The PDR structure and kinematics around the compact HII regions S235 A and S235 C with [CII], [^{13}CII], [OI] and HCO^+ line profiles

Maria S. Kirsanova

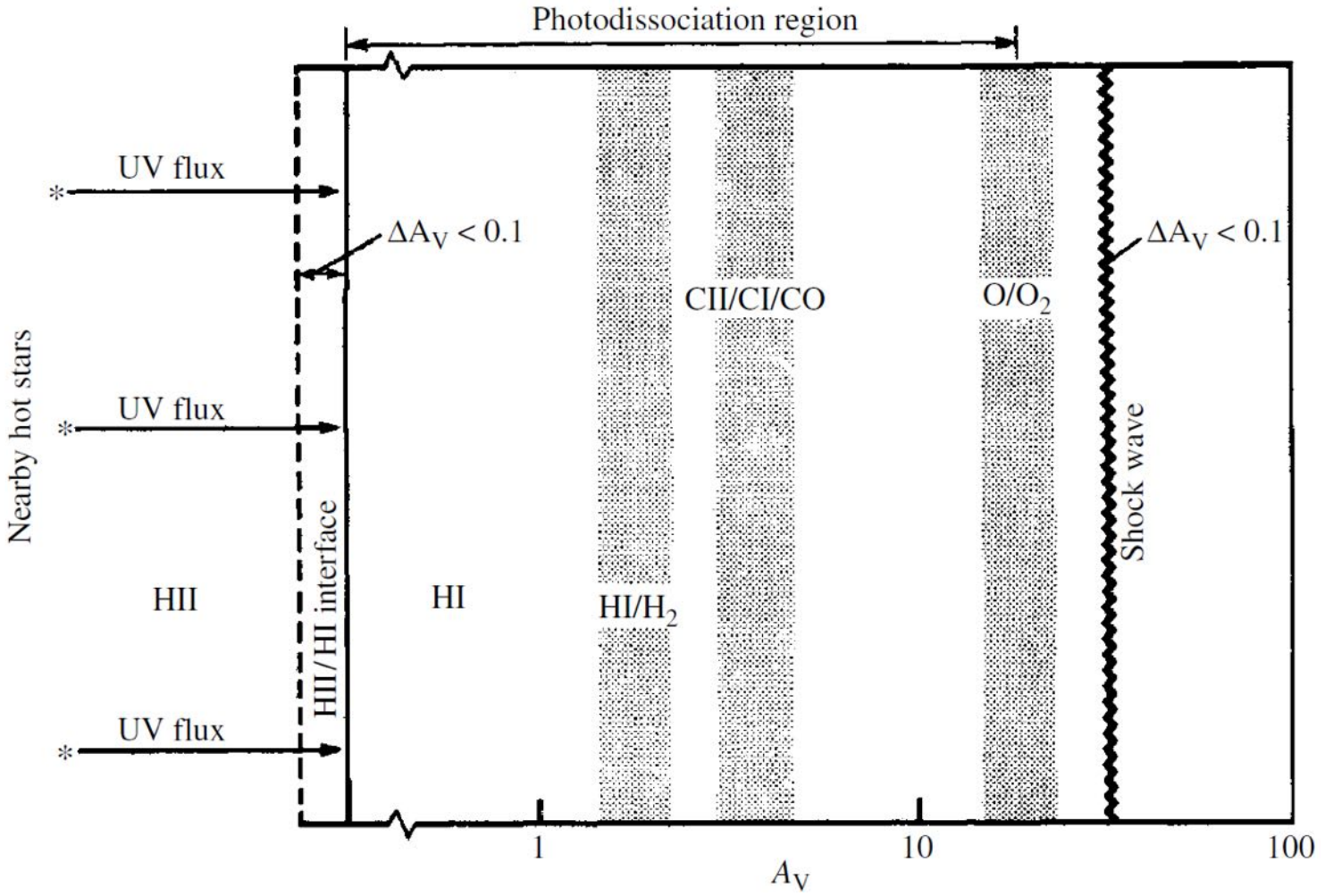
Institute of Astronomy, Russian Academy of Sciences

SOFIA tele-talk
November 4, 2020

in collaboration with:
Ossenkopf-Okada, V., Anderson, L. D., Boley, P. A., Bieging, J. H., Pavlyuchenkov, Ya N., Luisi, M., Schneider, N., Andersen, M., Samal, M. R., Sobolev, A. M., Buchbender, C., Aladro, R., Okada, Y.

paper: 2020 MNRAS 497 2651

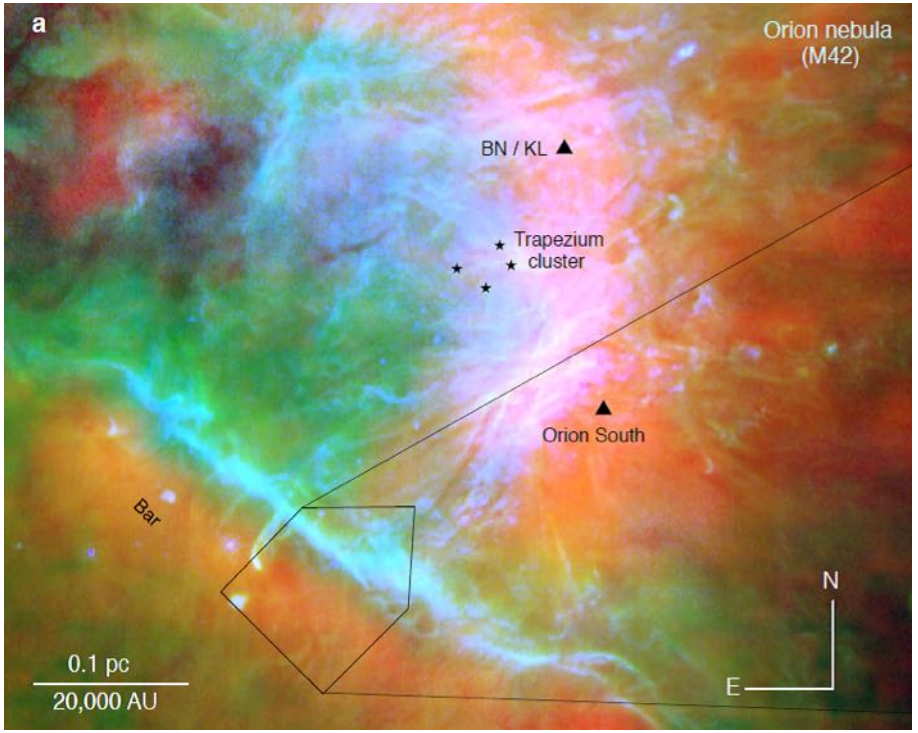
Photodissociation regions:



Tielens & Hollenbach, 1985

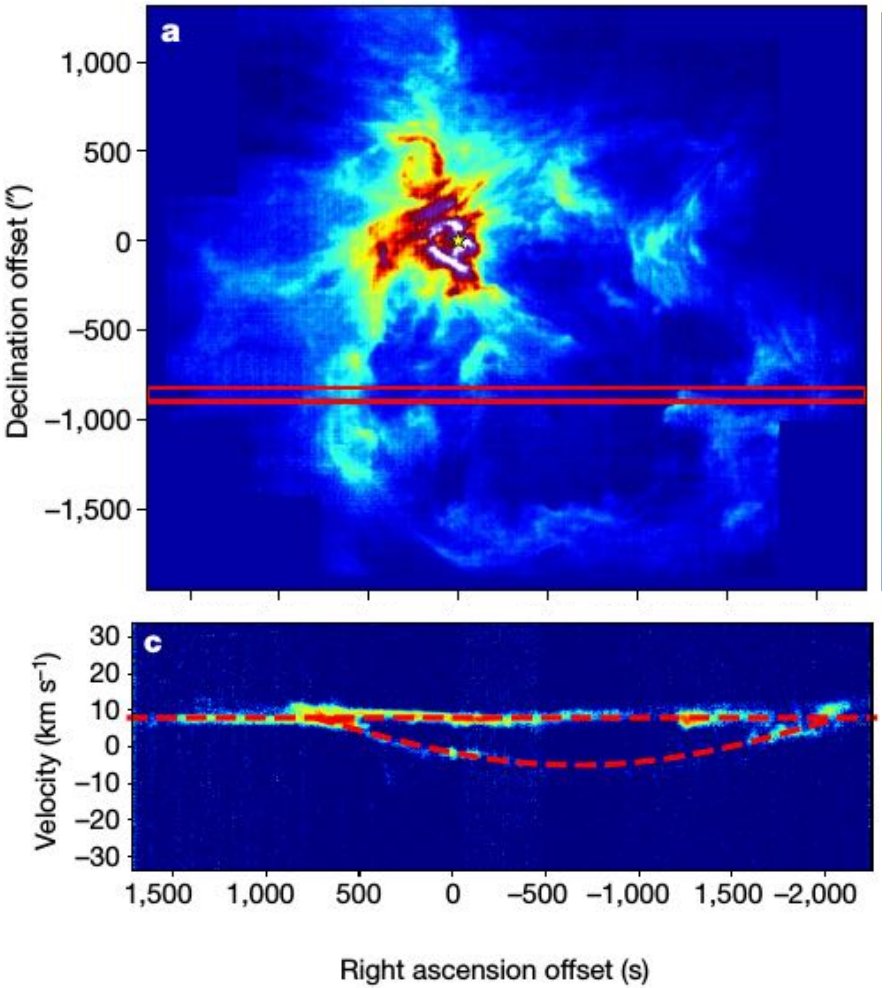
Expanding HII regions → expanding PDRs

- Recent observations:



