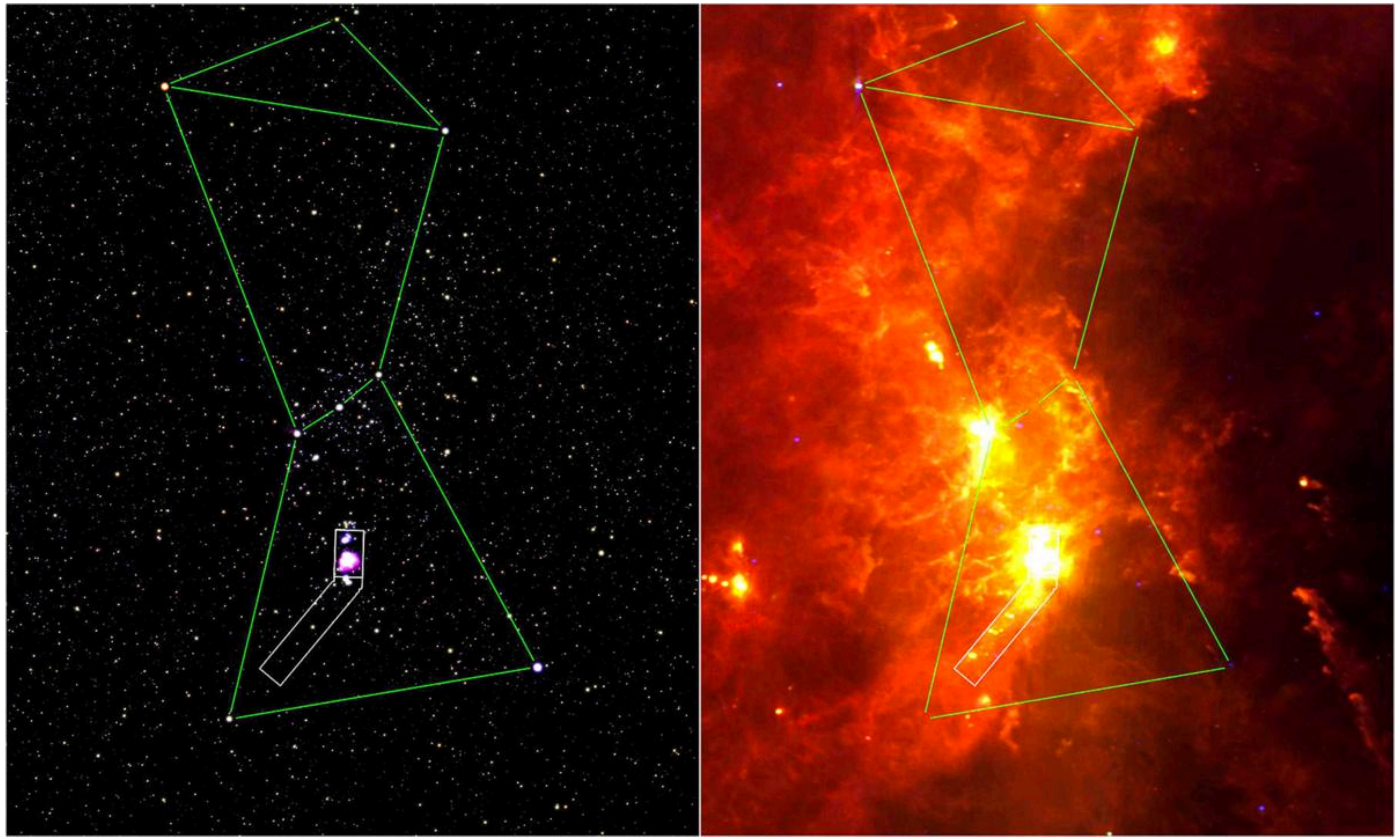
Disentangling the Causes and Consequences of the [CII] Deficit

Jessica Sutter, Dissertation Defense, Feb. 2021

NGC6946, Image Credit: Subaru Telescope and Robert Gendler

Outline

- Quick intro to extragalactic astronomy
- Definition of the [CII] deficit and why it is a problem worth solving
- The KINGFISH and BtP Samples
- Isolating [CII] by ISM phase
- Testing the Causes of the Deficit
- Conclusions and Questions



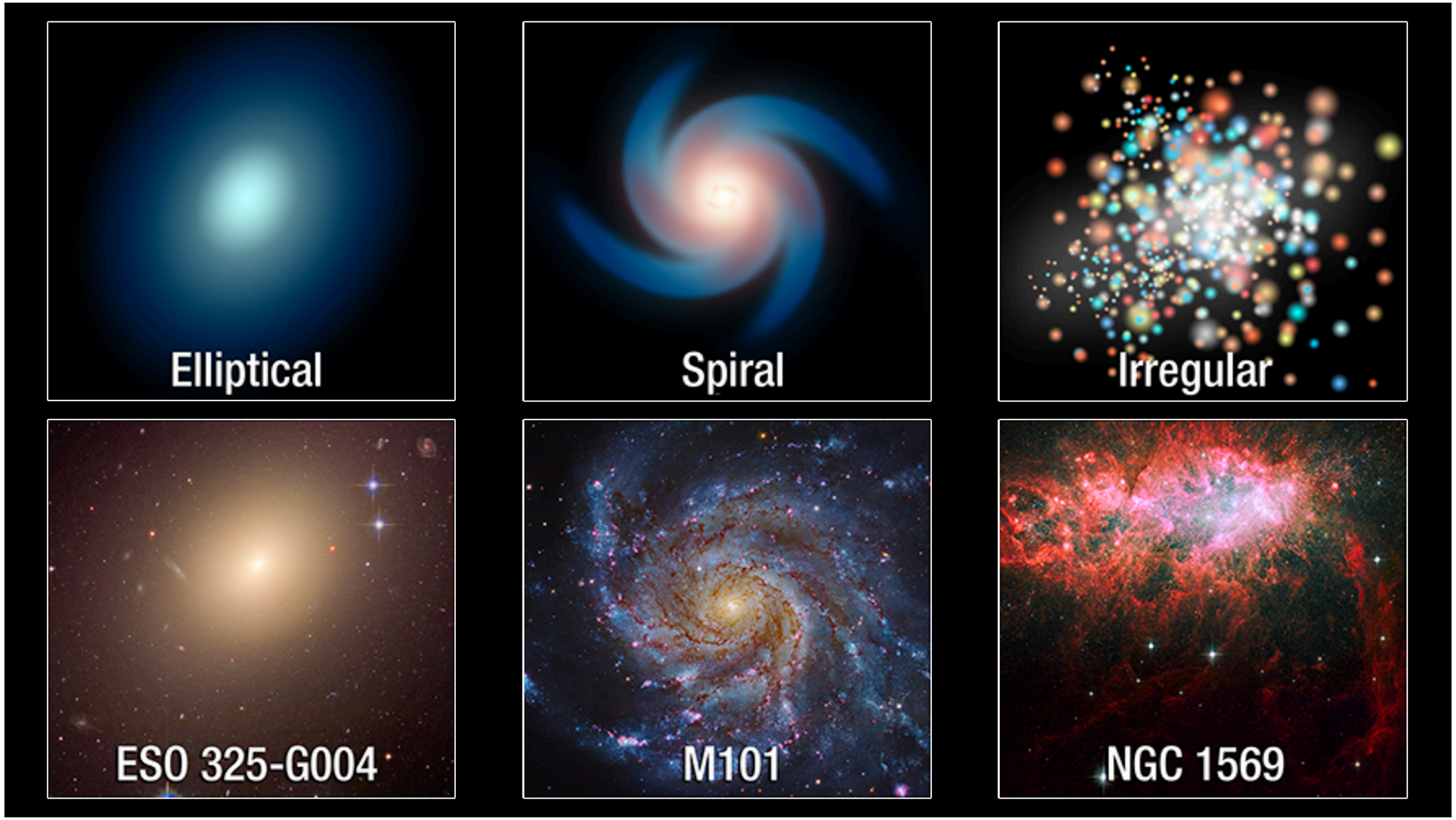
Orion Constellation with Orion Nebula highlighted, in both optical and infrared light (Image credit: NASA/Spitzer)

Extragalactic Astronomy

NGC7331 and Beyond. Image Credit R. Jay GaBany, accessed through APOD)

What do we know about galaxies?

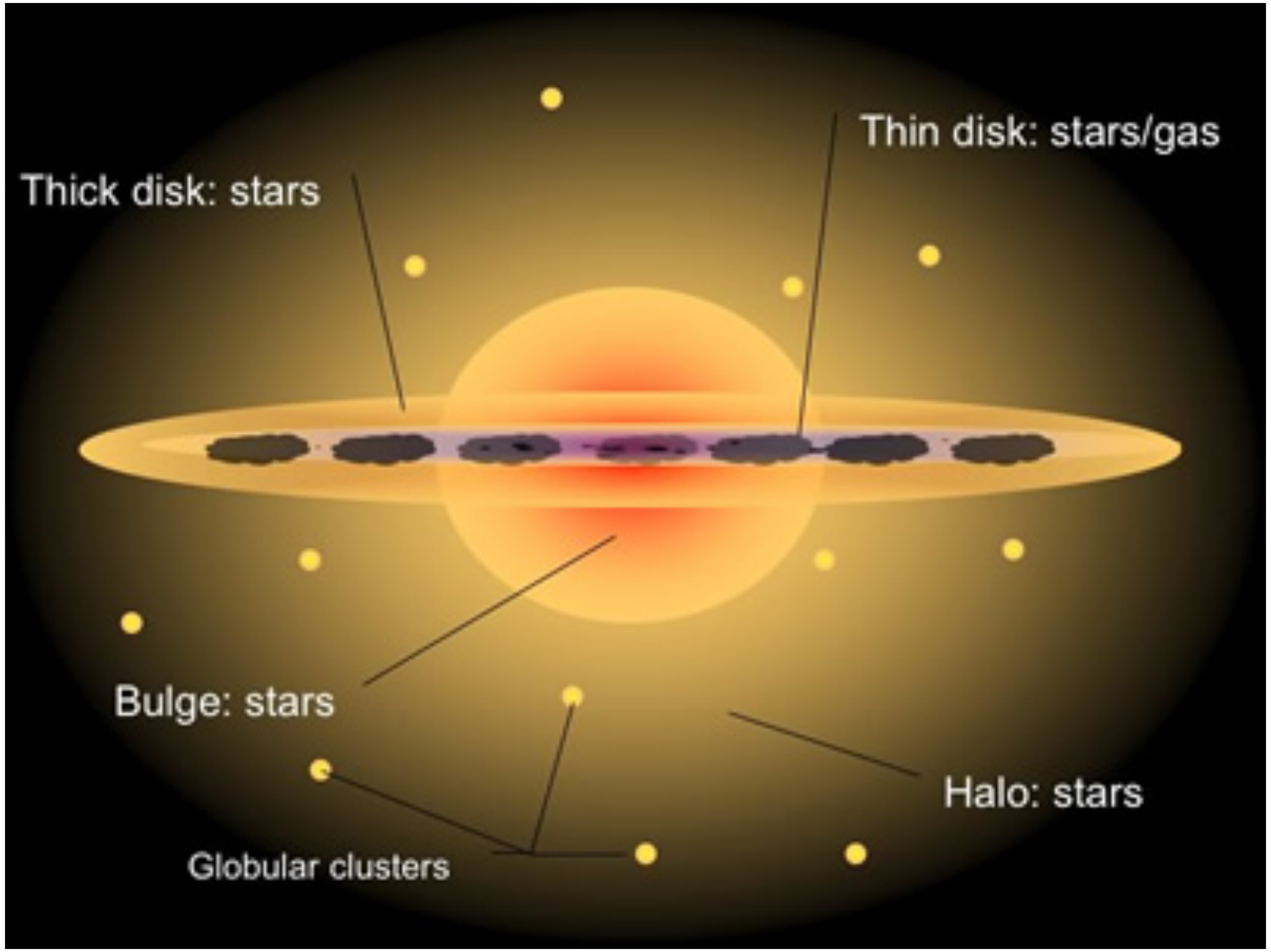
- Galaxies come in three main types
- The shape and color of a galaxy can tell us what's happening inside
- Star formation in galaxies is a major part of these differences



The three major types of galaxies. Image Credit: HubbleSite.org

Inside a galaxy

- Galaxies are made of stars, gas, dust, and dark matter
- Measurements of EM radiation teach us about the components
- Observing galaxies in different wavelengths give us a wide range of information

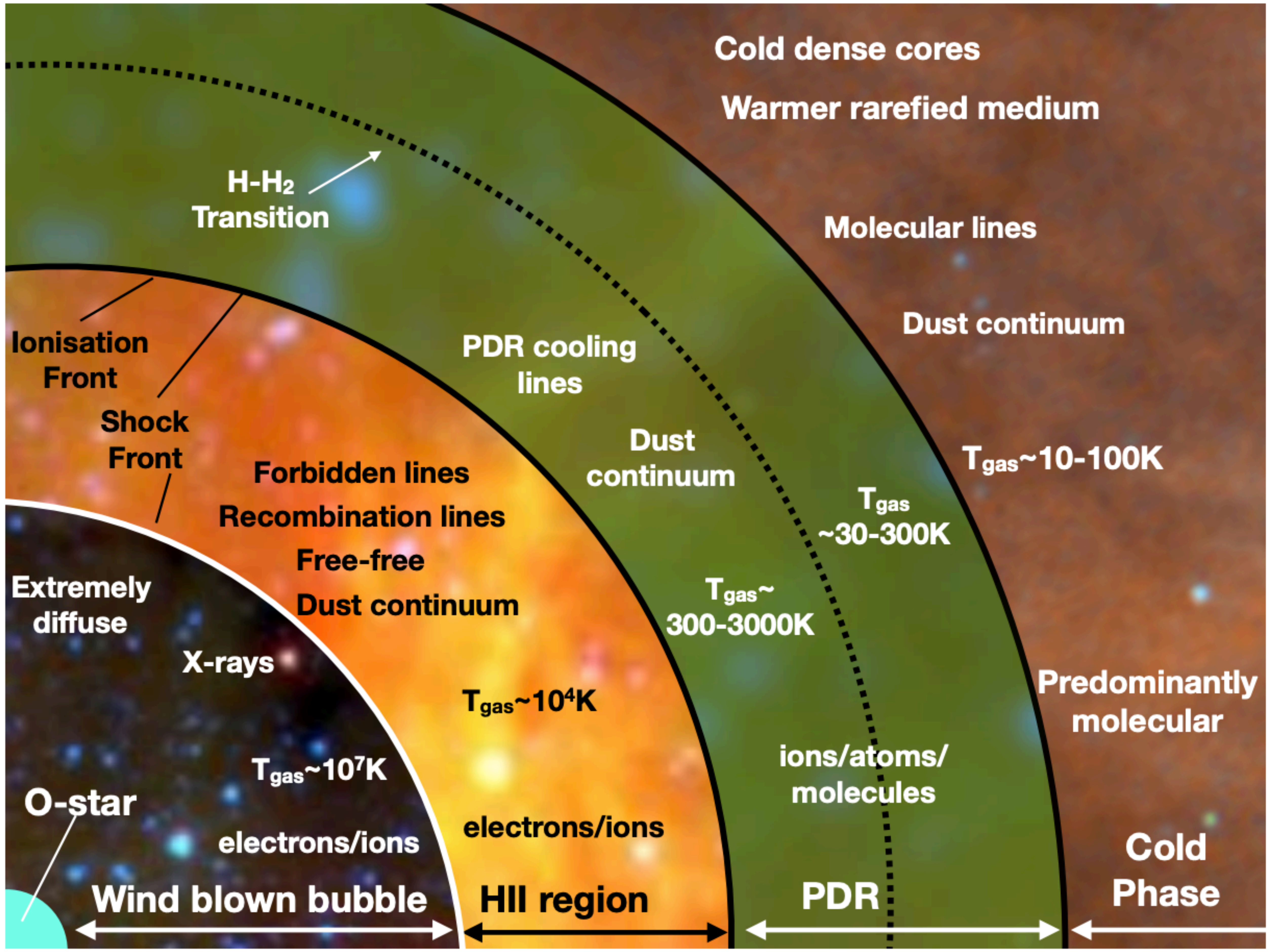


Model of a typical Spiral Galaxy. Image Credit: Swinburne University of Technology


Radio
Microwave
Infrared
UV
X-Ray
Gamma Ray
Radio
60,000 nm
600 K
Infrared
1200-800 nm (10-3.6 um)
4,500 K
Optical
450-750 nm
6,000 K
Ultraviolet
400-200 nm
10,000 K
X-ray
100-10 nm
10,000,000 K
Multiwavelength Whirlpool Galaxy
COLD GAS: Radio waves reveal regions of gas cool enough for CO_2 molecules to exist.
COOL STARS: Infrared shows smaller cool red stars that make up most of the galaxy.
SOLAR STARS: Optical light comes from stars around the size of the Sun.
HOT STARS: Ultraviolet shows the larger hot blue stars that are less frequent in galaxies.
HOT GAS: X-rays are emitted from the hottest regions of gas where atoms are ionized.
COOL LOW ENERGY RADIATION
VISIBLE LIGHT
HOT HIGH ENERGY RADIATION

Galactic Ecosystem

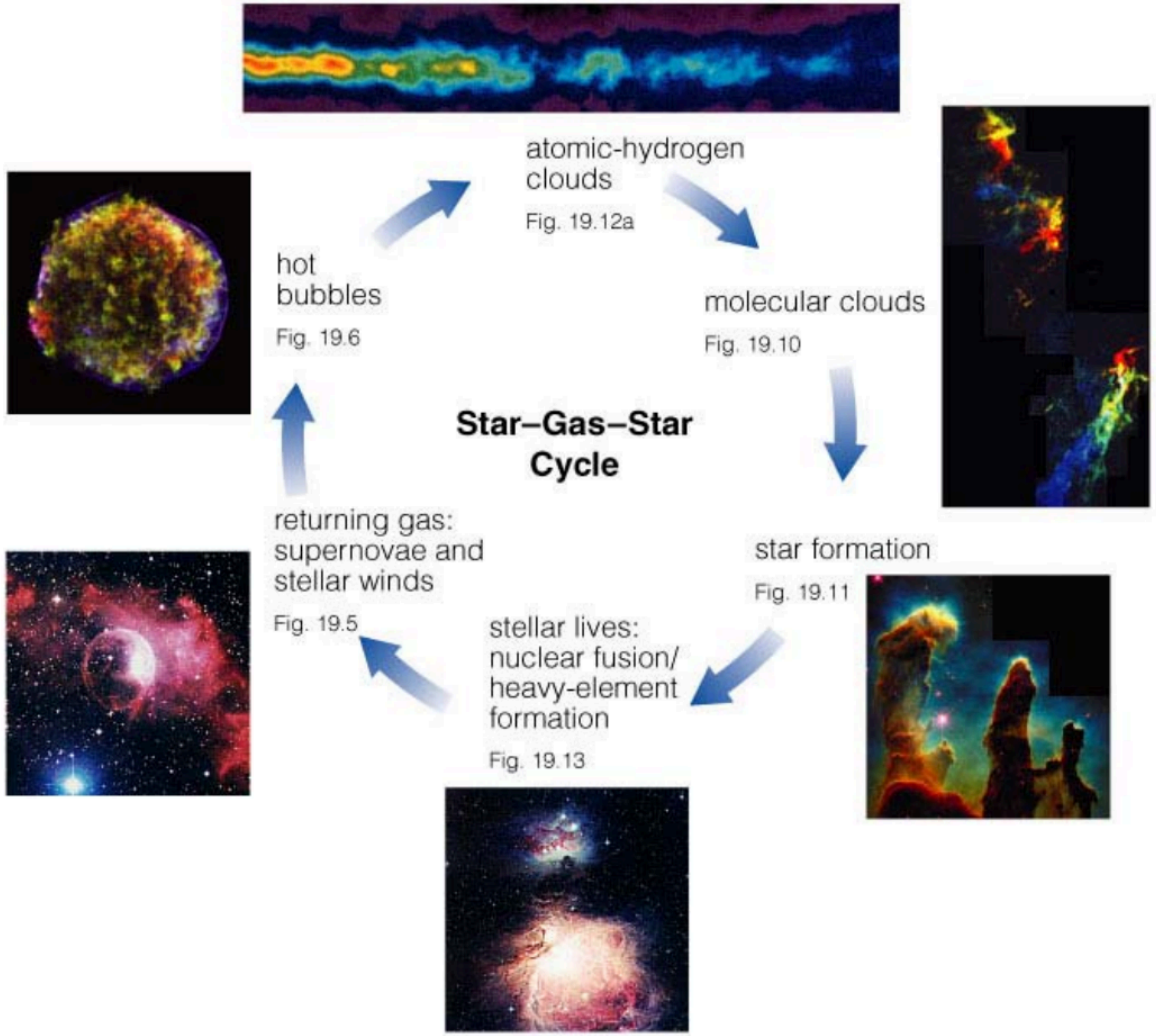
- The gas and dust between stars is commonly referred to as the Interstellar Medium, or ISM
- The ISM can be divided into ‘phases’ based on the ionization state of hydrogen
  - ✦ Ionized, neutral, or molecular
- Star forming regions are surrounded by ionized gas in a HII region, as well as a layer of neutral gas, called a PDR



Basic model of a star-forming region. Image Credit: Haworth+2018

Measuring Star Formation Rate

- Star formation rate (SFR) is one of the key indicators of galaxy conditions
- Star formation occurs when gas clouds becomes dense enough to fragment and gravitationally collapse
- Measured through detections of high-energy light from young stars
  - ✦ UV light, Hα emission, etc.



