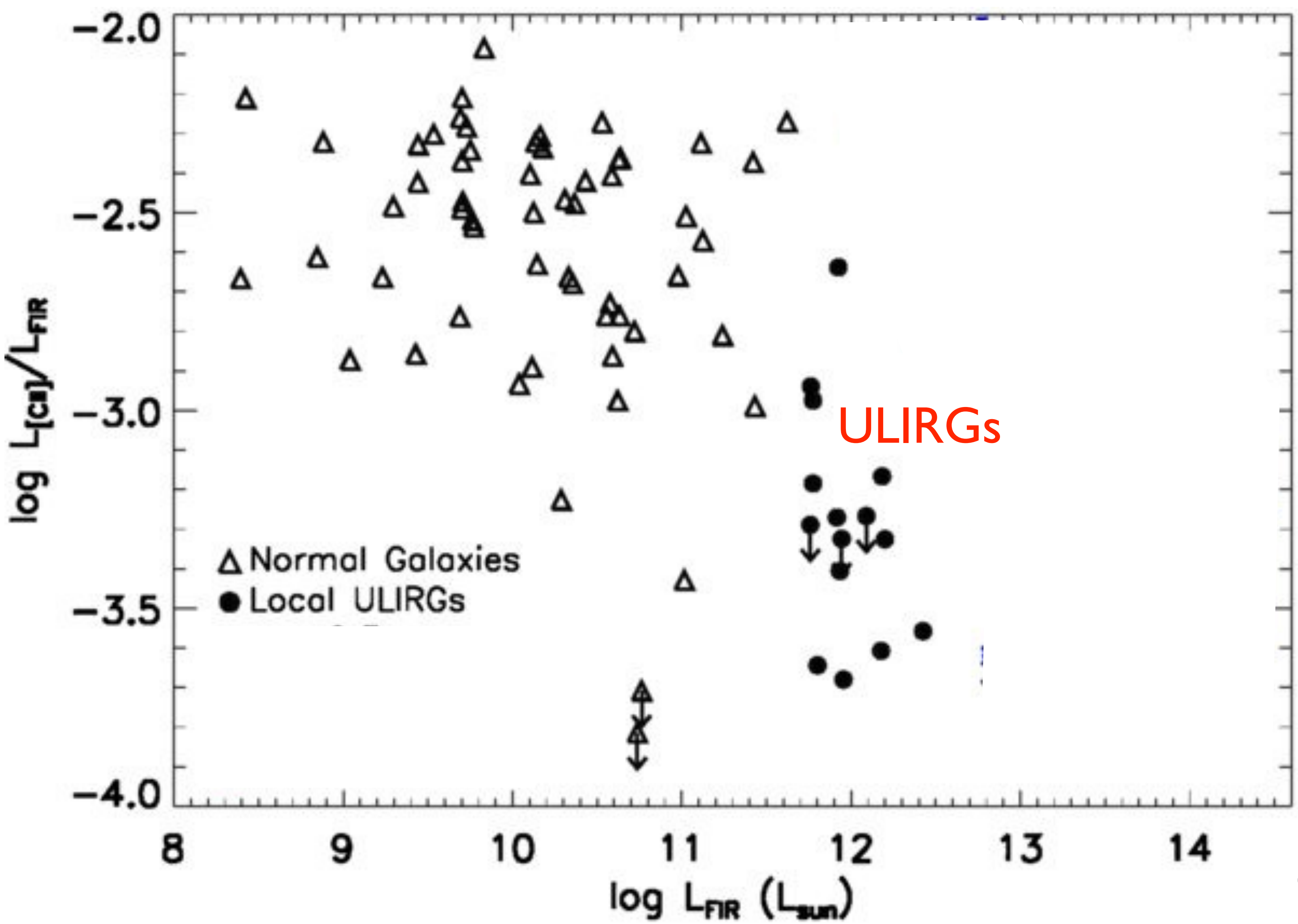


[C II] 158 μm is a dominant cooling line in PDRs, can come from neutral, ionized gas.
[O I] 63 μm also a strong cooling line, can be emitted from denser parts of clouds.
Extremely strong far-IR lines, ~1/300 of entire far-IR luminosity L(8-1000 μm).
Line ratios are sensitive to density and ionization parameter in PDRs.

