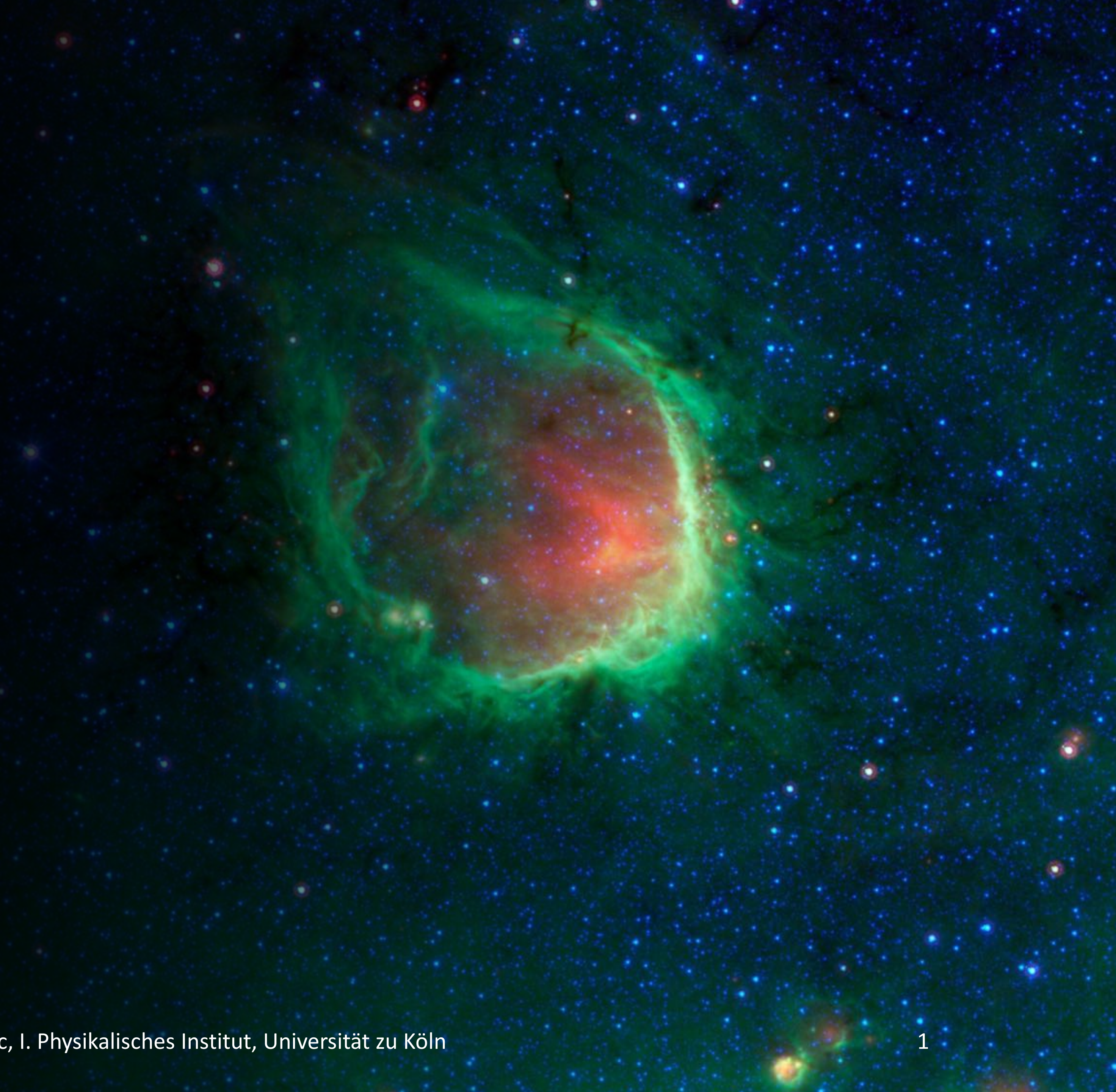
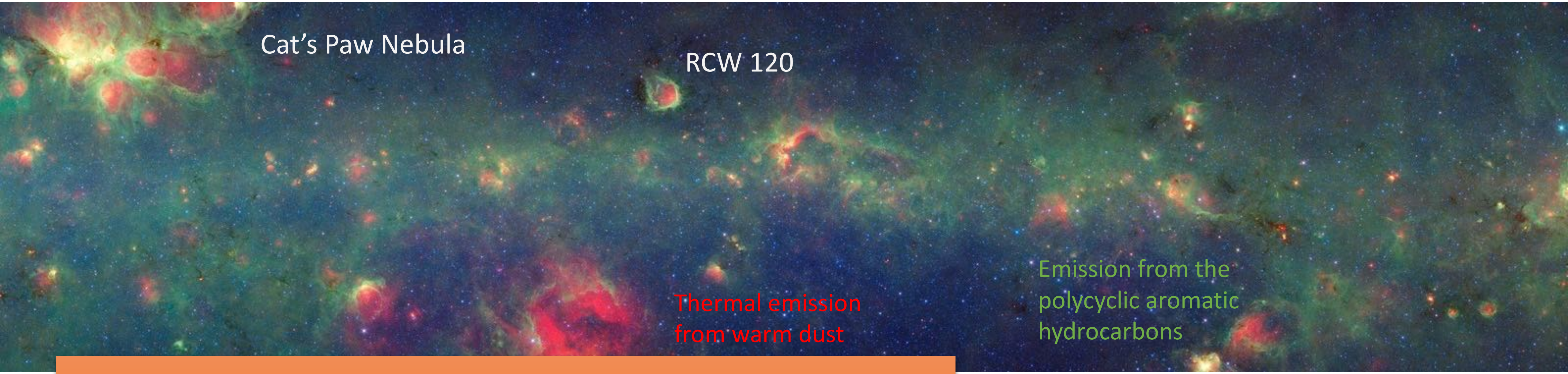
Self-absorption in [CII], ^{12}CO and HI in RCW 120: An explanation for large amounts of cold C^+



Slawa Kabanovic
and the FEEDBACK consortium

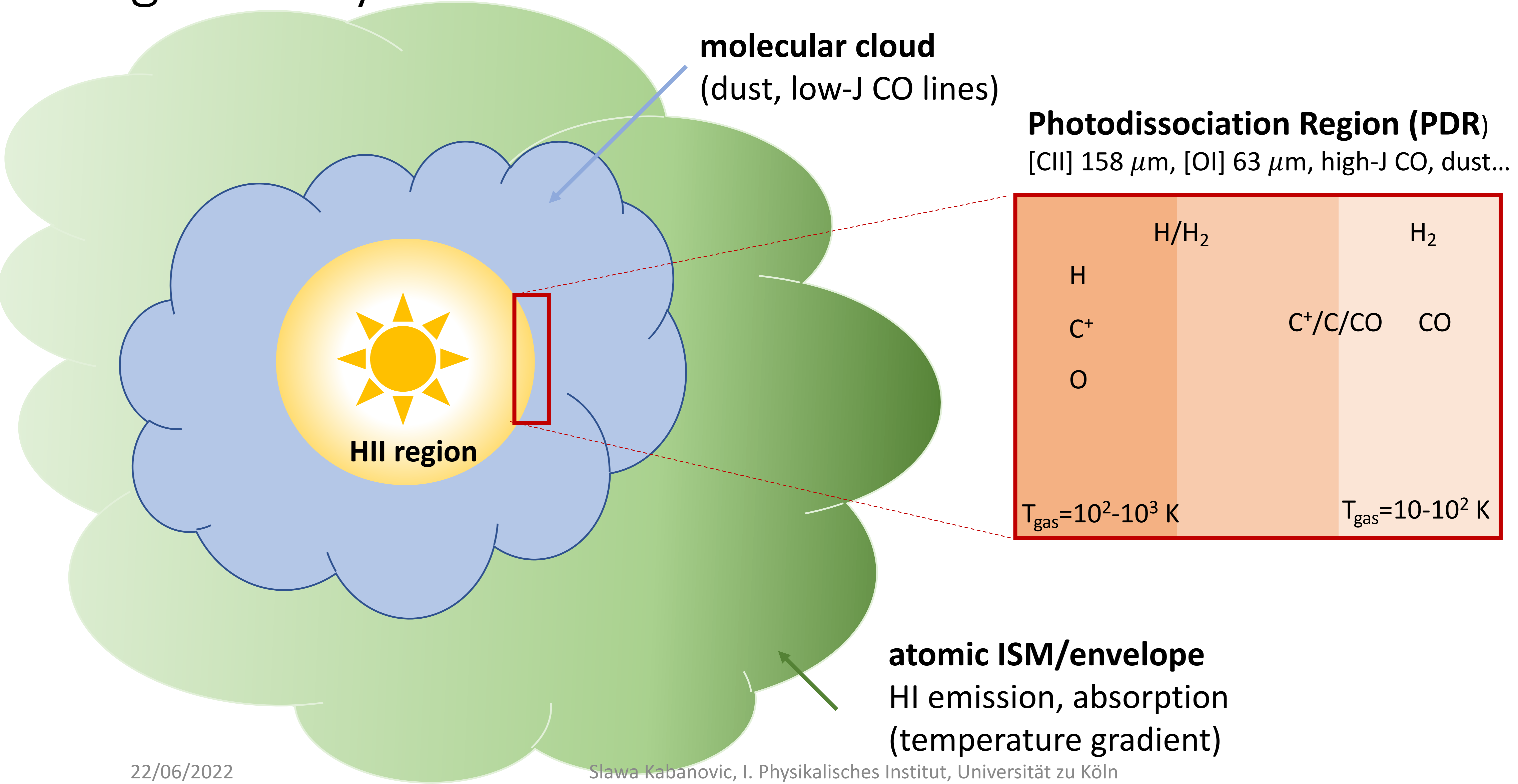
Bubble Universe



Credit: NASA/JPL-Caltech/Univ. of Wisconsin

- The ISM filles up the space between the stars.
- Energy and momentum transfer by stellar radiation and stellar winds.
- HII regions emerge from the ISM as the most prominent features.
- How does stellar feedback influence the evolution of the ISM?
- Are circular HII regions 3D bubbles?

Multi-wavelength observations to disentangle geometry and excitation conditions



Understanding the origin of [CII] emission

- [CII] emission originates from gas at T $\lesssim$ 100 K (PDR) up to 10^4 K (HII region) over a large range of densities, critical density n_{cr} for T ~ 100 K is 9 cm^{-3} (e^-), $3x10^3$ cm^{-3} (HI), $6x10^3$ cm^{-3} (H_2) (e.g. Goldsmith+2012)

- [CII] traces all: *the warm ionized medium, the warm and cold diffuse atomic medium, and warm and dense molecular gas, in particular* ***CO-dark H_2 gas***.

From GOTC+-survey (Pineda+2013, Langer+2014) and Velusamy+2015:

~47% PDRs, ~28% CO-dark H_2 gas, ~21% cold atomic gas, ~4% ionized gas

Understanding the origin of [CII] emission

Guevara + (2020)

- [CII] line shows strong self-absorption features in MonR2, M43 and M17.
- Modelling emission derived large amounts of cold C^+.
- Where does the cold C^+ come from?

Tentative explanations:

Background emission comes from very clumpy UV-illuminated surfaces.
Foreground gas is not diffuse but has a minimum density of a few 10^4 cm^{-3}.

-> More observations of [CII] in massive star-forming regions are required!

