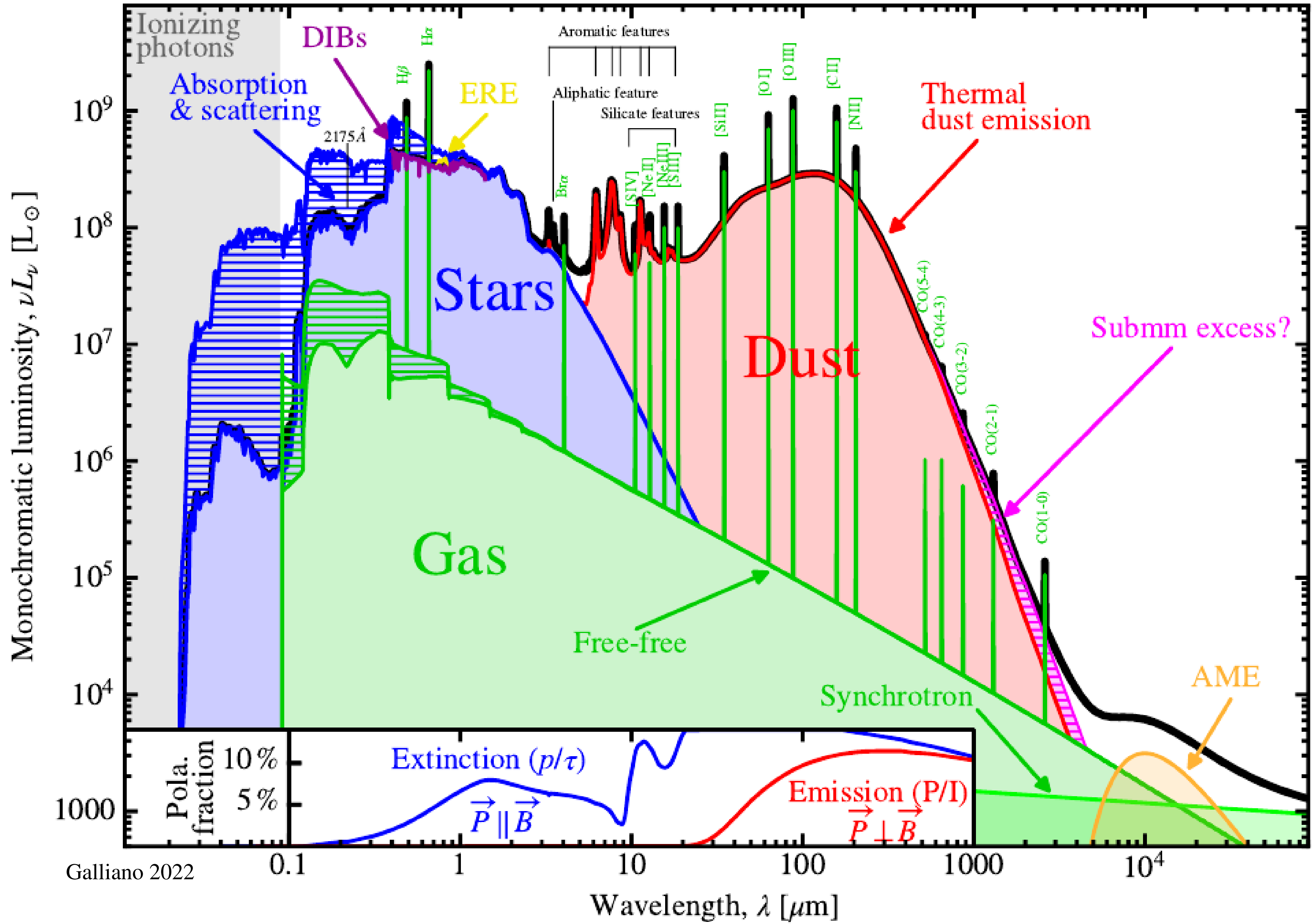
The far-infrared has its share of prominent emission lines

What type of environment is responsible for these relatively low-energy transitions?



Galliano 2022

Photo-Dissociation Regions

See image examples of PDRs at the course website

HII regions: prominent optical/infrared/radio emitters
PDRs: prominent infrared emitters (most FUV is absorbed by dust, both large grains and PAHs)

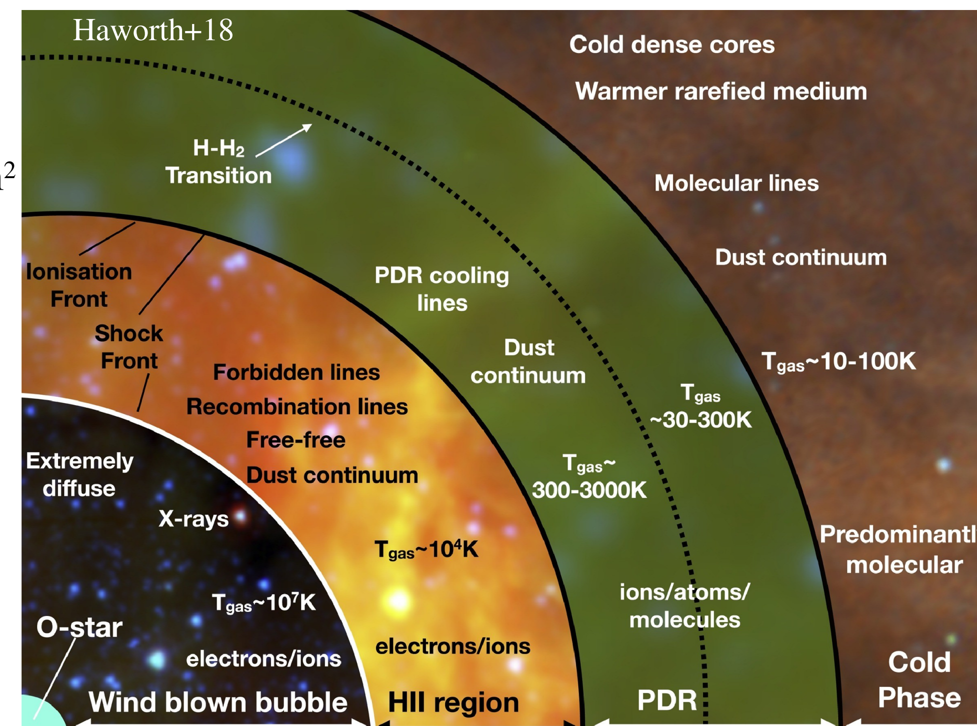
One can think of PDRs as the interface between HII regions and molecular clouds, but the formal definition is any region where the photon field is dominated by far-ultraviolet (FUV) 6-13.6 eV light, which corresponds to a wavelength range of ________ Å.

In addition to standard astronomical parameters like density, temperature, and mass, it is common to characterize PDRs by:

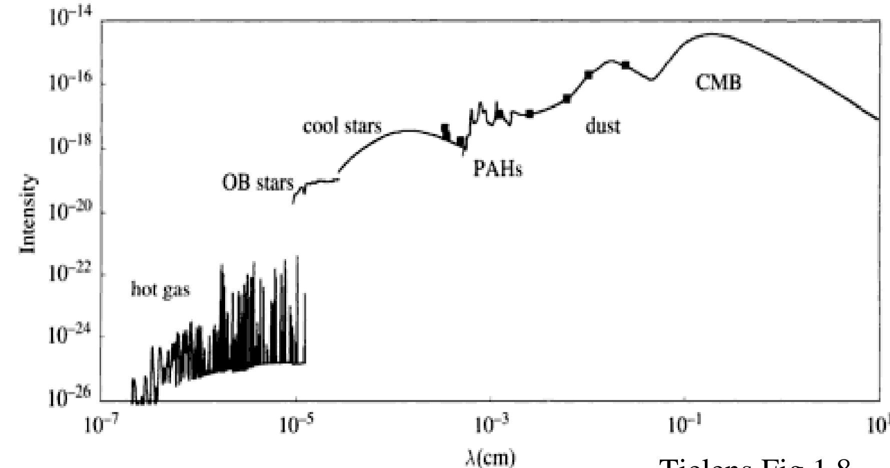
G_0 – __________________
“Habing units”: 1.2×10^{-4} erg/s/cm²/sr or 1.6×10^{-3} erg/s/cm²
The average ISRF (interstellar radiation field) in our solar neighborhood is $\sim1.7G_0$.

FIR or TIR – ___________________________

G_0/n – ____________________

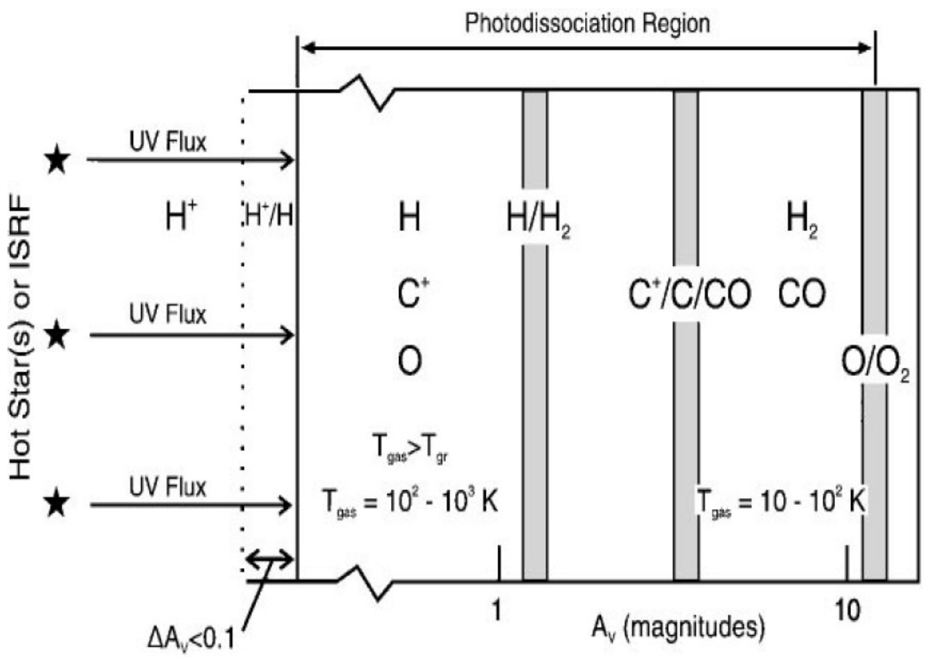


See Figures 1.8 & 1.9 in Tielens
Are these spectra consistent with ~1.7G_0?



Tielens Fig 1.8

Since PDRs are flooded with 6-13.6 eV light, they are by by definition_________.   But only in the _______ sense...



