[CII] Emission as a Star Formation Rate Tracer

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PhD thesis work for
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KINGFISH collaboration

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Star Formation in the Milky Way and Nearby Galaxies

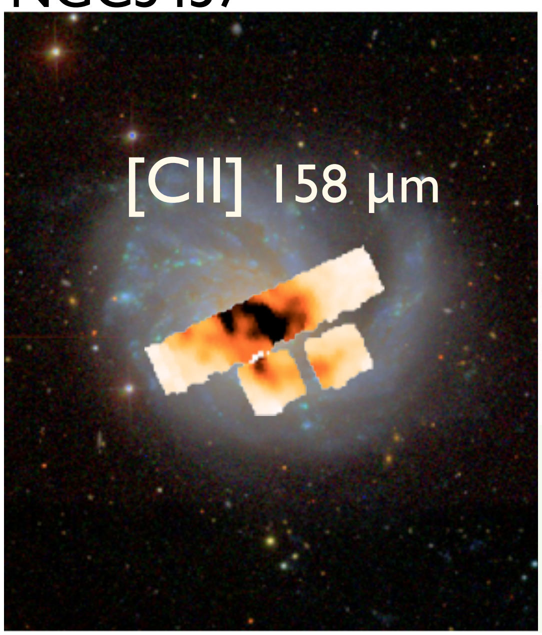
Robert C. Kennicutt, Jr.,[1] and Neal J. Evans II[2]

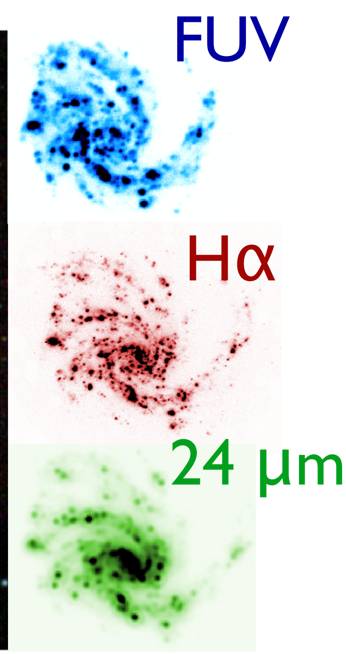
2012ARA&A, 50, 531K

Regarding the use of [CII] 158 µm as a SFR tracer...

The availability of a rich new set of [CII] observations from *Herschel*, combined with the detection of redshifted [CII] emission in submillimeter galaxies (SMGs) from ground-based instruments, has sparked a resurgence of interest in this application.

NGC5457





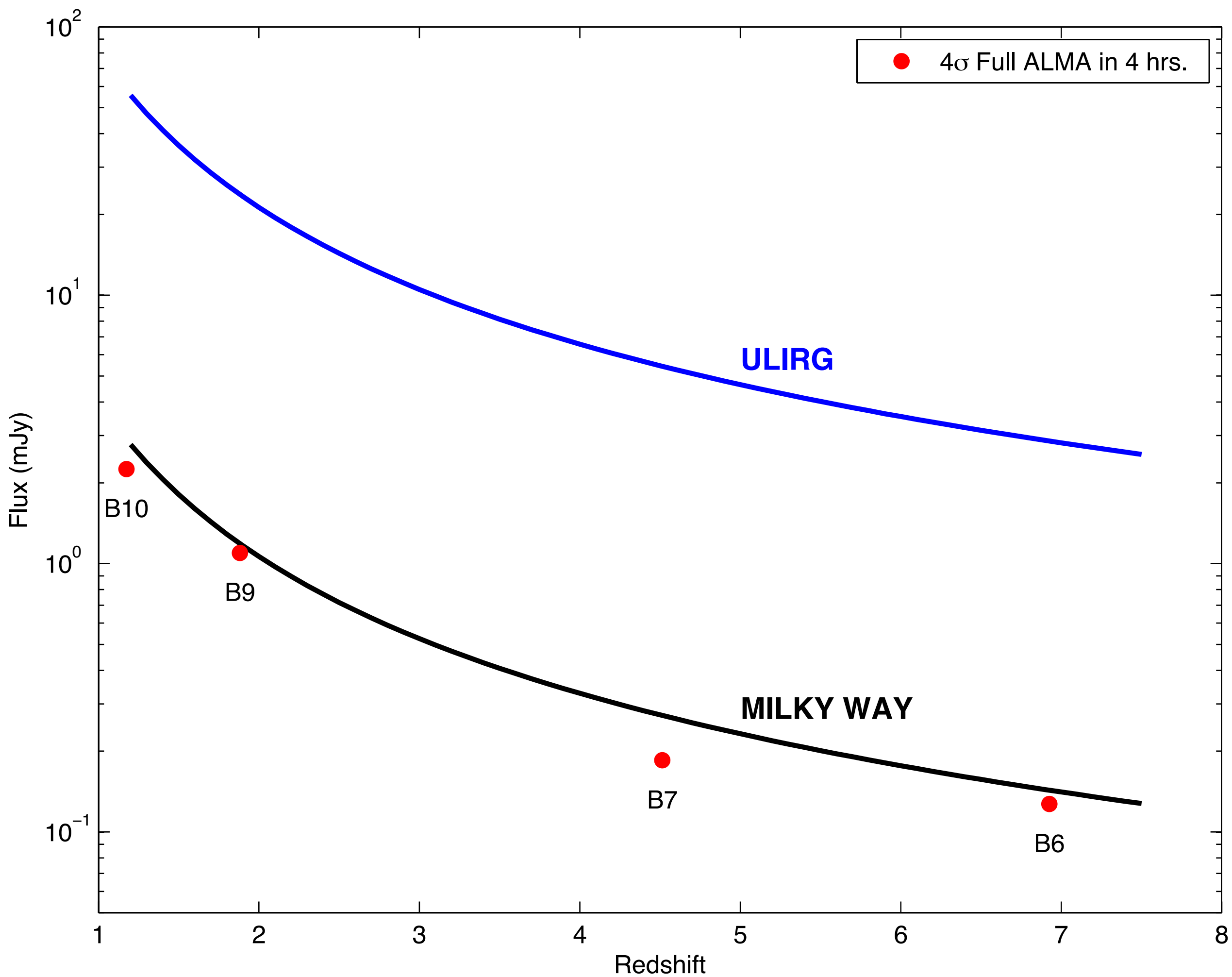
Advantages

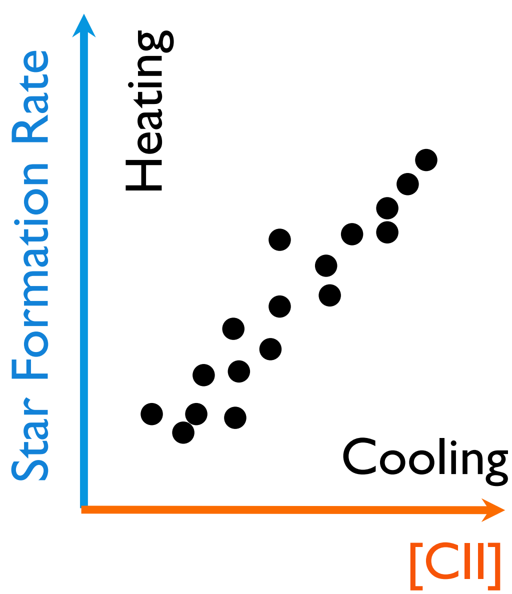
1. Very bright line in star forming galaxies (~0.1 - 1% L_{FIR})
2. Major coolant for the diffuse, neutral ISM
3. ALMA will detect [CII] in normal star forming galaxies at $z \gtrsim 2$

Caveats

1. [CII] could be produced in regions of the galaxy that are not necessarily associated to star formation
2. [CII] “deficit”

