The Evolving ISM of Star Forming Galaxies Over the Last 10 Billion Years

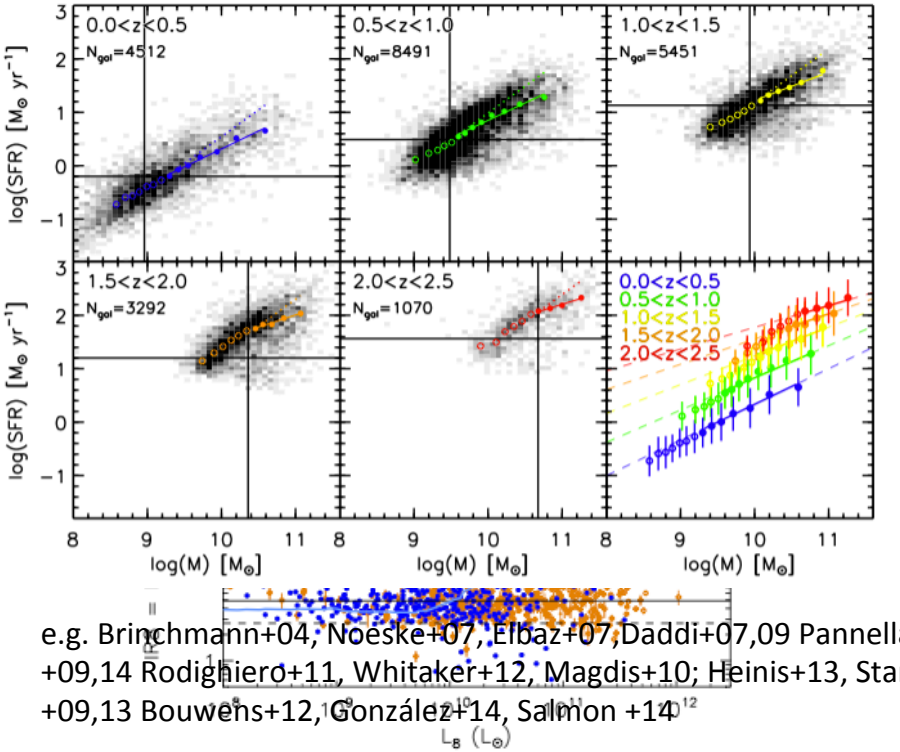
Georgios Magdis

Overview

Over the last 10 Billion Years (the majority) of star forming galaxies appear to obey the following (among others) relations :

1. SFR – M_* (Main Sequence)
2. $\Sigma_{SFR} - \Sigma_{gas}$ (SF law)
3. $L_{IR} - L_8$

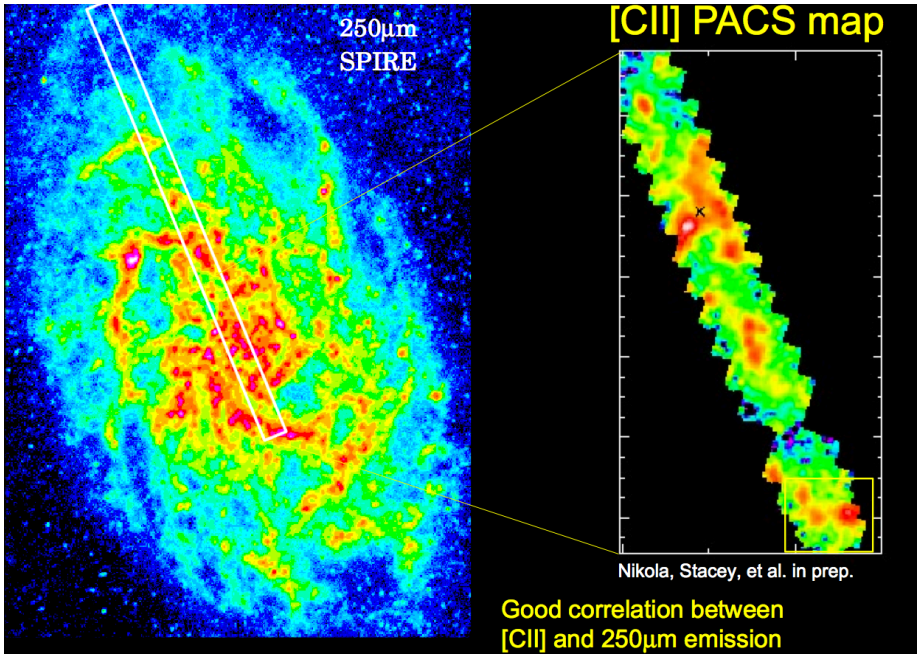
4. $L_{FIR} - L_{[CII]}$



e.g. Brinchmann+04, Noeske+07, Elbaz+07,Daddi+07,09 Pannella +09,14 Rodighiero+11, Whitaker+12, Magdis+10; Heinis+13, Stark +09,13 Bouwens+12, González+14, Salmon +14

They mirror the process of star formation though cosmic time

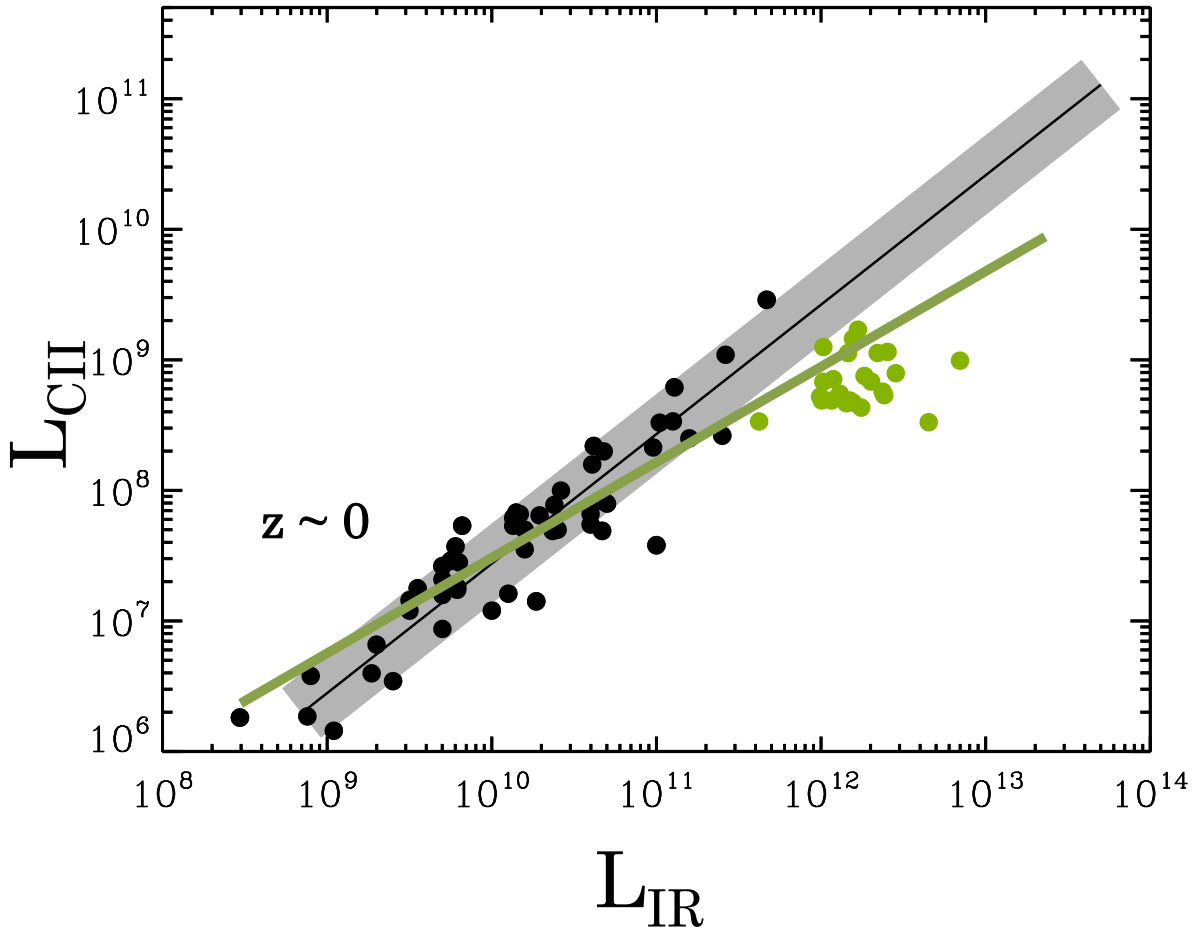
[CII] Emission



Credit: AstroImagerDia

- [CII] 158μm is one of the strongest ISM cooling lines (T~90K)
- Accounts for 0.1-1% of the L_{IR}
- One of the most powerful spectroscopic tracers of the ionized & neutral components of the ISM
- Tracer of Star Formation Rate (?)

L_{CII} – L_{IR} correlation



Local Galaxies ($L_{IR} < 10^{11} L_{\odot}$)

Almost linear correlation

e.g. Malhotra+97,+01, Herrero-Camus+14,

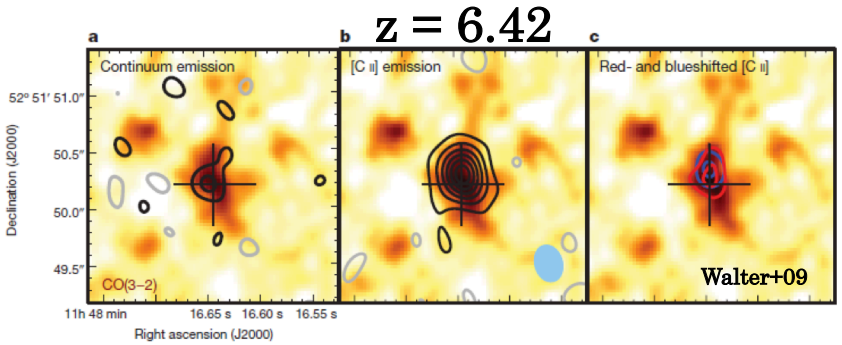
Local ULIRGs - CII deficit

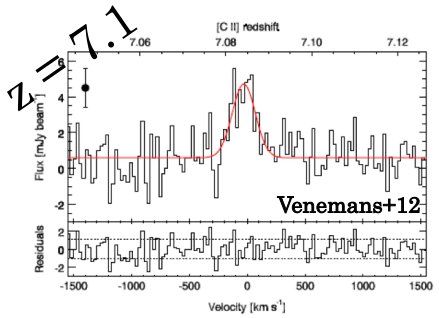
e.g. Luhman+03, Garcia-Carpio+11, Farrah+2013, Diaz-Santos+2013

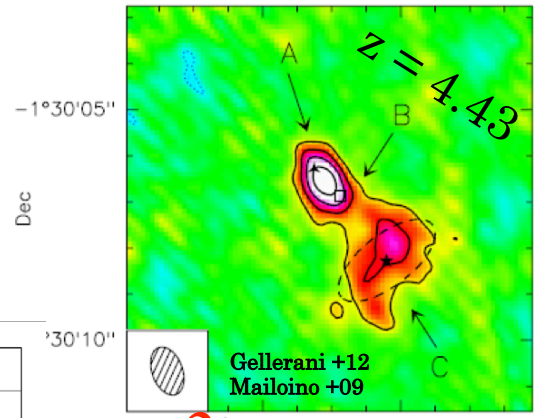
Origin of the deficit:

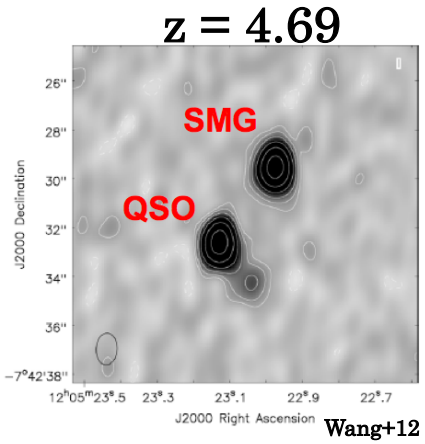
- AGN contamination → excess L_{IR} with respect to L_{CII}
- Stronger interstellar radiation fields (U) → increased dust to gas opacity
- n_H densities > n_{crit}, → recombination of C+ to C
- Self absorption