A&A 659, A36 (2022)
https://doi.org/10.1051/0004-6361/202142575

Astronomy & Astrophysics

Self-absorption in [C II], ^{12}CO, and H I in RCW120

Building up a geometrical and physical model of the region[⋆,⋆⋆]

S. Kabanovic[1], N. Schneider[1], V. Ossenkopf-Okada[1], F. Falasca[2], R. Güsten[3], J. Stutzki[1], R. Simon[1], C. Buchbender[1], L. Anderson[4,5], L. Bonne[6], C. Guevara[1], R. Higgins[1], B. Koribalski[7,8], M. Luisi[5,9], M. Mertens[1], Y. Okada[1], M. Röllig[1], D. Seifried[1], M. Tiwari[3,10], F. Wyrowski[3], A. Zavagno[11,12], and A. G. G. M. Tielens[10,13]

SOFIA/upGREAT Legacy Program: FEEDBACK

(PIs N. Schneider and A. Tielens)

Publications of the Astronomical Society of the Pacific, 132:104301 (19pp), 2020 October
https://doi.org/10.1088/1538-3873/aba840

CrossMark

FEEDBACK: a SOFIA Legacy Program to Study Stellar Feedback in Regions of Massive Star Formation

N. Schneider[1], R. Simon[1], C. Guevara[1], C. Buchbender[1], R. D. Higgins[1], Y. Okada[1], J. Stutzki[1], R. Güsten[2], L. D. Anderson[3], J. Bally[4], H. Beuther[5], L. Bonne[6], S. Bontemps[6], E. Chambers[7], T. Csengeri[6], U. U. Graf[1], A. Gusdorf[8], K. Jacobs[1], M. Justen[1], S. Kabanovic[1], R. Karim[9], M. Luisi[3], K. Menten[2], M. Mertens[1], B. Mookerjea[10], V. Ossenkopf-Okada[1], C. Pabst[11], M. W. Pound[9], H. Richter[12], N. Reyes[2], O. Ricken[2], M. Röllig[1], D. Russeil[13], Á. Sánchez-Monge[1], G. Sandell[14], M. Tiwari[9], H. Wiesemeyer[2], M. Wolfire[9], F. Wyrowski[2], A. Zavagno[13], and A. G. G. M. Tielens[9,11]

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[11] Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands
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Received 2020 May 26; accepted 2020 July 20; published 2020 September 16

- Survey of 11 galactic high mass star forming regions in [CII] and [OI], ~ 100h observing time, ~ 75% done

Objectives of FEEDBACK

- Quantify the kinetic & turbulent energy input into the ISM
- Quantify the radiative coupling of UV photons with the ISM
- Link feedback to star formation activity and vice versa
- Provide a framework to interpret studies of distant galaxies over cosmic time

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SOFIA/upGREAT Legacy Program: FEEDBACK – First Results
(PIs N. Schneider and A. Tielens)

SCIENCE ADVANCES | RESEARCH ARTICLE

ASTRONOMY

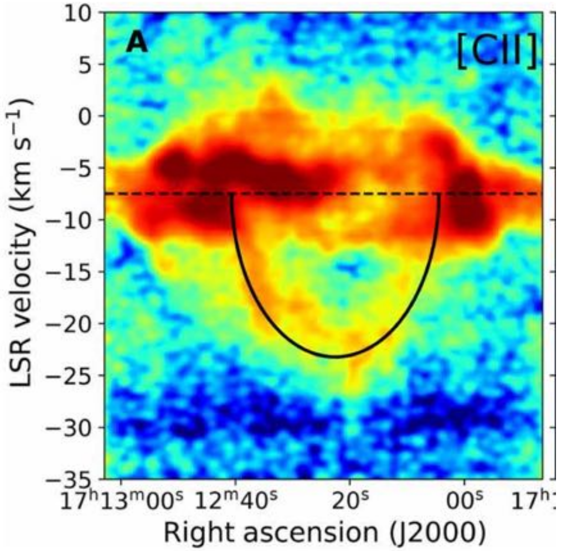
Stellar feedback and triggered star formation in the prototypical bubble RCW 120

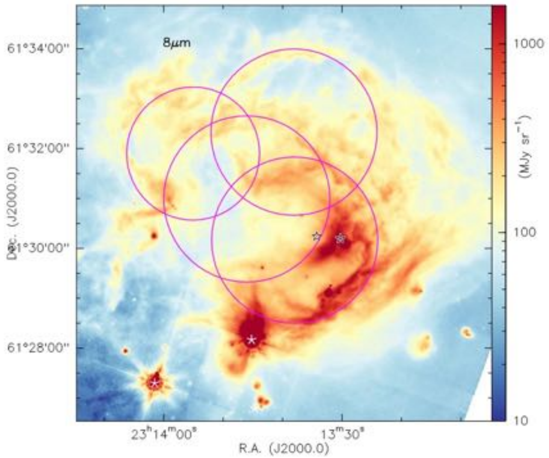
Matteo Luisi[1,2]*, Loren D. Anderson[1,2,3], Nicola Schneider[4], Robert Simon[4], Slawa Kabanovic[4], Rolf Güsten[5], Annie Zavagno[6], Patrick S. Broos[7], Christof Buchbender[4], Cristian Guevara[4], Karl Jacobs[4], Matthias Justen[4], Bernd Klein[5], Dylan Linville[1,2], Markus Röllig[4], Delphine Russeil[6], Jürgen Stutzki[4], Maitraiyee Tiwari[5,8], Leisa K. Townsley[7], Alexander G. G. M. Tielens[8,9]

Radiative and mechanical feedback of massive stars regulates star formation and galaxy evolution. Positive feedback triggers the creation of new stars by collecting dense shells of gas, while negative feedback disrupts star formation by shredding molecular clouds. Although key to understanding star formation, their relative importance is unknown. Here, we report velocity-resolved observations from the SOFIA (Stratospheric Observatory for Infrared Astronomy) legacy program FEEDBACK of the massive star-forming region RCW 120 in the [CII] 1.9-THz fine-structure line, revealing a gas shell expanding at 15 km/s. Complementary APEX (Atacama Pathfinder Experiment) CO J = 3-2 345-GHz observations exhibit a ring structure of molecular gas, fragmented into clumps that are actively forming stars. Our observations demonstrate that triggered star formation can occur on much shorter time scales than hitherto thought (<0.15 million years), suggesting that positive feedback operates on short time periods.

FEEDBACK from the NGC 7538 HII region*,**

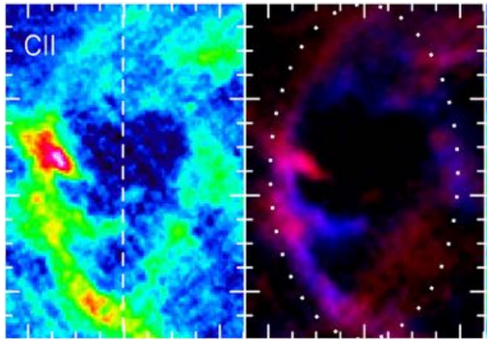
H. Beuther[1], N. Schneider[2], R. Simon[2], S. Suri[1,3], V. Ossenkopf-Okada[2], S. Kabanovic[2], M. Röllig[2], C. Guevara[2], A. G. G. M. Tielens[4,5], G. Sandell[6], C. Buchbender[2], O. Ricken[7], and R. Güsten[7]

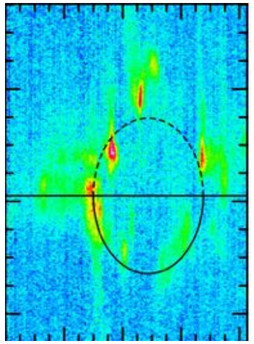




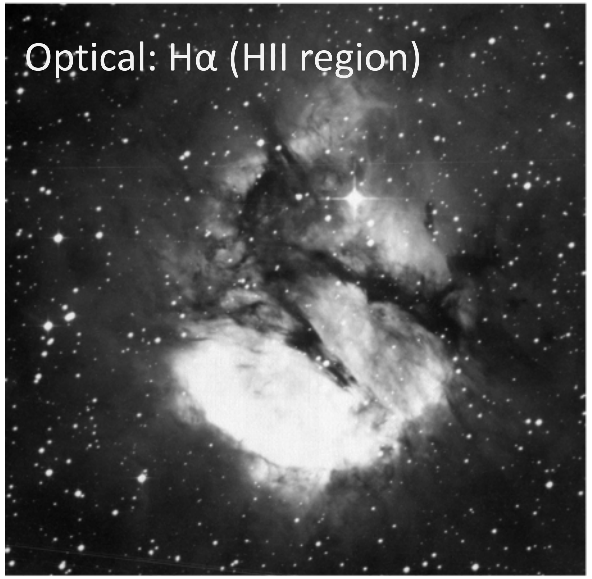
SOFIA FEEDBACK survey: exploring the dynamics of the stellar wind driven shell of RCW 49

M. Tiwari,[1,2] R. Karim,[1] M. W. Pound,[1] M. Wolfire,[1] A. Jacob,[2] C. Buchbender,[3] R. Güsten,[2] C. Guevara,[3] R.D. Higgins,[3] S. Kabanovic,[3] C. Pabst,[4] O. Ricken,[2] N. Schneider,[3] R. Simon,[3] J. Stutzki,[3] and A. G. G. M. Tielens[1,4]

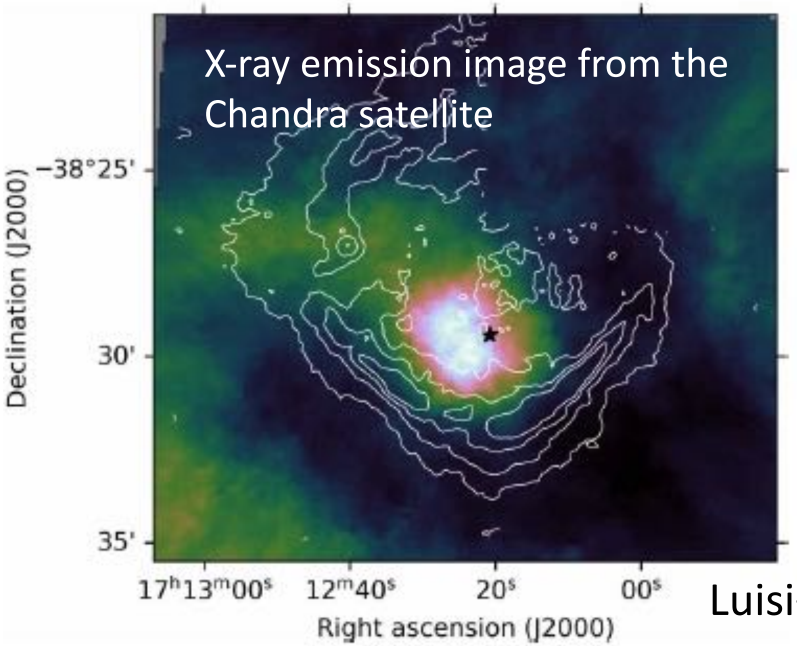




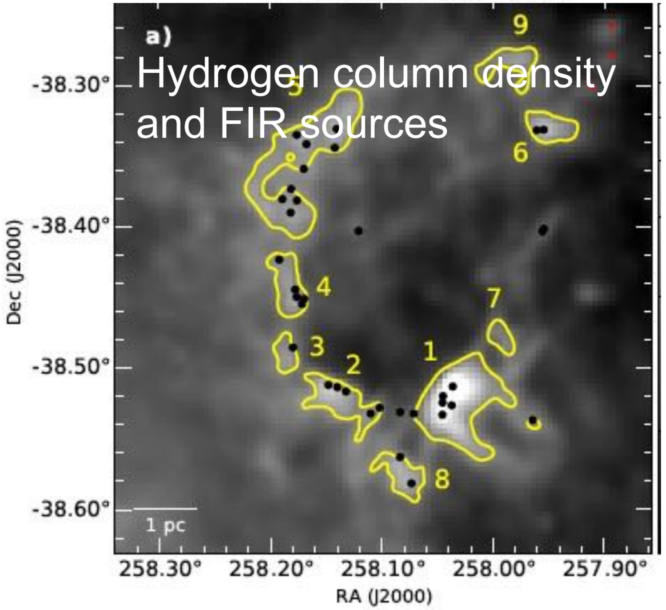
RCW 120 – The perfect Bubble?