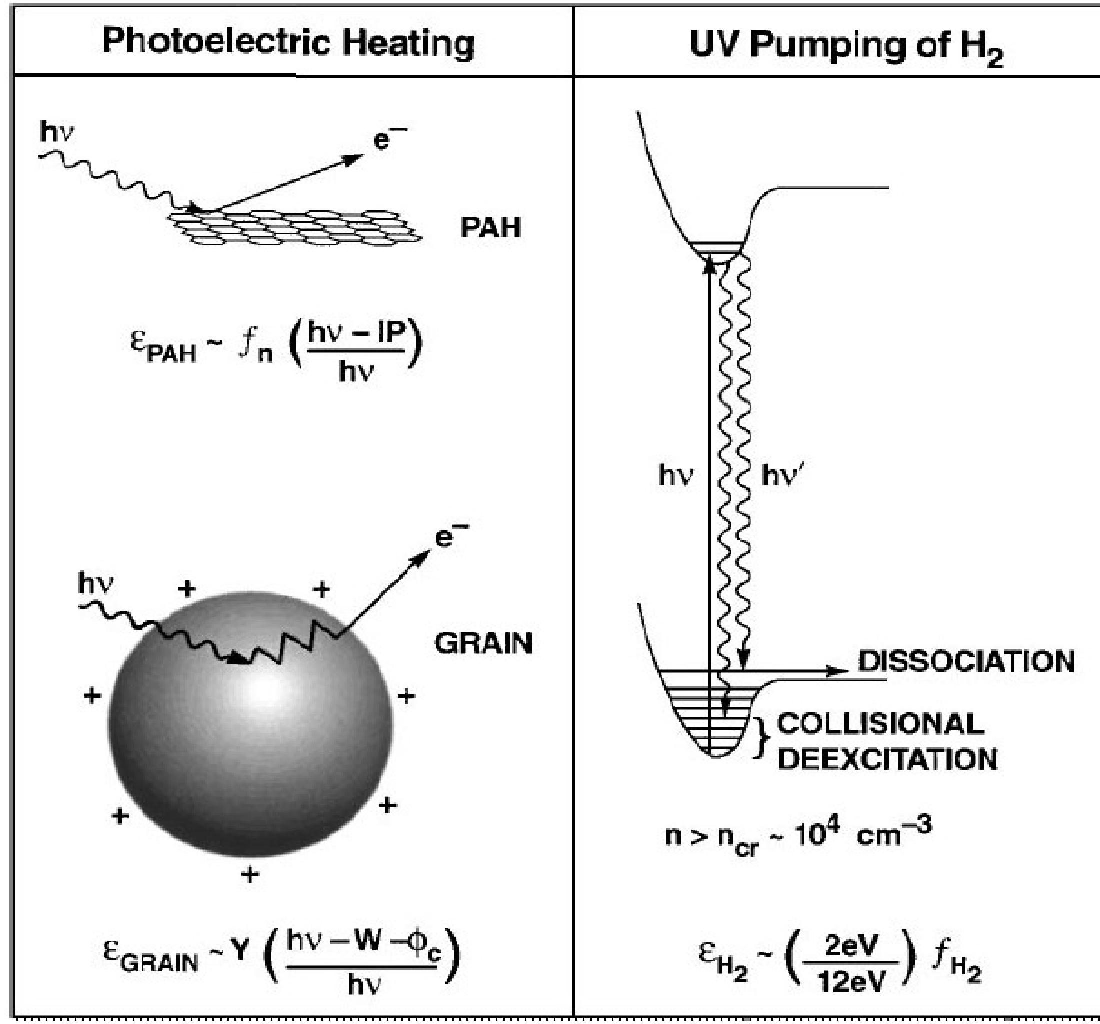
Hollenbach & Tielens 1997 & Figure 9.1 of the Tielens text

All of the atomic and most of the molecular cloud material are in PDRs.

Heating

Some e-s are liberated from metals in PDRs (can you name two?), but metals are relatively rare and so most of the heating of PDRs is via the _______________ on ______________.

What fraction of the incident FUV flux is converted to photo-ejected electrons?



Hollenbach & Tielens 1997

Recall that the maximum efficiency of photo-electric heating is ___ for large grains and ___ for PAHs (and will be smaller if the grains are _________).

Another avenue for heating PDR gas is H_2 pumping. FUV photons pump H_2 to a bound excited electronic state, followed by fluorescence down to either the *vibrational continuum* of the ground state and ____________ (10-15% occurrence) or to an excited vibration of the ground electronic state (85-90% of the time).

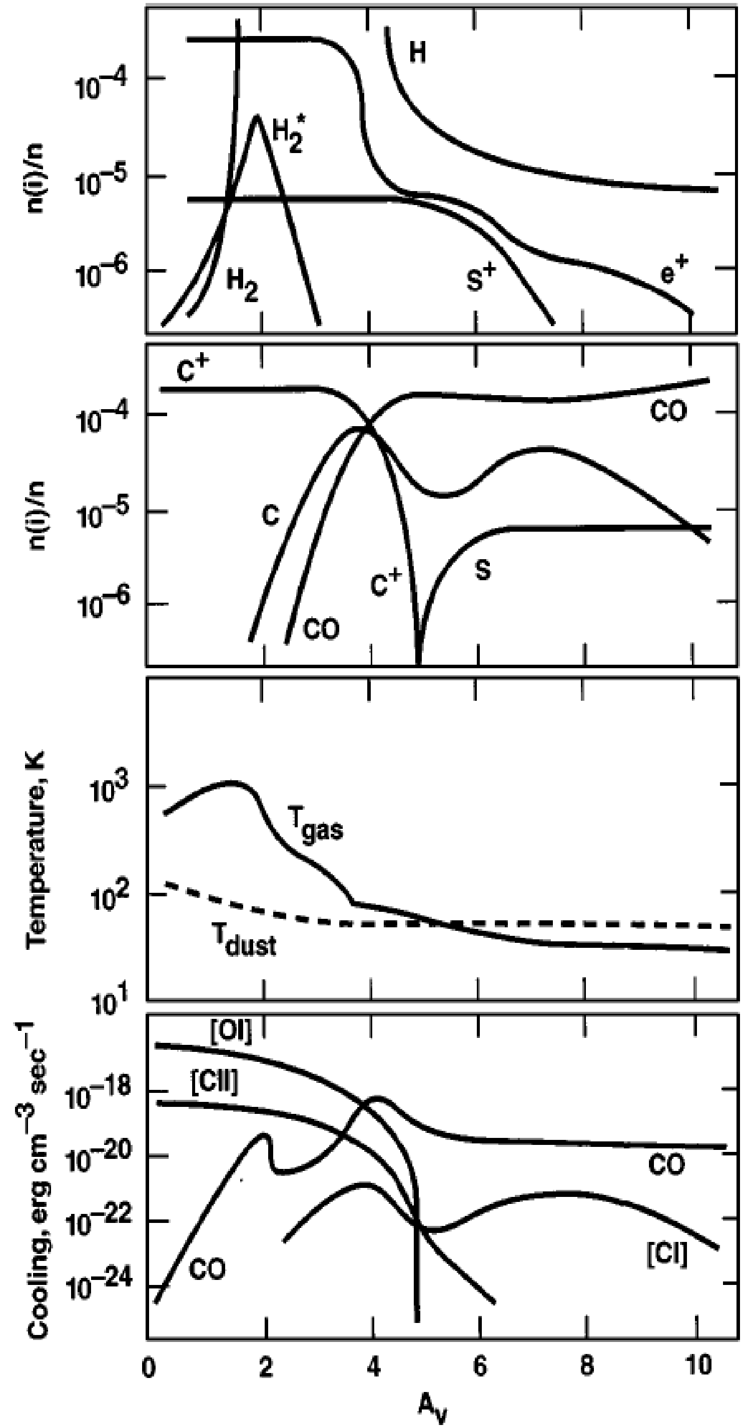
At high densities (n>10^4 cm^{-3}), collisions with H can be an important de-excitation mechanism, leading to gas heating. The efficiency is ε_{H2}~$(E_{vib}/h\nu)f_{H2}$~$0.17f_{H2}$. When $G_0/n<10^{-2}$ cm^3, H_2 self-shielding is important, the H/H_2 transition is near the PDR surface, most of the photons that can pump H_2 are absorbed by H_2 rather than dust, and f_{H2}~0.25.

Photo-Dissociation Regions

Object	NGC 2023	Orion Bar	NGC 7027	Sgr A	M 82
Line intensities[a]					
[OI] 63 μm	4. (−3)	4. (−2)	1. (−1)	2. (−2)	1. (−2)
[OI] 145 μm	2. (−4)	2. (−3)	5. (−3)	7. (−4)	1.5 (−4)
[SiII] 35 μm	2. (−4)	9. (−3)	—	2. (−2)	1. (−2)
[CII] 158 μm	7. (−4)	6. (−3)	1. (−2)	2. (−3)	2. (−3)
[CI] 609 μm	—	5. (−6)	1.8 (−6)	4. (−5)	2. (−5)
H_2 1–0 S(1)	5. (−5)	2. (−4)	8. (−4)	9. (−4)	5. (−5)
CO J = 1–0	3. (−8)	4. (−7)	1.5 (−6)	7 (−7)	2.6 (−7)
CO J = 7–6	5. (−5)	2. (−4)	—[b]	1.5 (−3)	5. (−5)
CO J = 14–13	—	3. (−4)	—[b]	3. (−4)	—
FIR[c]	8. (−1)	5. (0)	4. (1)	5. (1)	6. (0)
PAHs[d]	9. (−2)	1.5 (−1)	1.8 (0)	—	1.4 (−1)
G_0	1.5 (4)	4. (4)	6. (5)	1. (5)	1. (3)
Physical conditions					
Interclump					
n [cm^{-3}]	7.5 (2)	5. (4)	1. (5)[e]	1. (5)	1. (4)
T [K]	250	500	1000[e]	500	250
M_a/M_m	0.2	0.6	0.3	0.04	0.1
Clump					
n [cm^{-3}]	1. (5)	1. (7)	1. (7)[e]	1. (7)	—
T [K]	750[f]	(2000)	(2000)[e]	(2000)	—
f_v	0.1	0.005	0.05	0.06	4. (−4)
References[g]	1–5	6–8	9–13	13–16	14, 17–19

[a]Intensities in units of erg cm^{-2} s^{-1} sr^{-1}.

See also Table 9.3



Hollenbach & Tielens 1997

The gas in the surface layer of PDRs is heated to several hundreds of degrees Kelvin, and drops off as you proceed into the molecular clouds. The dust grains hold onto a more steady temperature of ~30-75 K. Why are the deeply-buried dust grains at a similar temperature to the grains near the surface?