A model of the Star-Gas cycle in galaxies. Image credit: Pearson Education

Measuring Star Formation Rate

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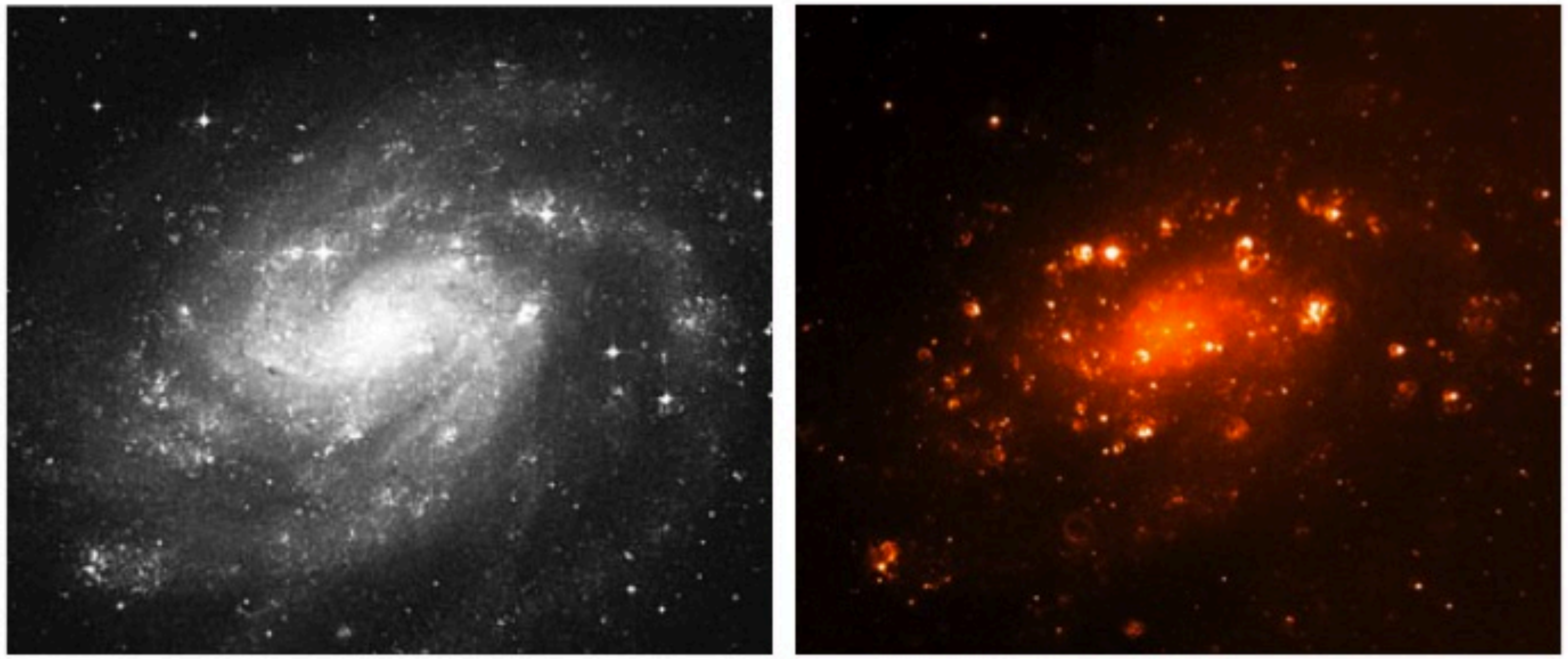

Optical and Hα images of galaxy NGC300. Image Credit: F. Bresolin, through the MOSDEF Collaboration

Issue of Dust

- Dust in galaxies blocks and scatters optical and UV light
  - ✦ can absorb and re-radiate up to almost 100% of a galaxy's radiative energy
- Attenuation by dust needs to be accounted for in optical and UV SFR indicators
- Typically done by measuring infrared light emitted by warm dust

Smoke in the air changes the color of the sky, similar to dust in galaxies. Image Credit: CBS News

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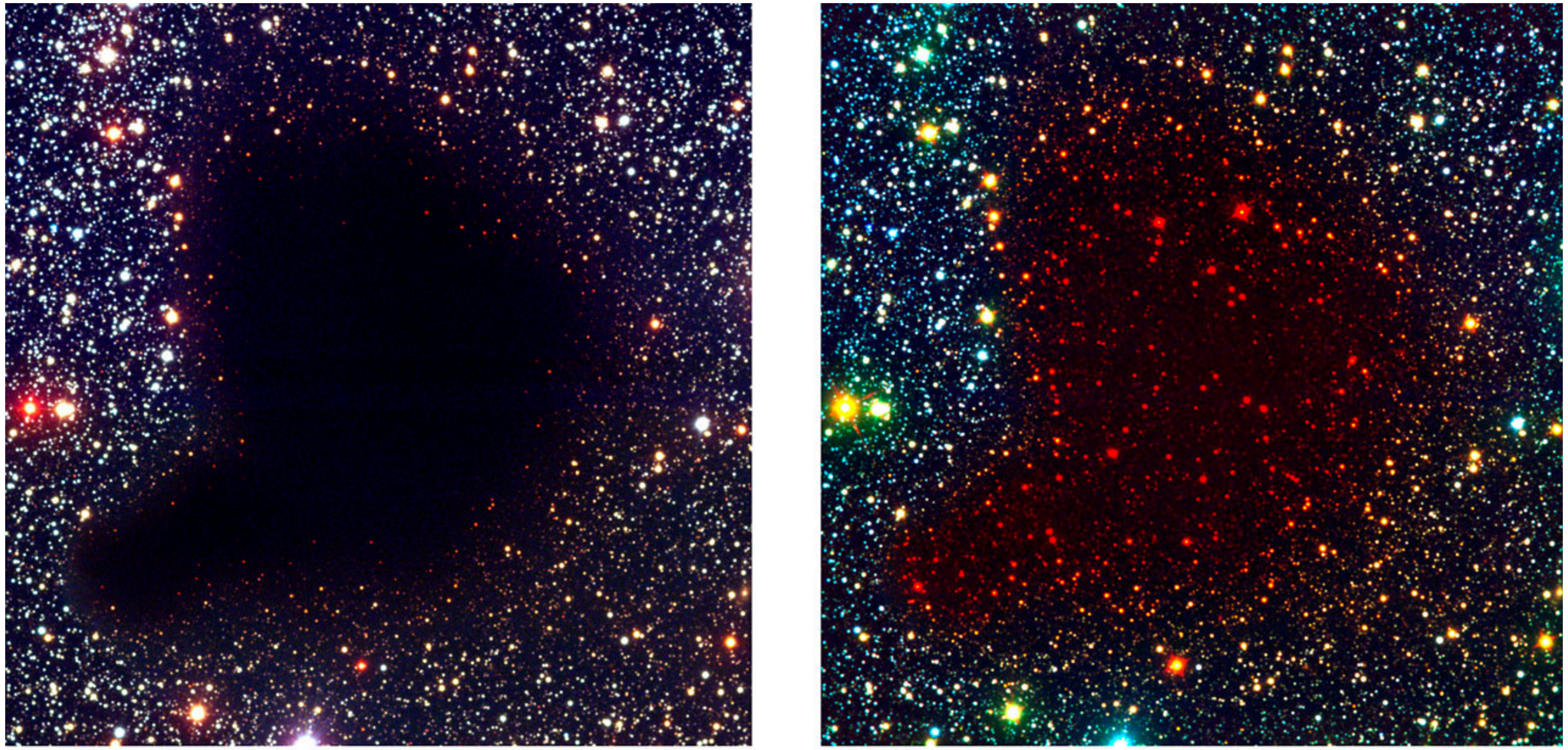


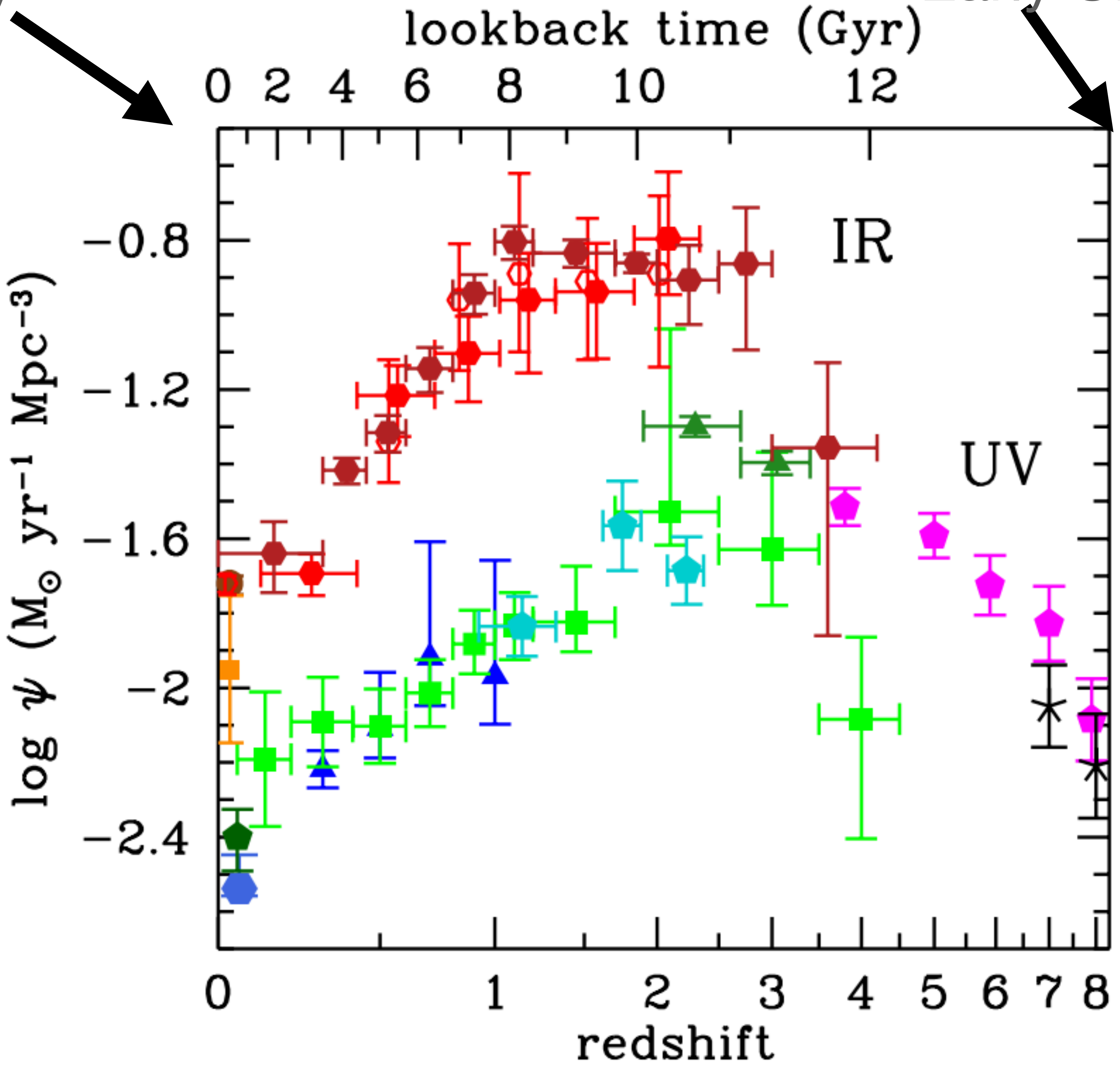
Bok Globule in visible and infrared to show dust extinction. Image Credit: ESO

Cosmic Star Formation History

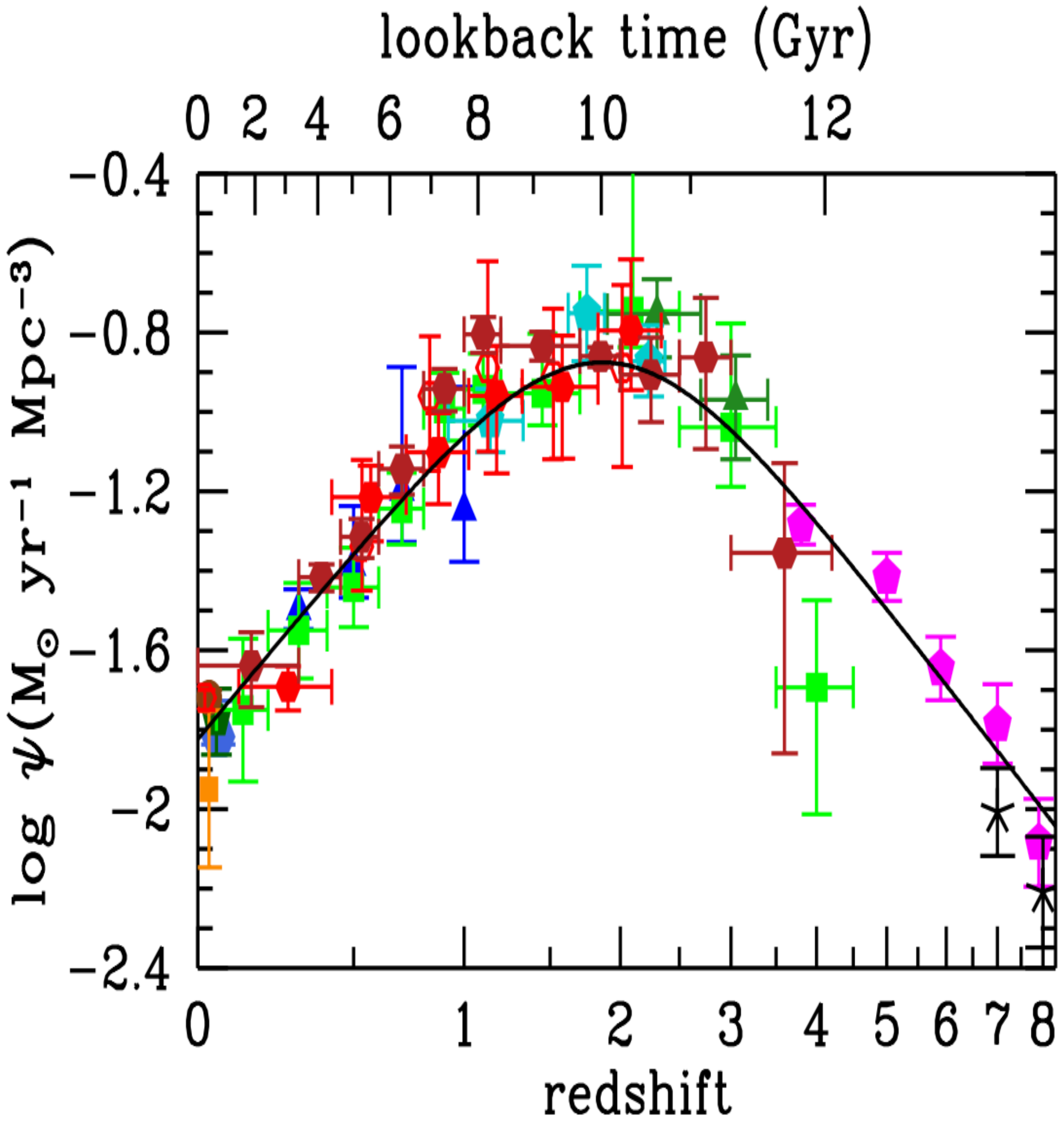
Today

Early Universe

More active star formation



The Cosmic Star Formation History without dust corrections. Image Credit: Madau, 2014



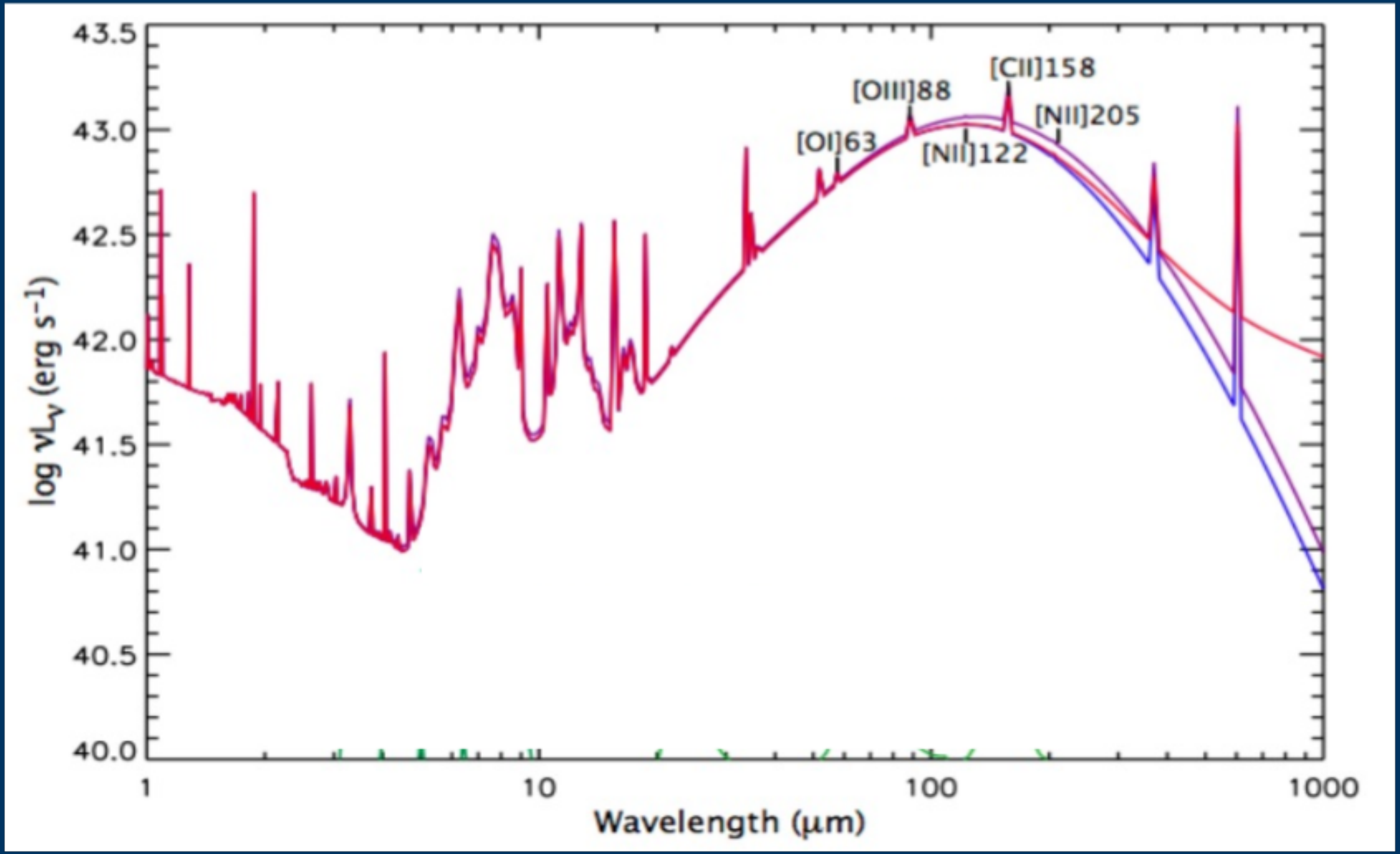
The Cosmic Star Formation History with dust corrections. Image Credit: Madau, 2014

Summary of Extragalactic Astronomy

- Galaxies are awesome
- Galaxies contain stars, gas, dust, and dark matter, which we measure through different types of EM radiation (or gravitational effects)
- Galactic environments can be divided into phases
- Star formation rate is an important indicator of galaxy properties