ALMA can detect the Milky Way in [CII] at any z



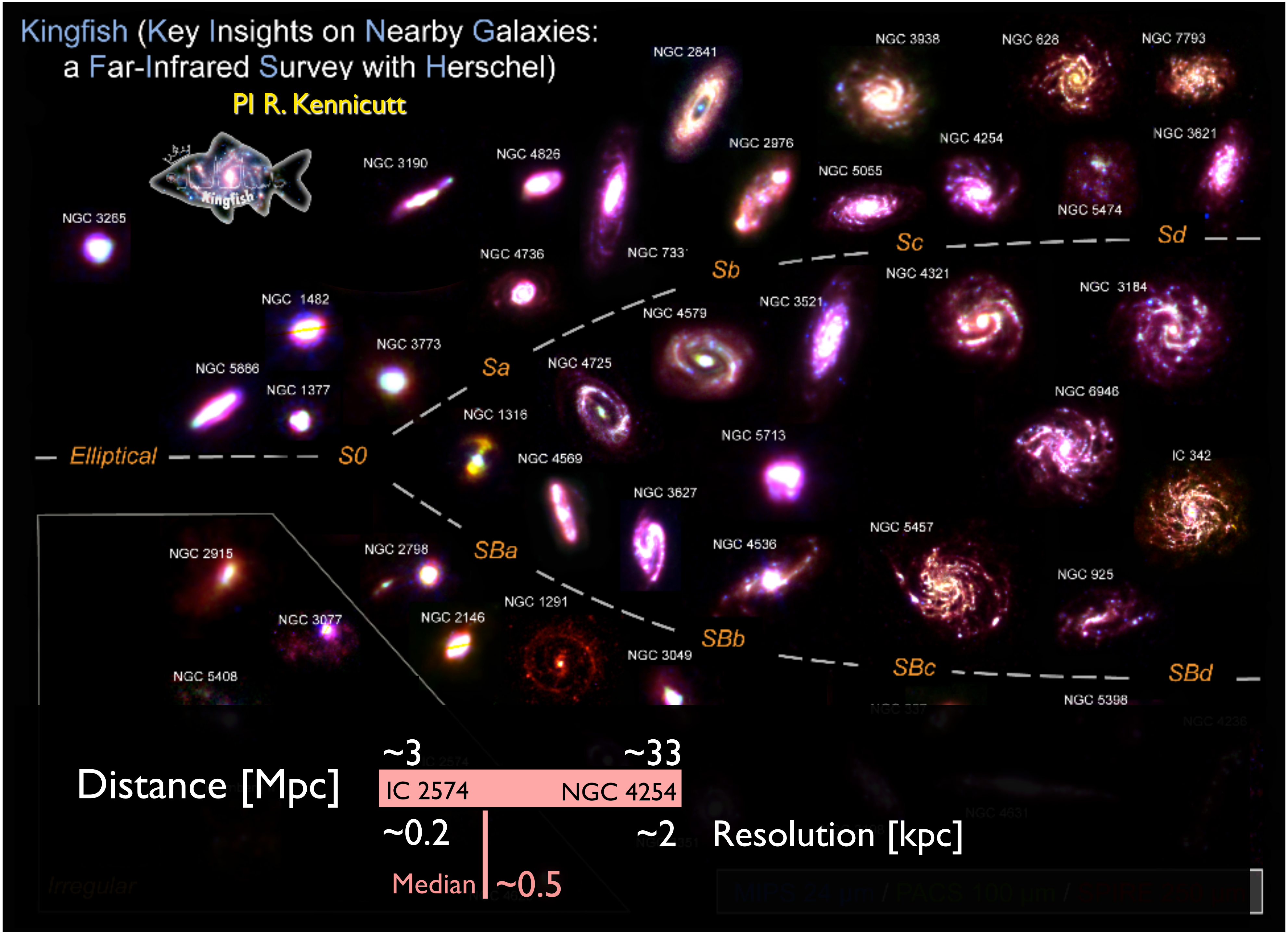


The Goal

Use resolved regions from a sample of 50 KINGFISH galaxies

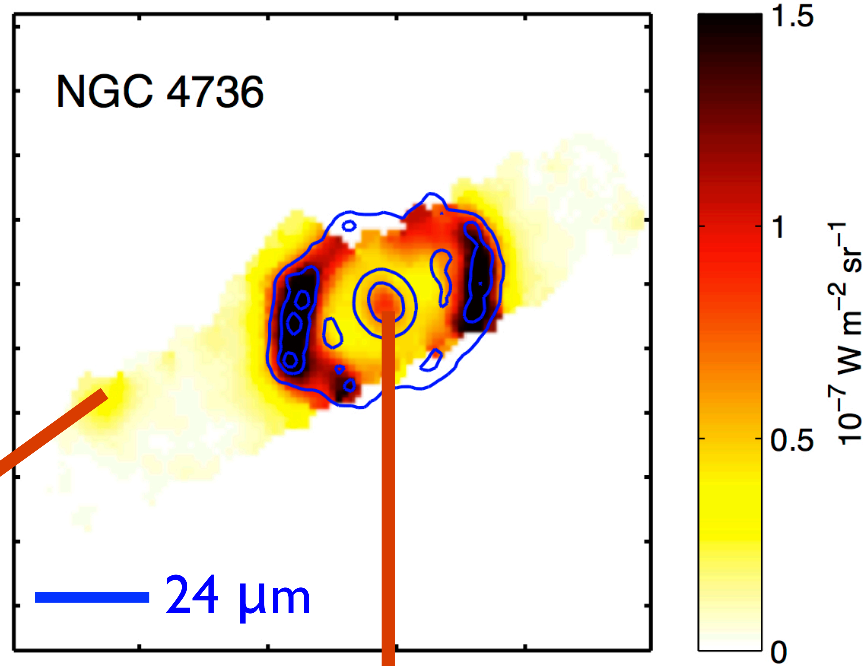
Study how [CII] 158 μm emission correlates with other star formation tracers

Derive a SFR calibration based on [CII] 158 μm



Kingfish (Key Insights on Nearby Galaxies:
a Far-Infrared Survey with Herschel)
PI R. Kennicutt
Kingfish
NGC 3265
NGC 3190
NGC 4826
NGC 2841
NGC 2976
NGC 3938
NGC 628
NGC 7793
NGC 5055
NGC 4254
NGC 3621
NGC 5474
Sc
Sd
Sb
NGC 4736
NGC 7331
NGC 4321
NGC 3184
NGC 1482
NGC 4579
NGC 3521
NGC 3773
Sa
NGC 4725
NGC 5866
NGC 1377
NGC 1316
NGC 6946
NGC 5713
IC 342
Elliptical
S0
NGC 4569
NGC 3627
NGC 2915
NGC 2798
SBa
NGC 4536
NGC 5457
NGC 925
NGC 3077
NGC 2146
NGC 1291
NGC 3049
SBb
SBc
SBd
NGC 5408
NGC 5398
Distance [Mpc]
~3
~33
IC 2574
NGC 4254
~0.2
~2
Resolution [kpc]
Median
~0.5

[CII] versus 24 μm associated to SF



24 μm

"Cirrus" Contribution

e.g. dust heated by old stars

To remove the cirrus contribution we use the procedure described in Leroy+12

Fraction of 24 μm associated to cirrus:

avg. $f_{24\mu m,cirrus}$ ~ 20%

(~19% Leroy+12, 7% Law+11)

AGN Contribution

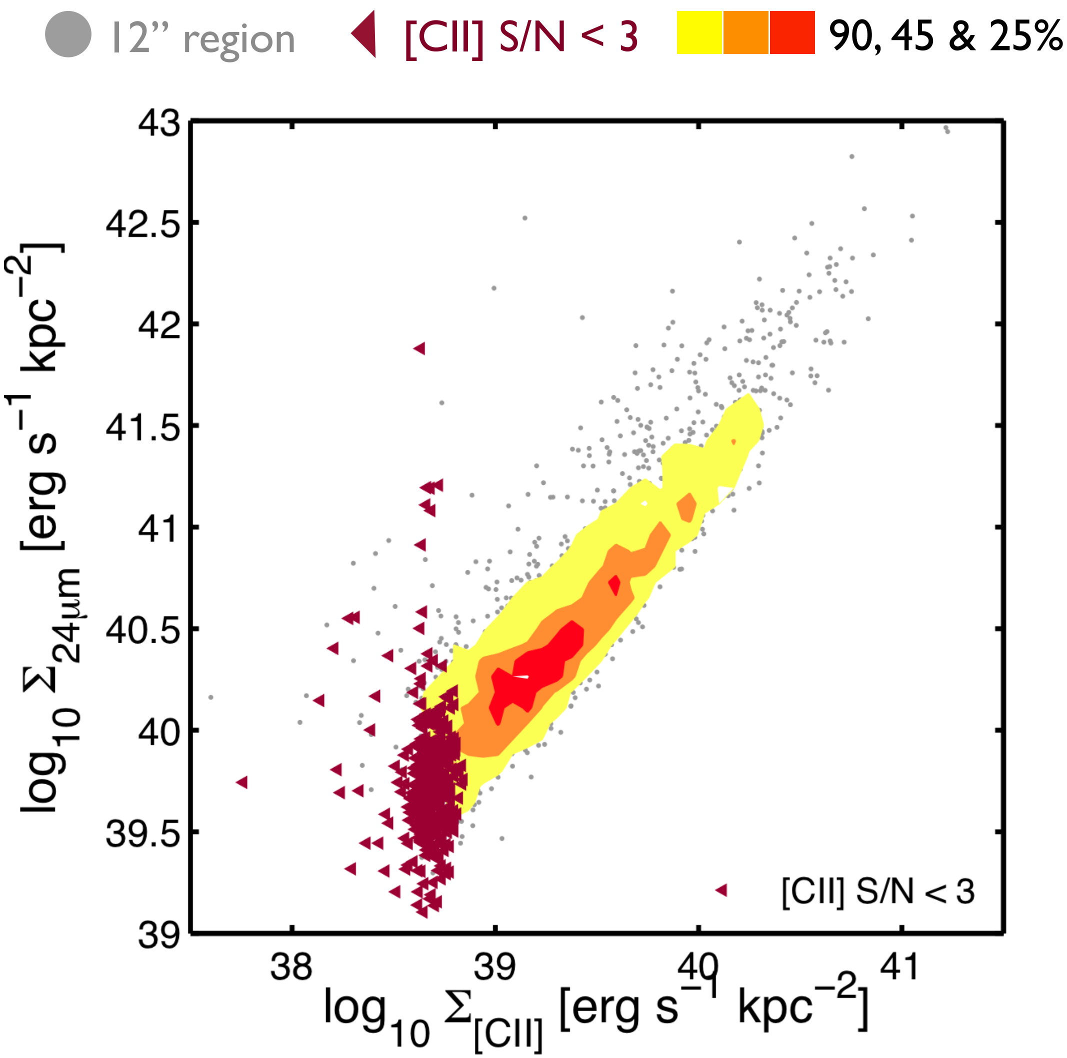
X-ray Dominated Regions

contribute to 24 μm

contribute to [CII] emission

Stacey+10: ~10% (47% PKS 0215)