C ionization potential 11.3 eV, [C II] 158 : nominal n_crit ~ 4e3 cm^-3
O ionization potential 13.6 eV, [O I] 63 : n_crit ~ 6e5

The "[C II] deficit"

L_[C II]/L_FIR



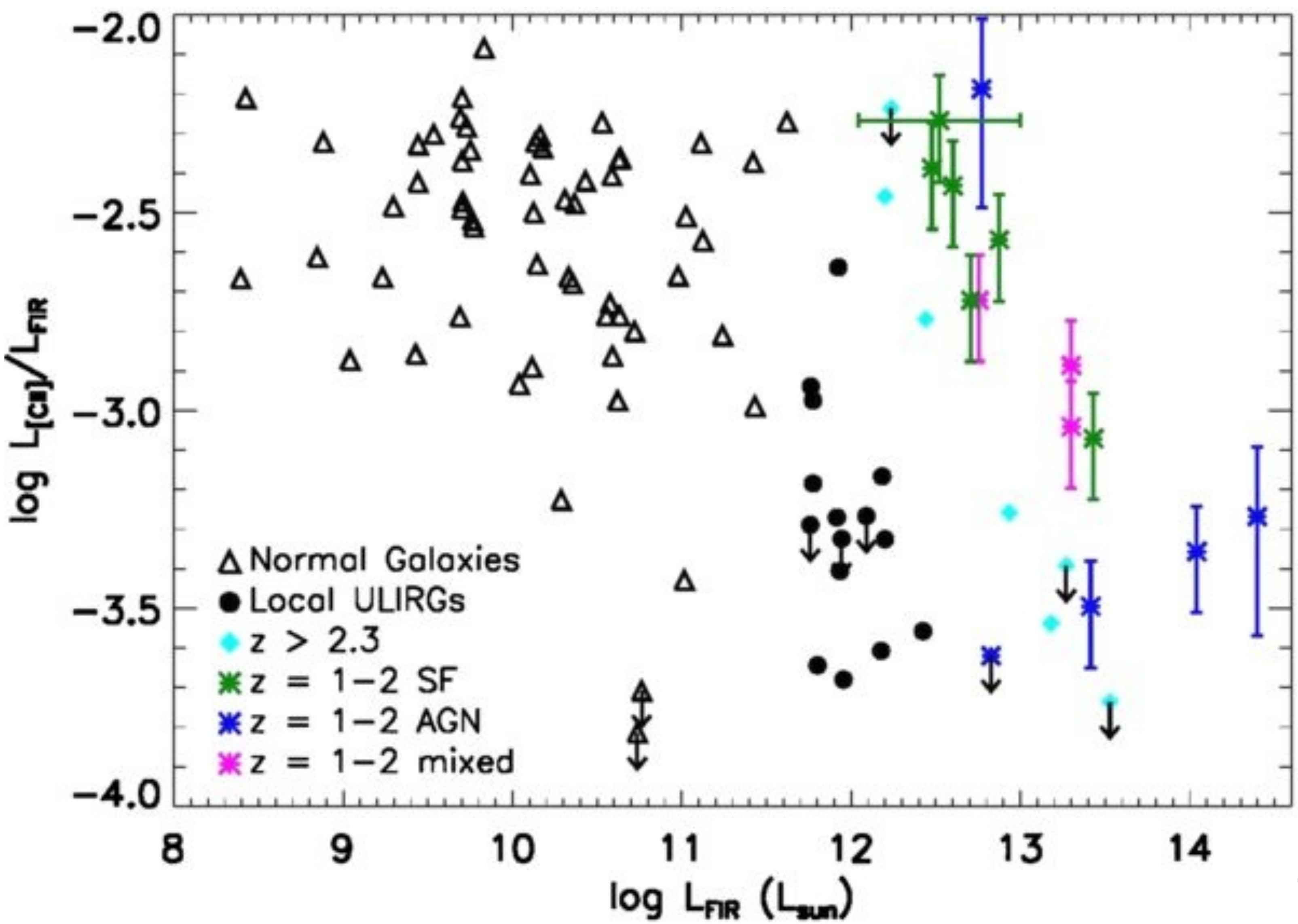
(from Stacey+ 2010)

Malhotra+ 2001, Luhman+ 2003: ISO spectra of [C II] 158 μm in SF galaxies and ULIRGs show that [C II]/FIR declines slowly with L_FIR, but is very low in ULIRGs, the [C II] deficit.

May be caused by higher ionization parameter and density in the ULIRGs; and/or FIR emission from non-PDR regions.
Linear scaling relations do not mean a ULIRG is simply a bigger star-forming galaxy or molecular cloud.

