Disentangling the Causes and Consequences of the [CII] Deficit

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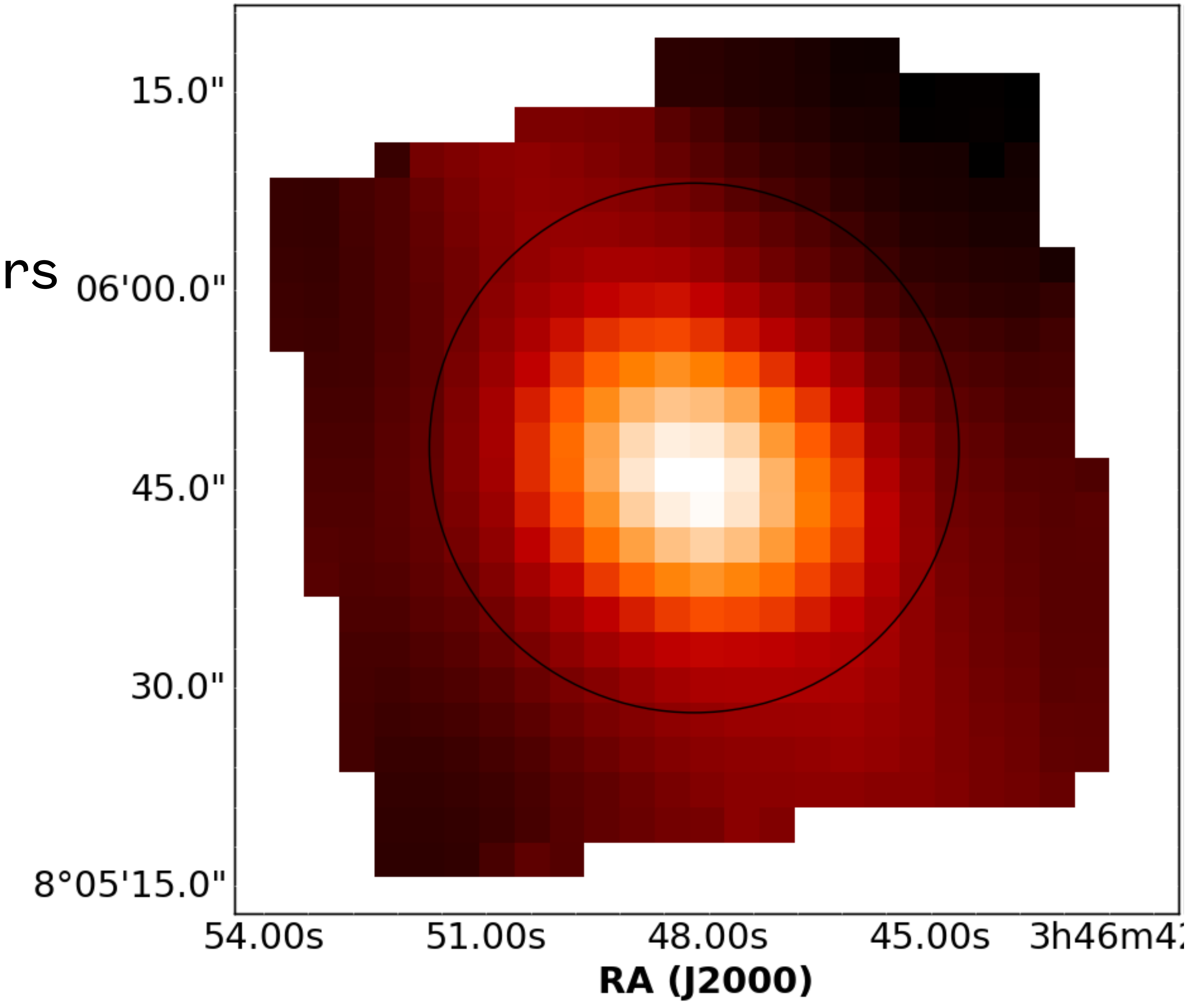
Outline

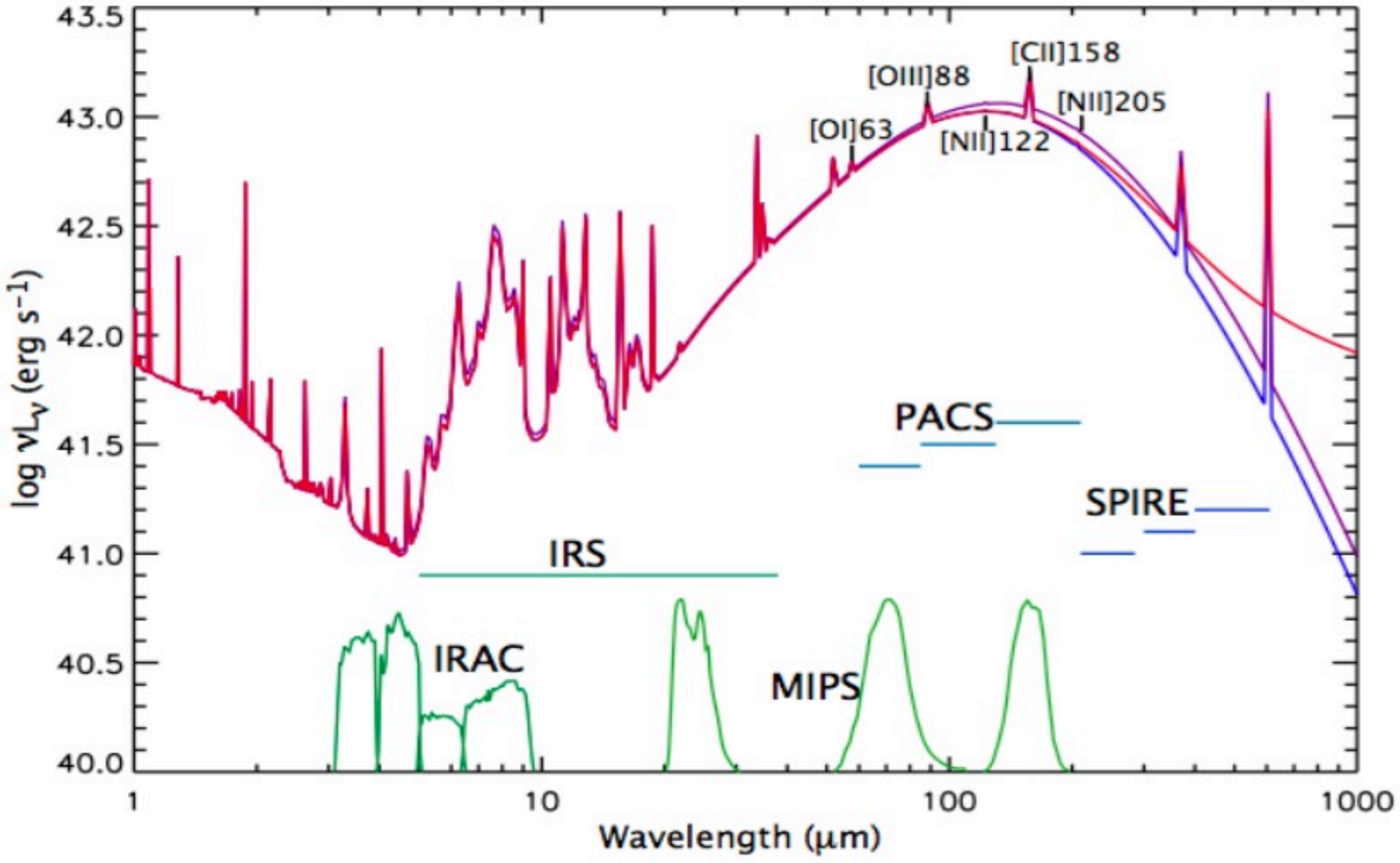
- Overview of the problem: why the [CII] deficit matters
- KINGFISH and BtP sample
- Isolating [CII] by ISM phase
- Testing causes of the deficit
- Conclusions and Questions



[CII] Emission from IC 342 (Image Credit: Sutter+2019)

[CII] 158 µm Emission

- Often the brightest *observed* emission line in star-forming galaxies
- One of the primary cooling channels of photodissociation regions (PDRs)
- Detectable in both local and high-z galaxies
- Potential tool for measuring SFR across cosmic time



Typical Infrared Galaxy Spectra (Image Credit, Kennicutt+2012)