Herschel 70, 160, 250 µm



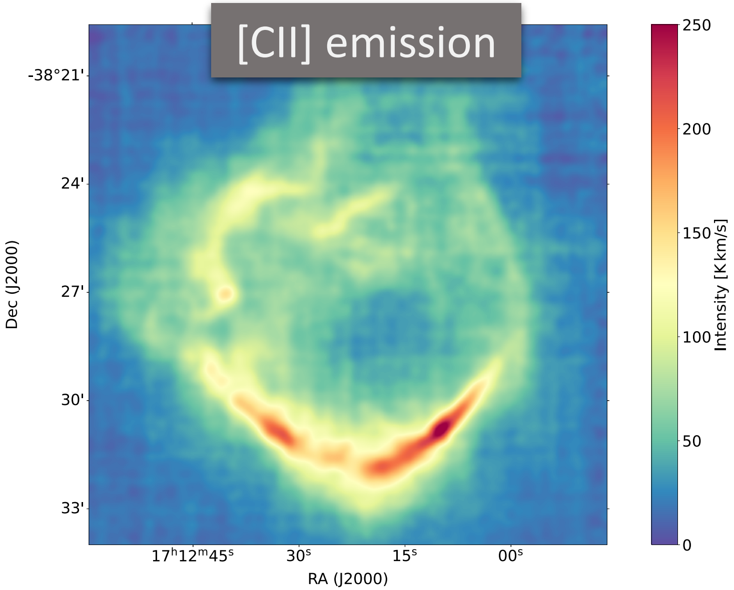
Luisi+2021



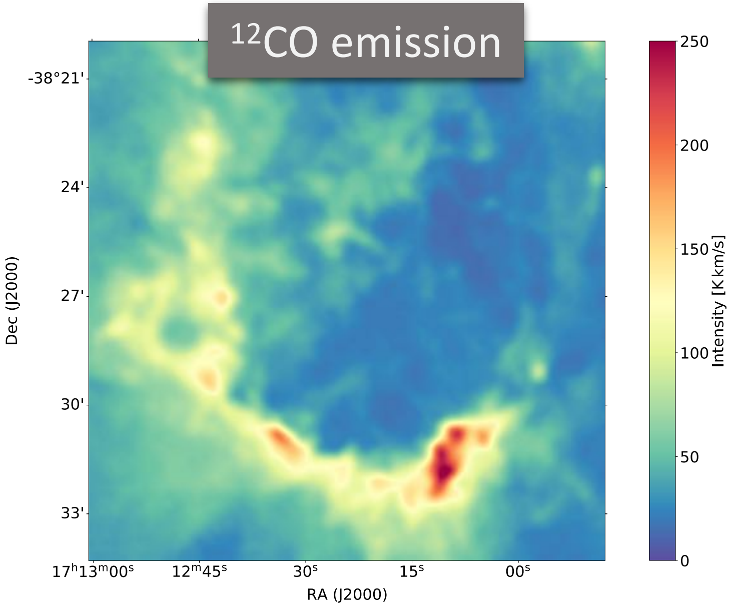
Figueira+2017

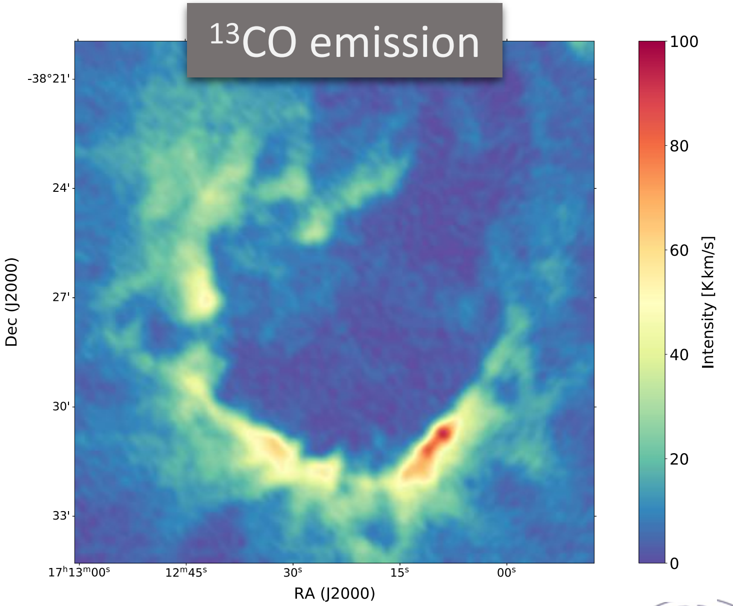
- Almost perfect circular (spherical?) structure
- Distance 1.7 kpc, one exciting O8V star, strong stellar wind
- Dark lanes indicate foreground material
- Star formation along the ring

Velocity resolved observations of RCW 120 with SOFIA and APEX



- [CII]: confined bubble with an opening in the north and west.
- CO (3-2): emission from a fragmented shell with a deficit in the HII region center.





SCIENCE ADVANCES | RESEARCH ARTICLE

ASTRONOMY

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Matteo Luisi[1,2]*, Loren D. Anderson[1,2,3], Nicola Schneider[4], Robert Simon[4], Slawa Kabanovic[4], Rolf Güsten[5], Annie Zavagno[6], Patrick S. Broos[7], Christof Buchbender[4], Cristian Guevara[4], Karl Jacobs[4], Matthias Justen[4], Bernd Klein[5], Dylan Linville[1,2], Markus Röllig[4], Delphine Russeil[6], Jürgen Stutzki[4], Maitraiyee Tiwari[5,8], Leisa K. Townsley[7], Alexander G. G. M. Tielens[8,9]

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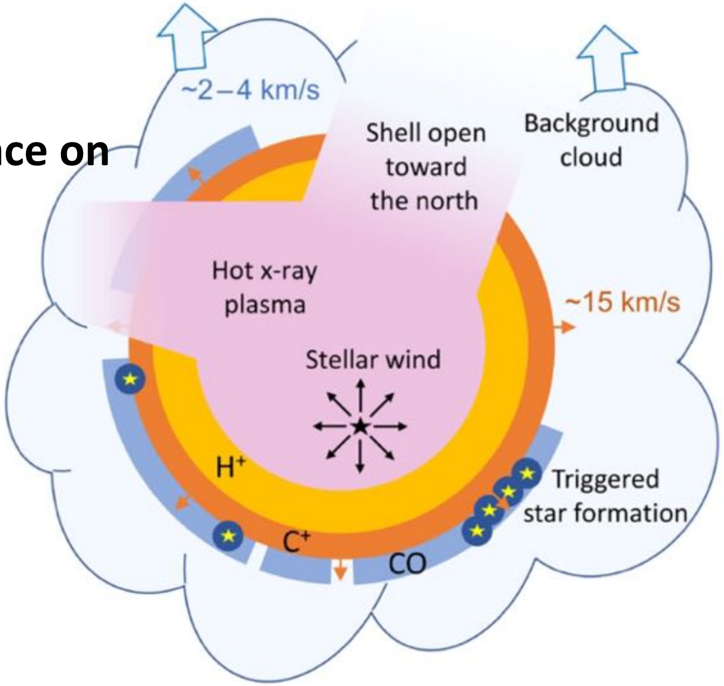
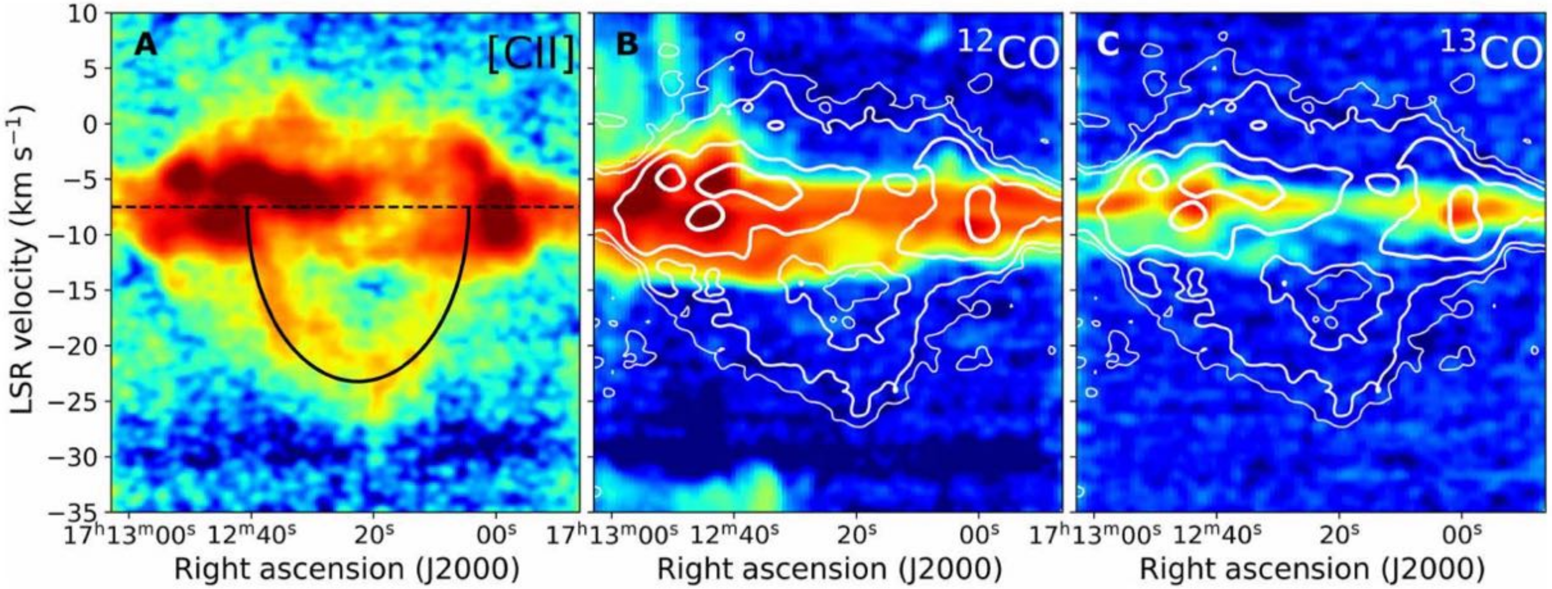
Face on

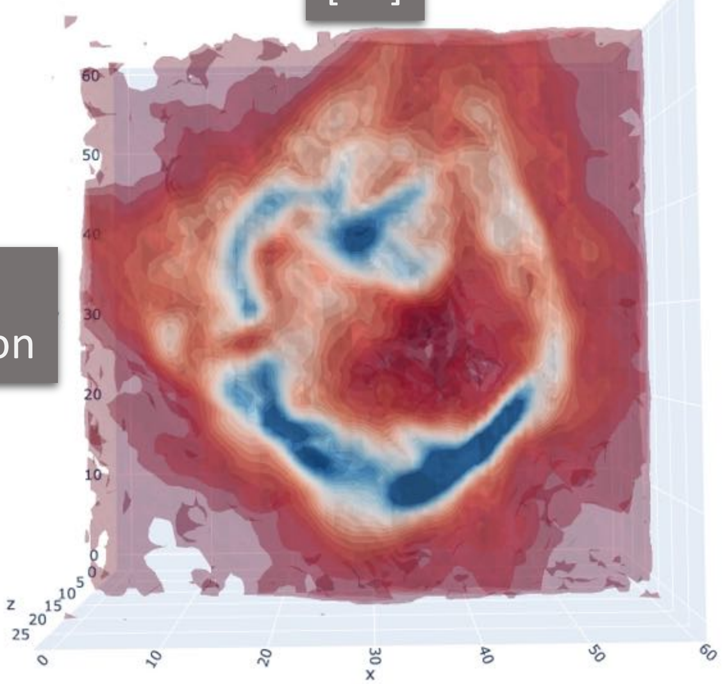




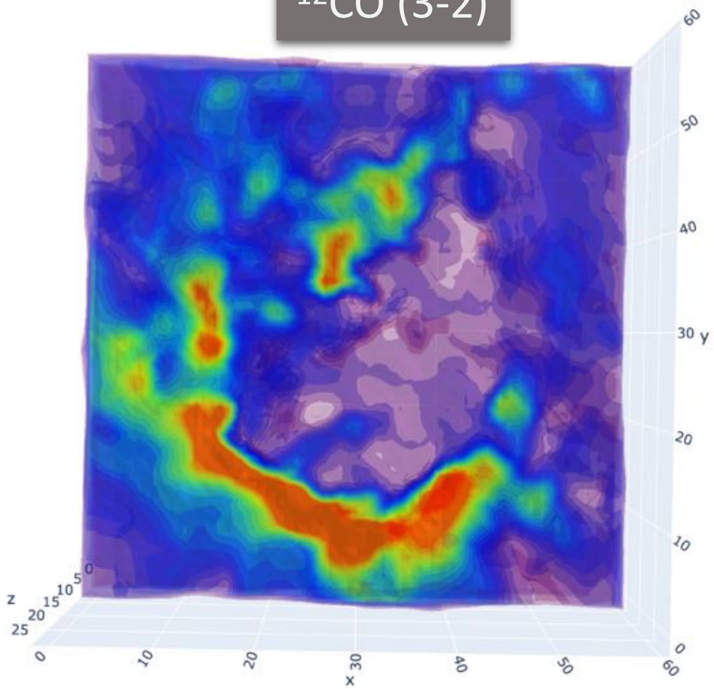
[Luisi+2021]()

