Carbon lines towards Orion A

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SOFIA tele-talk,
4 March 2020

Photodissociation regions

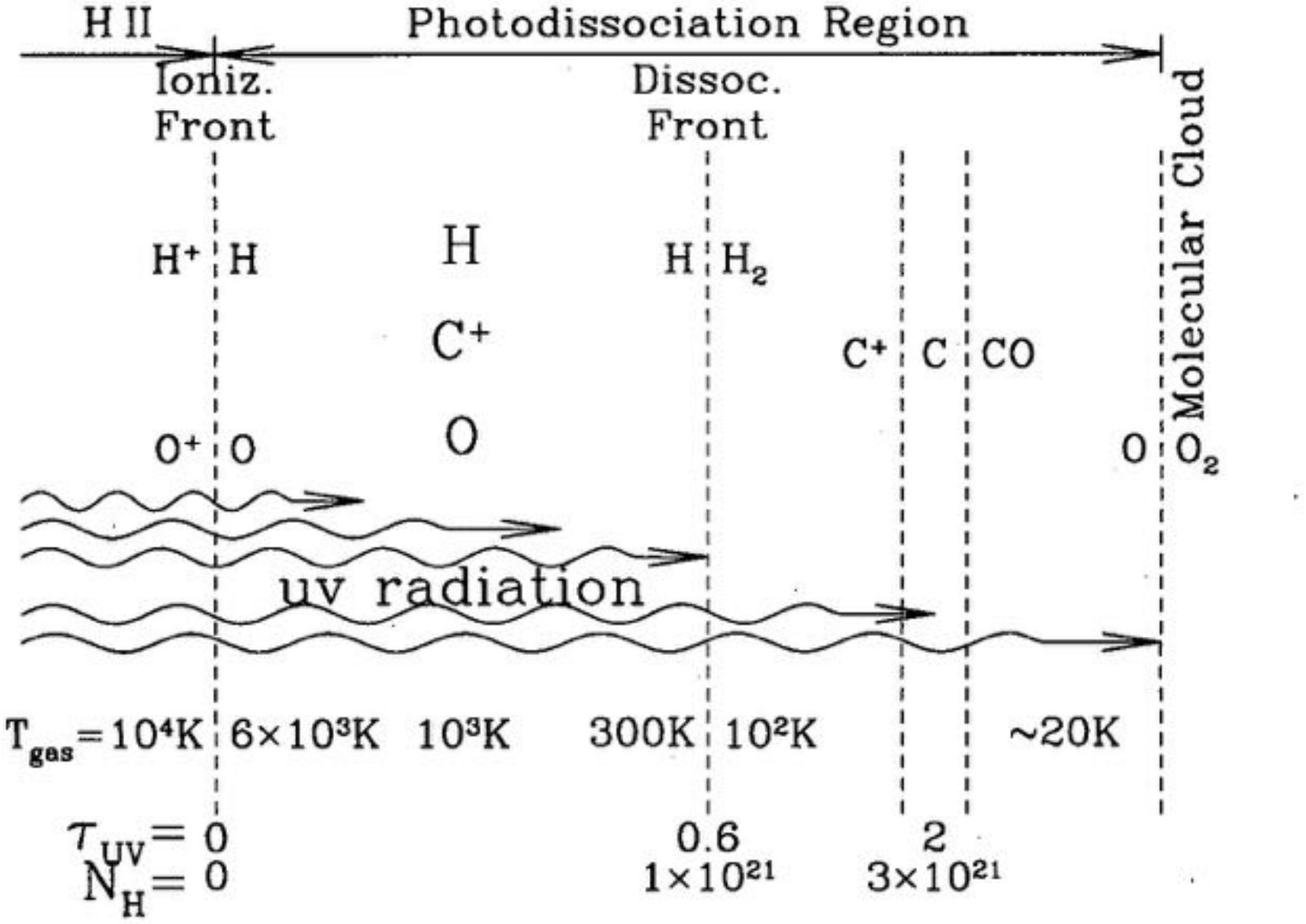


Figure 31.2 Structure of a PDR at the interface between an H II region and a dense molecular cloud.

Draine's ISM book

Photodissociation regions

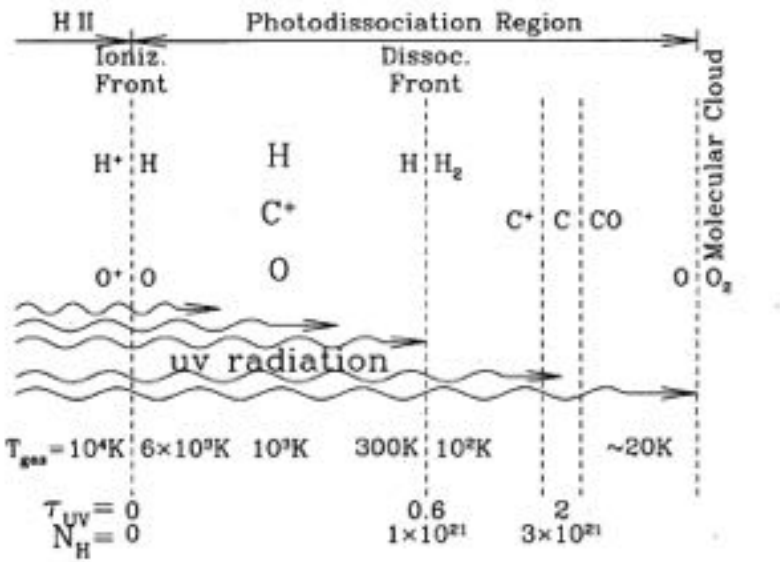
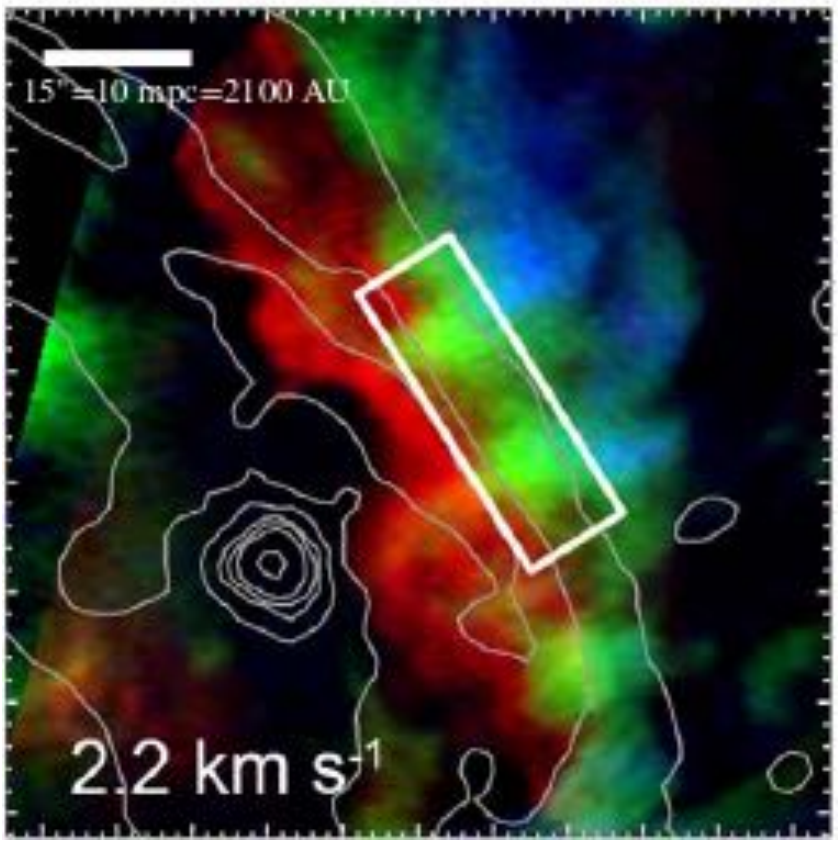


Figure 31.2 Structure of a PDR at the interface between an H II region and a dense molecular cloud.

Draine's ISM book

- PDRs are everywhere in the ISM.
- PDRs in the interface between HII regions and molecular clouds are bright (e.g., Orion).
- They are great laboratories for studying ISM's physics.
- Emission from Orion-like PDRs dominates the IR spectrum of galaxies.
- They are used to interpret observations.