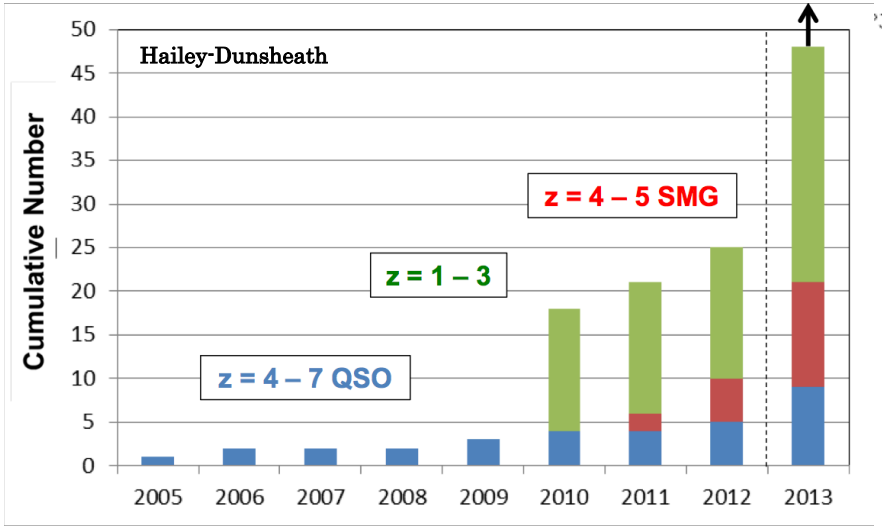
[CII] at high-z

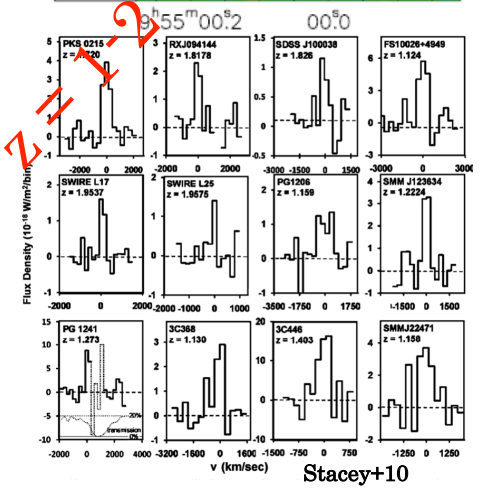

z = 6.42
a
b
c
Continuum emission
[C II] emission
Red- and blueshifted [C II]
CO(3–2)
Walter+09

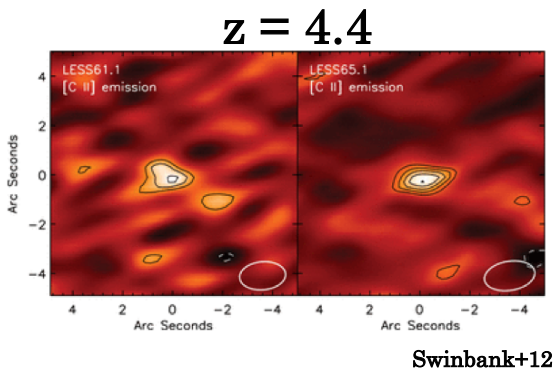

z = 7.1
[C II] redshift
Venemans+12

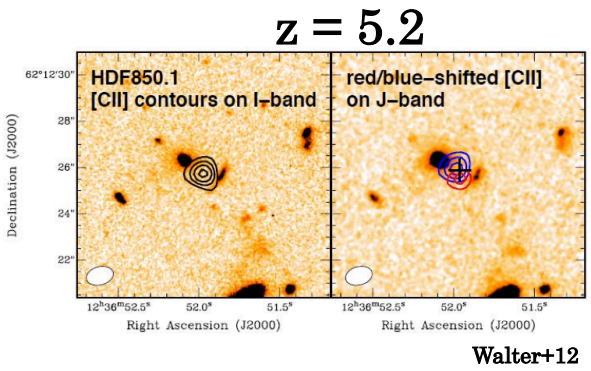

z = 4.43
A
B
C
Gellerani +12
Mailoino +09

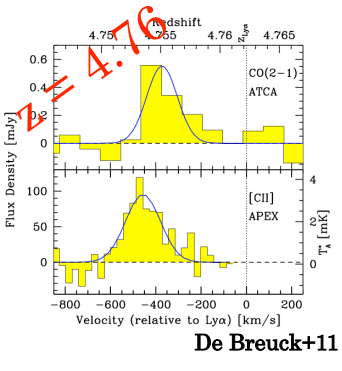

z = 4.69
SMG
QSO
Wang+12

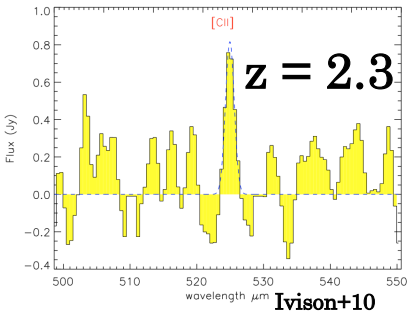

Hailey-Dunsheath
Cumulative Number
z = 4 – 5 SMG
z = 1 – 3
z = 4 – 7 QSO


z = 2.2
z = 1.5
Stacey+10

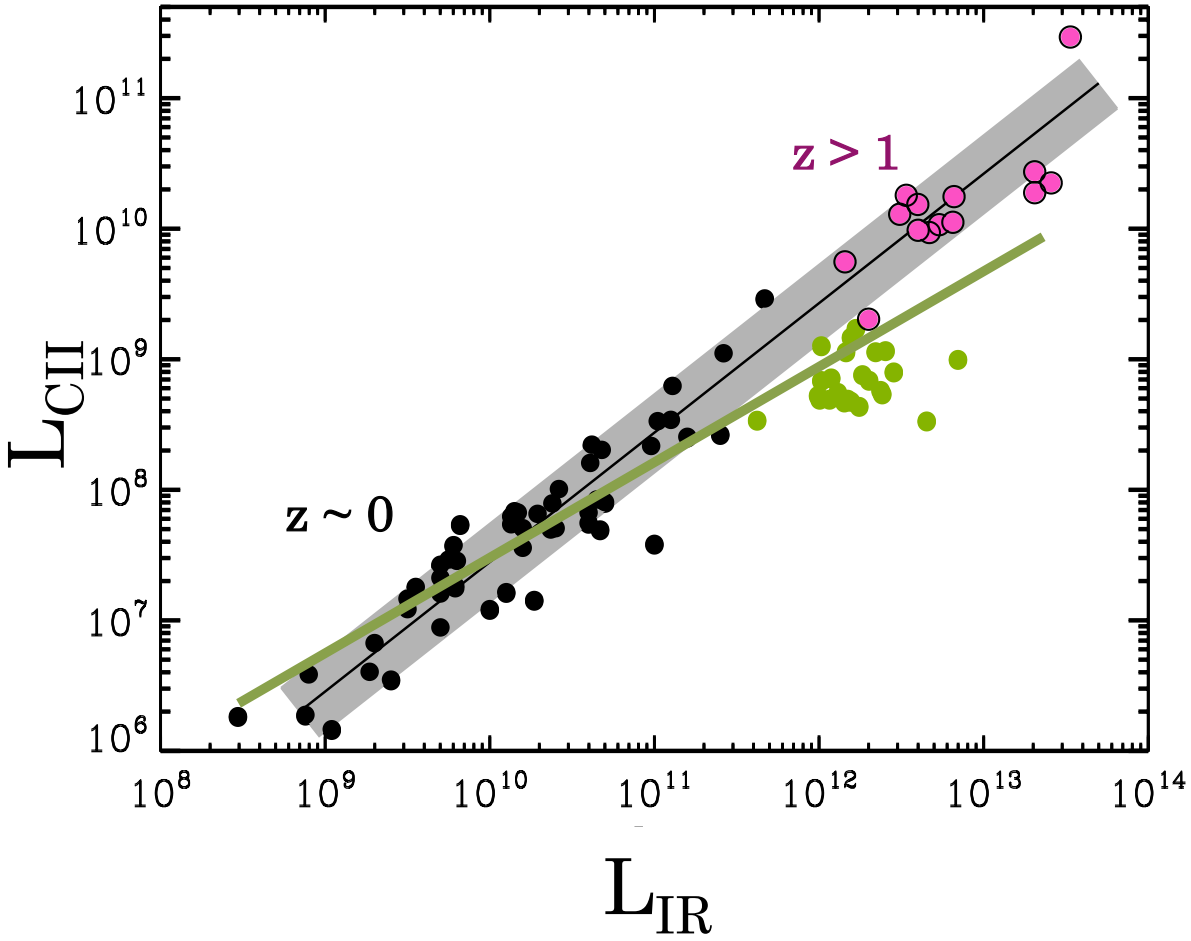

z = 4.4
LESS61.1
[C II] emission
LESS65.1
[C II] emission
Swinbank+12


z = 5.2
HDF850.1
[CII] contours on I–band
red/blue–shifted [CII]
on J–band
Walter+12


z = 4.76
CO(2–1)
ATCA
[CII]
APEX
De Breuck+11


z = 2.3
[CII]
Ivison+10

$L_{CII} - L_{IR}$ correlation



Local Galaxies ($L_{IR} < 10^{11} L_{\odot}$)
Almost linear correlation

e.g. Malhotra+97,+01, Herrero-Camus+14,

Local ULIRGs – CII deficit

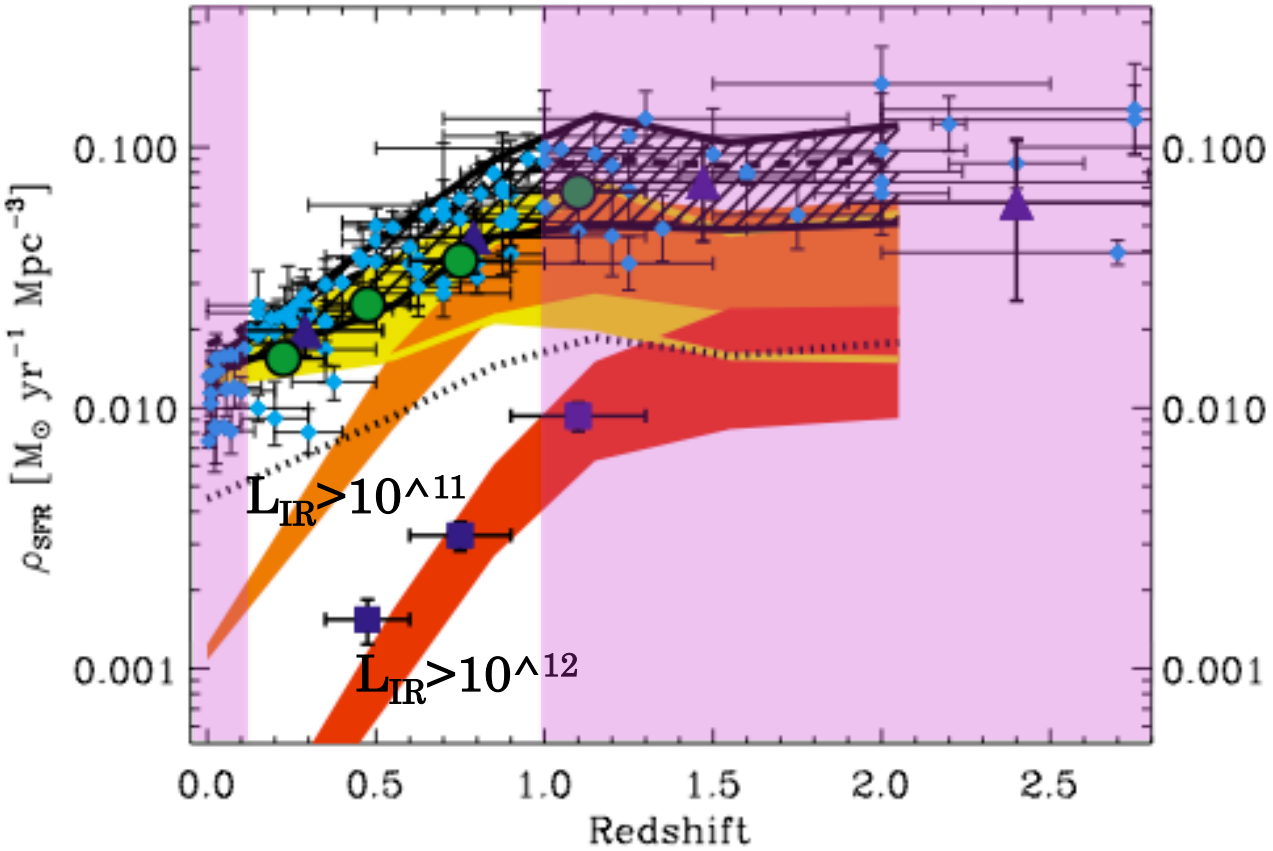
e.g. Luhman+03, Garcia-Carpio+11, Farrah+2013, Diaz-Santos+2013