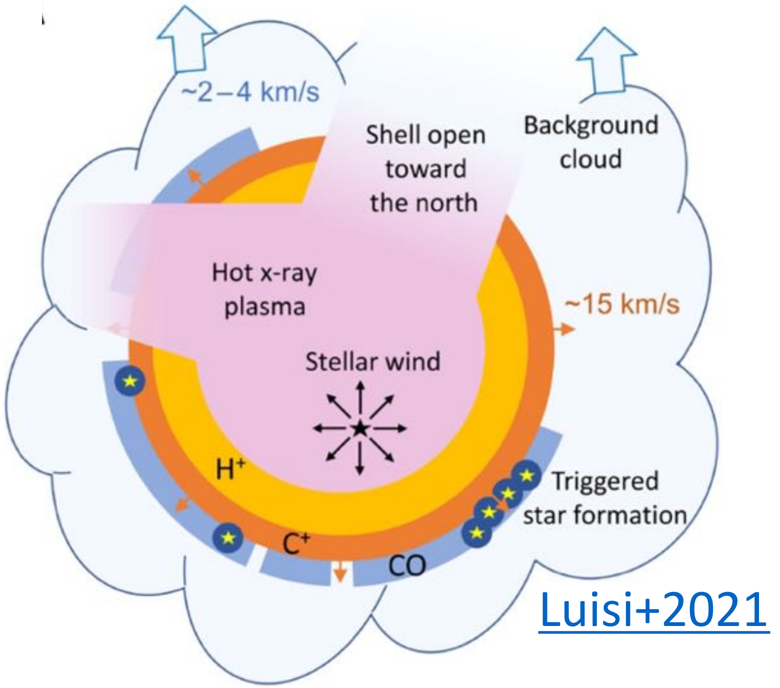
Spatial Distribution

[CII]



^{12}CO (3-2)

