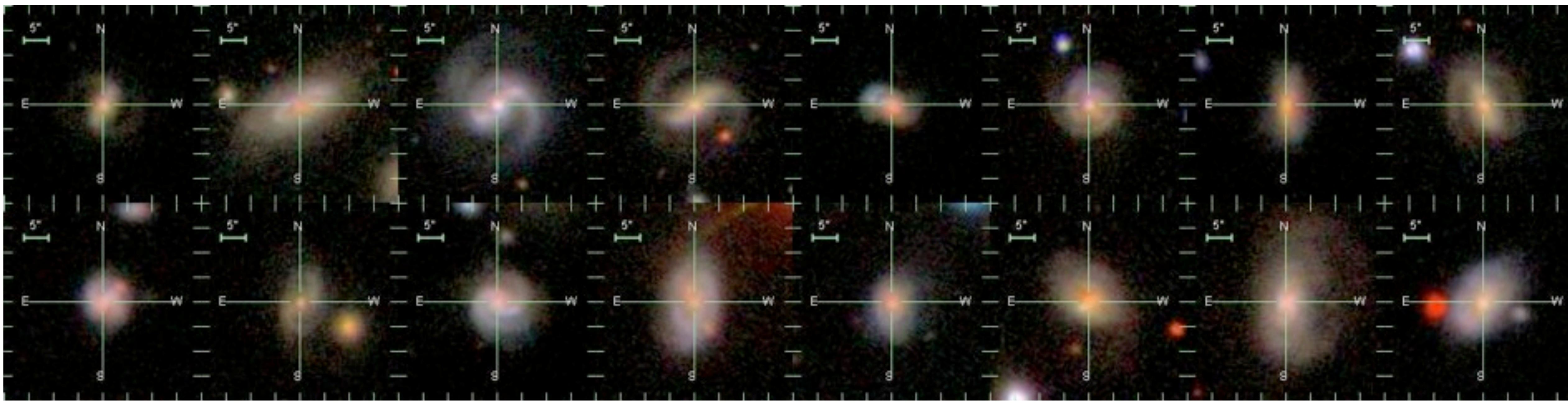
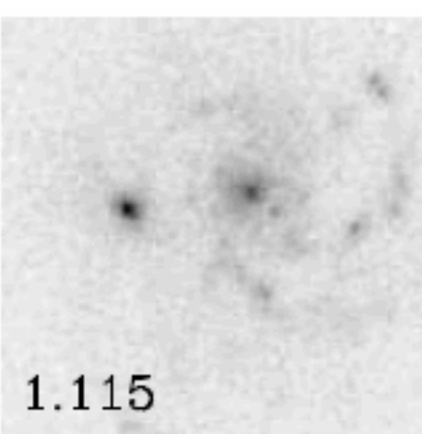
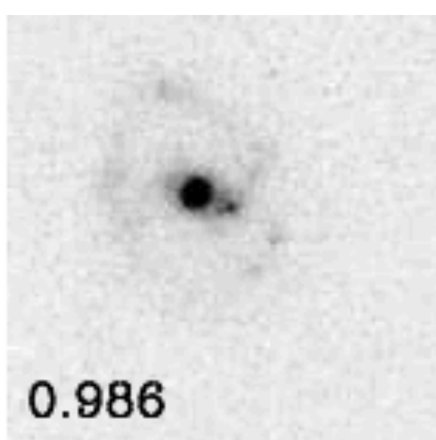
Evolution in dust and gas properties in star forming galaxies - what are low redshift analogs of high z galaxies?

Clues from Herschel spectra of the ISM



z=0.1





z=1

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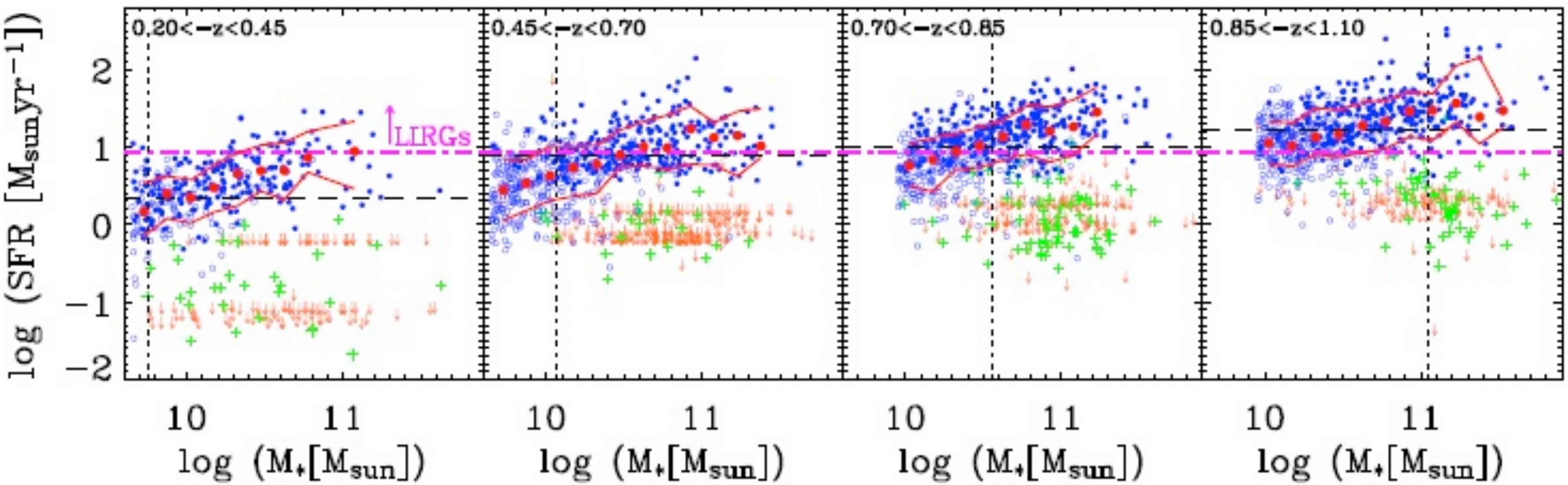
At low redshift, dust SED, temperature, and far-IR lines such as [C II] are functions of IR luminosity and properties like merger stage.

At z = 1-2, high SFR galaxies are much more common.
What can we use as local templates for high-z galaxies?
If a distant LIRG or ULIRG (L>10^11, 10^12 Lsun) is different from the local LIRGs and ULIRGs, is there a better local analog?

Sizes of the SF area in high-z galaxies show they are typically larger than low-z ULIRGs, likely explaining some of the evolution in dust SEDs.

We have found z ~ 0.1 large disky galaxies that do not suffer a [C II] deficit, similar to high-z SFGs. These could be useful analogs for high-z galaxies, and their line ratios can probe the ISM and conditions in star-forming regions.

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

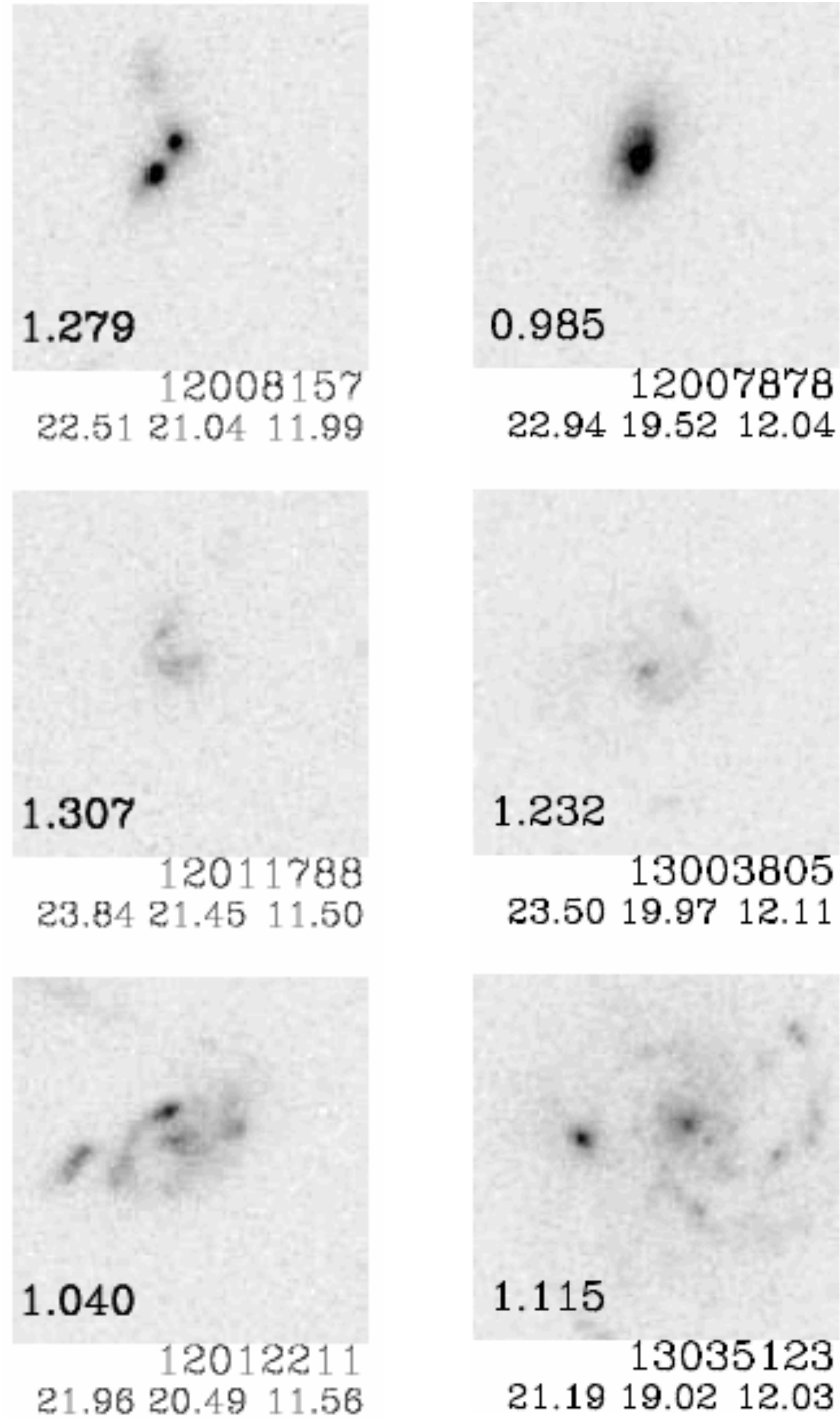


(from Kai Noeske, BJW et al 2007; also X. Zheng+ 2007; Elbaz+ 2007)

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 predictors of high-z properties.