Indirect: no separation between the H_2 and CO dissociation fronts

Goicoechea et al., 2016

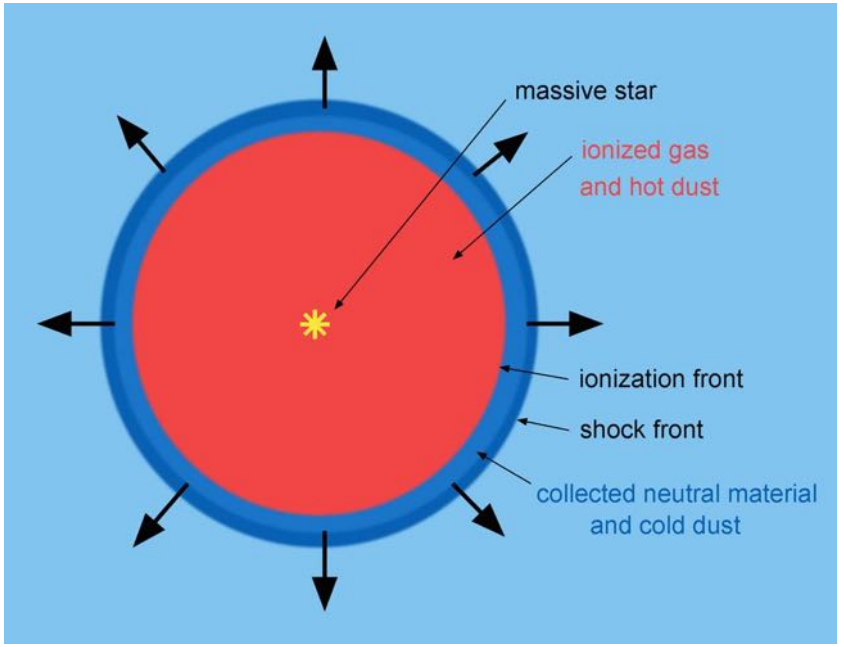


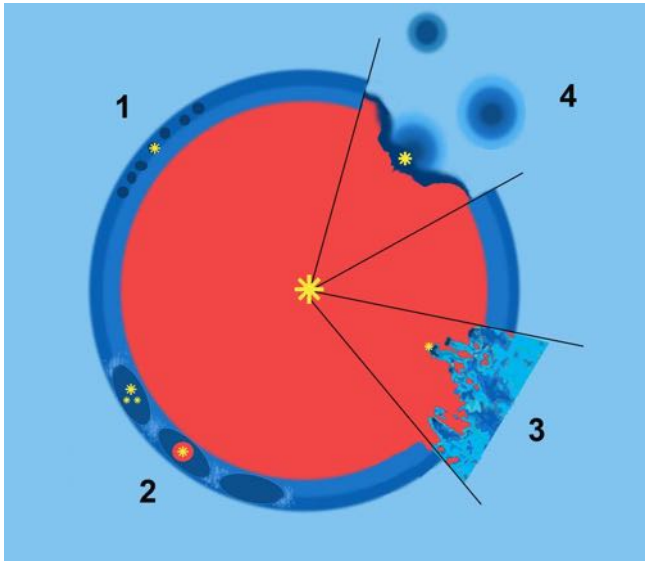
Direct: [CII] 158 micron pv diagram

Pabst et al., 2019, 2020

Expanding HII regions → expanding PDRs

- Time-dependent PDR models:





1D spherical or plane-parallel geometry

Hosokawa & Inutsuka, 2005
Kirsanova et al., 2009
Bron et al., 2018

non-uniform density structure

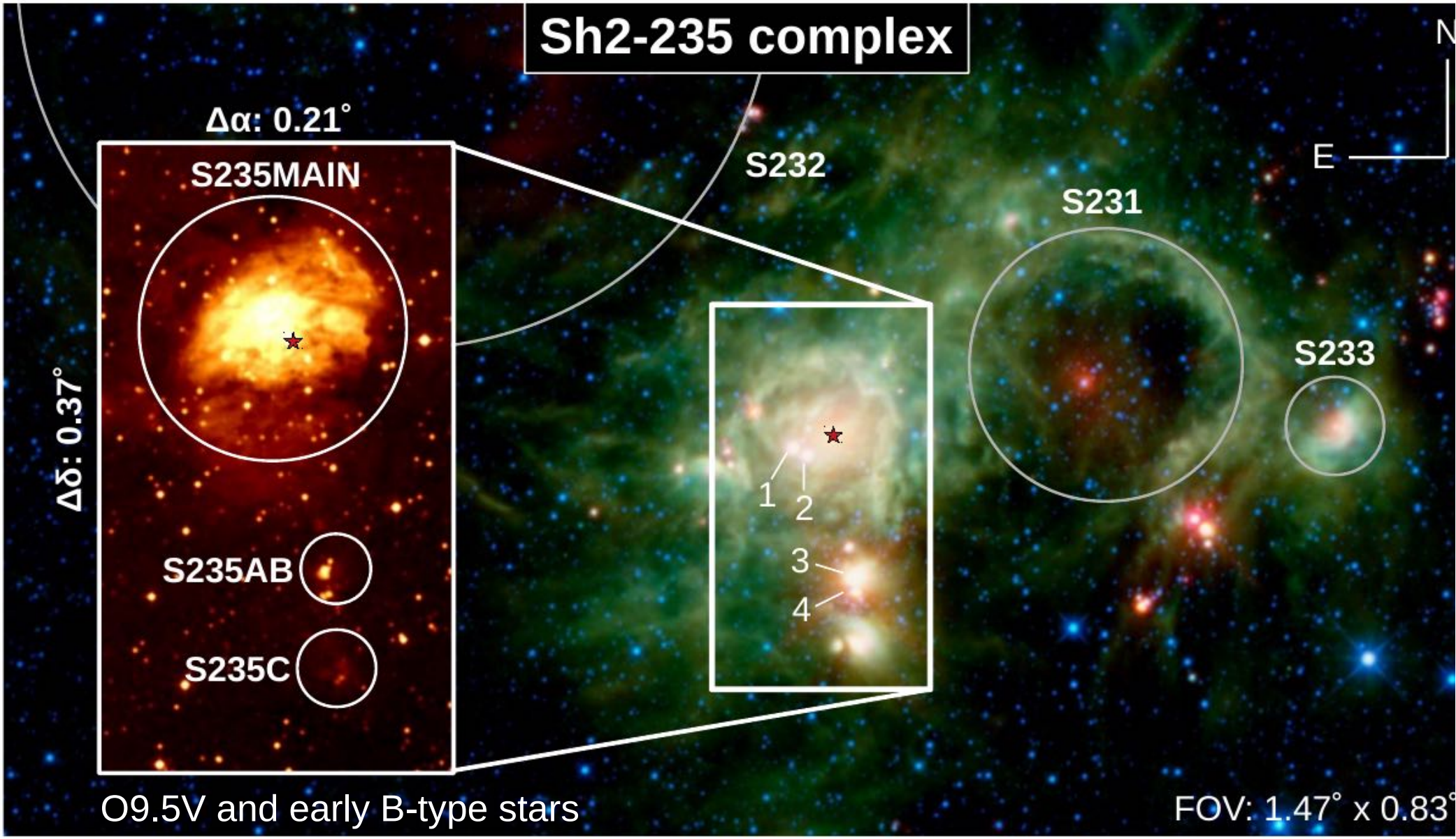
Krumholz et al., 2007
Peters et al., 2010
Arthur et al., 2011

images: Deharveng et al., 2010

Aims of study

1) Study the geometry and gas kinematics in PDRs around two compact HII regions. Does the [CII] line trace the kinematics there?

2) Test whether the observed properties of the PDRs match the predictions of spherical models.