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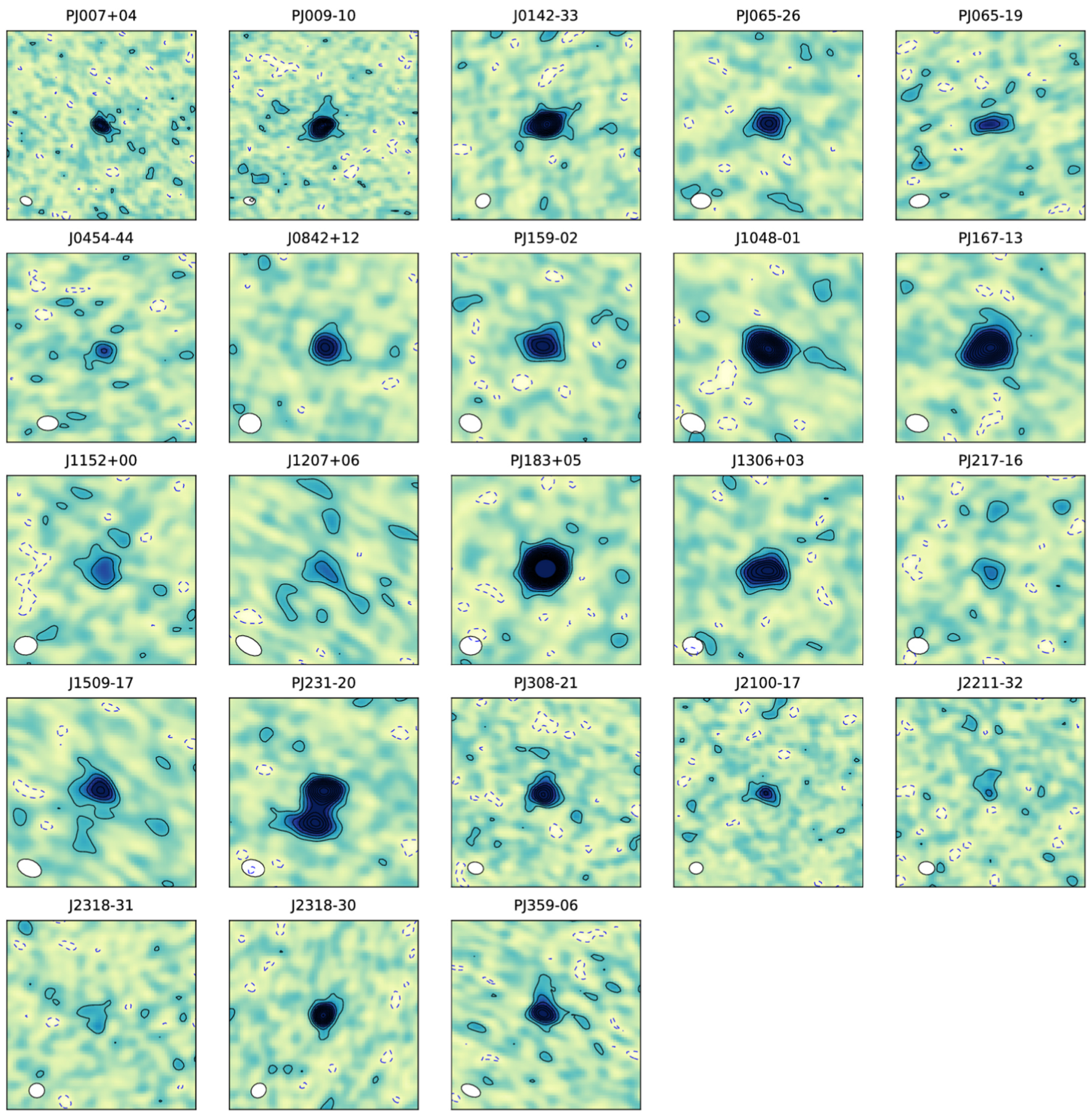
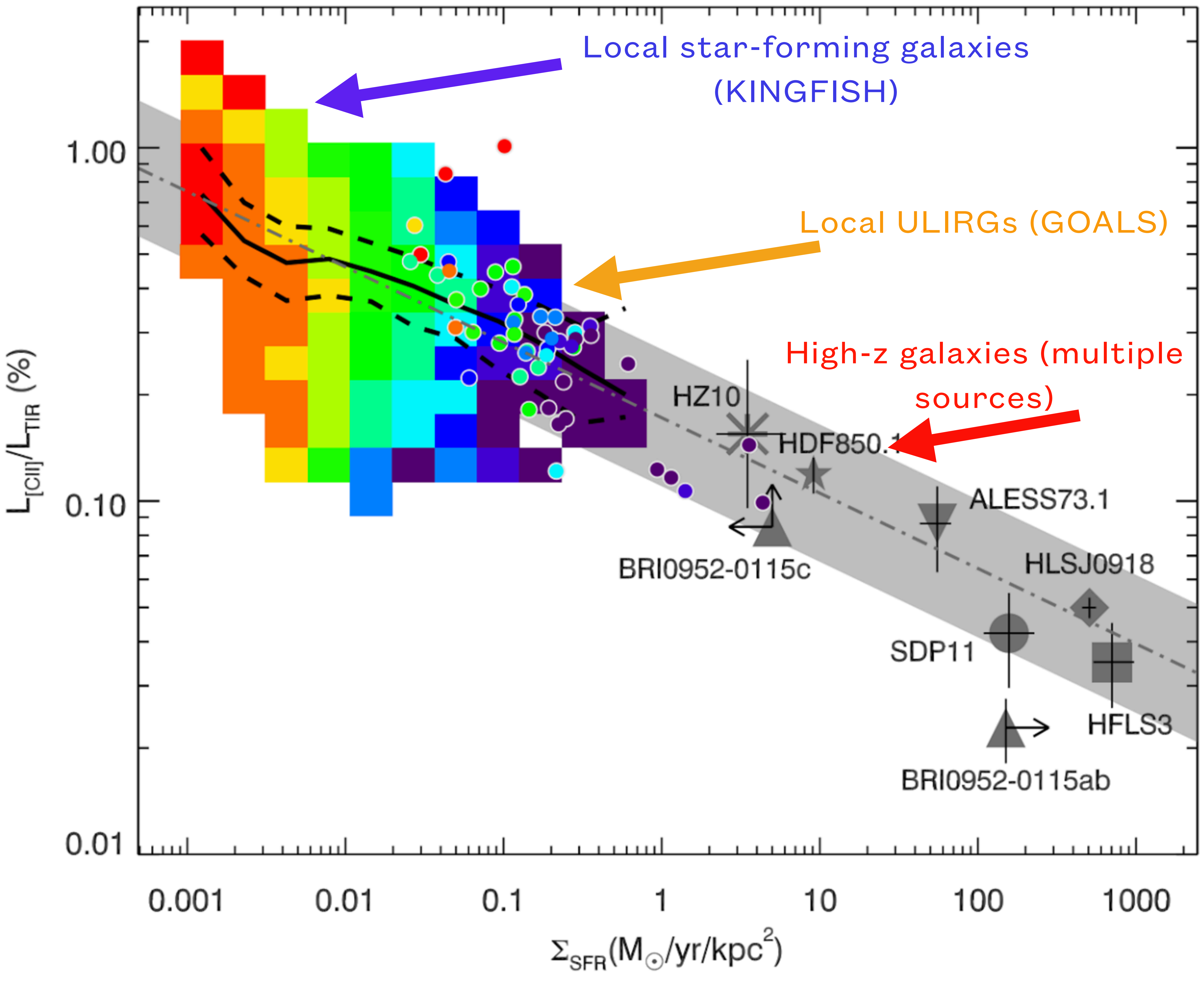


ALMA [CII] detections from z~6 quasars (Image Credit: Decarli+2018)

The [CII] Deficit

- Decreasing trend in [CII]/TIR in more actively star-forming galaxies
- Especially detrimental to efforts to use [CII] as SFR
- Indicative of poorly understood underlying physical processes in the ISM



The [CII] Deficit across a range of galaxy types and redshift. (Image credit: Smith+2017)

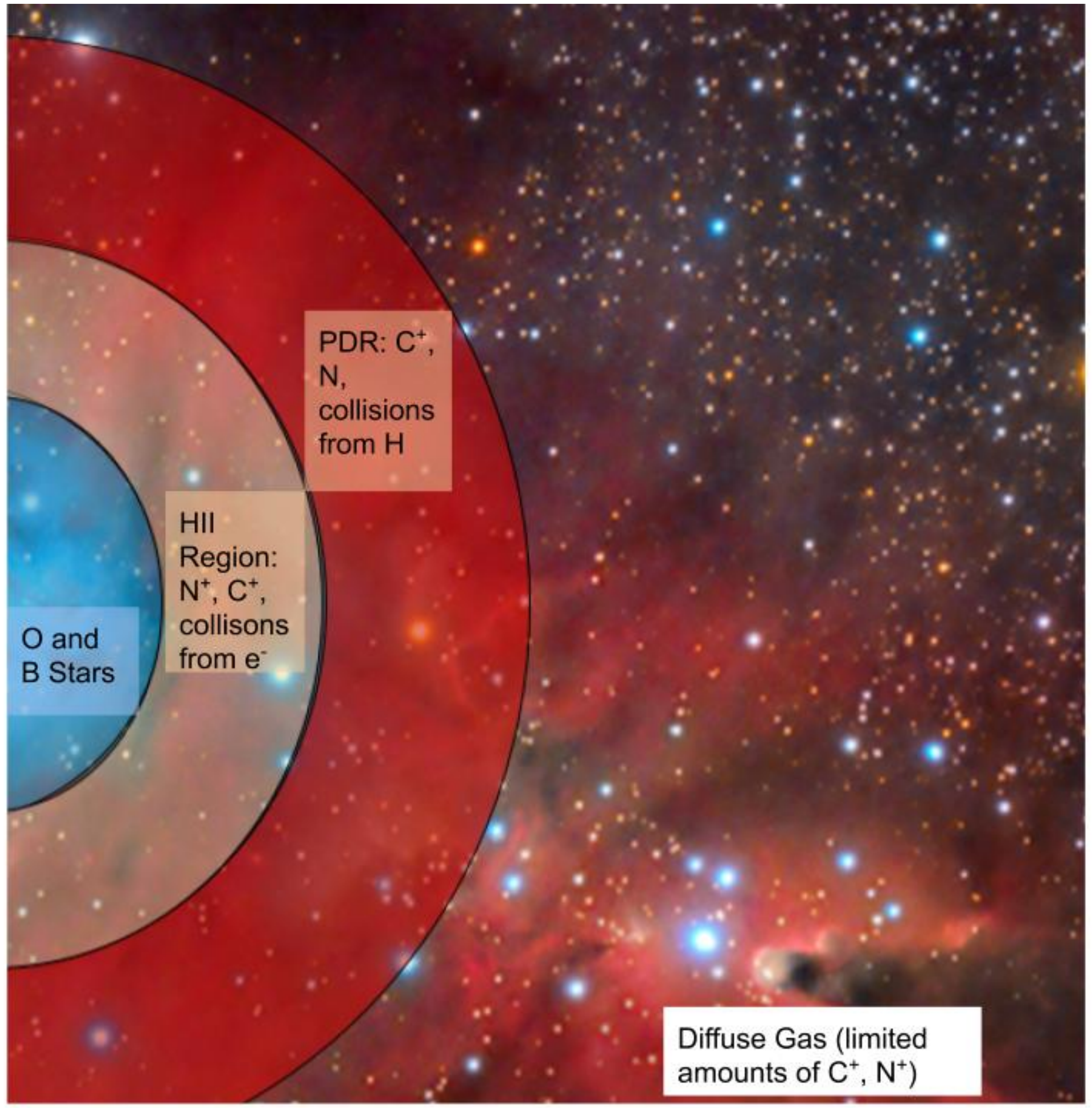
[CII] & [NII] 205 µm Measurements

- KINGFISH: Key Insights in Nearby Galaxies: a Far Infrared Survey with Herschel
  - 31 star-forming regions in 28 galaxies targeted using PACS-Spec on *Herschel*
- BtP: Beyond the Peak
  - 20 regions further mapped at 205 microns using SPIRE on *Herschel*, targeting more quiescent areas around SF regions
- Nearby, Star-forming galaxies
  - D ~ 3 - 30 Mpc
  - 12+log(O/H) ~ 8.1 - 8.7