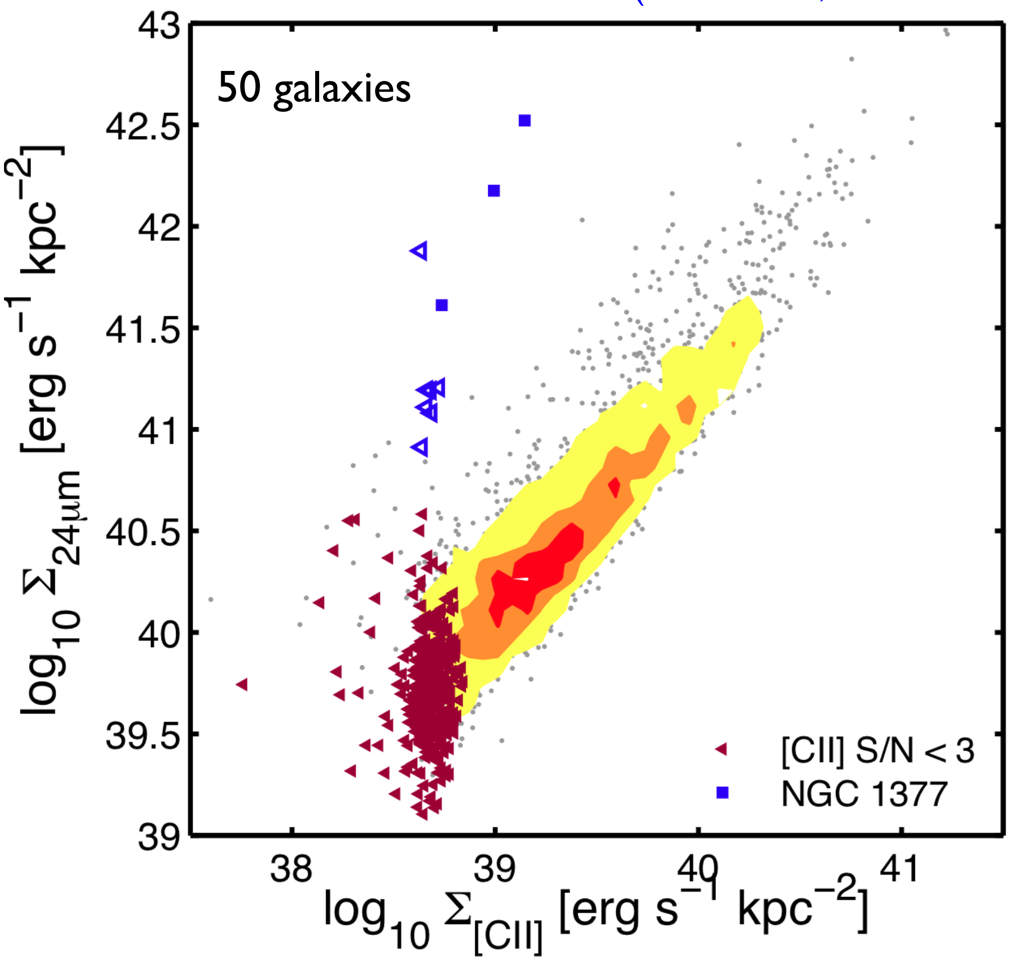
The [CII] - 24μm Correlation



We find good $\Sigma_{[CII]}$ - $\Sigma_{24\mu m}$ correlation. Most of the [CII] upper limits are consistent with the correlation.

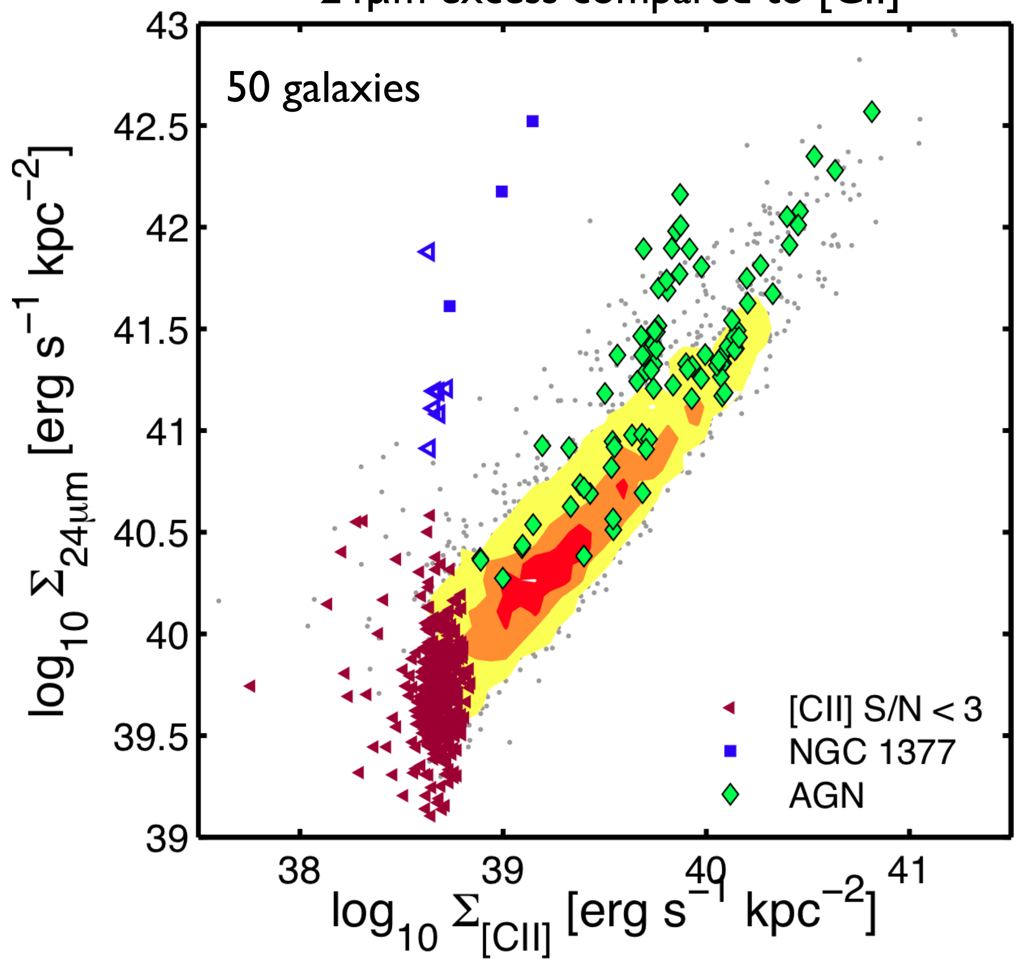
The [CII] - 24µm Correlation

NGC 1377: Nascent Starburst or buried AGN?
(Roussel+06; Imanishi+09)



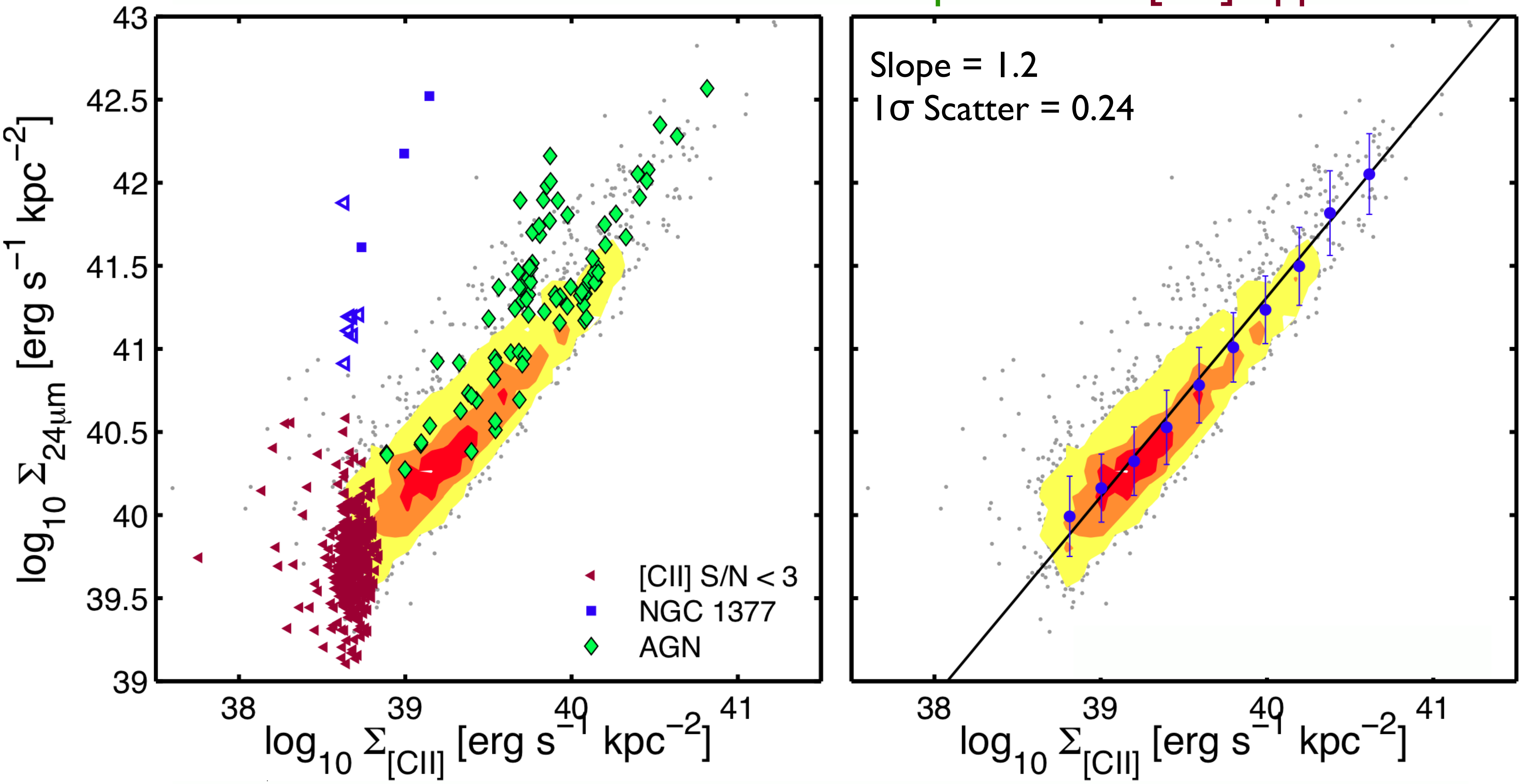
AGN Contribution: mask the central ~0.5 kpc region