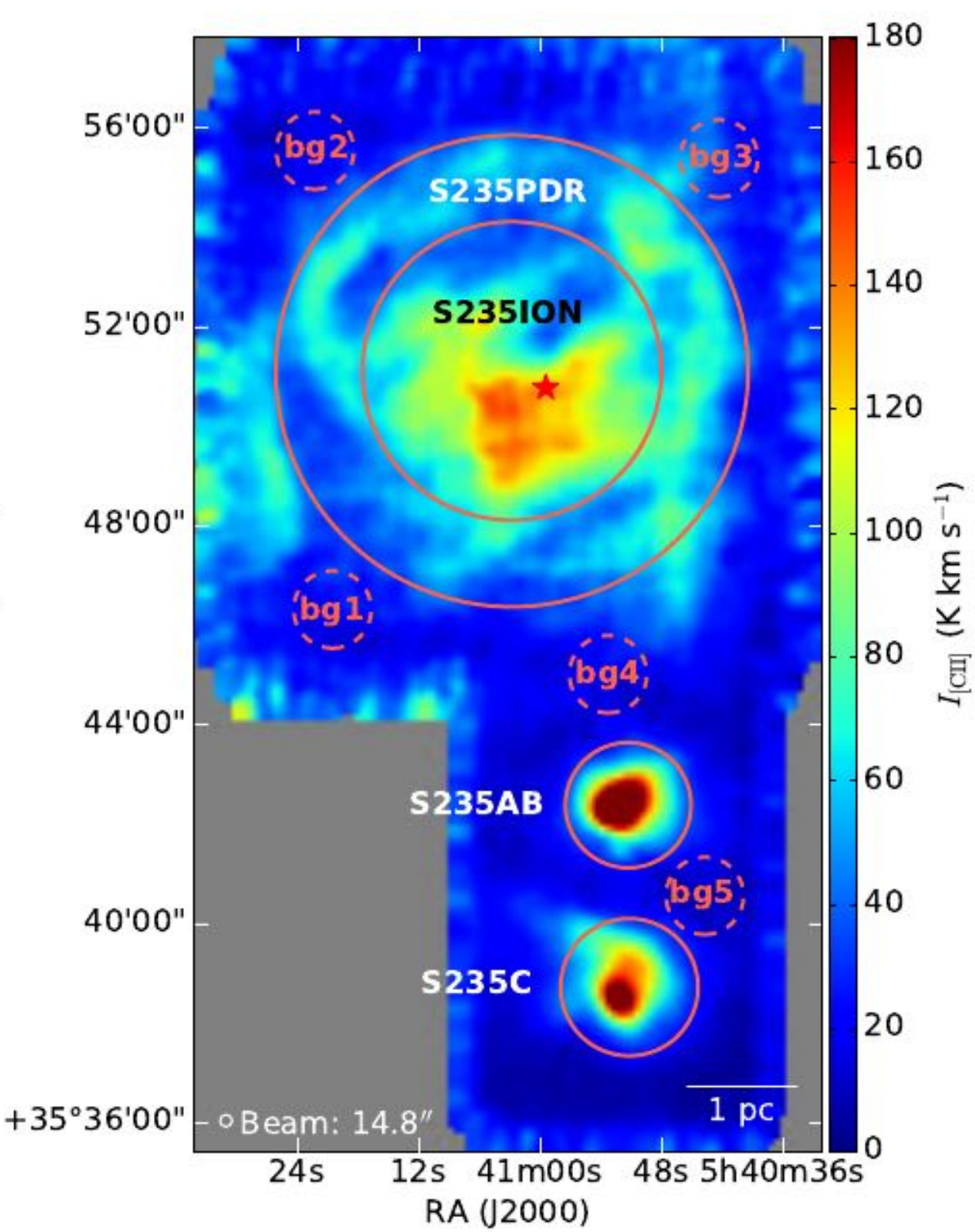


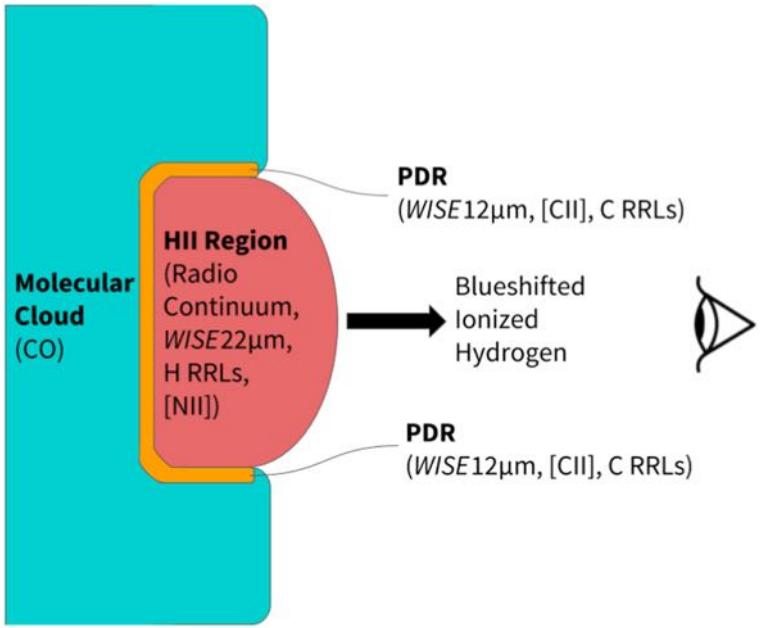
1.6 kpc, G174+2.5

Anderson et al., 2019

[CII] at 158 micron:

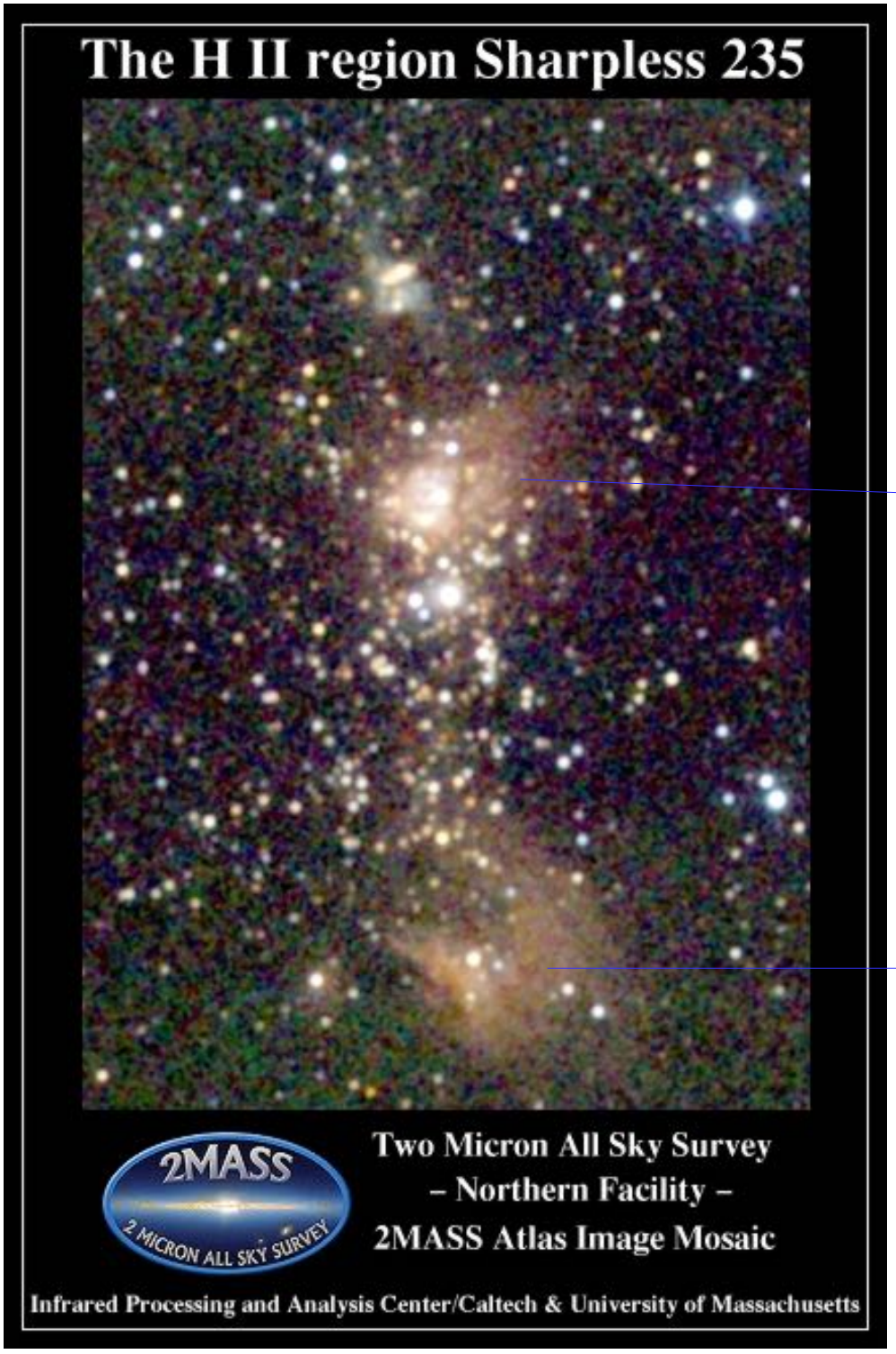
– no emission from the from neutral wall

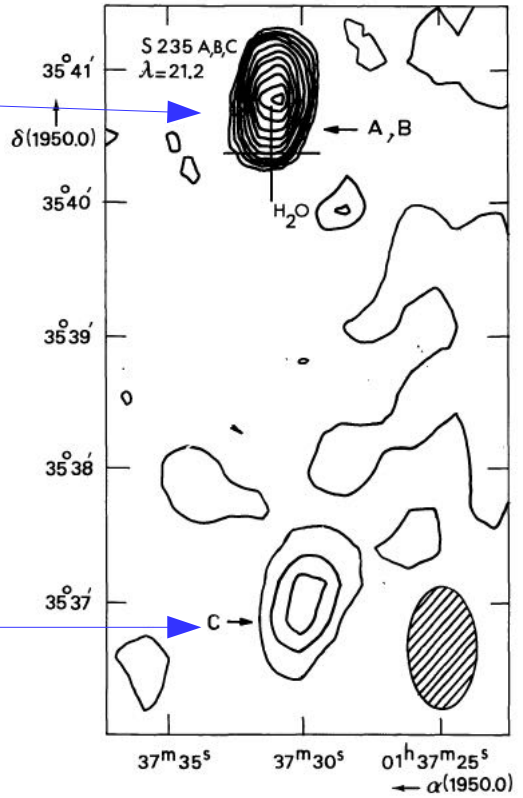




Anderson et al., 2019

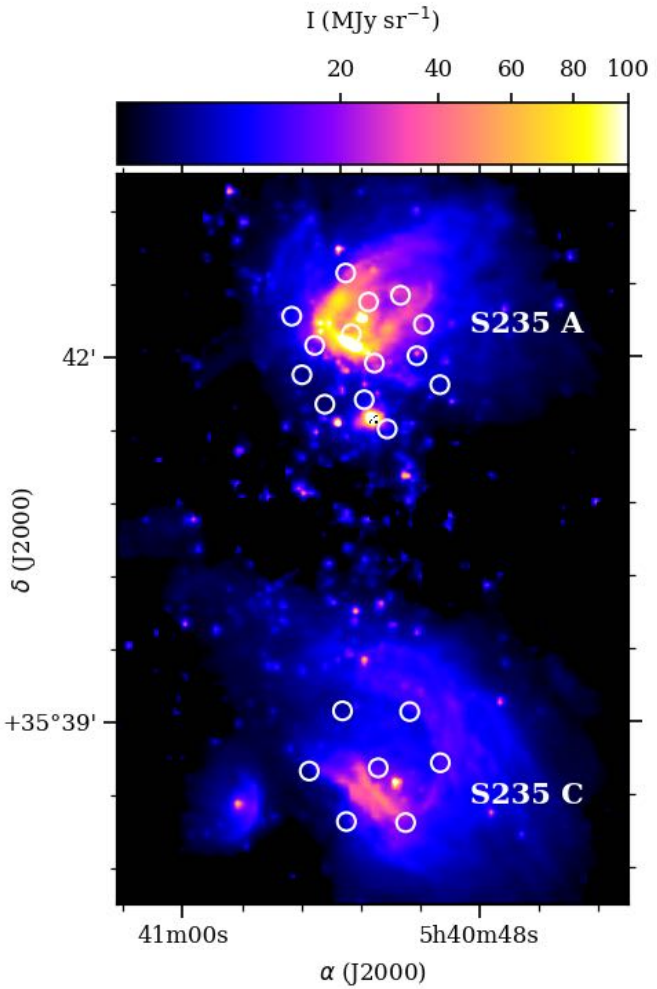
Compact HII regions S235A and S235C and a stellar cluster between them