NGC 6946 70-100-160 KINGFISH images, regions with [CII] detections

Separating by ISM Phase

- IP Carbon: 11.3 eV
- IP Nitrogen: 14.5 eV
  - C^+ can exist in both ionized and neutral phases of the ISM
  - N^+ will primarily exist in the ionized phases of the ISM
  - We can therefore use the ratio of [CII]/[NII] to isolate the [CII] emission from ionized and neutral phases of the ISM



Simple representation of an HII region

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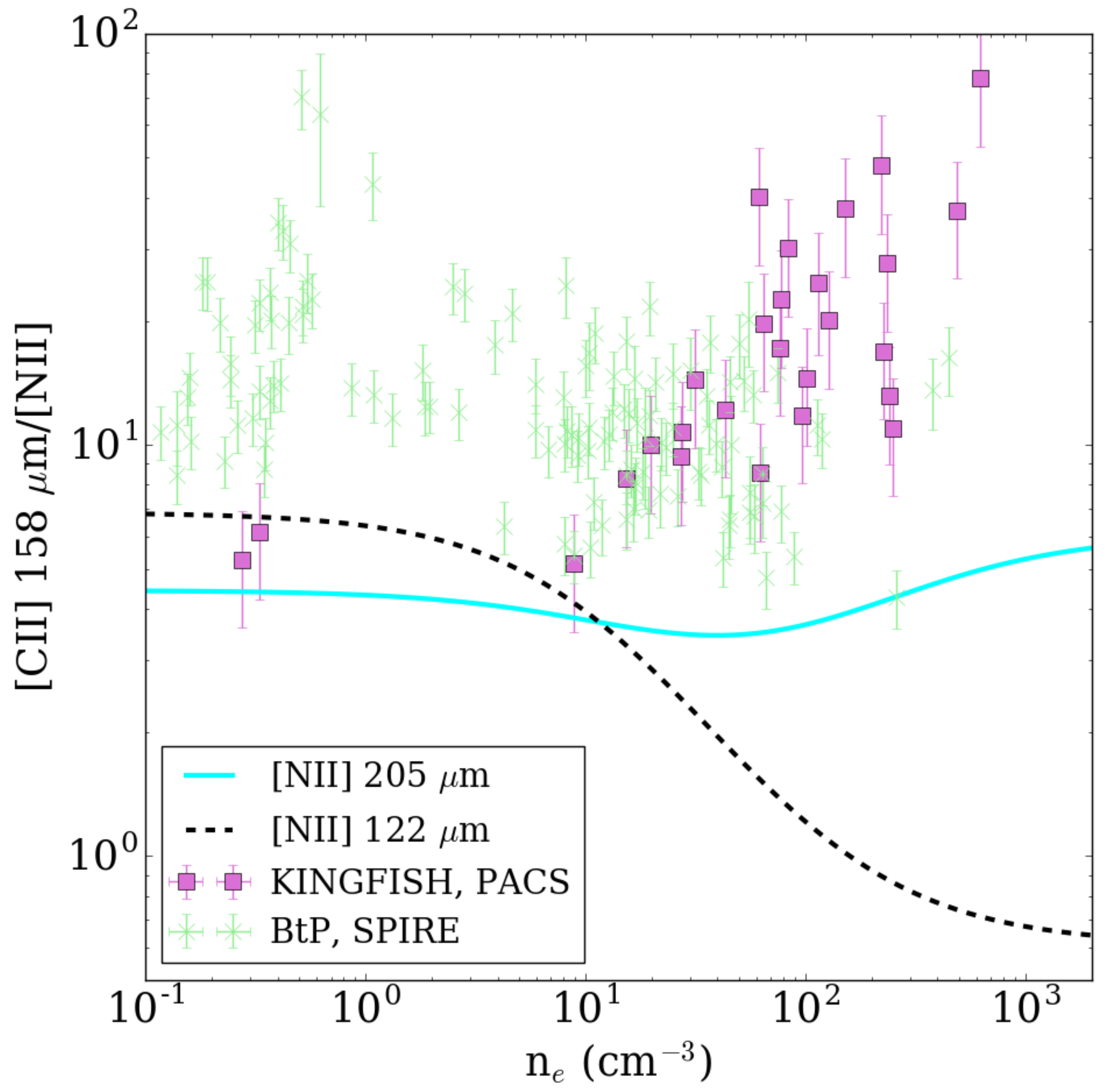
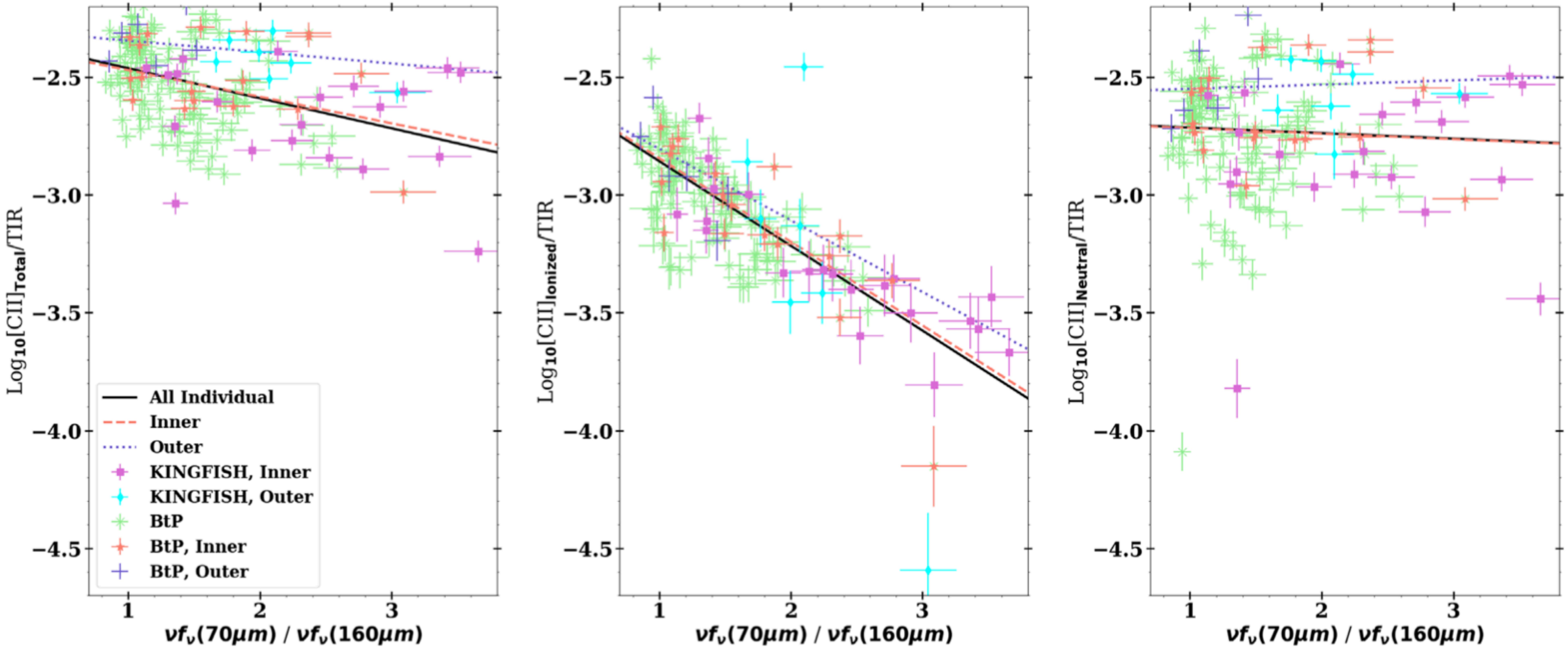


[CII] 158 micron to [NII] line ratios as a function of n_e, determined using the [NII] line ratio(Image Credit Sutter+2021)