About half of the AGN regions show a moderate 24μm excess compared to [CII]



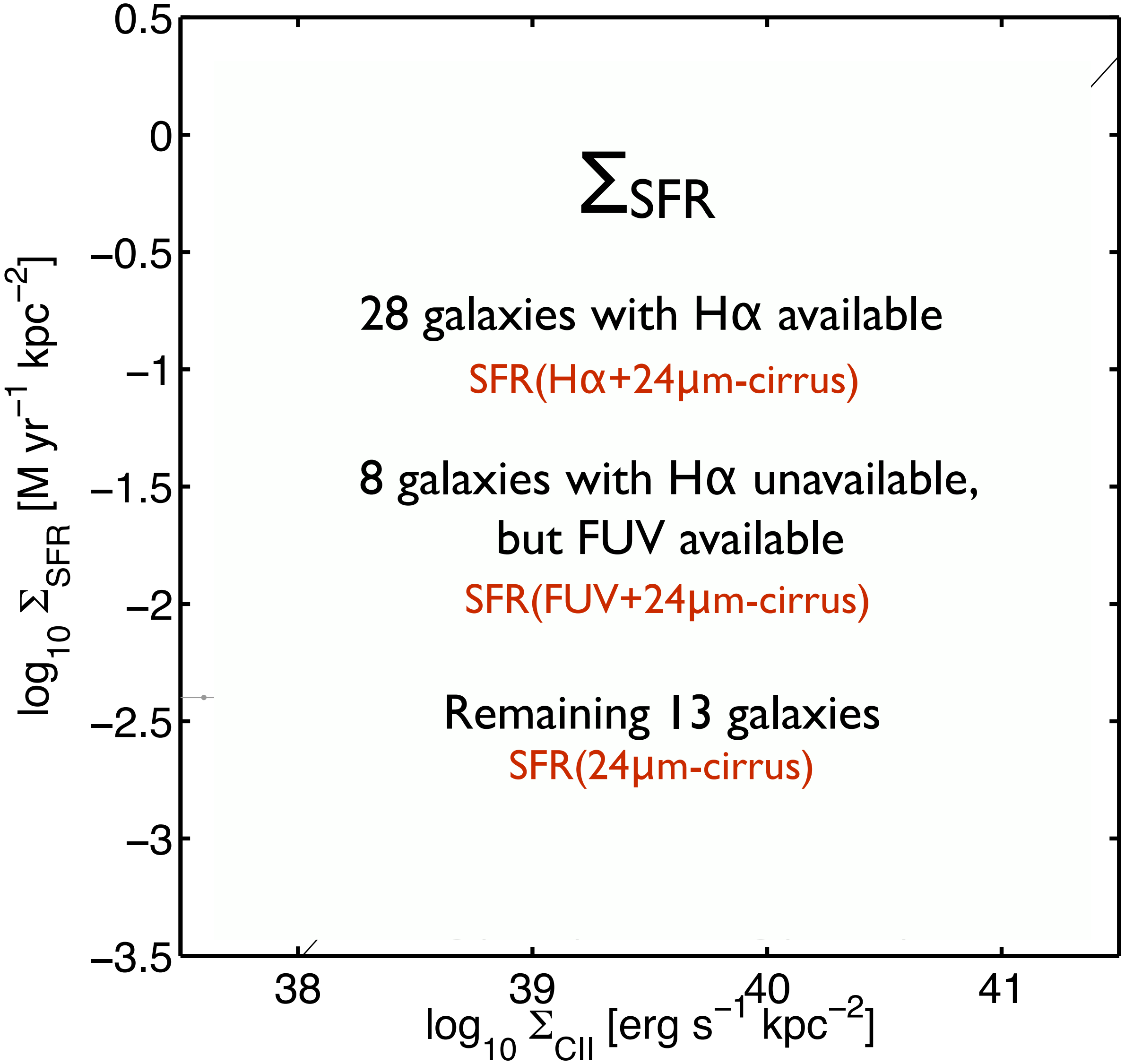
Regions from 28 Galaxies classified as AGNs (Moustakas+10; Grier+11)

Remove NGC 1377, AGN points and [CII] upper limits

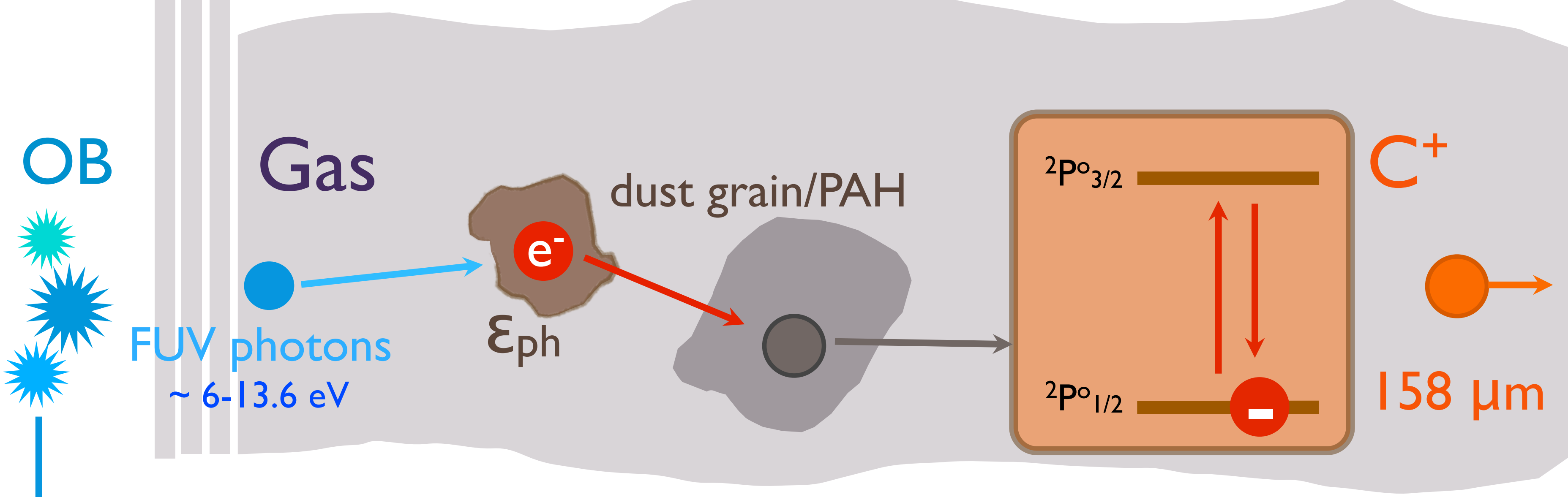


We find good $\Sigma_{[CII]}$ - $\Sigma_{24\mu m}$ correlation with a ~0.24 dex scatter

The [CII] - SFR Correlation



We find tight, nearly linear correlation between $\Sigma_{[CII]}$ and Σ_{SFR} with a ~0.23 dex 1σ scatter