High-z ULIRGs - CII deficit

e.g.Iviison+2010, Hailey-Dunsheath+10, Stacey+10, Valtchanov+11

- A large fraction high-z ULIRGs behave like local normal galaxies
- Strong evolution of their [CII] emission

L_{CII} – L_{IR} correlation



- We are building the picture in the two ends of evolution
- Need for intermediate redshift (0.2 < z < 1.0) observations
- 158μm x (1+z) for 0.2<z<1 ~ 200-350μm → not accessible from the ground

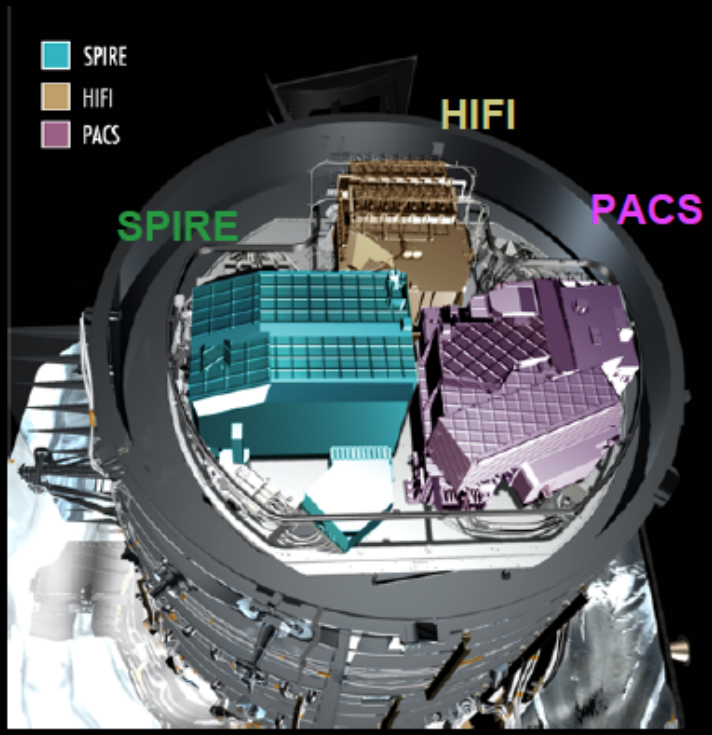
Herschel Space Observatory

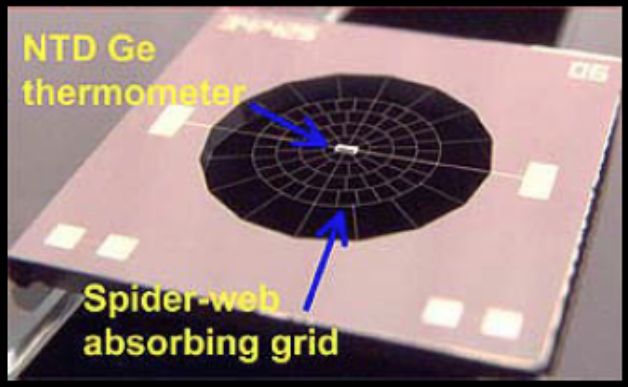
The Herschel Satellite

- 8x4x4m
- 4 tonnes on launch
- 3.5m mirror
- 2200 litres of He
- Cooled to 0.3K
- 3 instruments
- 70-700 microns

Herschel Space Observatory

Instruments





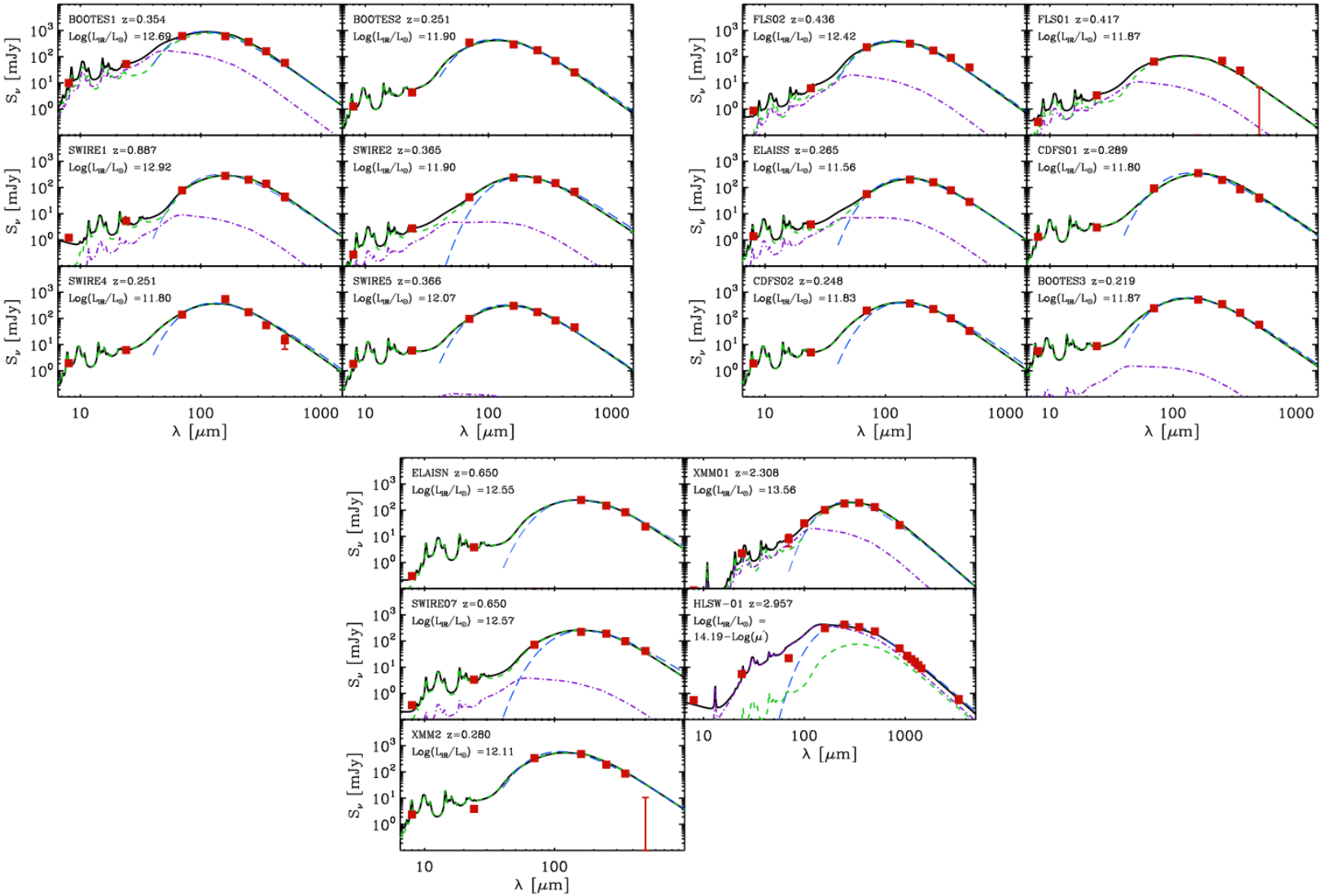
- SPIRE (200 - 670 μm)
- Imaging photometer
- Fourier transform spectrometer

- HIFI (157- 212 and 240 - 625μm)
- Heterodyne spectrometer

Far-IR spectra of 0.2<z<0.6 (U)LIRGs

Magdis+14

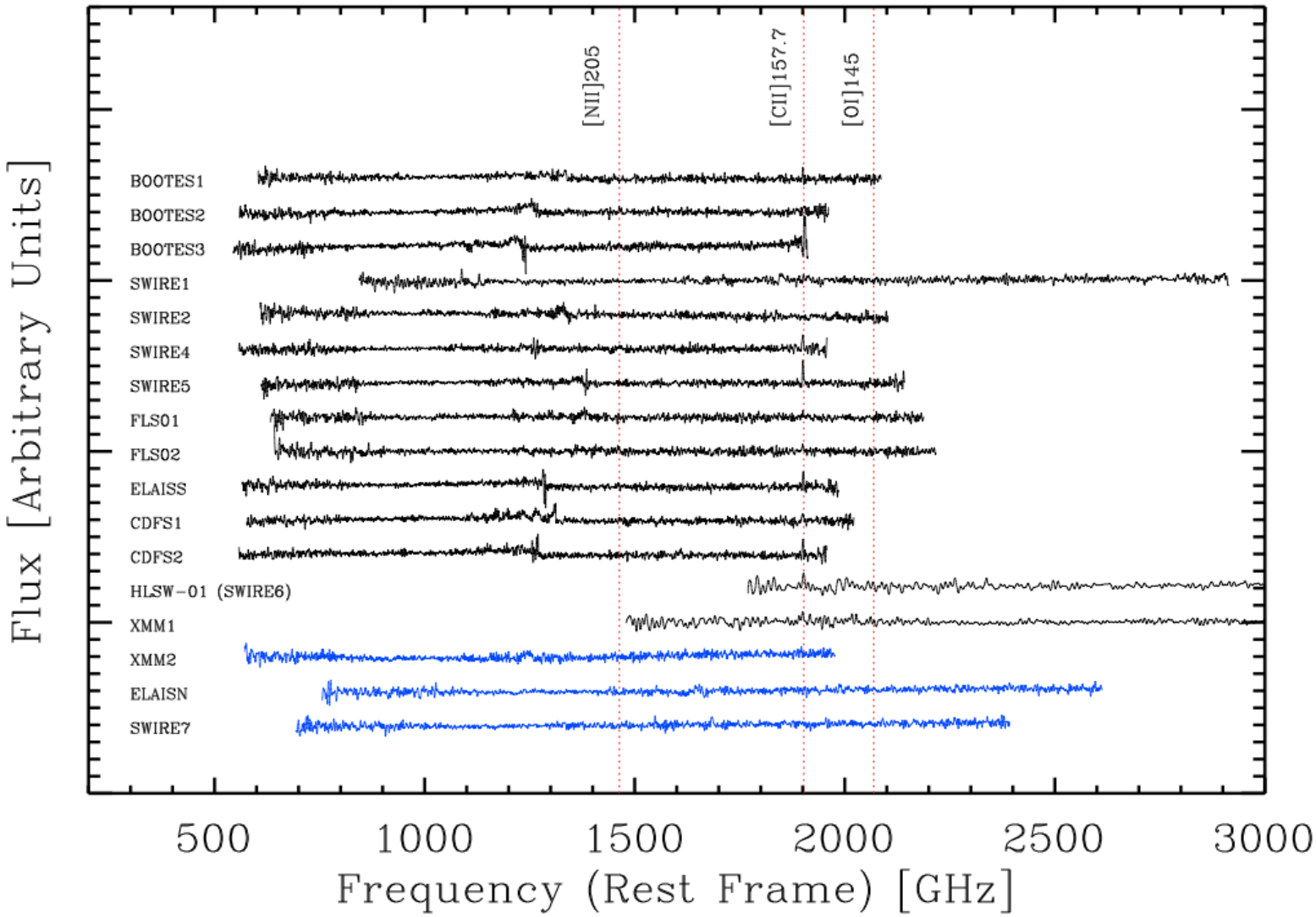
- Selected 17 (U)LIRGS with S_{250} >170mJy @ 0.2<z<0.6
- Follow up with FTS onboard Herschel (C+) and IRAM (CO)