M101 Image Credit: Hubble Legacy

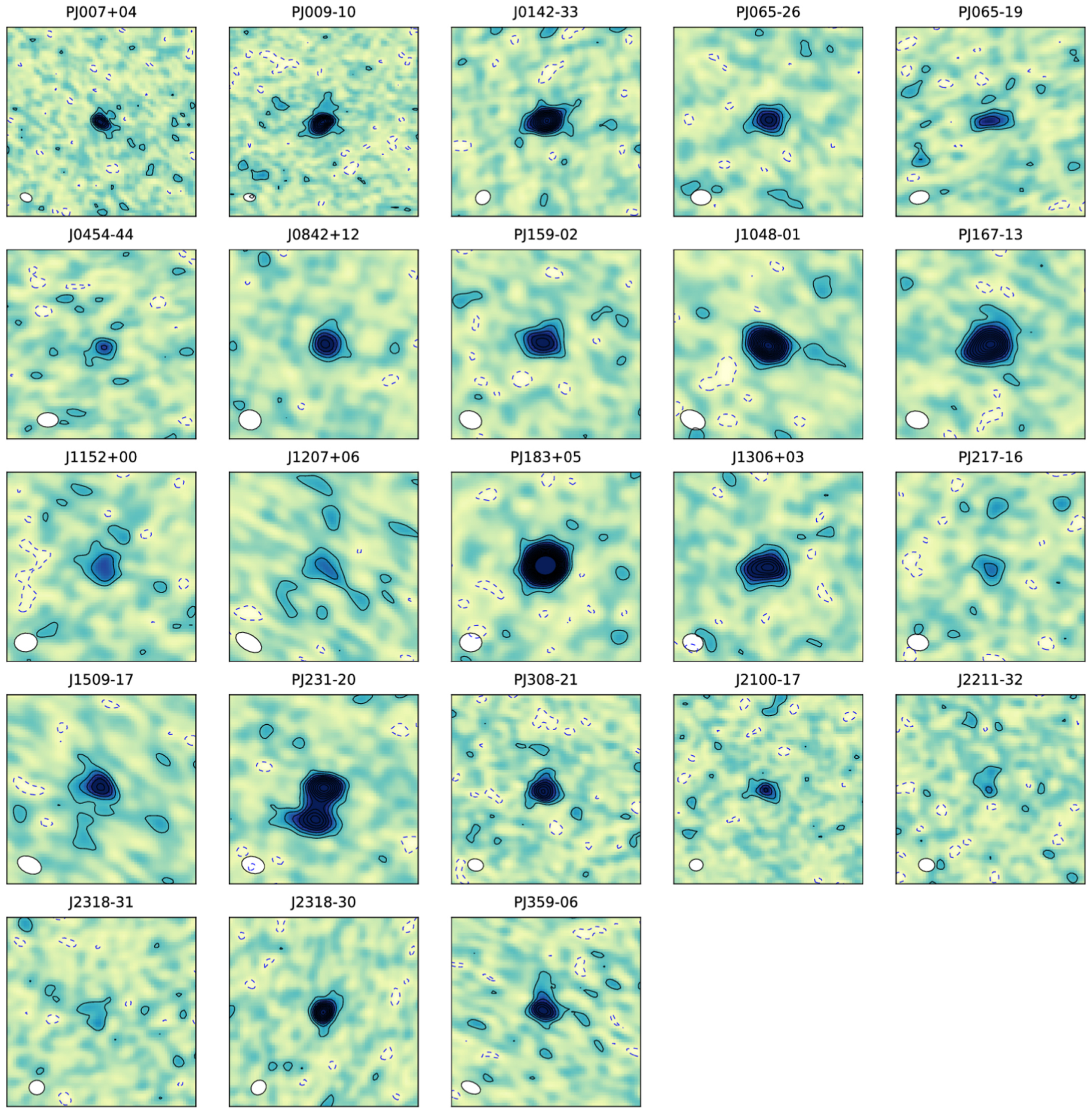
[CII] 158 µm Emission



The IR SED of a star-forming galaxy. Image Credit: Kennicutt+2012

[CII] 158 µm Emission

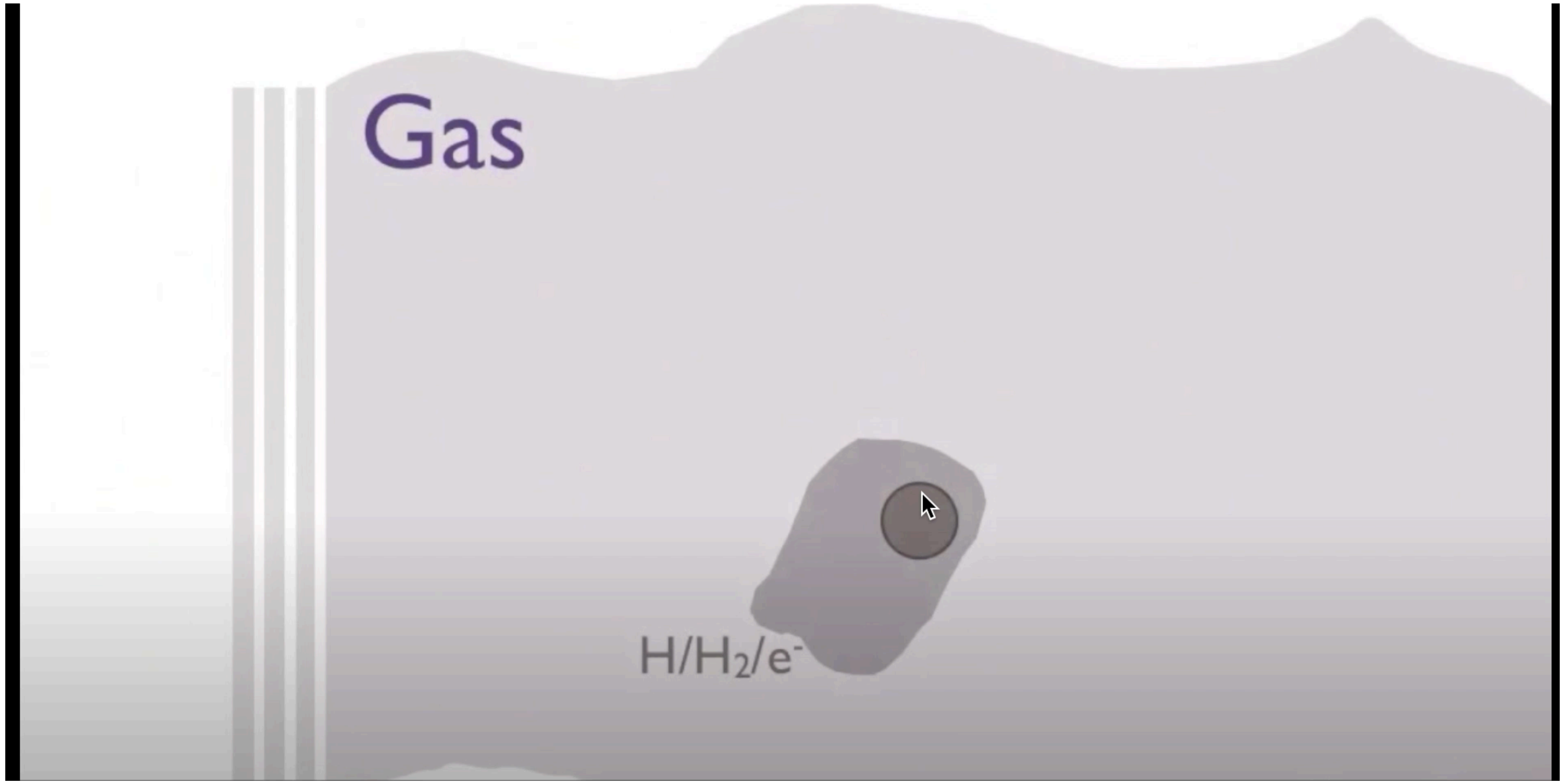
- Often the brightest *observed* emission line in star-forming galaxies
- C is the fourth most prevalent element in the universe
- 158 µm wavelength allows for little to no dust attenuation
- Detectable in both local and high-z galaxies



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

[CII] Cooling

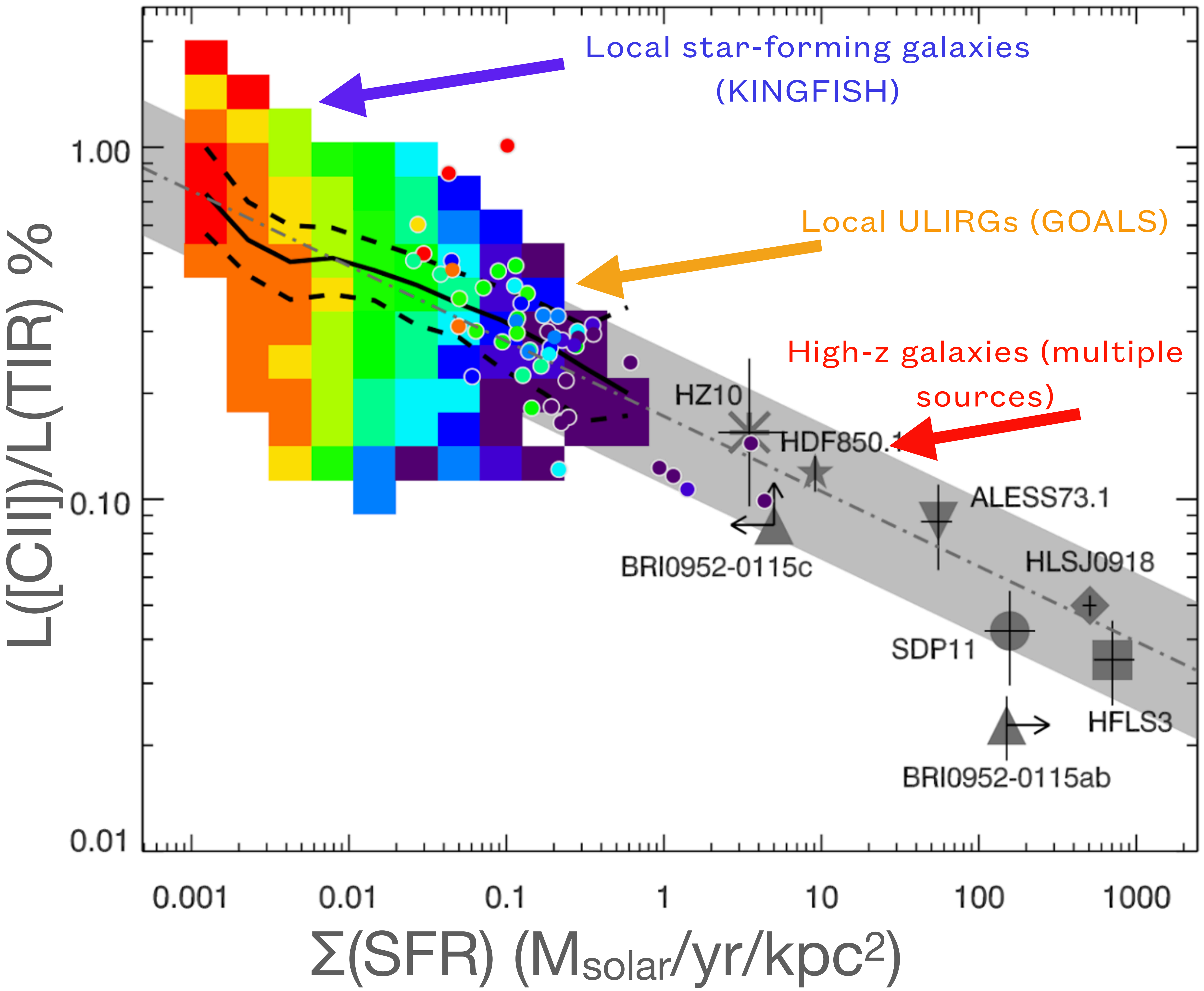
- [CII] is one of the major cooling channels for the neutral ISM
- Collisions between electrons and hydrogen and C^+ convert kinetic energy to 158 μm photons
- Long-wavelength photons escape dense PDRs, carrying energy out of the ISM
- If heating by young stars is balanced by cooling from [CII], [CII] should trace SFR



A basic model of [CII] emission. Video Credit: R. Herrera-Camus

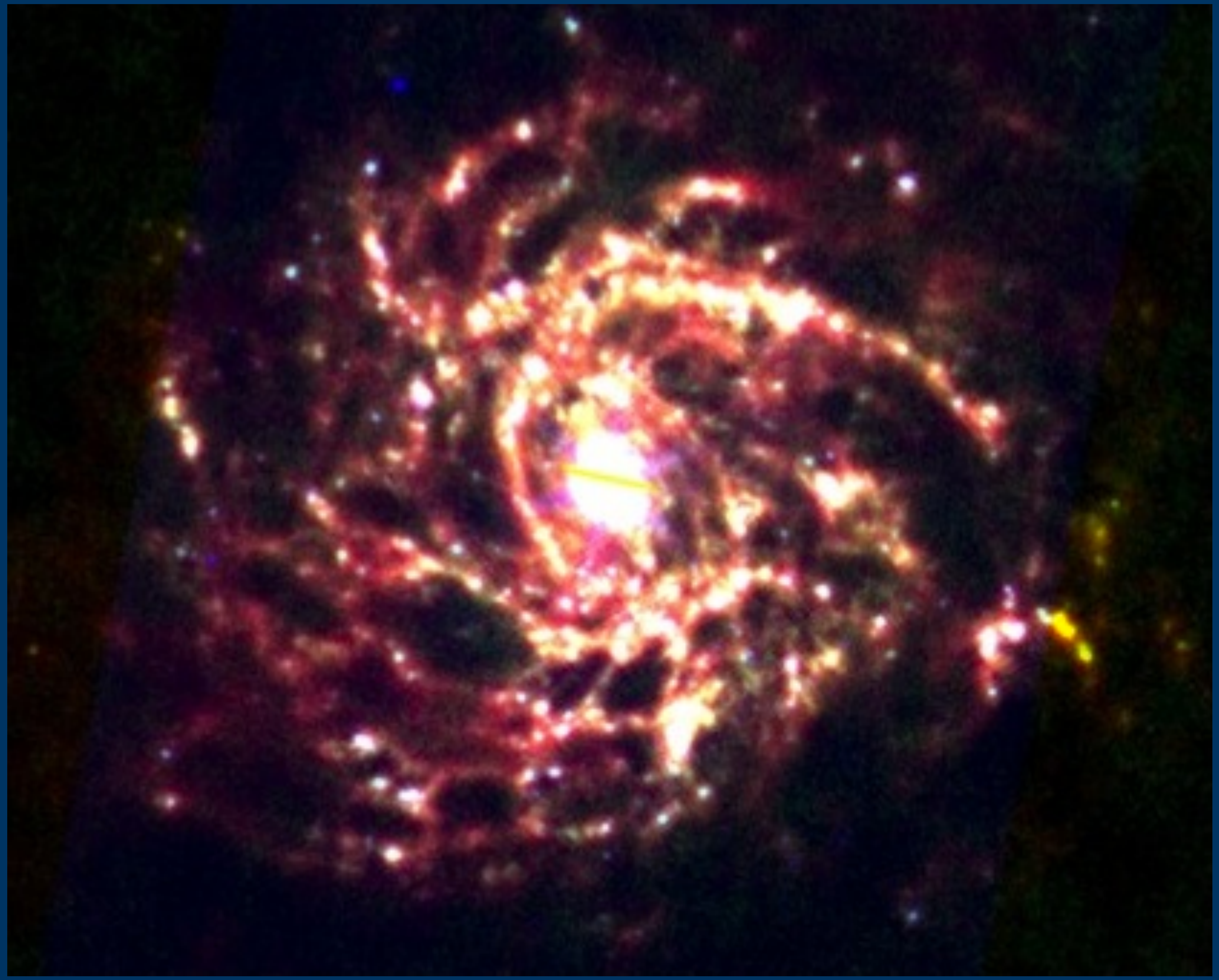
The [CII] Deficit

- 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

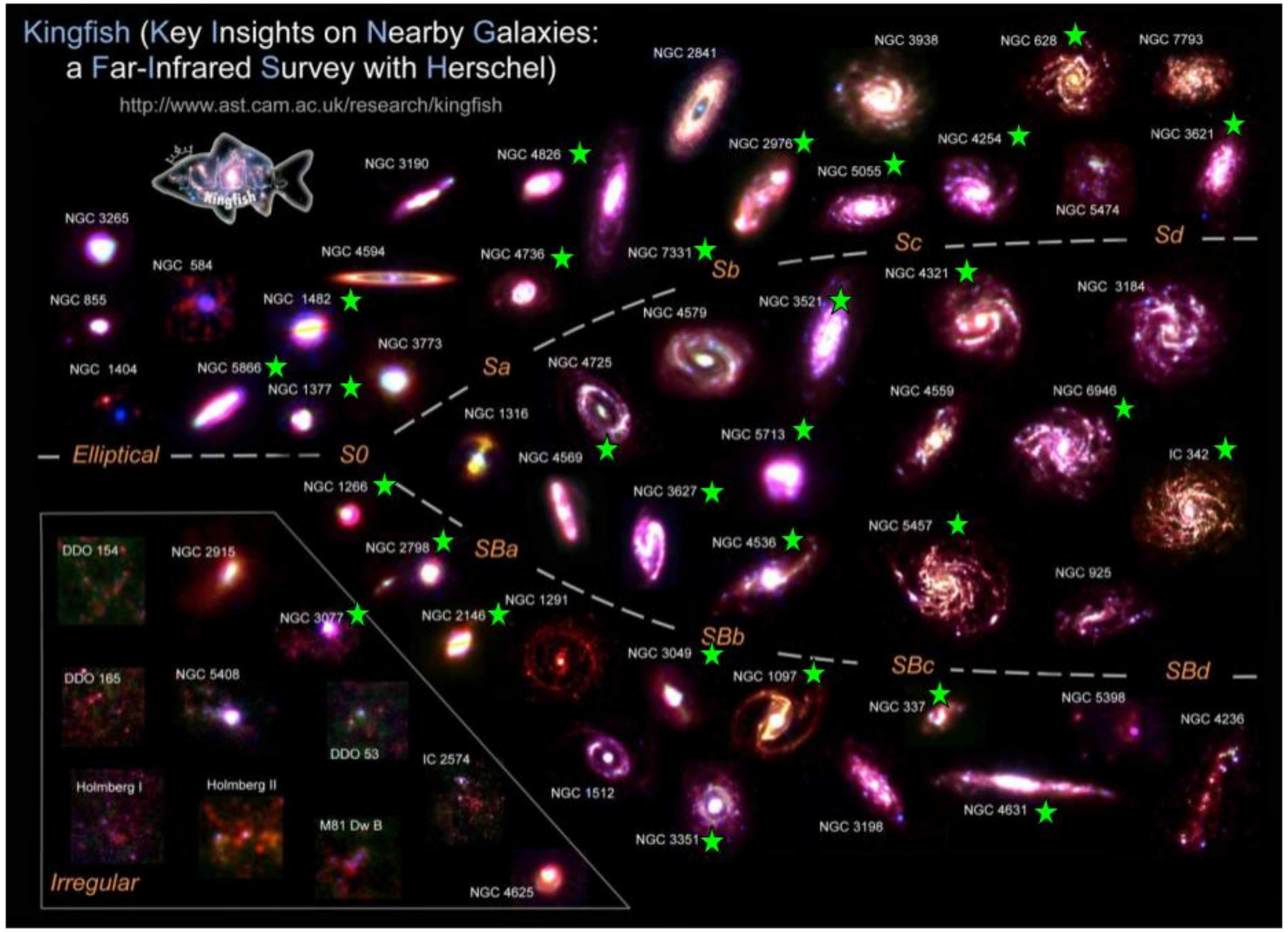
Determining the Cause of the [CII] Deficit in the KINGFISH and BtP Samples



IC342 in 70-100-160 microns. Image Credit: Herschel Space Observatory

The KINGFISH and BtP Surveys

- KINGFISH: Key Insights in Nearby Galaxies: a Far Infrared Survey with Herschel
- BtP: Beyond the Peak
- Nearby, Star-forming galaxies
  - ✦ D ~ 3 - 30 Mpc
  - ✦ Z ~ 0.25 $Z_\odot$ - 1 $Z_\odot$



The KINGFISH Galaxies, with green stars indicating galaxies with [CII] data. Image Credit: Dr. Maud Galametz

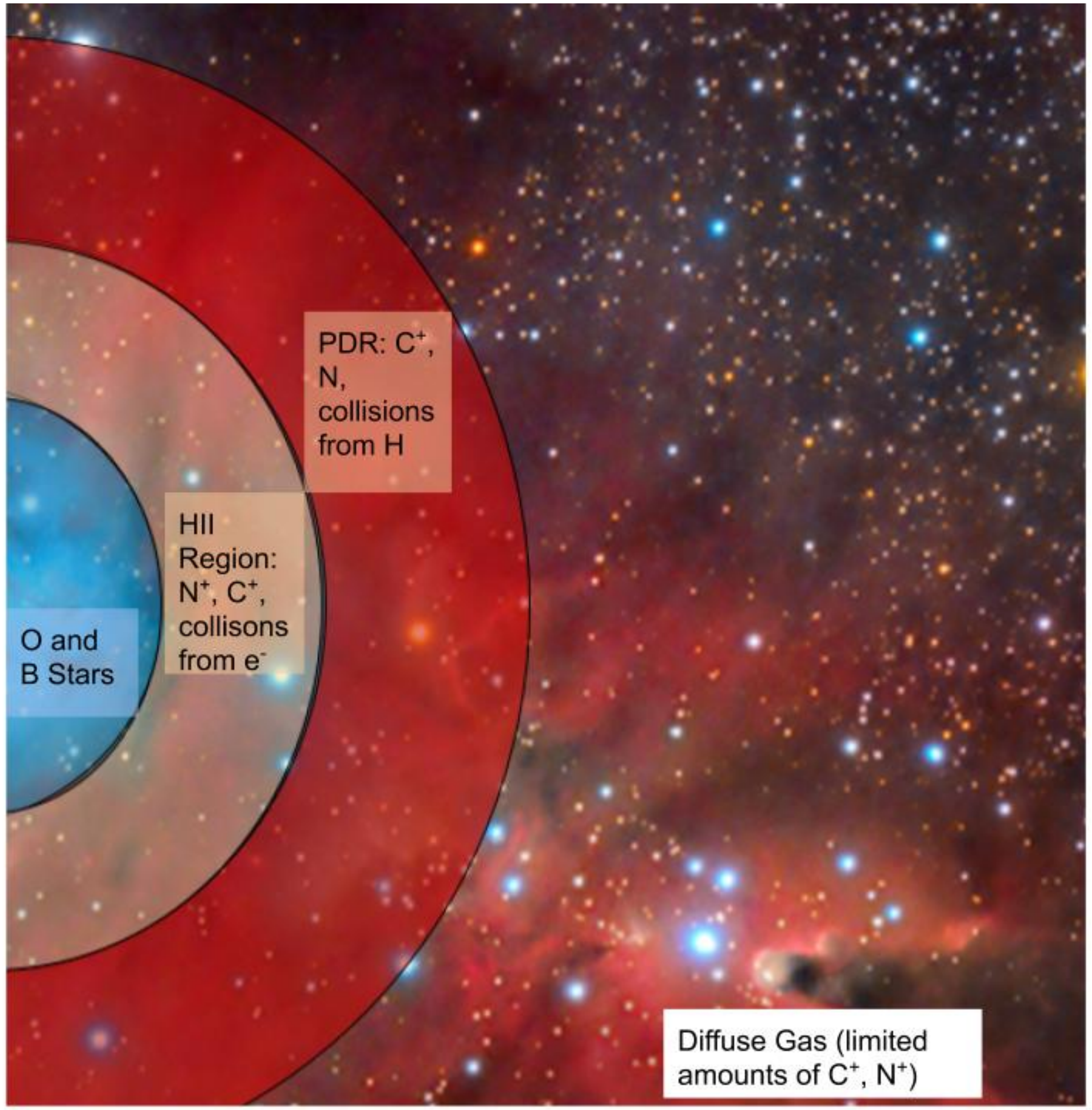
[CII] & [NII] 205 µm Measurements

- 31 star-forming regions in 28 galaxies targeted using PACS-Spec on *Herschel*
- 20 regions further mapped at 205 microns using SPIRE on *Herschel*, targeting more quiescent areas around SF regions
- Physical sizes of 11" PSF ranges from 200-2000 pc