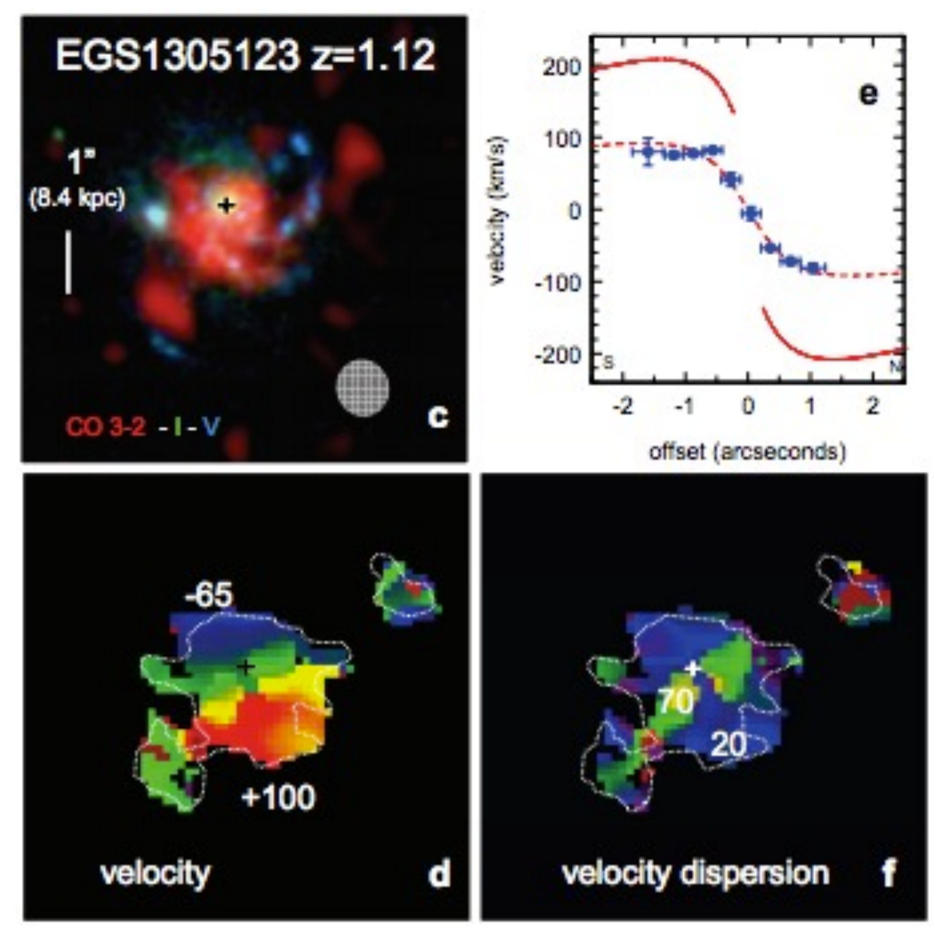
Extended Groth Strip, z~1, MIPS 24 um sample

HST/ACS I-band U/LIRGs at z~1

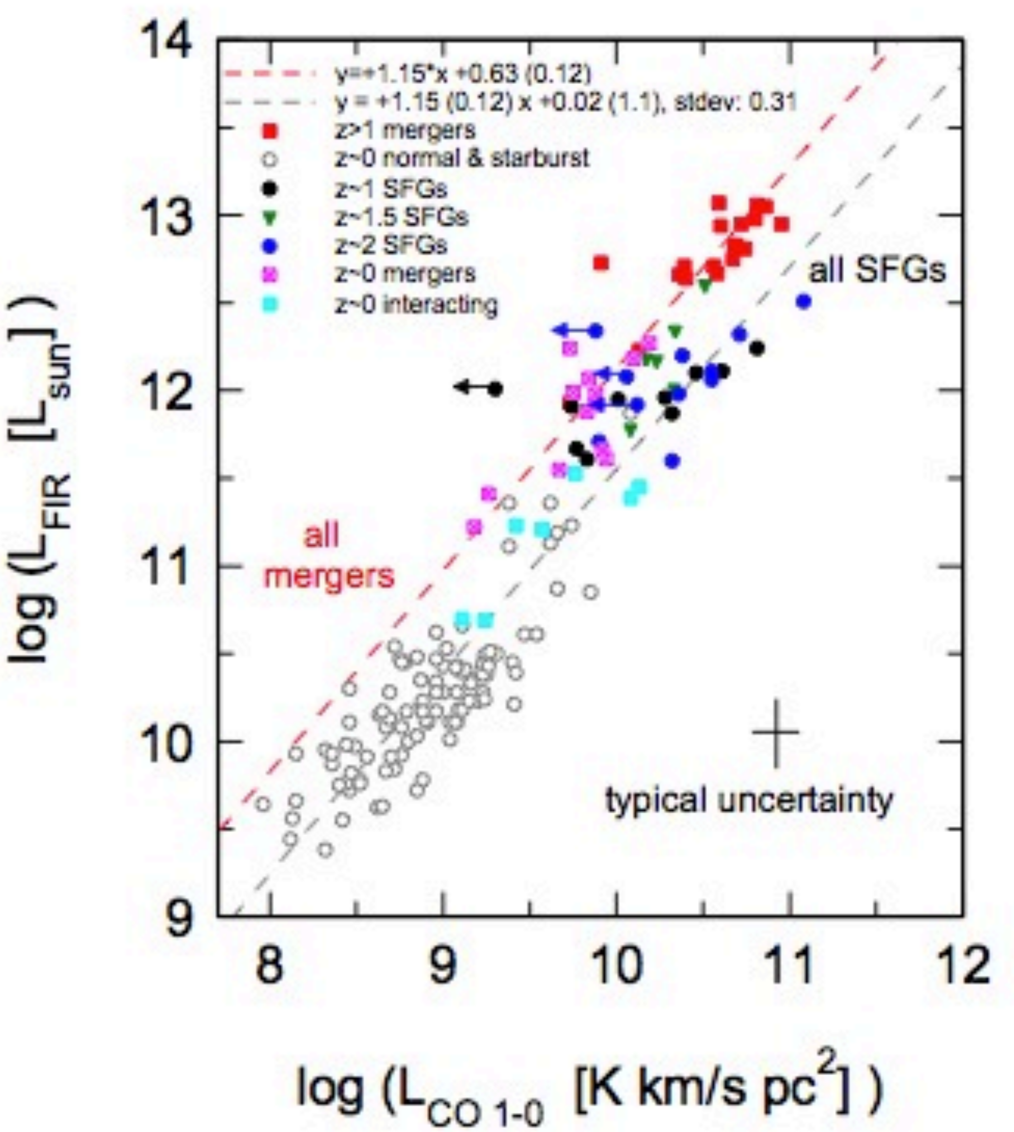
Arguments over disk vs. merger fraction -
but the main point to remember:
even the spirals can have SFR 30-100 Msun/yr.