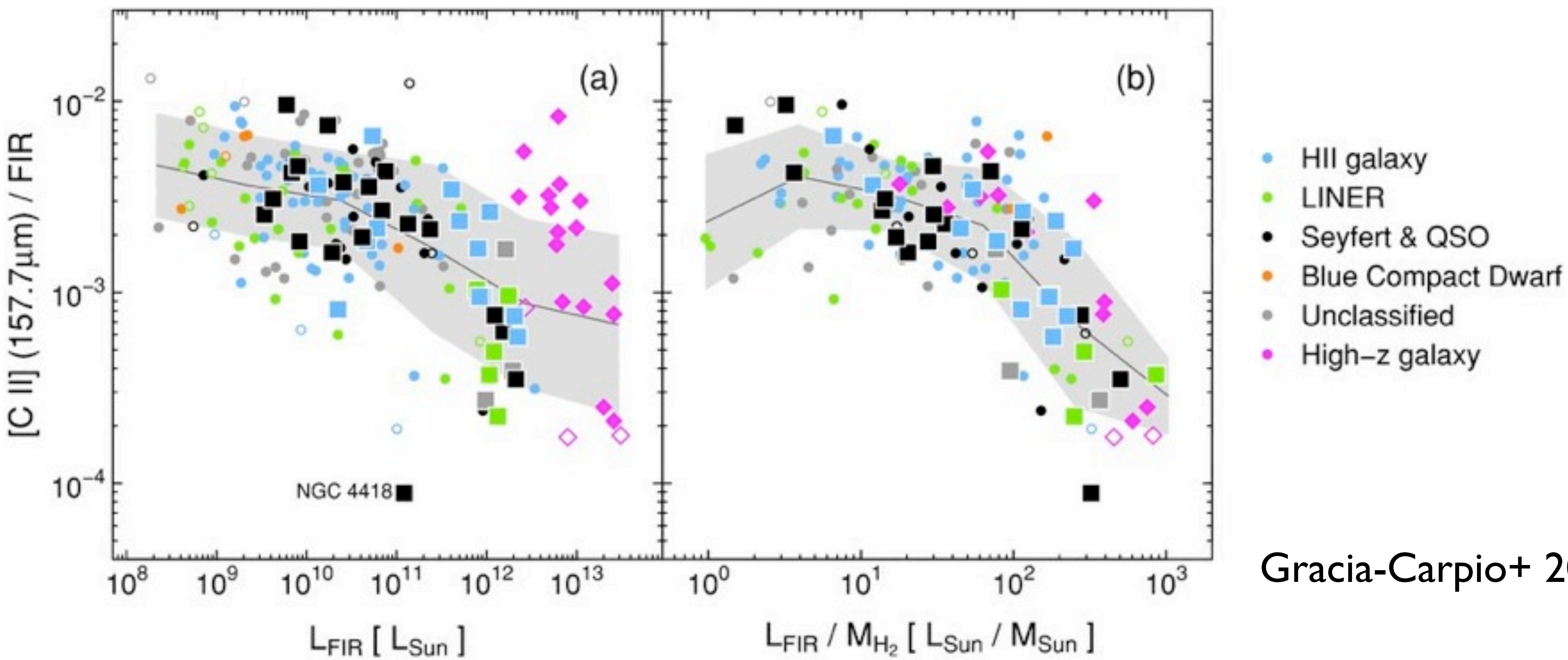
The "[C II] deficit" - high-z counterexamples

L_[C II]/L_FIR



(from Stacey+ 2010)