NGC 6946 70-100-160 KINGFISH images, regions with [CII] detections. Image Credit: Maud Galametz

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

Separating by ISM Phase

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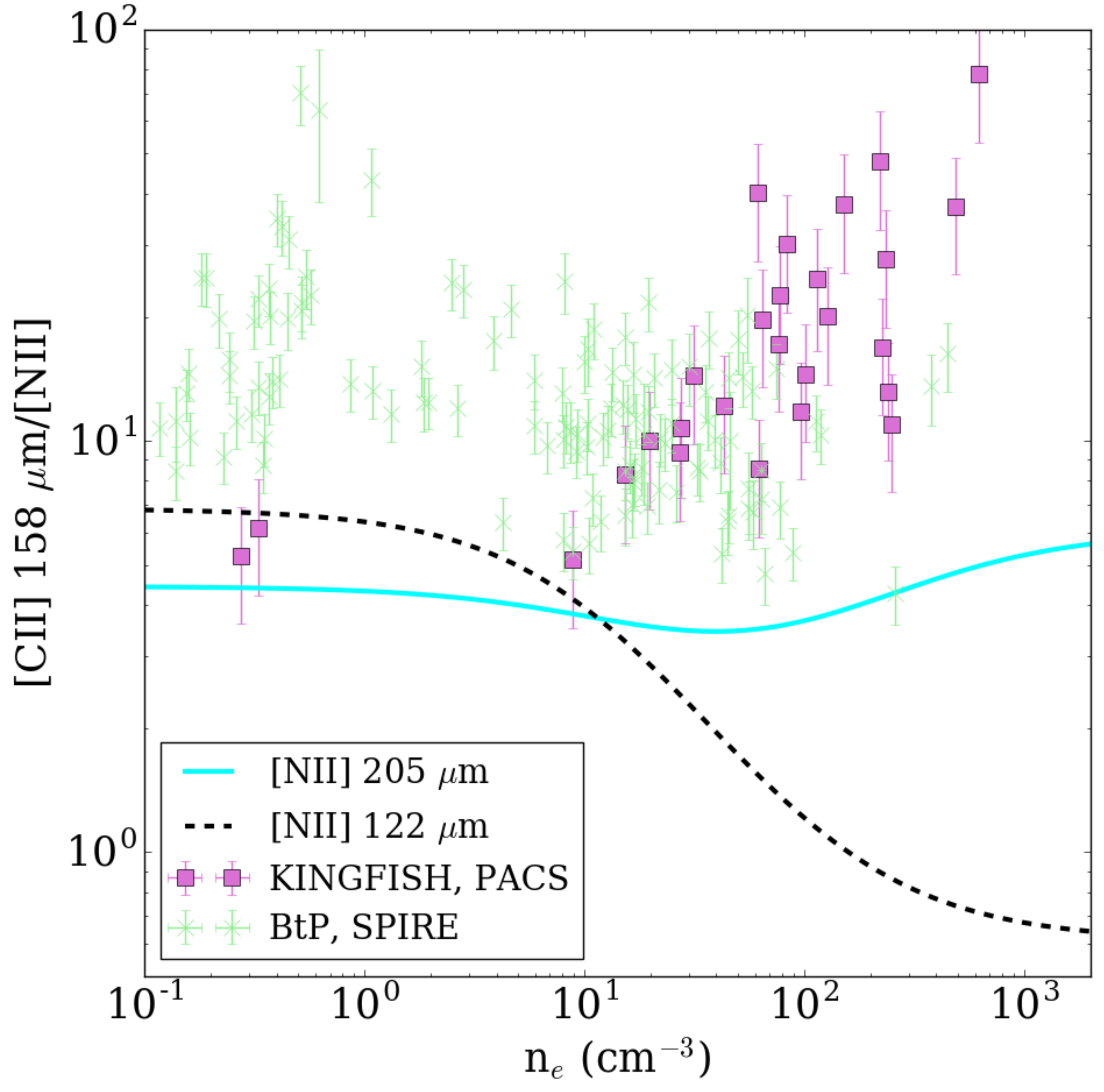

[CII] 158 micron to [NII] line ratios as a function of n_e, determined using the [NII] line ratio. Image Credit Sutter+2021

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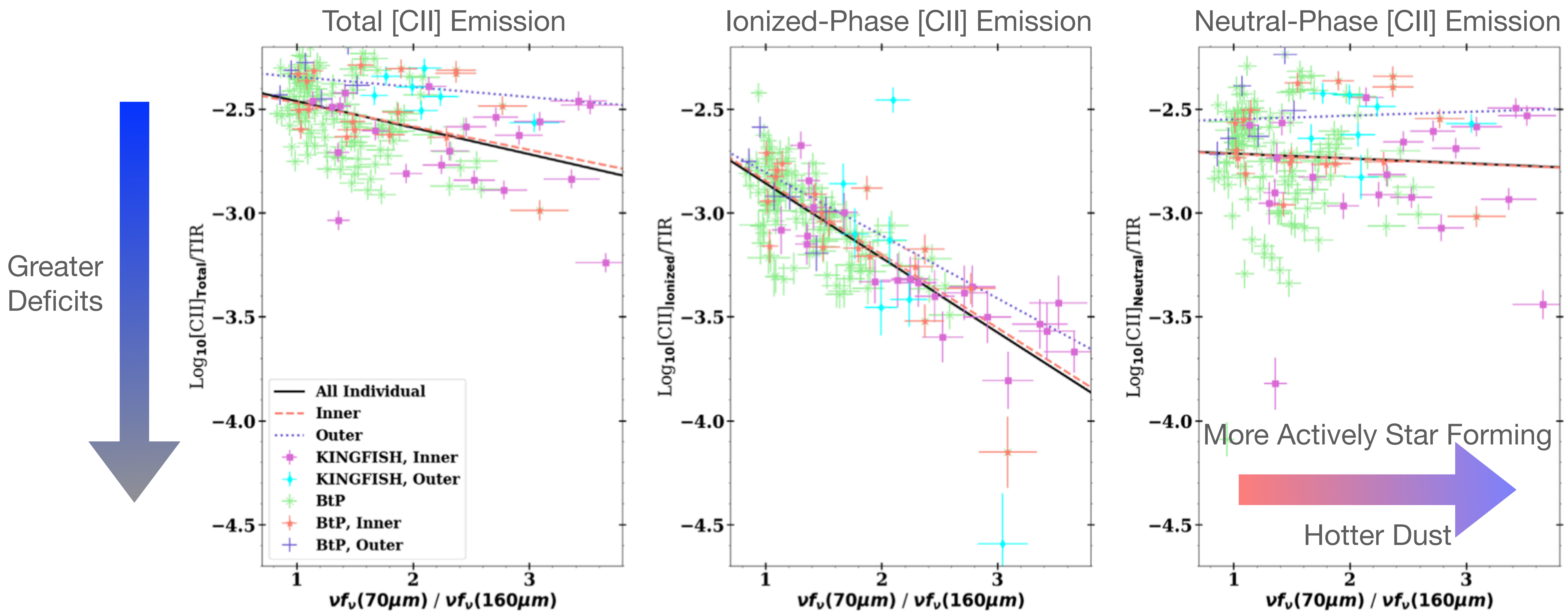
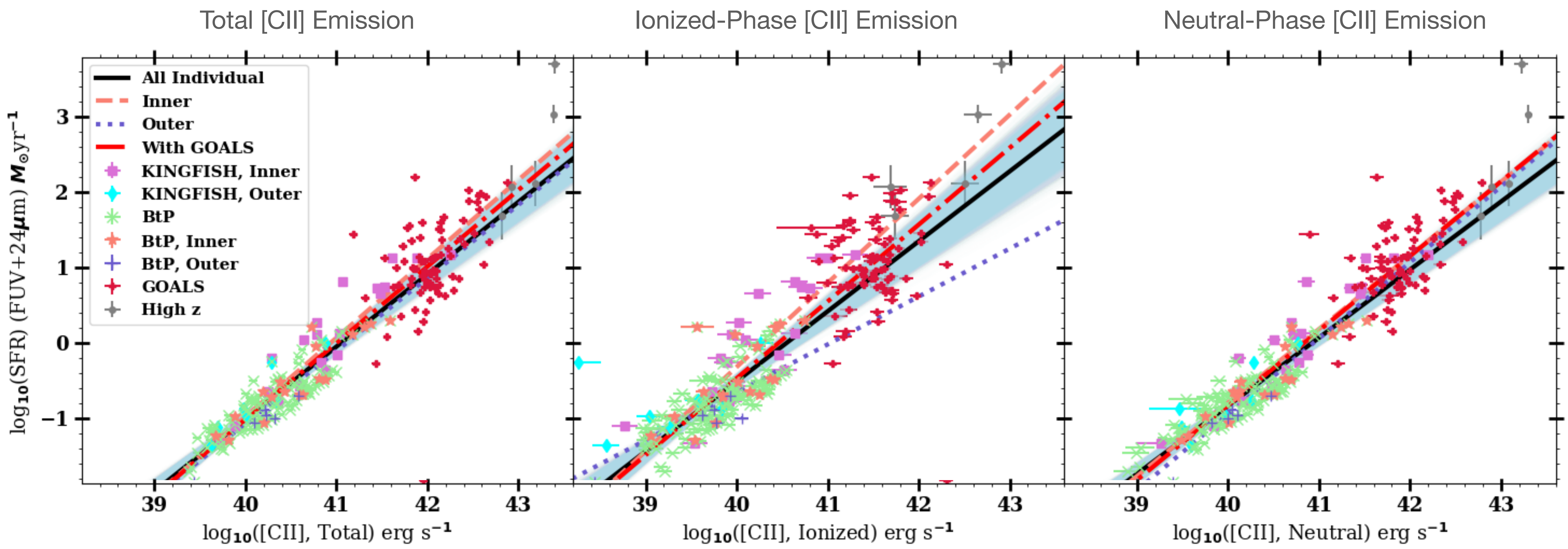
The [CII] Deficit



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

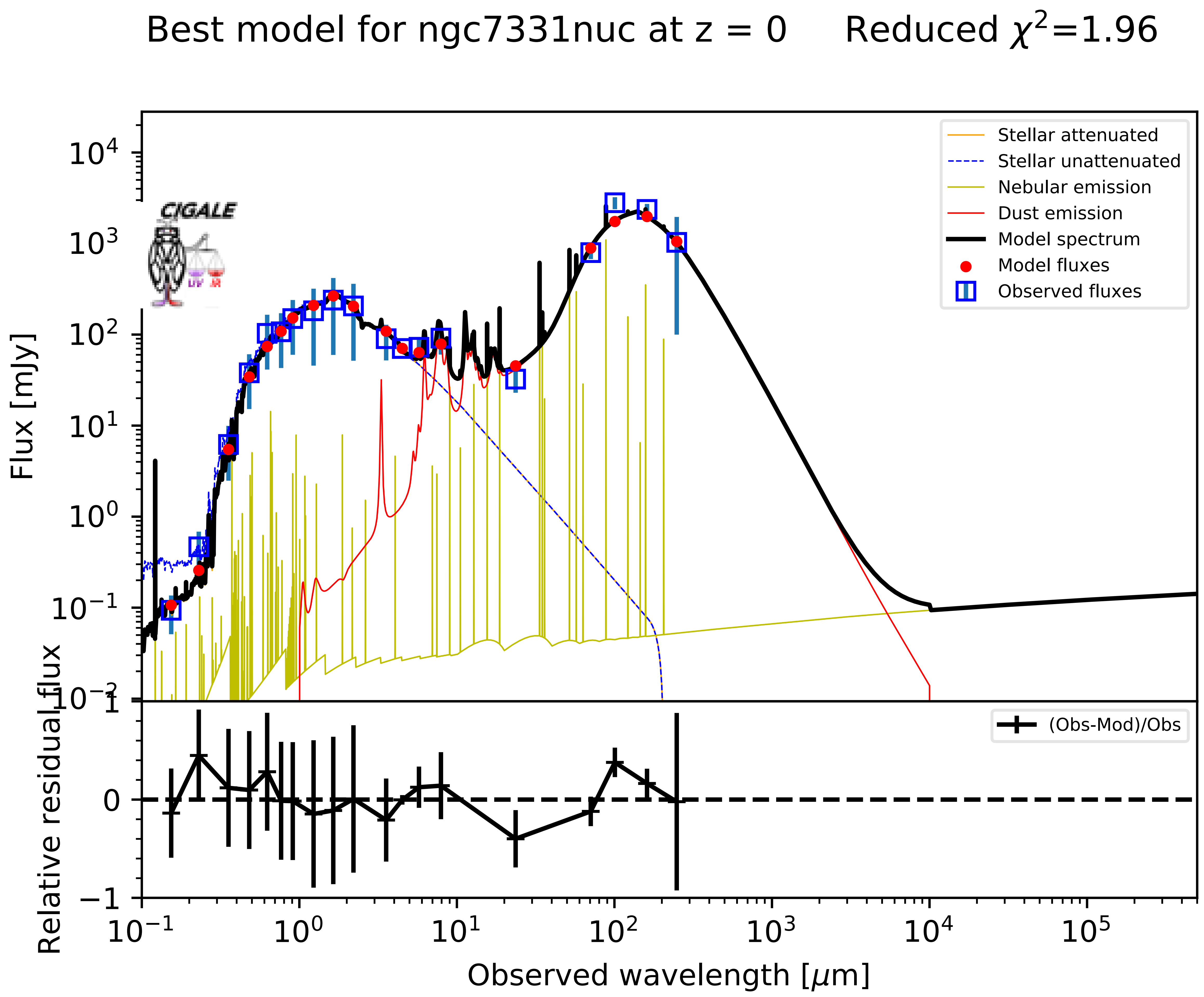
[CII] and SFR



The ISM-Phase Isolated [CII]-SFR relationship. Image Credit: Sutter+2019

Dividing TIR

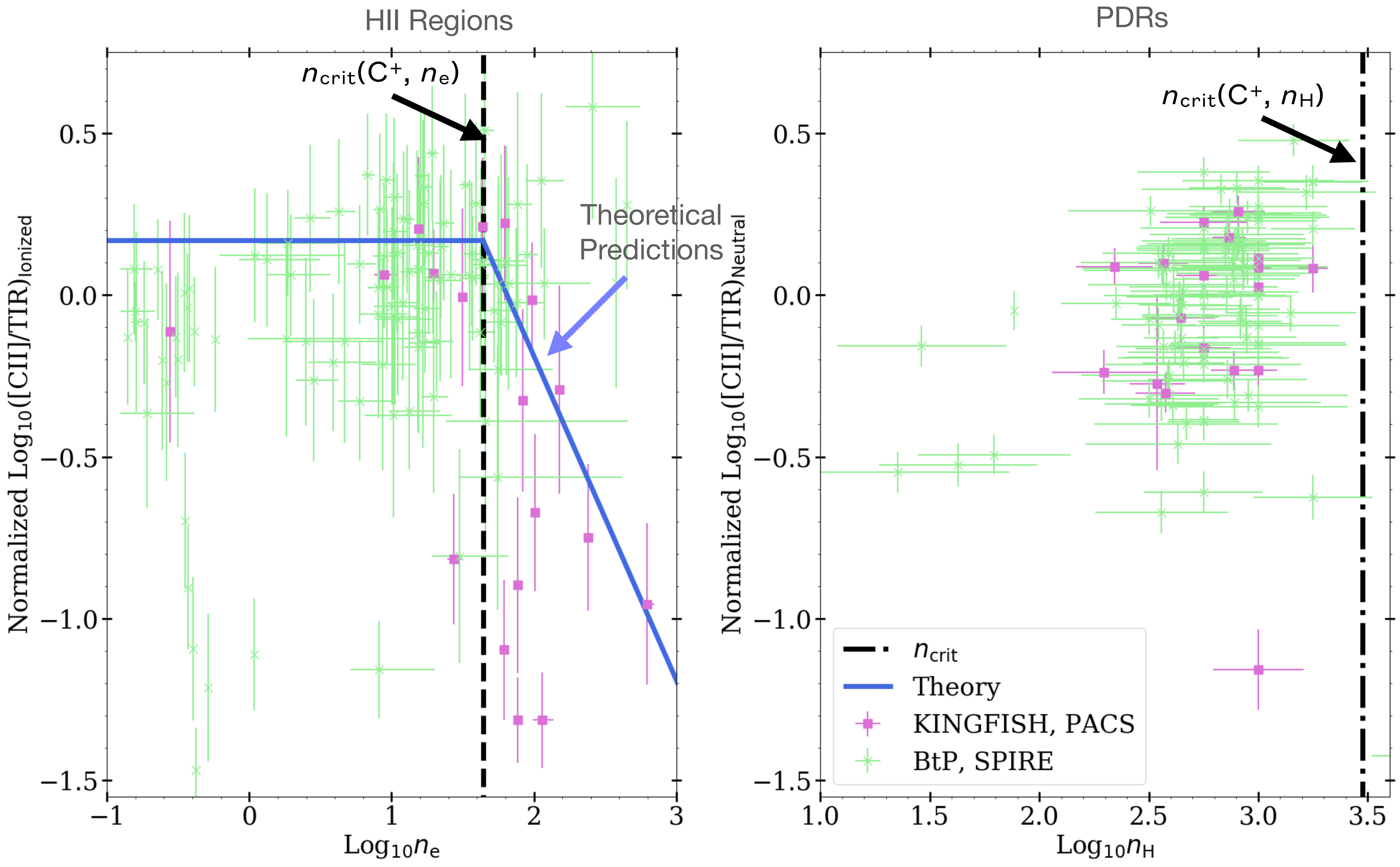
- Using CIGALE SED fitting, TIR can also be ISM phase-separated
- $f(L_{\text{dust}}; U > U_c) = \dfrac{\gamma ln(U_{\text{max}}/U_c)}{(1-\gamma)(1-U_{\text{min}}/U_{\text{max}}) + \gamma ln(U_{\text{min}}/U_{\text{max}})}$
- U_C set to Strömgren Radius U value