Photodissociation regions



^{12}CO(2–1), ^{13}CO(2–1), C^{18}O(2–1).
Yamagishi+2019

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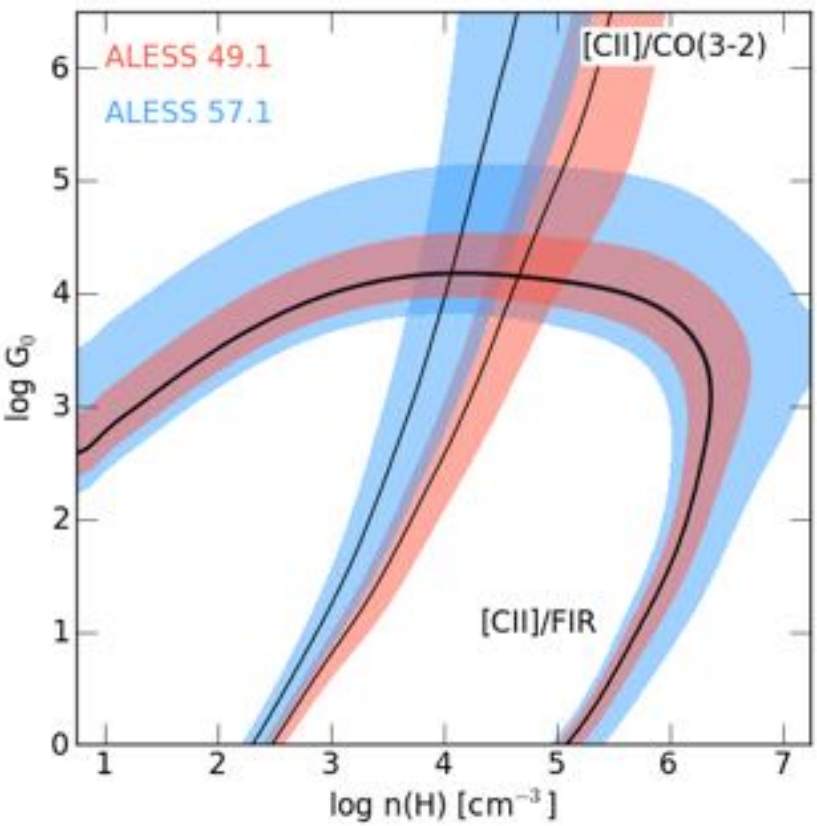
Photodissociation regions



Rybak+2019

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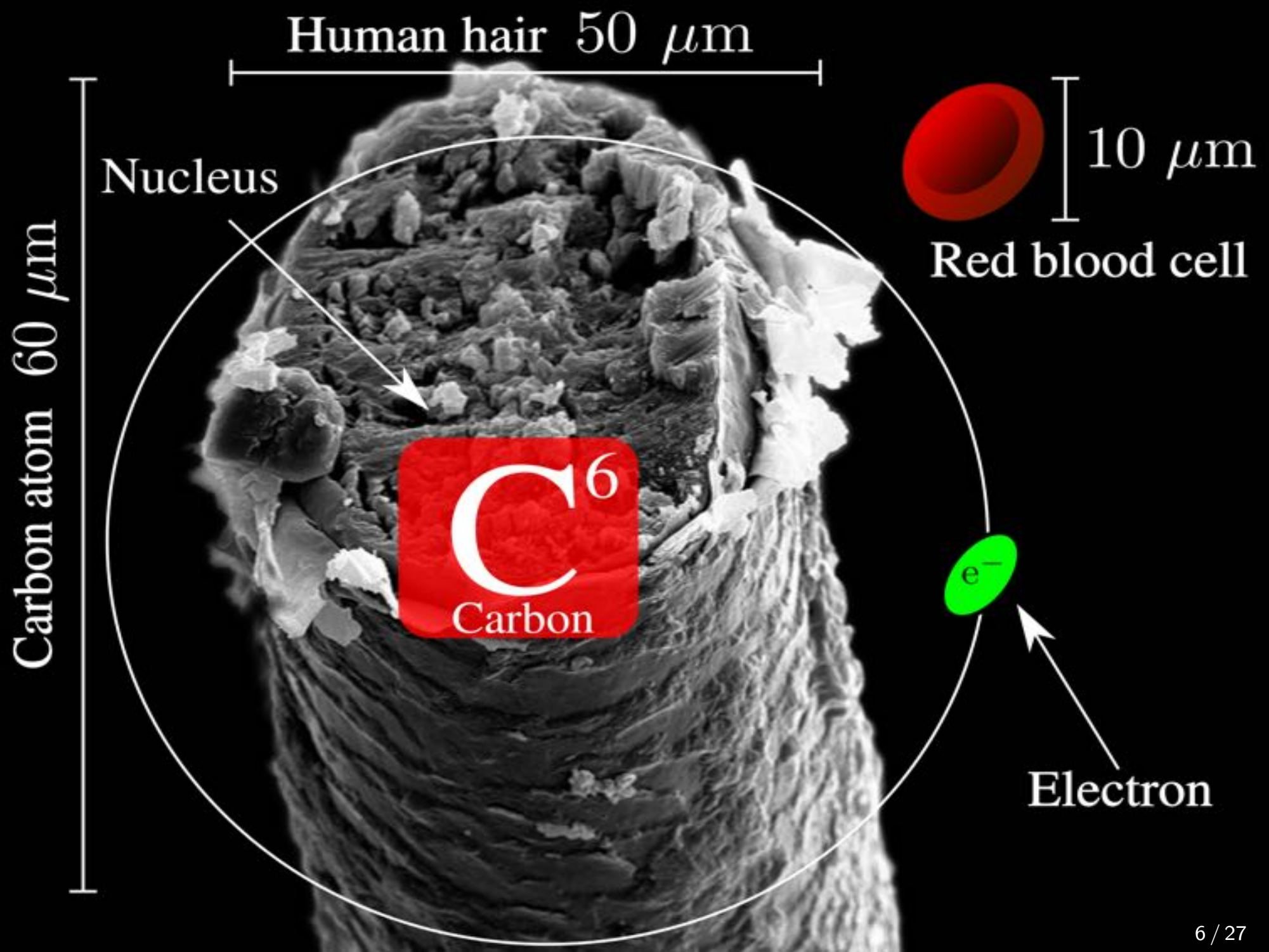
Motivation

- Previous studies (e.g., Natta+1994, Tsivilev 2014) showed that the gas physical properties (density and temperature) can be determined by using CRRLs and the FIR [CII] line.
  $\rightarrow$ How does this change in light of new observations and models?
  $\rightarrow$ Can we isolate the cold gas using the velocity information?
- If we can determine the physical properties of the gas, What is the gas heating efficiency?
- What is the pressure in the atomic layers of the Orion bar PDR?


Human hair 50 μm
Carbon atom 60 μm
Nucleus
10 μm
Red blood cell
C 6
Carbon
e$^-$
Electron

Carbon radio recombination lines

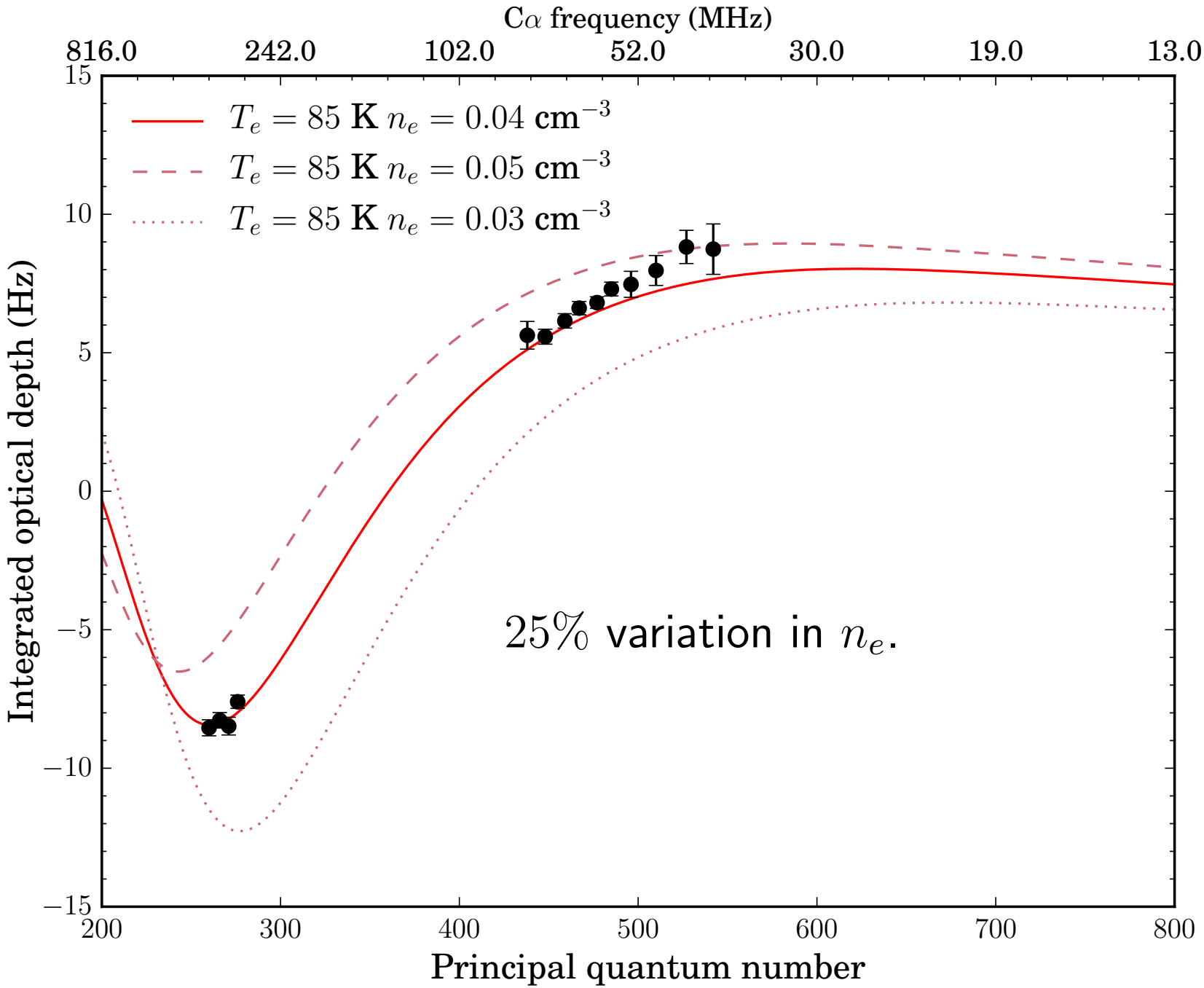
- Line intensity:

$$I \propto (T_{\rm gas} b_{n'} + T_{\rm bkgd} b_n \beta_{nn'}) T_{\rm gas}^{-2.5} EM_{\rm C^+}$$