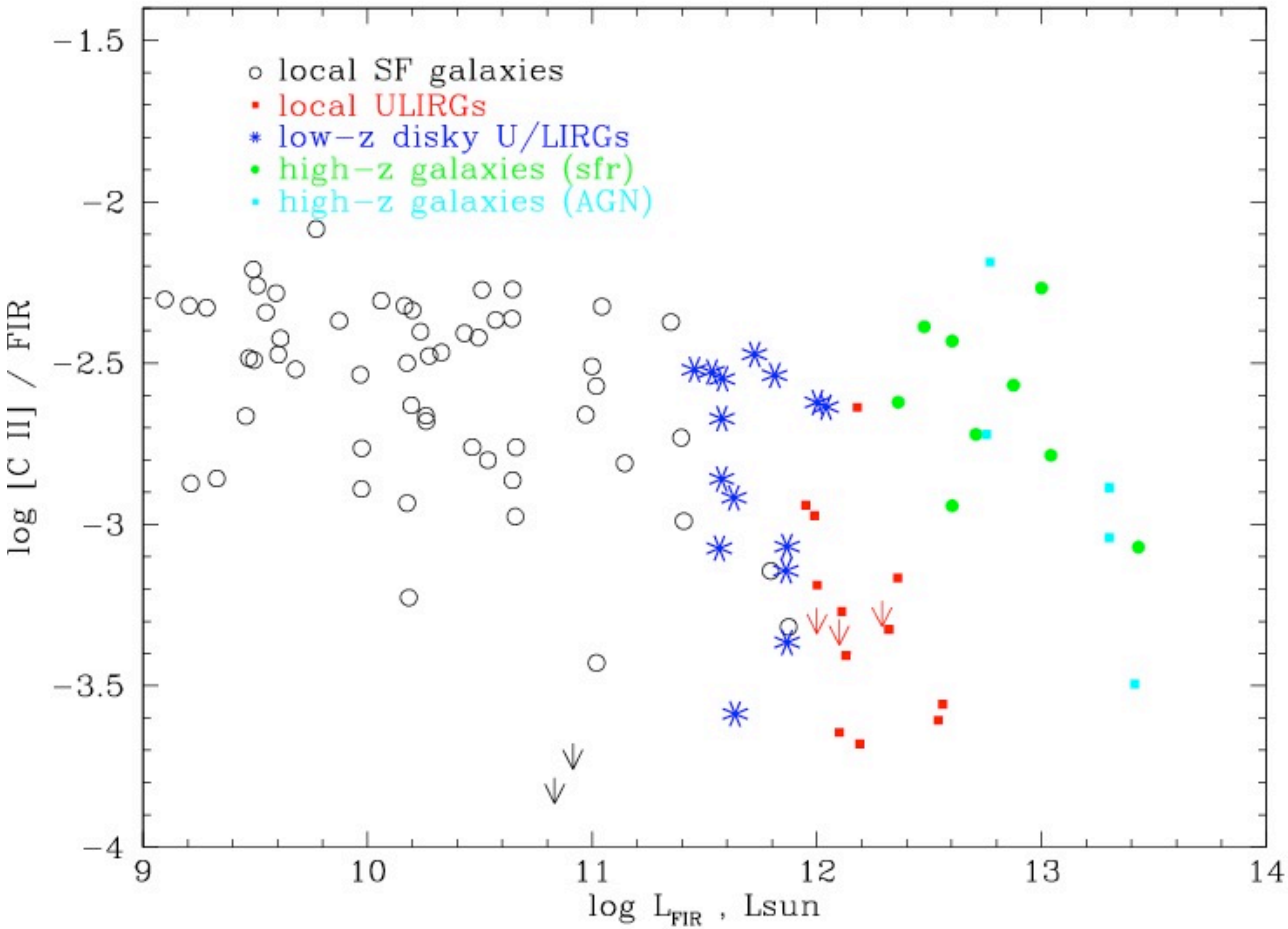
Stacey et al 2010: Recent measurements of [C II] in z=1-2 extremely IR-luminous galaxies (mostly sub-mm from ZEUS at CSO) often do not show the low [C II]/FIR seen in the local universe. Especially so for star formation dominated galaxies. Sign of different physical conditions compared to local ULIRGs? Perhaps larger star forming area?
But these are extreme objects, and getting far-IR line spectra of z>1 LIRG/ULIRGs is very difficult even for Herschel.



Gracia-Carpio+ 2011

Herschel/PACS spectra of [C II] in low-z galaxies from SHINING key project:
[C II] deficit at high L_IR still seen, exists in other far-IR lines as well.
May get lower scatter by plotting against L_IR / M(H2) -
if both ratios are related to density this is sensible.