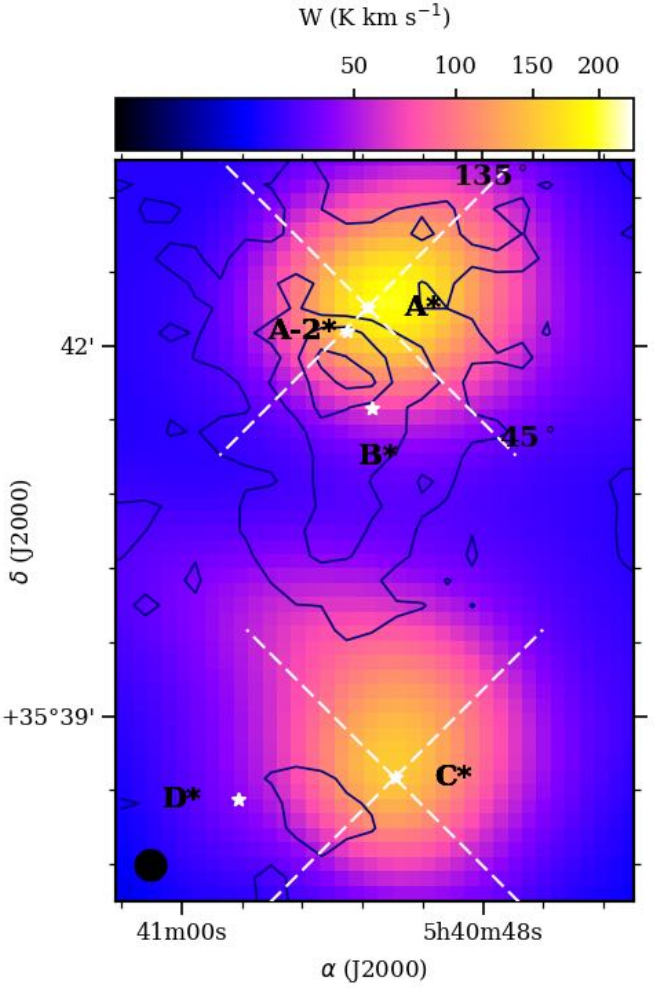


Israel & Felli, 1978

[^{13}CII] and [CII] at 158 micron, HCO^+(3–2) at 267 GHz



Spitzer 3.6 micron
+
SOFIA upGRADE deep integrations

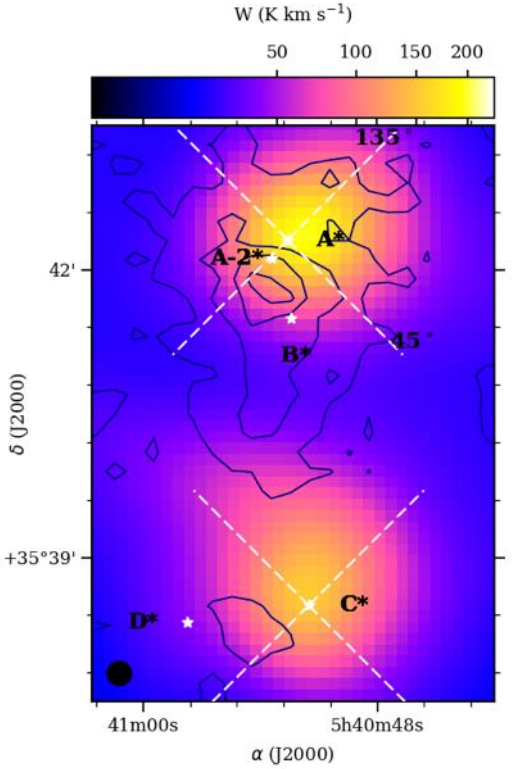


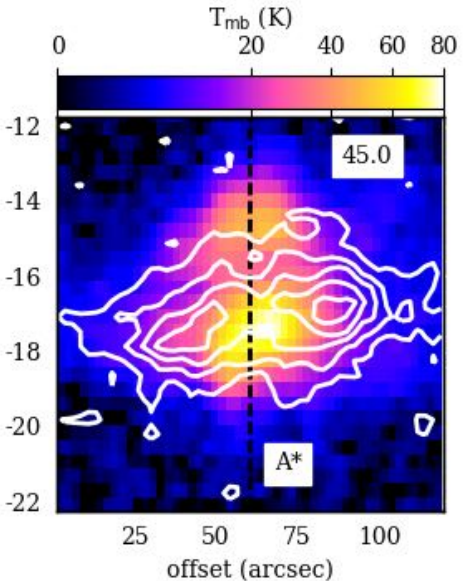
SOFIA [CII] line (colour)
+
SMT HCO^+(3–2) line (contours)

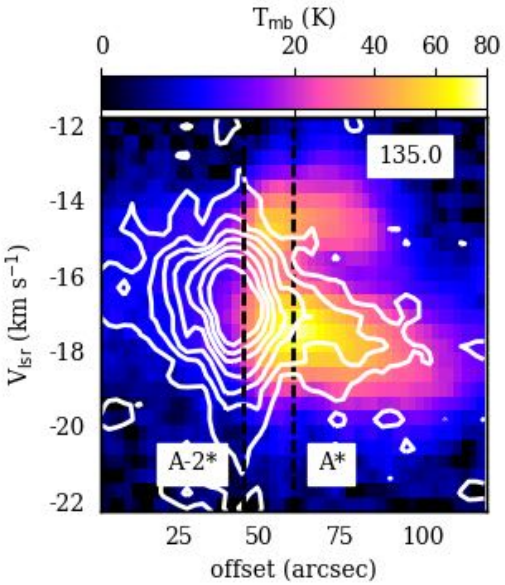
Pv diagrams for [CII] и HCO^+(3-2)

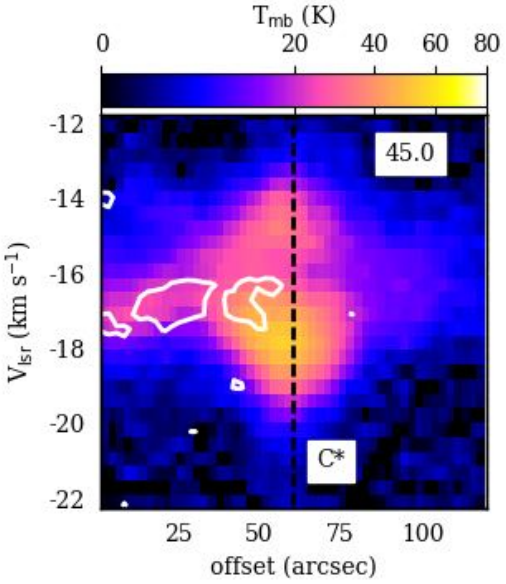
Do the PDRs expand with V_{exp} = 2 km s^{-1} ?

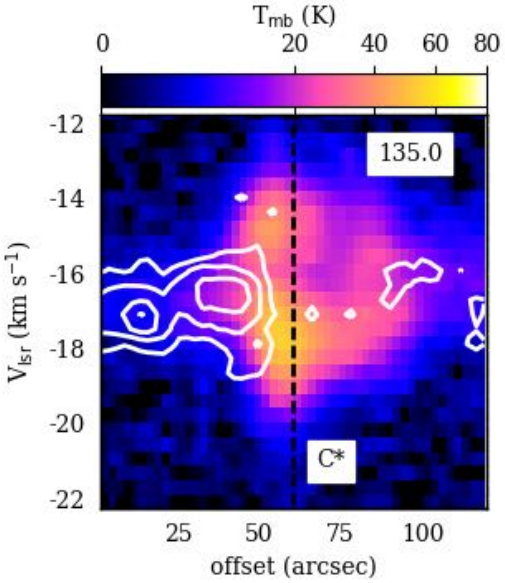
The [CII] profiles might be affected by self-absorption effect and do not trace expansion





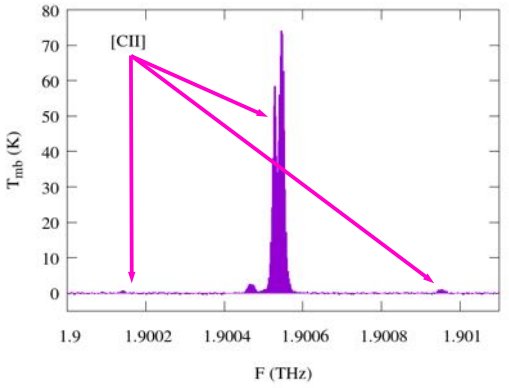


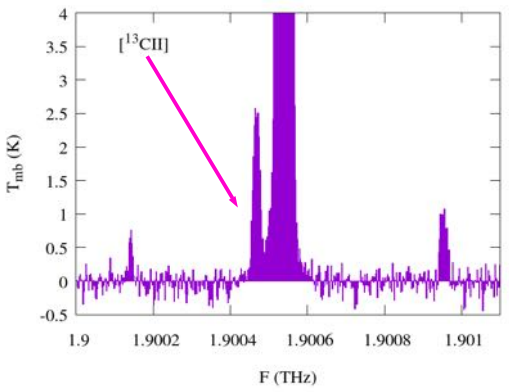


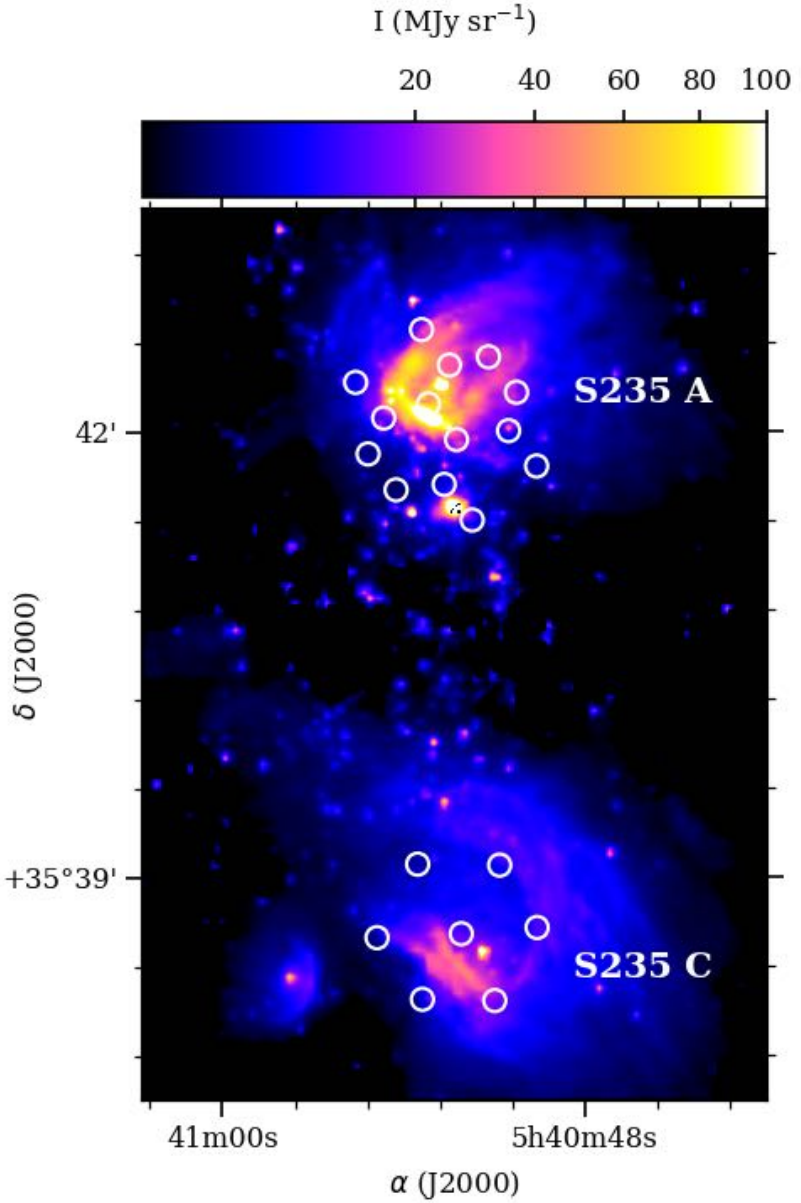


Deep integrations to observe [^{13}CII]