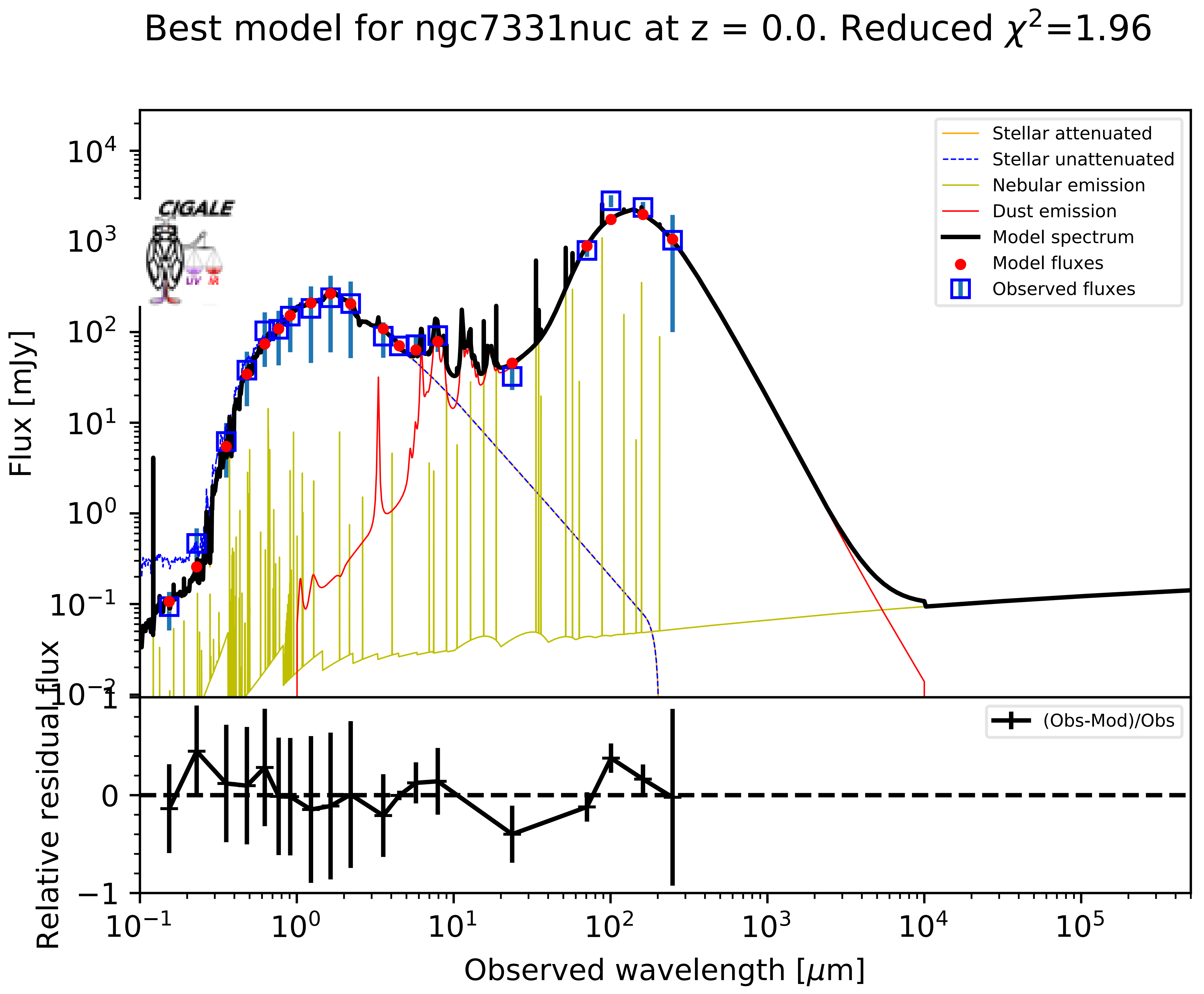
Subdivided [CII] Deficit



The ISM-Phase Isolated [CII] Deficit (Image Credit: Sutter+2019)

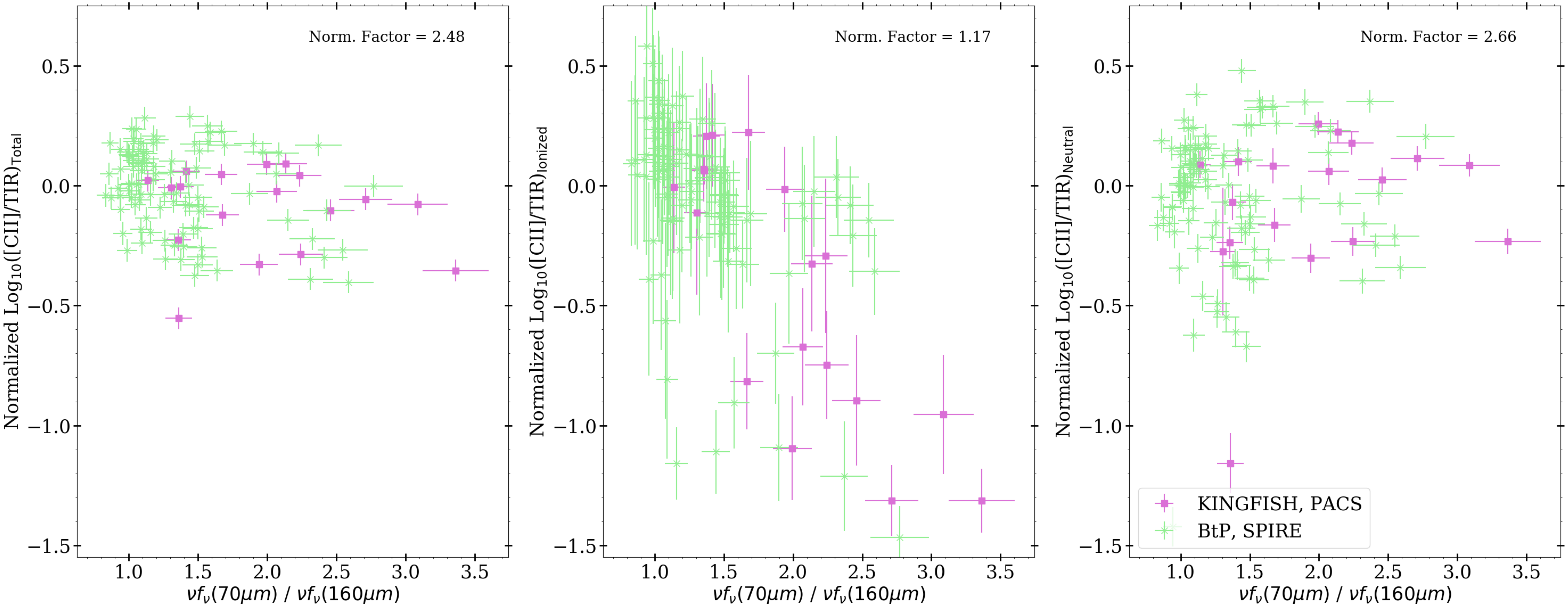
Dividing TIR

- Using CIGALE SED fitting, TIR can also be ISM phase-separated
- $f(L_{\text{dust}}; U > U_c) = \dfrac{\gamma ln(U_{\max}/U_c)}{(1-\gamma)(1-U_{\min}/U_{\max}) + \gamma ln(U_{\min}/U_{\max})}$
- U_C set to Strömgren Radius U value



CIGALE SED fit for NGC 7331 Nuclear Region (Image Credit: Sutter+2021, in prep)

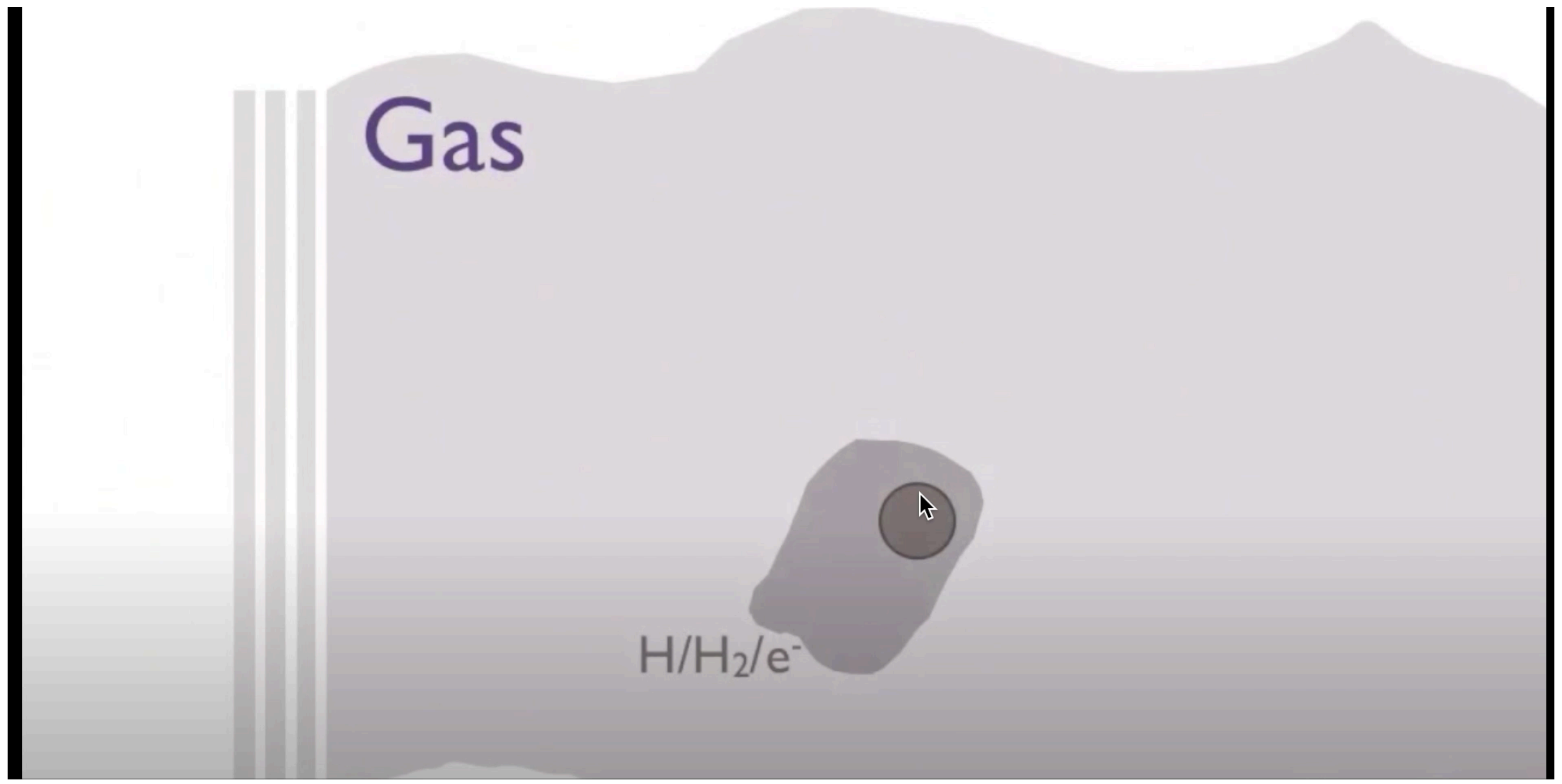
Dividing TIR



The ISM-Phase Isolated [CII]/TIR Measurements (Image Credit: Sutter+2021)