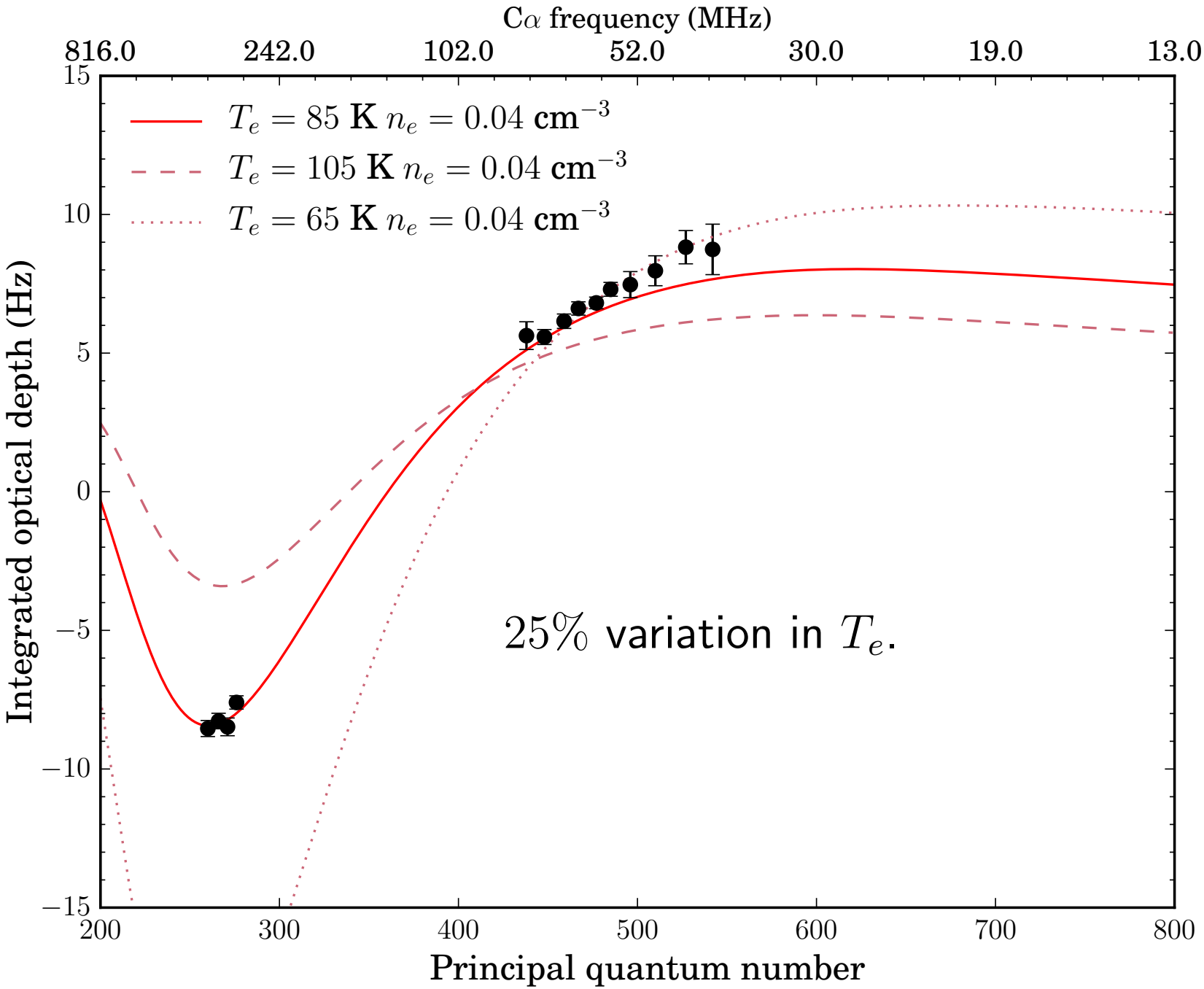
→ Spontaneous emission.

→ Stimulated emission and absorption.

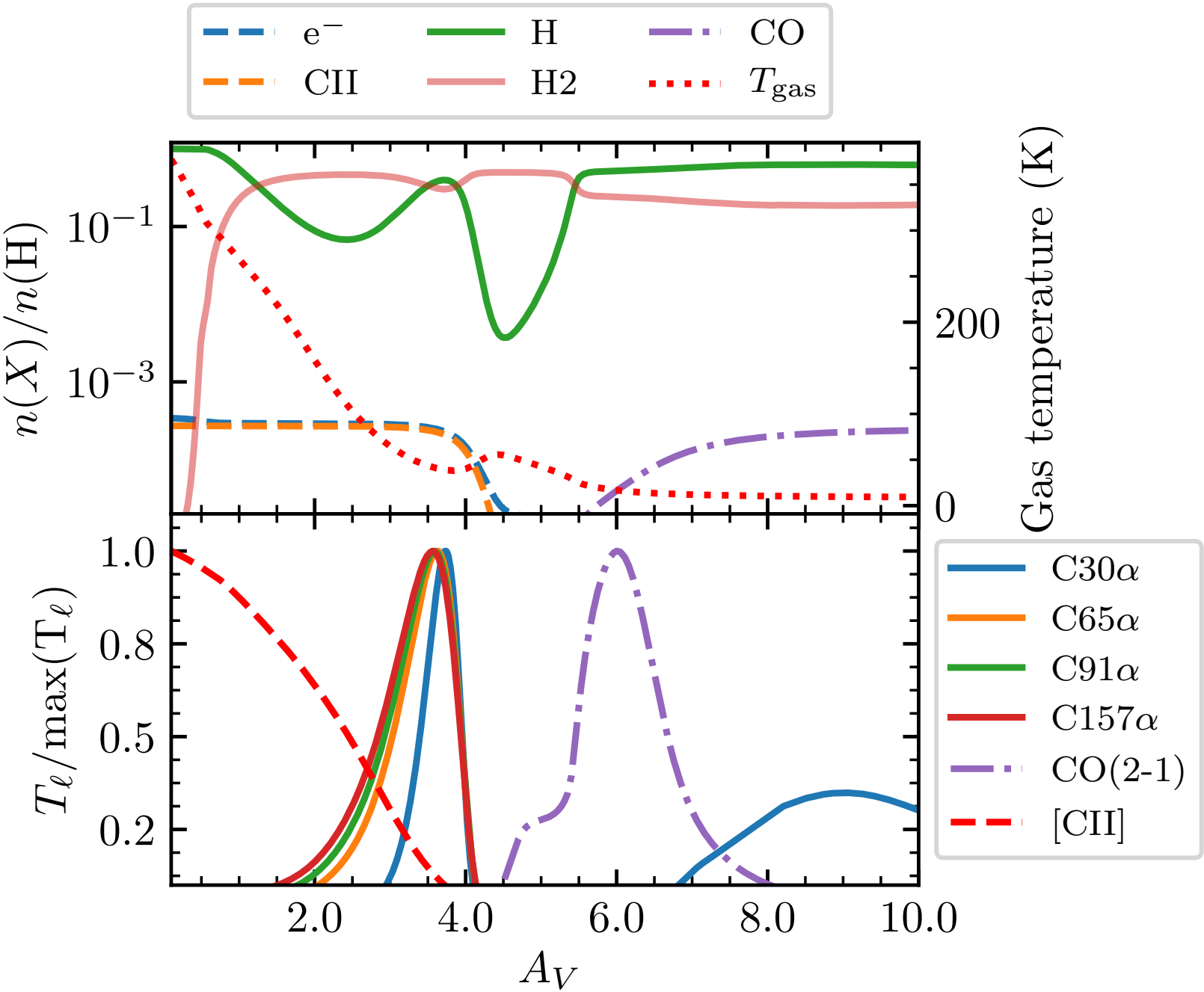
→ b_n and $\beta_{nn'}$ depend on atomic physics and physical conditions.


Cα frequency (MHz)
816.0
242.0
102.0
52.0
30.0
19.0
13.0
$T_e = 85$ K $n_e = 0.04$ cm^{-3}
$T_e = 85$ K $n_e = 0.05$ cm^{-3}
$T_e = 85$ K $n_e = 0.03$ cm^{-3}
25% variation in n_e.
Integrated optical depth (Hz)
Principal quantum number
15
10
5
0
−5
−10
−15
200
300
400
500
600
700
800

Oonk+2017


Cα frequency (MHz)
816.0
242.0
102.0
52.0
30.0
19.0
13.0
$T_e = 85$ K $n_e = 0.04$ cm^{-3}
$T_e = 105$ K $n_e = 0.04$ cm^{-3}
$T_e = 65$ K $n_e = 0.04$ cm^{-3}
25% variation in T_e.
Integrated optical depth (Hz)
Principal quantum number
15
10
5
0
−5
−10
−15
200
300
400
500
600
700
800