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

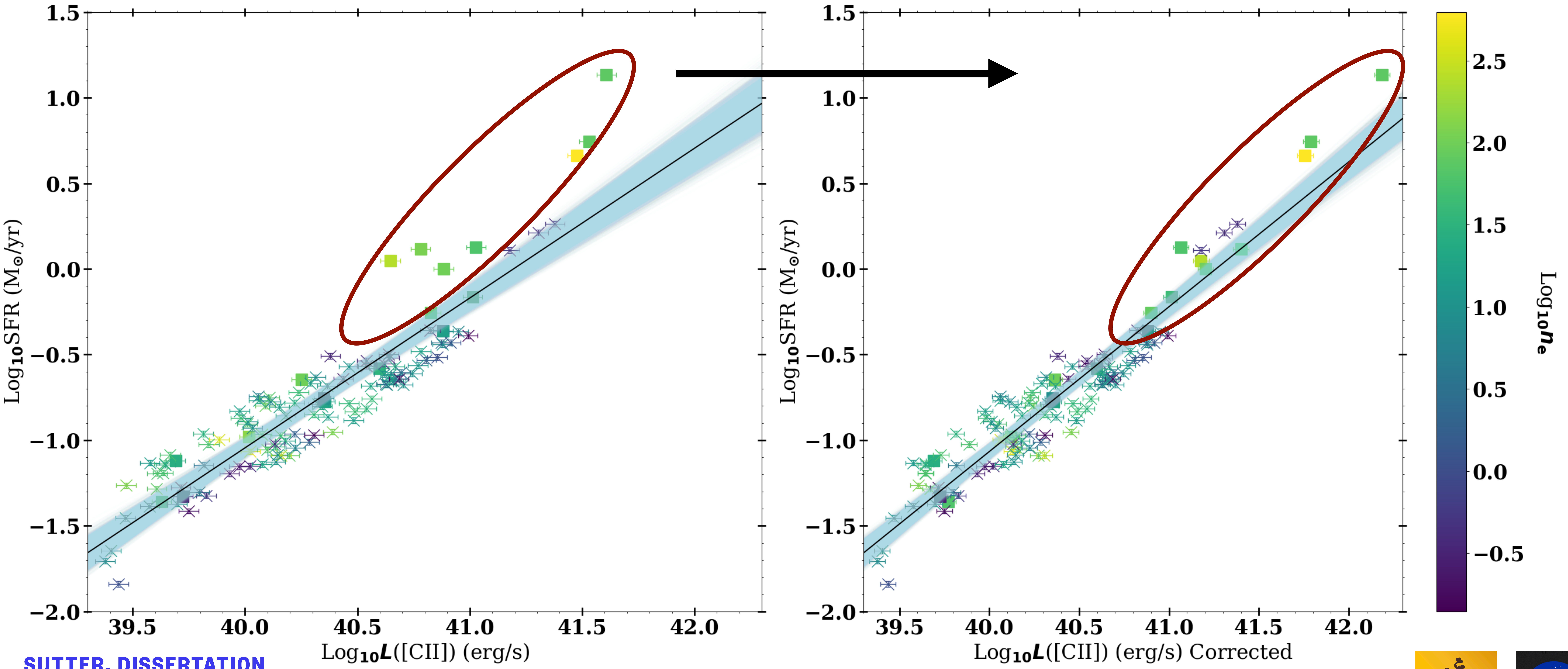
Thermalization in Ionized ISM

- 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



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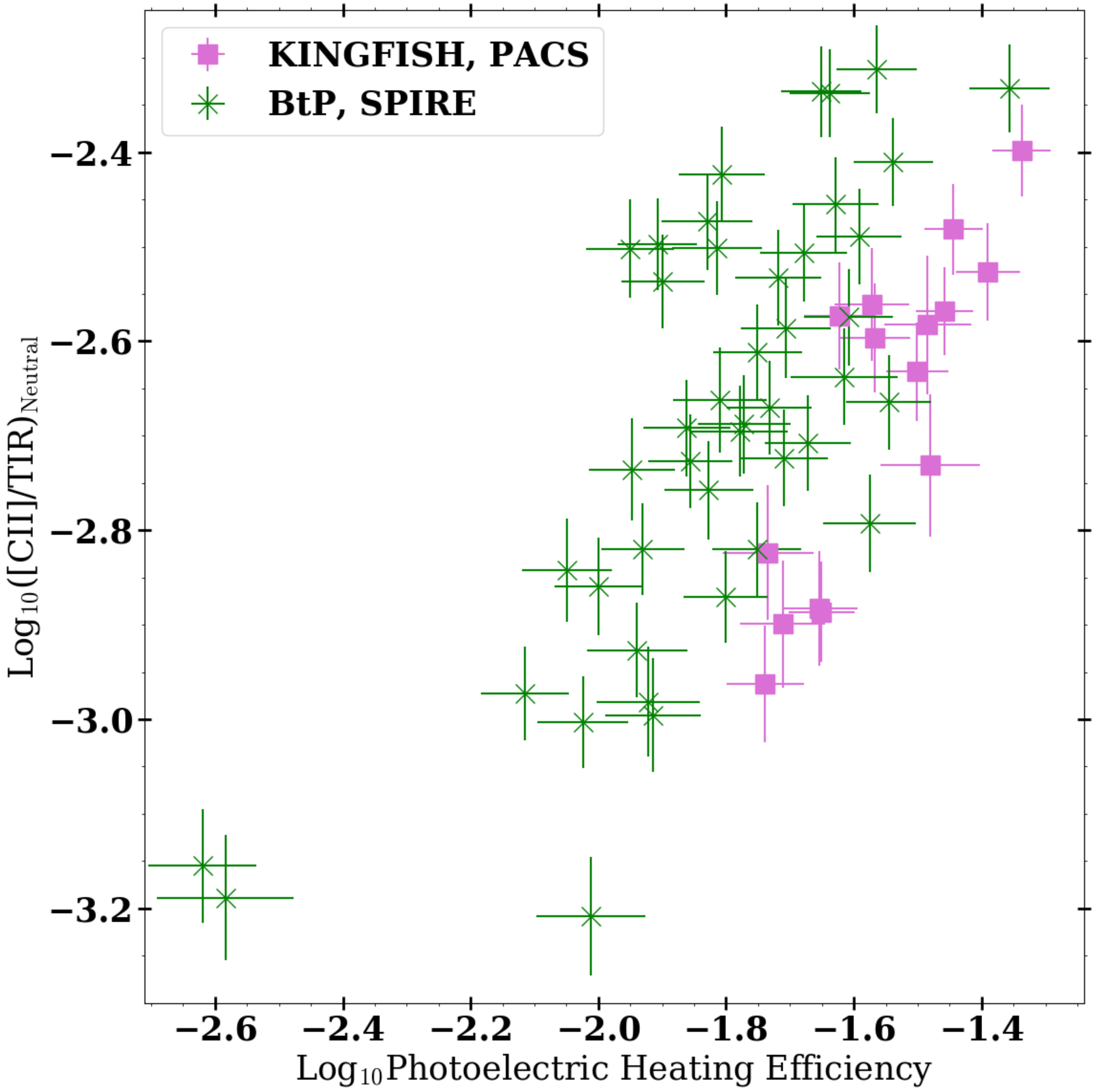
L([CII]) as a SFR indicator, before and after corrections for thermalization. Sutter+2021, in prep.

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 and Future Work

LMC, Image Credit Carlos Fairbairn

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
- Further studies of the [CII] emission from the LMC and SMC are planned as part of the COLD-Z project

Thanks to:

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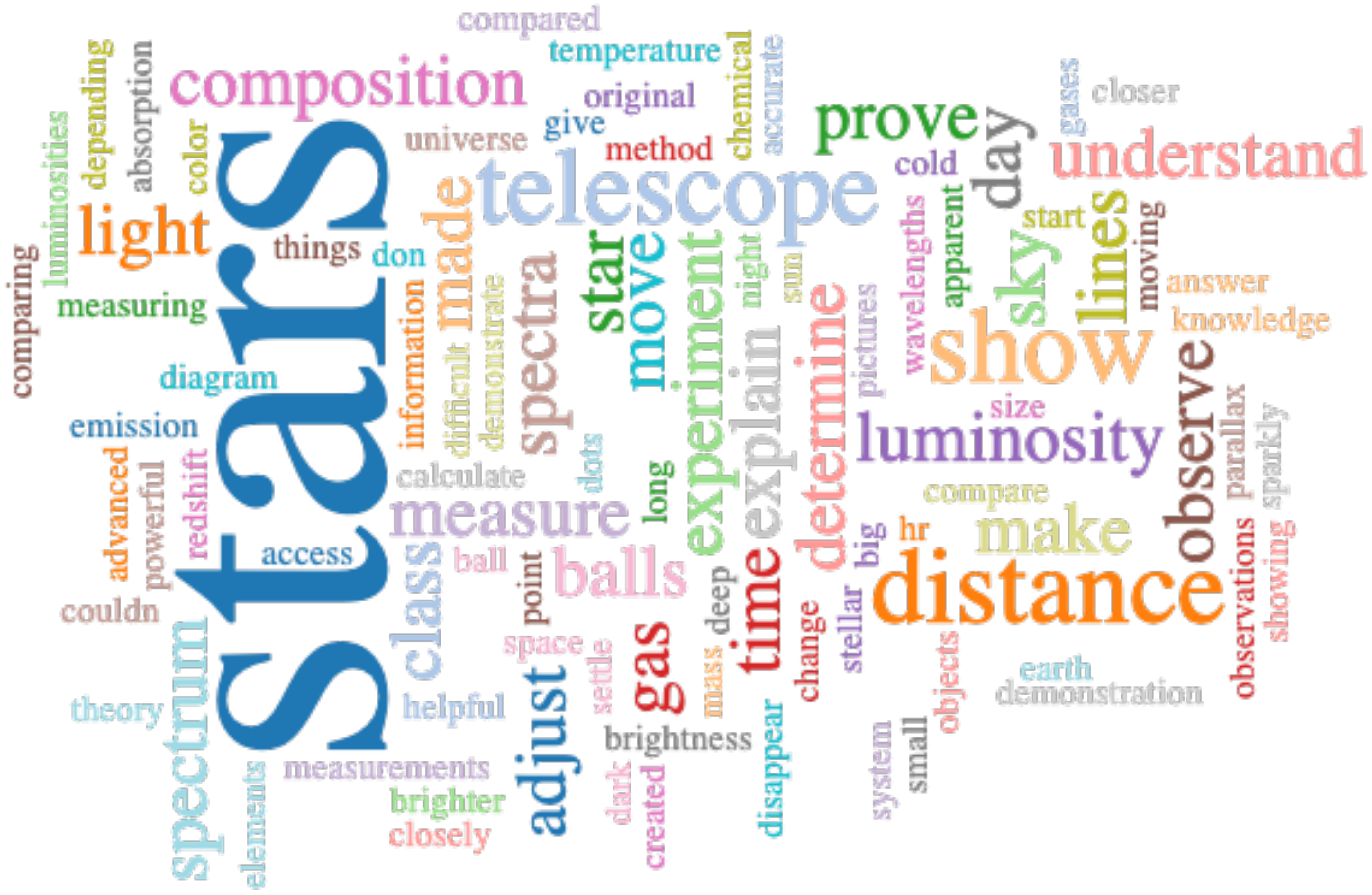
The *Herschel* Space Observatory

and the wonderful KINGFISH and WEGOAT Teams!

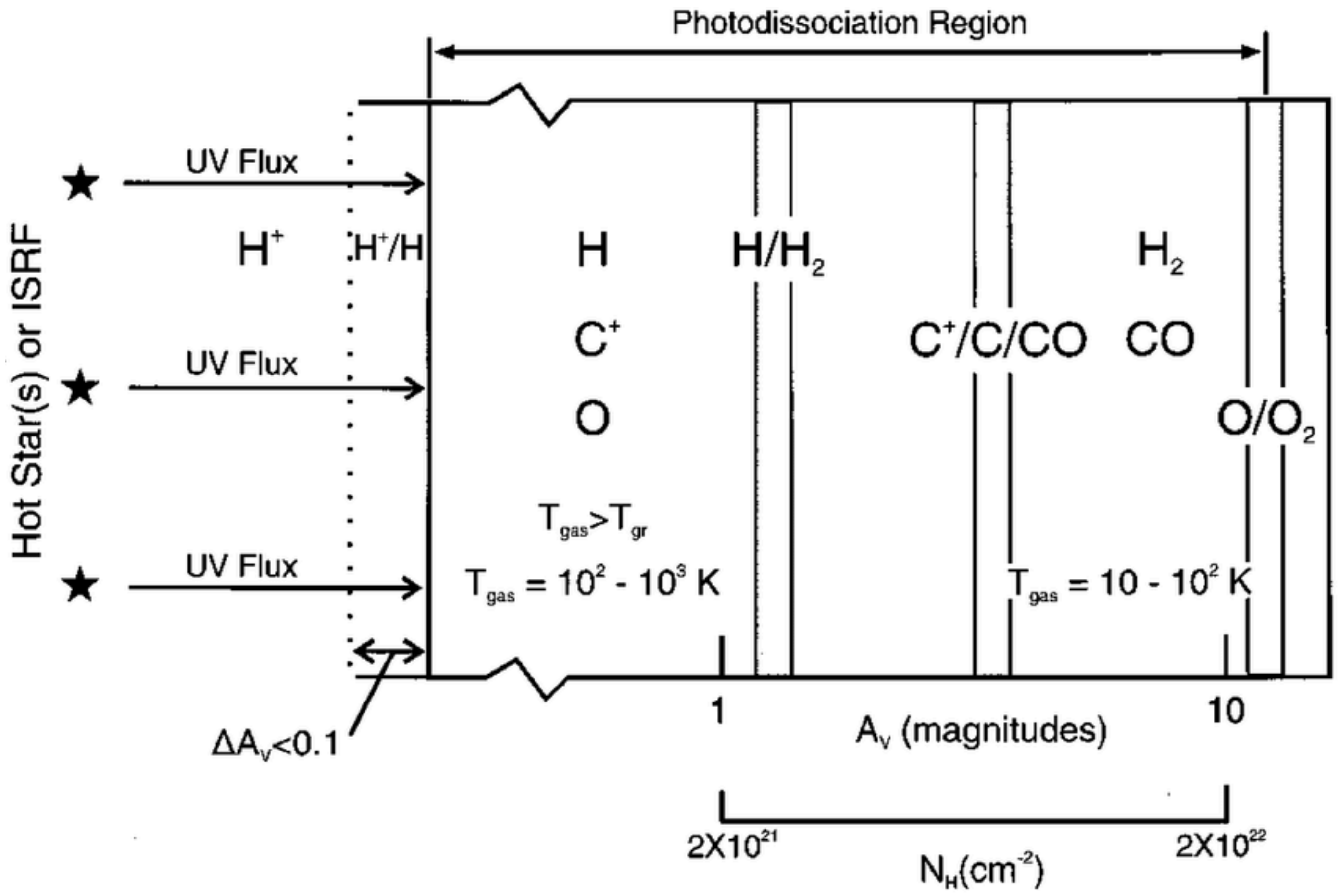
W yoming
E xtra
G alactic
O bservational
A stronomers
T eam

Pre Test

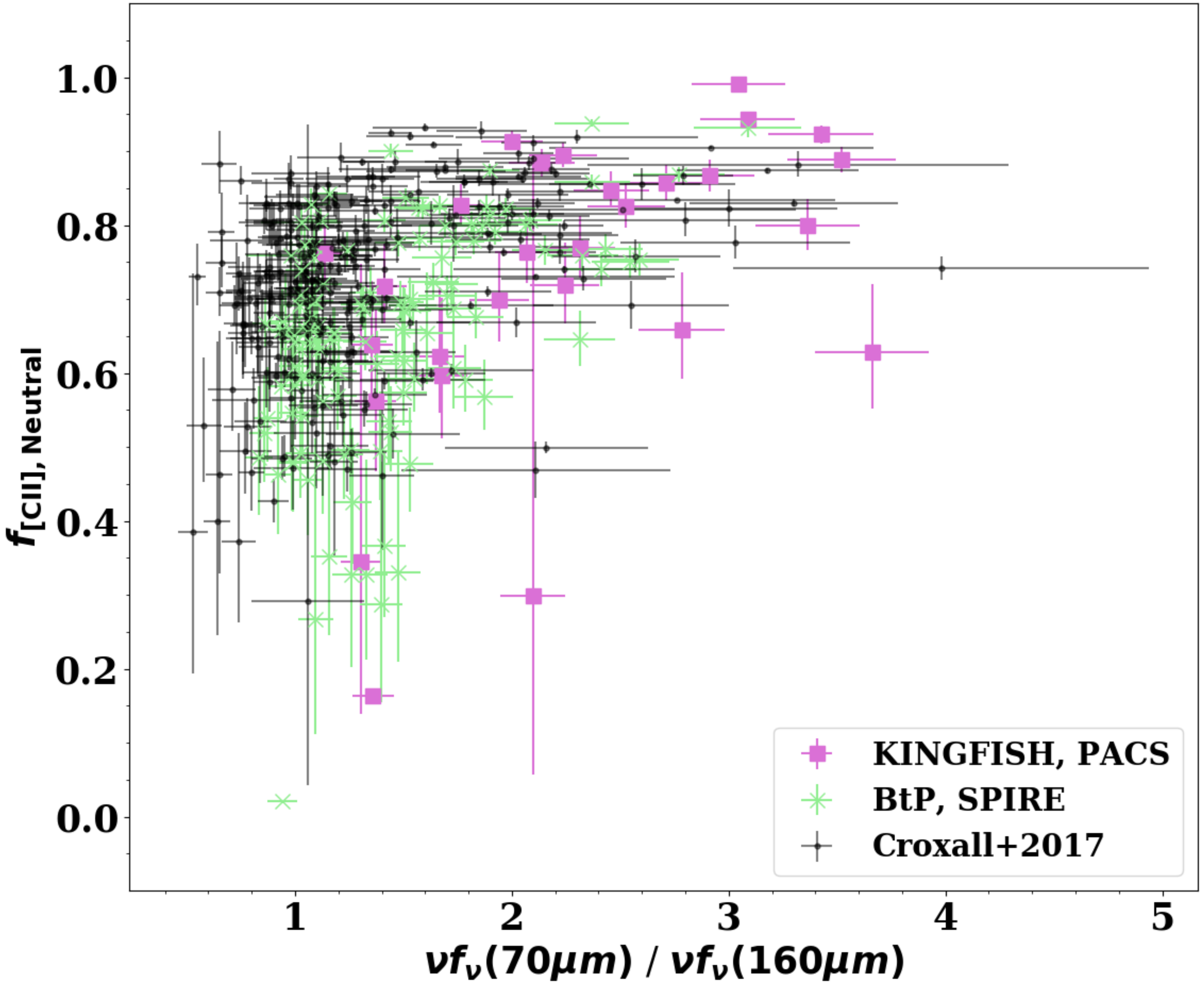


Post Test

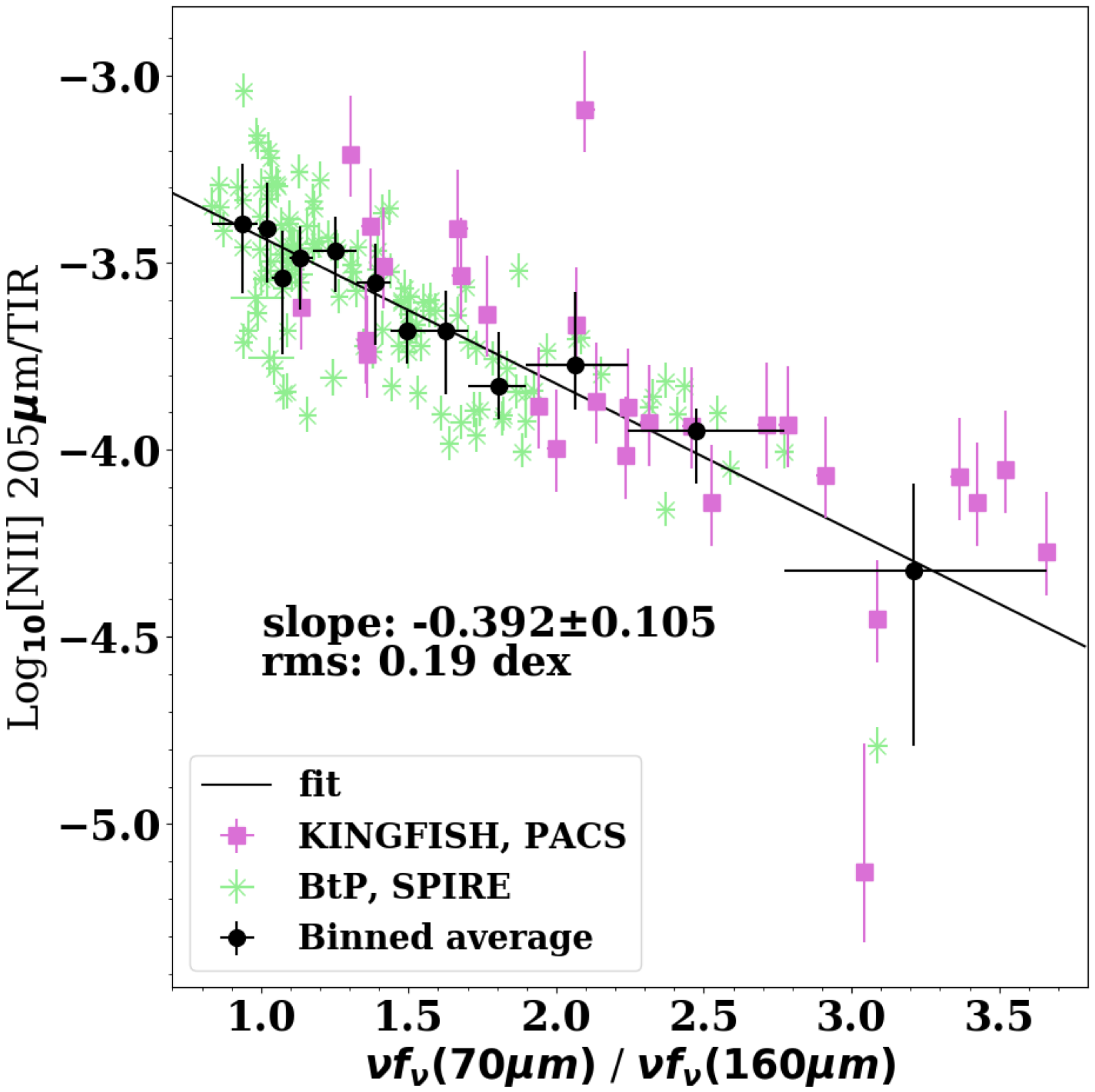
Additional Slides



PDR Slab Diagram. Image Credit Tielens 2015



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


slope: -0.392±0.105
rms: 0.19 dex
fit
KINGFISH, PACS
BtP, SPIRE
Binned average
$\mathrm{Log_{10}}$[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