Thermalization as a factor

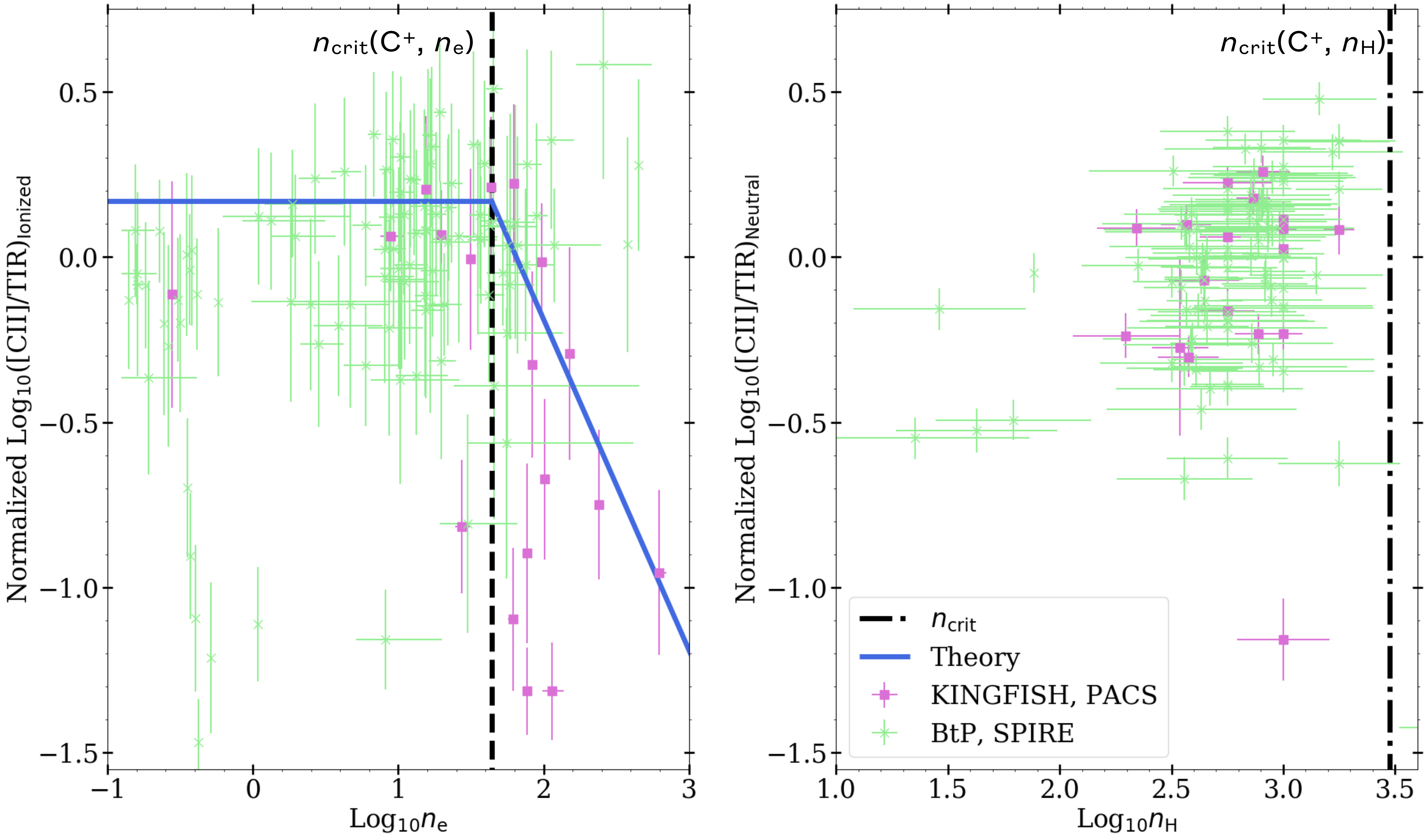
- n_{crit} ([CII], e^-) = 32 cm^{-3}
- Typical HII densities: 1-10^5 cm^{-3}
- [CII] can be thermalized in typical HII regions
  - This leads to L(TIR) increasing while L([CII]) remains relatively constant
  - Could play a role in the observed deficit behavior



[CII] emission in PDRs. (Movie credit: Dr. Rodrigo Herrera-Camus)

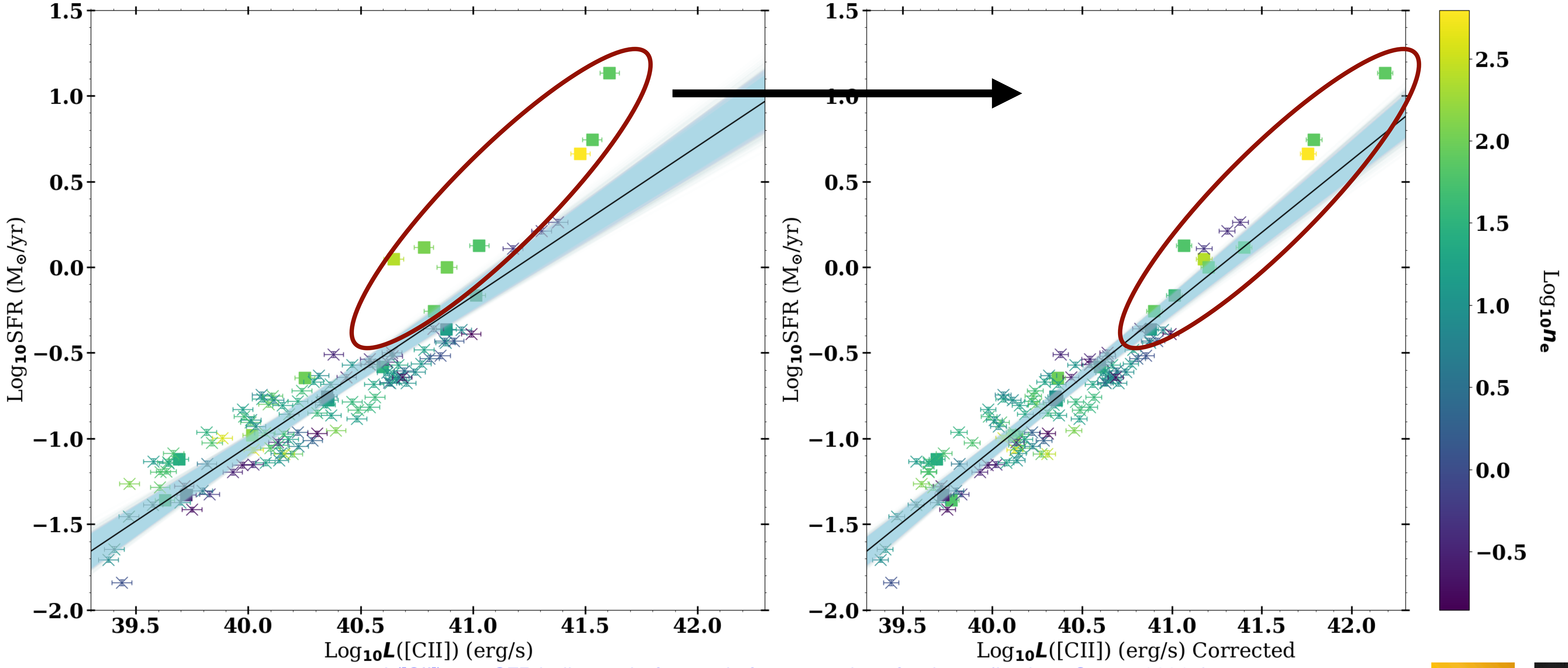
Thermalization in Ionized ISM

- Drop in [CII]/TIR from ionized phases along n_{crit}
- Data follow theoretical predictions
- Could play important factor in deficit observed in this limited sample
  - Ionized fraction is only ~20-30% of [CII] typically



Subdivided [CII]/TIR measurements as a function of density (Image Credit: Sutter+2021)

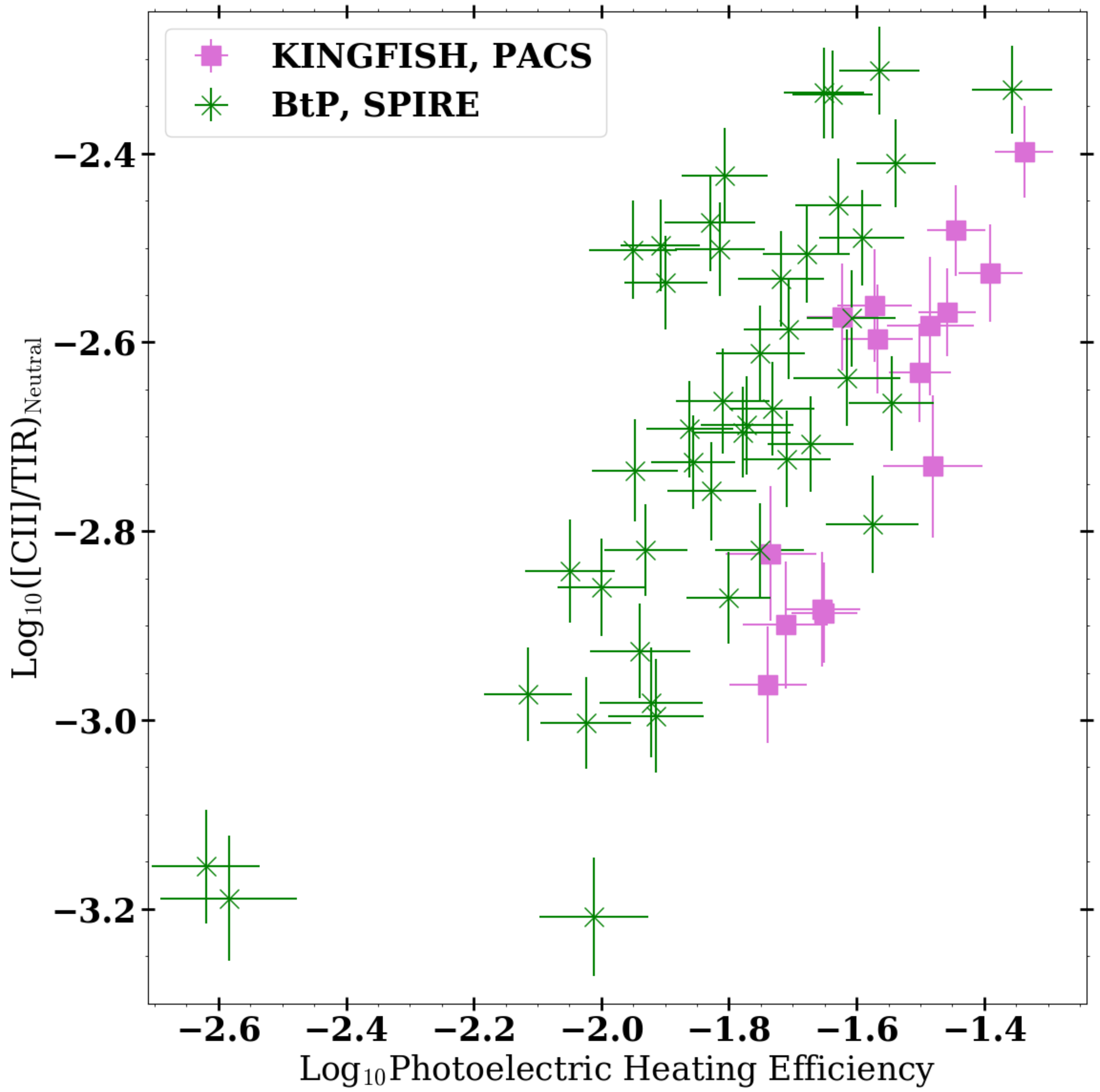
Correcting for Thermalization



L([CII]) as a SFR indicator, before and after corrections for thermalization. Sutter+2021, in prep.