Oonk+2017

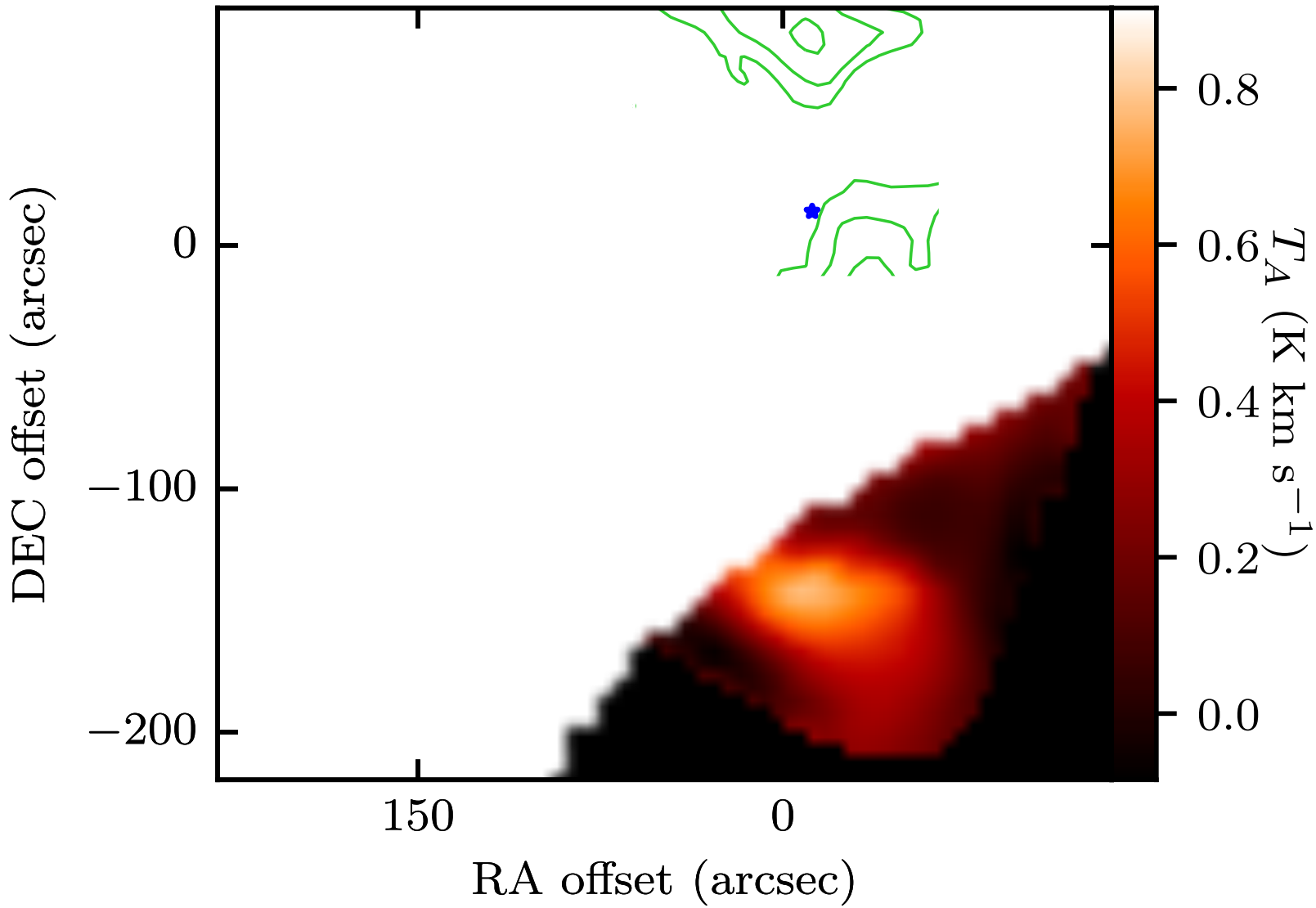

e⁻
CII
H
H2
CO
$T_{\rm gas}$
$n(X)/n(\mathrm{H})$
10^{-1}
10^{-3}
200
0
Gas temperature (K)
$T_\ell/\max(\mathrm{T}_\ell)$
1.0
0.8
0.5
0.2
C30α
C65α
C91α
C157α
CO(2-1)
[CII]
2.0
4.0
6.0
8.0
10.0
A_V

Salas+2019

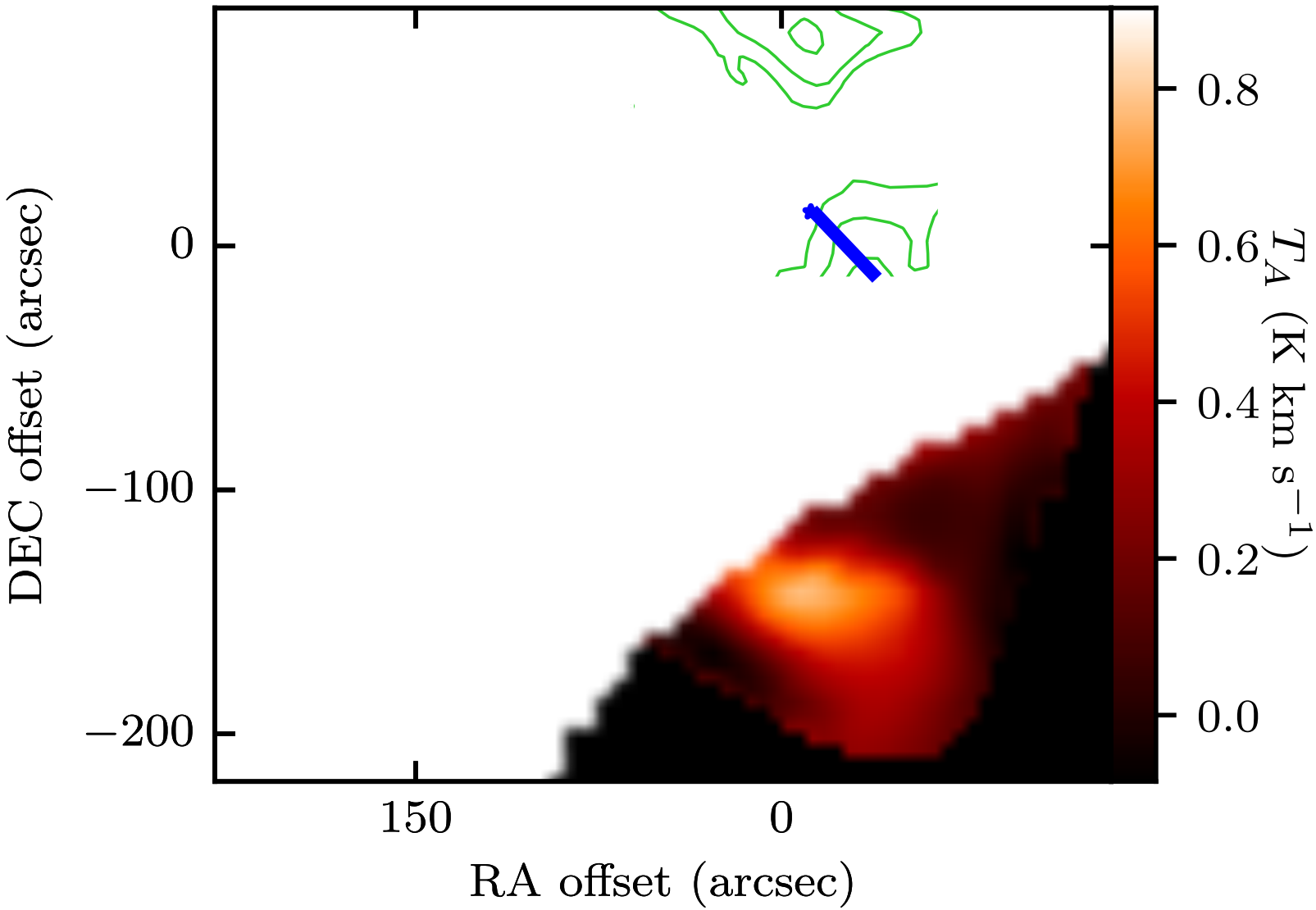
Vojtech Bauer

Observations

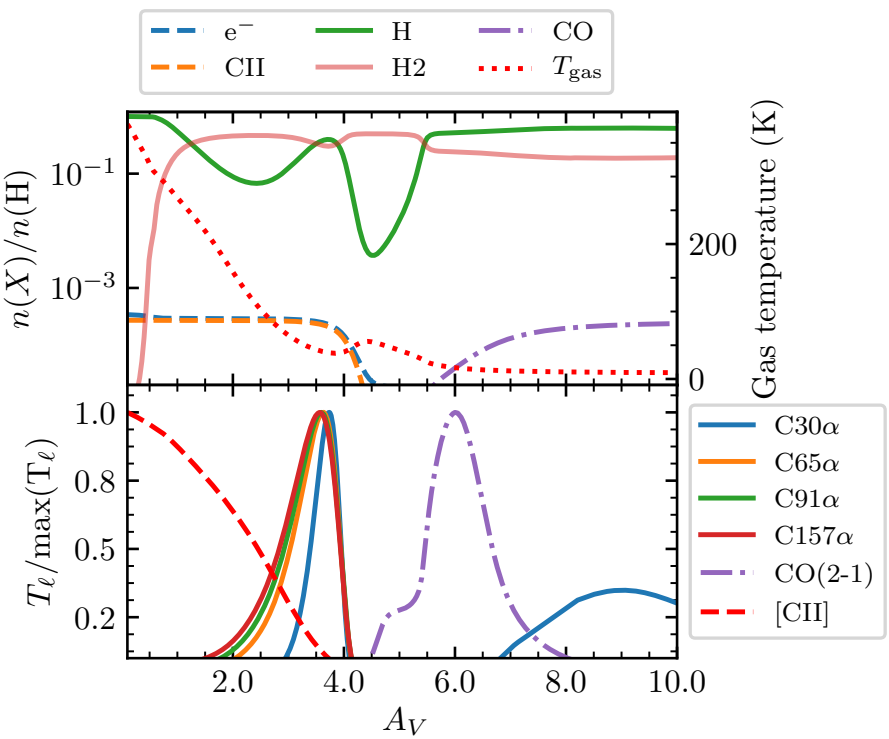
Line	Telescope	Angular resolution	Reference
[CII]	SOFIA	$16''$	Pabst+2019
C30α	ALMA TP	$28''$	Bally+2017
C65α	Effelsberg 100m	$40''$	Wyrowski+1997
C91α	VLA	$40''$	Wyrowski+1997
C137–280α	GBT	$4.5'$–$41'$	Salas+2019
C351α	LOFAR	$3'$	Salas+2019
C40α	IRAM 30m	$25''$	Cuadrado+2019
C50β	IRAM 30m	$25''$	Cuadrado+2019
C60γ	IRAM 30m	$29''$	Cuadrado+2019