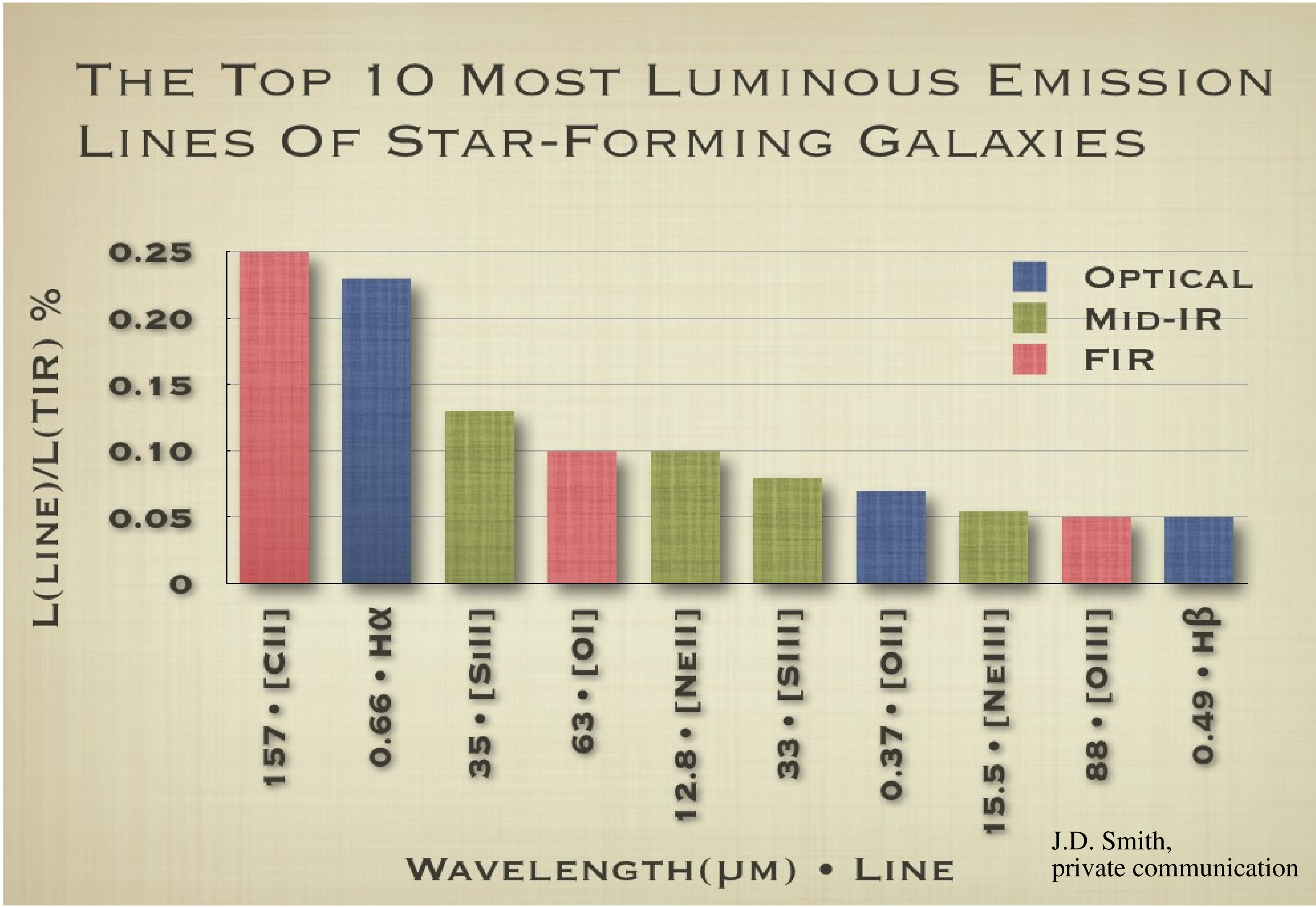
Cooling

Usually we are accustomed to dust grains being much cooler than the gas (HII regions).
How can the deeply-buried gas in PDRs be cooler than the deeply-buried dust?

Notice how C^+ drops off at A_V~4 mag. Moreover, see how the cooling is dominated by O and C^+ at small optical depths, and then by C and CO deeper in. Why?

[CII]158μm is the dominant coolant of the neutral ISM, partly because carbon is relatively prevalent and partly because the transition is so energetically weak that it only requires collisional excitations from cool gas @ $\Delta E/k \sim 91$ K.

It is also perhaps *the* brightest observed line.



Hydrogen is far more abundant than carbon, so why aren't Lyα/Hα/Hβ/etc brighter in galaxies?

Now compare C^+ and O:

[CII]158μm and [OI]63μm are responsible for the bulk of the gas cooling in PDRs (at least down to A_V~4 mag), with C^+ cooling the colder, less dense gas and O cooling the warmer, denser gas. Can you think of a reason why O would cool warmer PDR gas (than C^+)?

Kaufman, Wolfire, & Hollenbach 2006

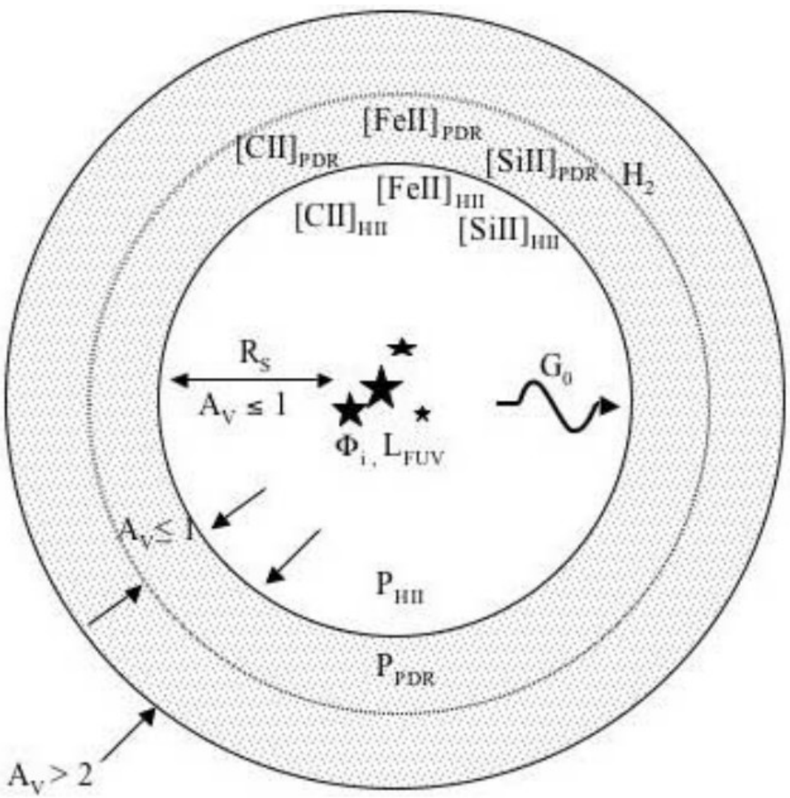


FIG. 16.—Schematic representation of the merged H II region and PDR models. $P_{\rm H\,II} = P_{\rm PDR}$. Starburst99 is used for the cluster spectrum. Mappings is used for the H II region structure; emitted H II region spectrum; $[{\rm Fe\,II}]_{\rm H\,II}$, $[{\rm Si\,II}]_{\rm H\,II}$, and $[{\rm C\,II}]_{\rm H\,II}$ emission; and $R_{\rm S}$. The emitted spectrum plus $R_{\rm S}$ gives G_0. Our PDR models give $[{\rm Fe\,II}]_{\rm PDR}$, $[{\rm Si\,II}]_{\rm PDR}$, $[{\rm C\,II}]_{\rm PDR}$, and H_2 emission. A_V in the H II region is $\lesssim 1$, A_V in the PDR is $\gtrsim 2$, and A_V at the H I/H_2 boundary is $\lesssim 1$.

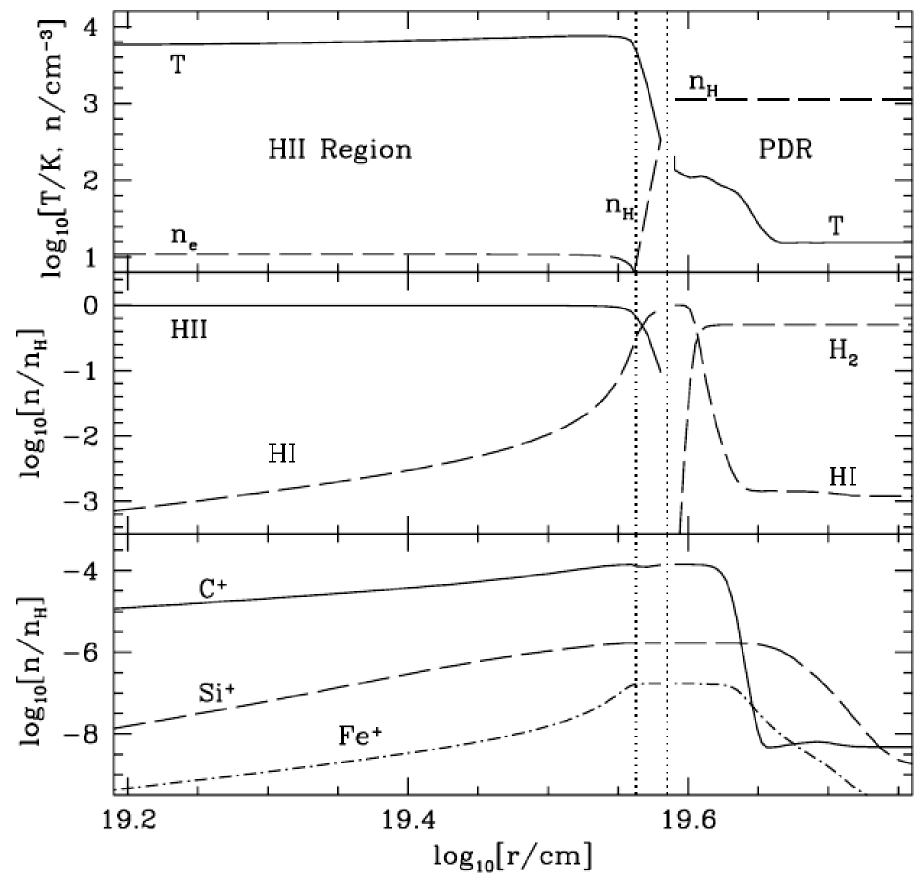


FIG. 18.—Structure of a merged H II region / PDR model, for H II region electron density $n_e = 10$ cm^{-3} and number of H-ionizing photons $\Phi_i = 10^{49}$ s^{-1}. The star cluster is to the left, and the H II region extends to $\sim 3.3 \times 10^{19}$ cm. The transition region (see § 3.1) is indicated by the dotted lines. *Top*: Temperature and density. *Middle*: Fraction of H nuclei that are ionized (H II), neutral atomic (H I), or molecular (H_2). *Bottom*: Fractional abundances of C^+, Si^+, and Fe^+.