Other Potential Effects

- Seven proposed causes of the deficit are tested
- Qualitatively rule out dust absorption, self absorption, higher fractions of C++/C+, [OI] cooling
- Some indication that changes in photoelectric heating efficiency play a role
- Limits of the KINGFISH sample make it likely other causes have a significant effect in more extreme cases



[CII]/TIR from the neutral ISM as a function of photoelectric heating efficiency. Sutter+2021, in prep

Conclusions

- For the normal, star-forming galaxies of the KINGFISH survey, the [CII] deficit mainly occurs in ionized phases of the ISM
- This could be partially due to thermalization of the [CII] line in HII regions
- Correcting for thermalization tightens relationship between L([CII]) and SFR in more actively star-forming regions
- We should consider this when analyzing [CII] detections from high-z galaxies
- Continued testing of deficit methods are underway
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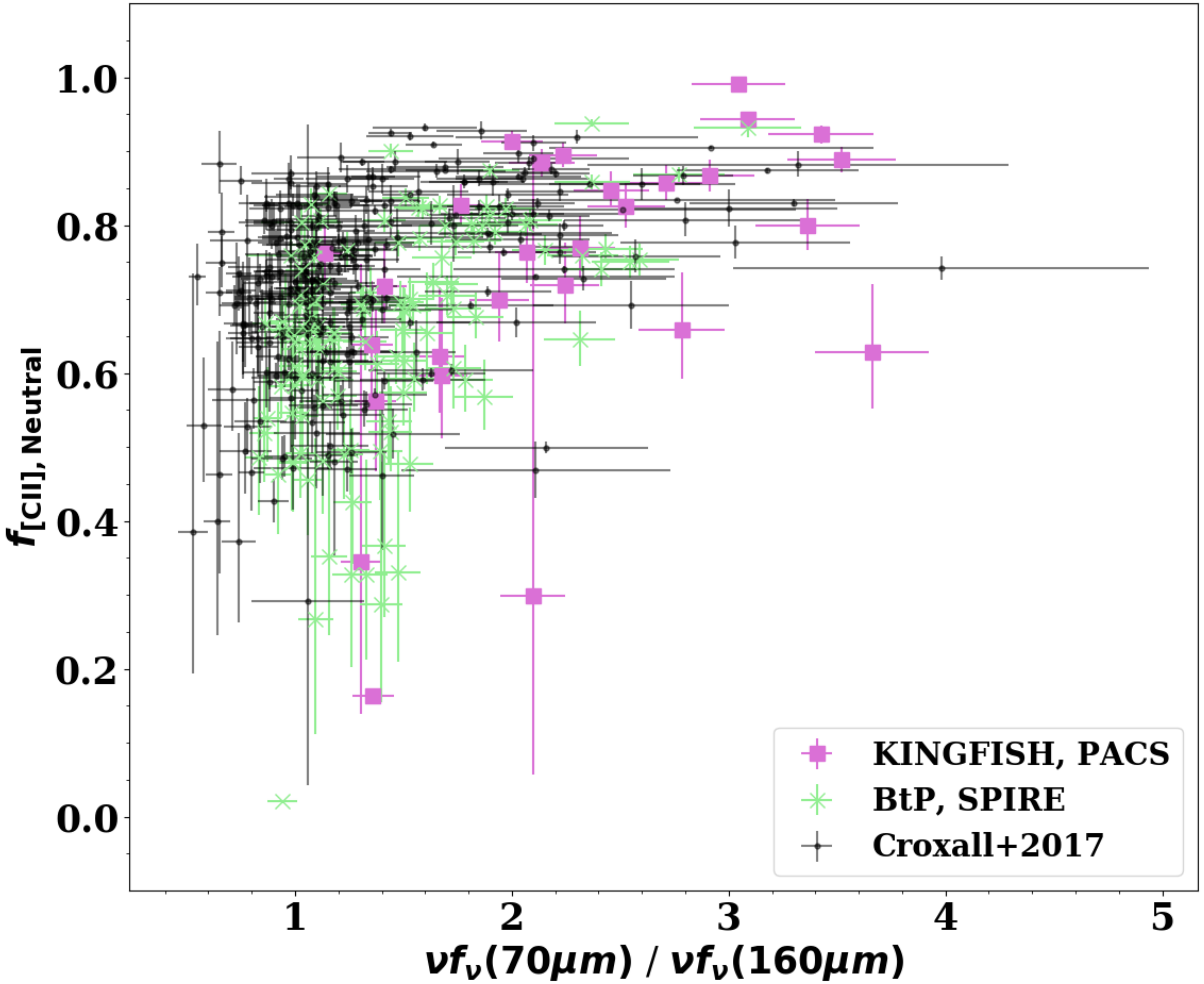
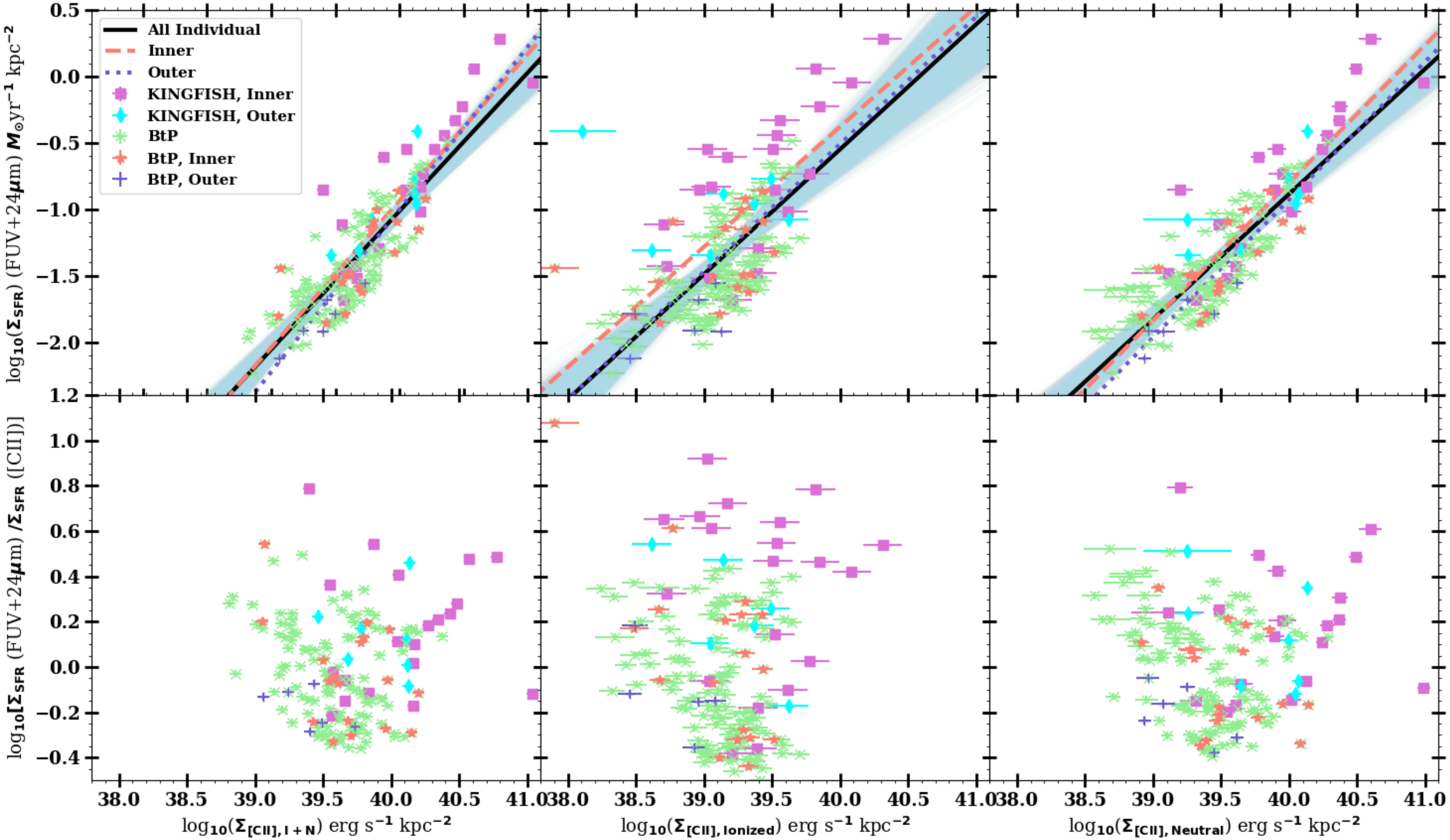
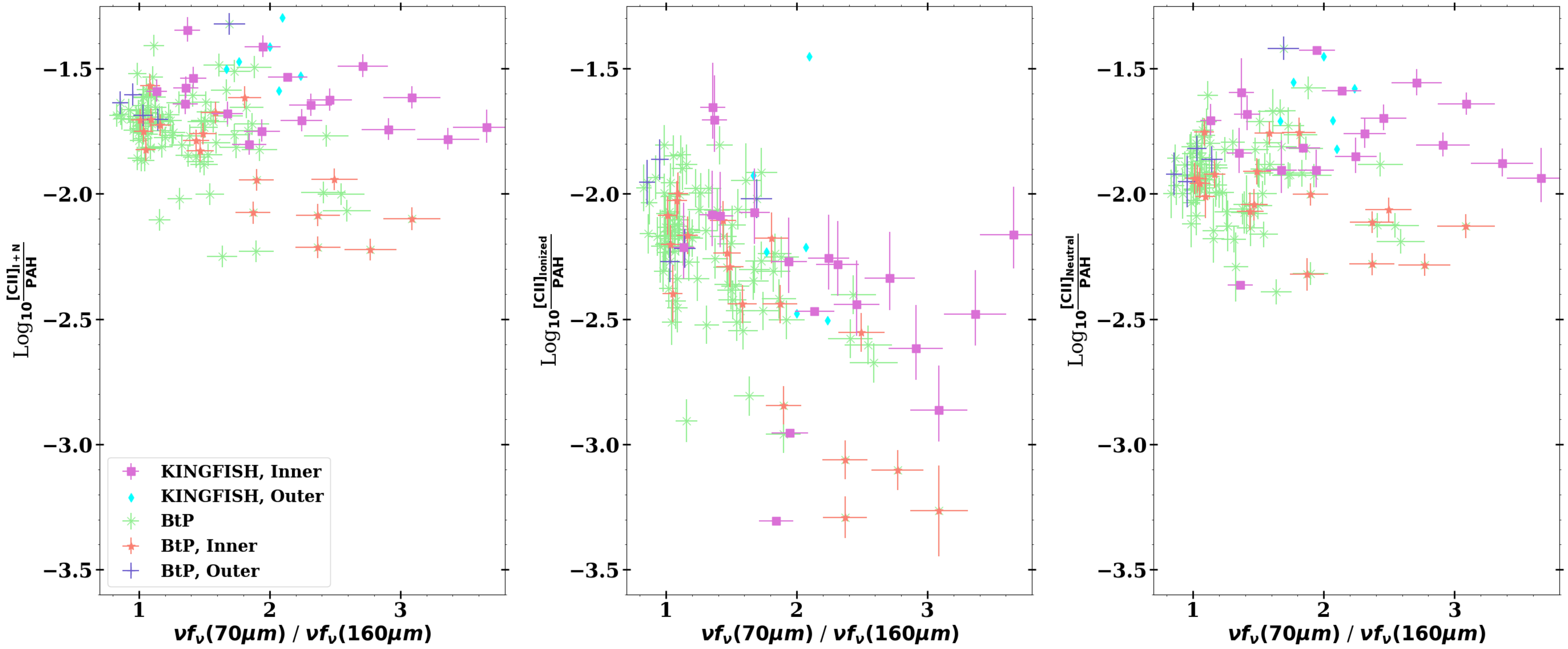
Additional Slides