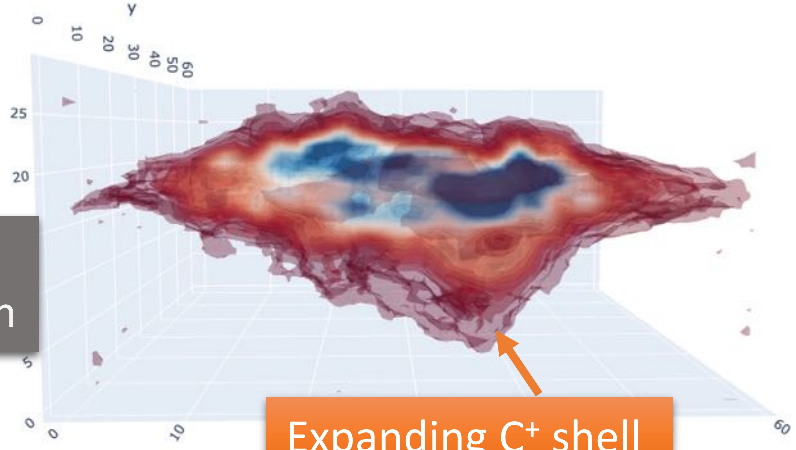




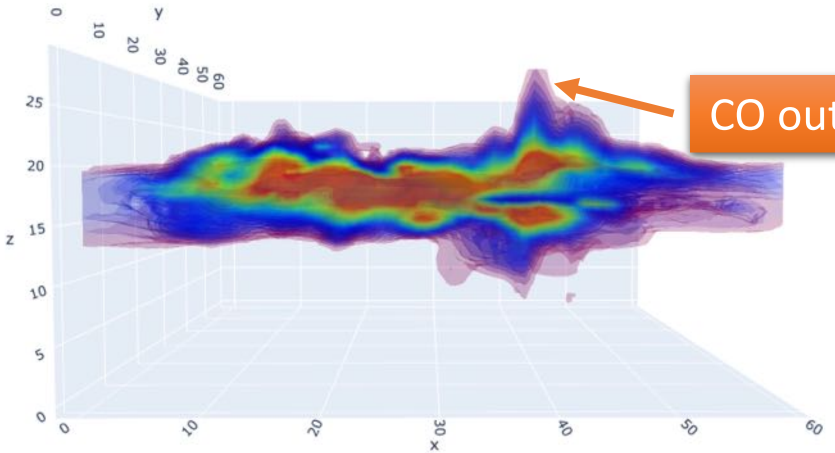
Luisi+2021

https://hera.ph1.uni-koeln.de/~nschneid/feedback.html

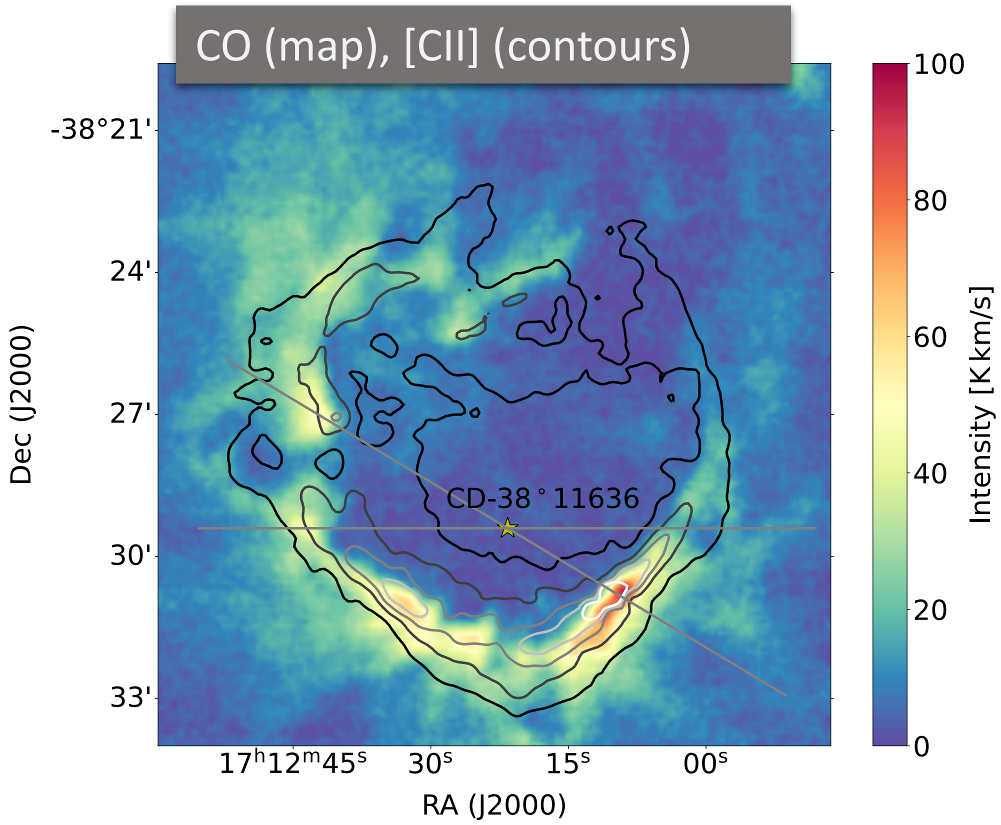
Velocity Distribution

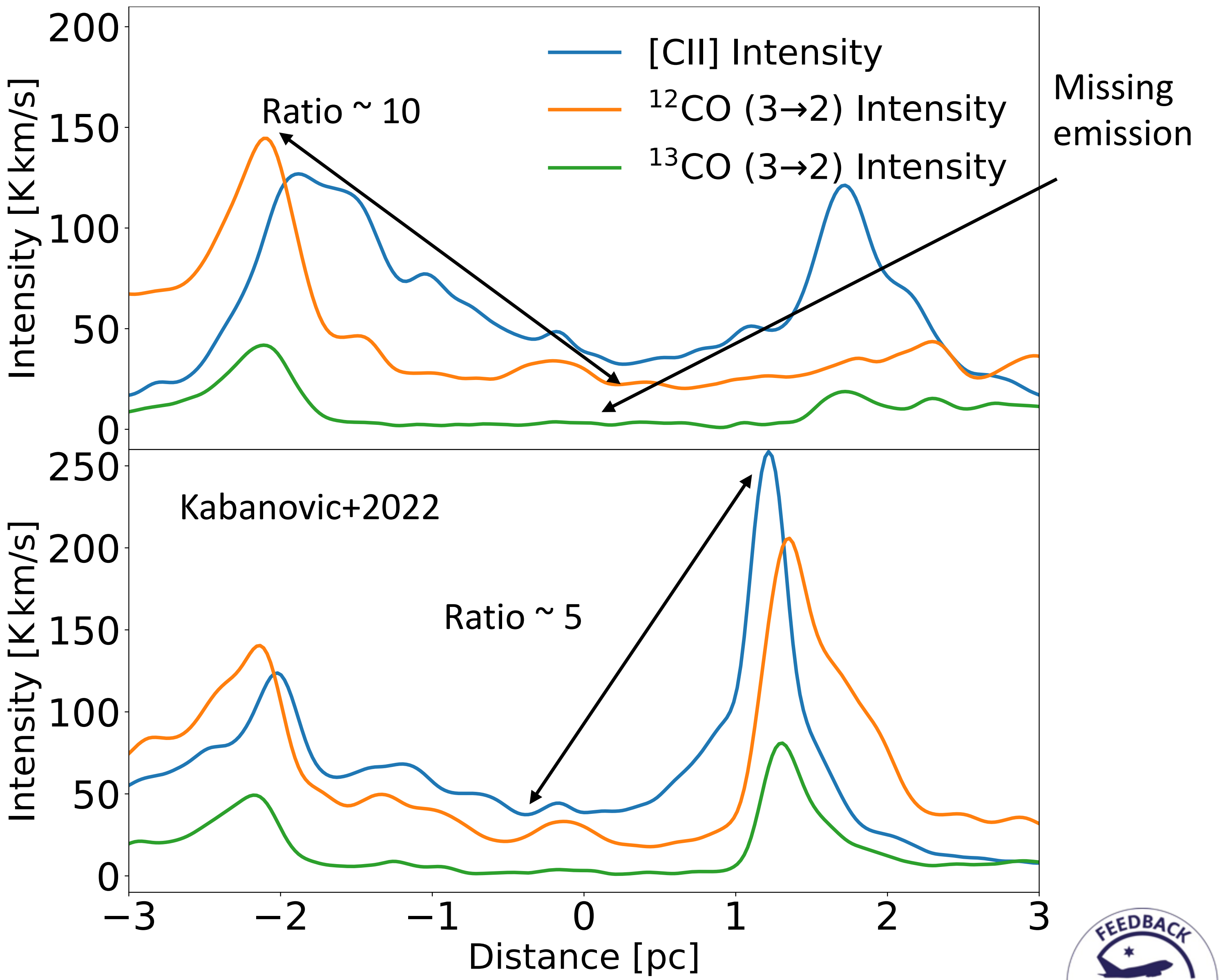


Expanding C^+ shell



CO outflow

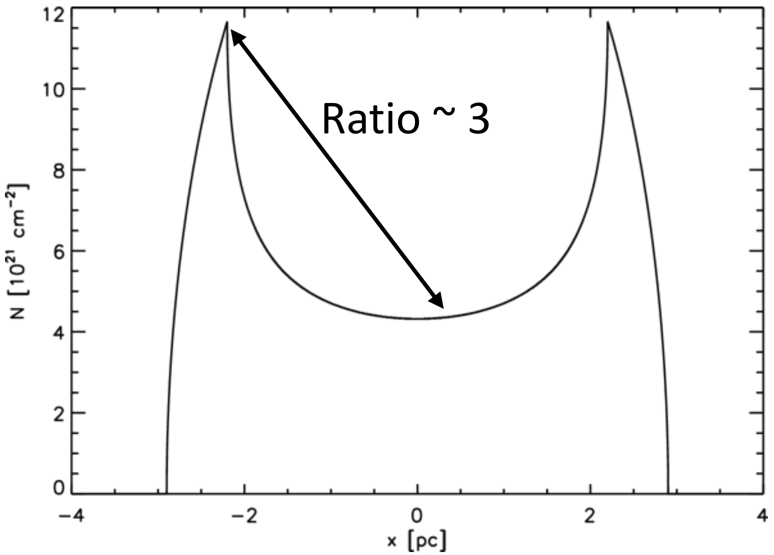


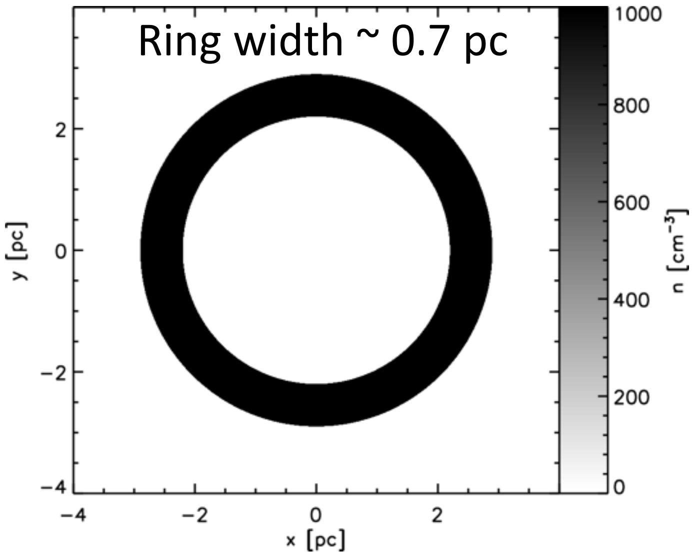


High ratio between the emission from the ring and the ring interior:

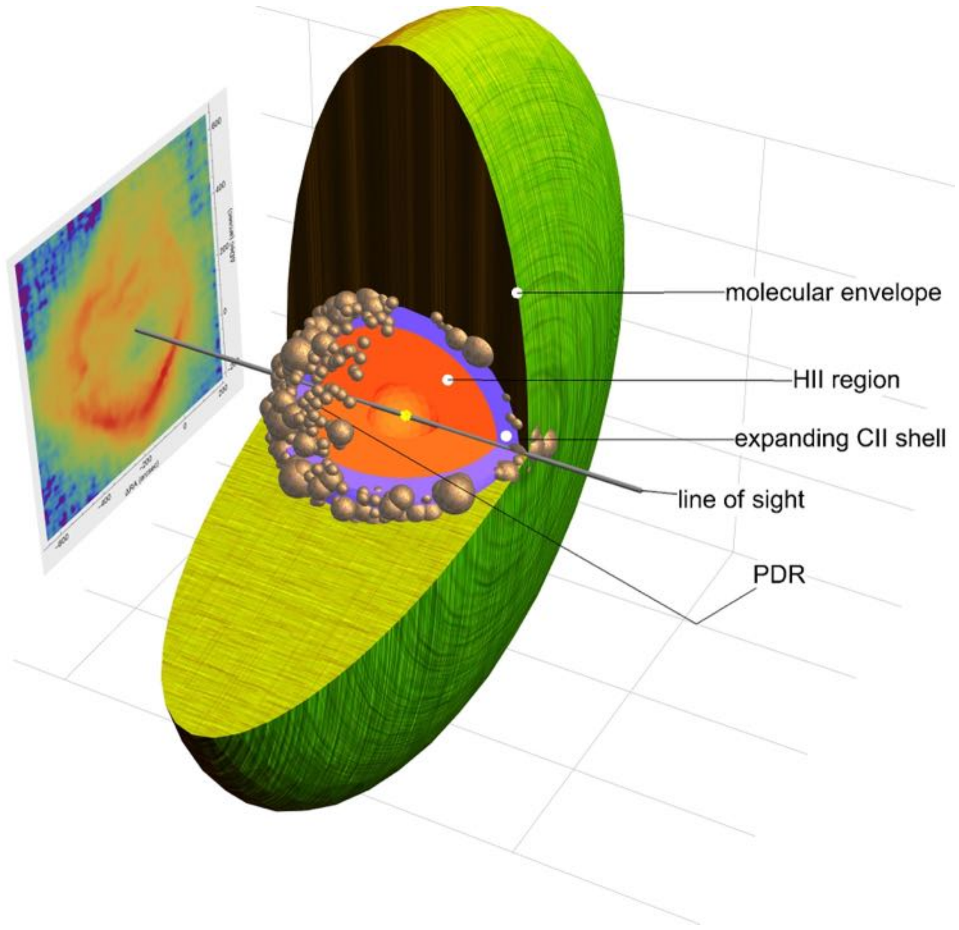
- [CII] ~ 3-5
- ^{12}CO ~ 5-10
- ^{13}CO > 10

- The observed large ratio (ring/center) can not be explained by limb brightening.
- The observations suggest a flat geometry of the parental molecular cloud (Beaumont and Williams 2010).
- Are we tricked by self-absorption effects?





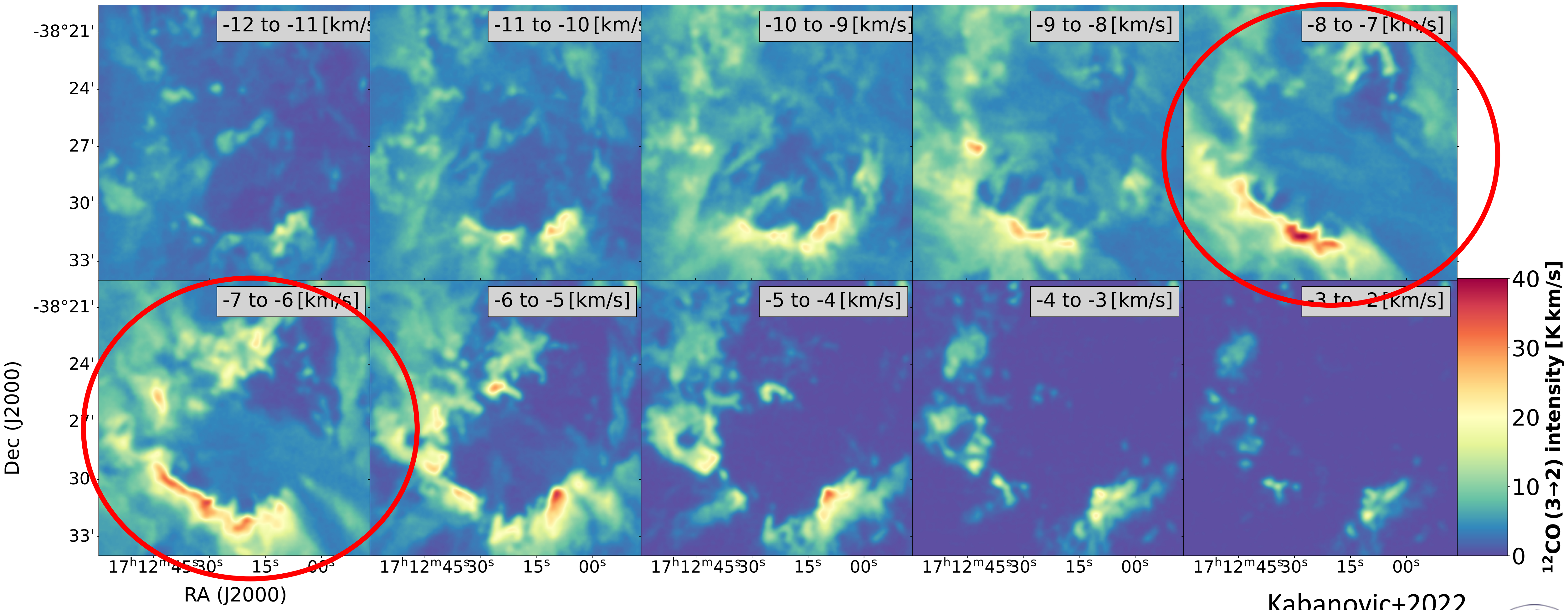
SimLine, Ossenkopf+2001



Kabanovic+2022

Velocity resolved CO emission

^{12}CO channel maps show self absorption features at the systemic velocity!

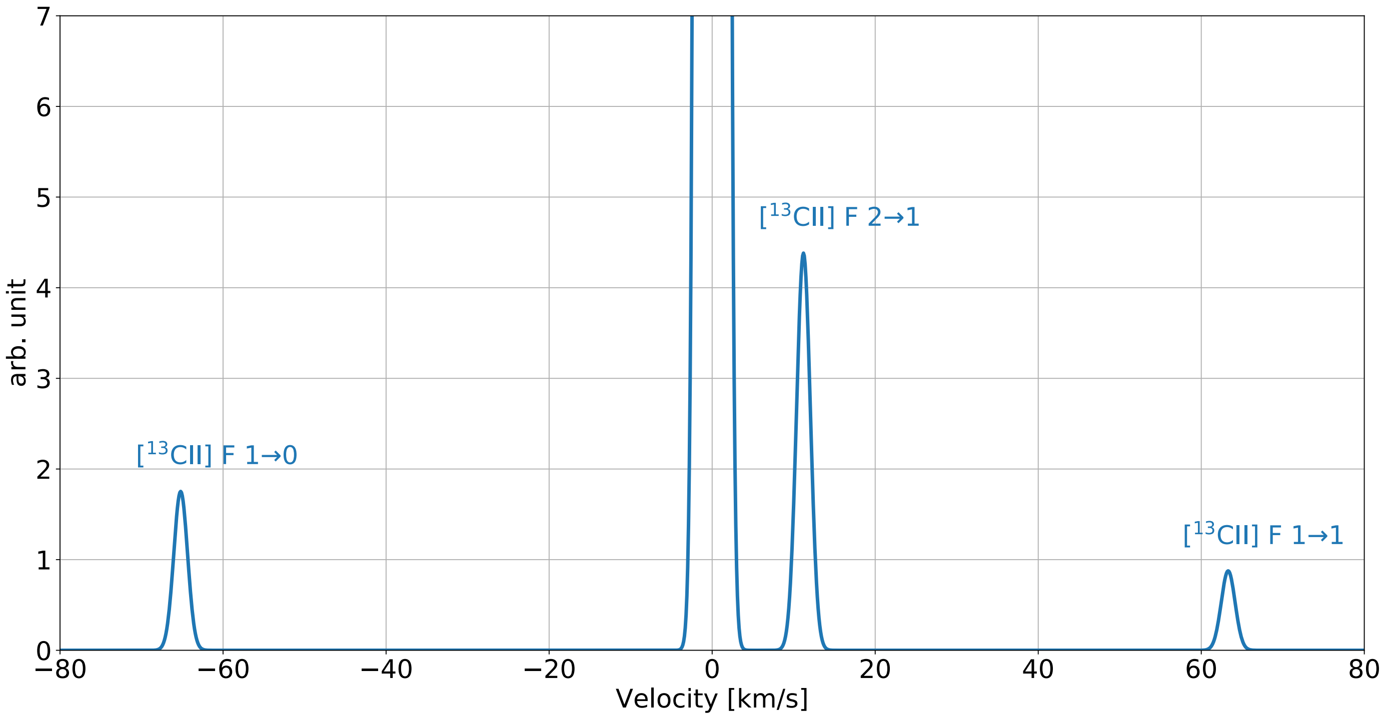


Kabanovic+2022

[^{13}CII] Hyperfine (HFS) Transition Lines

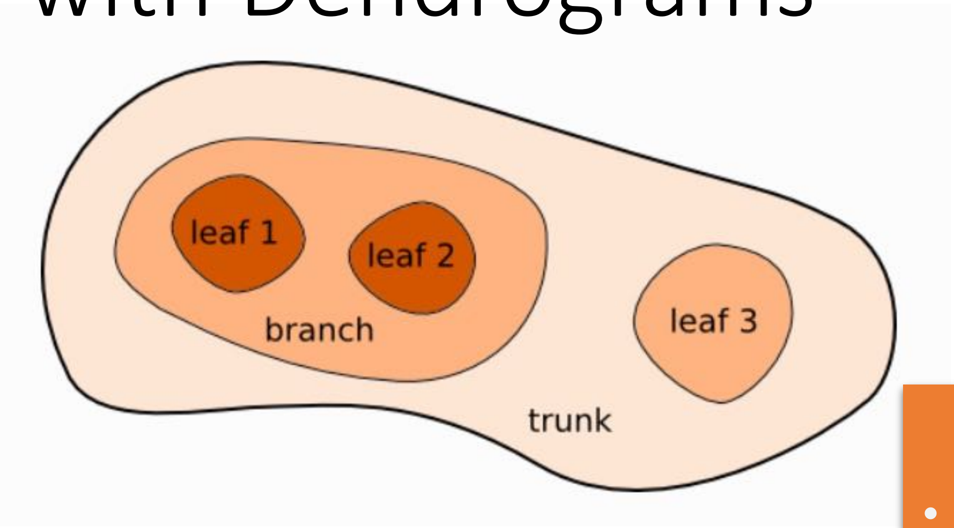
Table 1: [^{12}CII] and [^{13}CII] spectroscopic parameter.