Photo-Dissociation Regions

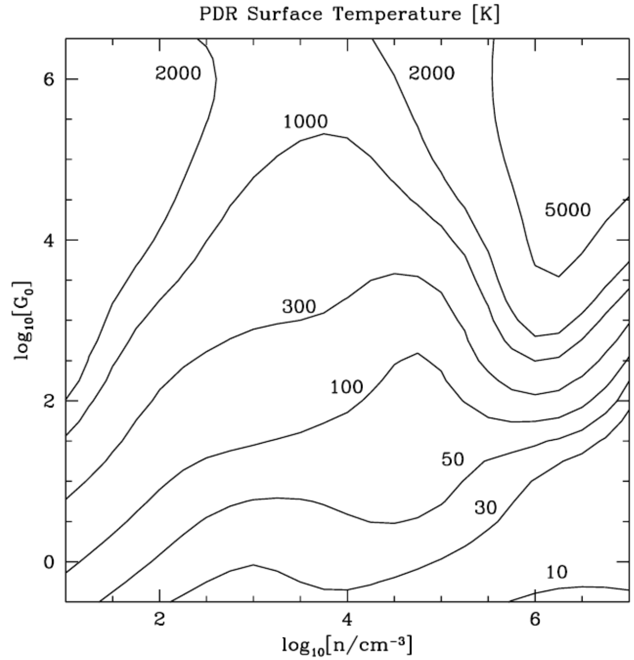


FIG. 1.—Surface temperature of the atomic gas as a function of n and G_0. Contour levels are in kelvins.

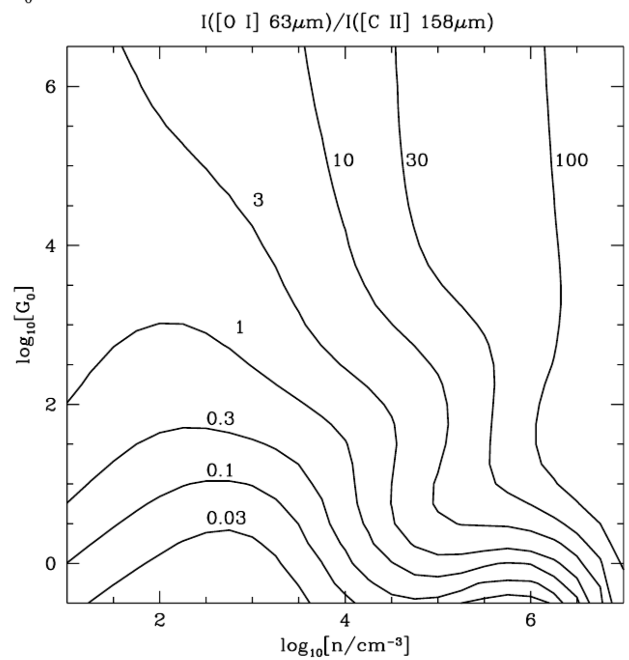


FIG. 4.—Ratio of the intensity of the [O I] 63 μm line to the intensity of the [C II] 158 μm line emitted from the surface of a photodissociation region as a function of the cloud density, n, and the FUV flux incident on the cloud, G_0, for our standard model parameters.

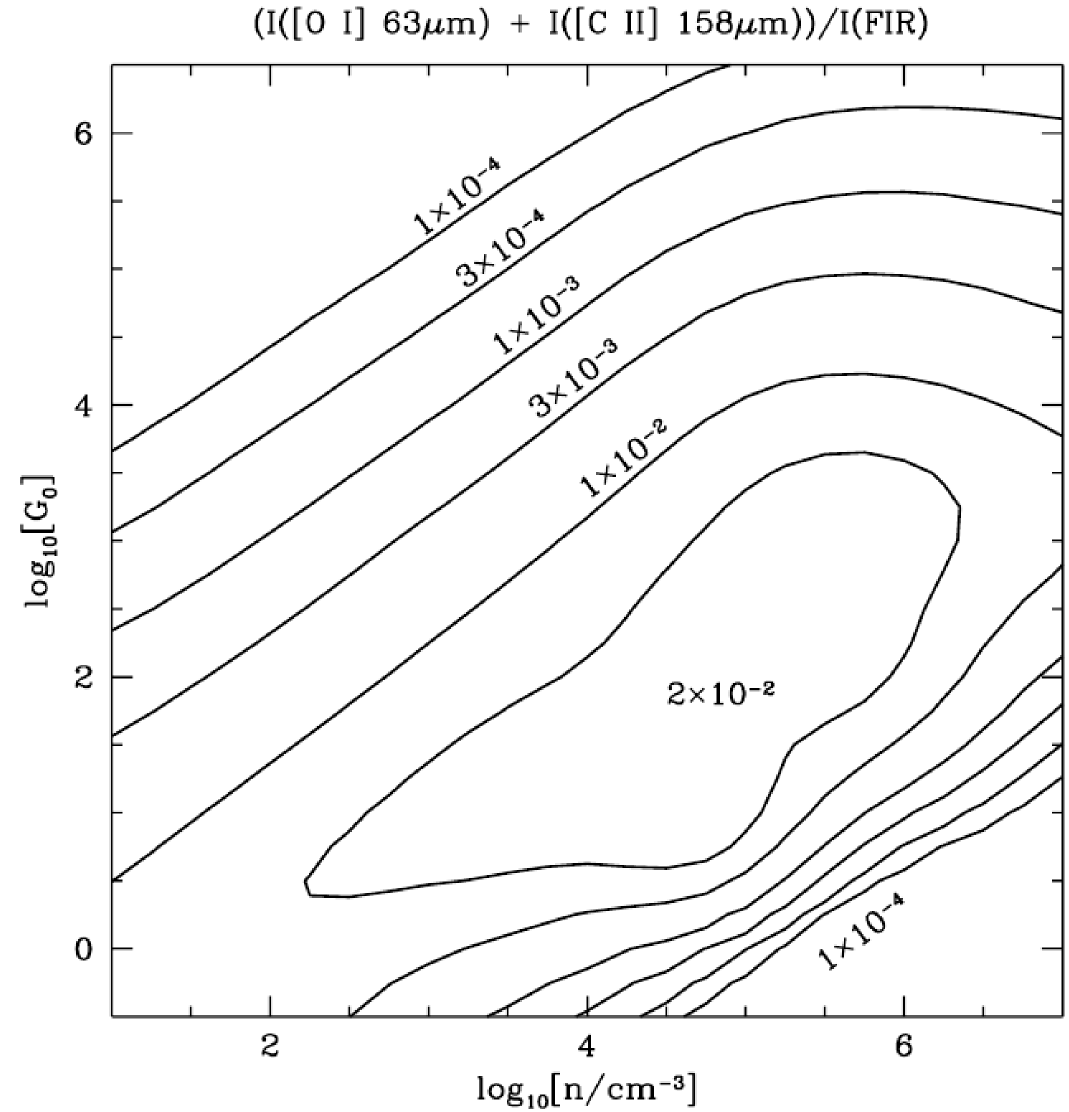
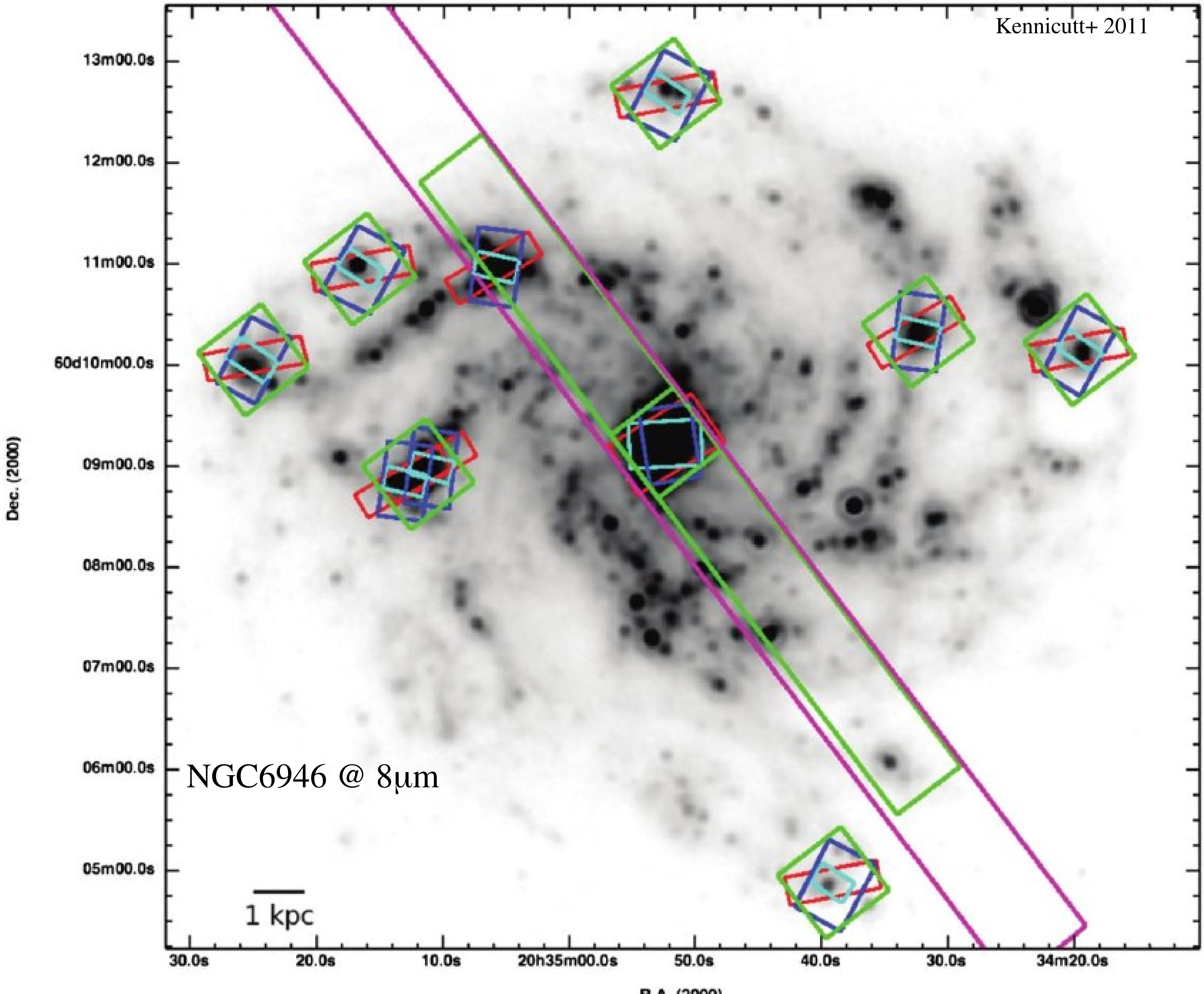


FIG. 6.—Ratio of the intensity of the [C II] 158 μm and [O I] 63 μm lines to the total far-infrared intensity emitted from the surface of a photodissociation region as a function of the cloud density, n, and the FUV flux incident on the cloud, G_0, for our standard model parameters. See text for cautions on using this figure.