Starburst99 code

Leitherer+99

Model stellar populations

$L_{FUV} = f(\mathrm{SFR}, \mathrm{time})$

$L_{FUV} \longrightarrow L_{CII}$

PE Heating Efficiency

$\varepsilon_{ph} \sim 0.1 - \text{few } \%$

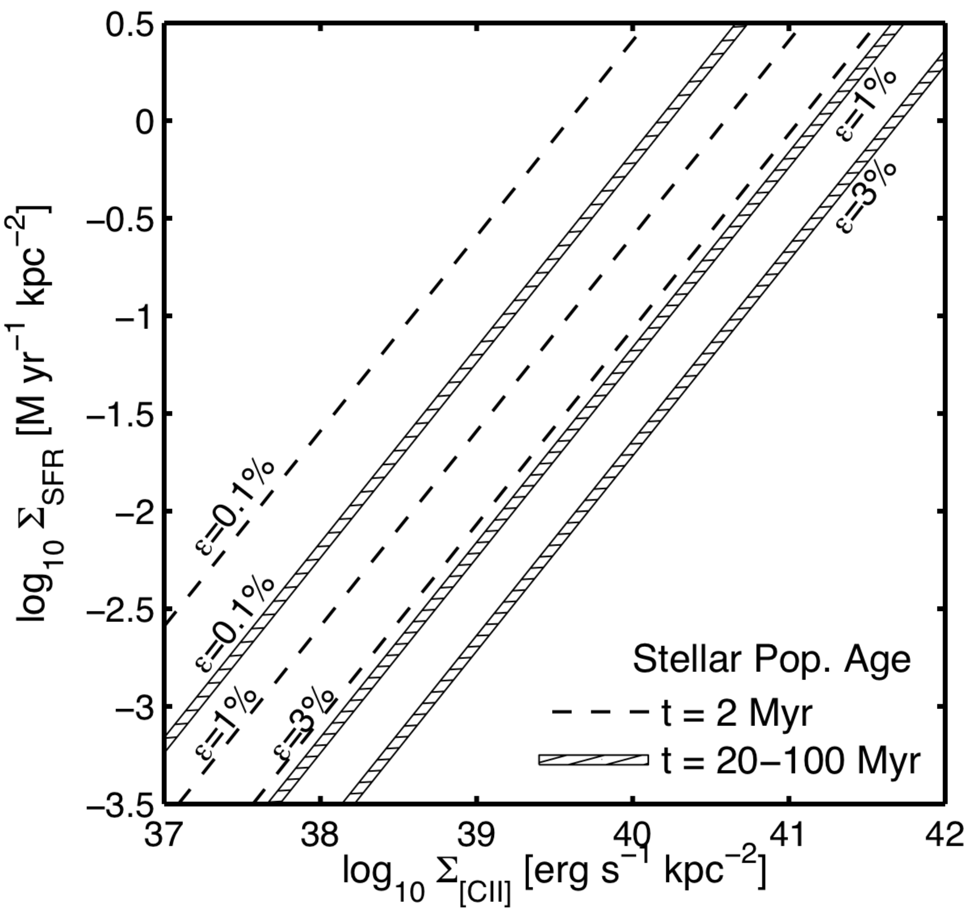
$L_{CII} = \varepsilon_{ph} \times L_{FUV}$

$$L_{CII} = \varepsilon_{ph} \times f(\mathrm{SFR}, \mathrm{time})$$

Comparison to SB99 model

Time = 2 Myr, ε_{ph} = 0.1,1 & 3%

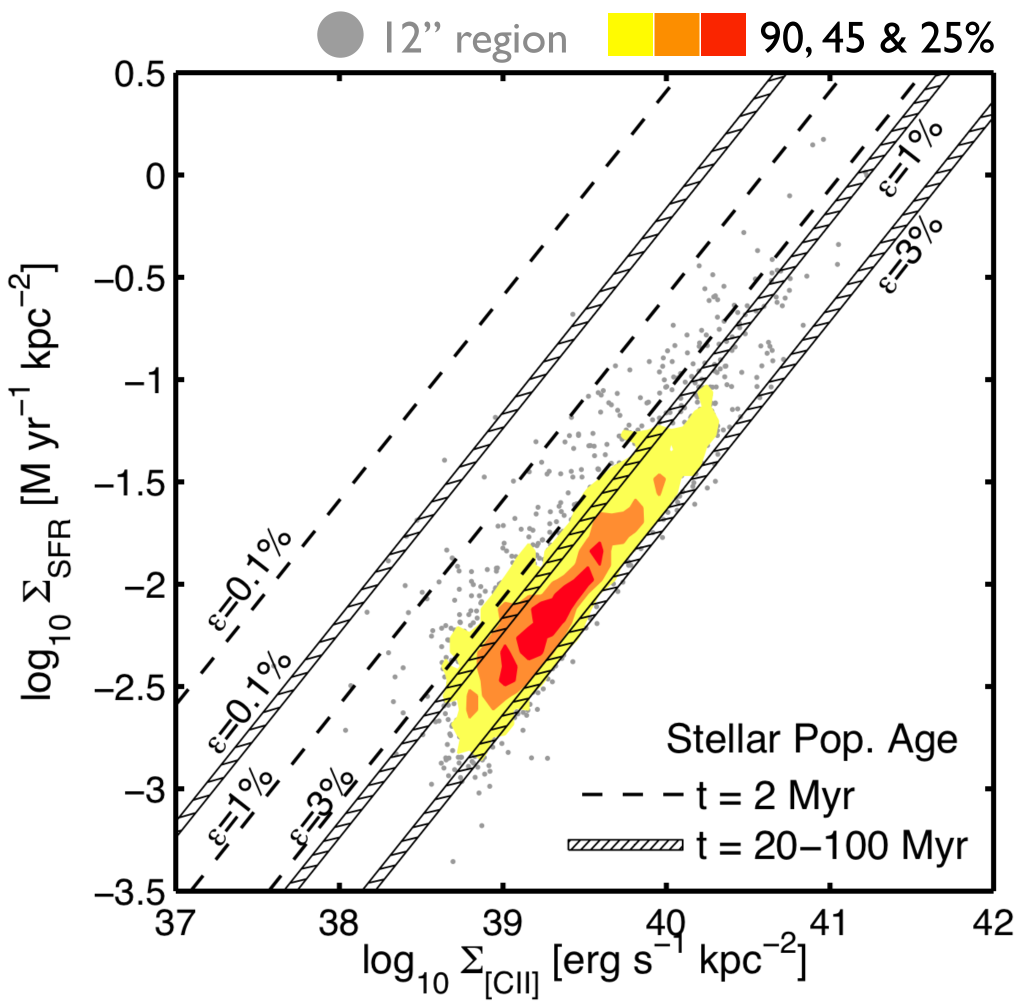
Time = 20-100 Myr, ε_{ph} = 0.1,1 & 3%

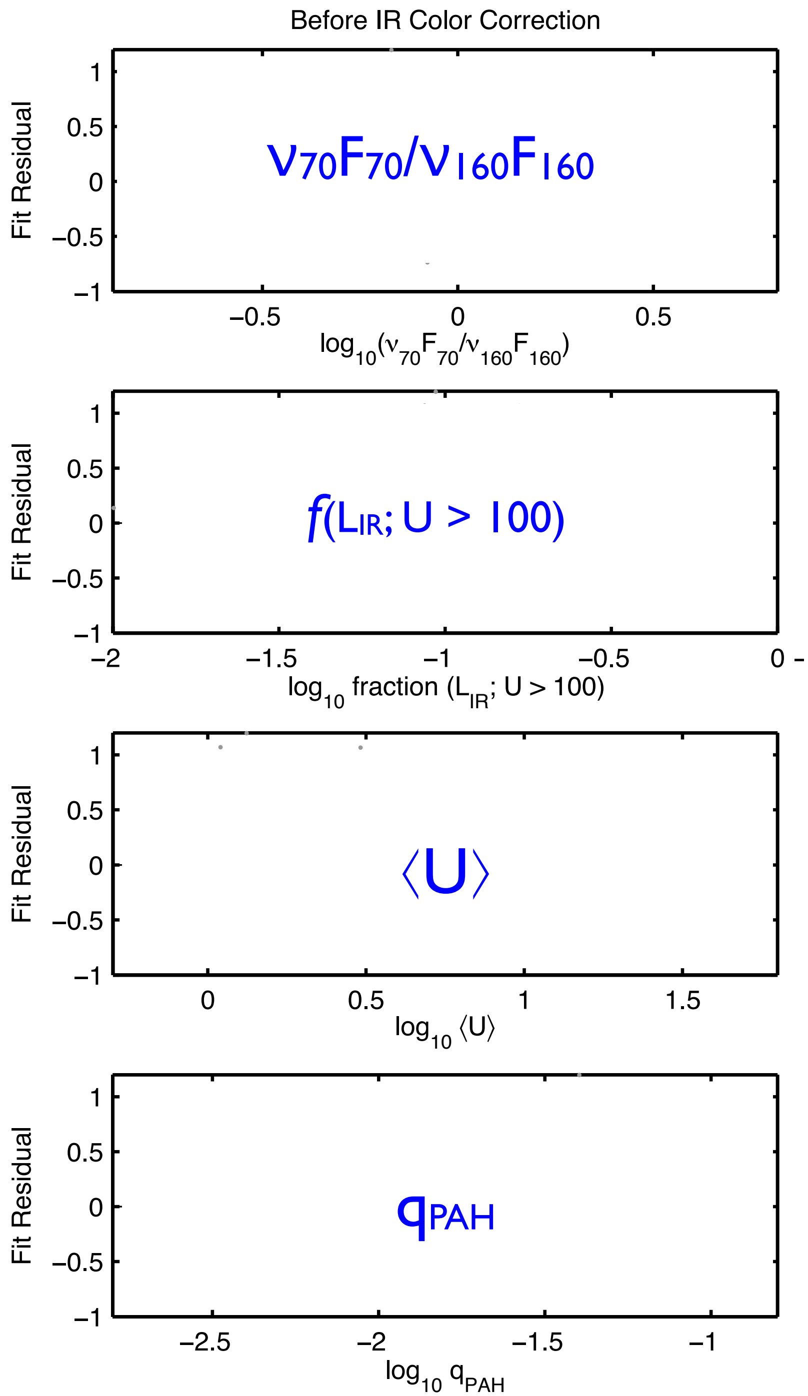


At a given Σ_{SFR}, increasing ε_{ph} implies higher $\Sigma_{[CII]}$

Comparison to SB99 model

Bulk of the data explained by a continuous star formation episode with duration >20 Myr, and $\boldsymbol{\varepsilon_{ph}}$ ~1%-3%