Far-IR spectra of 0.2<z<0.6 (U)LIRGs

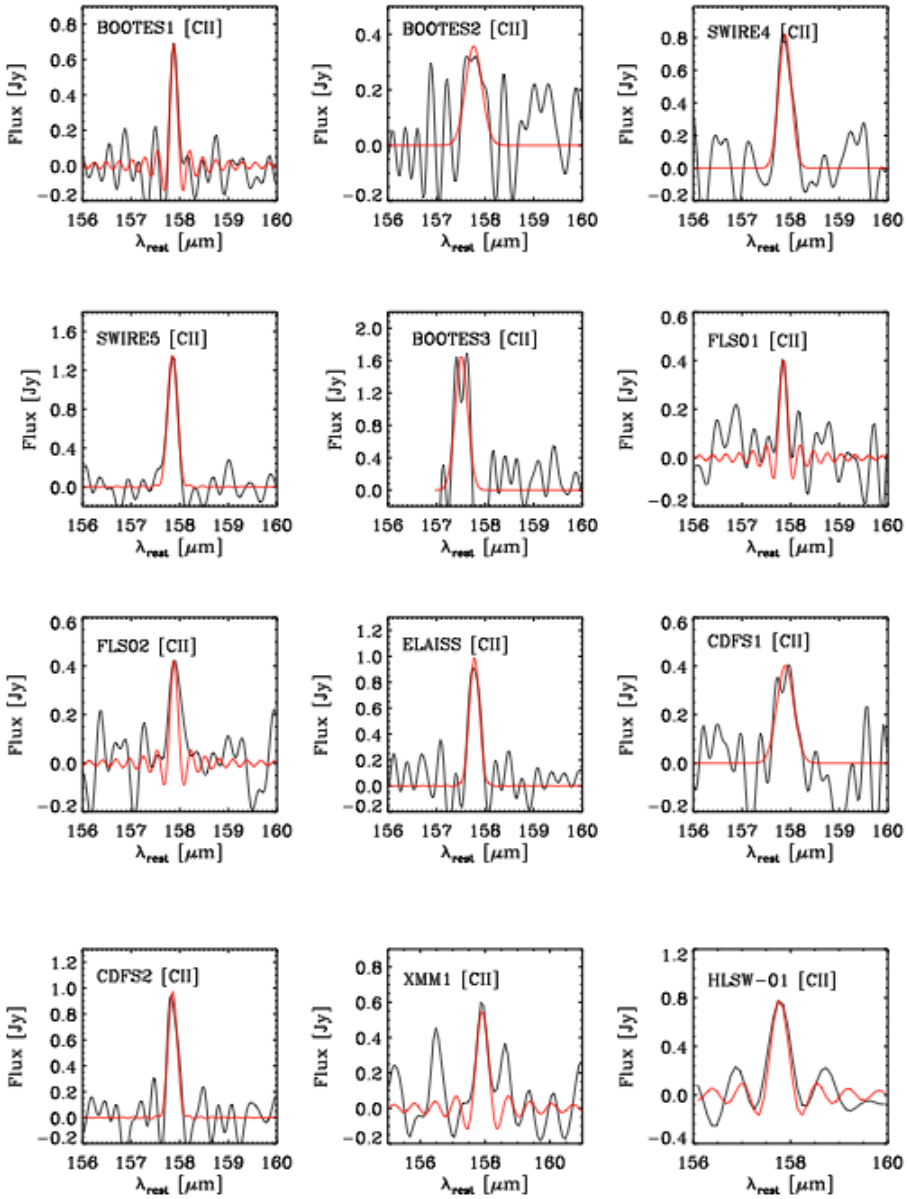
Magdis+14

FTS spectra



Far-IR spectra of 0.2<z<0.6 (U)LIRGs

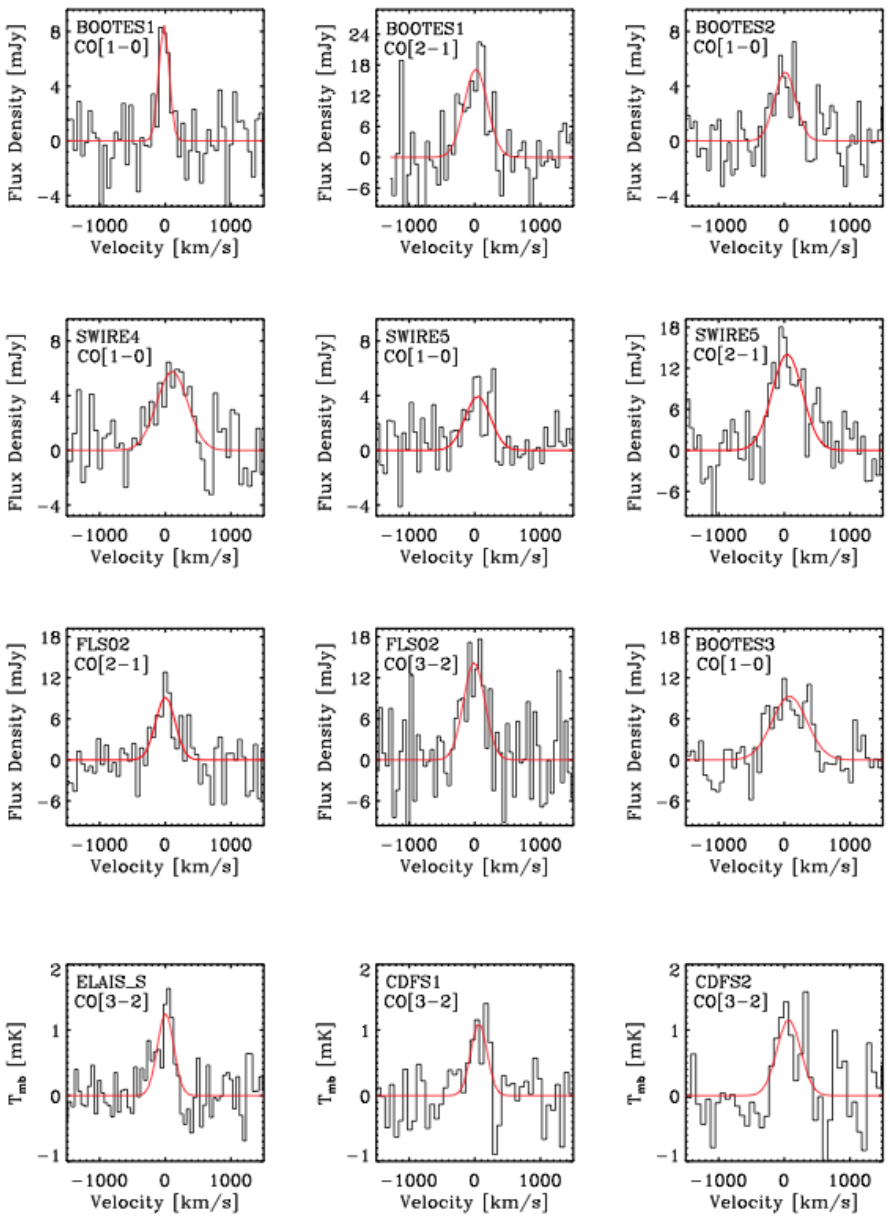
Magdis+14



[CII] 157.7 μm (FTS)

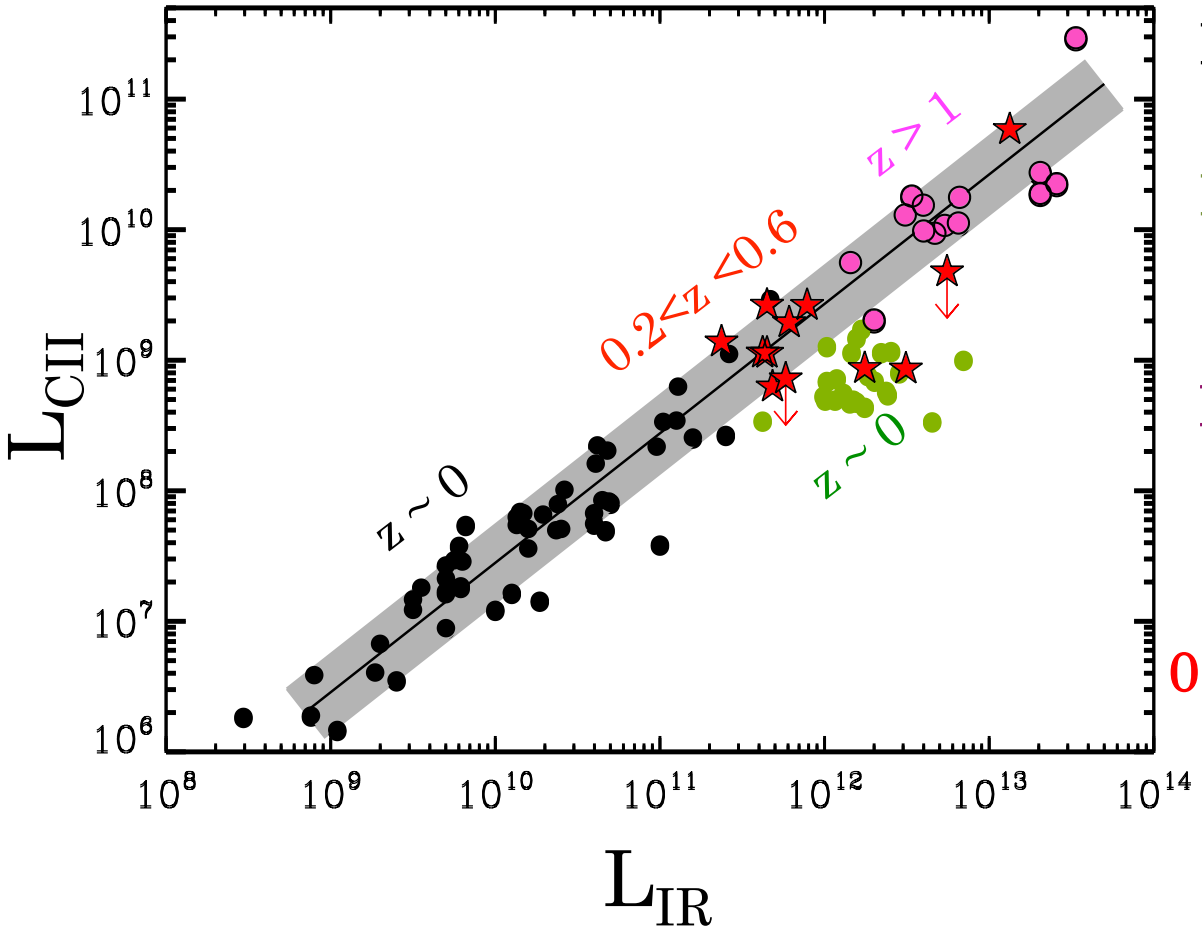
Far-IR spectra of 0.2<z<0.6 (U)LIRGs

Magdis+14



CO[1-0]
CO[2-1]
CO[3-2]
(APEX-IRAM)