- Theoretical Predictions of Thermalization

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

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

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

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

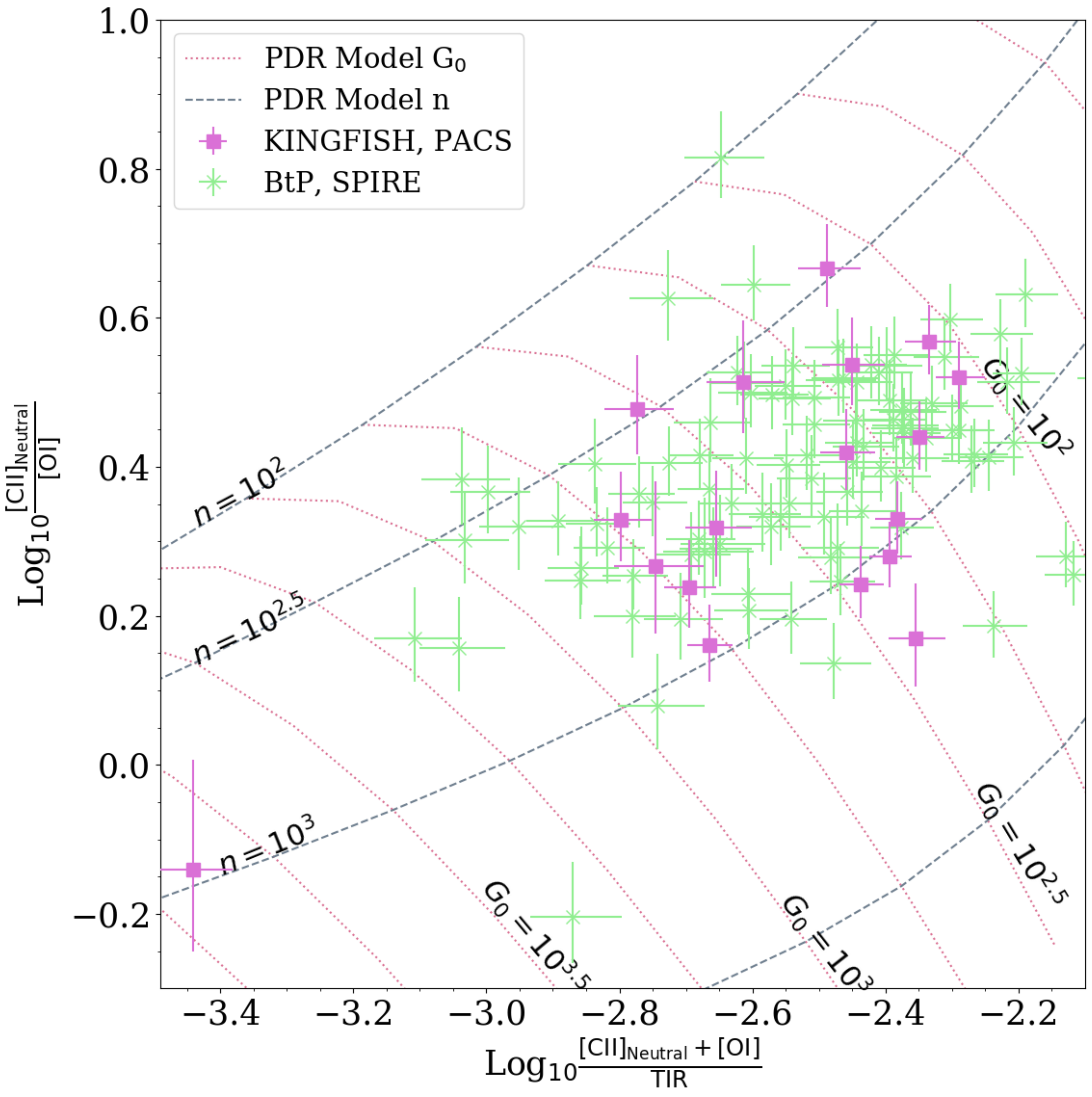
$$\frac{[\text{CII}]}{\text{TIR}} = \frac{n_{[\text{CII}]} \gamma_{[CII]} E_{158}}{n_e \alpha E_{UV} f_{IR}}.$$

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

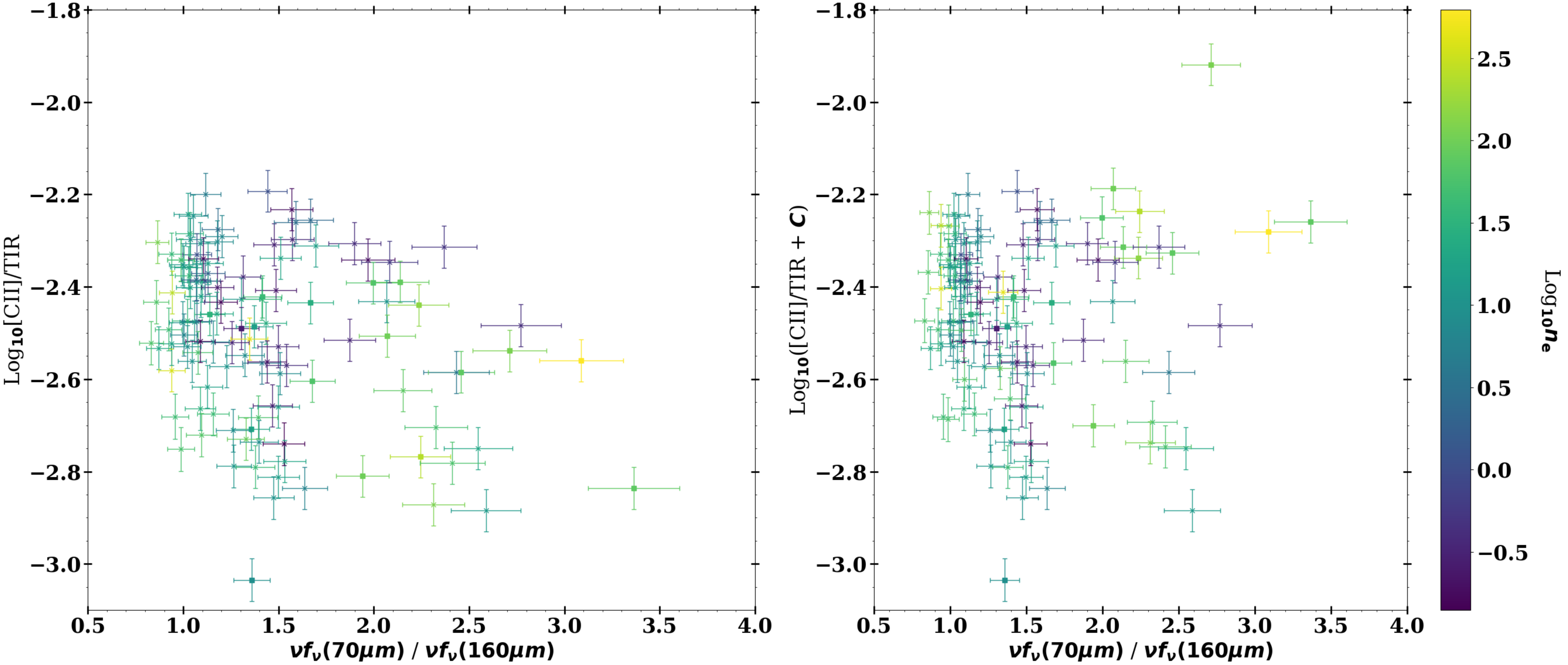
$$\frac{[\text{CII}]}{\text{TIR}} = 0.13$$

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


Norm. Factor = 2.48
Norm. Factor = 1.17
Norm. Factor = 2.66
Normalized Log10([CII]/TIR)Total
Normalized Log10([CII]/TIR)Ionized
Normalized Log10([CII]/TIR)Neutral
νfν(70μm) / νfν(160μm)
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



C = 0.13(1-n/ncrit)f_HII

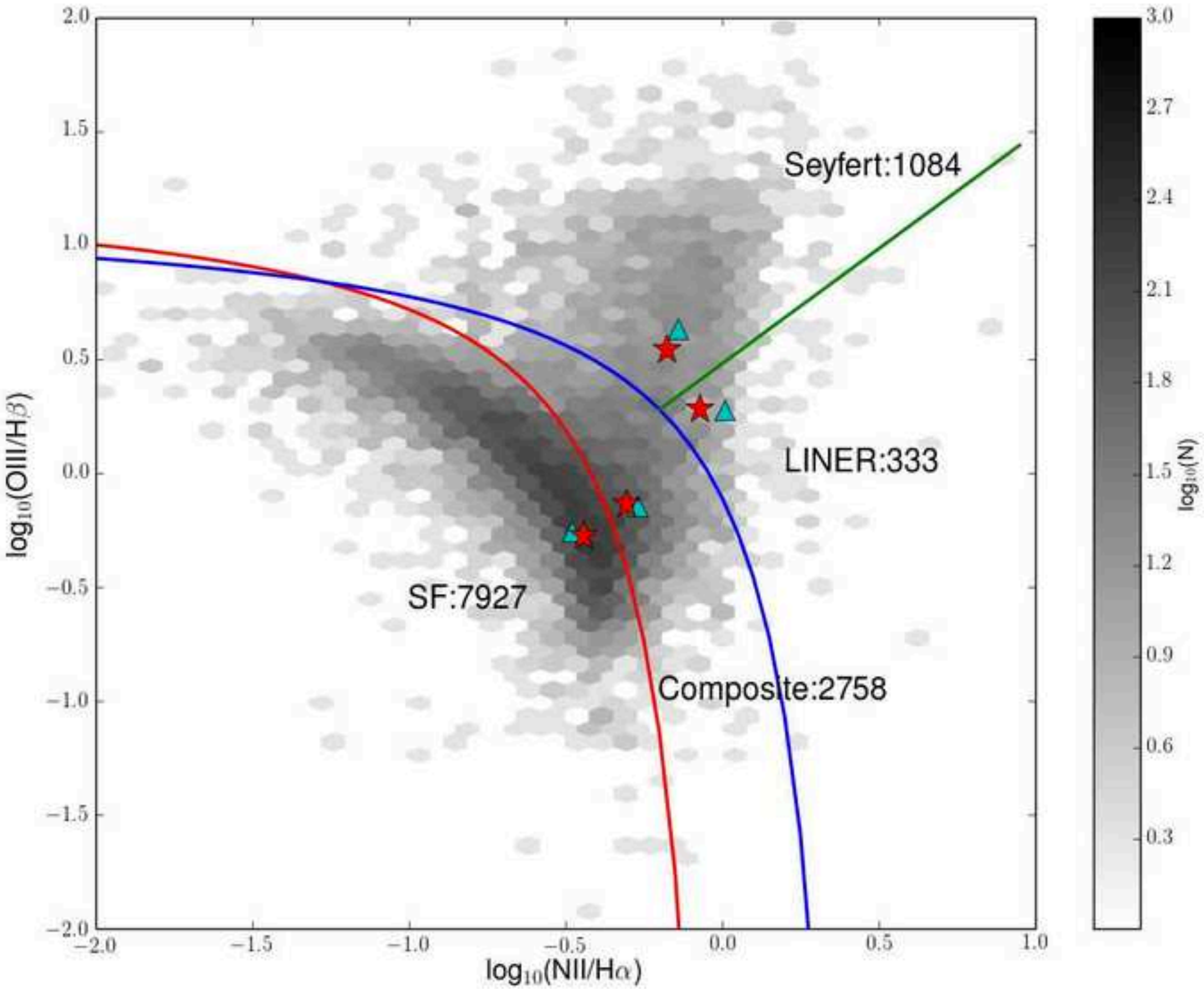


Image Credit Wang et al, 2017

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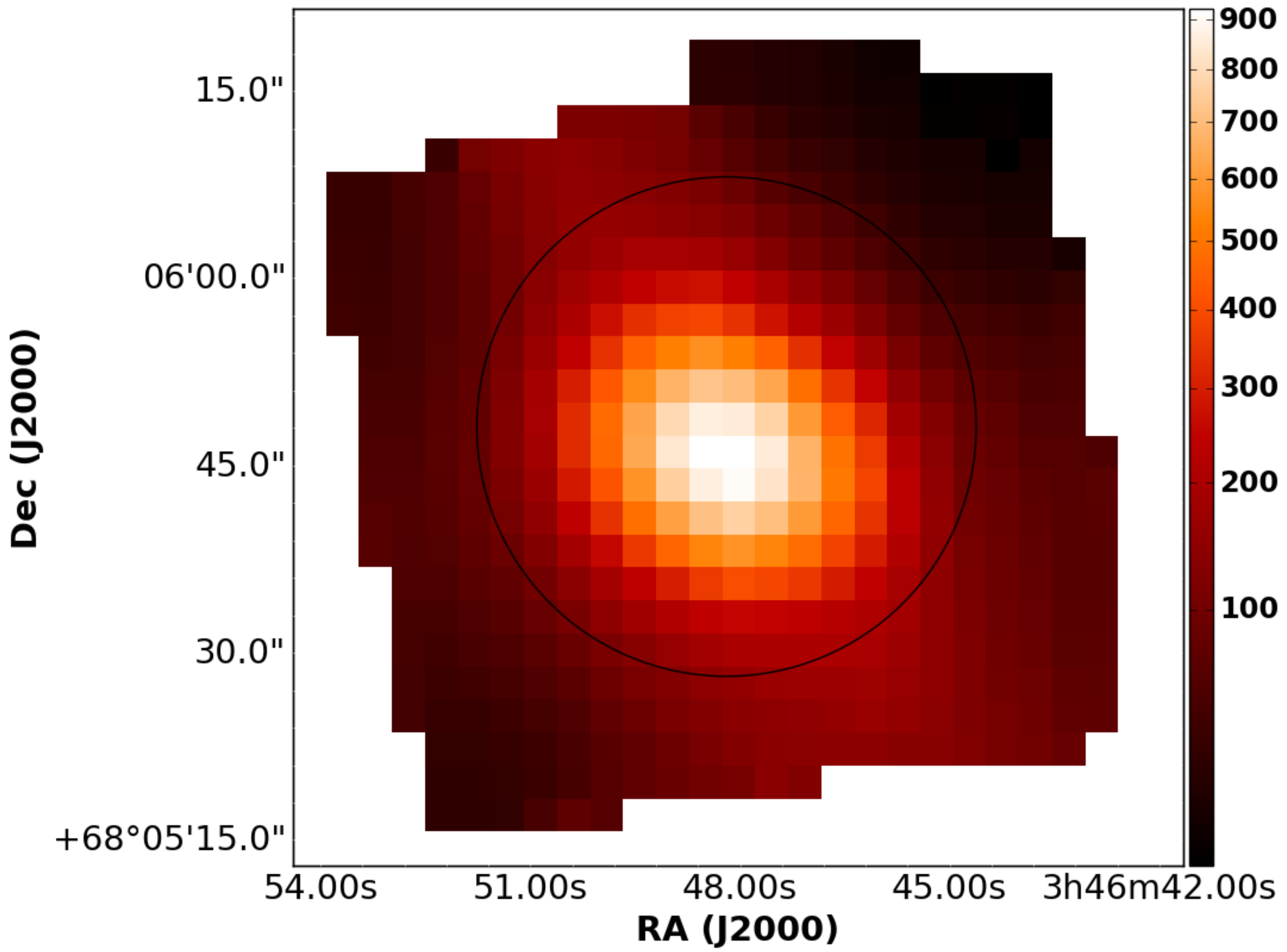
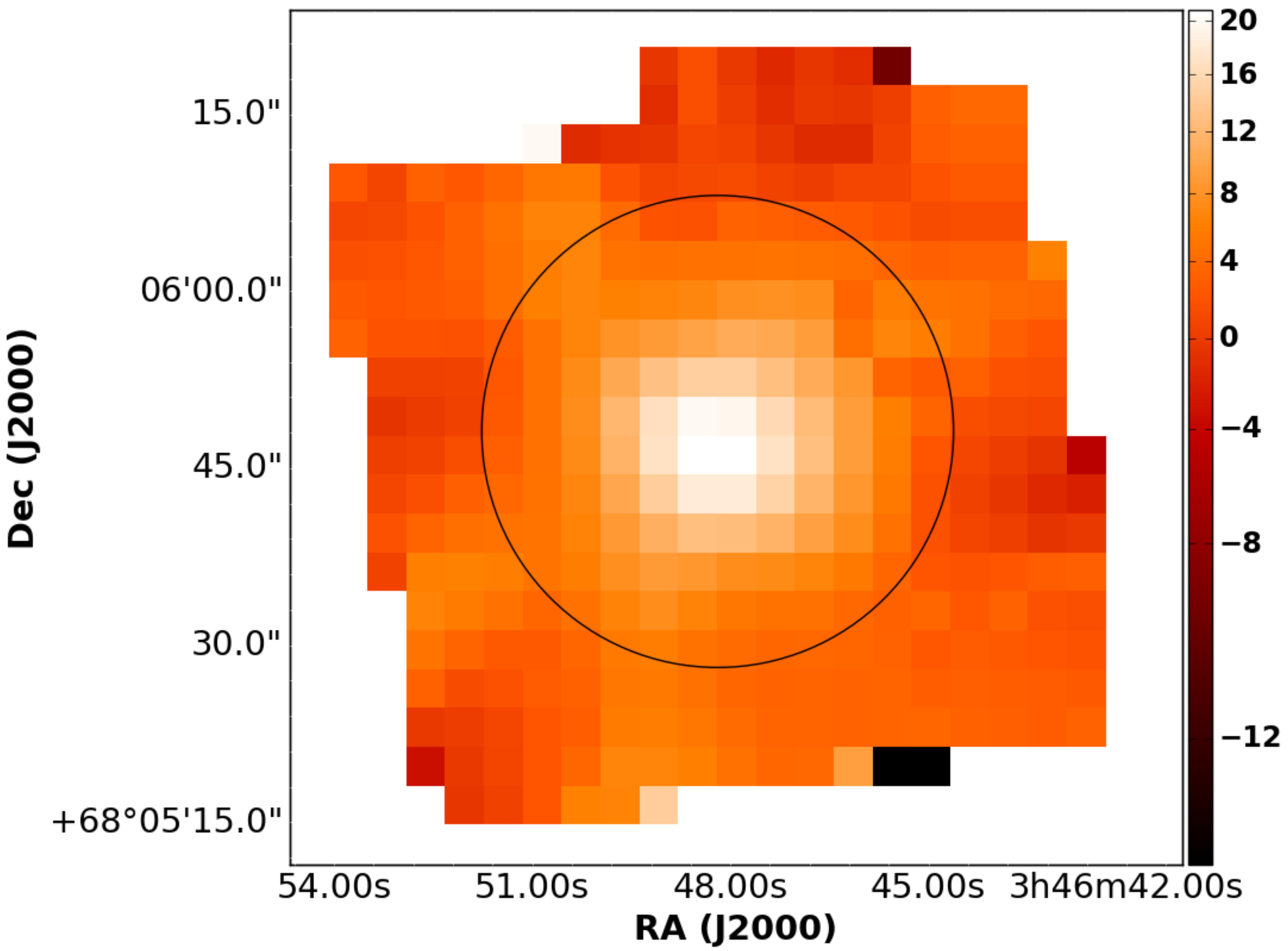
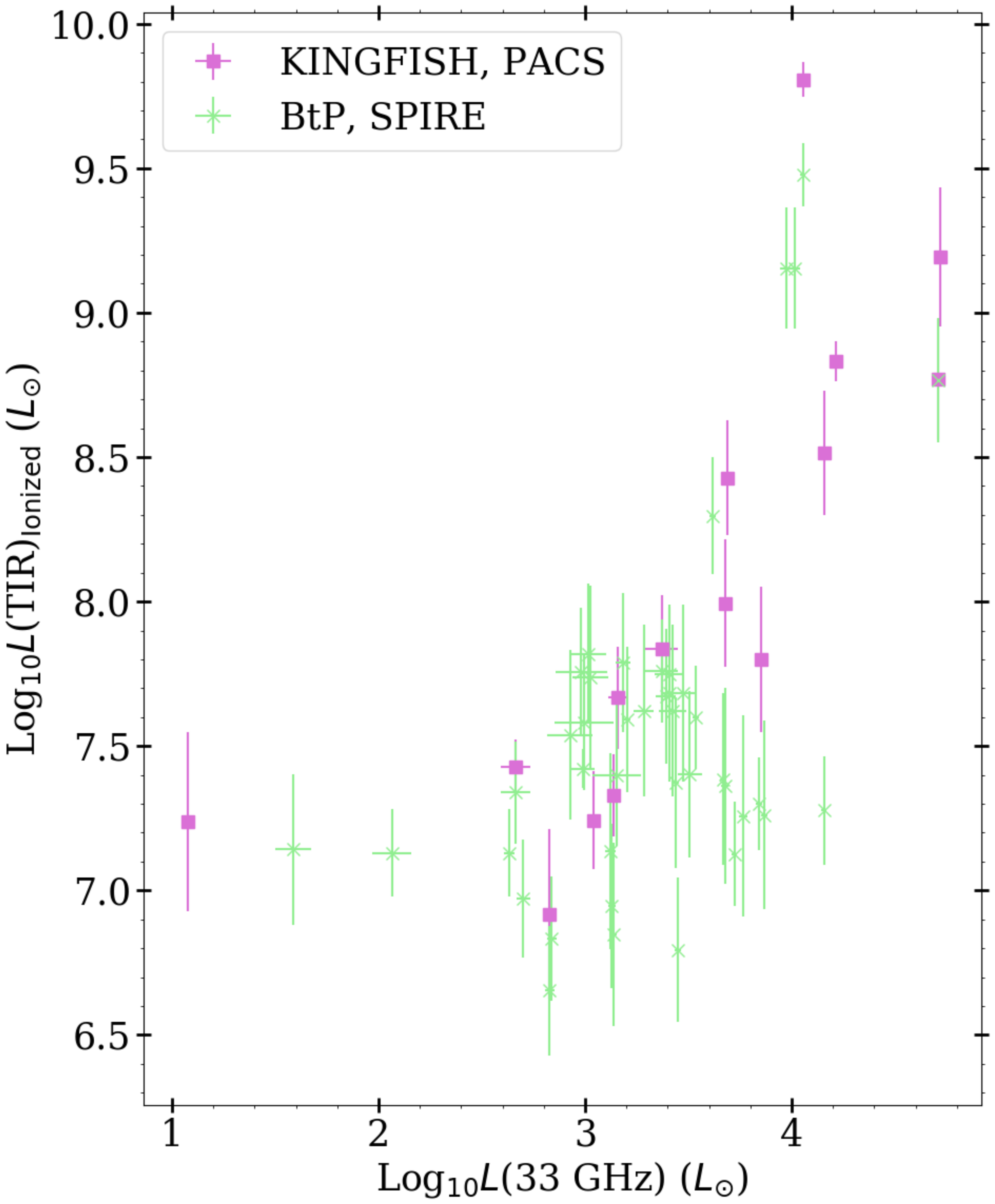