1. FIR color/Dust Temperature

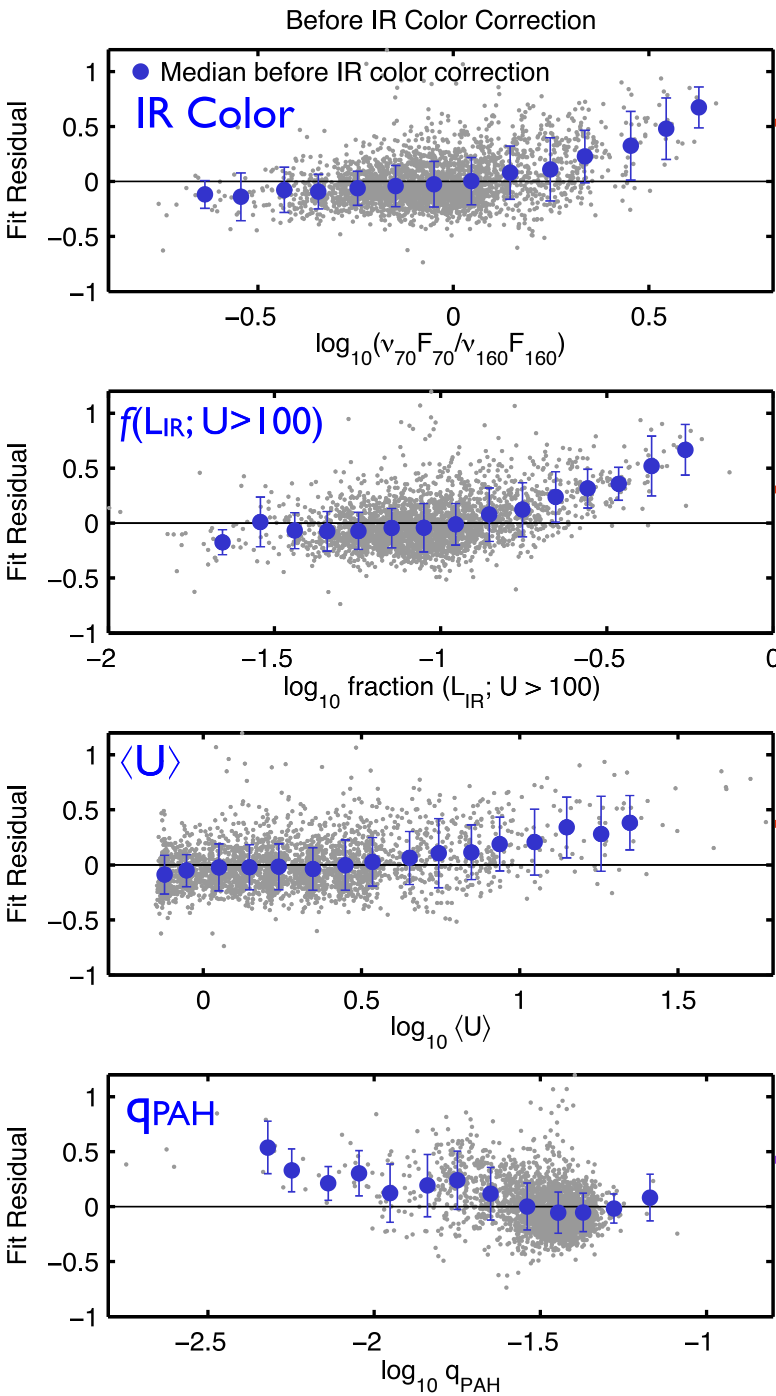
2. Fraction of the dust luminosity radiated from regions with intense radiation fields (U > 100)

3. Dust-weighted mean starlight intensity

4. Percentage of the total grain mass contributed by PAHs

2, 3 & 4: Parameters from Draine & Li Model 2007

Aniano +12

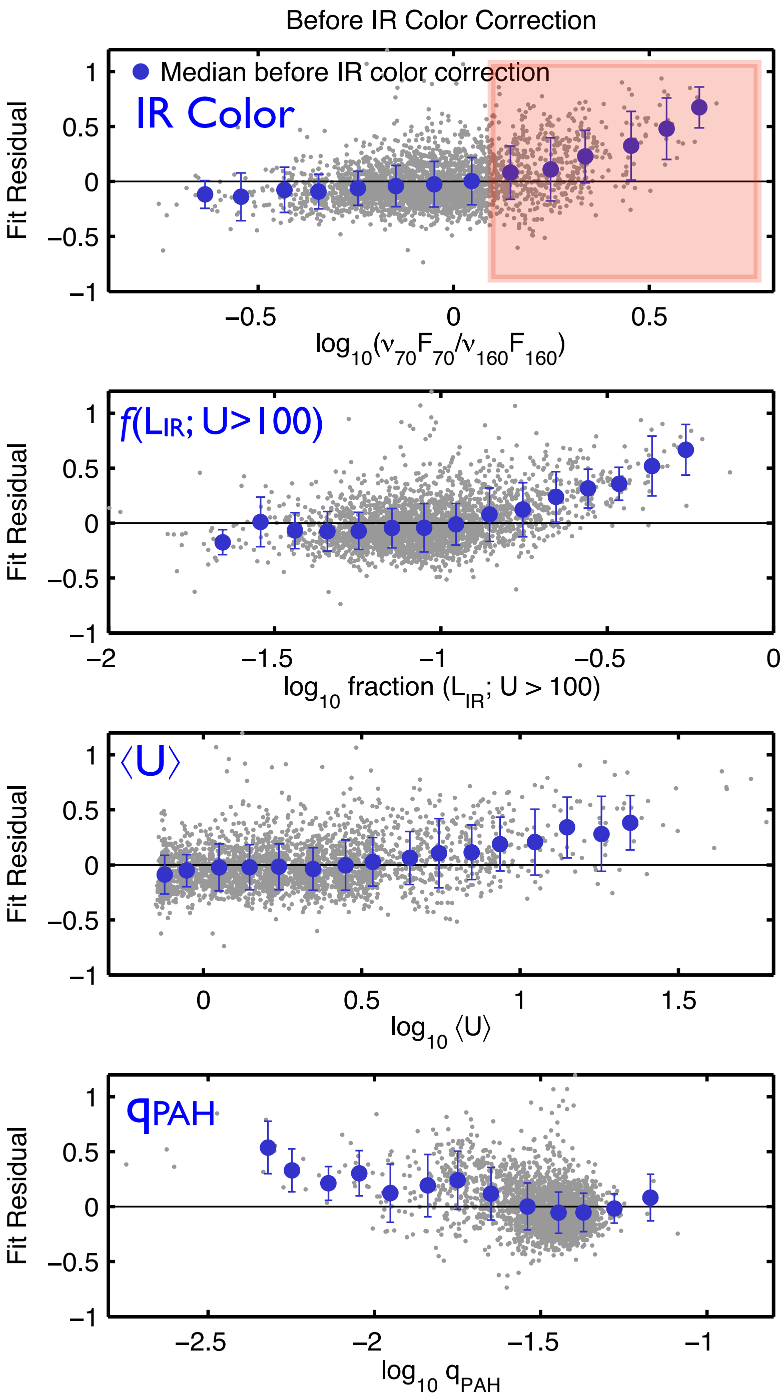


Positive means [CII] is underluminous wrt SFR

Positively charged dust grains

a higher charge implies a higher Coulomb barrier to overcome, thus decreasing the energy per ejected electron (Tielens & Hollenbach+95; Malhotra+97; Luhman+03; Croxall+12; Beirao+12)