Our PACS disky U/LIRG sample: strong [C II] emission, little deficit

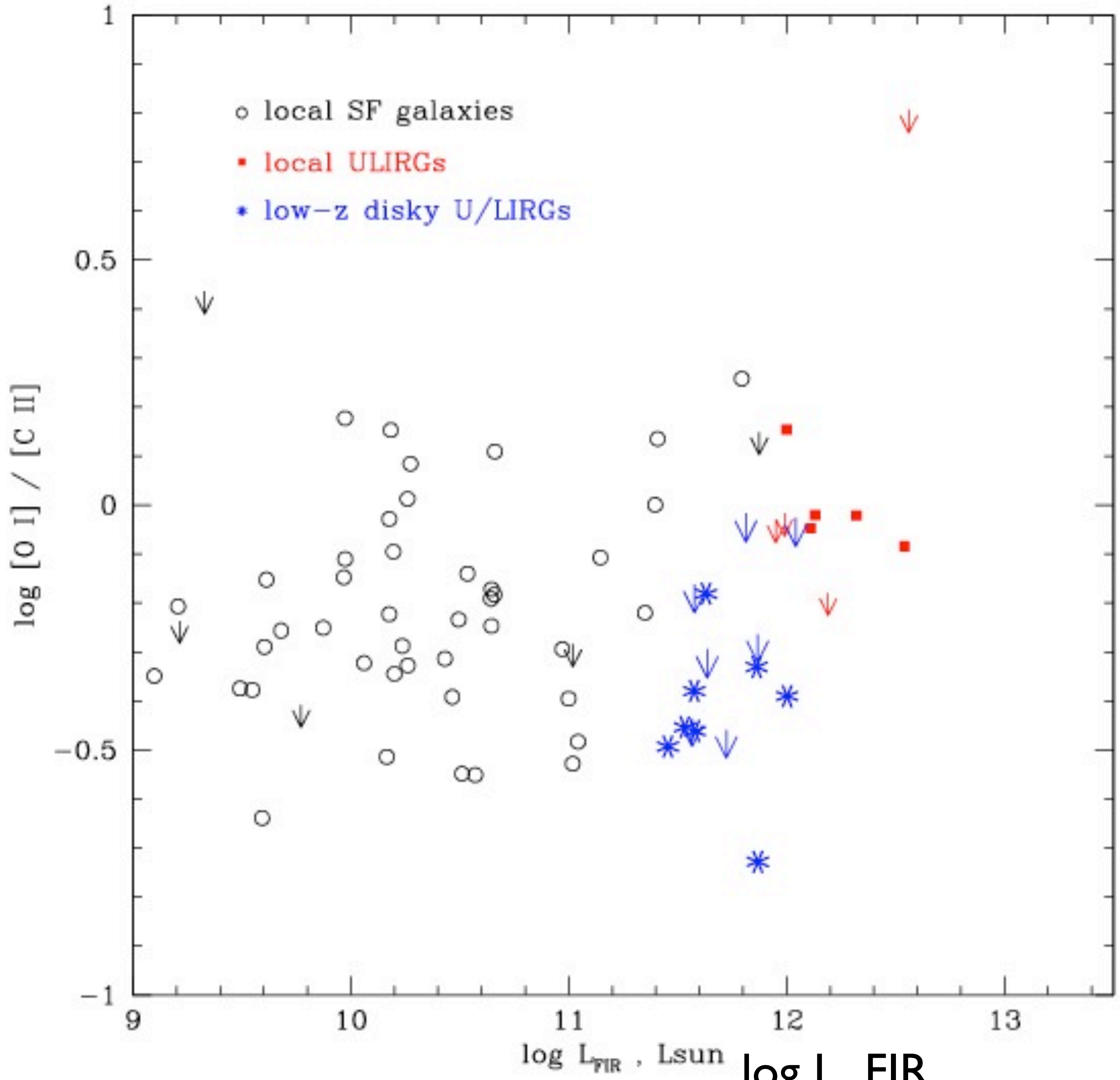


ISO:
Malhotra+ 2001
Luhman+ 2003
CSO high-z:
Stacey+ 2010
PACS disky
U/LIRGs

High [C II] / L_FIR in the disky galaxies suggests that surface density is a controlling factor, distinguishing them from low-z ULIRGs, more like high-z galaxies.
In fact, the lowest [C II] among our disks are also the smallest in Hα diameter.