L_{CII} – L_{IR} correlation



Local Galaxies

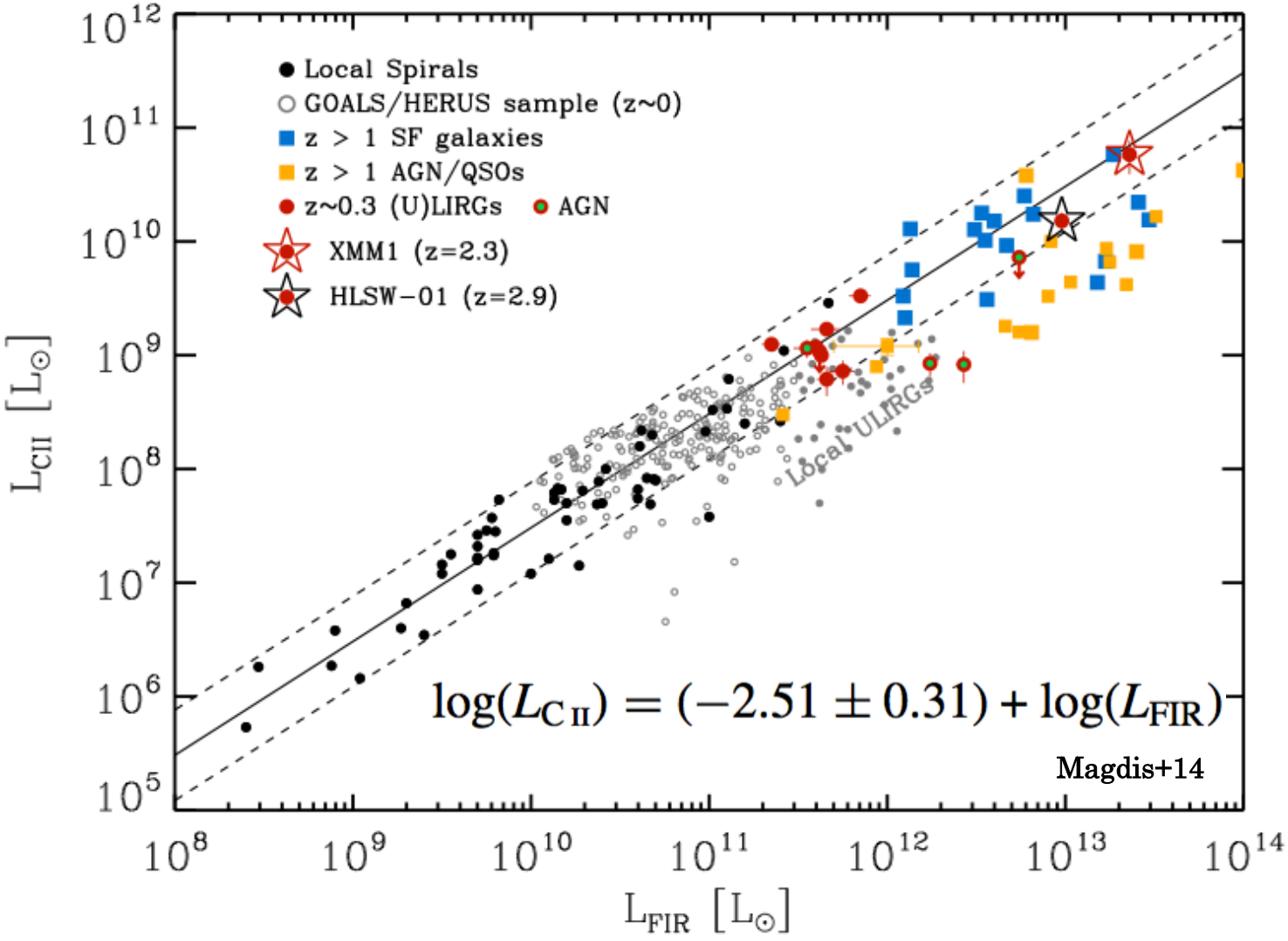
Local ULIRGs – CII deficit

High-z ULIRGs - CII deficit

0.2<z<0.6 ULIRGs - CII deficit

- Bridge the gap between local and high-z ULIRGs
- Evolution already at place @z~0.3-0.4

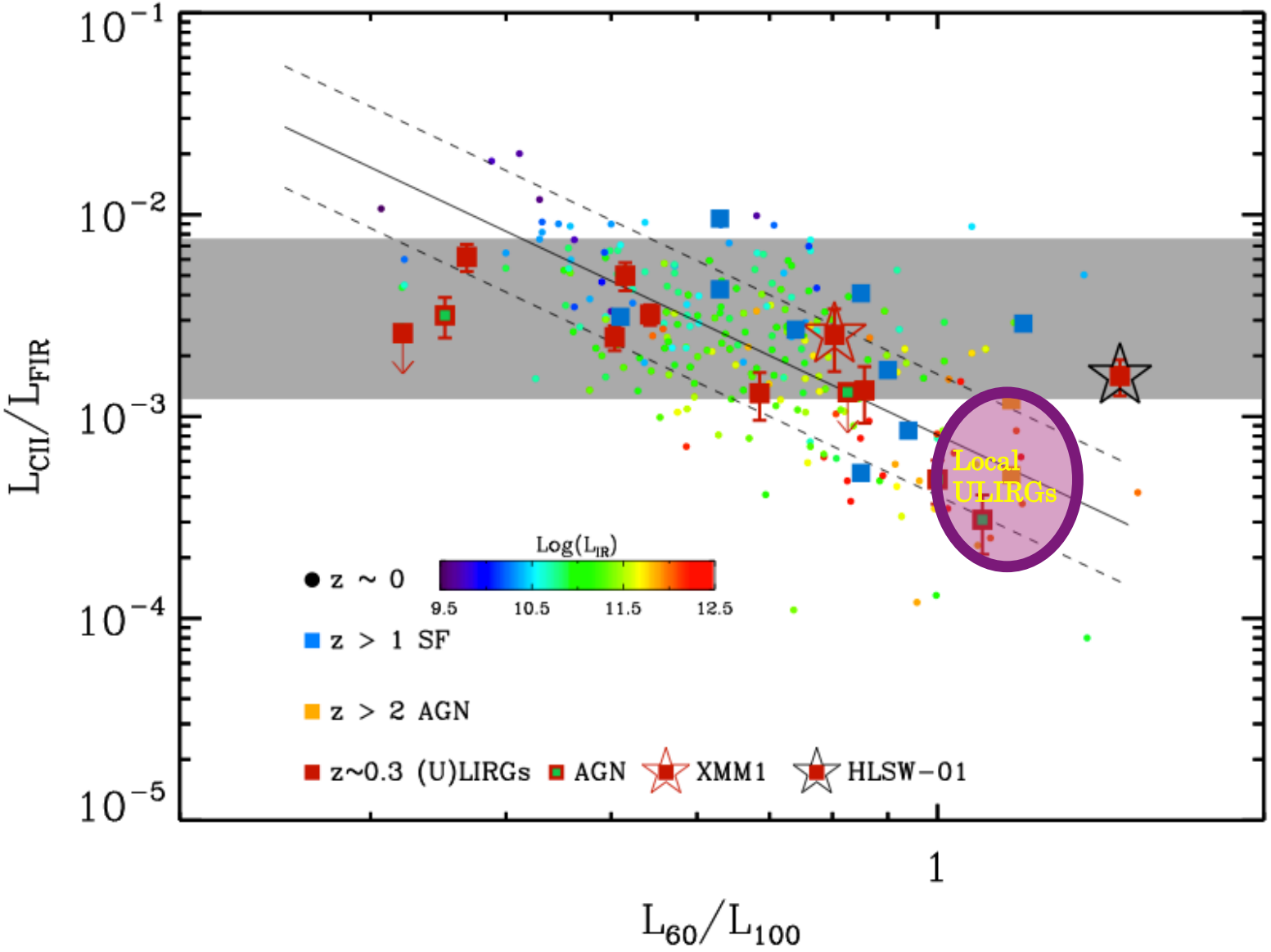
$L_{CII} - L_{IR}$



The majority of galaxies at all redshifts follow a universal L_{CII}–L_{IR} relation

Local ULIRGs and QSO's appear [CII] deficient.

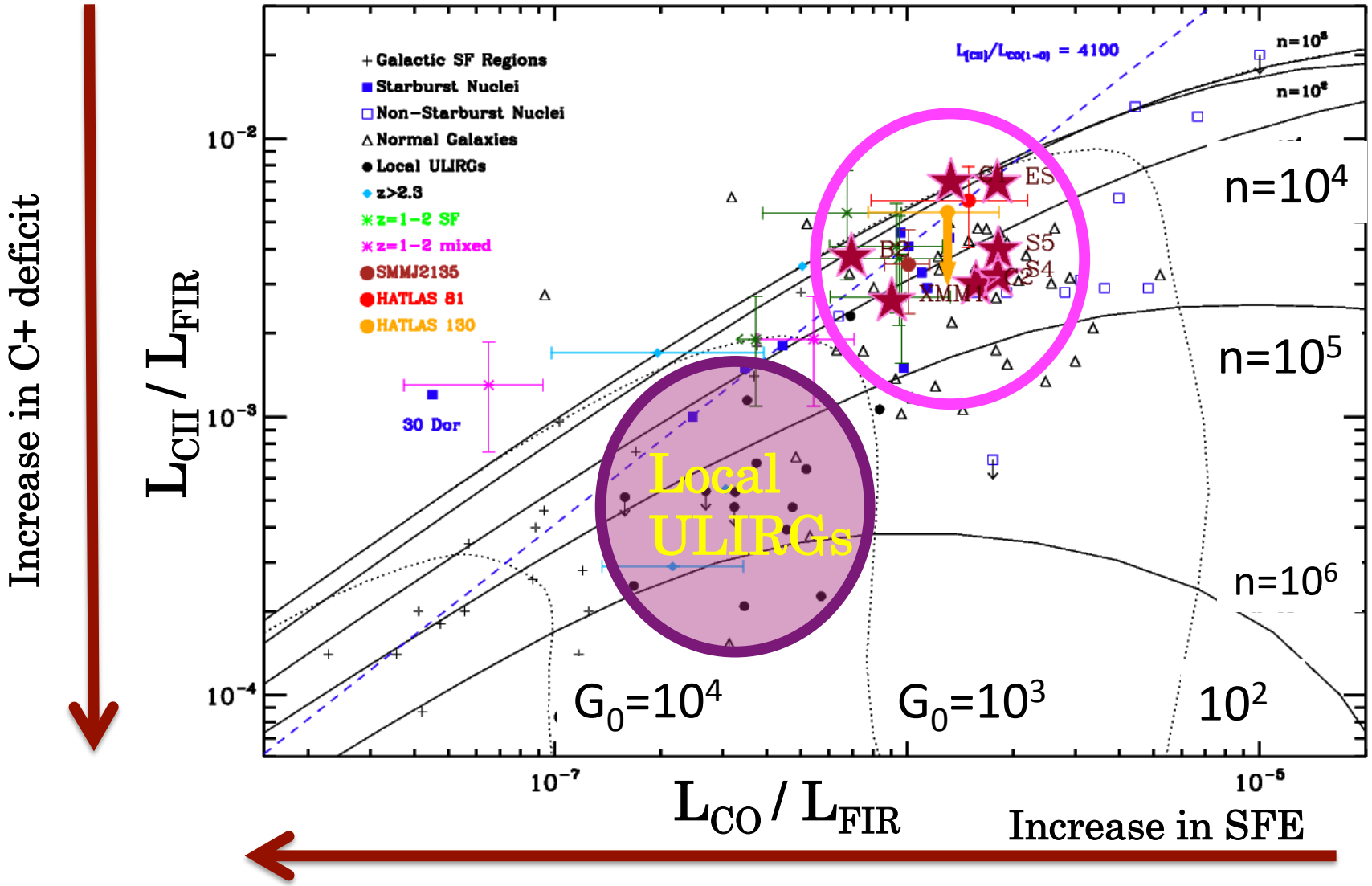
$L_{CII}/L_{IR} - T_d$



Distant ULIRGs are colder, lower radiation field <U>, more extended star formation