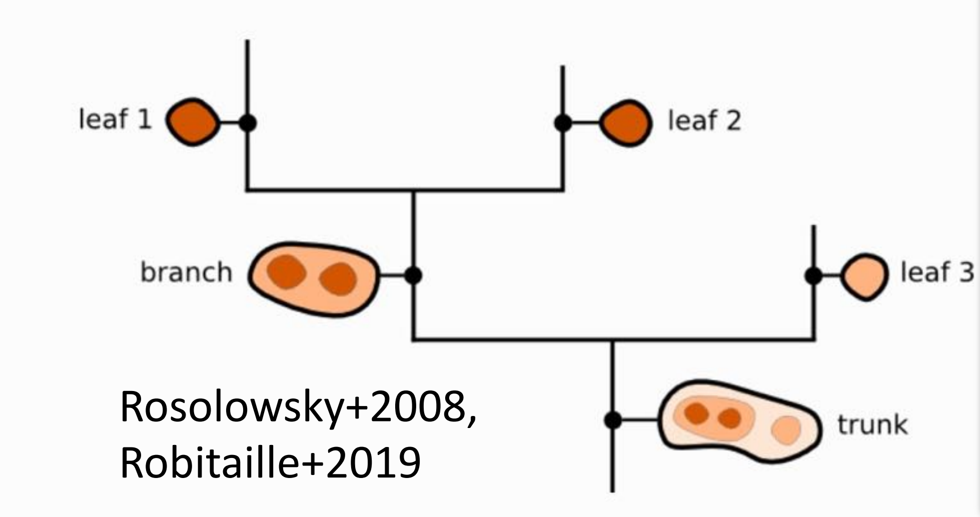
Line	Statistical Weight g_u	g_l	Frequency ν [GHz]	Velocity Offset Δv [km/s]	Relative Intensity $s_{F\rightarrow F'}$
[^{12}CII] $^3P_{3/2} \rightarrow ^2 P_{1/2}$	4	2	1900.5369	0	-
[^{13}CII] F = 2 → 1	5	3	1900.4661	+11.2	0.625
[^{13}CII] F = 1 → 0	3	1	1900.9500	-65.2	0.25
[^{13}CII] F = 1 → 1	3	3	1900.1360	+63.3	0.125



- ^{12}C/ ^{13}C ratio of ~ 60
- Hyperfine splitting of the [^{13}CII] line
- Strongest [^{13}CII] F(2-1) satellite is often contaminated by the [^{12}CII] wing
- Results in a usually weak [^{13}CII] emission which requires:
    1. High integration times (Guevara+2020)
    2. "Smart" averaging over large areas (dumping the noise while dumping the signal does not help)