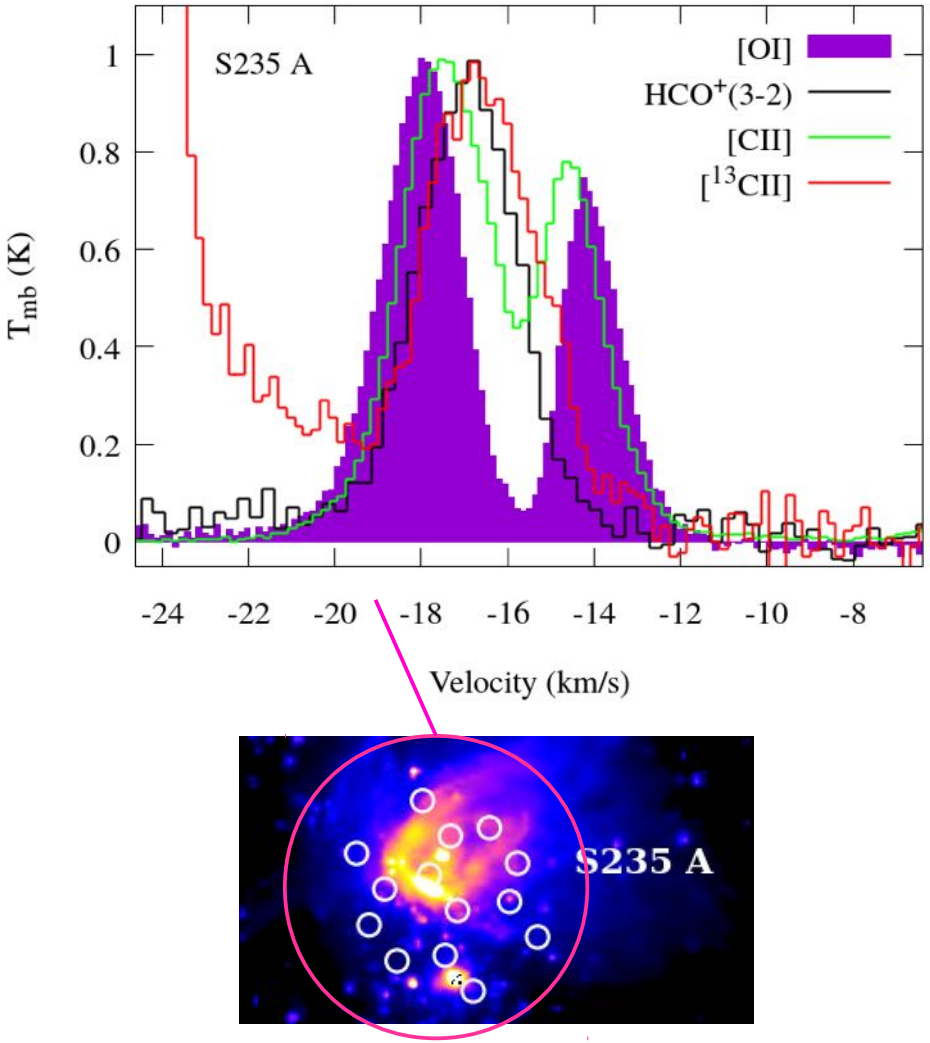
We observed additional positions in the [CII] and [^{13}CII] micron lines in order to determine the optical depth of the [CII] emission + [OI] line at 63 micron to estimate gas density.

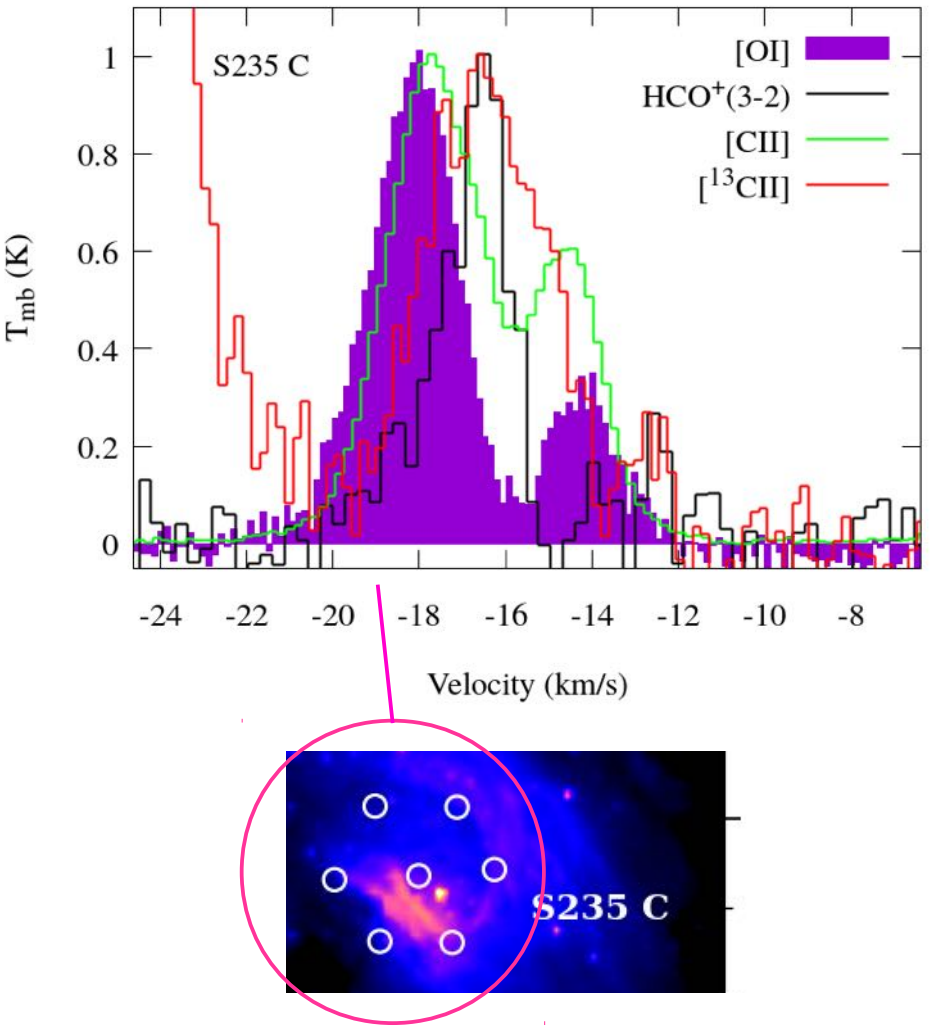






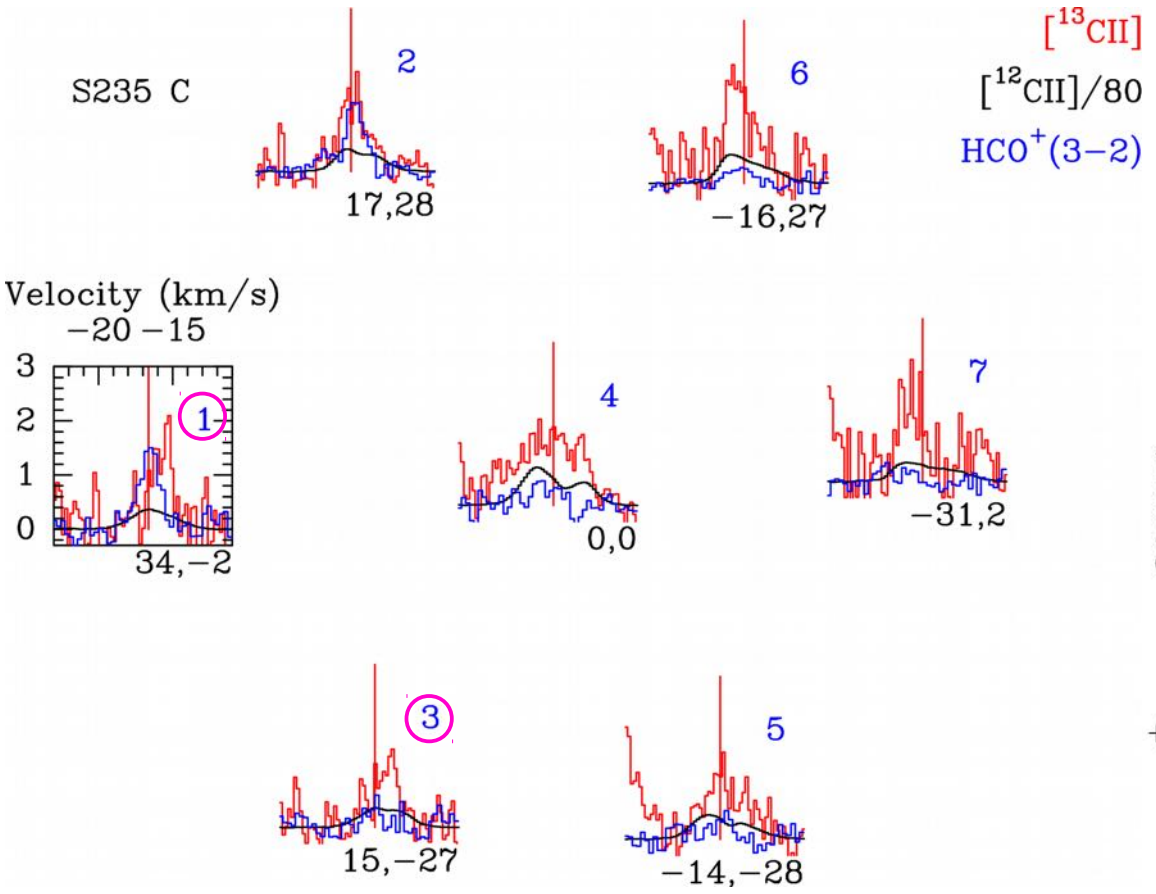
Averaged spectra





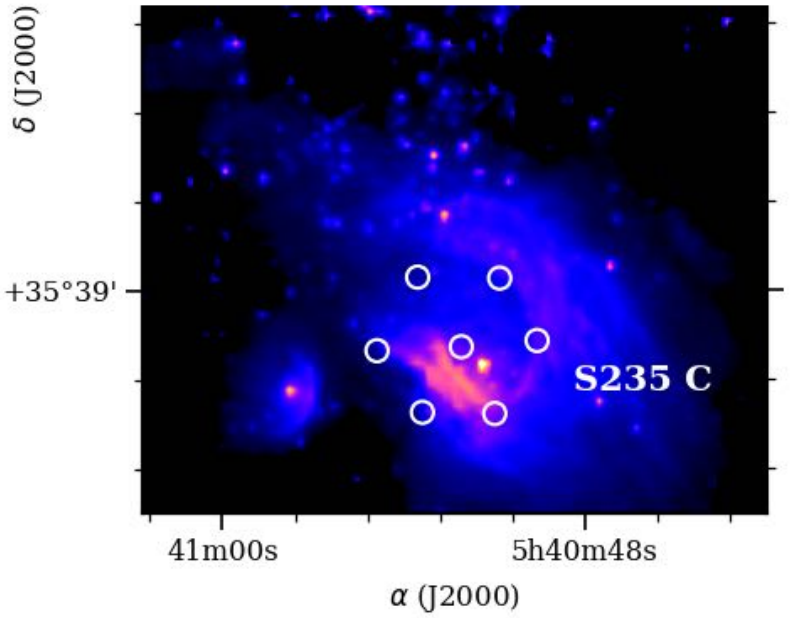
Both the [CII] and [OI] lines have a dip at –16 km s^{-1}.