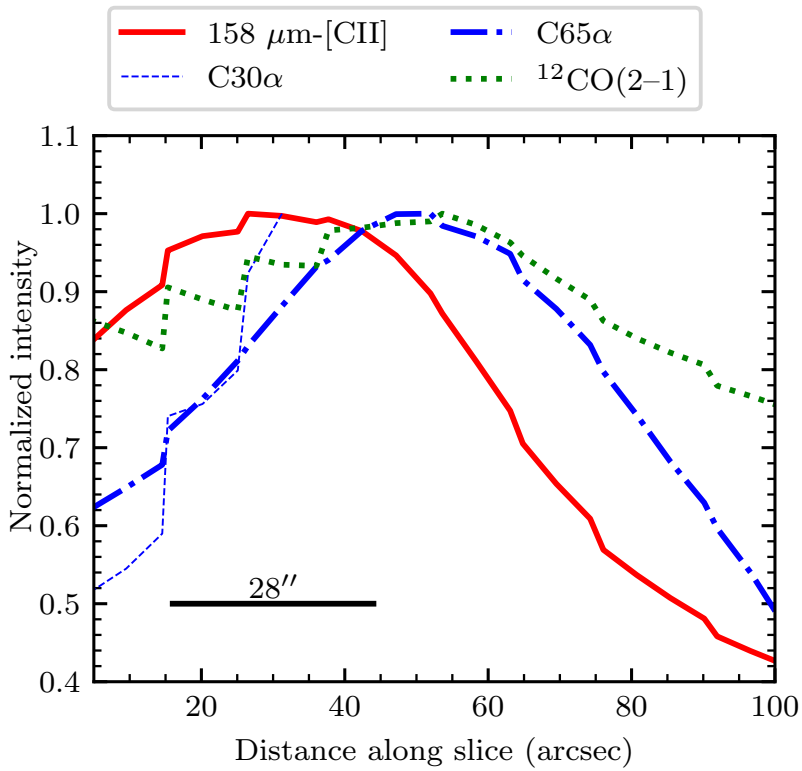

DEC offset (arcsec)
0
−100
−200
150
0
RA offset (arcsec)
0.8
0.6
0.4
0.2
0.0
T_A (K km s^{-1})

Salas+2019

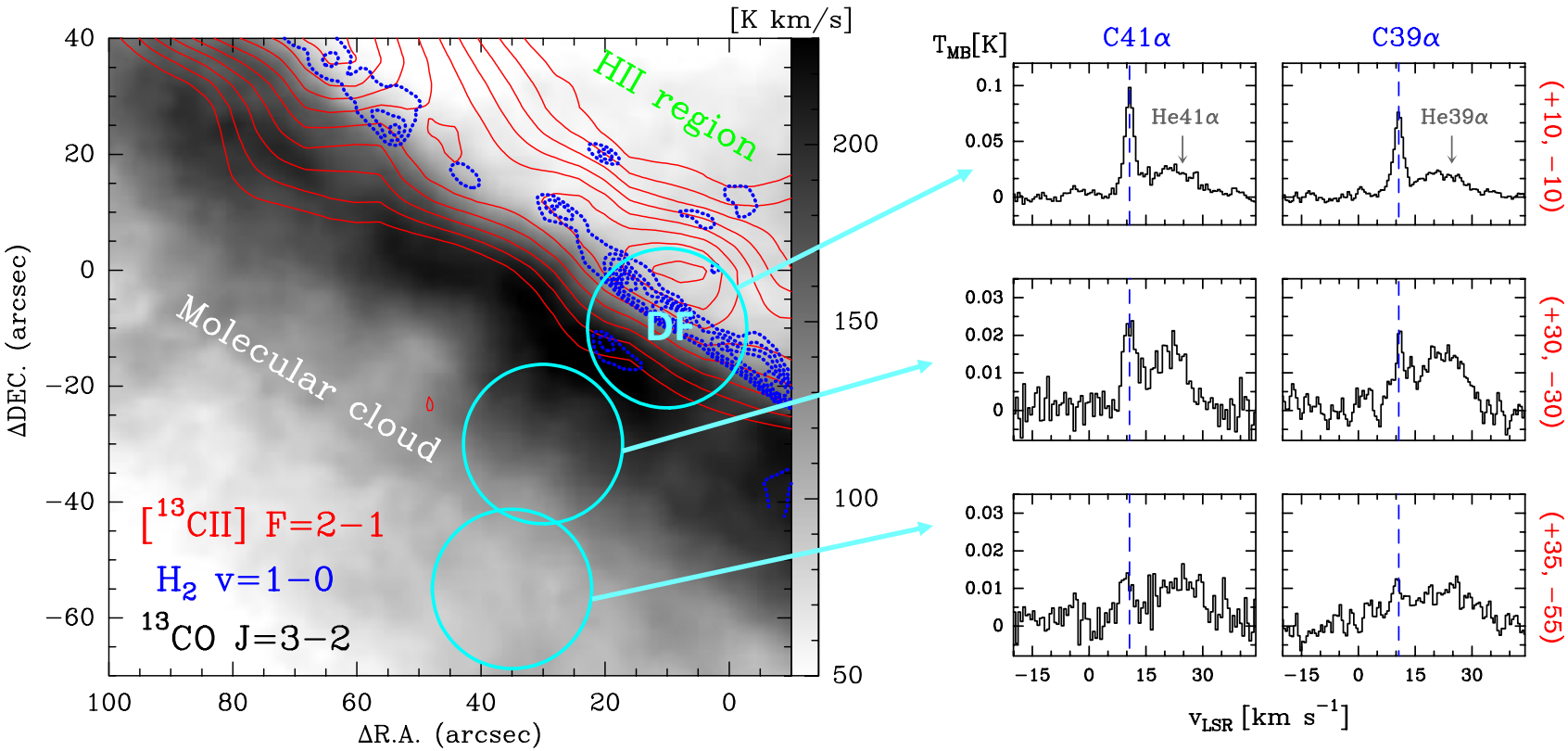

DEC offset (arcsec)
0
−100
−200
150
0
RA offset (arcsec)
0.8
0.6
0.4
0.2
0.0
T_A (K km s^{-1})

Salas+2019


e⁻
CII
H
H2
CO
T_{gas}
$n(X)/n(H)$
10^{-1}
10^{-3}
200
0
Gas temperature (K)
$T_\ell/\max(T_\ell)$
1.0
0.8
0.5
0.2
2.0
4.0
6.0
8.0
10.0
A_V
C30α
C65α
C91α
C157α
CO(2-1)
[CII]

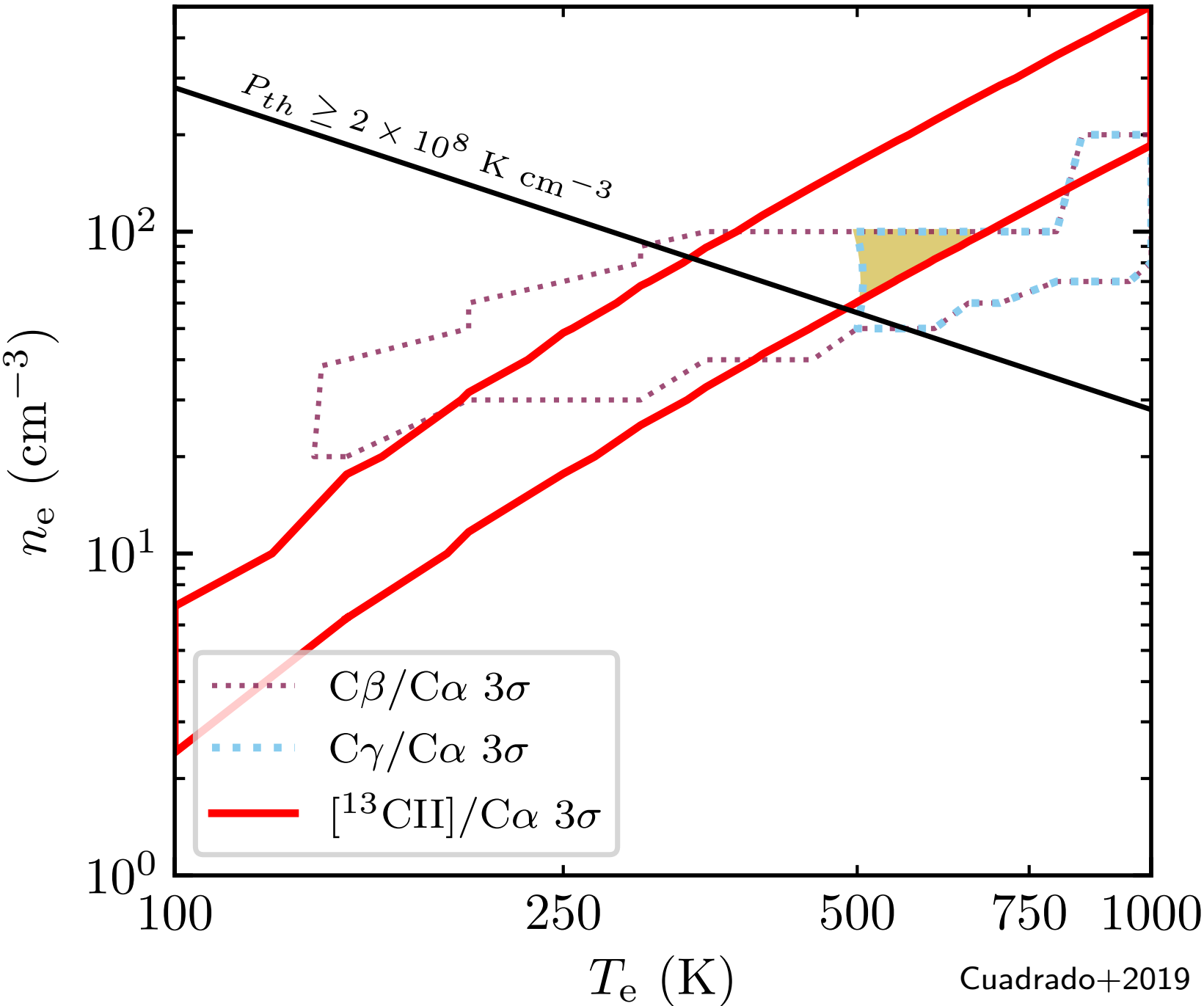

158 μm-[CII]
C30α
C65α
^{12}CO(2–1)
Normalized intensity
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
28″
20
40
60
80
100
Distance along slice (arcsec)