PDR fitting of [CII],CO, L_{IR}

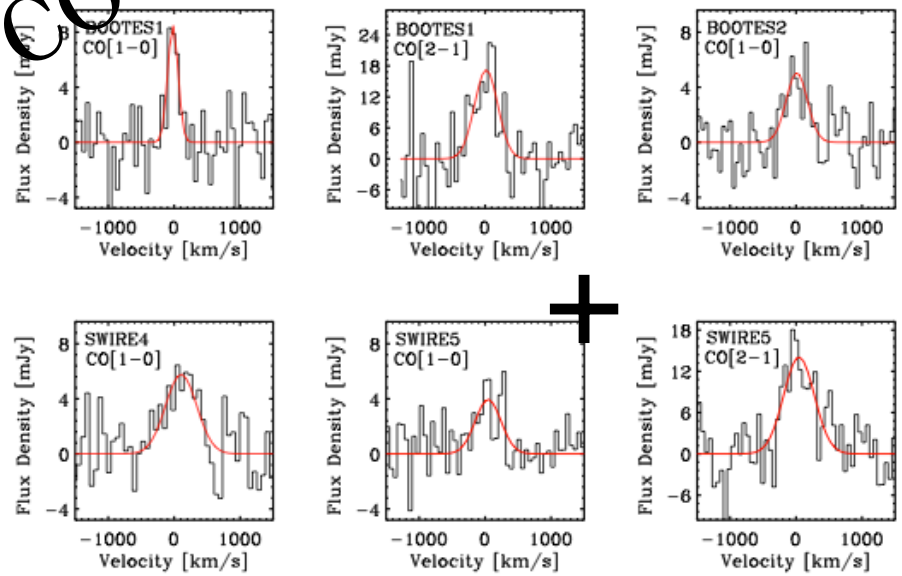
Rigopoulou+14



Softer radiation fields

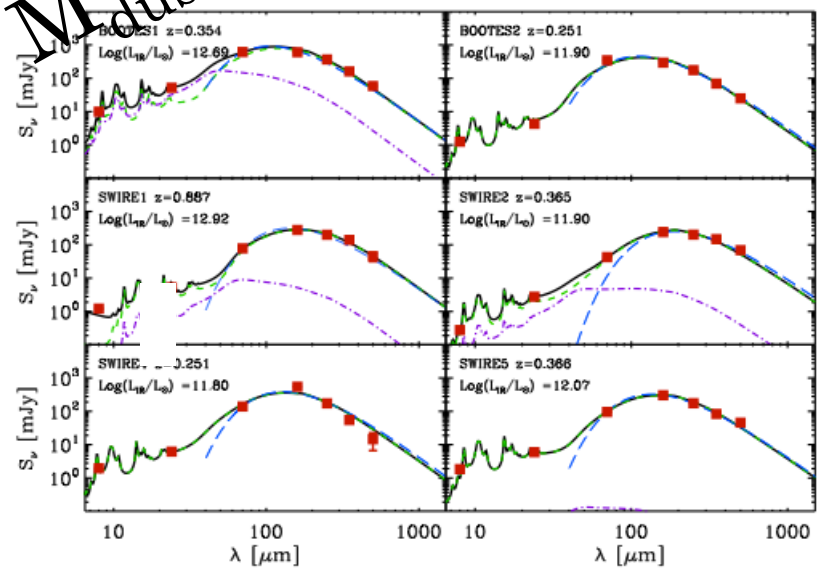
Dust to Gas Mass Ratio Approach

CO



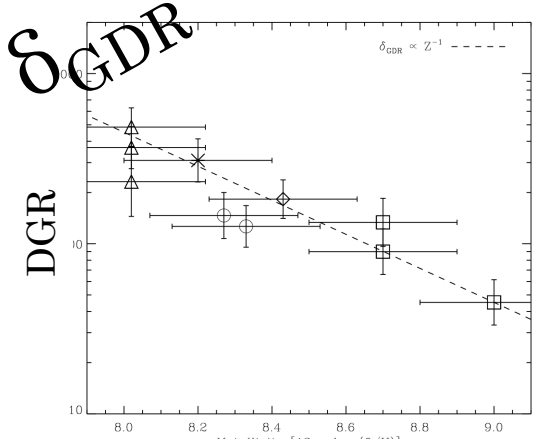
+

M_{dust}



+

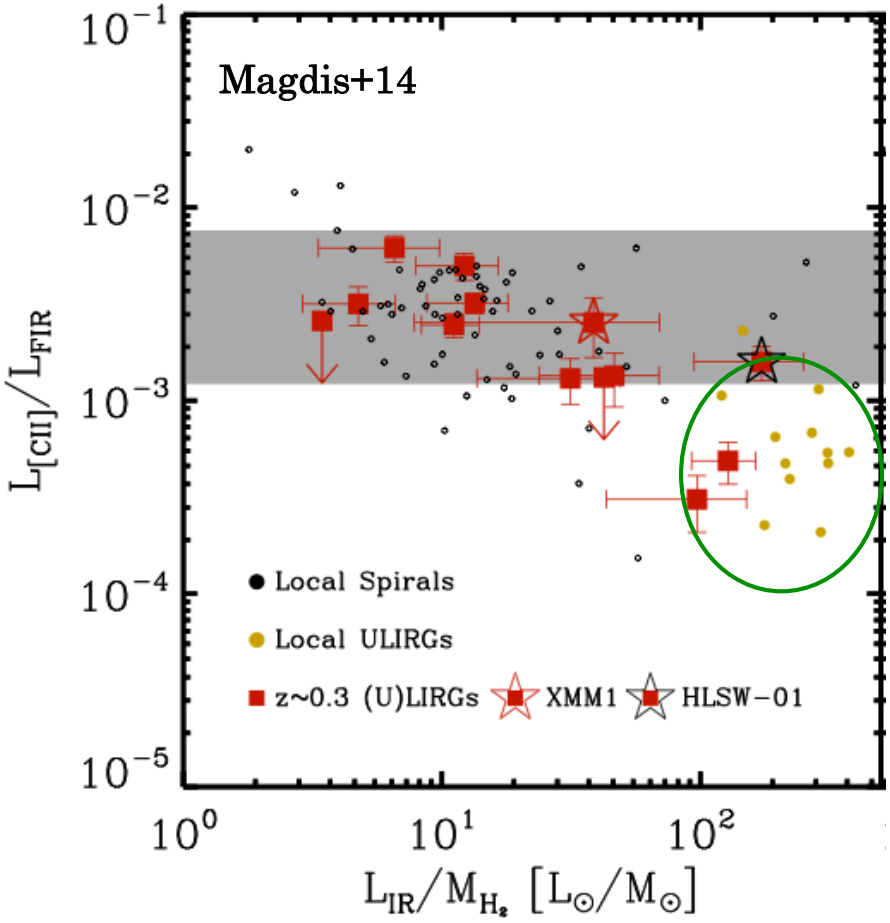
δ_{GDR}



$$\alpha_{CO} = (M_d \times \delta_{GDR}) / I_{CO}$$

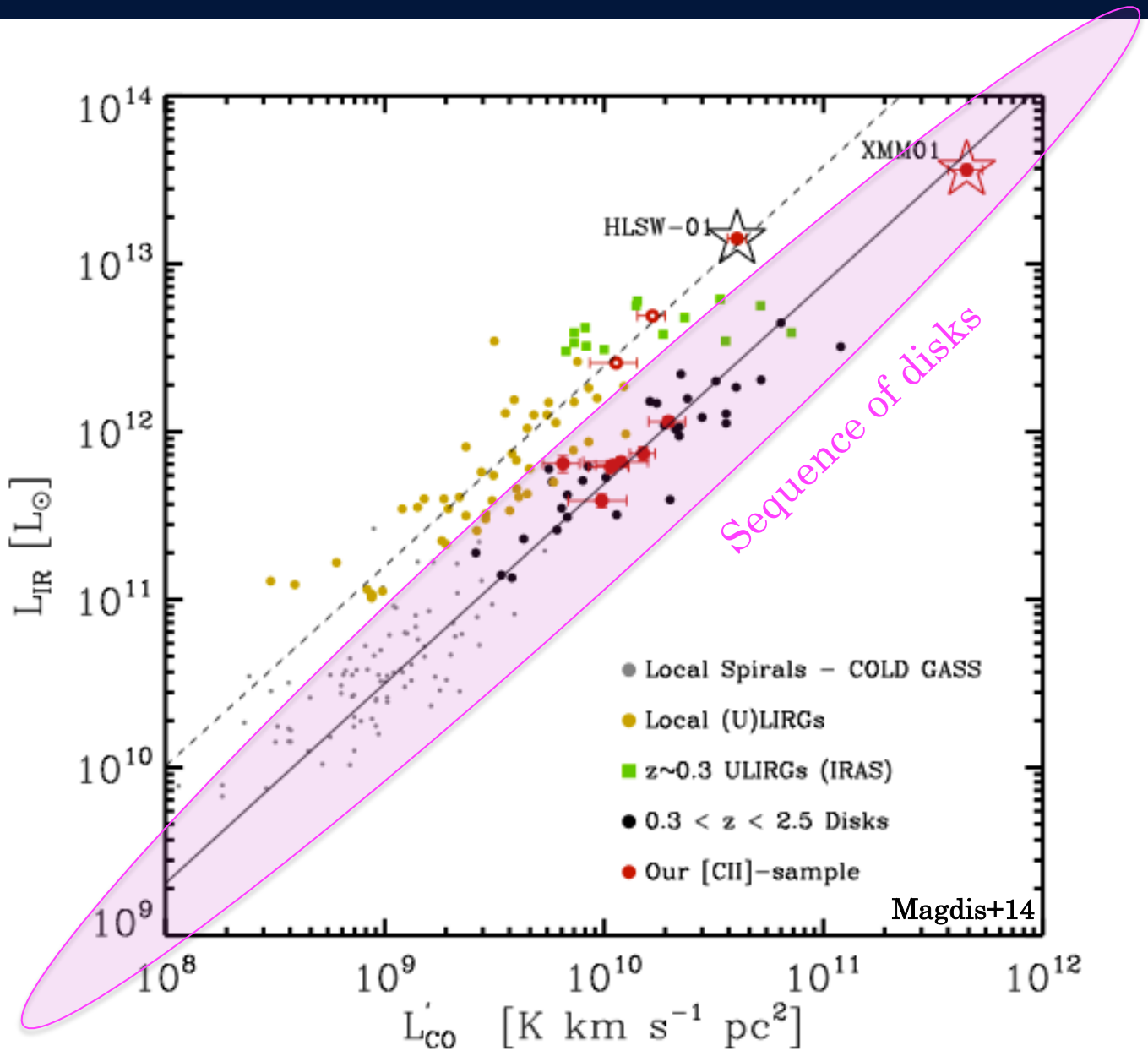
$z \sim 0.3$ ULIRGs, $\alpha_{CO} \sim 4.5$ (disk-like)

L_{CII}/L_{IR} vs SFE



[CII] deficit pronounced for sources with high SFE =SFR/M_{H2}

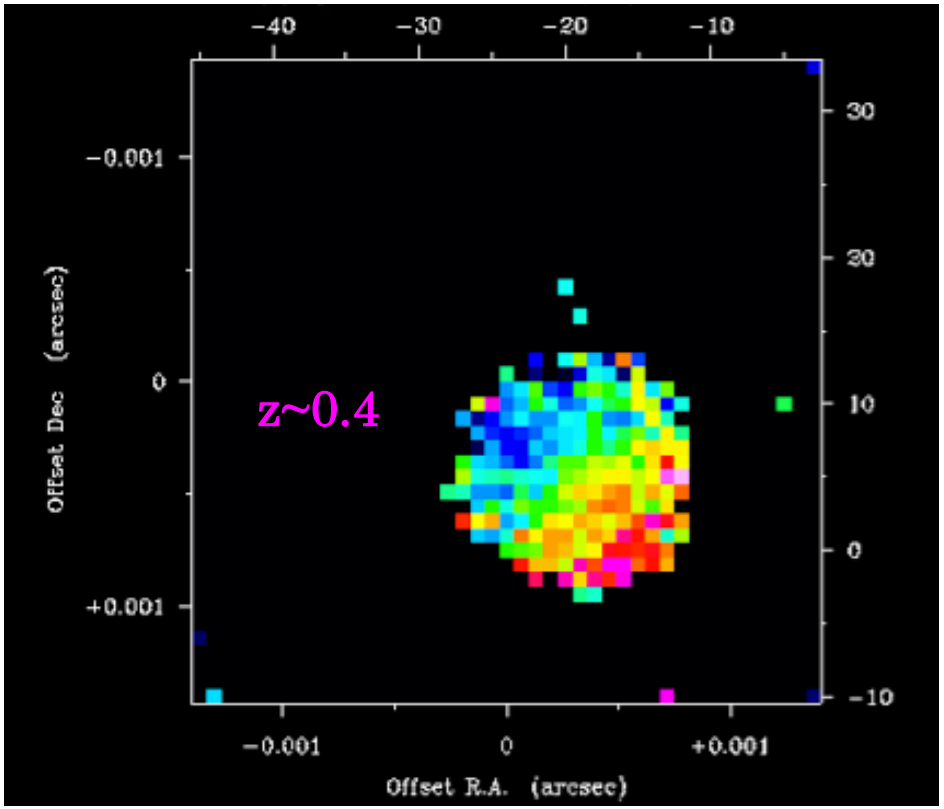
Possible Scenario : High SFE and hard radiation fields due to compressed star formation triggered by mergers.