Map of the [^{13}CII] spectra in S235 C



1) east-west velocity gradient

2) $V_{[13CII]} > V_{HCO+(3–2)}$ in positions 1 and 3

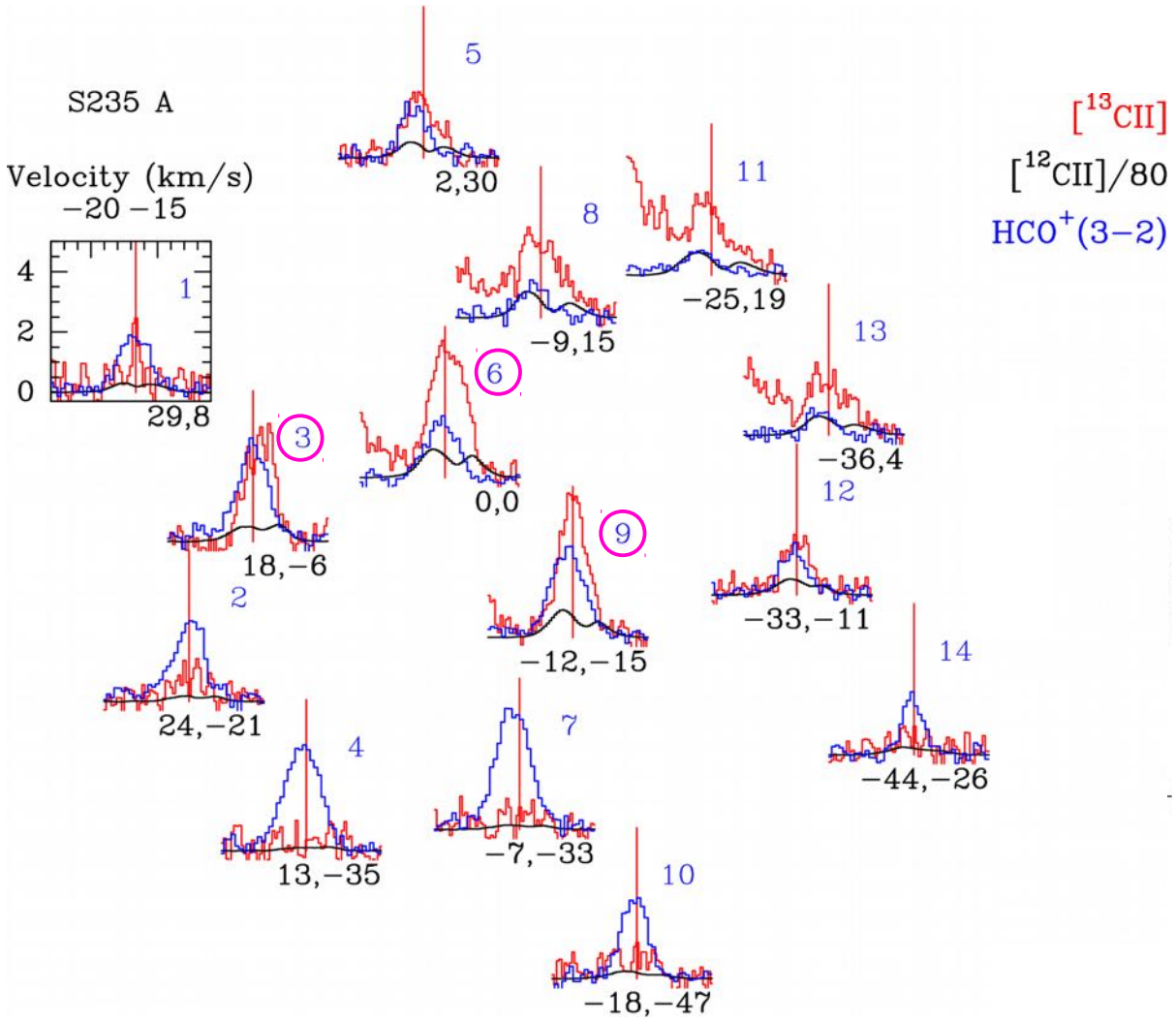


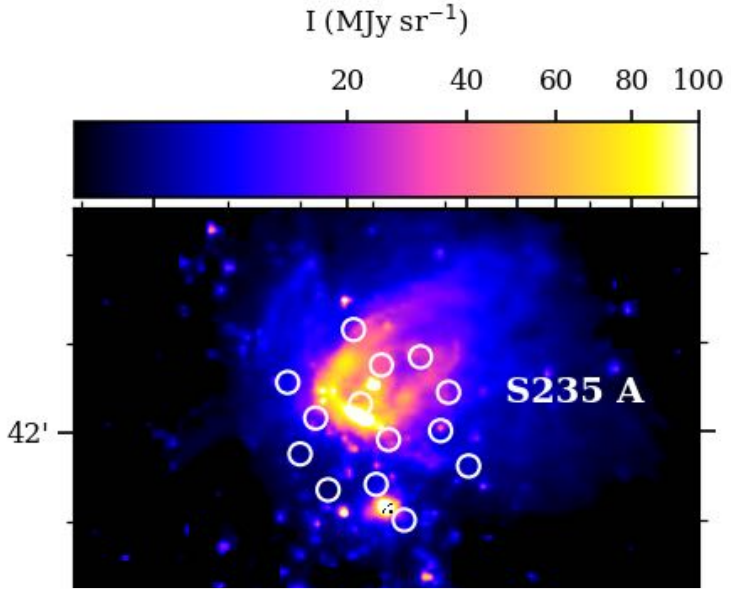
$$\frac{T_{mb[^{13}CII]}}{T_{mb[CII]}} = \frac{1-\exp(-\tau_{C^+}/r)}{1-\exp(-\tau_{C^+})}$$

$2 \le \tau_{[CII]} \le 5$

$T_{ex} \approx 60\text{-}70$ K

Map of the [^{13}CII] spectra in S235 A





1) east-west velocity gradient

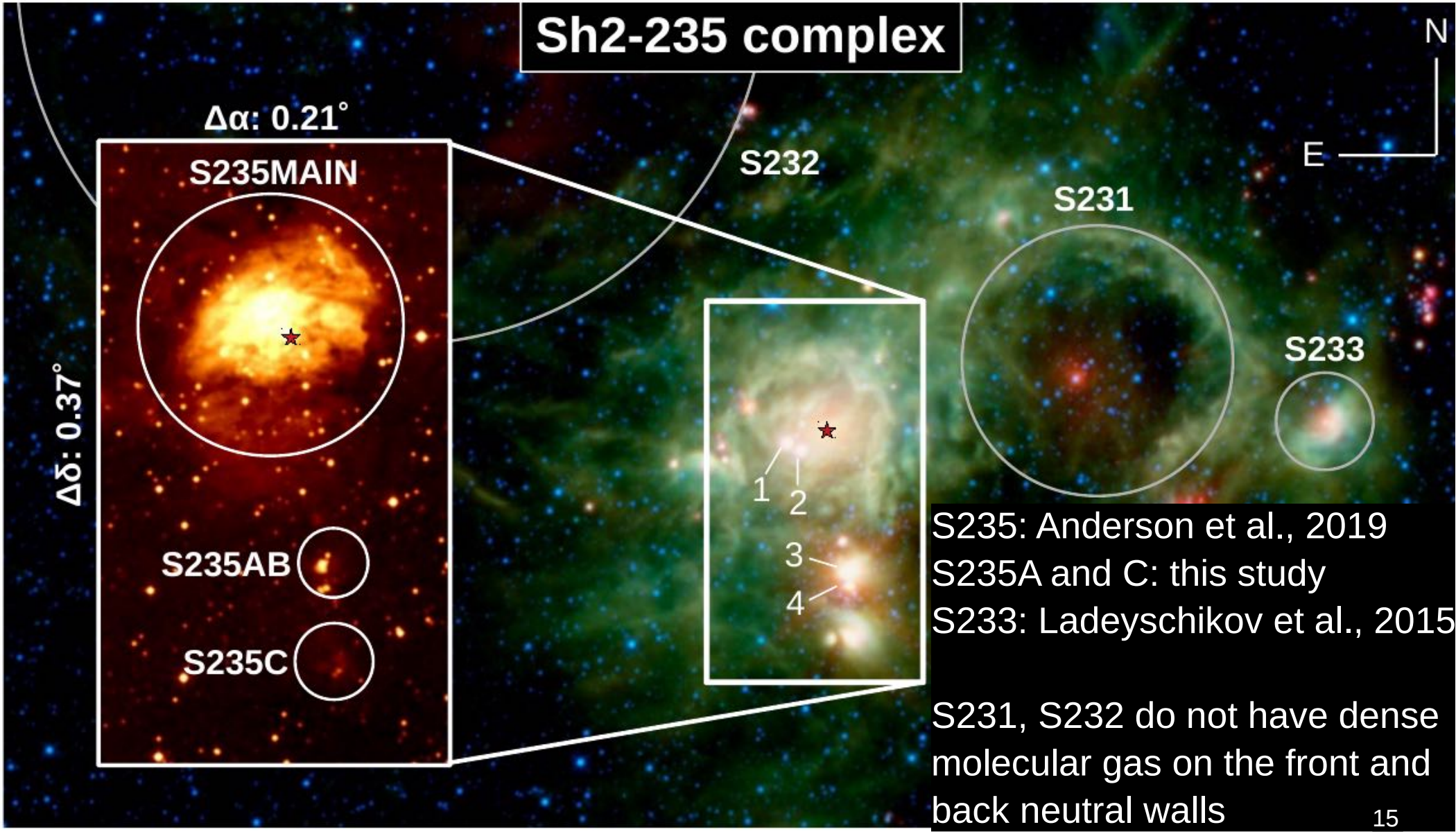
2) $V_{[13CII]} > V_{HCO+(3–2)}$ in positions 3, 6 and 9