[CII] 158 μm Emission



[NII] 205 μm Emission



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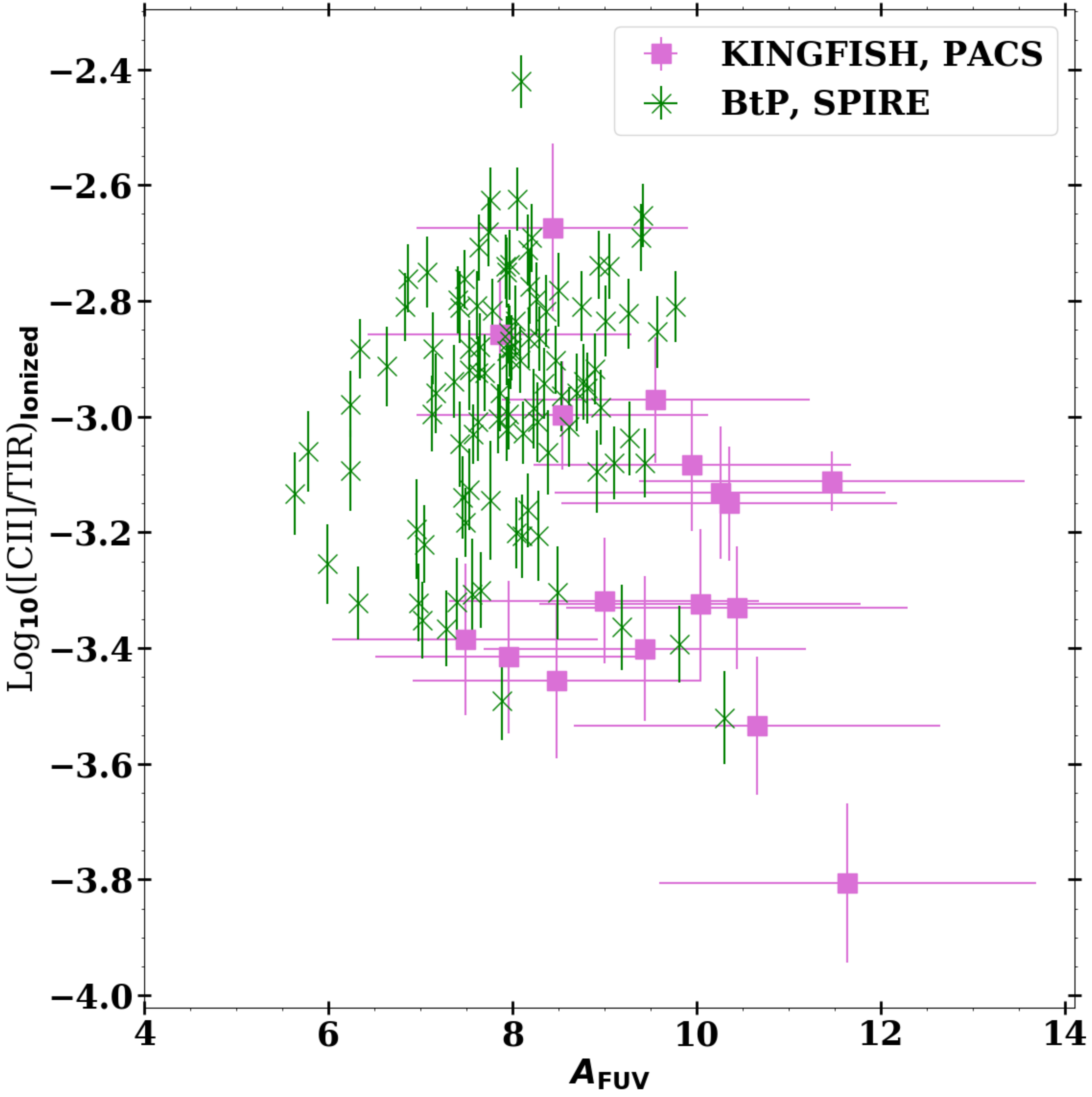

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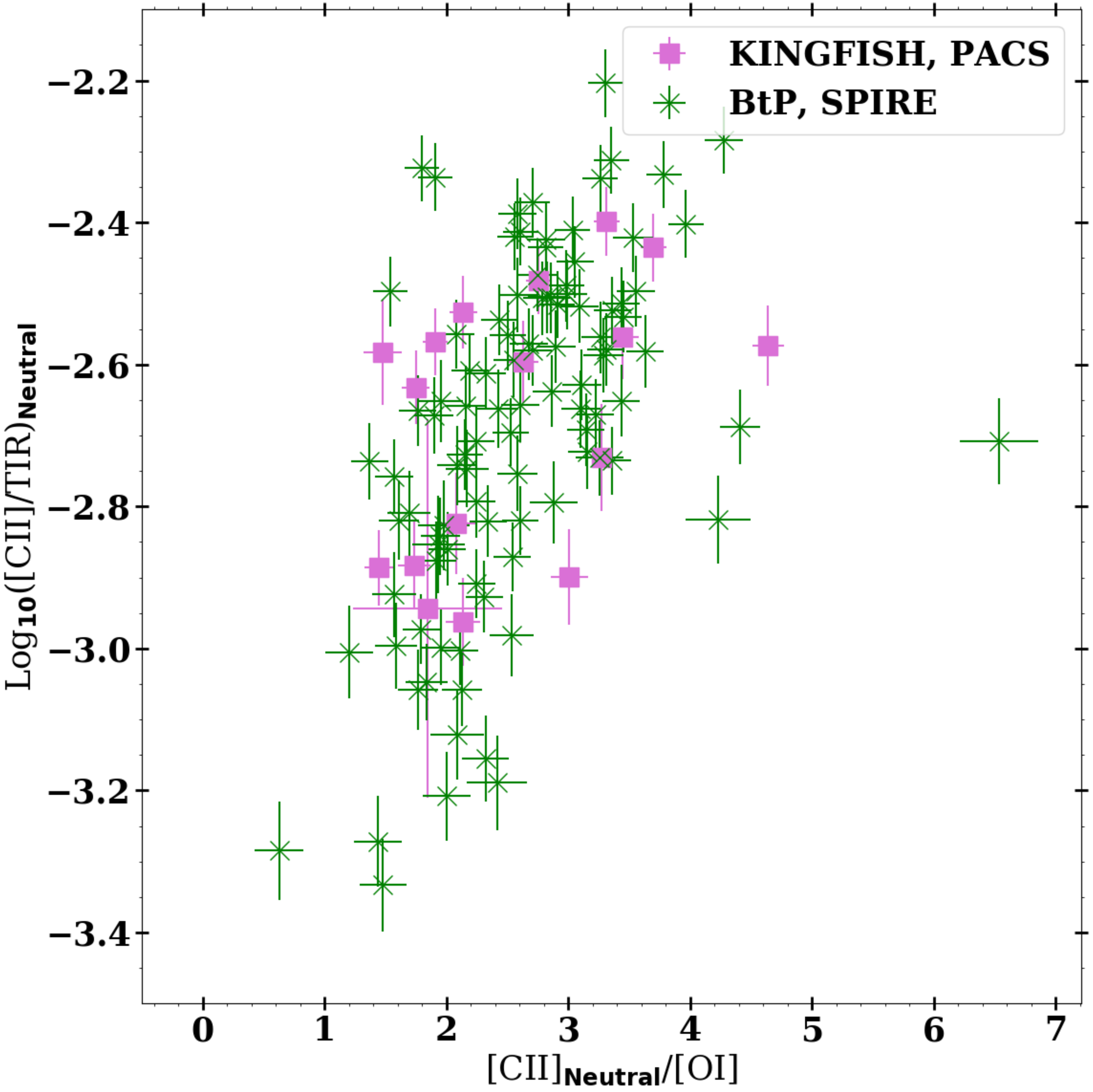

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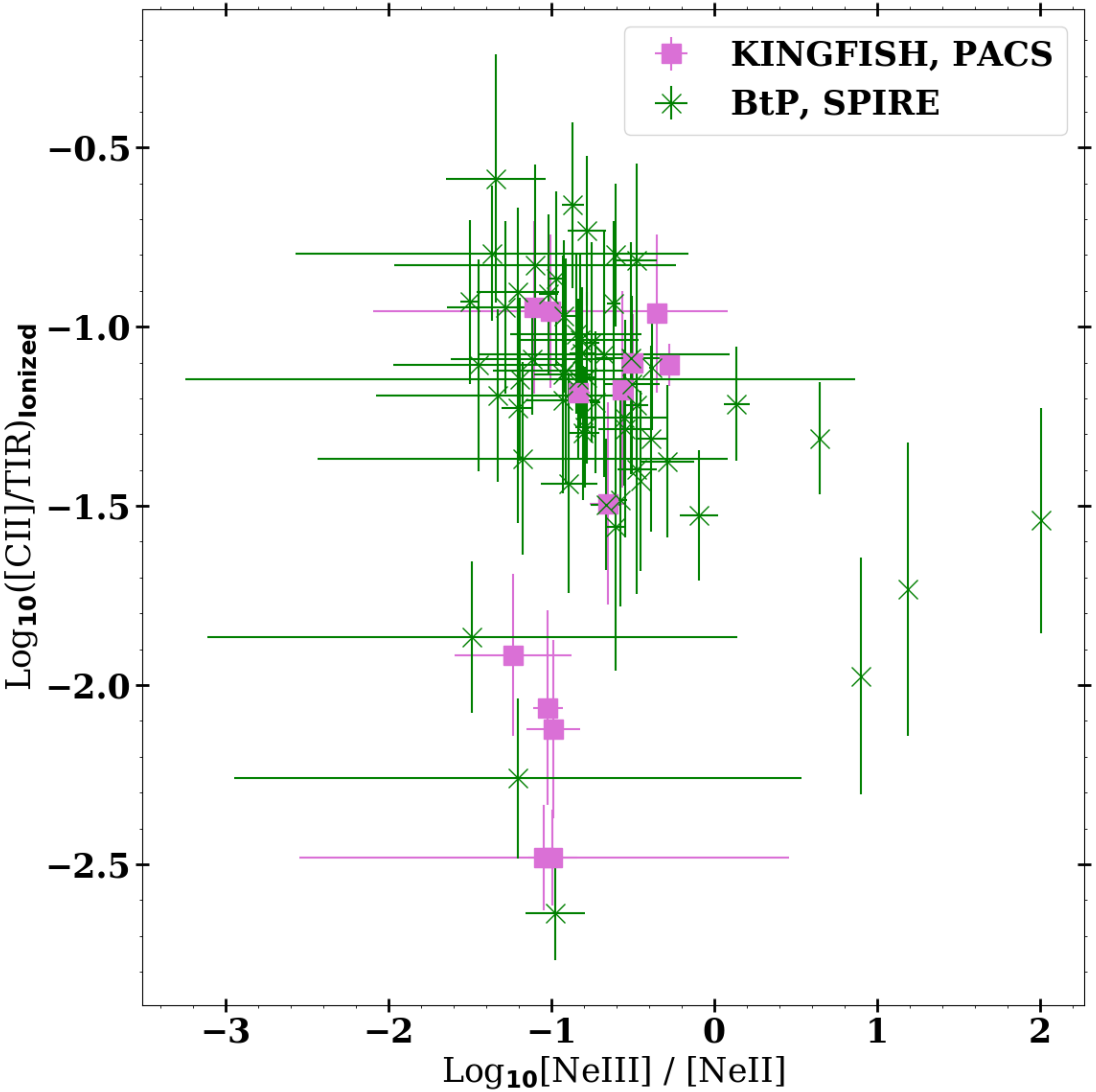

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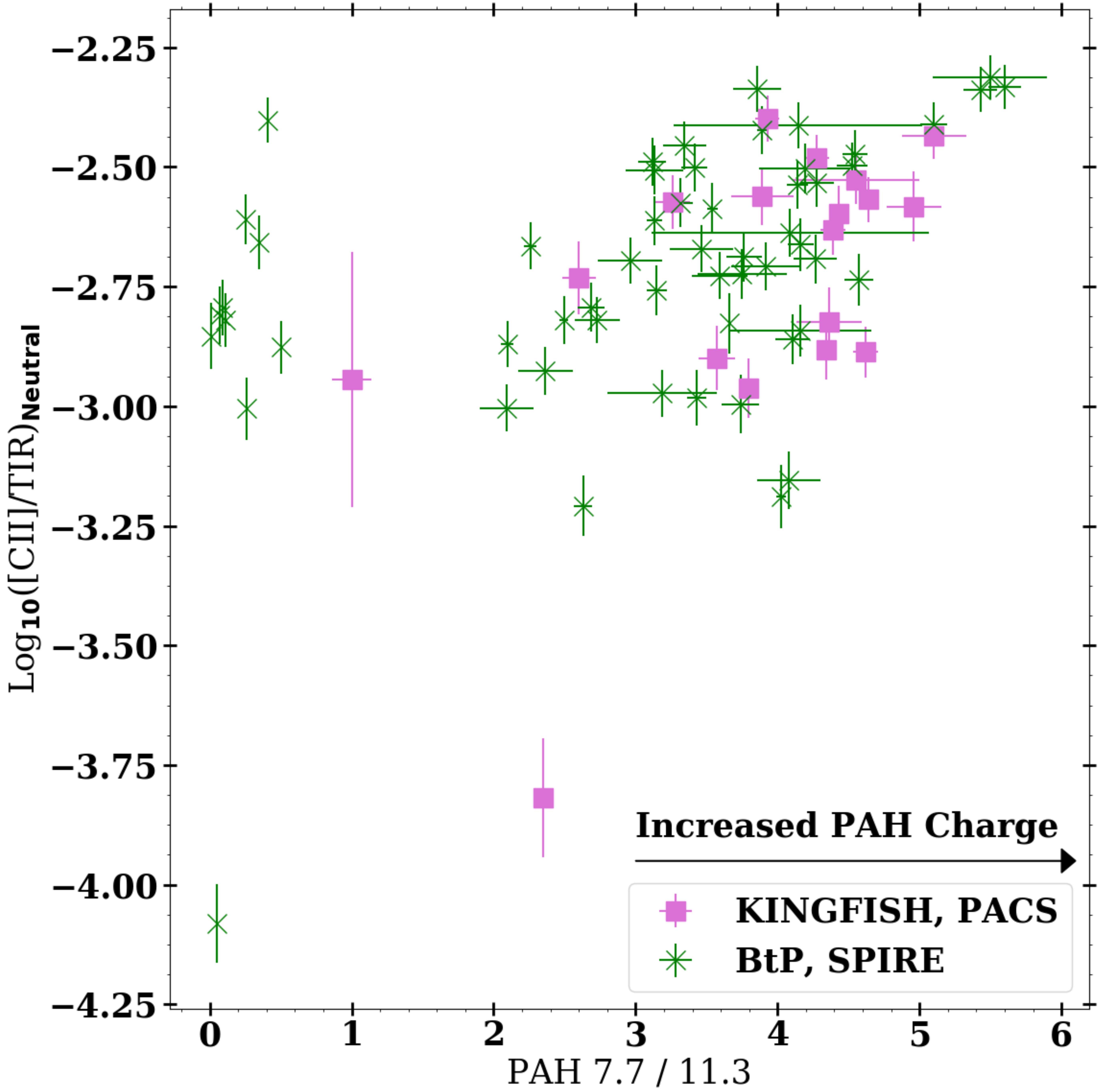

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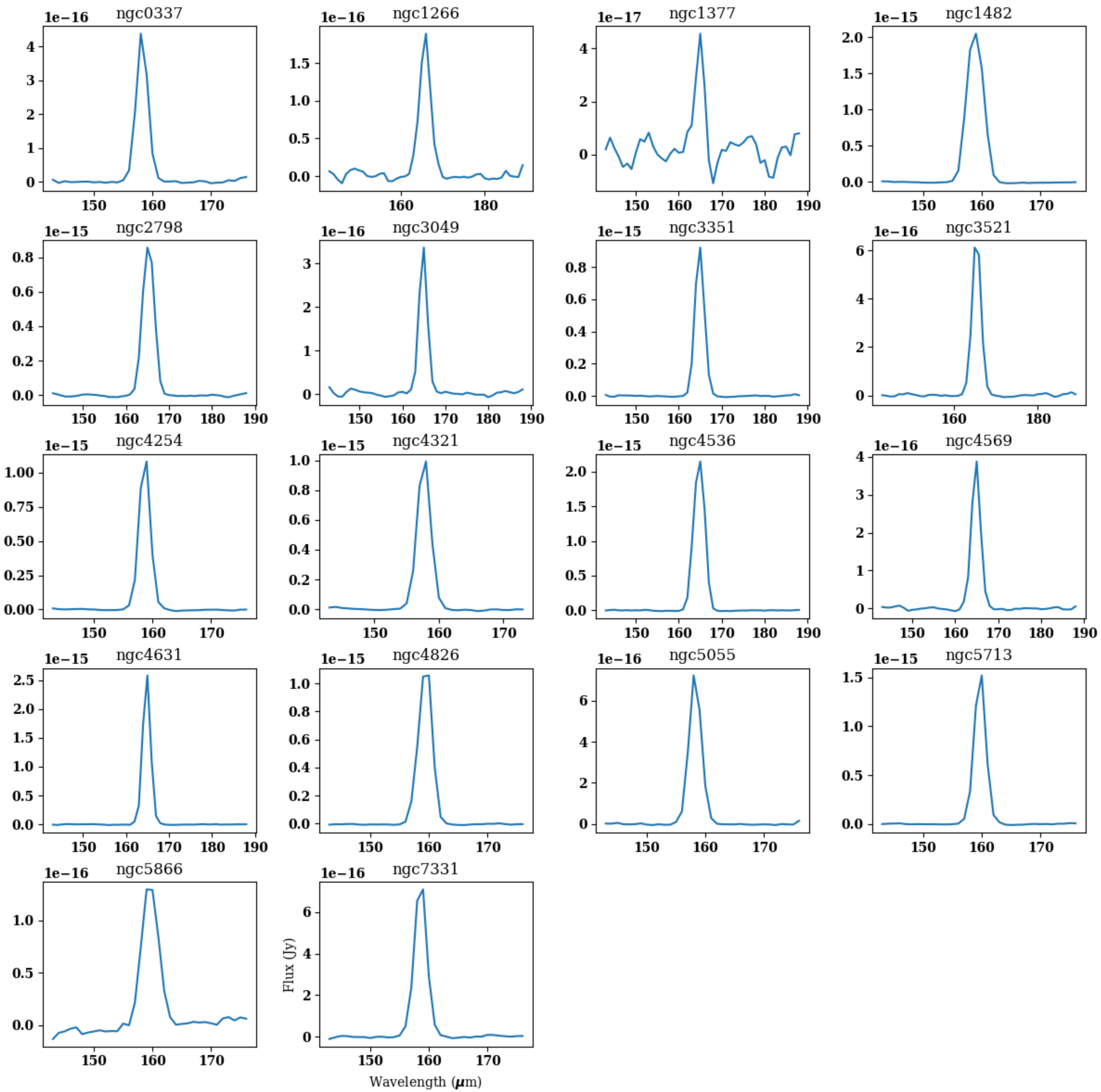