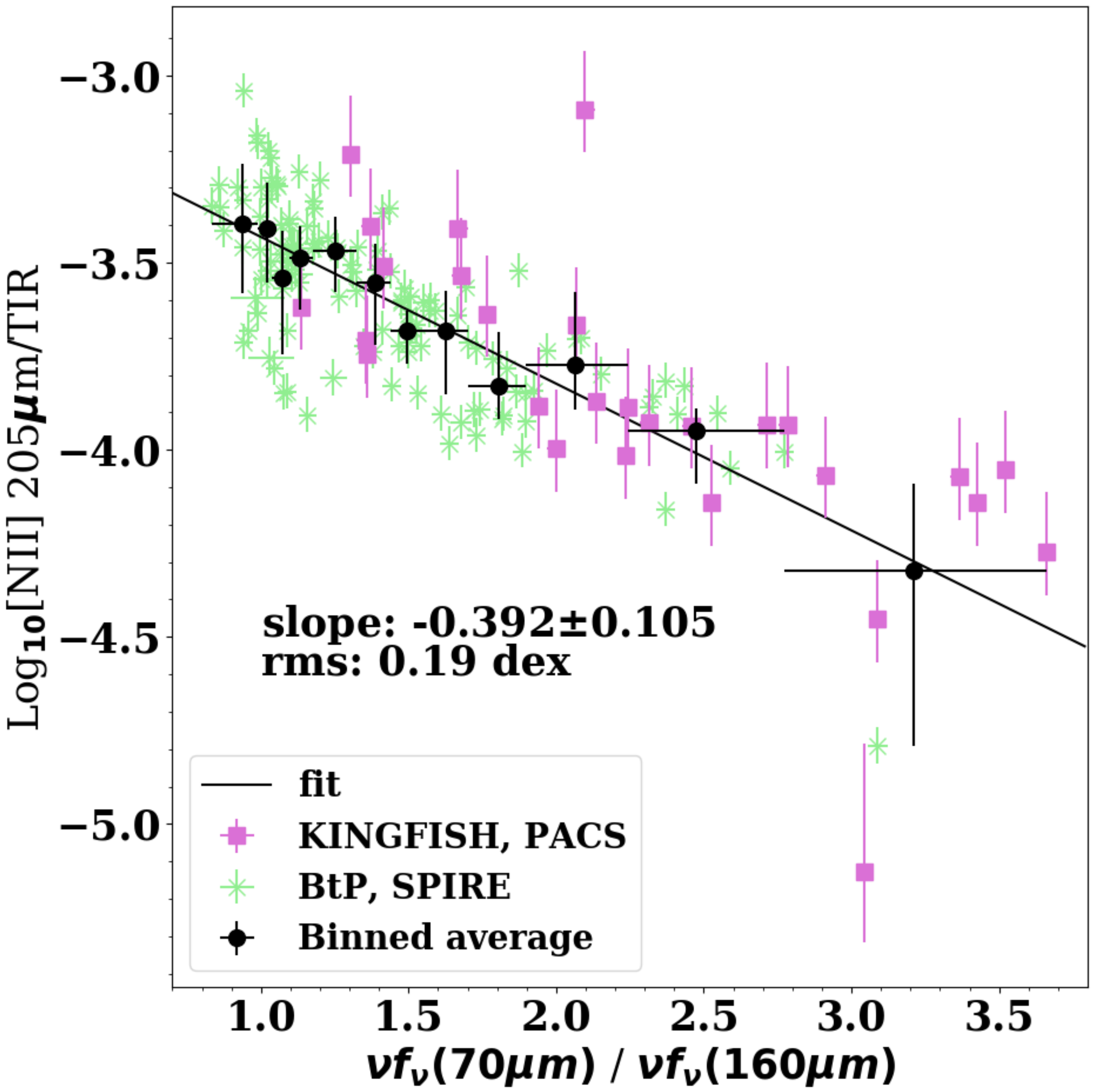
1.0
0.8
0.6
0.4
0.2
0.0
$f_{[CII], Neutral}$
1
2
3
4
5
$\nu f_\nu(70\mu m)$ / $\nu f_\nu(160\mu m)$
KINGFISH, PACS
BtP, SPIRE
Croxall+2017


All Individual
Inner
Outer
KINGFISH, Inner
KINGFISH, Outer
BtP
BtP, Inner
BtP, Outer
$\log_{10}(\Sigma_{SFR})$ (FUV+24μm) $M_\odot yr^{-1} kpc^{-2}$
$\log_{10}[\Sigma_{SFR}$ (FUV+24μm) $/\Sigma_{SFR}$ ([CII])]
$\log_{10}(\Sigma_{[CII], I+N})$ erg s^{-1} kpc^{-2}
$\log_{10}(\Sigma_{[CII], Ionized})$ erg s^{-1} kpc^{-2}
$\log_{10}(\Sigma_{[CII], Neutral})$ erg s^{-1} kpc^{-2}

[CII] Emission and PAHs

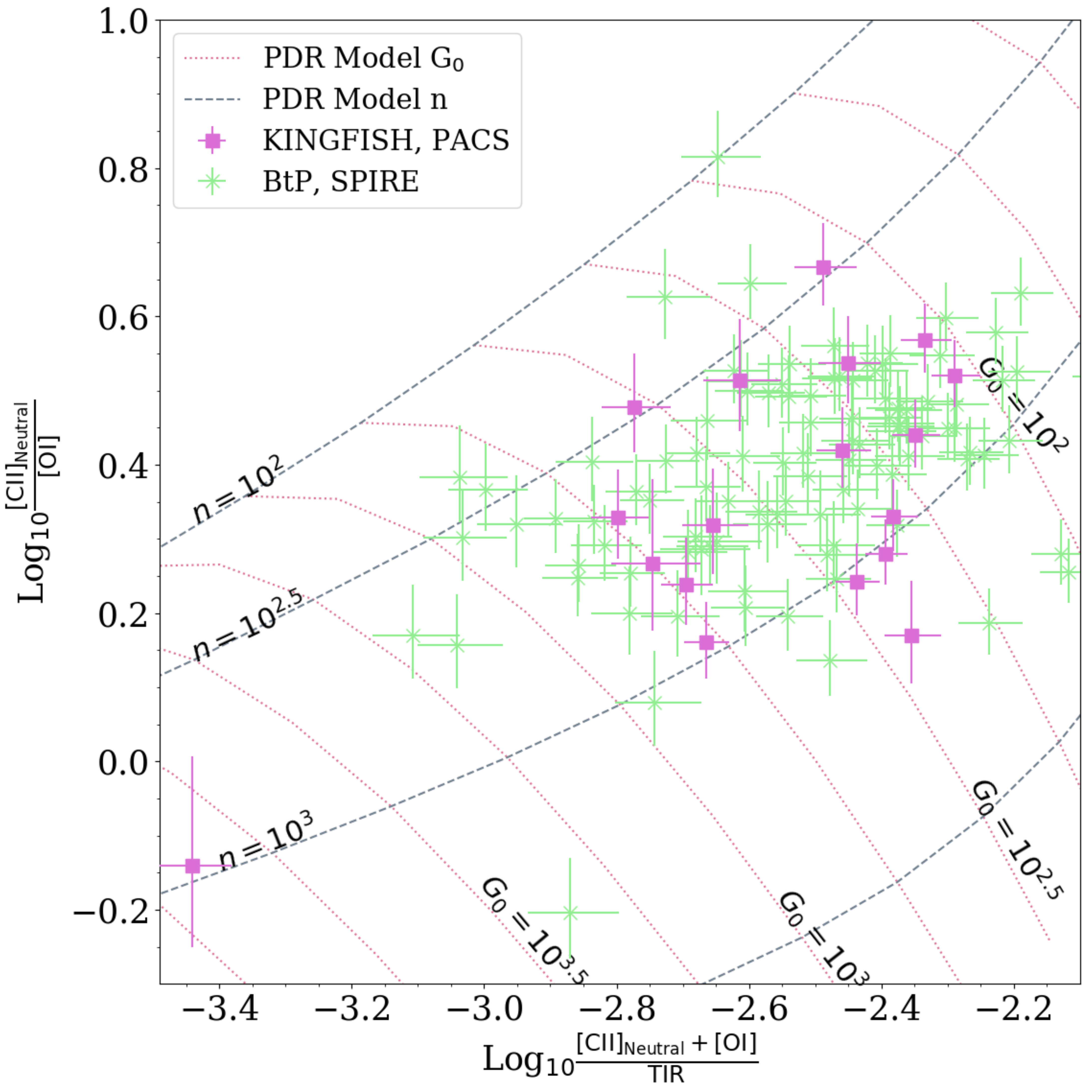


Isolated ISM-phase [CII]/PAH measurements (Image Credit: Sutter+2019)