ISM in such galaxies: probably thicker disk,
higher velocity dispersion and streaming motions.
Large complexes of SF regions

"Super-M51"
SFR ~ 100
CO disk
Tacconi+ 2010



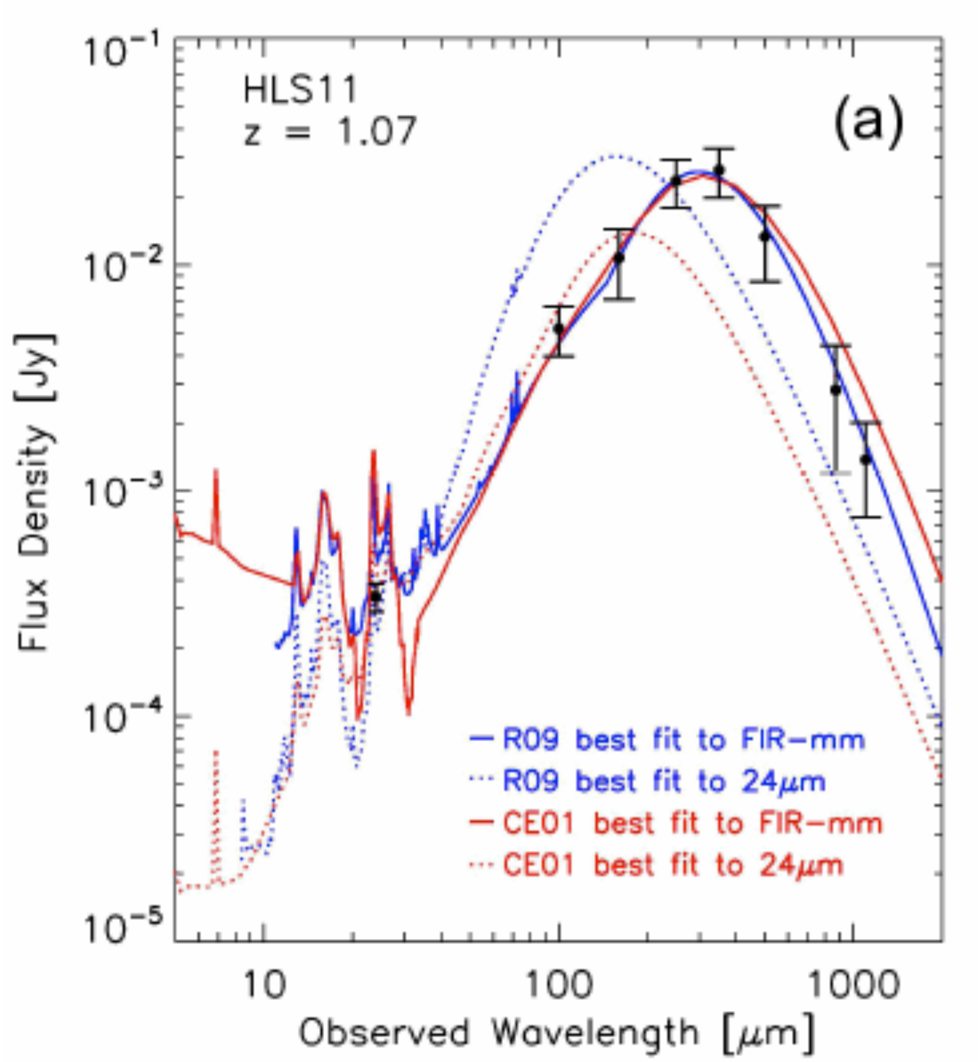
Are there two “modes” or density regimes of SF - mergers and disks?
Controversial, but spread may be related to spatial extent of star formation

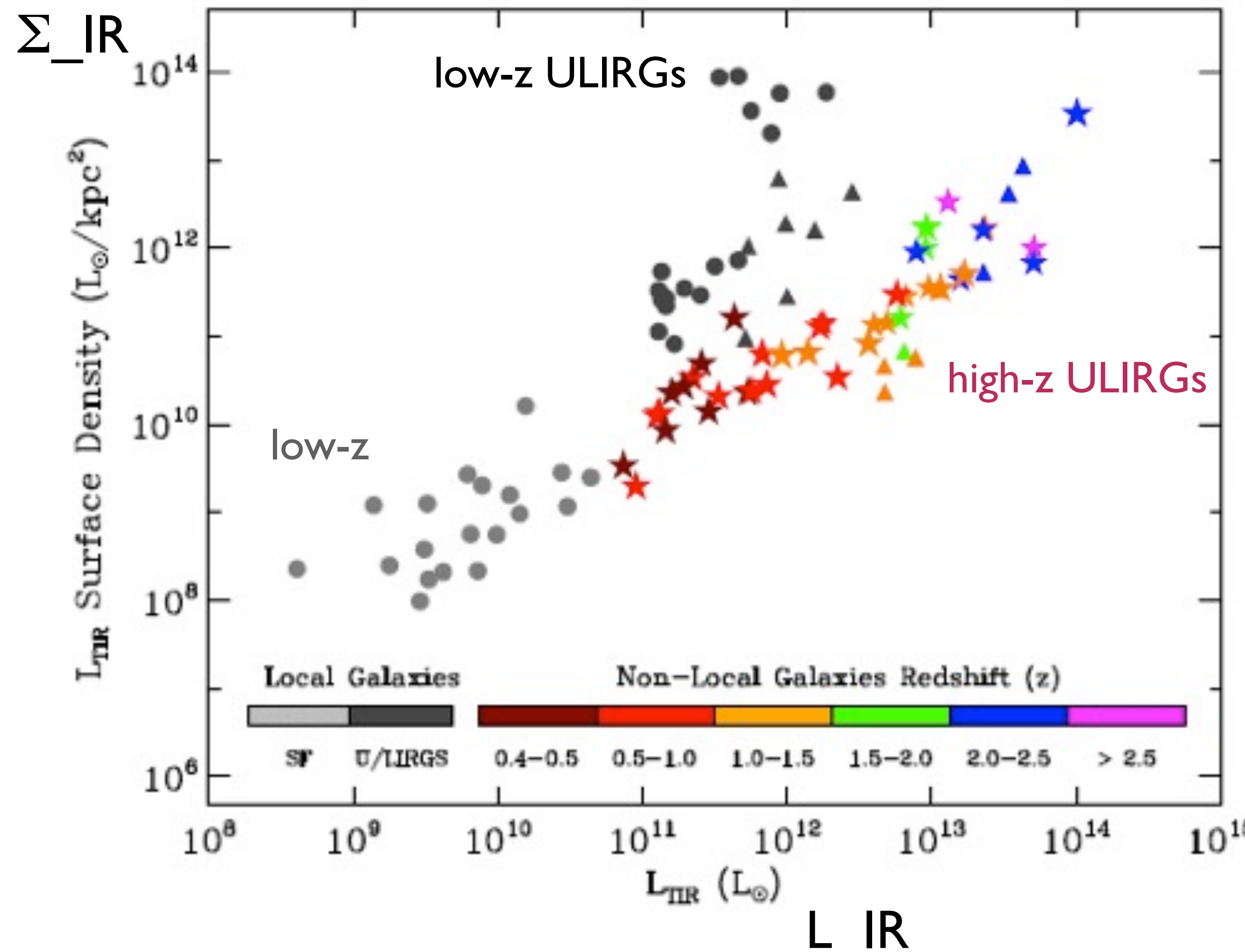


(Tacconi et al 2010; Genzel et al 2010)

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.
Existence of separate K-S 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)

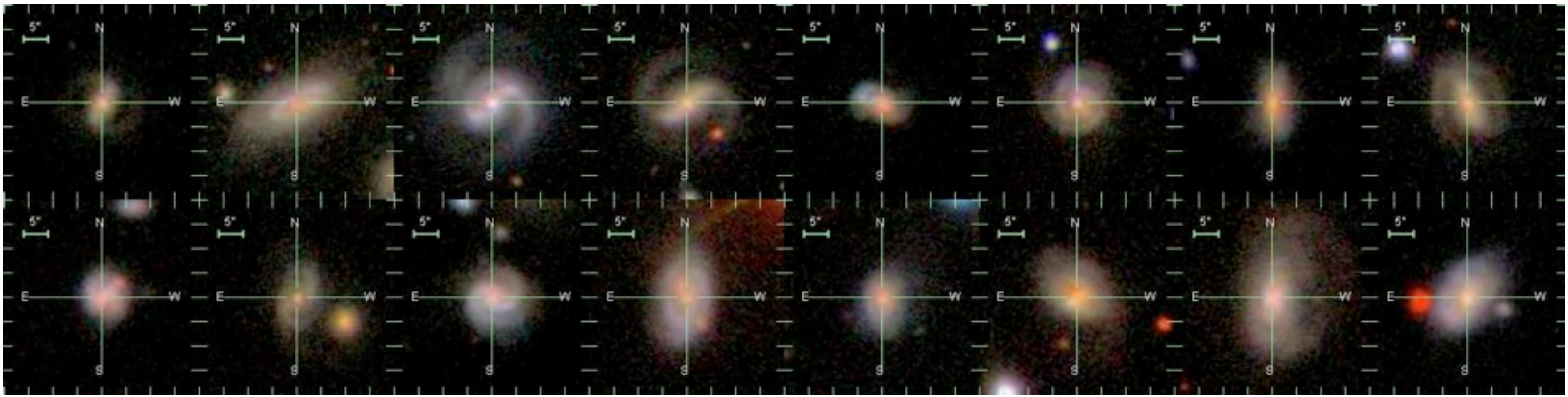
Rujopakarn et al 2010:

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, good for PACS spectra.