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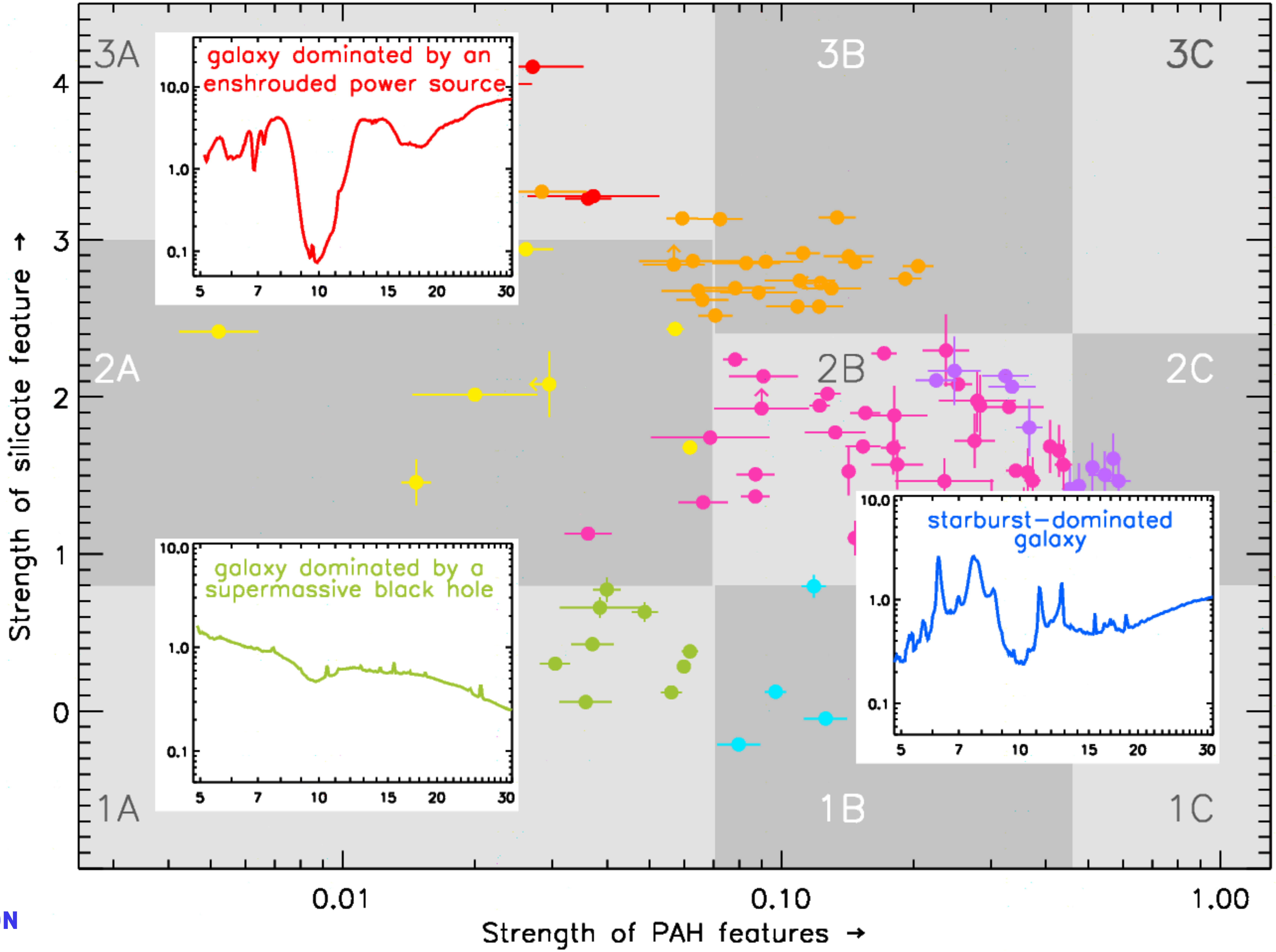

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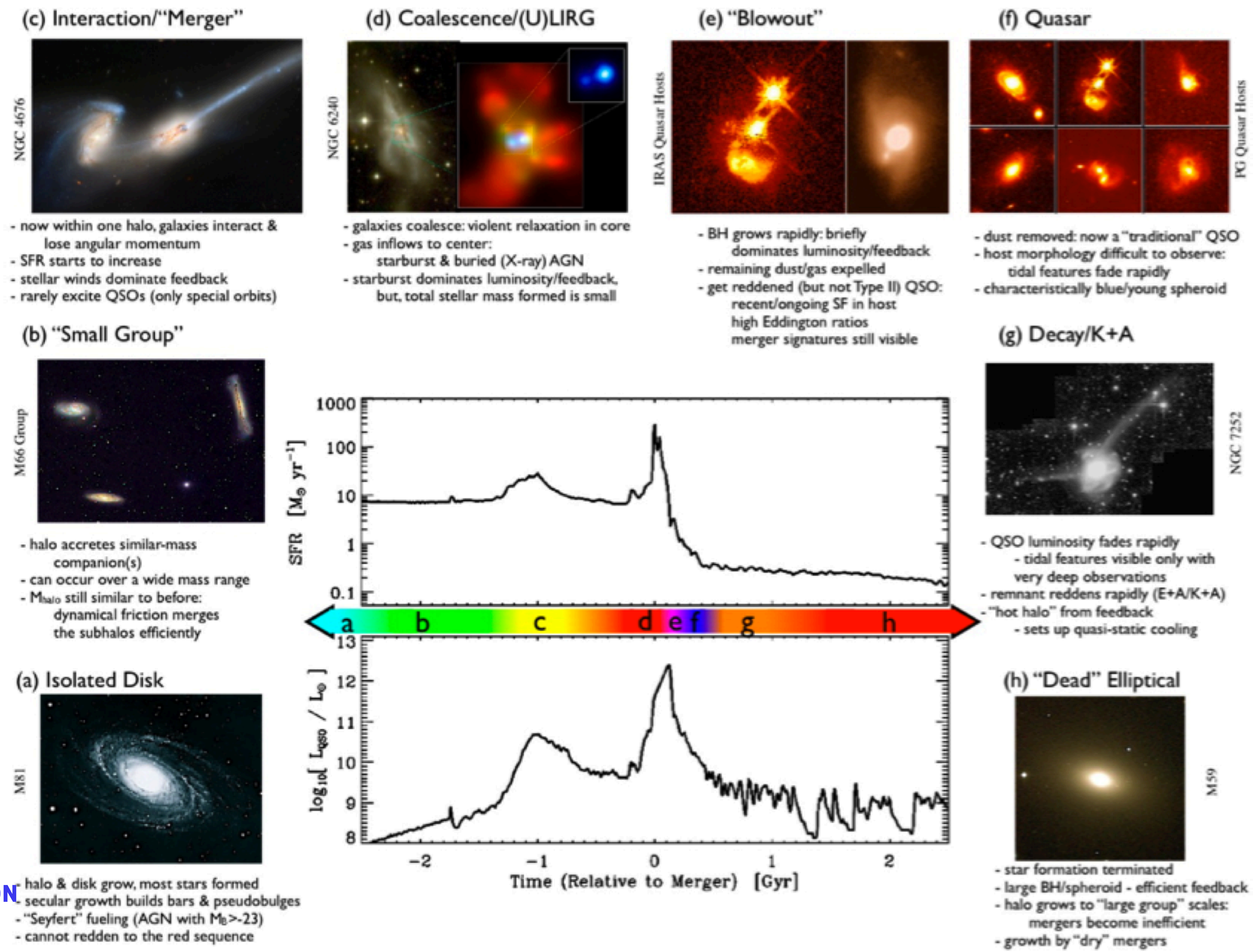

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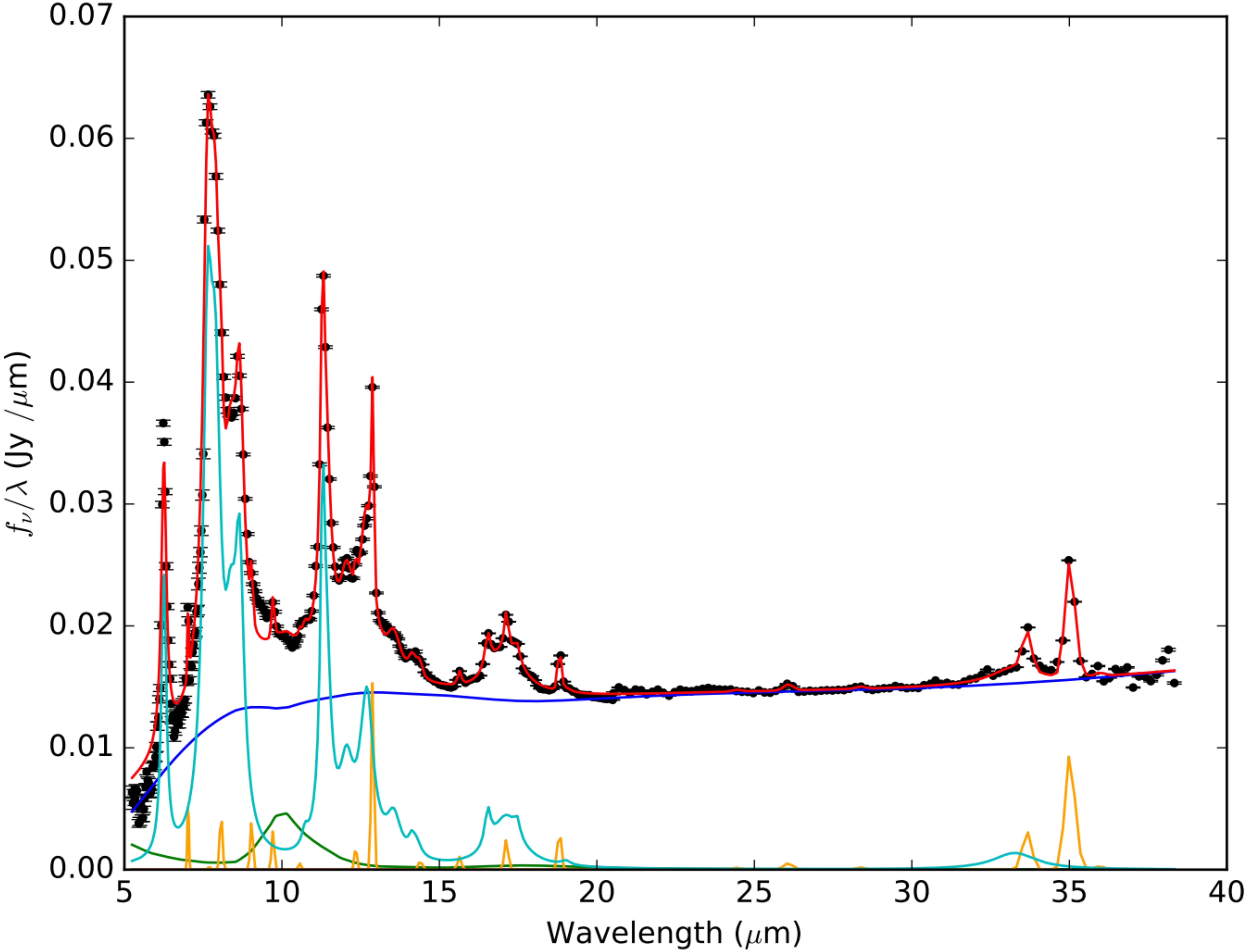
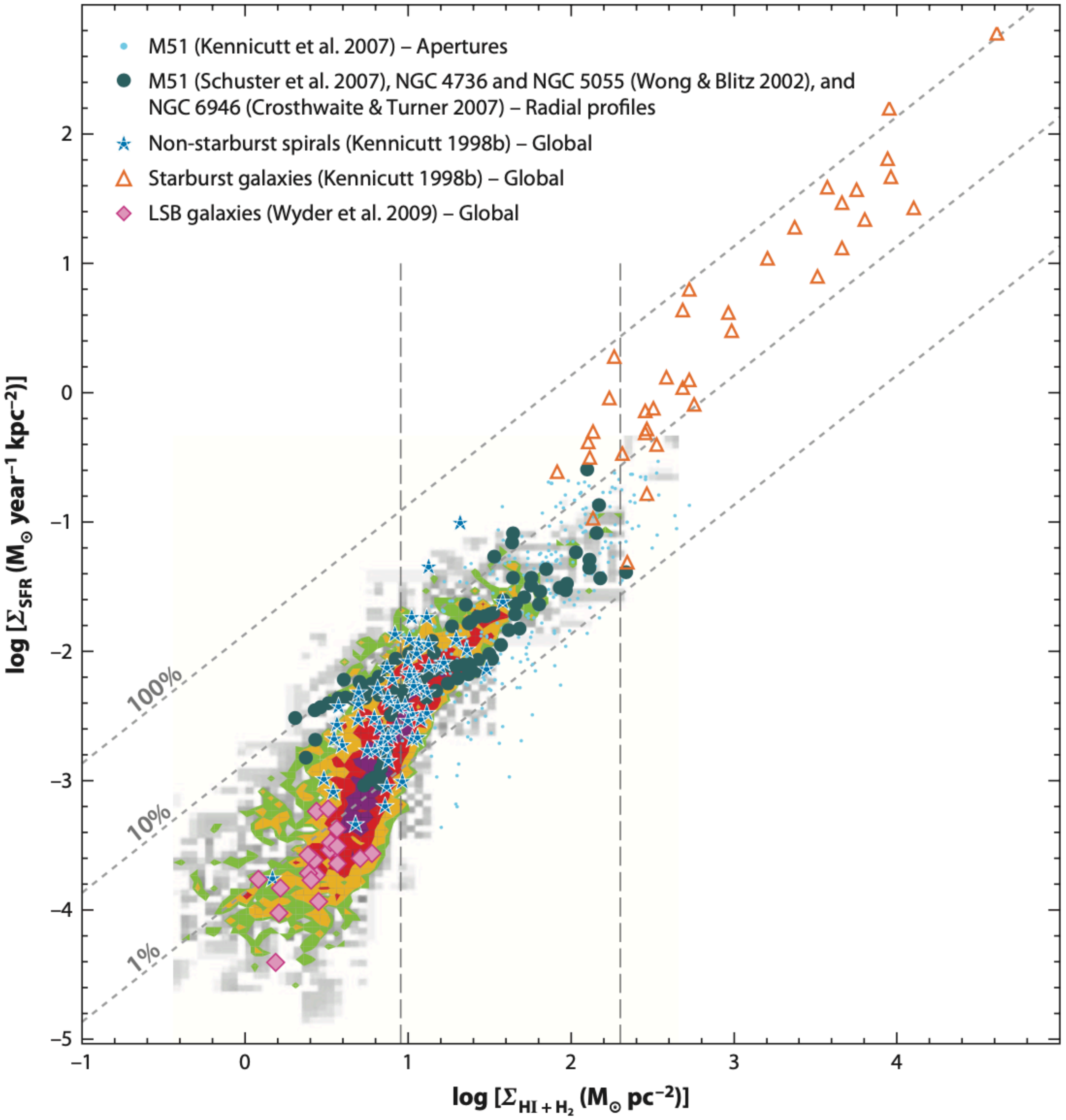
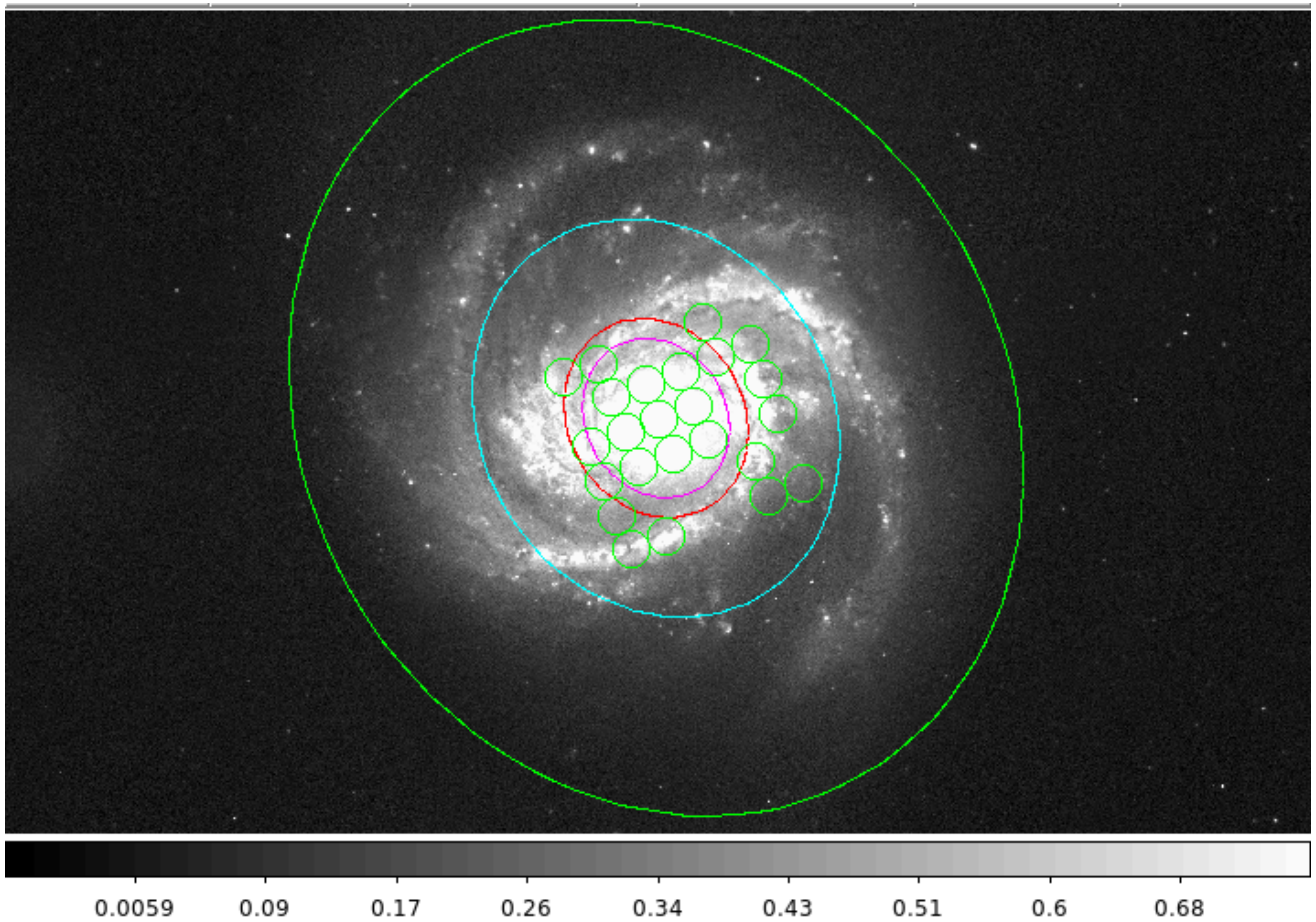


SUTTER, DISSERTATION

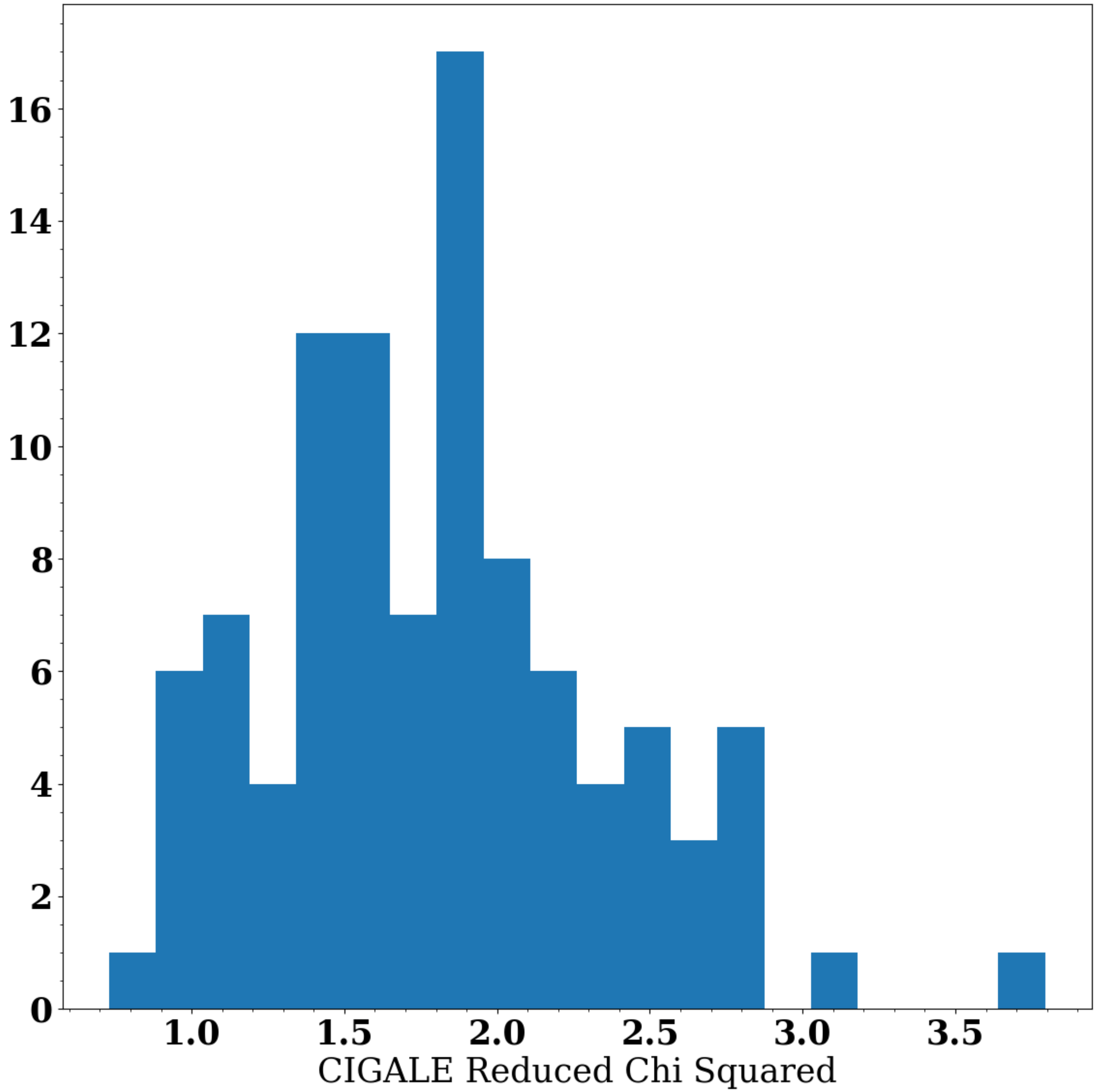


SUTTER, DISSERTATION

−1.5
−2.0
−2.5
−3.0
−3.5
1
2
3
$Log_{10}\frac{[CII]_{I+N}}{PAH}$
$Log_{10}\frac{[CII]_{Ionized}}{PAH}$
$Log_{10}\frac{[CII]_{Neutral}}{PAH}$
$\nu f_\nu(70\mu m)$ / $\nu f_\nu(160\mu m)$
KINGFISH, Inner
KINGFISH, Outer
BtP
BtP, Inner
BtP, Outer



SUTTER, DISSERTATION


16
14
12
10
8
6
4
2
0
1.0
1.5
2.0
2.5
3.0
3.5
CIGALE Reduced Chi Squared