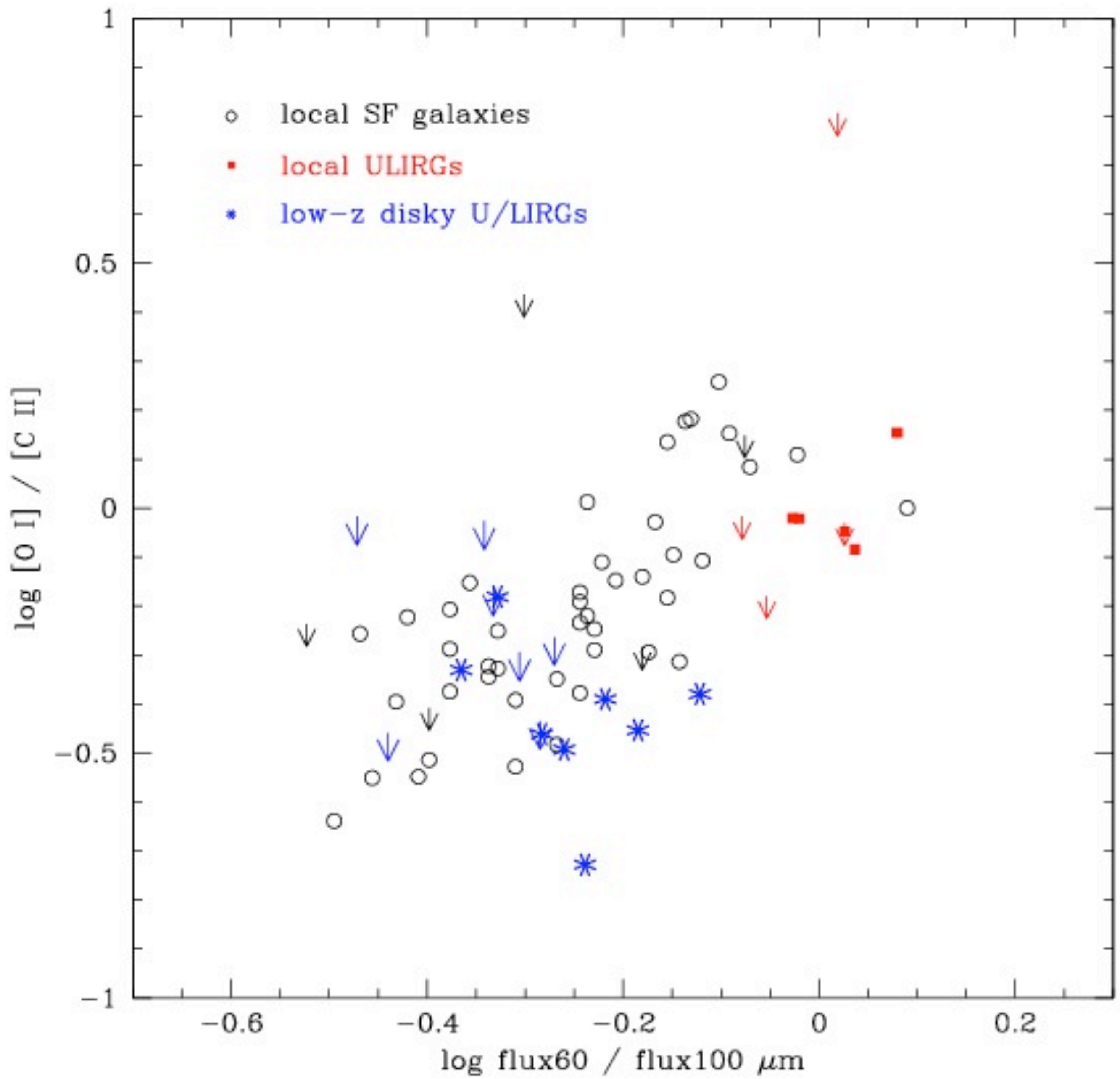
SF disks and ULIRGs are also offset in [O I] / [C II], possibly a density effect

log [O I] / [C II]



log L_FIR

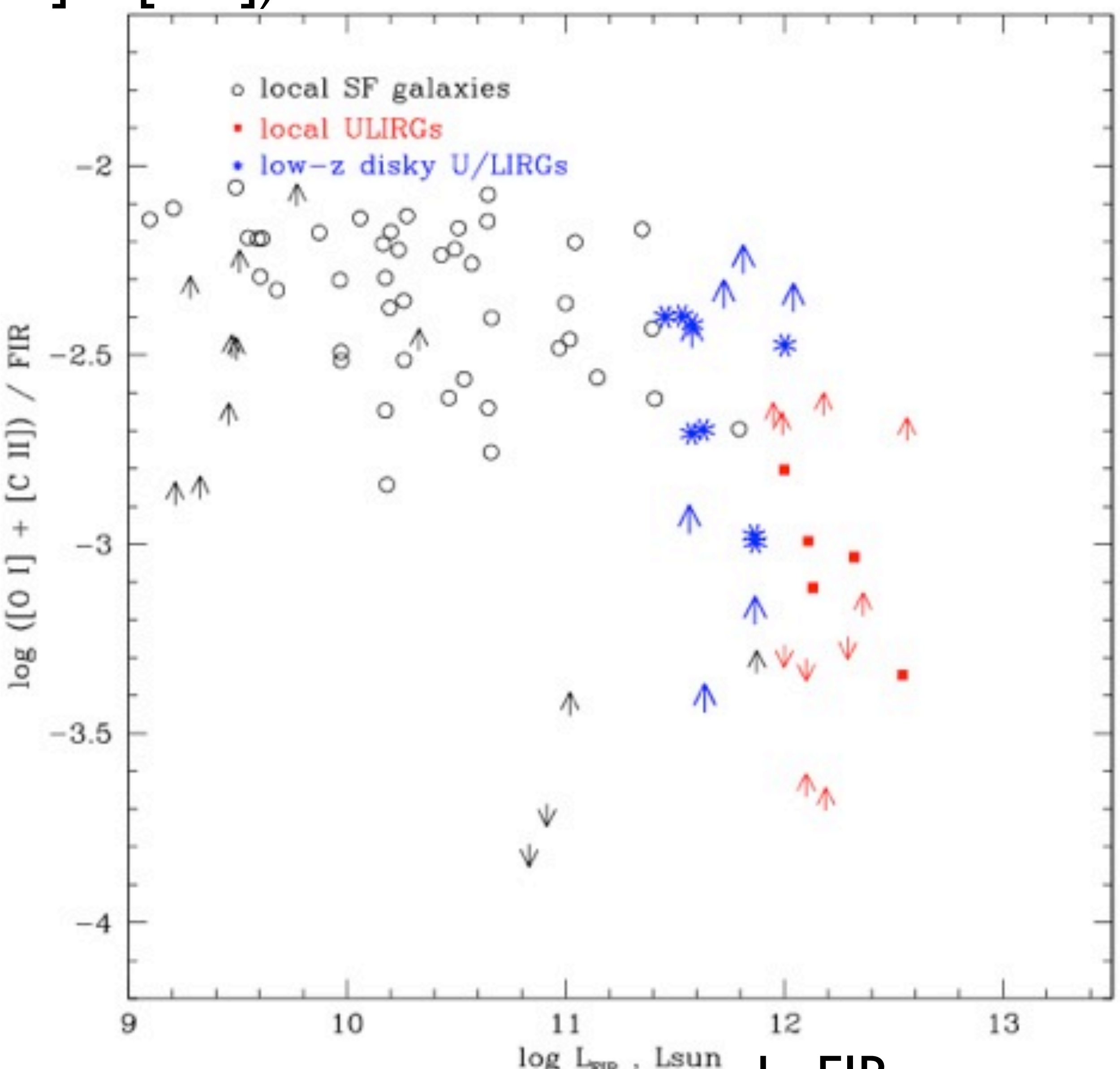
[O I] / [C II] ratio (density or ionization) is correlated with f_60 / f_100 (dust temperature)