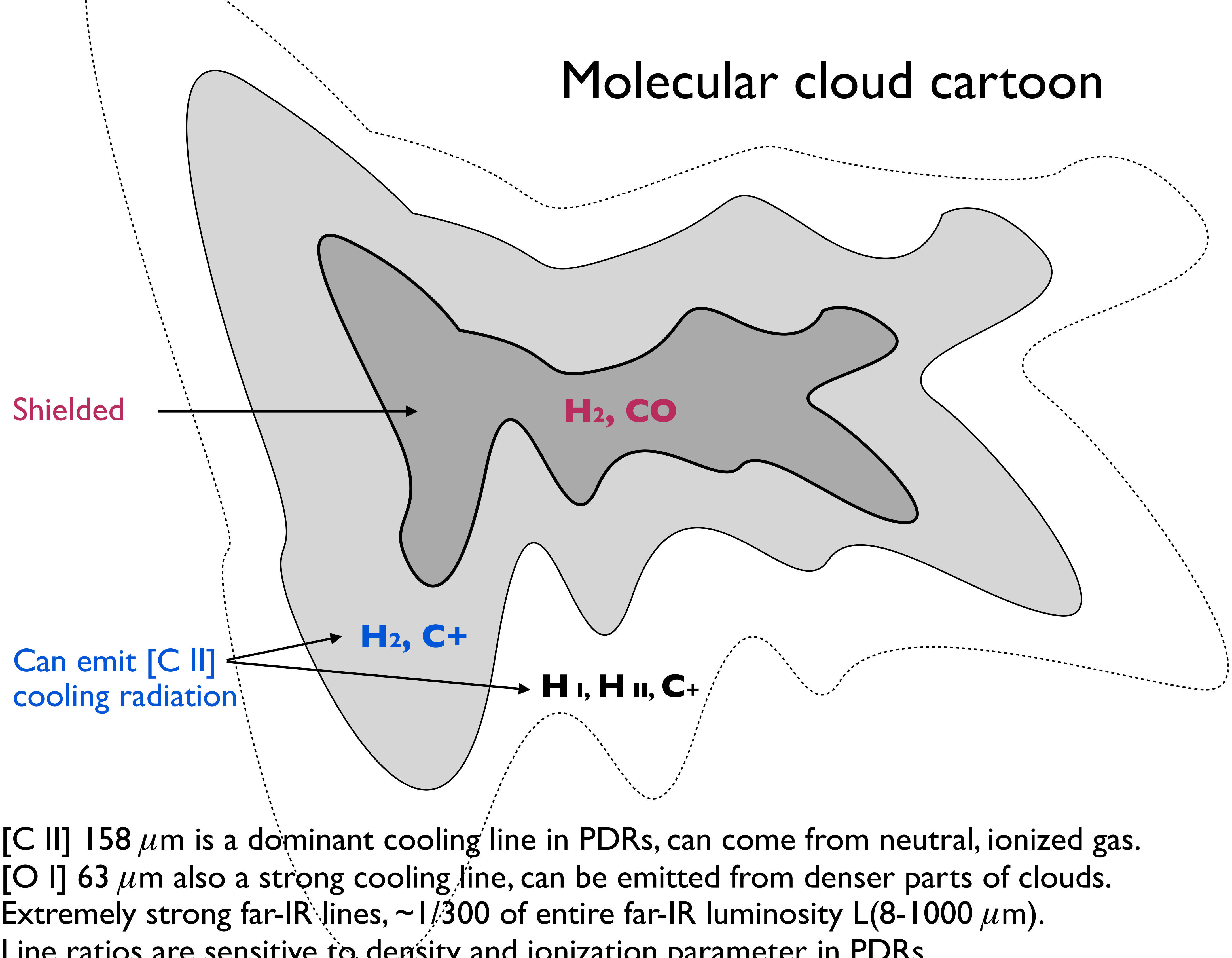


Even after a large-optical-diameter selection, these galaxies were only about 5% of the ULIRG/ bright LIRG population in IRAS + SDSS.

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

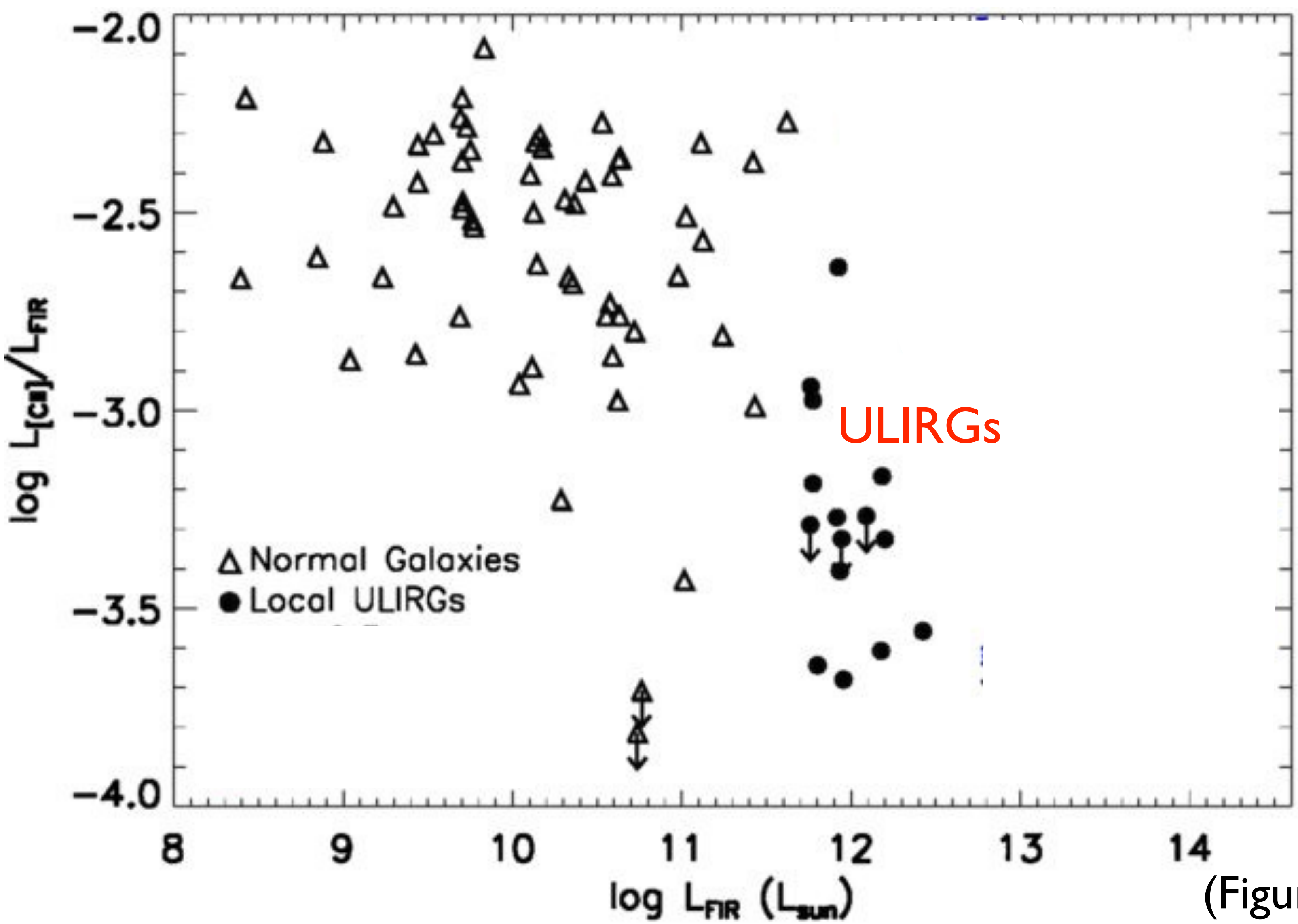


[C II] 158 μm is a dominant cooling line in PDRs, can come from neutral, ionized gas.
[O I] 63 μm also a strong cooling line, can be emitted from denser parts of clouds.
Extremely strong far-IR lines, ~1/300 of entire far-IR luminosity L(8-1000 μm).
Line ratios are sensitive to density and ionization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