molecular gas is expanding towards the observer
V_{exp} up to 1 km s^{-1}

$3 \leq \tau_{[CII]} \leq 10$

$40 \leq T_{ex} \leq 90$ K

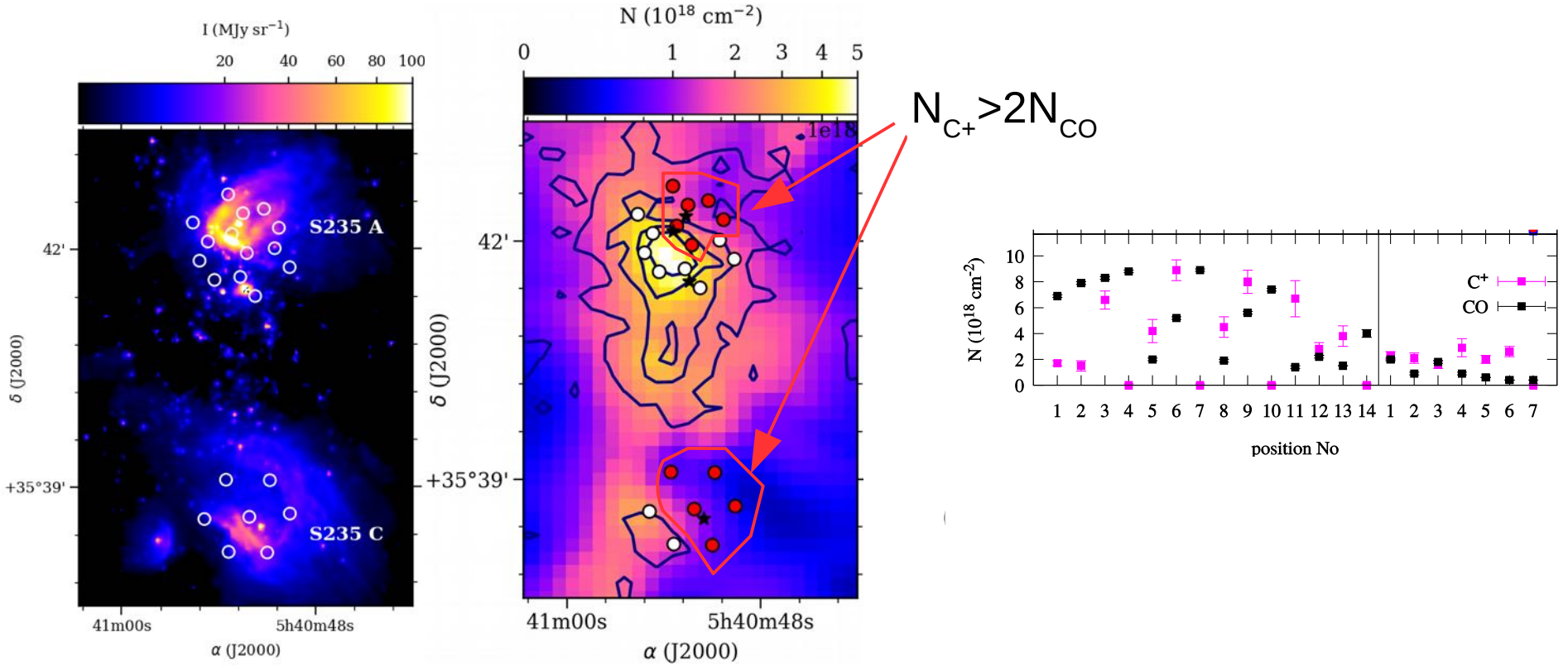
Interesting fact: the HII regions in the giant molecular cloud G174+2.5 are expanding towards the observer!



S235: Anderson et al., 2019
S235A and C: this study
S233: Ladeyschikov et al., 2015

S231, S232 do not have dense molecular gas on the front and back neutral walls

Comparison of N_{C+} и N_{CO}



Spitzer
3.6 micron

$N_{low\text{-}J\ CO}$ (archival data)

$N_{low\text{-}J\ HCO+}$

The HII regions are situated on the border between the dense molecular and more diffuse atomic gas.

MARION: chemo-dynamical model of an expanding HII region + PDR

– 1D gas/dust dynamics based on Zeus code.

– ionization & dissociation

– cooling & heating

– chemical reactions

after MARION calculation:

– Radiative transfer with SIMLINE code (Ossenkopf et al.-2001)

Gas in PDRs:

Kirsanova et al., 2009, 2019, 2020

Dust and PAHs in PDRs:

Pavlyuchenkov et al., 2013
Akimkin et al., 2015, 2017
Murga et al., 2019

Best model selection criteria:

We can trace the evolution of the physical parameters of the HII regions and select the moment of best agreement between the simulated and observed values of the parameters.

– radii of the HII regions ≈ 0.1 – 0.3 pc.

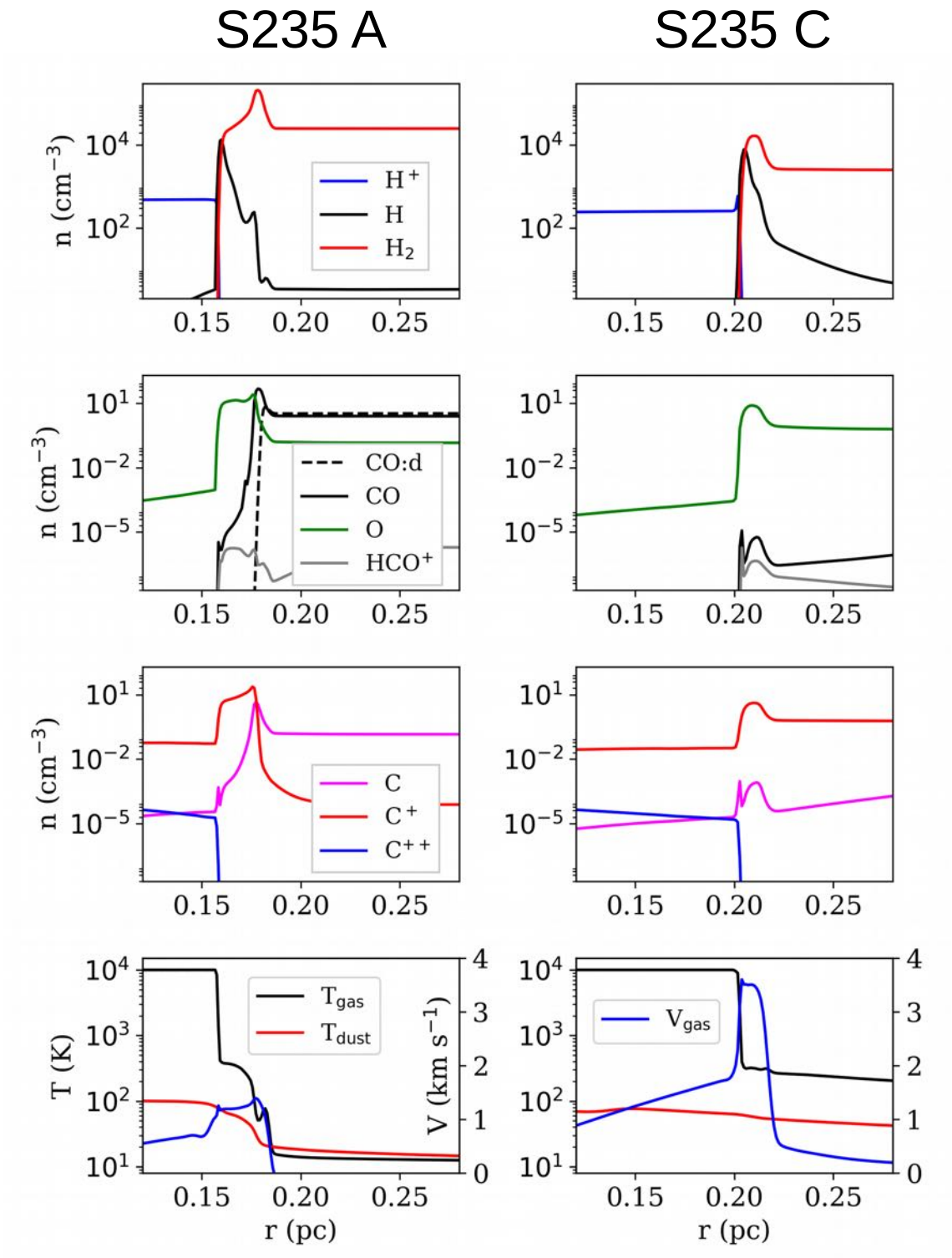
– n_e = 1000 and 500 cm^{-3} within a factor of 2 for S235A and C S235 C, respectively.

– single-peaked profiles of the [^{13}CII] and HCO^+(3–2) lines

– the average intensities of the [CII], [^{13}CII], [OI] and the [^{13}CII] lines are close to the observed values within a factor of 2.

– expansion velocity ≈ 1 km s^{-1}.

– $3 \leq \tau_{CII} \leq 10$ and $3 \leq \tau_{CII} \leq 5$ for S235 A and S235 C, respectively.