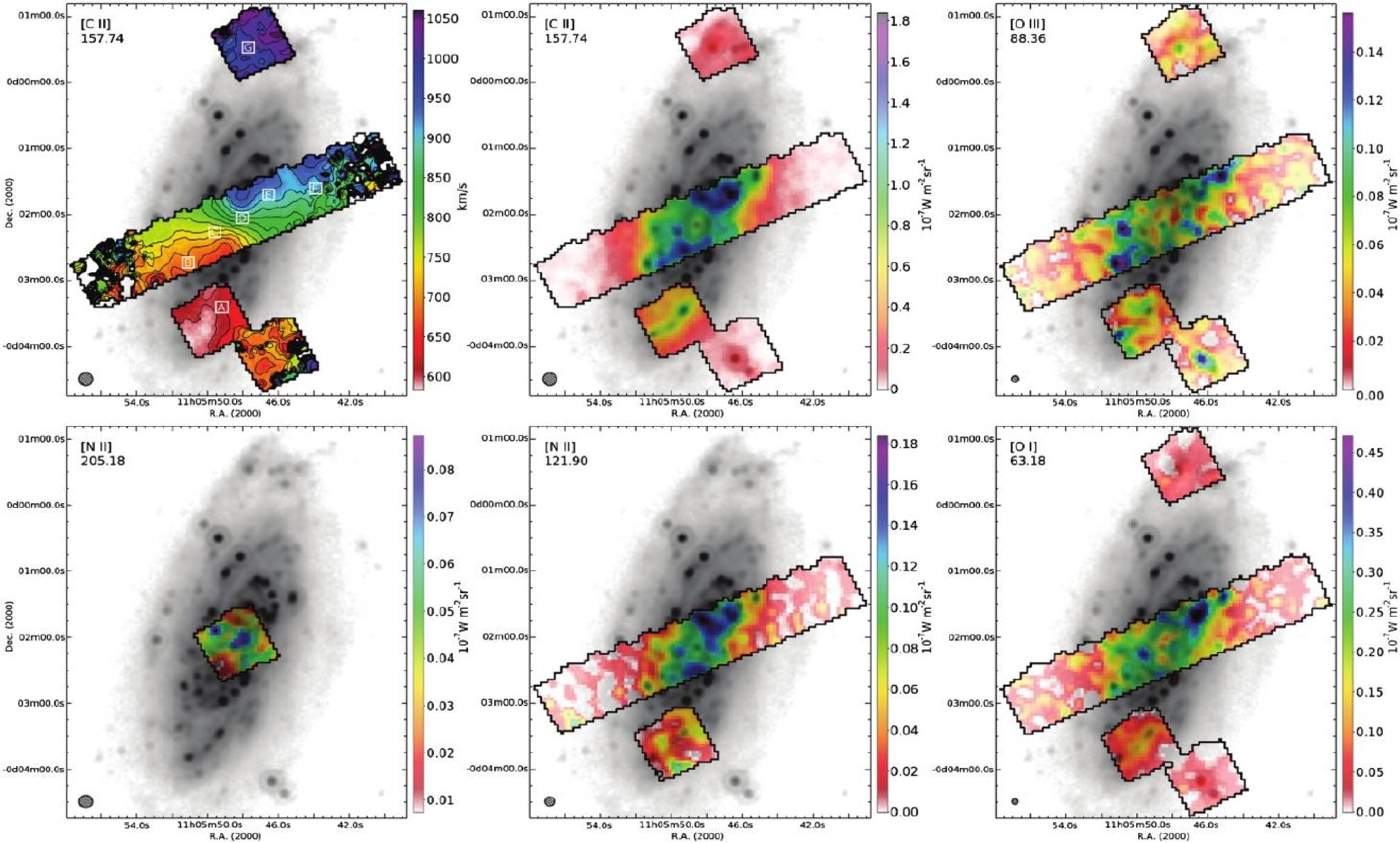
Kaufman, Wolfire, Hollenbach, & Luhman 1999

Photo-Dissociation Regions

Herschel Space Observatory spectroscopic targets overlap with Spitzer Space Telescope spectral regions



Herschel Space Observatory Far-IR Spectroscopy

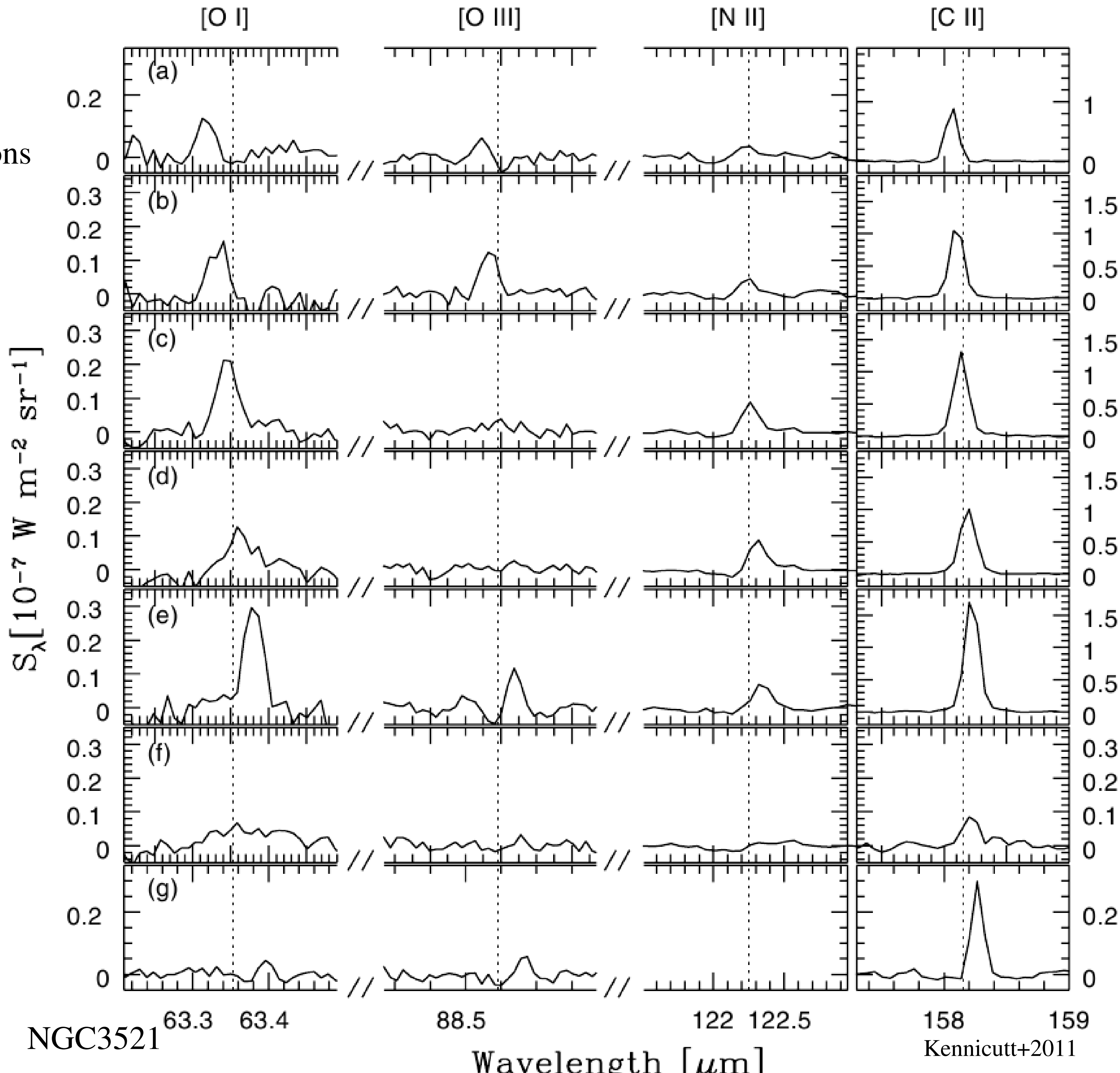


NGC3521 @ 24μm

Kennicutt+2011

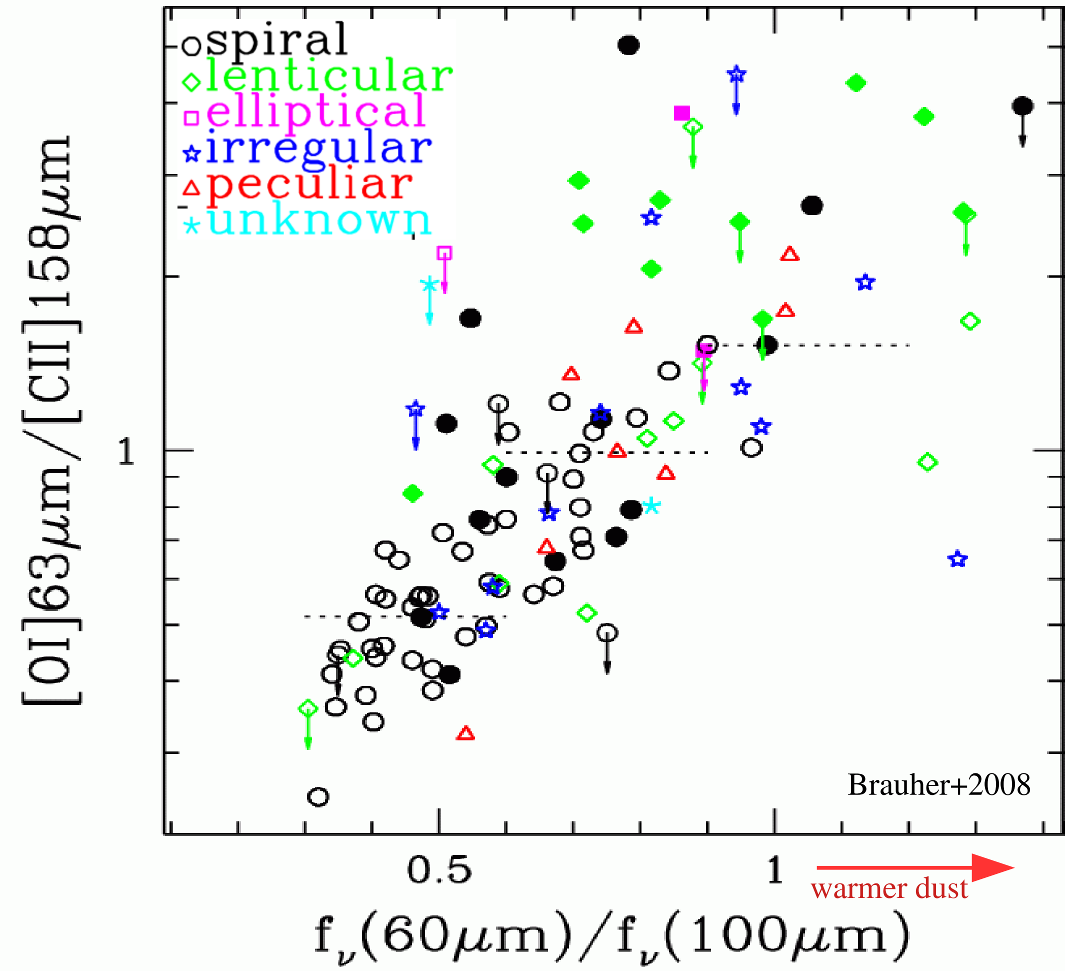
Spectral cut-outs for different regions within a single galaxy.