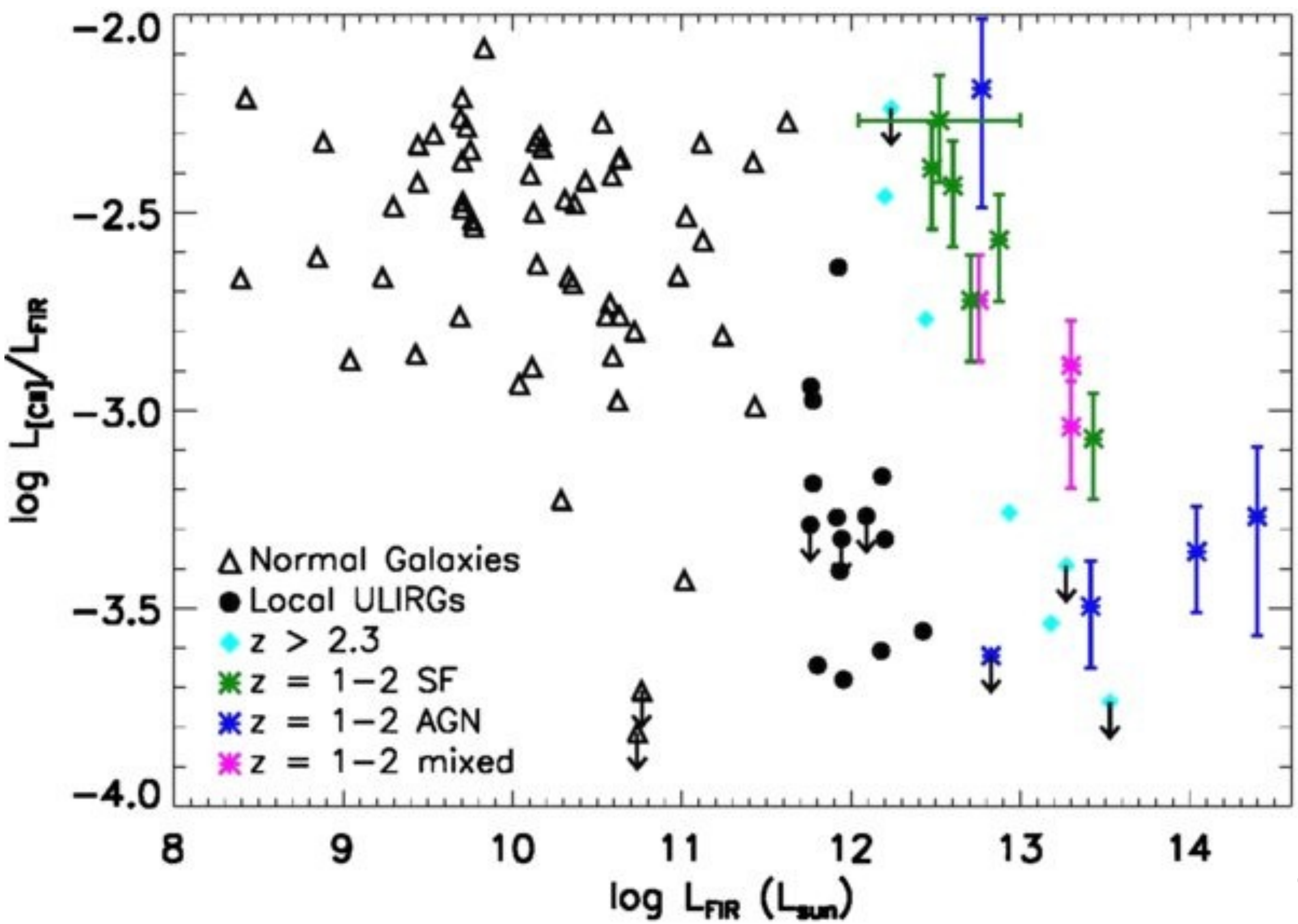
(Figure from Stacey+ 2010)

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. Suggests ULIRGs have larger fraction of gas+dust in the densest regions, where FIR is produced but [C II] is not.

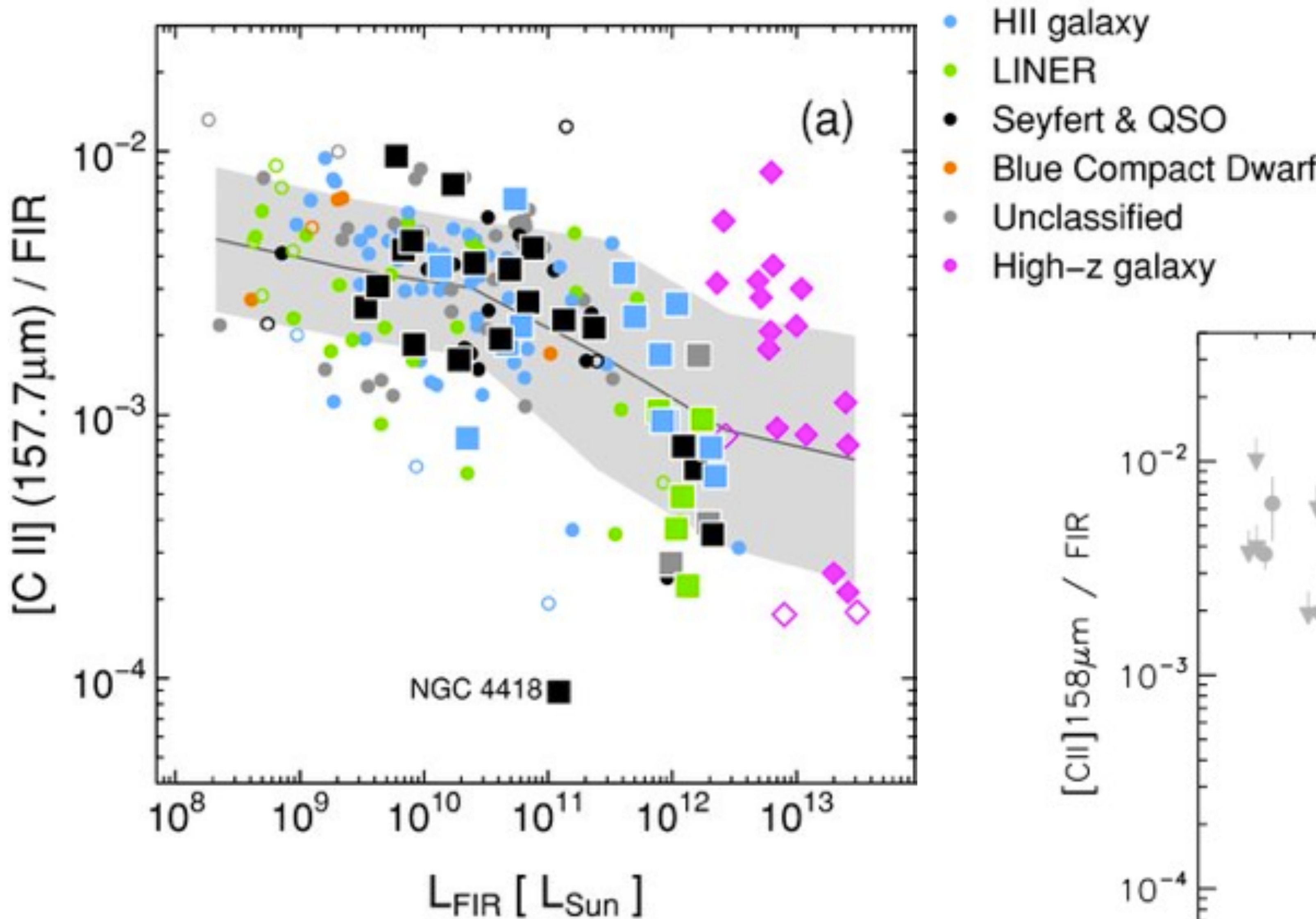
The “[C II] deficit” - high-z counterexamples

L_[C II]/L_FIR

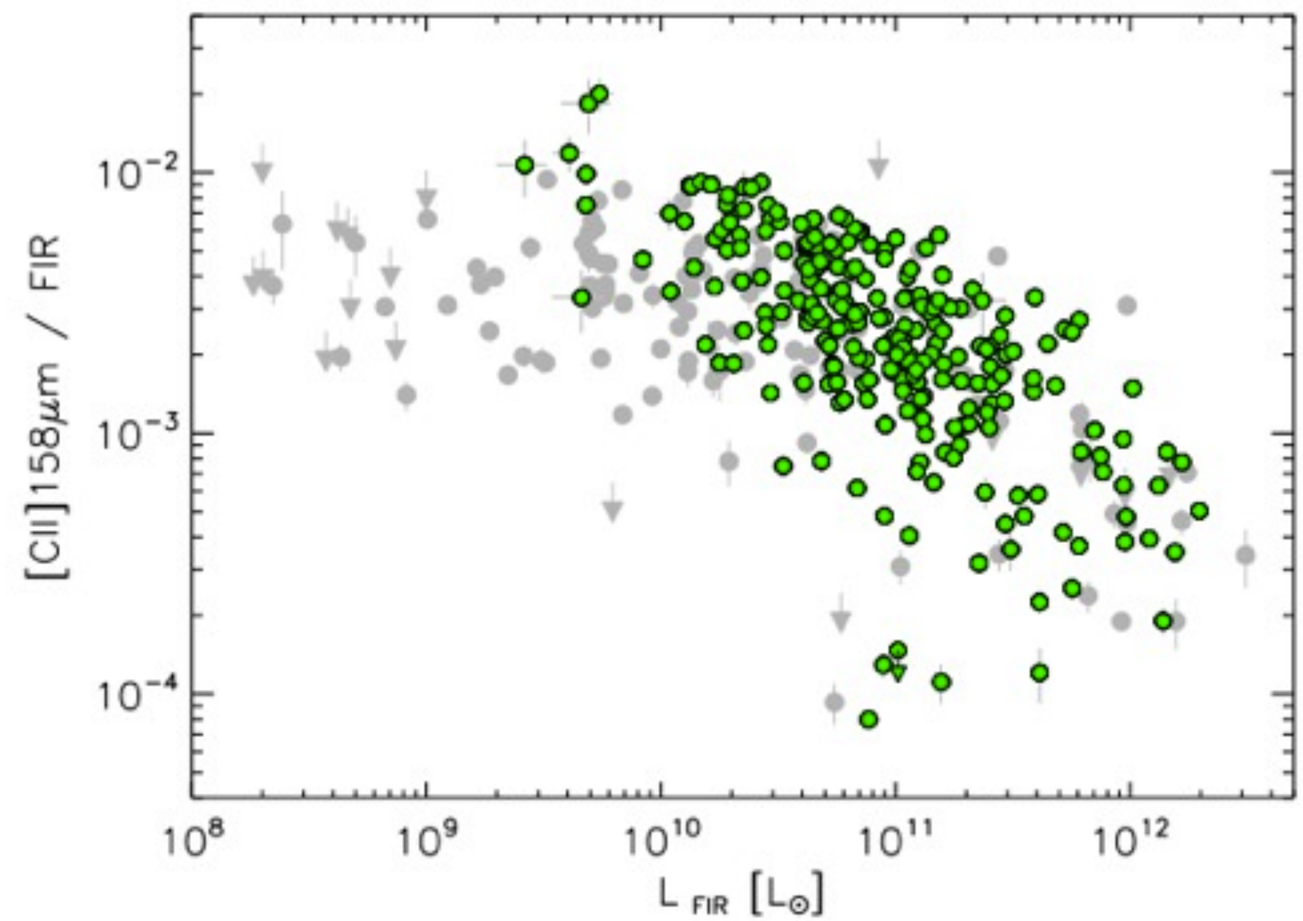


(from Stacey+ 2010)