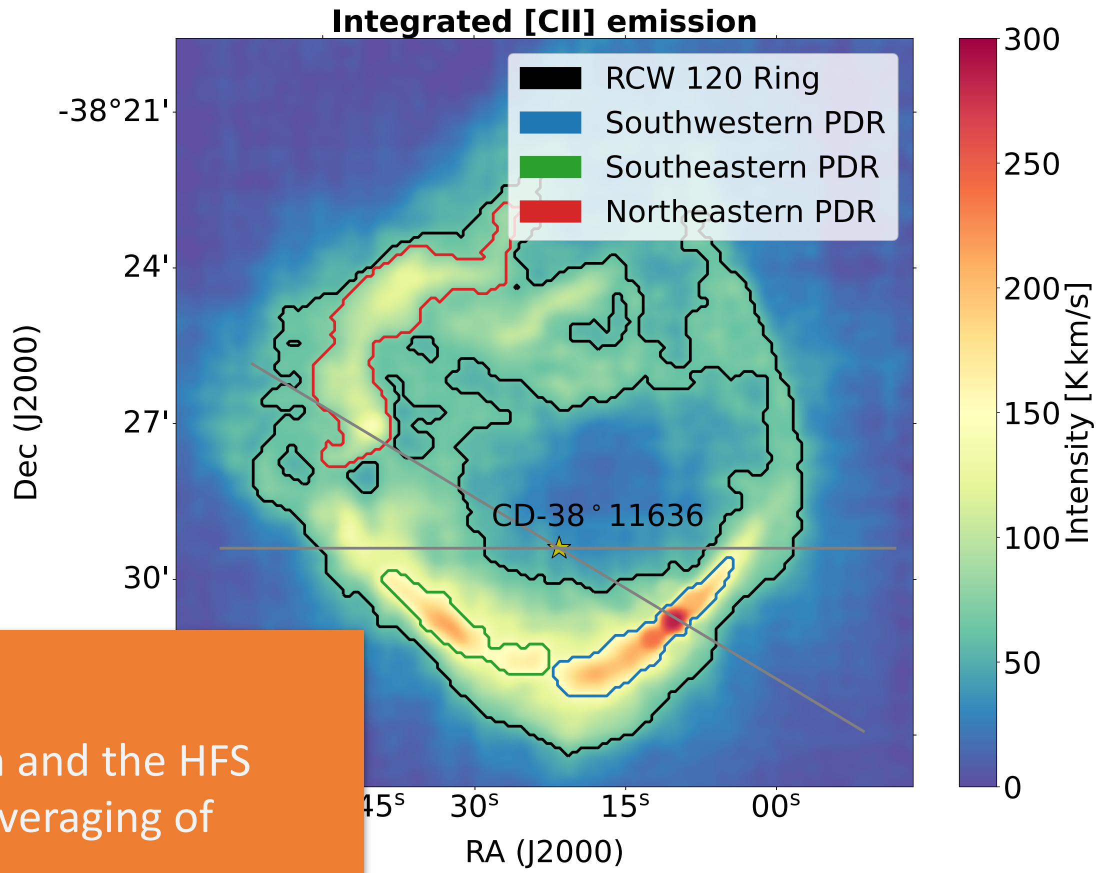
[CII] Clustering with Dendrograms



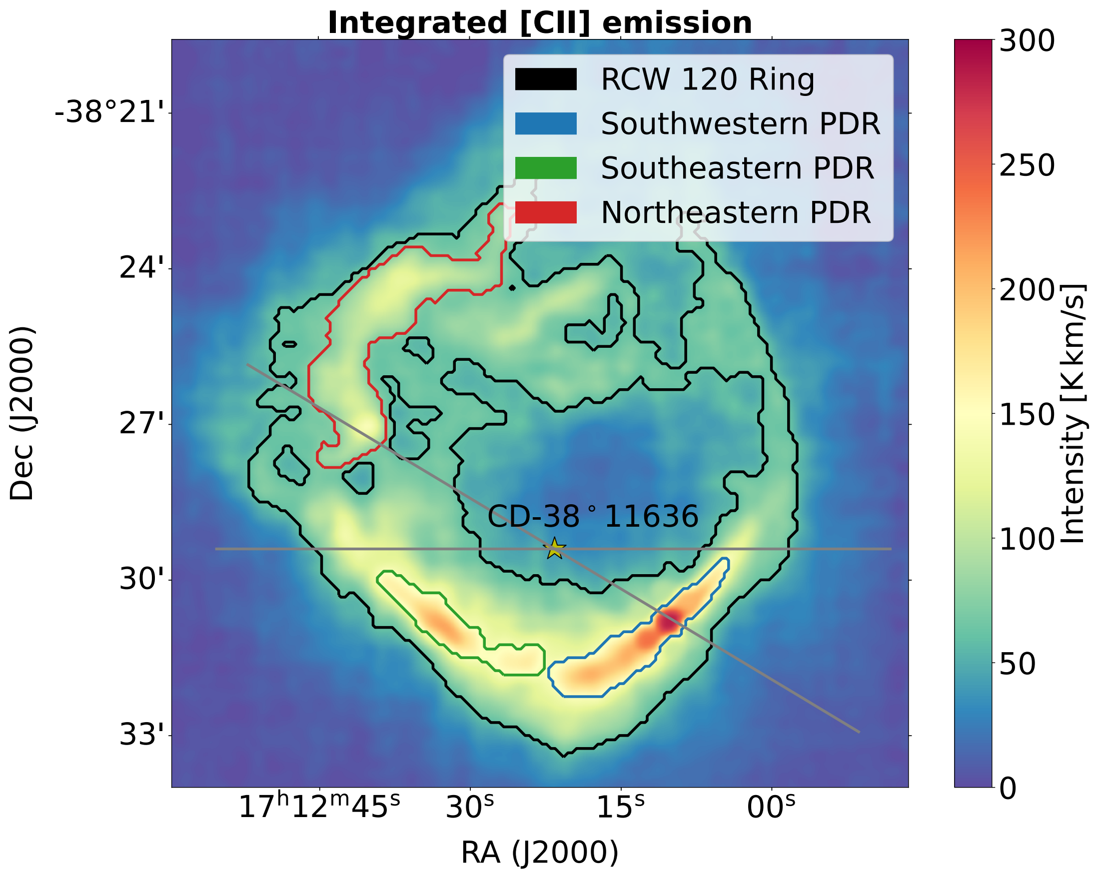


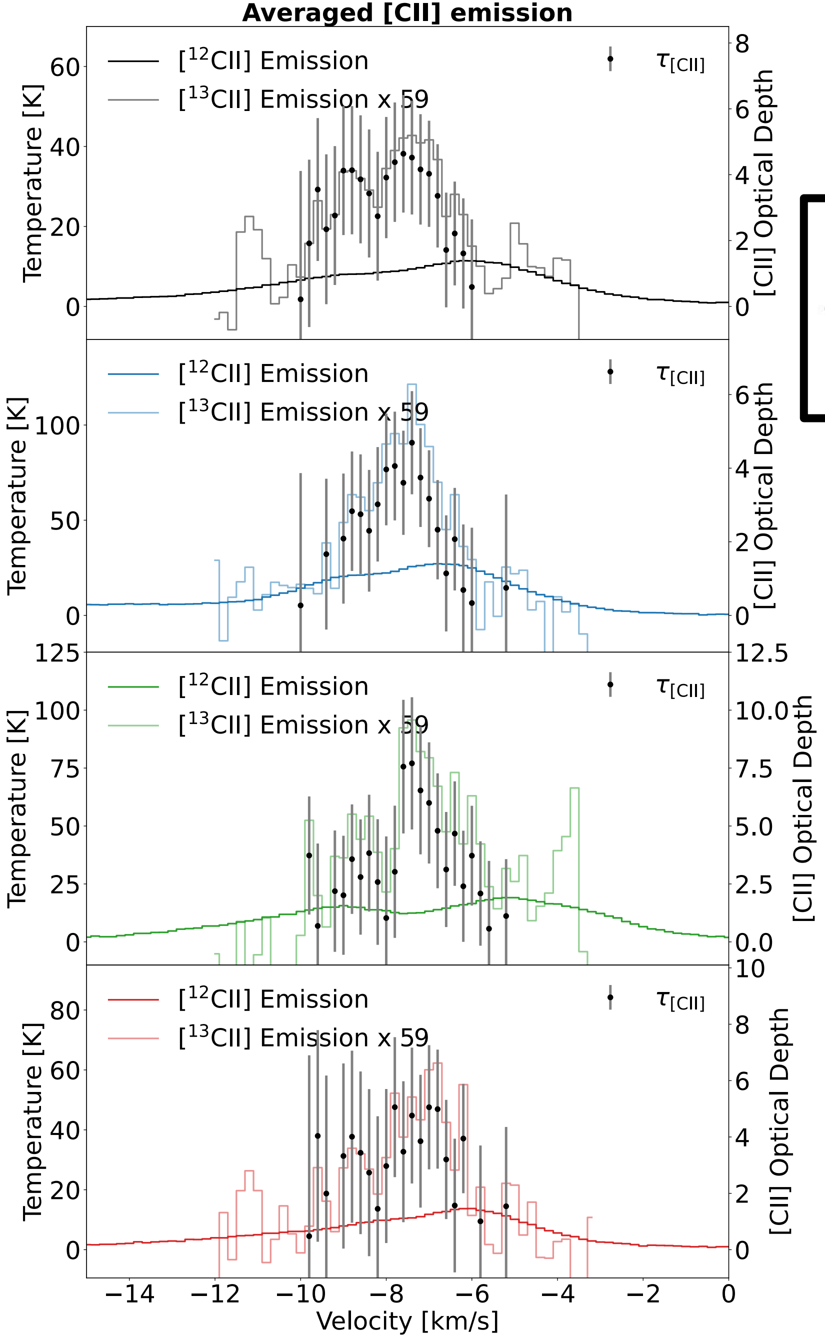
Rosolowsky+2008,
Robitaille+2019

- The weak emission and the HFS splitting requires averaging of arcmin² regions.
- We make use of astrodendro (www.dendrograms.org) a dendrograms based approach to average clusters of high intensity/ column density.



[CII] Optical Depth

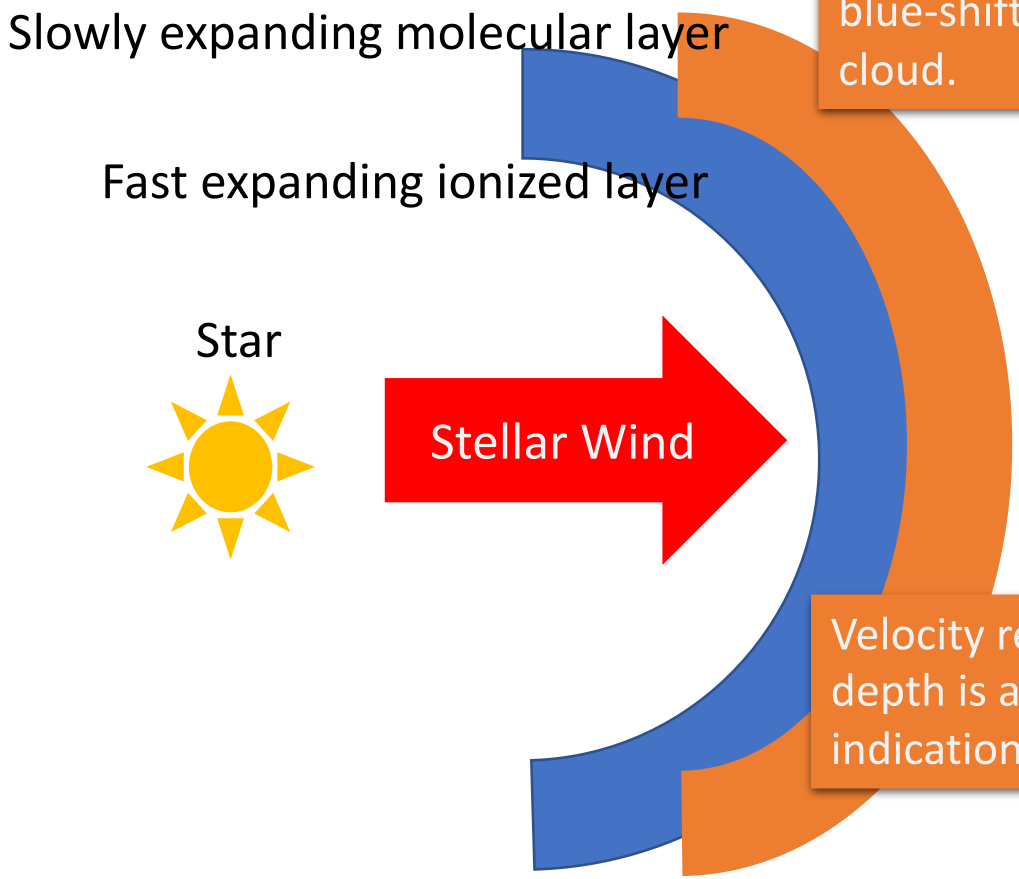




$$\frac{T_{\mathrm{mb},{}^{12}\mathrm{C}}(\mathrm{v})}{T_{\mathrm{mb},{}^{13}\mathrm{C}}(\mathrm{v})} = \frac{1 - e^{-\tau(\mathrm{v})}}{\tau(\mathrm{v})}\alpha$$

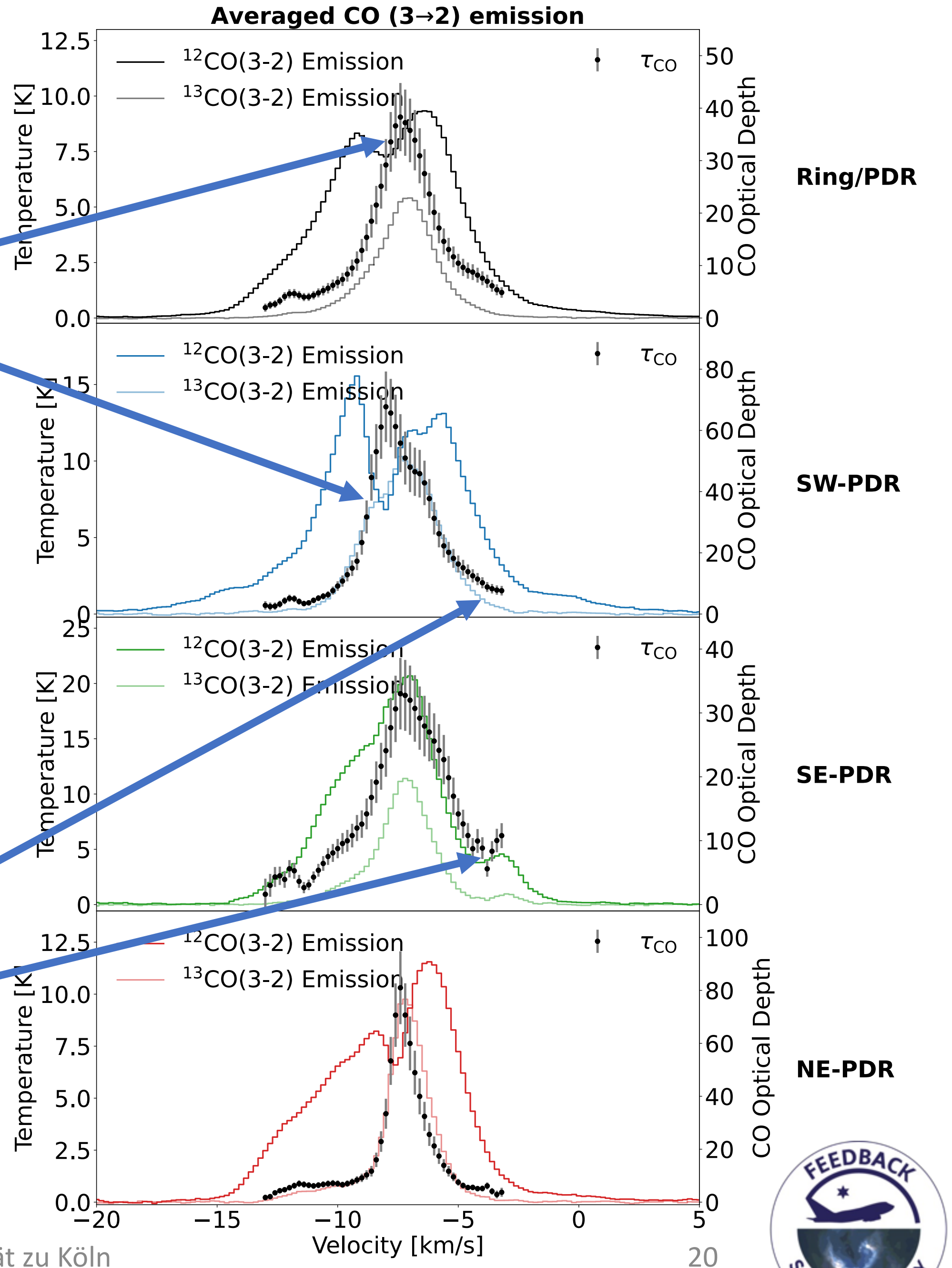
- Scaled up [^{13}CII] emission line is overshooting the [CII] emission.
- The velocity resolved optical depth is significantly above 1
- Strong optical depth effect similar to the finding by Guevara+2020

CO Optical Depth



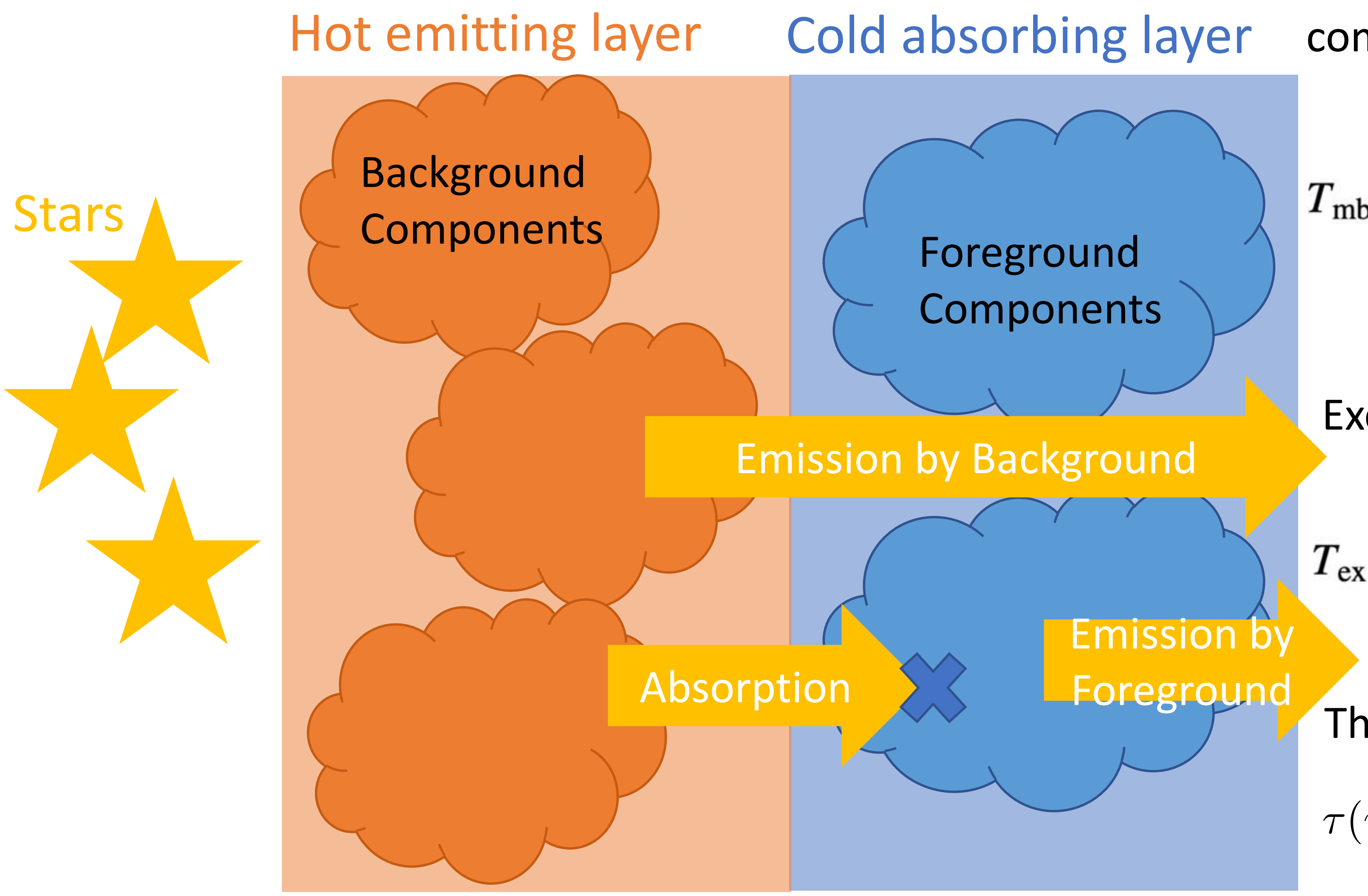
The absorption dip is ~1 km/s blue-shifted from the the cloud.