Why does the line center not always appear at the same wavelength?

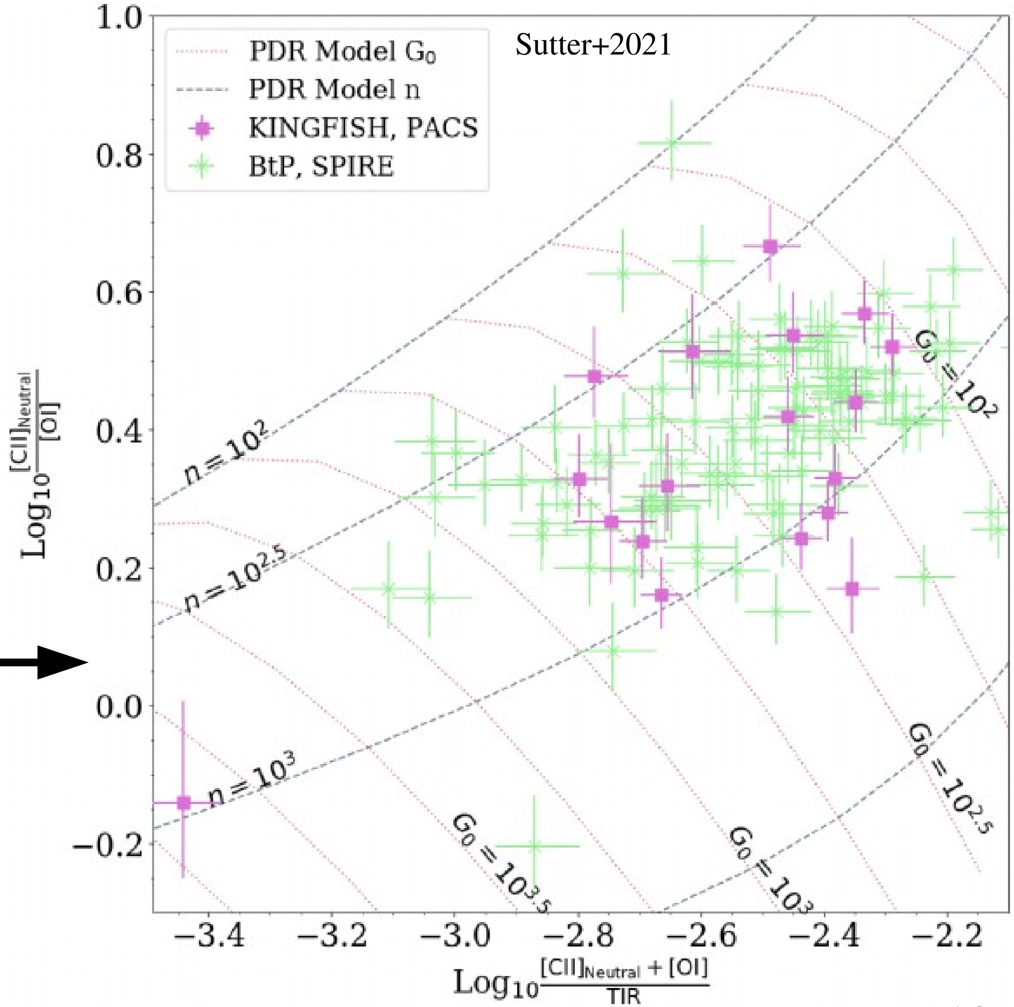


NGC3521

Kennicutt+2011

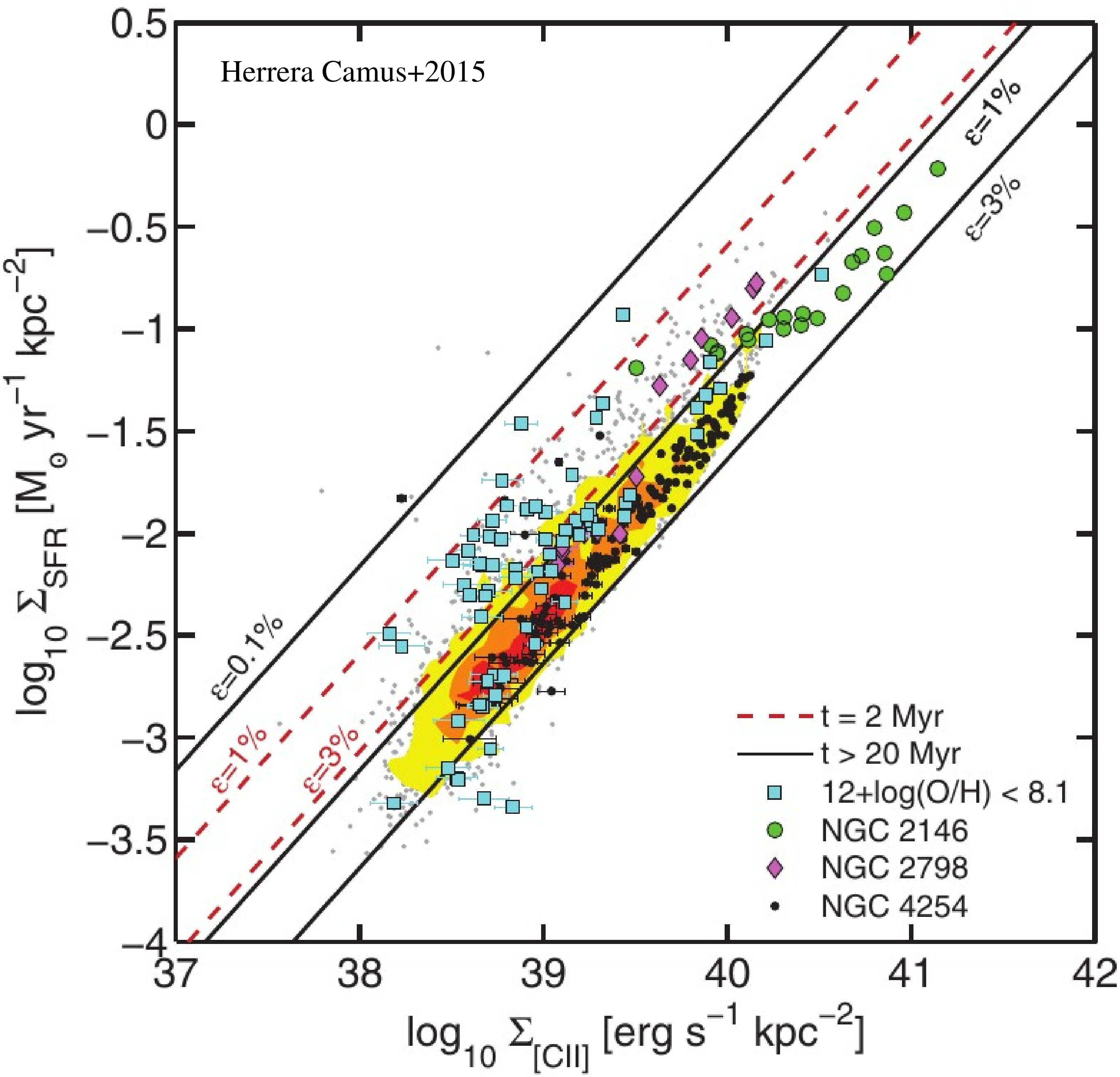


As expected, [OI]63/[CII]158 increases for increased dust temperature, supporting the notion that neutral oxygen cooling of PDRs occurs for the warmer (and denser) gas.



Theoretical models are being refined to further our physical interpretation of the data.

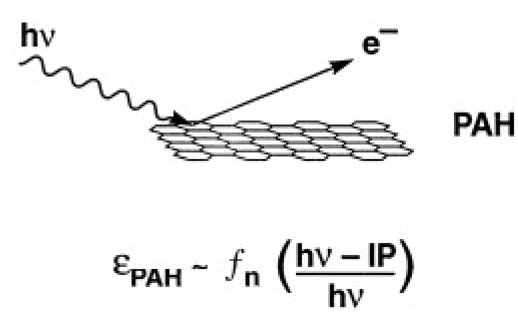
[CII]158μm as a SFR Indicator



Linear relationship

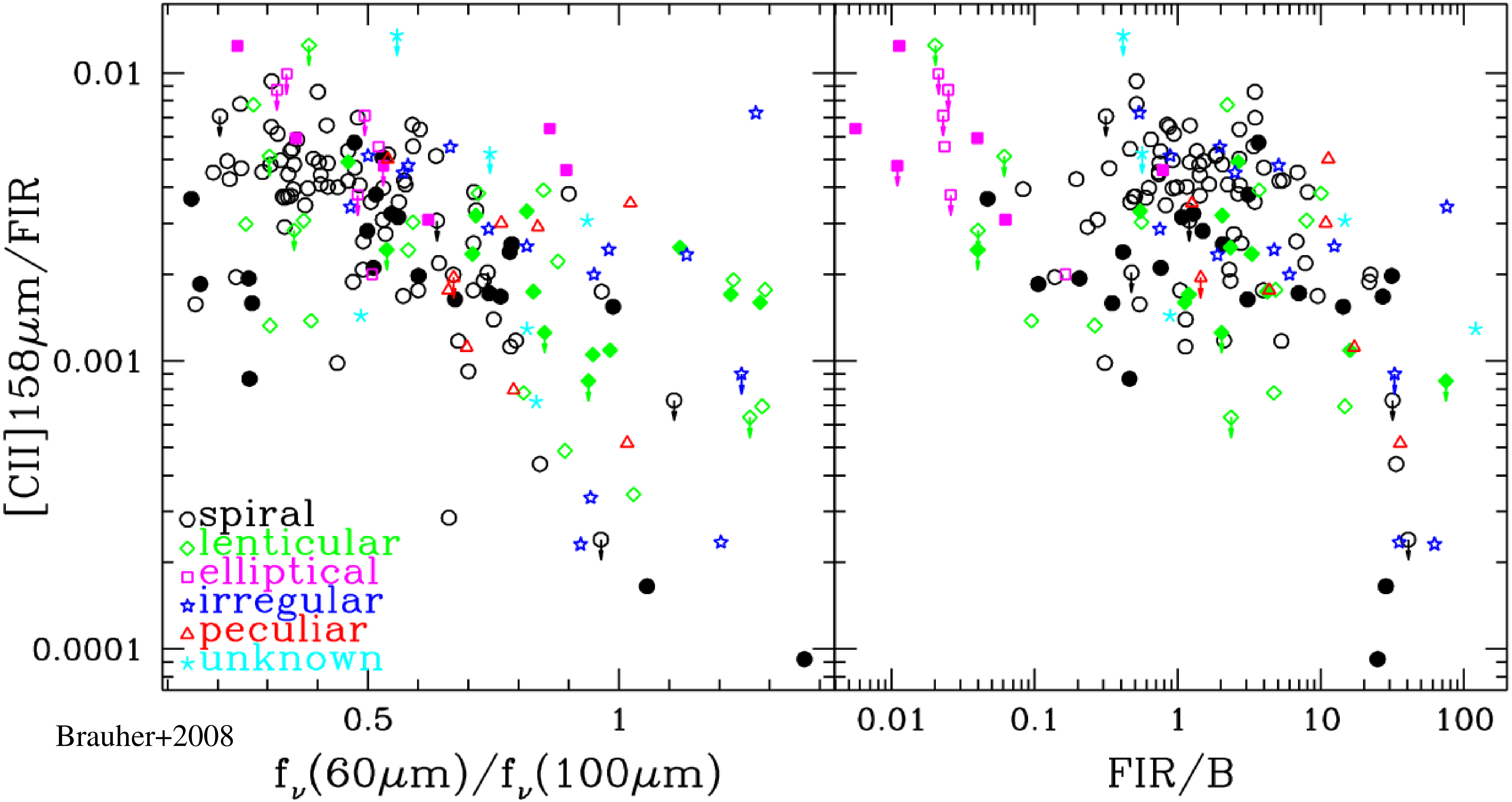
Interpretation via Starburst99 model:

- 6-13.6 eV luminosity illuminates PDR
- Assumes photo-electric heating
- $L(C^+) \sim \varepsilon\, L(FUV)$



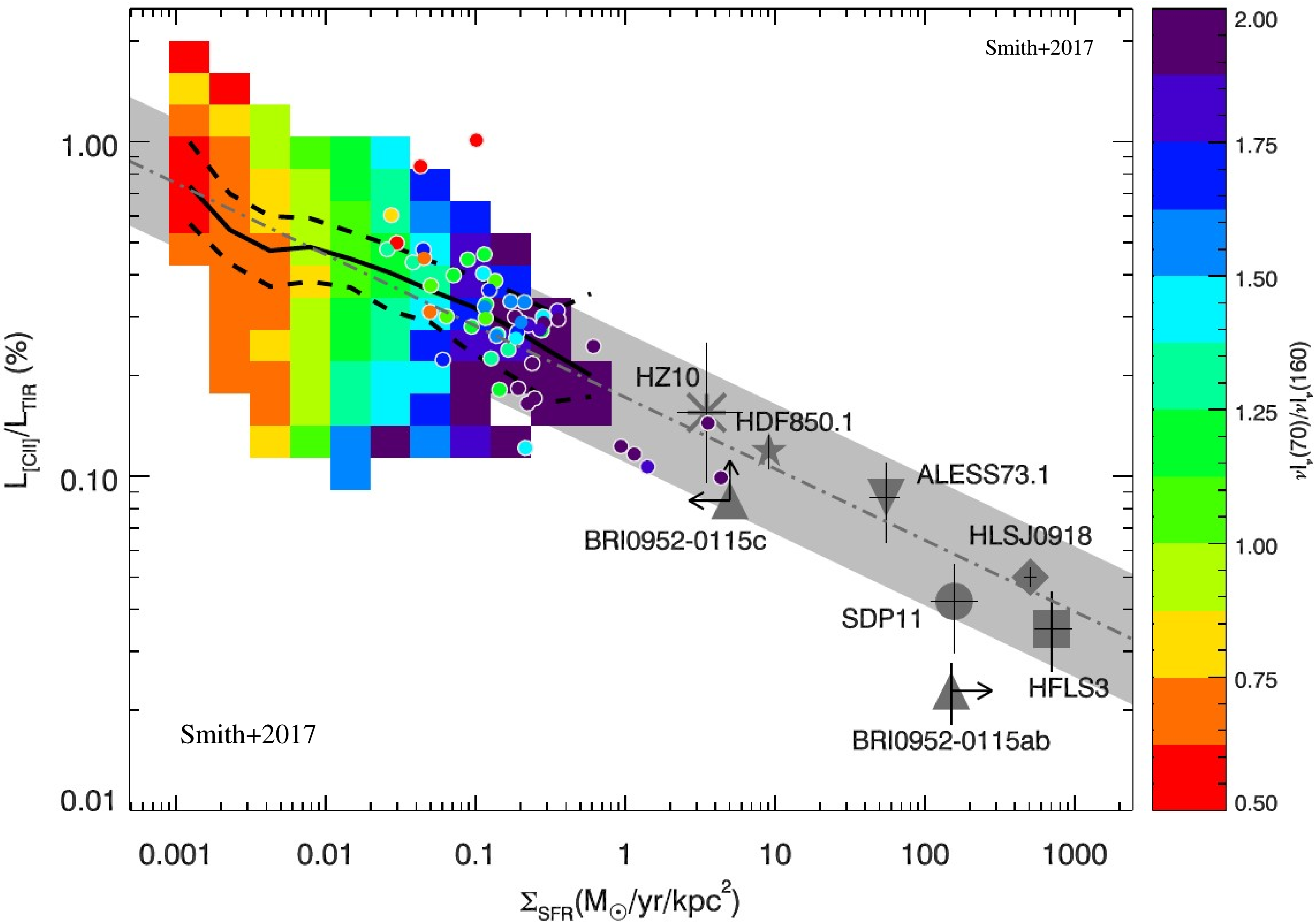
Hollenbach & Tielens 1999

The Ubiquitous "C+ Deficit"



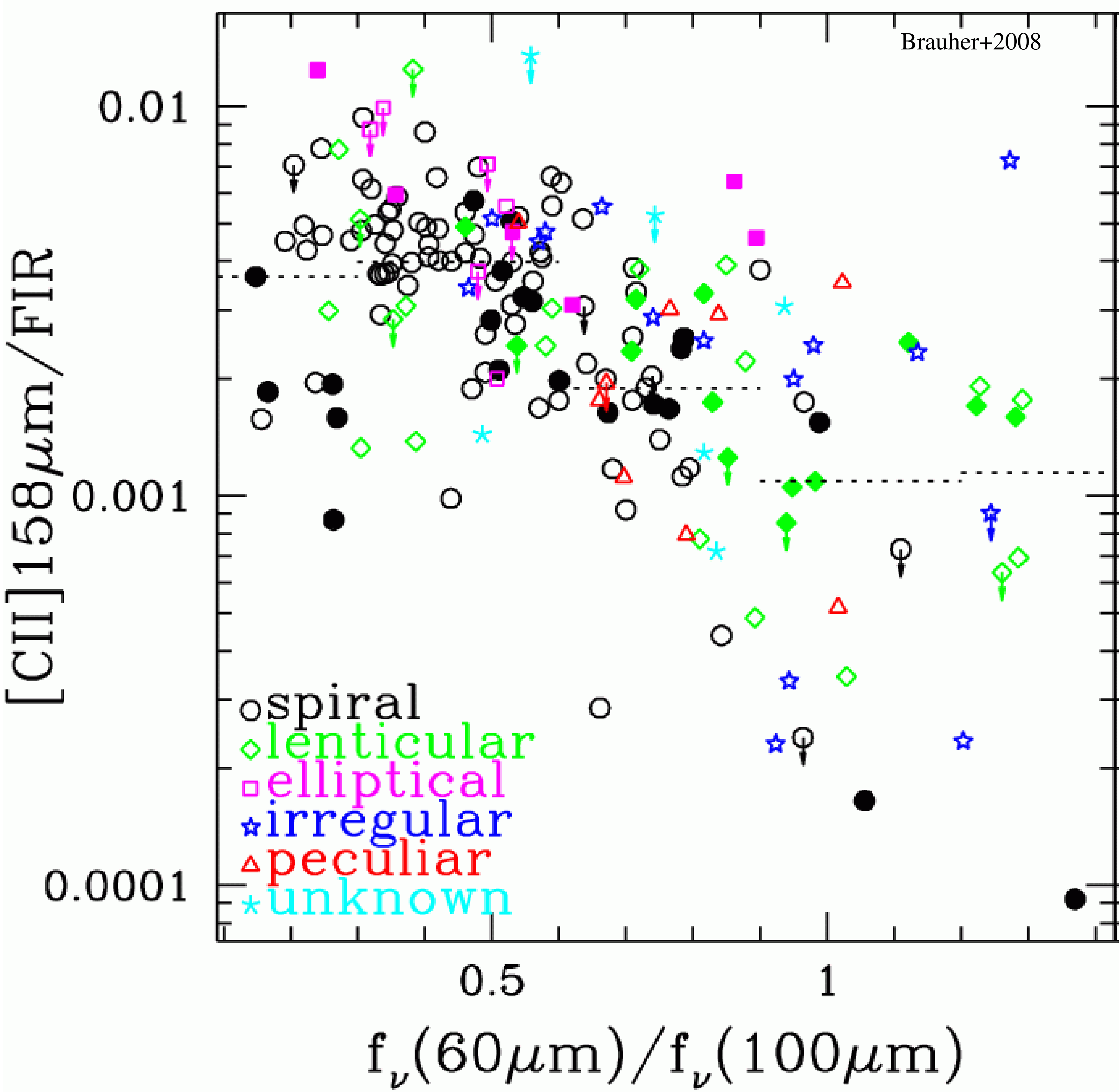
Brauher+2008

C^+ deficit as a function of SFR surface density (Σ_{SFR})