XMM01
HLSW-01
Sequence of disks
Local Spirals – COLD GASS
Local (U)LIRGs
z~0.3 ULIRGs (IRAS)
0.3 < z < 2.5 Disks
Our [CII]-sample
Magdis+14
L_{IR} [$L_\odot$]
L'_{CO} [K km s^{-1} pc^2]
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}

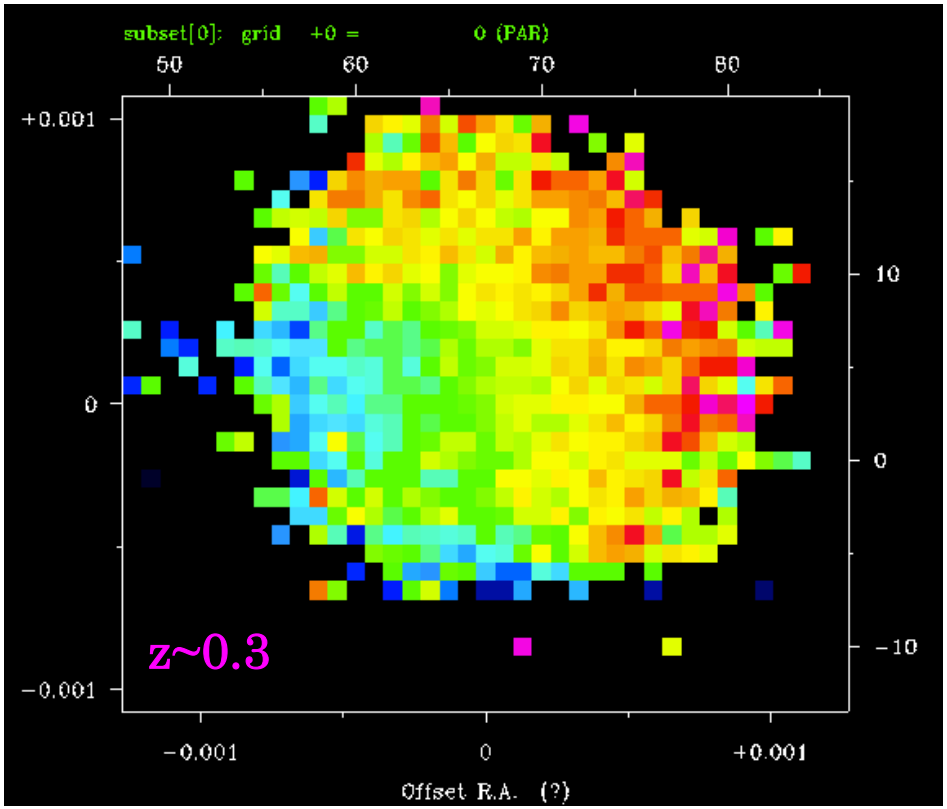
Kinematics of z~0.4 ULIRGs

Hα velocity maps – Oxford-SWIFT, IFU

$L_{IR} = 8.0 \times 10^{11} L_{\odot}$

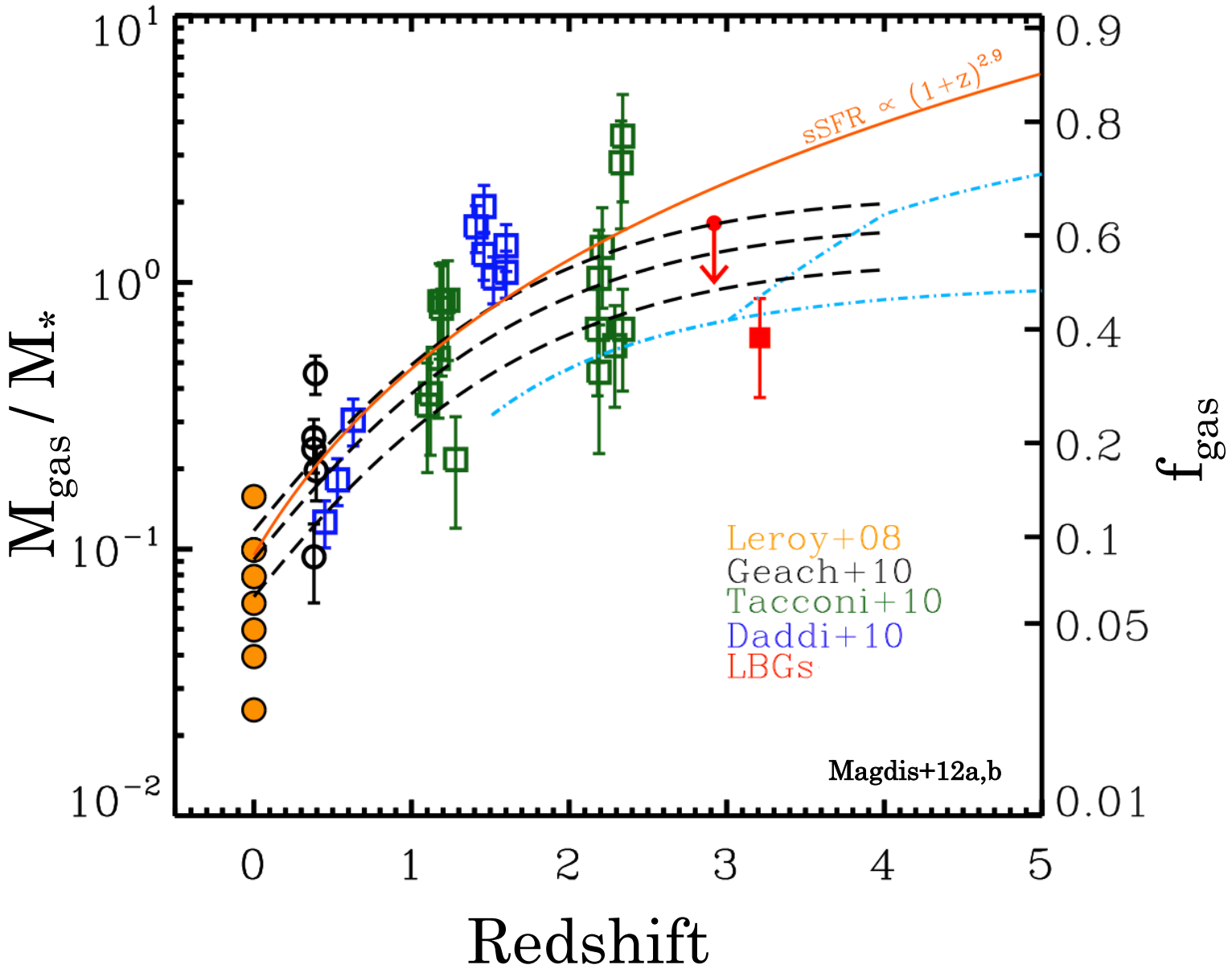


$L_{IR} = 1.1 \times 10^{12} L_{\odot}$

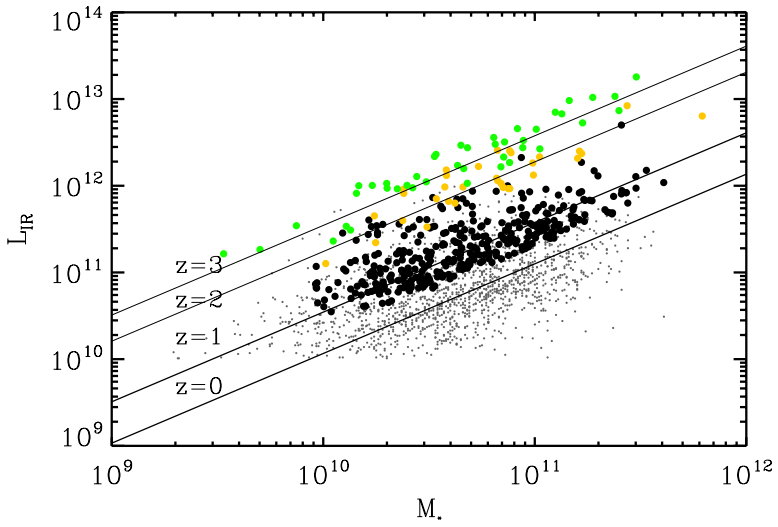


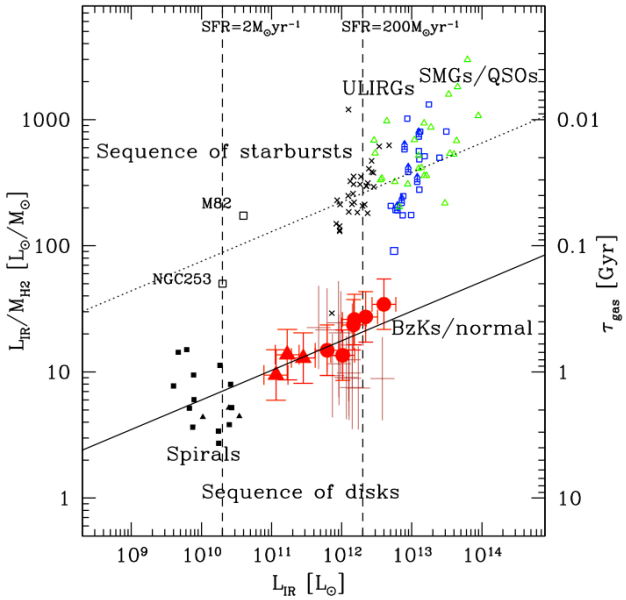
Magdis+14 in prep

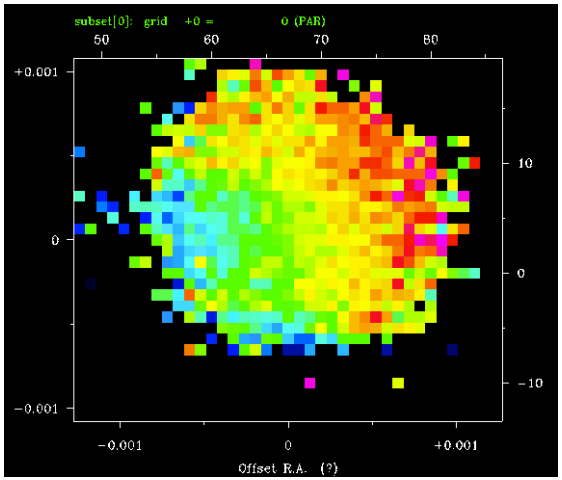
Evolution of Gas Fraction



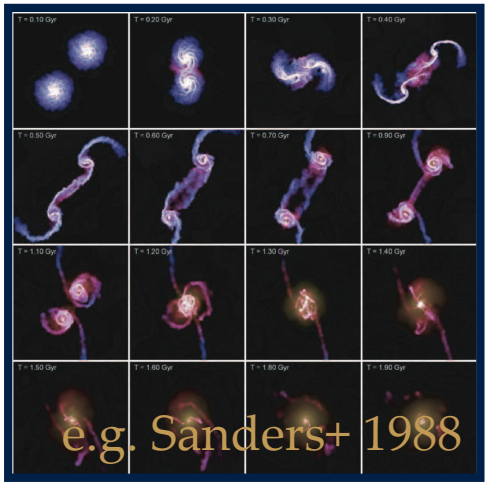
Secular Evolution vs Mergers

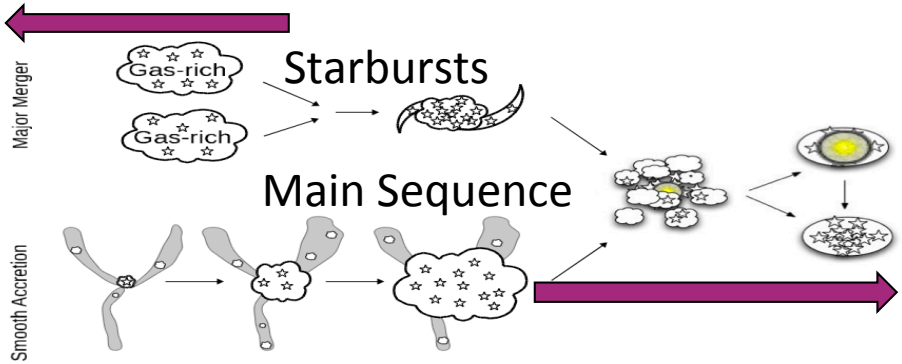




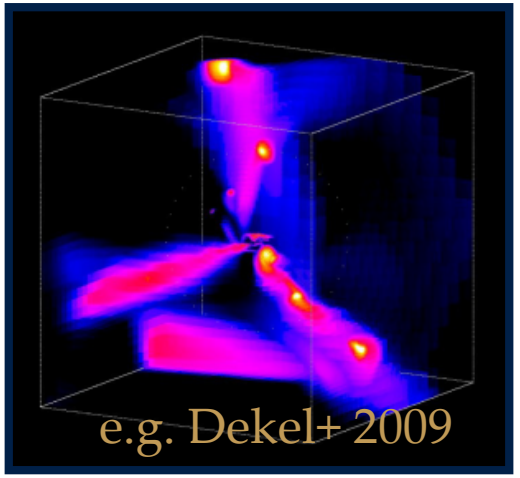


MAJOR MERGERS:
Short-lived starbursts





COLD GAS INFLOWS:
Long lasting, secular SF

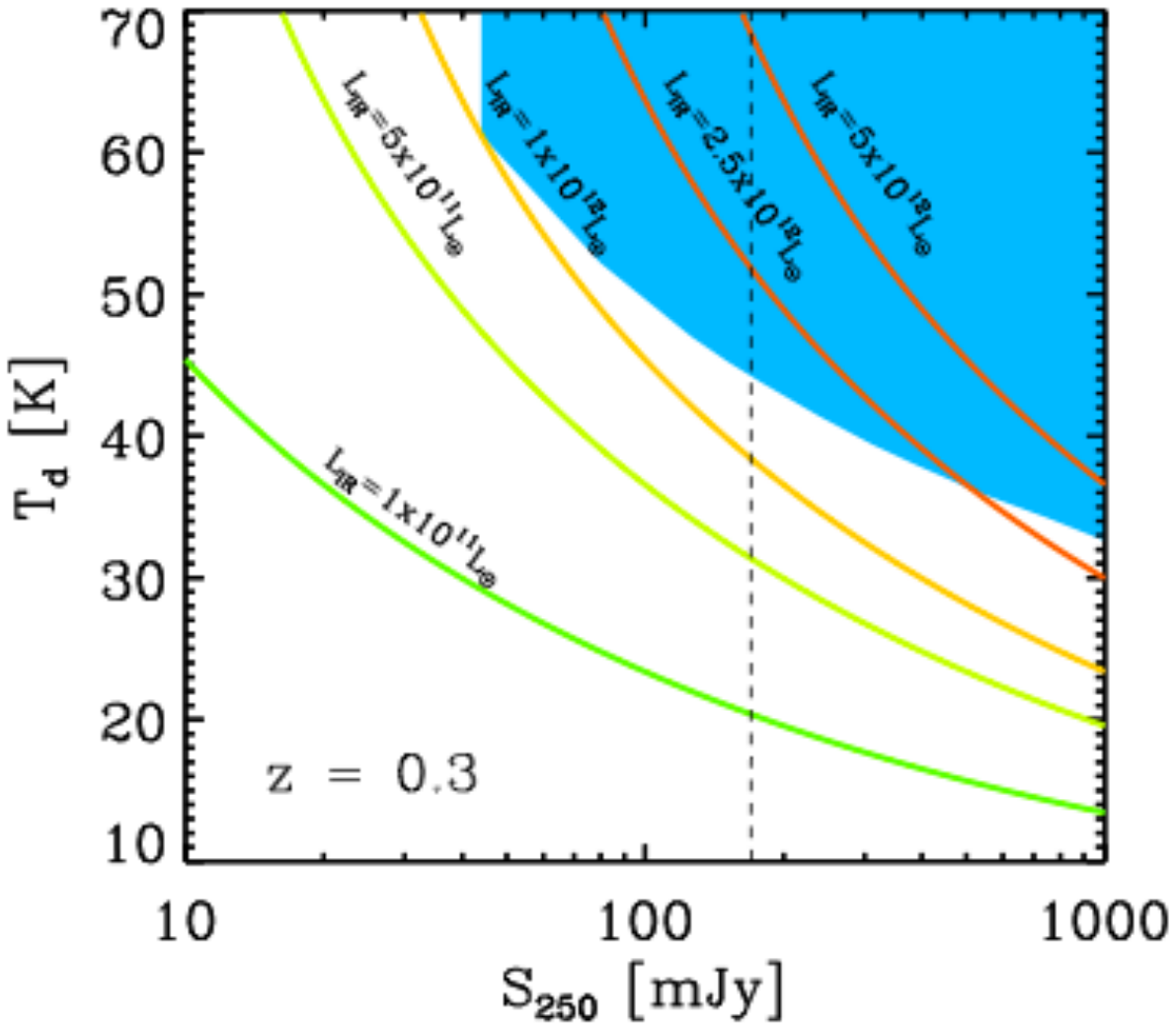


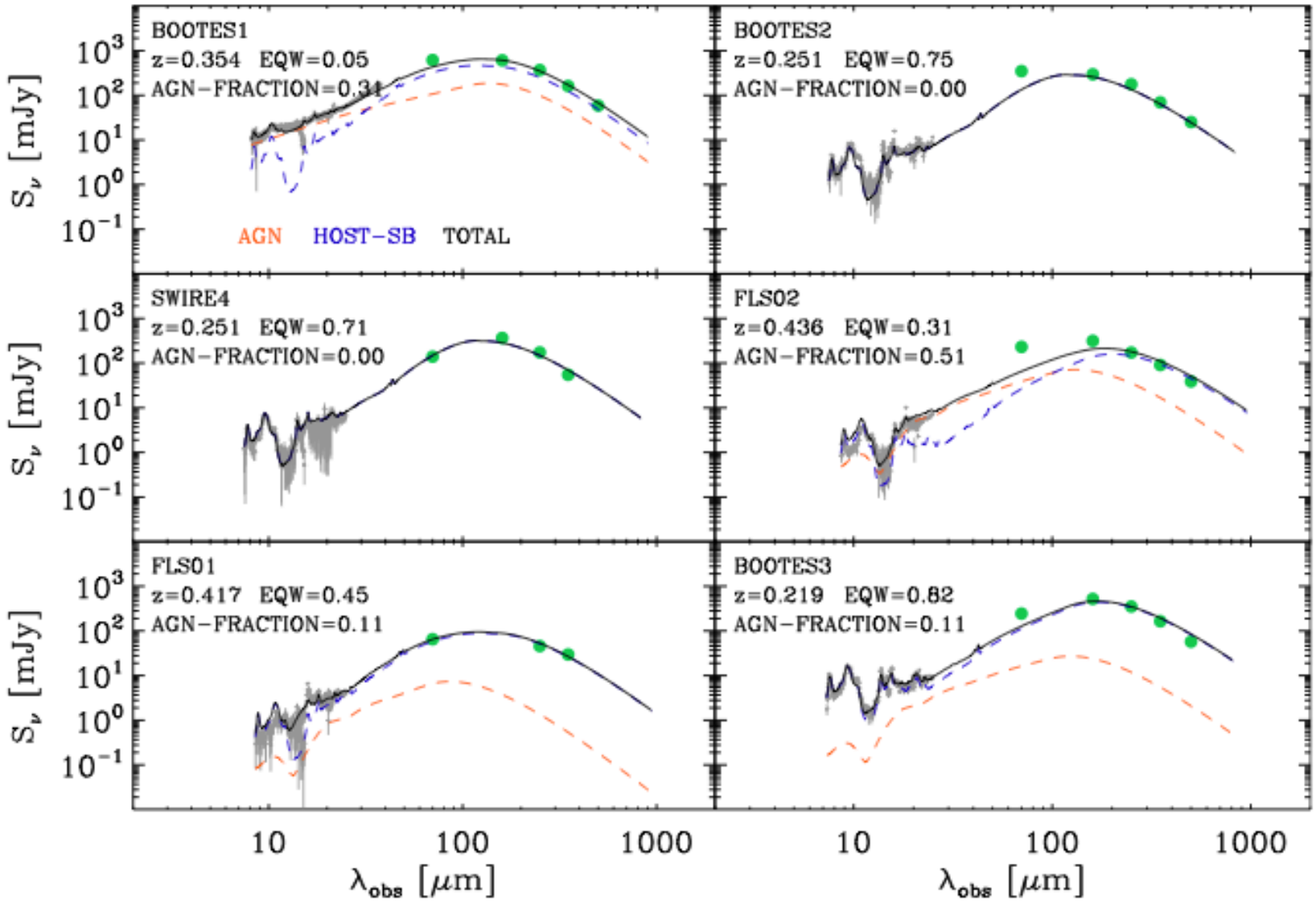