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



Gracia-Carpio etal 2011

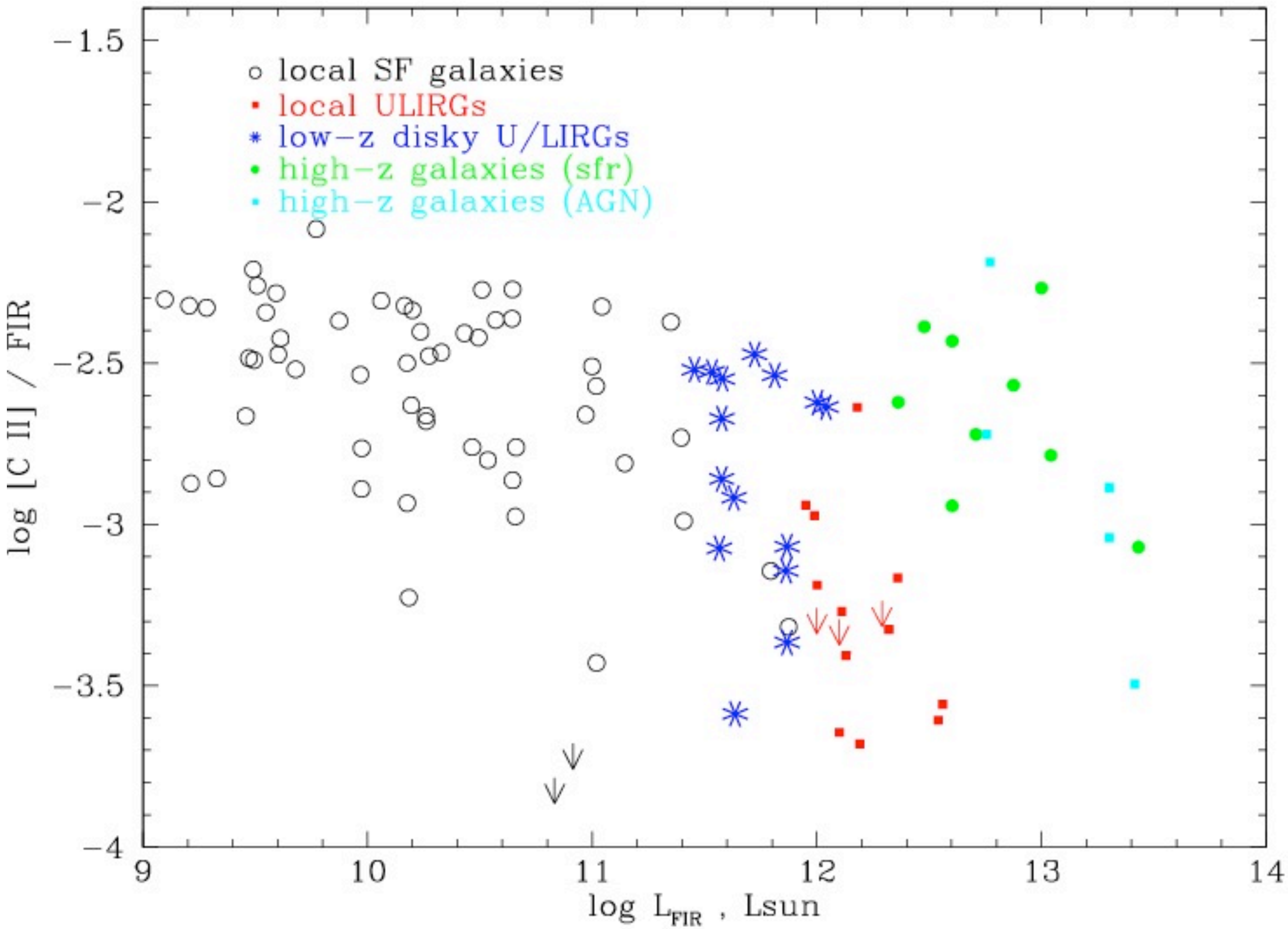


Diaz-Santos etal 2013

Herschel/PACS spectra of [C II] in low-z galaxies from SHINING and GOALS:
[C II] deficit at high L_IR, exists in other far-IR lines as well.

Line ratios may have lower scatter/better correlated with L_IR / M(H2),
or L_IR surface density.

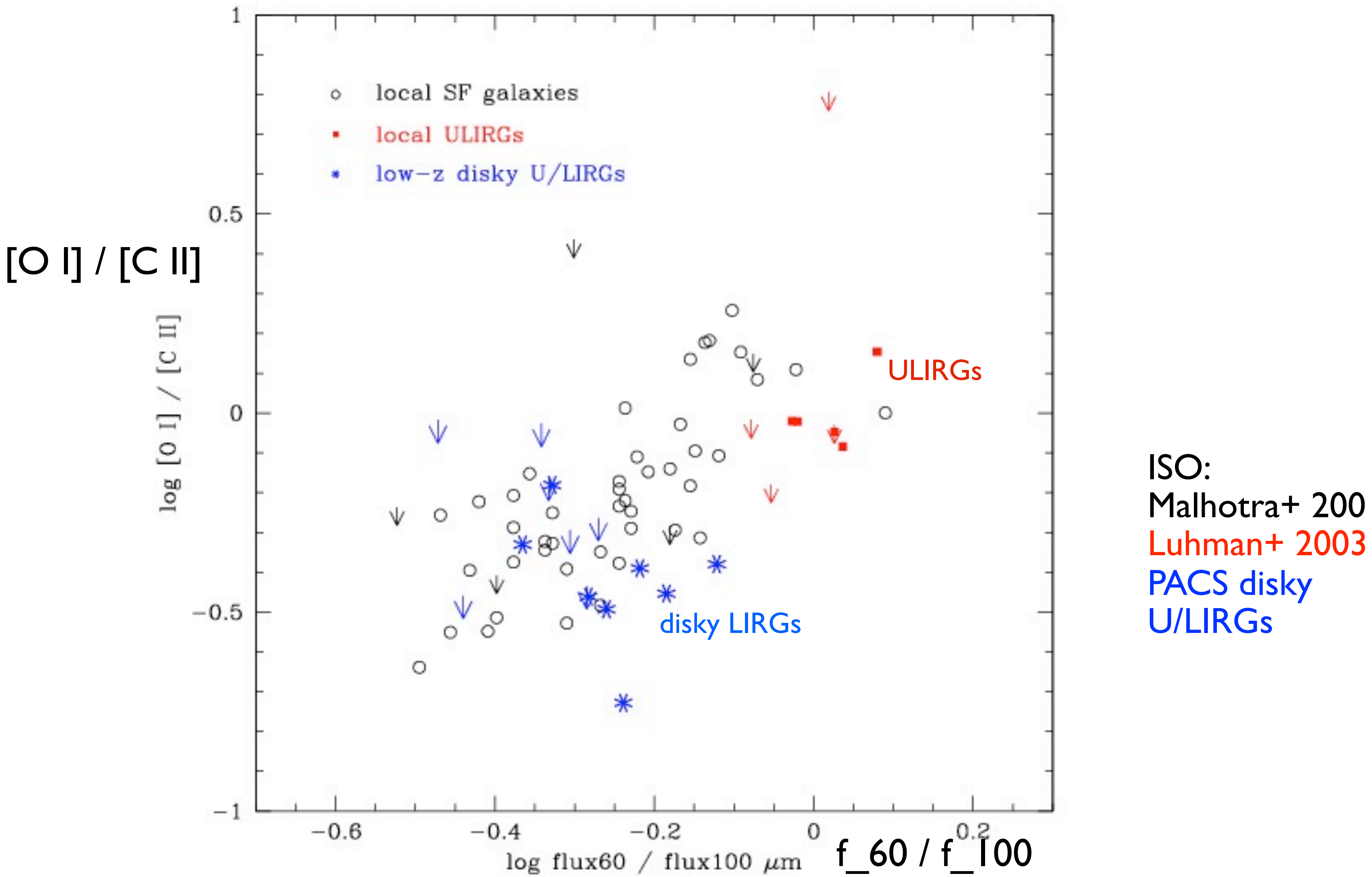
Our PACS disky U/LIRG sample: strong [C II] emission, little deficit