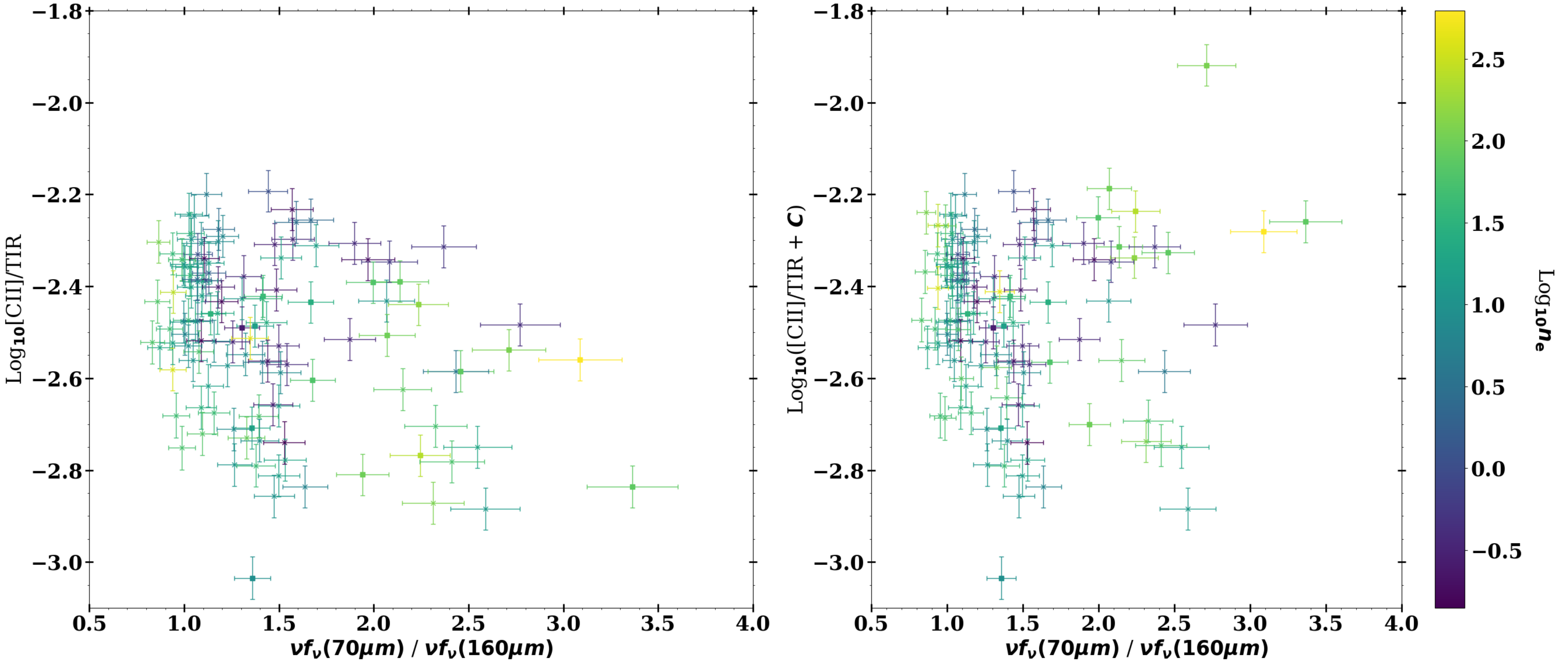


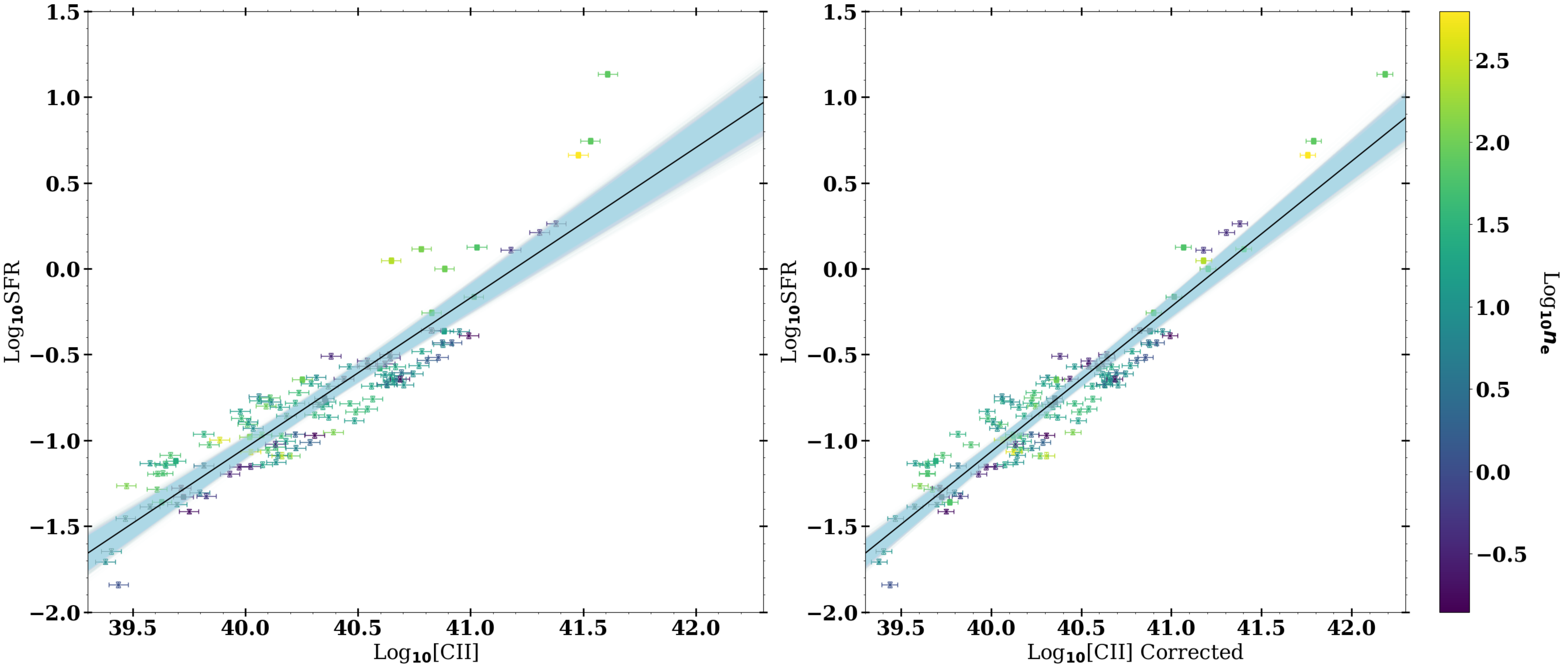
slope: -0.392±0.105
rms: 0.19 dex
fit
KINGFISH, PACS
BtP, SPIRE
Binned average
Log$_{10}$[NII] 205μm/TIR
$\nu f_\nu(70\mu m)$ / $\nu f_\nu(160\mu m)$
−3.0
−3.5
−4.0
−4.5
−5.0
1.0
1.5
2.0
2.5
3.0
3.5


Norm. Factor = 2.48
Norm. Factor = 1.17
Norm. Factor = 2.66
0.5
0.0
−0.5
−1.0
−1.5
1.0
1.5
2.0
2.5
3.0
3.5
Normalized $\mathrm{Log}_{10}([\mathrm{CII}]/\mathrm{TIR})_{\mathrm{Total}}$
Normalized $\mathrm{Log}_{10}([\mathrm{CII}]/\mathrm{TIR})_{\mathrm{Ionized}}$
Normalized $\mathrm{Log}_{10}([\mathrm{CII}]/\mathrm{TIR})_{\mathrm{Neutral}}$
$\nu f_\nu(70\mu m)$ / $\nu f_\nu(160\mu m)$
KINGFISH, PACS
BtP, SPIRE



PDR Model G0
PDR Model n
KINGFISH, PACS
BtP, SPIRE
n = 10^2
n = 10^2.5
n = 10^3
G0 = 10^2
G0 = 10^2.5
G0 = 10^3
G0 = 10^3.5
Log10 [CII]Neutral / [OI]
Log10 ([CII]Neutral + [OI]) / TIR
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−3.4
−3.2
−3.0
−2.8
−2.6
−2.4
−2.2


−1.8
−2.0
−2.2
−2.4
−2.6
−2.8
−3.0
Log10[CII]/TIR
0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
νfν(70μm) / νfν(160μm)
Log10([CII]/TIR + C)
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
Log10ne



Log10SFR
Log10[CII]
Log10[CII] Corrected
Log10 n_e
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
39.5
40.0
40.5
41.0
41.5
42.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

- Theoretical Predictions of Thermalization

$$L([\mathrm{CII}], n < n_{\mathrm{crit}}) = \frac{4}{3}\pi R^3 n_e n_{\mathrm{C+}} \gamma_{[CII]} E_{158}$$

$$L([\mathrm{CII}], n > n_{\mathrm{crit}}) = \frac{4}{3}\pi R^3 n_{[\mathrm{CII}]} \gamma_{[CII]} E_{158}.$$

$$L(TIR) = N_{\mathrm{Ly}} E_{UV} f_{IR}$$

$$N_{\mathrm{Ly}} = \frac{4}{3}\pi R^3 n_e^2 \alpha$$

$$\frac{[\mathrm{CII}]}{\mathrm{TIR}} = \frac{n_{[\mathrm{CII}]} \gamma_{[CII]} E_{158}}{n_e \alpha E_{UV} f_{IR}}.$$

$$\frac{[\mathrm{CII}]}{\mathrm{TIR}} = \frac{n_{[\mathrm{CII}]} n_{\mathrm{crit}} \gamma_{[CII]} E_{158}}{n_e^2 \alpha E_{UV} f_{IR}}.$$

$$\frac{[\mathrm{CII}]}{\mathrm{TIR}} = 0.13$$

$$\frac{[\mathrm{CII}]}{\mathrm{TIR}} = \frac{0.13 n_{\mathrm{crit}}}{n_e}.$$