Orion's bar



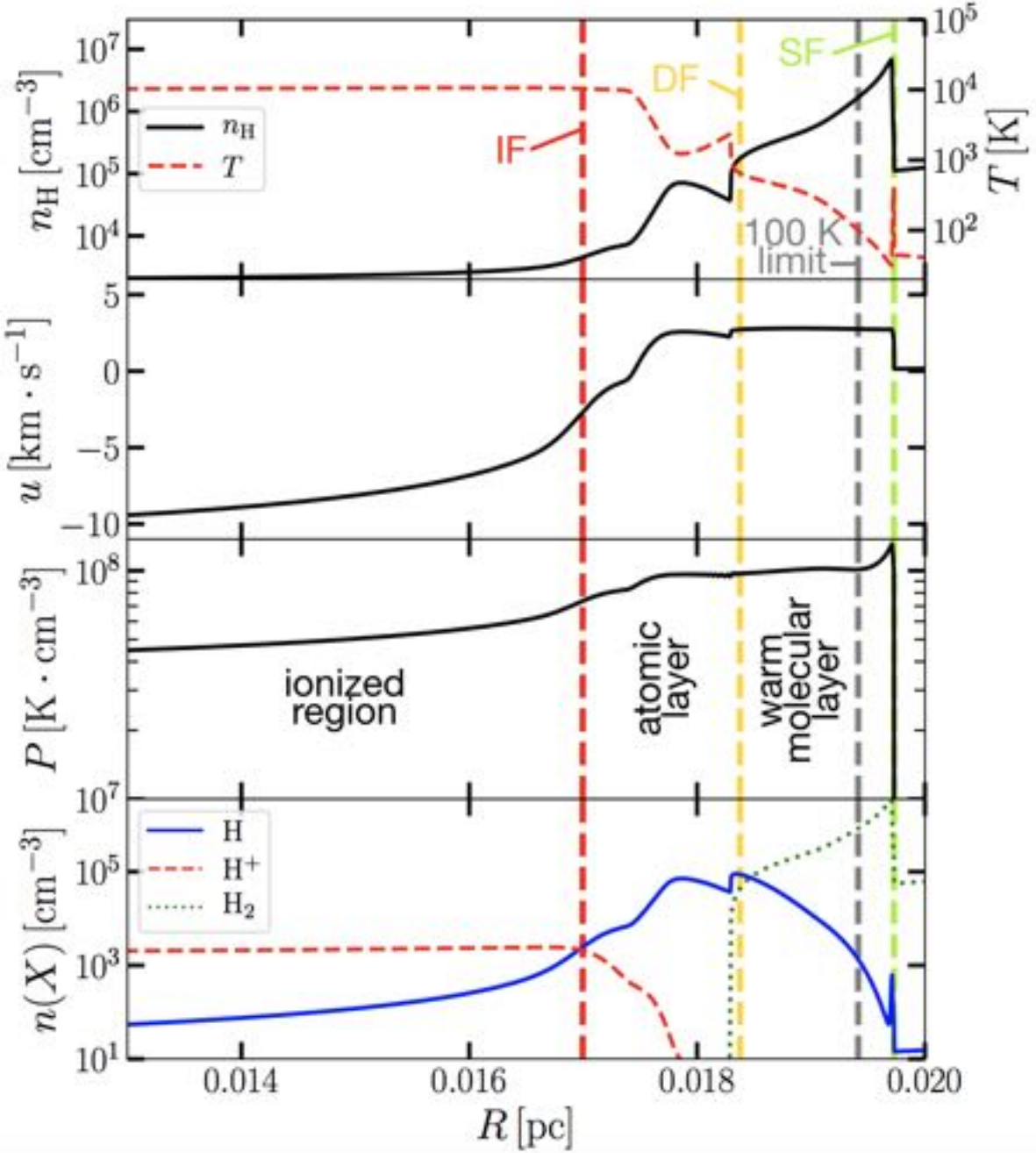
Cuadrado+2019

Orion's bar



Cuadrado+2019

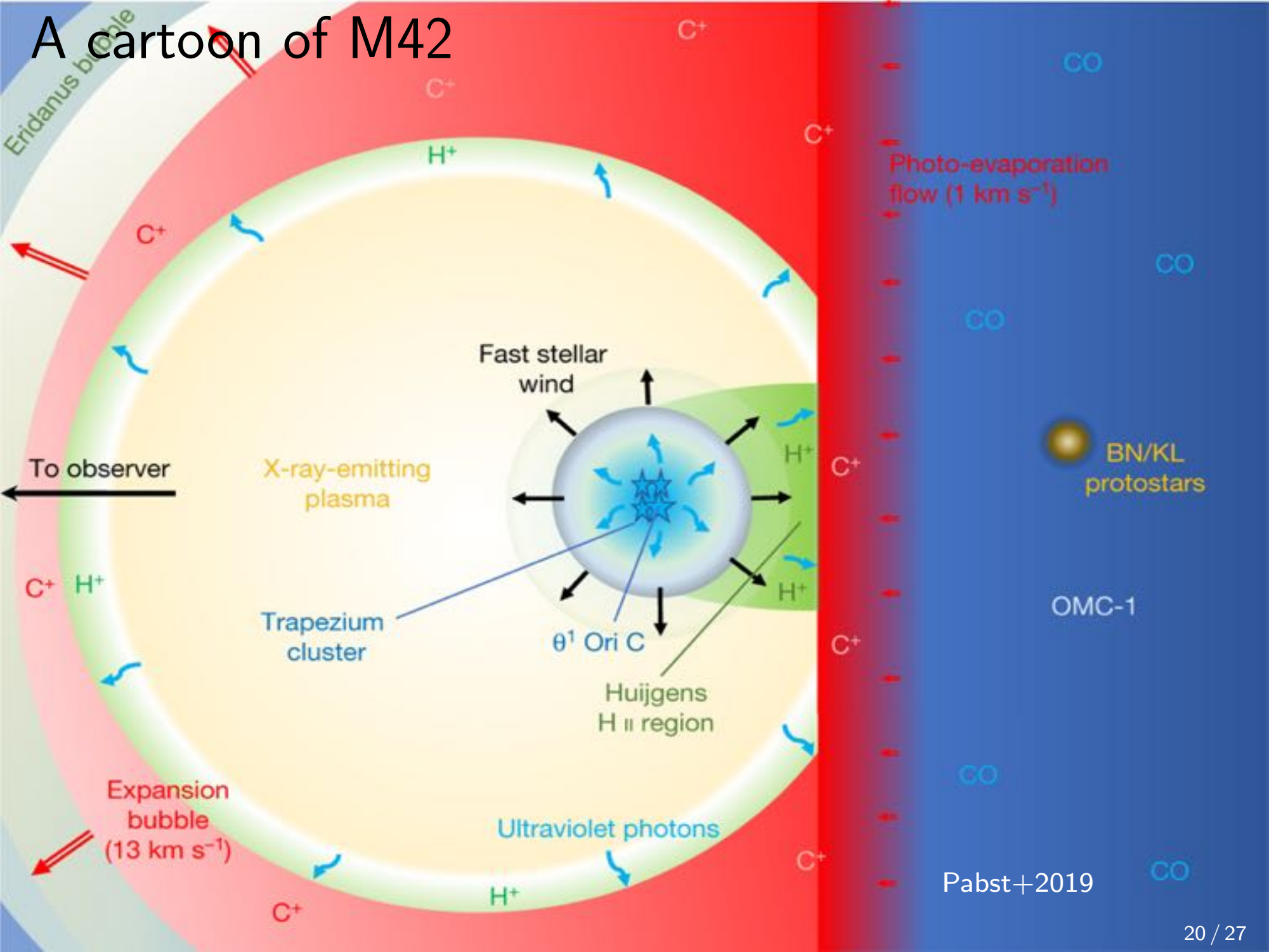
Orion's bar



Phase	Pressure (K cm^{-3})
HIM	10^5–10^6
HII	10^6–10^8
C$^+$/CI	$(2\text{–}8) \times 10^8$
CO	$\sim 3 \times 10^8$