Best models:

T_{eff}=27000K

S235A: $n_{gas}=5\cdot10^4$ cm^{-3}

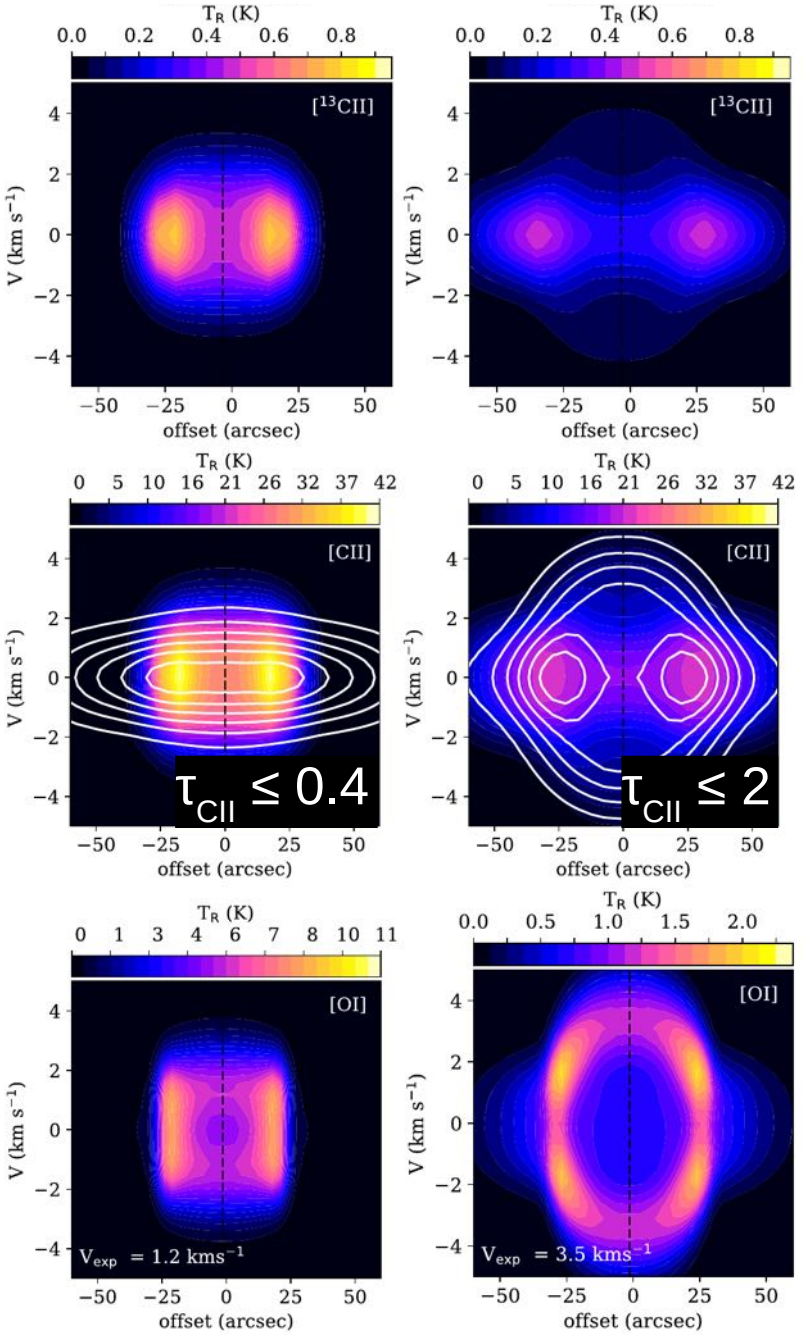
S235C: $n_{gas}=5\cdot10^3$ cm^{-3}

model age:

S235A: $6\cdot10^4$ years

S235C: $3\cdot10^4$ years

S235 A S235 C



PV diagrams for the best models:

– the [^{13}CII] is sigle-peaked

– the HCO^+(3–2) line is single-peaked

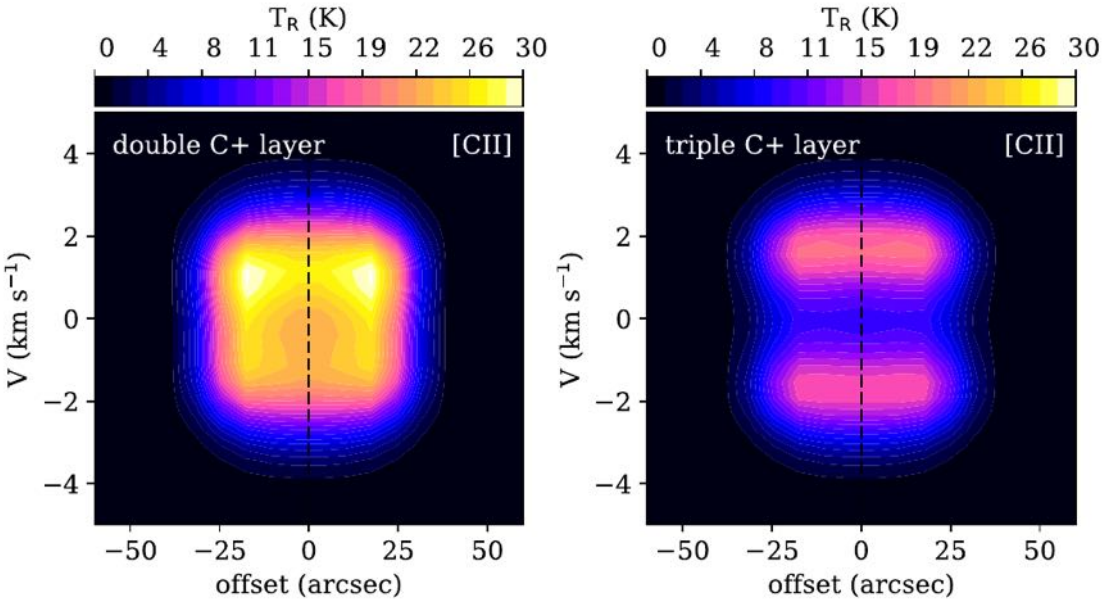
– the [CII] line is single-peaked, the line is not optically thick!

– the [OI] line is double-peaked

– the peak-to-peak velocity difference of the [OI] line is $V_{red} – V_{blue} = 2 \cdot V_{exp}$

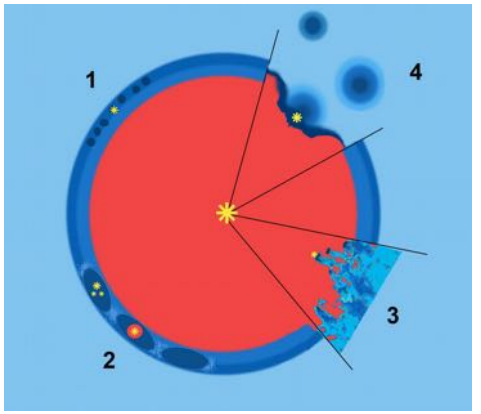
Problem: low τ_{CII}

Solution 1: increase thickness of the C^+ layer



original width multiplied by 2

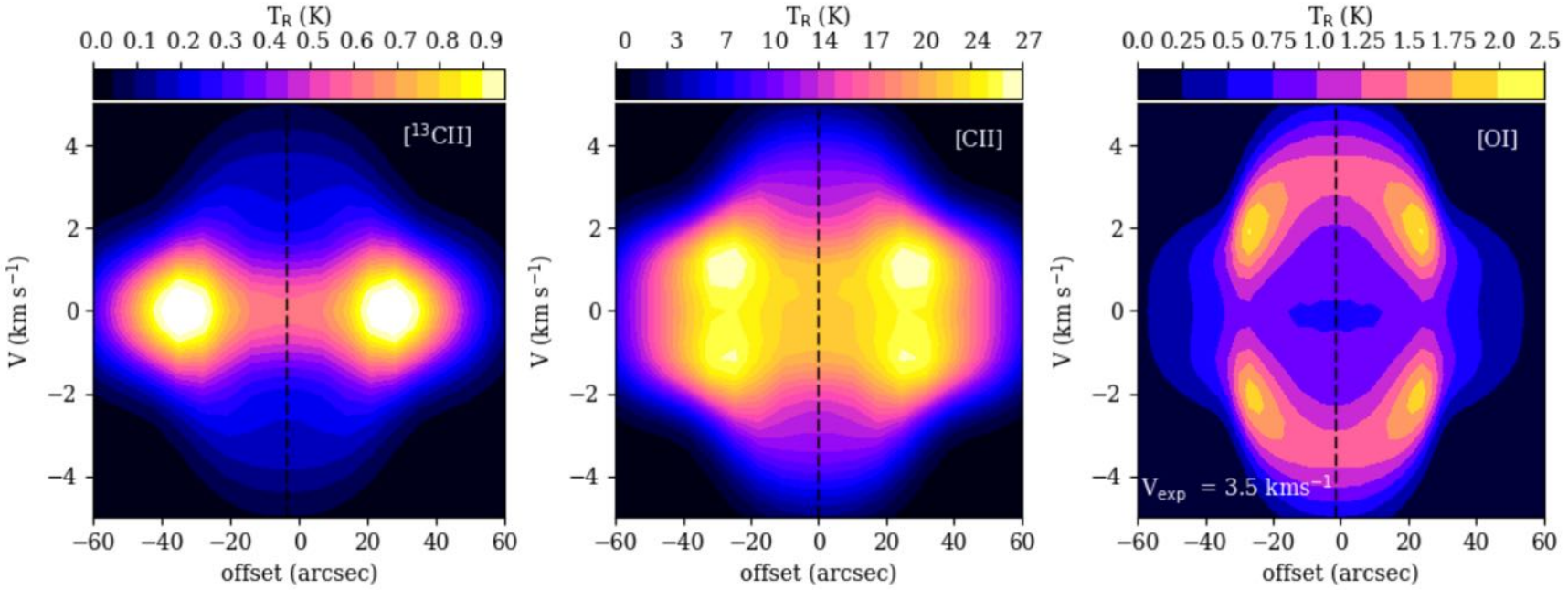
original width multiplied by 3



photons penetrate deeper in non-uniform and clumpy medium

Problem: low τ_{CII}

Solution 2: increase elemental abundances



CLOUDY «ISM» set of abundances: x(C)=2.5·10^{-4}
instead of
«high-metallicity» abundances: x(C)=1.2·10^{-4}
(Wakelam & Herbst, 2008)

Conclusions

The double-peaked [CII] and [OI] line profiles arise due to with high optical depth and are not tracing the expansion of the PDRs.

However, an expanding motion of the [CII]-emitting layer into the molecular layer with a velocity up to 1 $km\,s^{-1}$ was found in both PDRs with [^{13}CII] and HCO^+(3-2) lines.

Physical parameters of the HII regions and integrated intensities of the [^{13}CII], [CII], and [OI] lines are reproduced by a 1D spherical model. However, the model does not reproduce the double-peaked [CII] line profiles and high optical depth of the line.

The [OI] line profiles are the best tracers of the expanding motion in the considered PDR models in comparison with the [CII], [^{13}CII], and HCO^+(3-2) lines.

MSK is supported by RSF, #18-72-10132