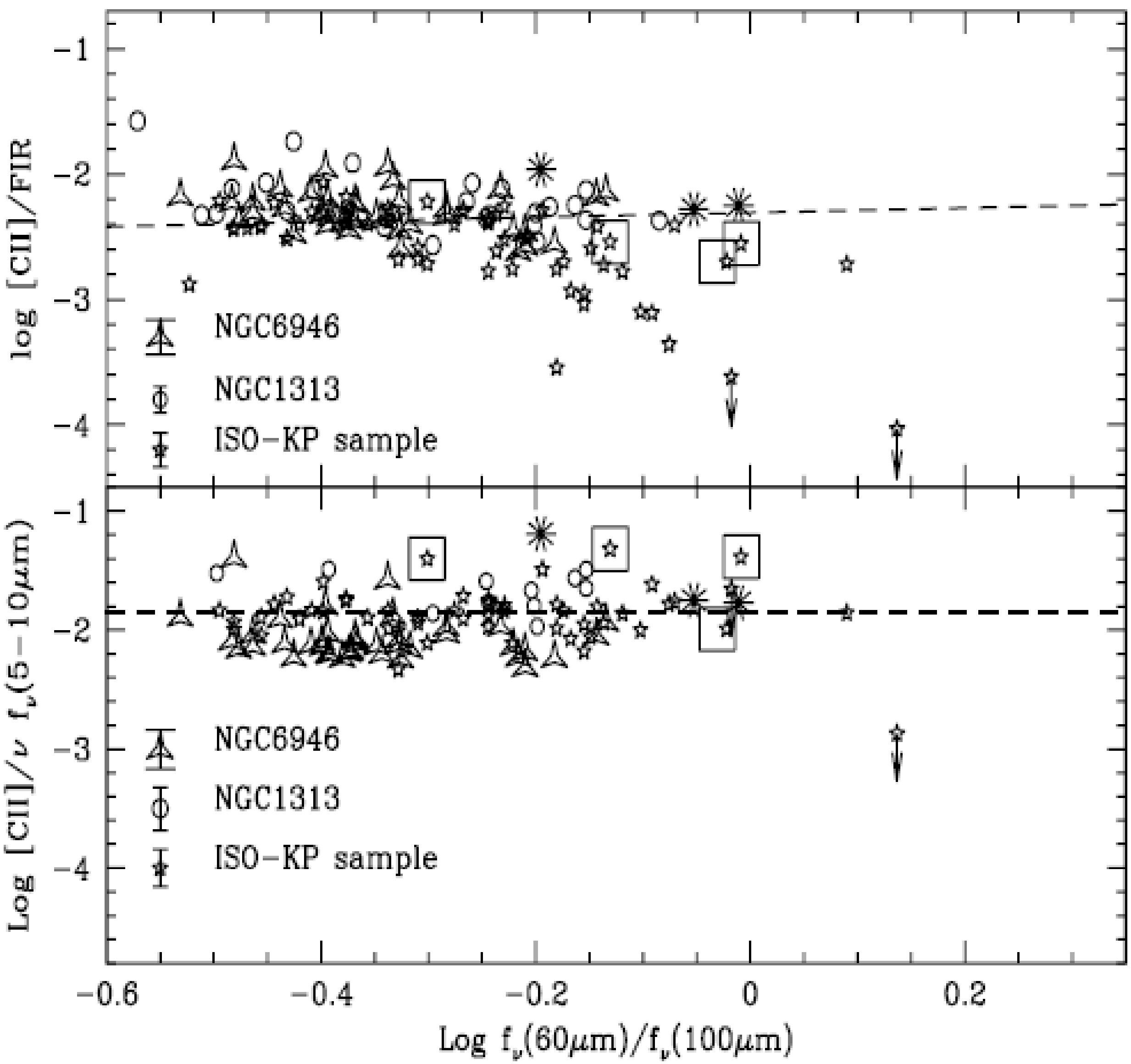


[CII]158 is triggered by collisions with free-roaming electrons. These electrons come from ______________________.

[CII]158/FIR drops with increasingly ______ infrared color, consistent with increased ________ of the photo-electric effect as PAHs become increasingly ________.



Addressing the "C^+ Deficit" – ISO work

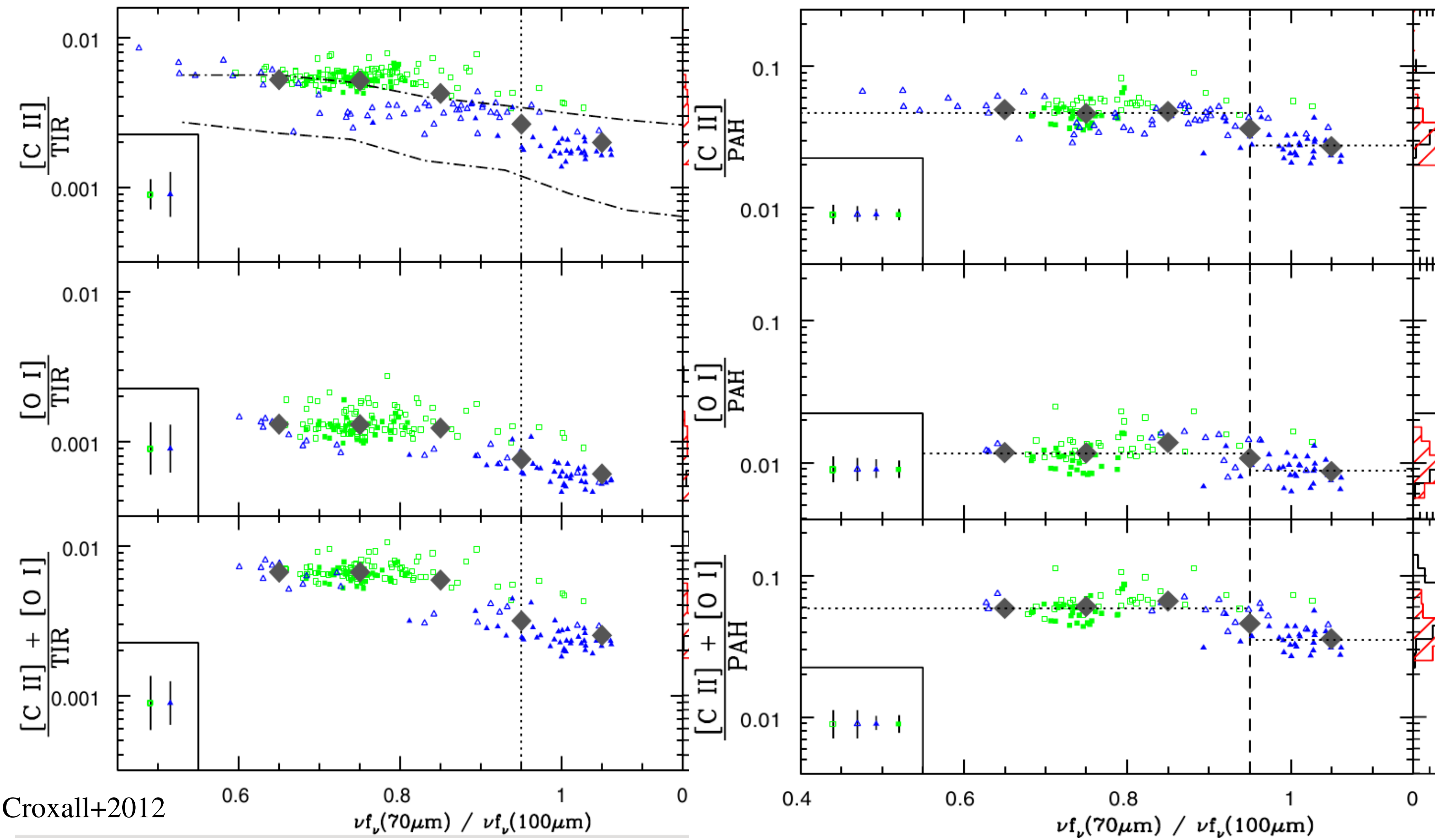


Contursi+2002

Highly-charged PAHs contribute fewer free electrons to ISM, necessary to trigger [CII]157.7μm

But since most neutral ISM e^-s come from PAHs, the C^+/PAH ratio is constant ...

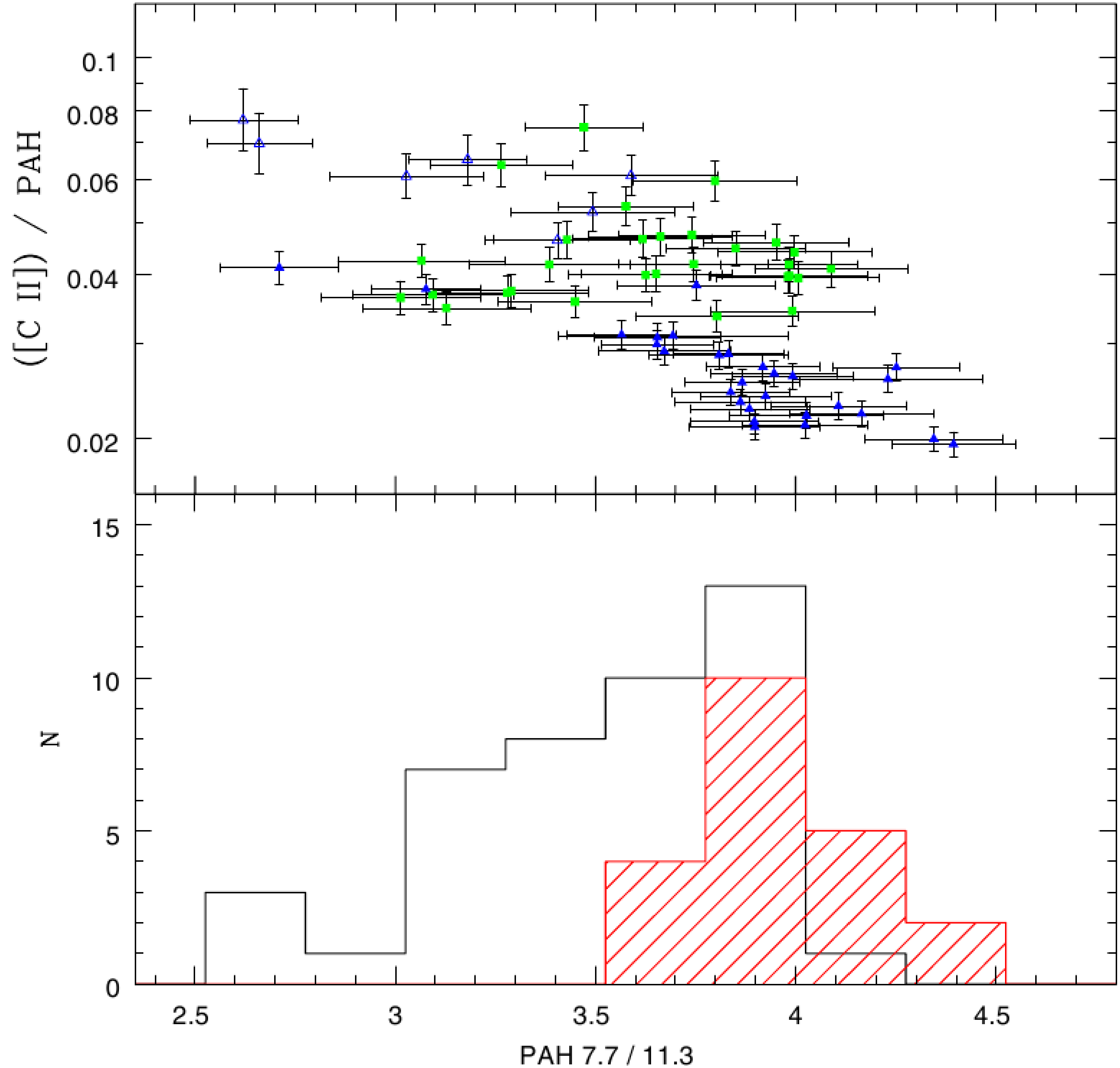
Herschel data for NGC1097 and NGC4559



Croxall+2012

Spitzer & Herschel:

C+/PAH drops for PAHs that are too ionized to yield photo-electric e-s



Croxall+2012