Low PAH abundance



Implement an IR color correction for

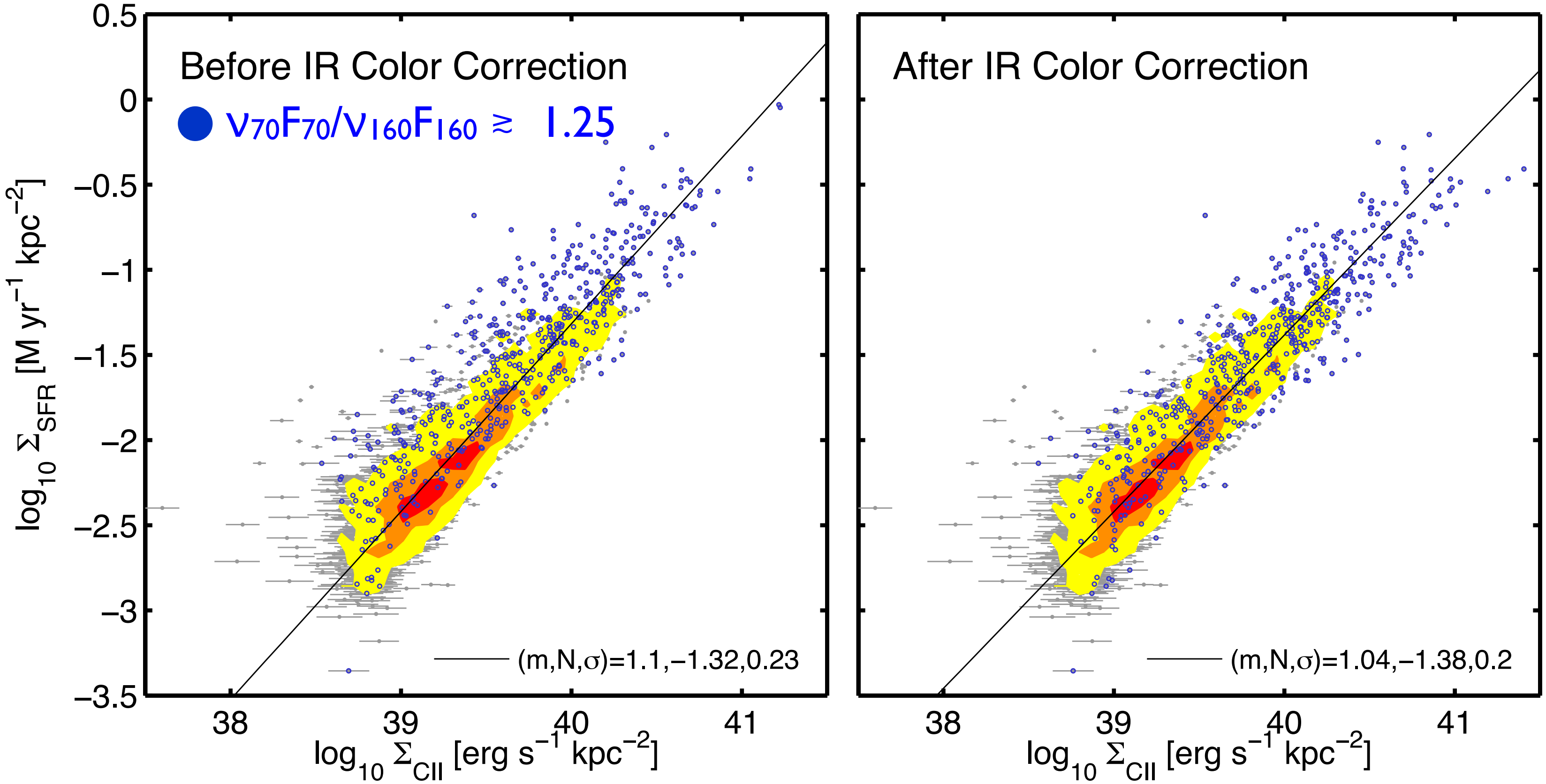
$\nu_{70}F_{70}/\nu_{160}F_{160} \gtrsim 1.25$

$\log_{10}\Sigma_{[CII]} \rightarrow \log_{10}\Sigma_{[CII]} + \log_{10}(\nu_{70}F_{70}/\nu_{160}F_{160}) - 0.1$

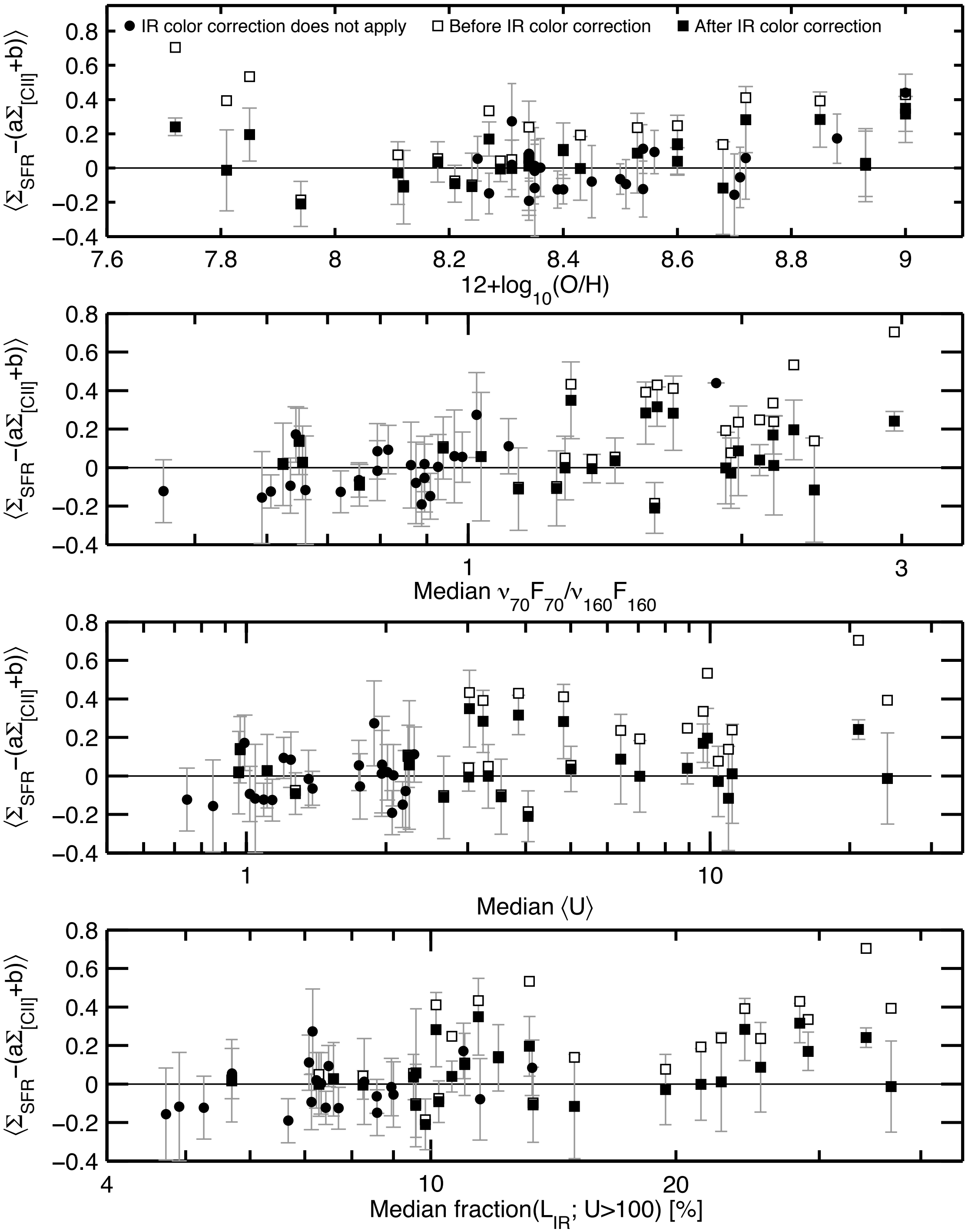
The [CII] - SFR Correlation

Before
IR Color Correction

After
IR Color Correction



$\log_{10}\Sigma_{[CII]}+\log_{10}(\nu_{70}F_{70}/\nu_{160}F_{160})-0.1$
[erg s^{-1} kpc^{-2}]