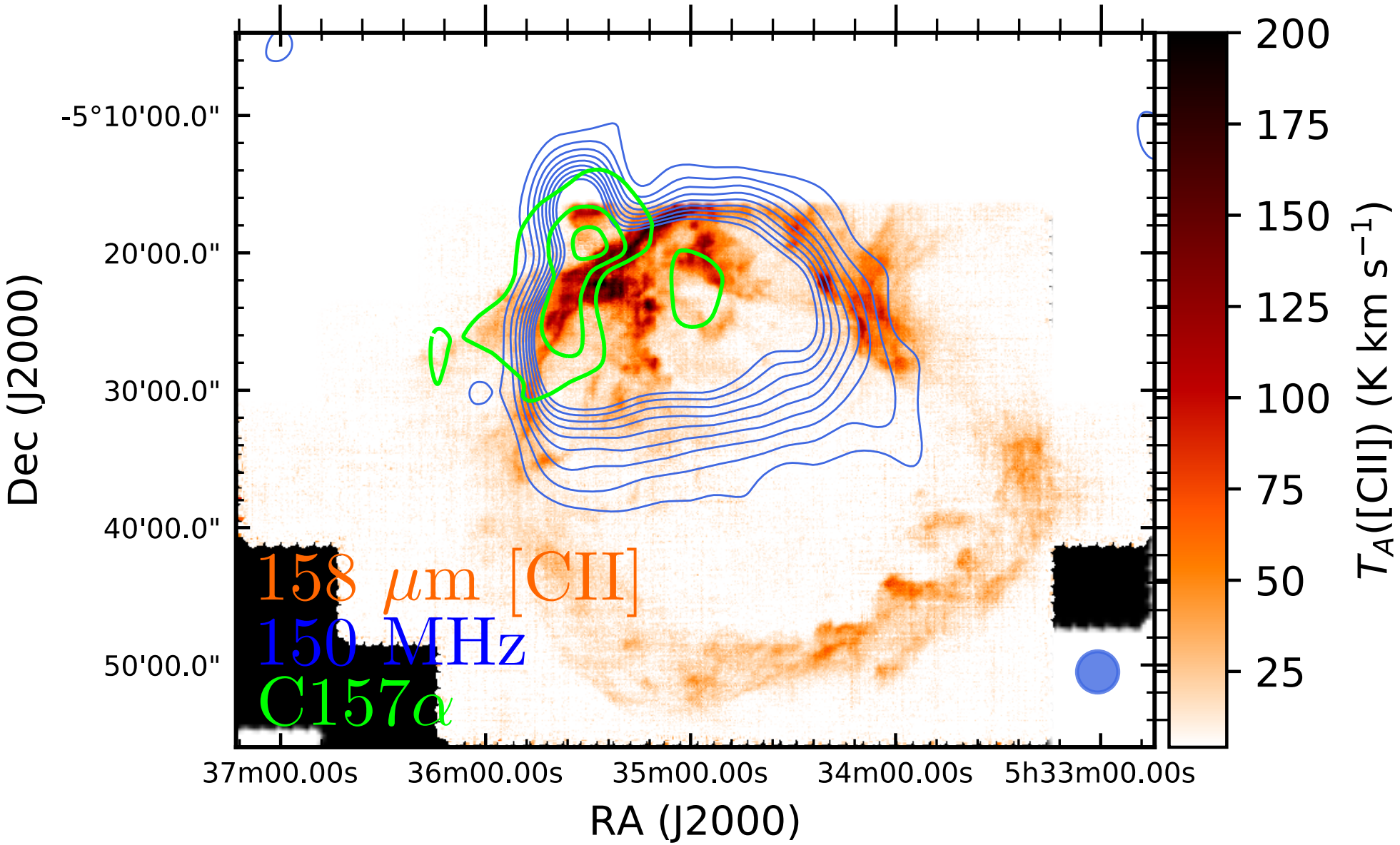
Bron+2018

A cartoon of M42



Pabst+2019

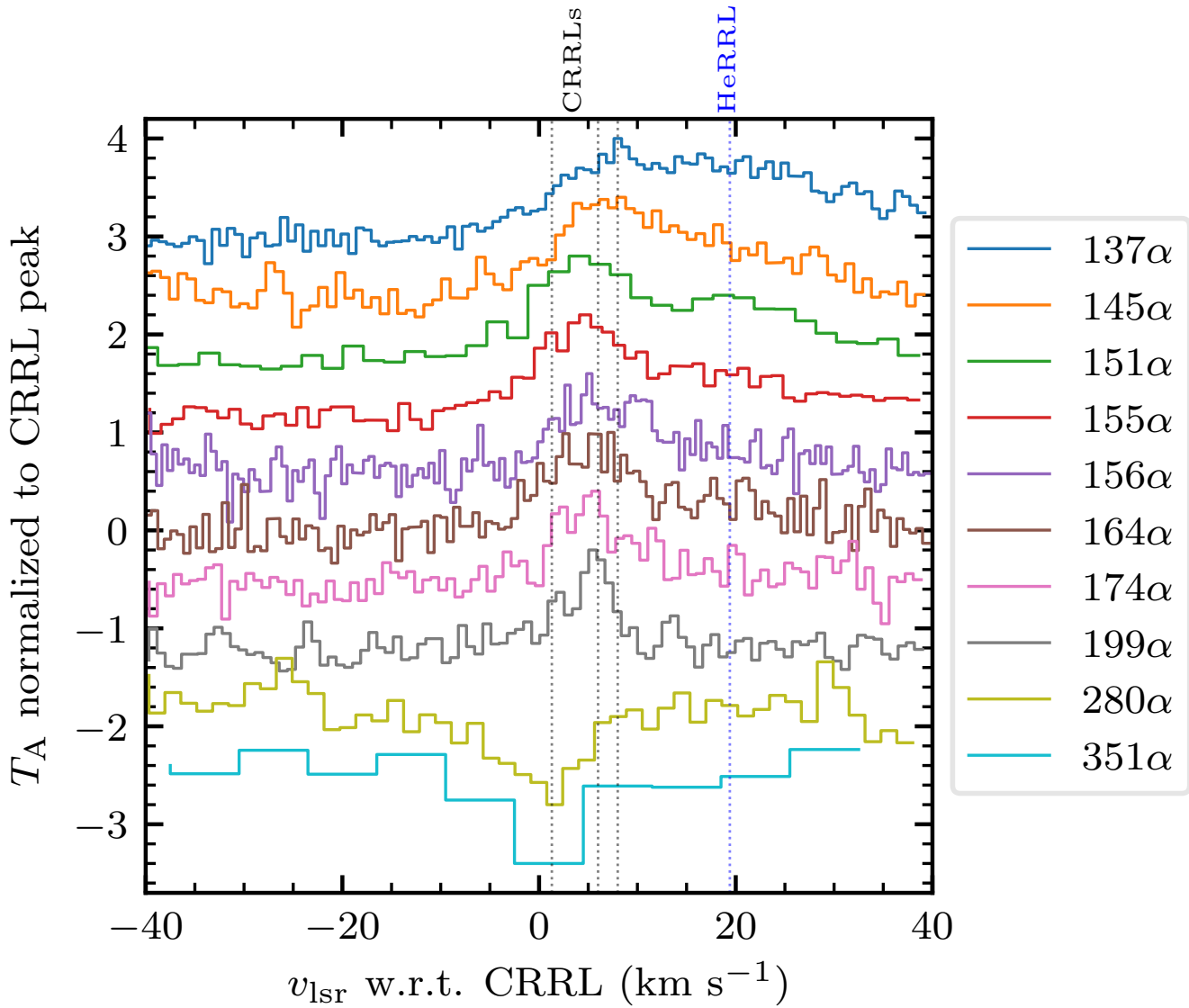
Orion's veil



Salas+2019

Orion's veil

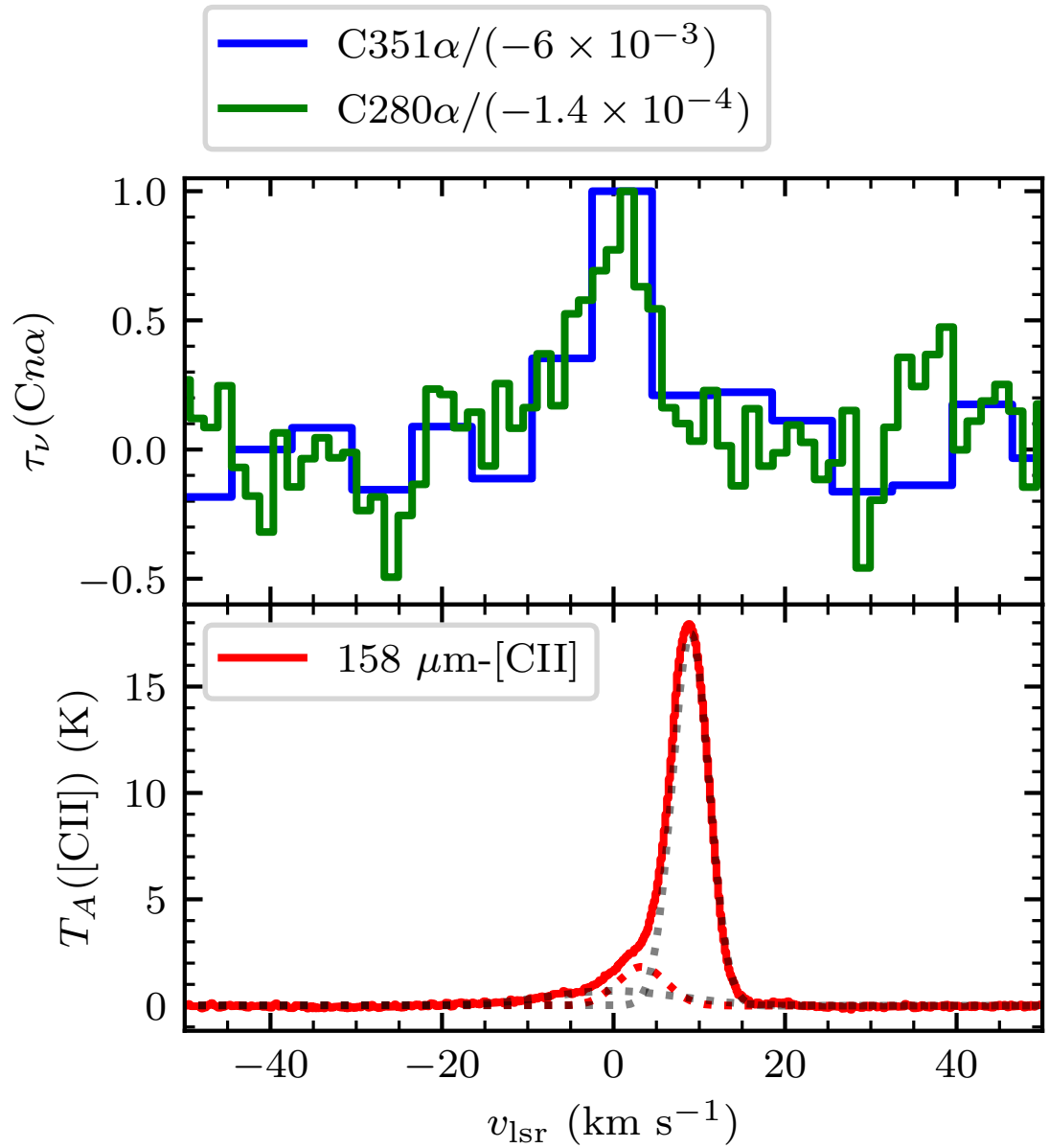
CRRL spectra



Salas+2019

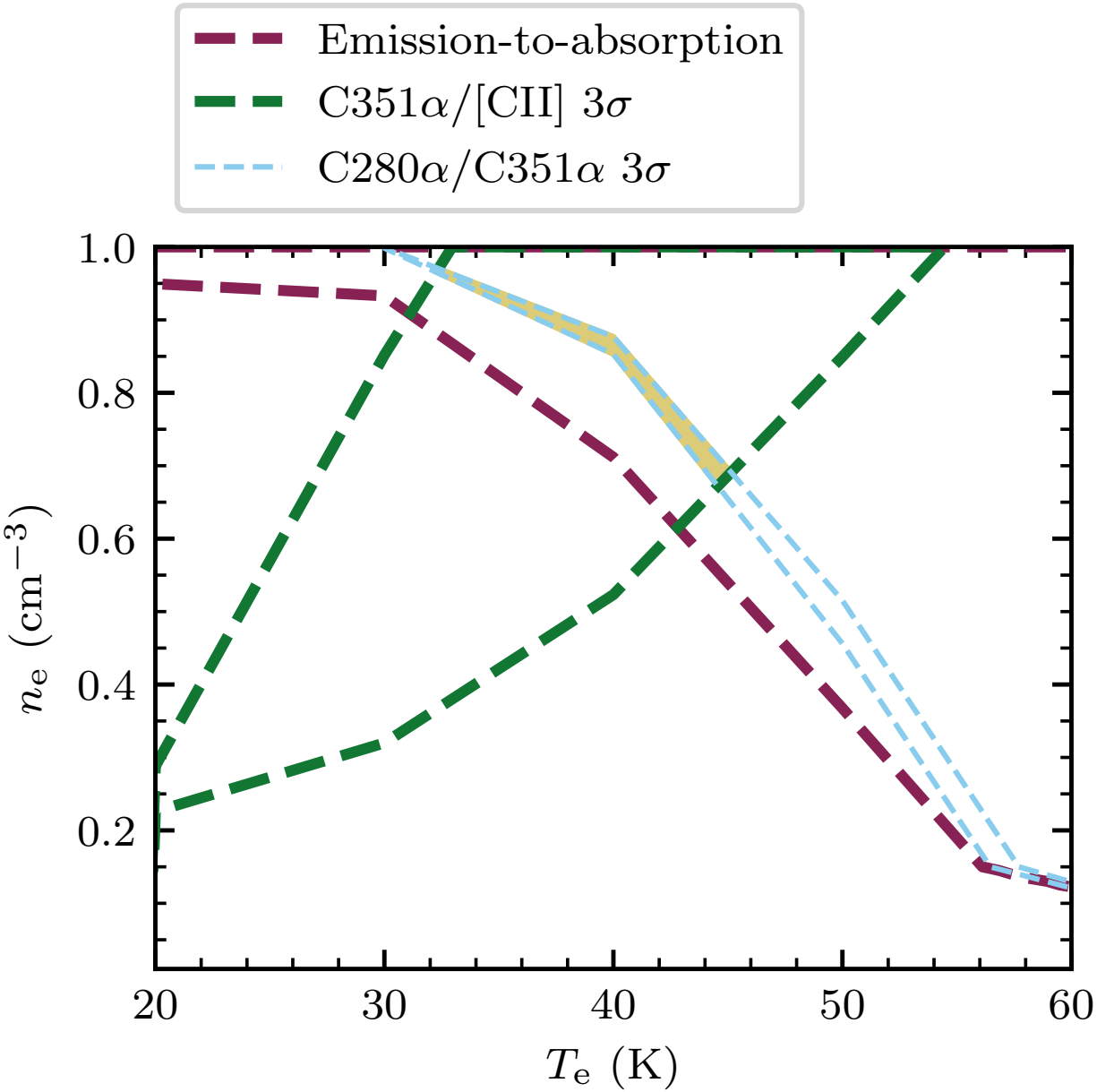
Orion's veil

[CII] and CRRLs



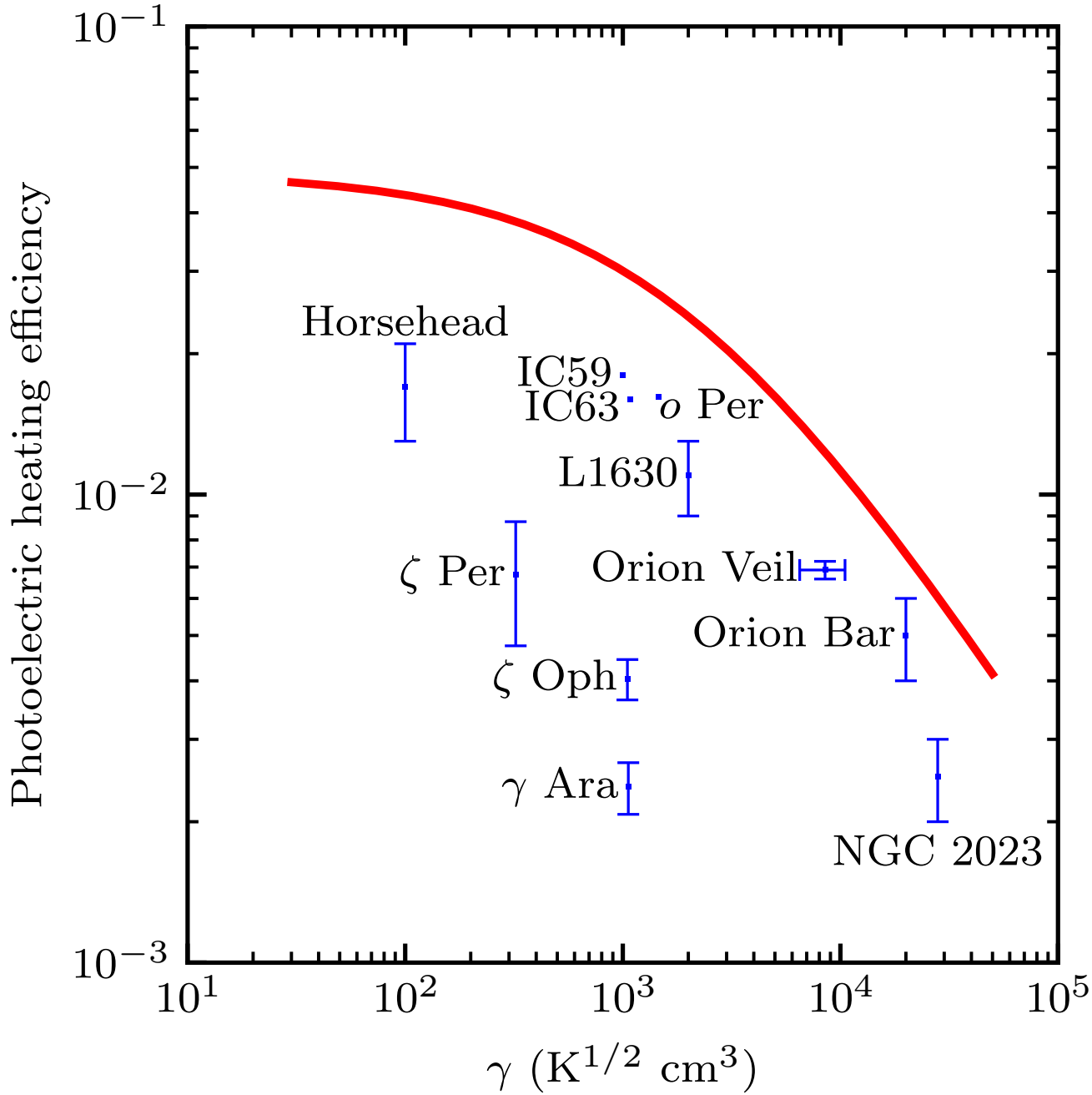
Salas+2019

Orion's veil



Salas+2019

Gas heating efficiency



Salas+2019

Summary

- PDRs are important as tools and laboratories to understand the ISM.
- Through FIR [CII] and CRRLs we can study the C^+/CI interface in PDRs; its kinematics and energetics.
- We will study a larger sample of HII regions to determine how the thermal pressure and heating efficiency change with environment.
- Higher angular resolution ($\lesssim 1''$) observations of CRRLs, or atomic carbon, are required to determine the distance between the C^+ and CO layer.


Thanks for
tuning in!