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

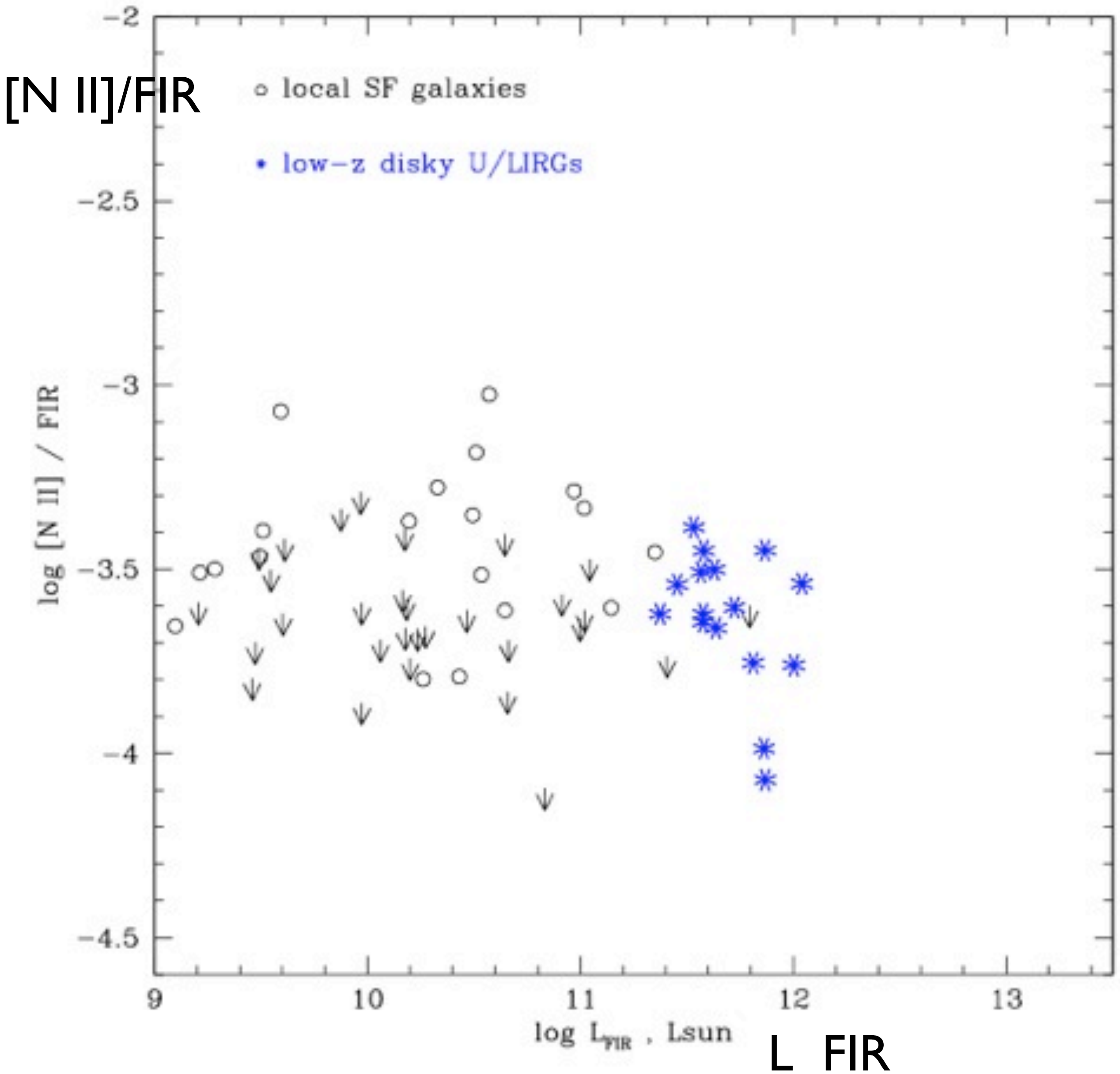
High [C II] / L_FIR in the disky galaxies suggests that surface density is a controlling factor, distinguishing them from low-z ULIRGs, more like high-z galaxies.
In fact, the lowest [C II] among our disks are also the smallest in Hα diameter.

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

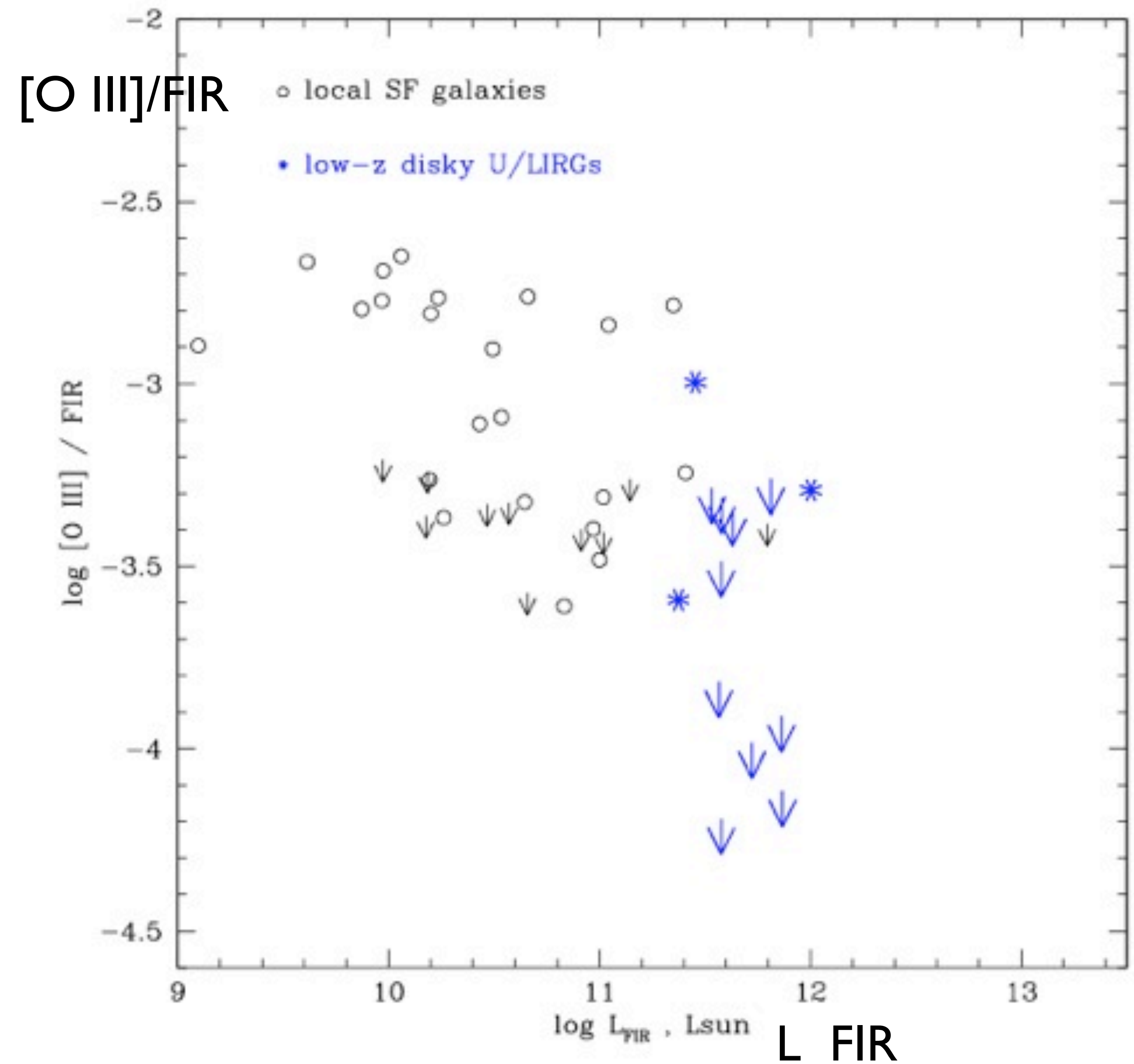


Correlation known from ISO data (Malhotra et al 2001). The disky LIRGs are cooler than ULIRGs, and shifted to lower [O I] or warmer dust compared to the lower-luminosity SFGs.