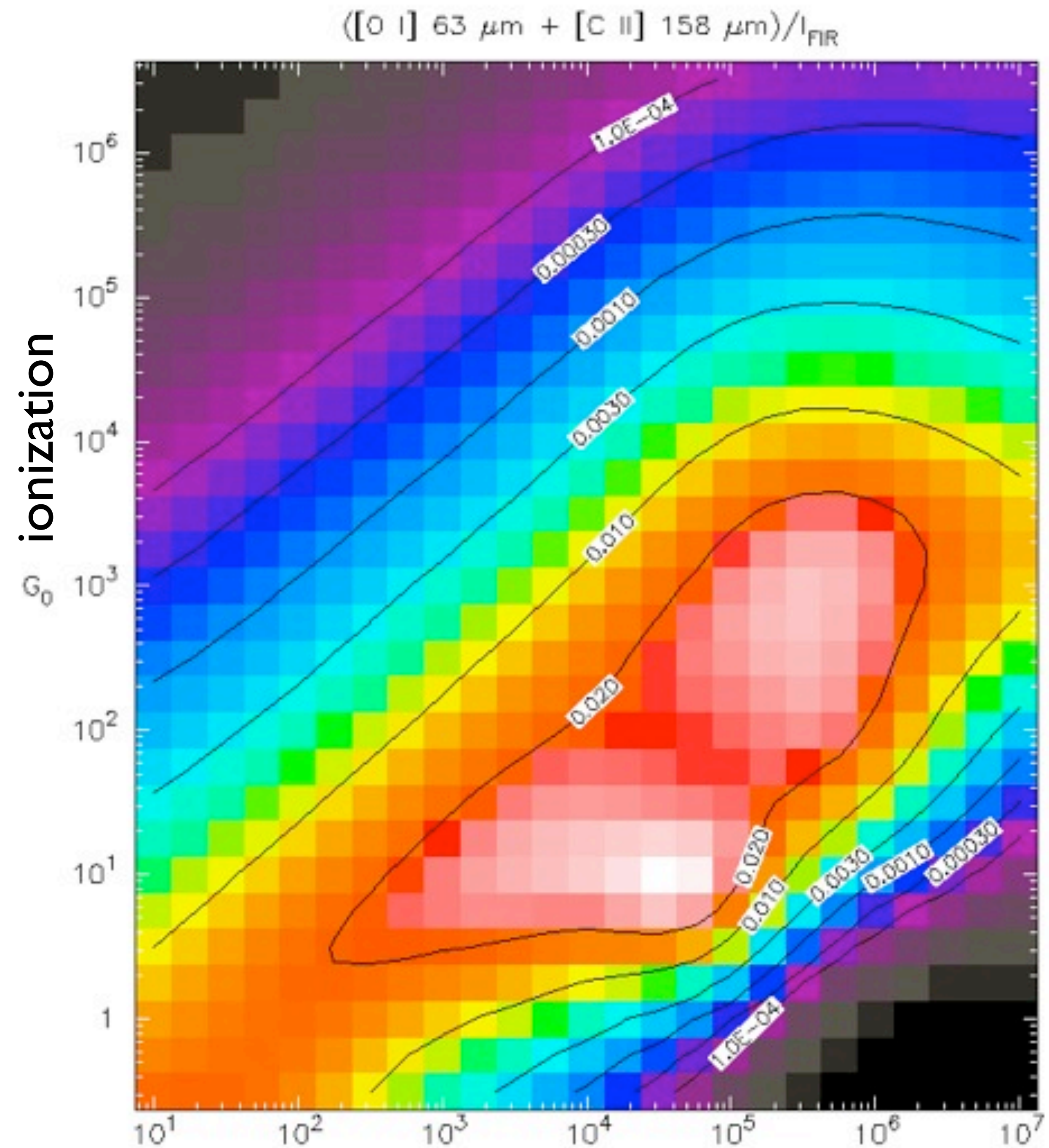
Correlation known from ISO data (Malhotra et al 2001). The disky LIRGs are cooler than ULIRGs, and shifted to lower [O I] or warmer dust compared to the lower-luminosity SFGs.