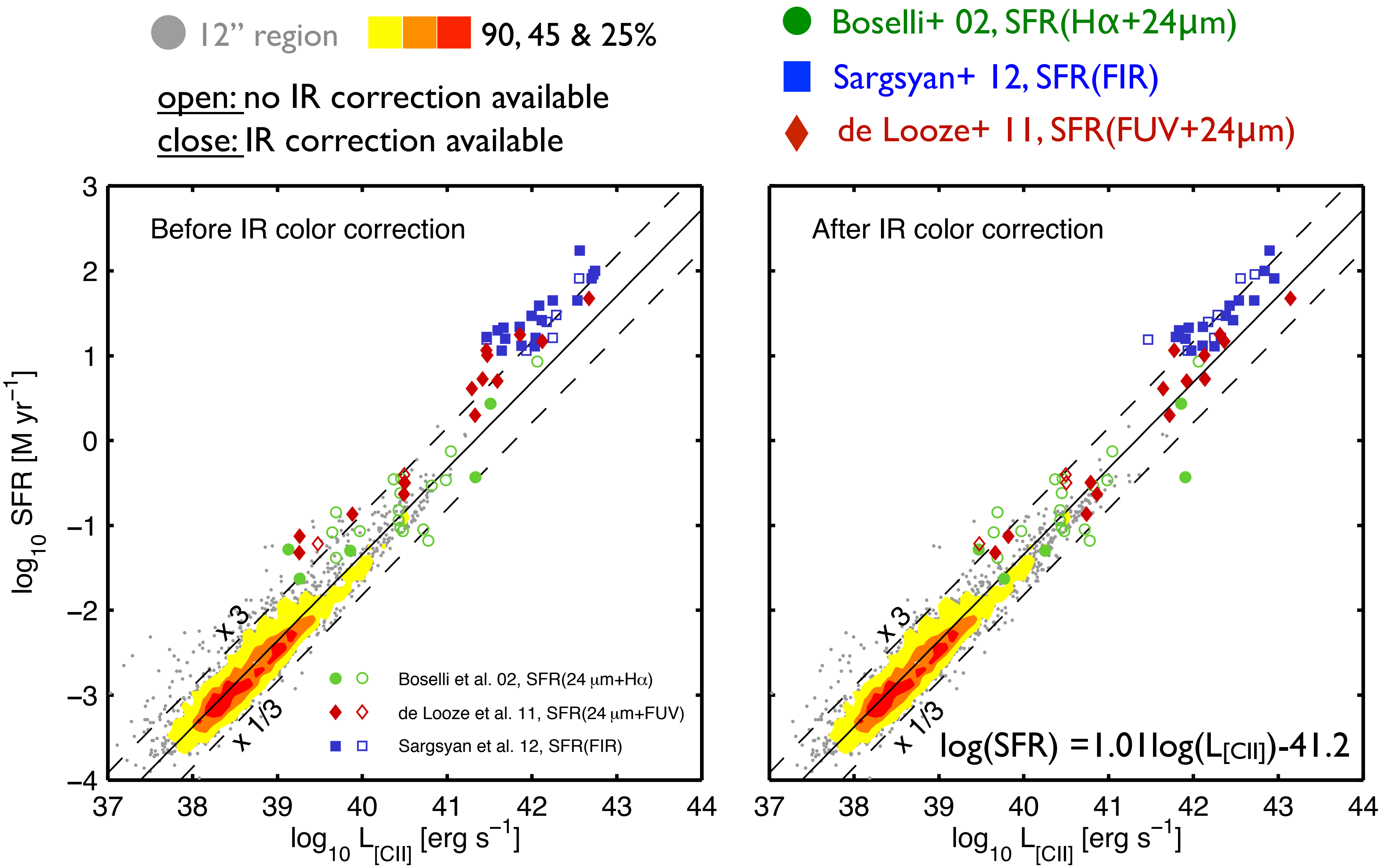


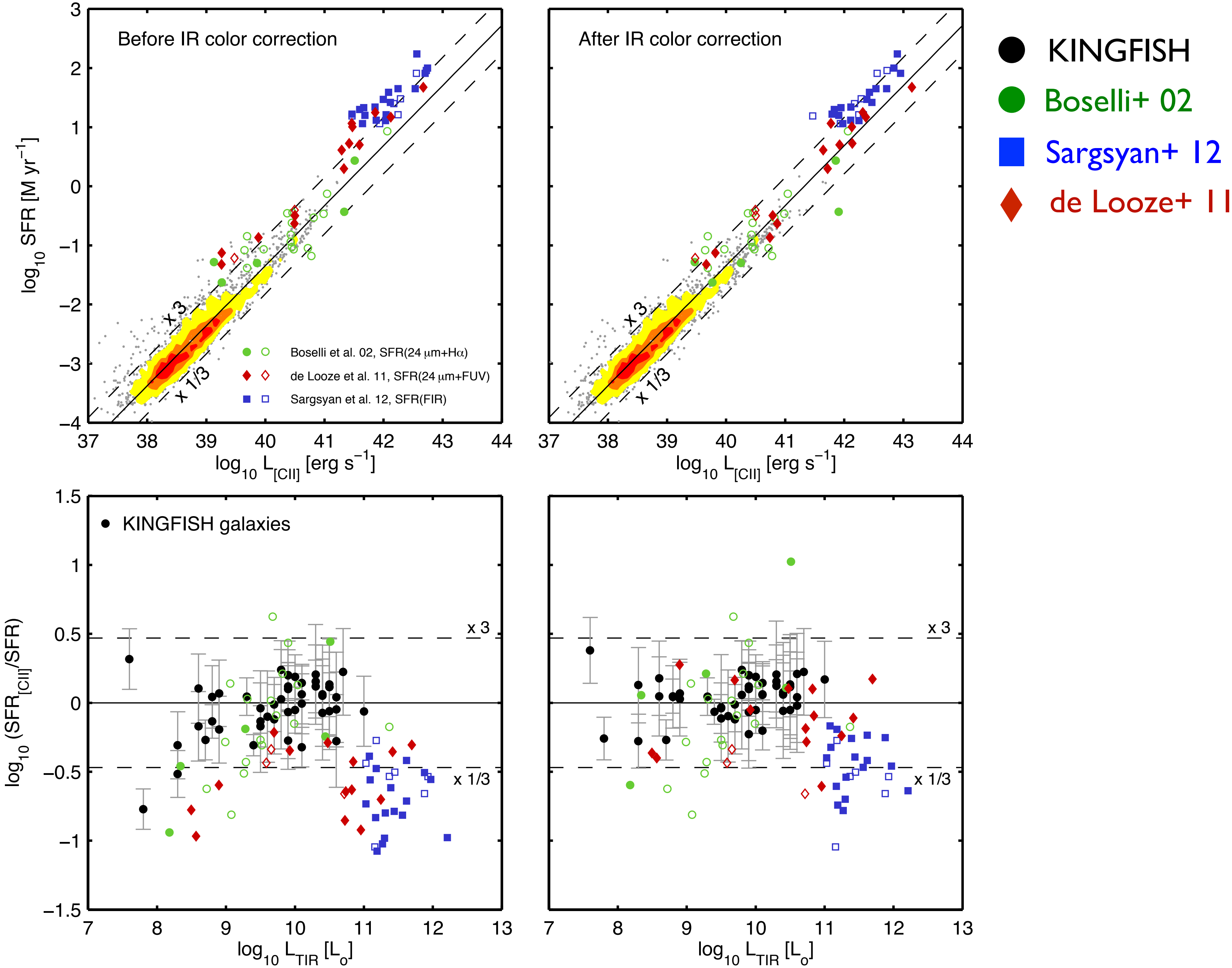
Residual in each galaxy for the KINGFISH sample

- IR color correction does not apply
- Before IR color correction
- After IR color correction

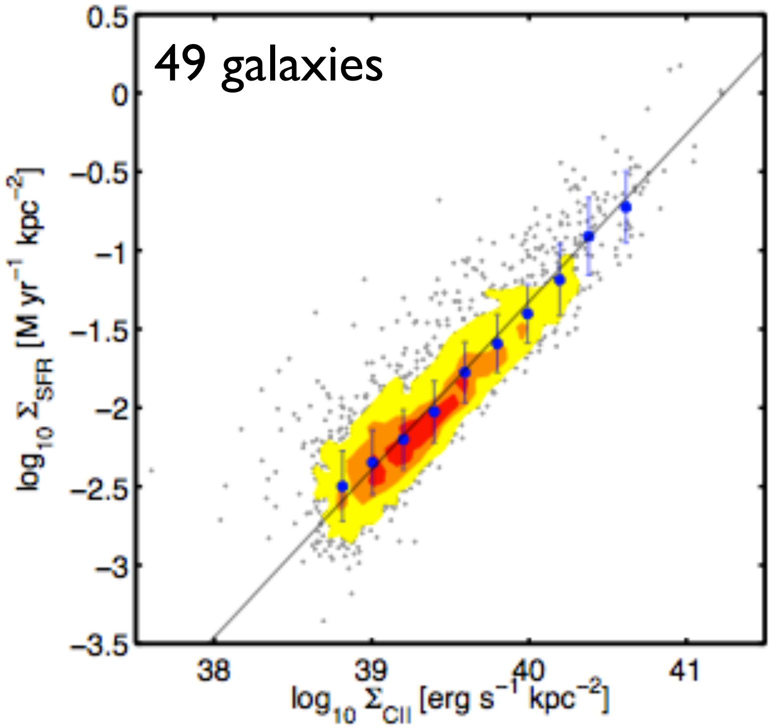
The [CII] - SFR Correlation

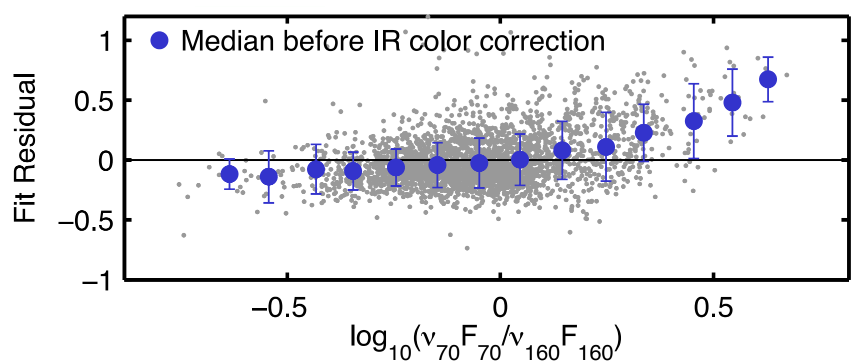
Comparison to previous studies




Before IR color correction
After IR color correction
x 3
x 1/3
Boselli et al. 02, SFR(24 μm+Hα)
de Looze et al. 11, SFR(24 μm+FUV)
Sargsyan et al. 12, SFR(FIR)
log10 SFR [M yr−1]
log10 L[CII] [erg s−1]
KINGFISH galaxies
log10 (SFR[CII]/SFR)
log10 LTIR [Lo]
KINGFISH
Boselli+ 02
Sargsyan+ 12
de Looze+ 11

$\Sigma_{[CII]}$ - Σ_{SFR}





Summary

We find a tight, nearly linear correlation between $\Sigma_{[CII]}$ and Σ_{SFR} with a ~0.2 dex 1σ scatter

$$\log_{10}(\Sigma_{SFR}) = 1.04 \log_{10}(\Sigma_{[CII]}) - 43.0$$

[$M_\odot$ yr^{-1} kpc^{-2}] [erg s^{-1} kpc^{-2}]

This includes the "color correction", applied to points with $\nu_{70}F_{70}/\nu_{160}F_{160} \gtrsim 1.25$

Even without this correction, there is a remarkably good correlation between SFR and [CII]. We need more work to see how it may apply in the $L_{FIR} > 10^{11}$ $L_\odot$ regime