Summary

1. Strong evolution in the star formation activity of ULIRGs, as traced by [CII], CO and Ha kinematics, already by z ~ 0.3

2. Properties of the galaxies are "decoupled" from L_{IR} as soon as z~0.3

Indication that galaxy growth was driven by steady and smooth mode of star formation activity.


70
60
50
40
30
20
10
T_d [K]
10
100
1000
S_{250} [mJy]
$L_{IR}=5\times10^{11}L_\odot$
$L_{IR}=1\times10^{12}L_\odot$
$L_{IR}=2.5\times10^{12}L_\odot$
$L_{IR}=5\times10^{12}L_\odot$
$L_{IR}=1\times10^{11}L_\odot$
z = 0.3


BOOTES1
z=0.354 EQW=0.05
AGN−FRACTION=0.31
AGN HOST−SB TOTAL
BOOTES2
z=0.251 EQW=0.75
AGN−FRACTION=0.00
SWIRE4
z=0.251 EQW=0.71
AGN−FRACTION=0.00
FLS02
z=0.436 EQW=0.31
AGN−FRACTION=0.51
FLS01
z=0.417 EQW=0.45
AGN−FRACTION=0.11
BOOTES3
z=0.219 EQW=0.82
AGN−FRACTION=0.11
S_ν [mJy]
λ_obs [μm]
10
100
1000

ALMA BAND10 down to 315μm → [CII] down to z ~ 1
SAFARI up tp 210μm → [CII] up to z ~ 0.3

up to 280μm → [CII] up to z ~ 0.8