[N II] traces ionized gas

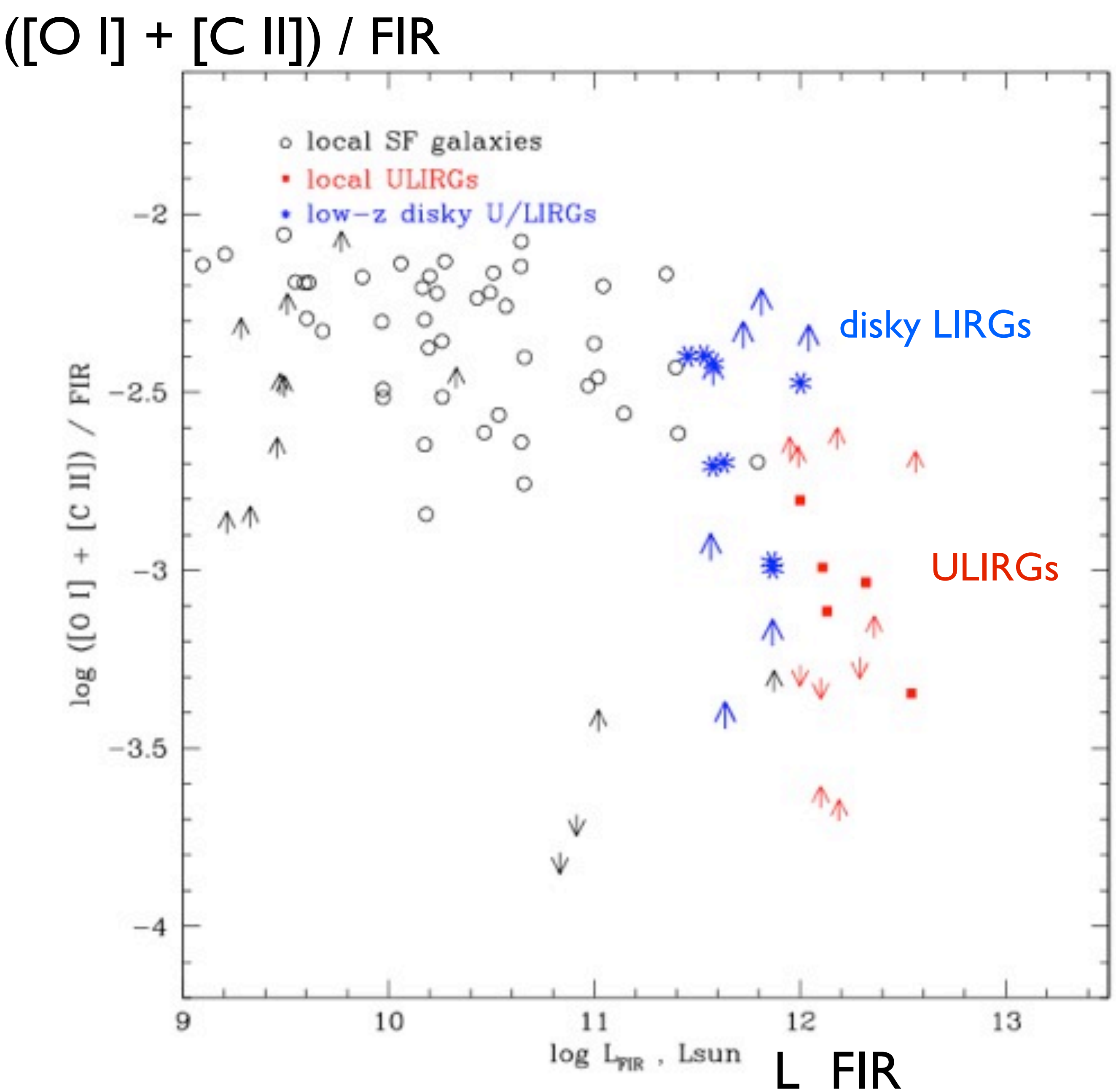


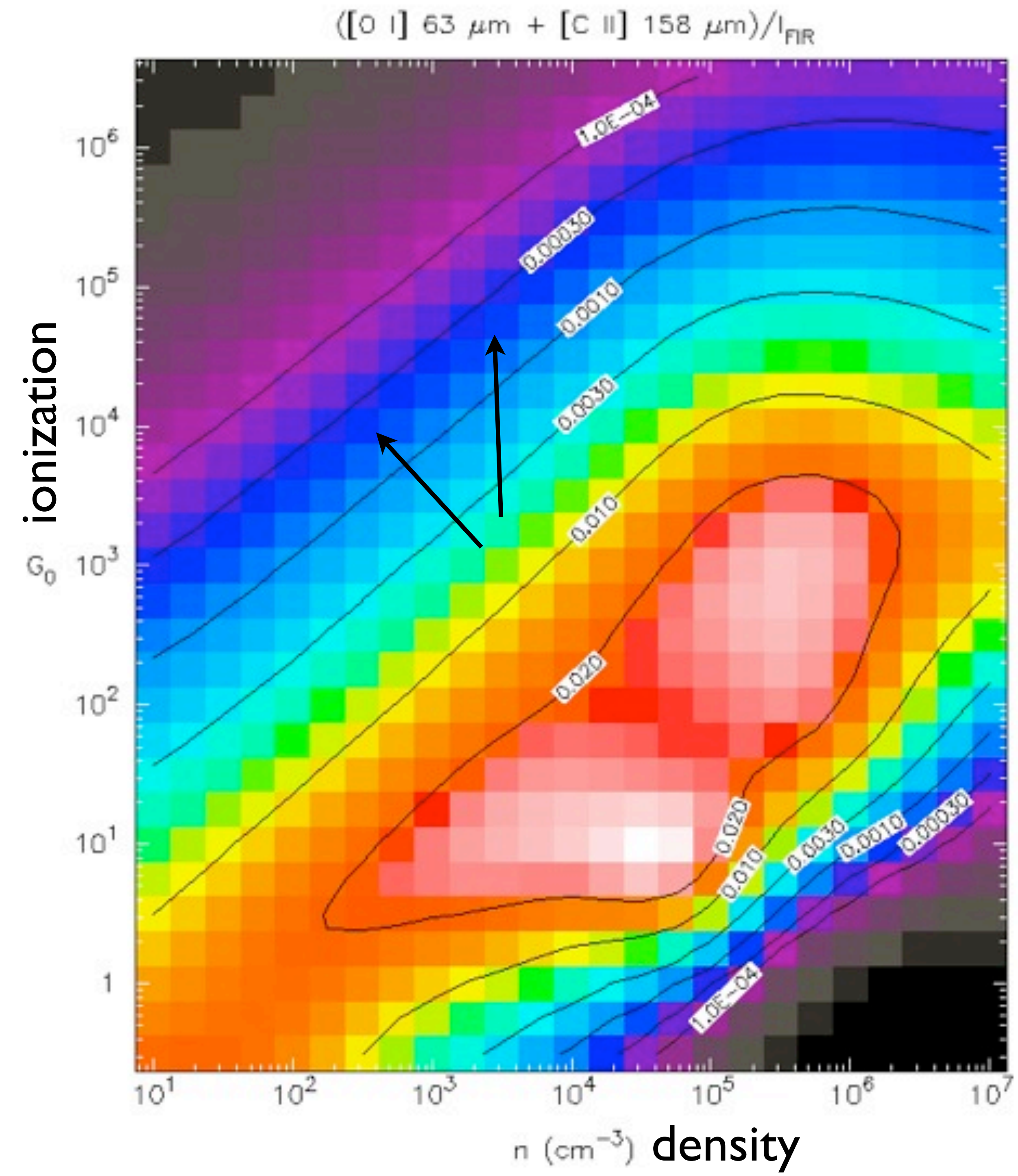
[O III] traces high ionization, correlated with T_dust



[N II]/FIR is fairly constant in SF galaxies including the big disks (declines in ULIRGs) but [O III]/FIR declines with L_FIR. This is a measure of ionization, suggests the luminous disks are achieving higher L_FIR without increasing ionization - possibly an effect of spreading SF over a larger area.

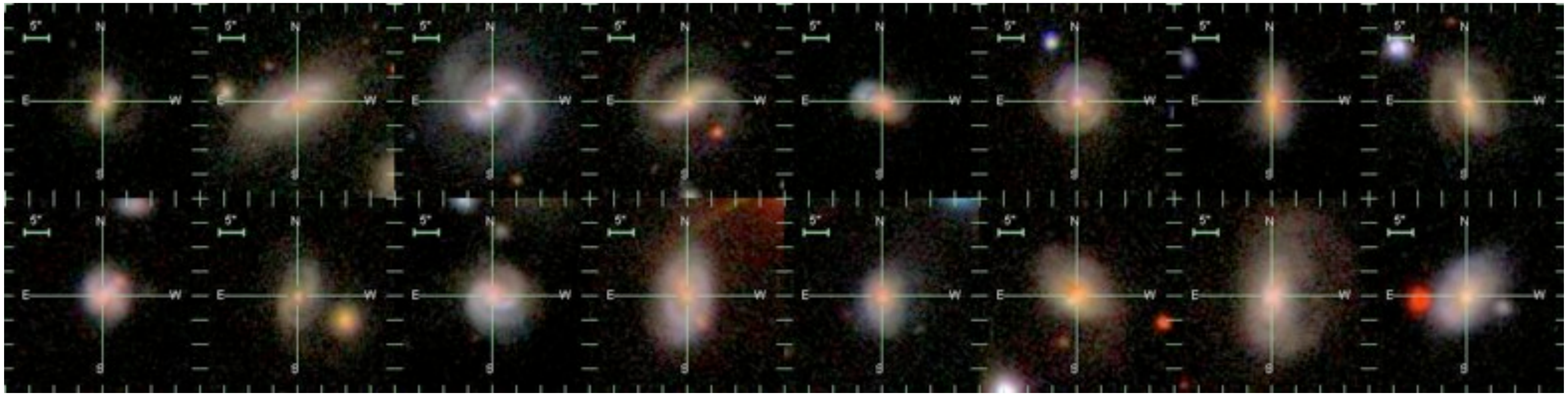
Line ratios and line/FIR can constrain density and ionization parameter in SF regions





From PDR Toolbox (Kaufman, Wolfire)

Summary: IR lines as probe of disks and 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]: disks have high [C II] / L_FIR, no [C II] deficit - unlike local ULIRGs, but similar to high-z SF galaxies and extreme objects.

Far-IR line ratios, including [O I] and [O III], may be explained by density effects: the disky objects have lower density or ionization, and lower dust temperature, than the ULIRGs. Different distribution of emitters across phases, and densities within molecular phase?

Low-z galaxies can help us study physical conditions as analogy for SF-main-sequence or even merger SF galaxies at higher redshift, with caution.
Forthcoming: optical spectra, spatially resolved metallicity and extinction, ALMA for resolved CO 1-0 in 6 of the disk galaxies.