Line ratios and line/FIR can constrain density and ionization parameter in SF regions

([O I] + [C II]) / FIR



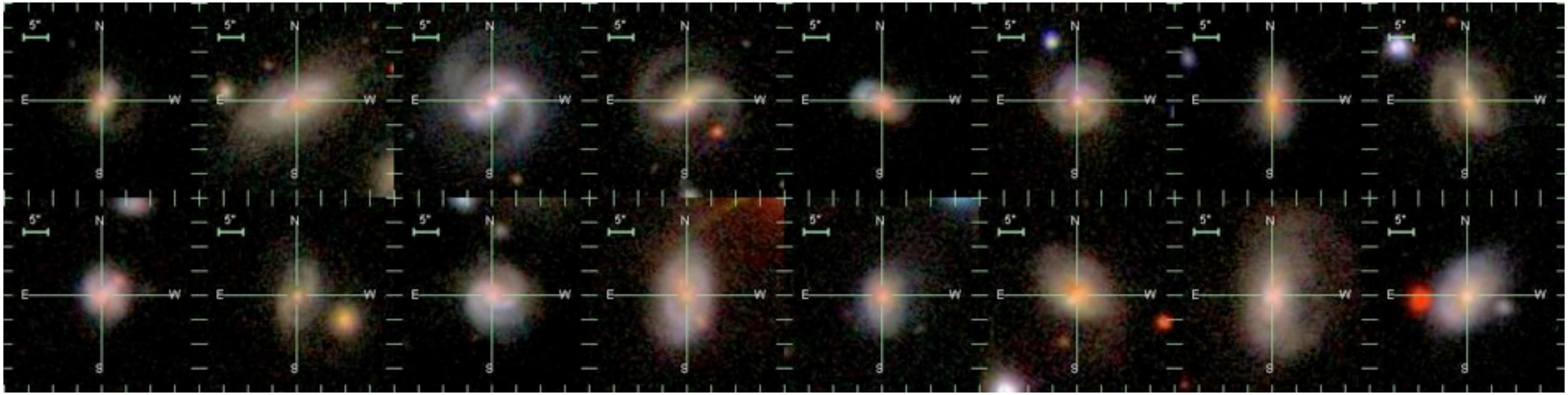
L_FIR



density

From PDR Toolbox (Kaufman, Wolfire)

Summary: disky U/LIRGs at low redshift



Local ULIRGs are smaller extent than high-z extreme starformers and not perfect analogs. Large, high SFR disks are rare at low redshift, but they do exist.

Herschel/PACS spectra of [C II] and [O I]: disks have high [C II] / L_FIR, no [C II] deficit. Thus unlike local ULIRGs, but similar to high-z SF galaxies and extreme objects.

The far-IR line ratios are plausibly explained by density effects: the disky objects have lower density or ionization, and lower dust temperature, than the ULIRGs.

These objects may be a good laboratory to understand physical conditions that are more common in main-sequence or even merger SF galaxies at higher redshift. We have optical spectra for resolved metallicity and extinction, and need CO measurements for surface density and SF efficiency; high resolution imaging to study distribution of SF regions.