Velocity resolved optical depth is asymmetric. Possible indication toward infall.



Two Layer Multicomponent Model

(Guevara+2020, Kabanovic+2022)



Radiative transfer equations for multiple components distributed in two layers :

Background

$$T_{\mathrm{mb}}(\mathrm{v}) = \left[\mathcal{J}_\nu(T_{\mathrm{ex,bg}})\left(1 - e^{-\sum_{i_{\mathrm{bg}}} \tau_{i_{\mathrm{bg}}}(\mathrm{v})}\right)\right] e^{-\sum_{i_{\mathrm{fg}}} \tau_{i_{\mathrm{fg}}}(\mathrm{v})} + \mathcal{J}_\nu(T_{\mathrm{ex,fg}})\left(1 - e^{-\sum_{i_{\mathrm{fg}}} \tau_{i_{\mathrm{fg}}}(\mathrm{v})}\right),$$

Foreground

Excitation Temperature

$$T_{\mathrm{ex}} = T_0 \ln\left(\frac{T_0}{T_{\mathrm{p,mb}}}\left(1 - e^{-\tau_{\mathrm{p}}}\right) + 1\right)^{-1}$$

The optical depth follows a Gaussian profile

$$\tau(v) = \tau_0 e^{-4\ln 2\,\left(\frac{v - v_0}{w}\right)^2}$$

[CII] Ring Emission

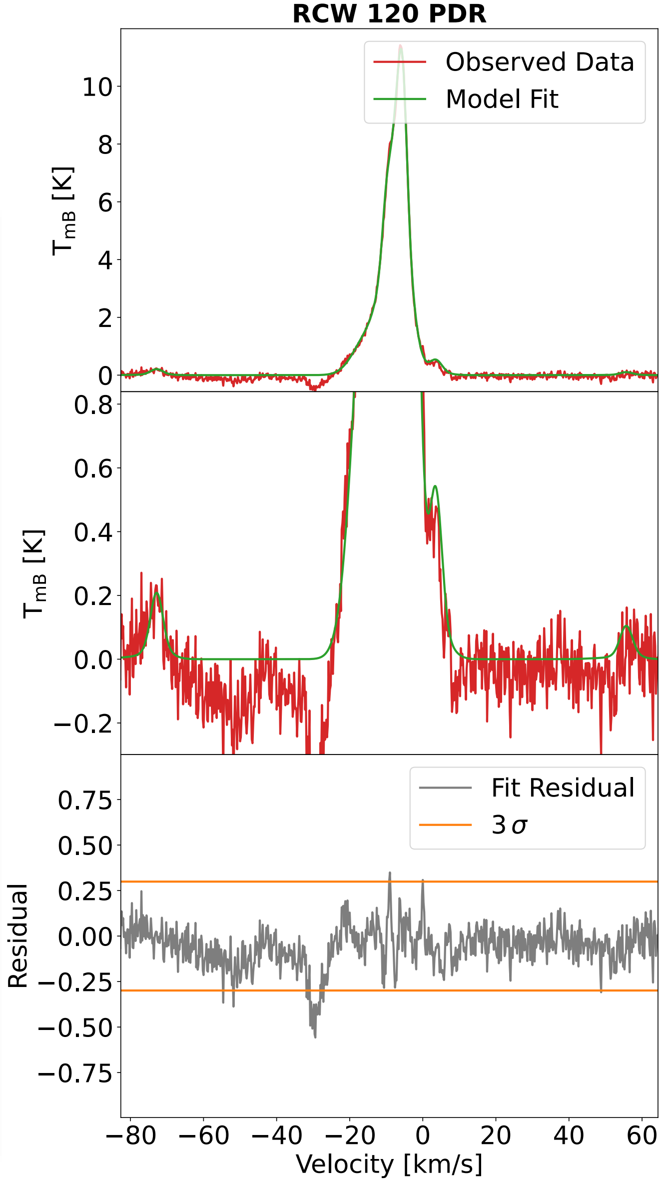
Kabanovic+2022

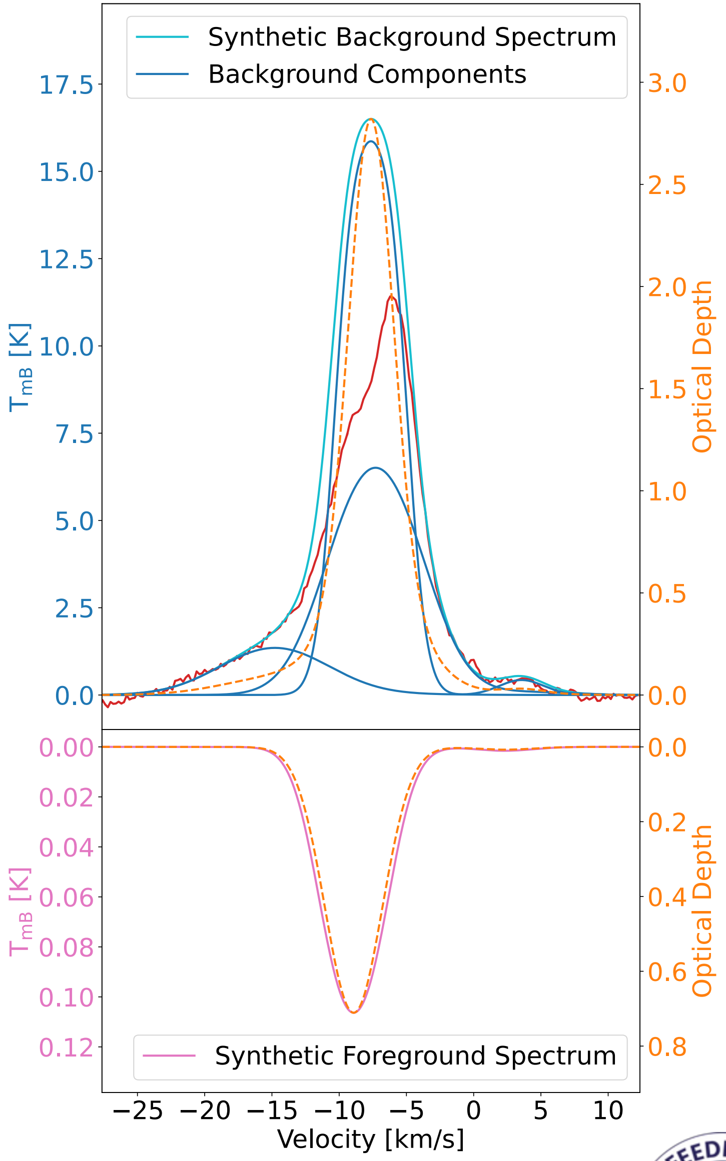
Left Panel:

1. Top sub-panel:
   - Red spectrum: Observed [^{12}CII] line
   - Green spectrum: Modeled Result
2. Middle sub-panel:
   - Same as top sub-panel for [^{13}CII]
3. Bottom sub-panel:
   - Gray data: Fit residual
   - Orange lines: 3 sigma level

Right Panel:

1. Top sub-panel:
   - Blue spectra: Background components
   - Orange dashed curve: Optical depth
2. Bottom sub-panel:
   - Pink spectra: Foreground component
   - Orange dashed curve: Optical depth

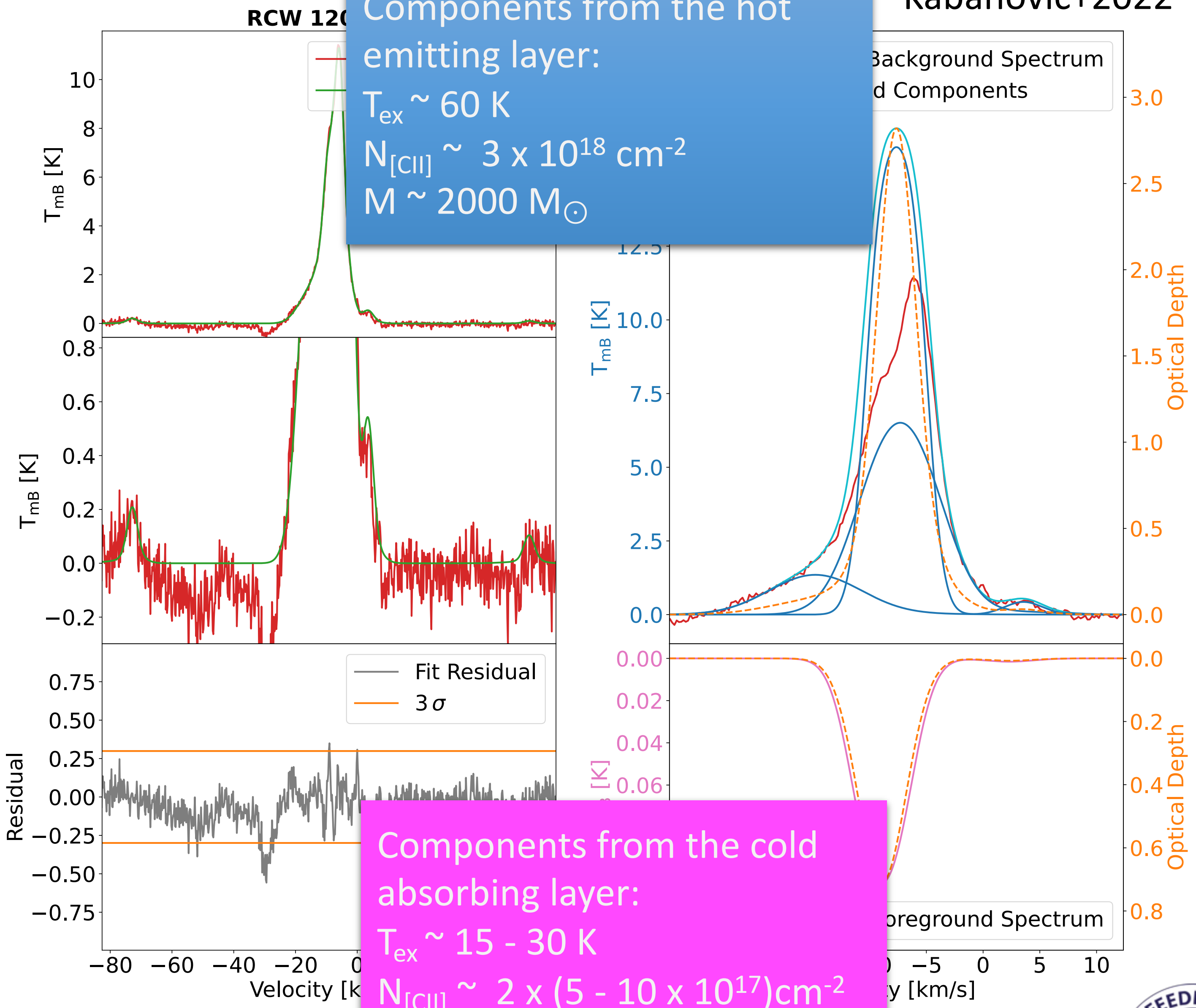




[CII] Ring Emission

- Lower temperature limit for the C+ absorbing layer is determined by solving the energy balance between heating of the layer by cosmic ray ionization and C+ cooling by line emission.
- Upper limit is confined by the observed visual extinction towards RCW 120 and the observed absorption dips in the spectrum.

Kabanovic+2022



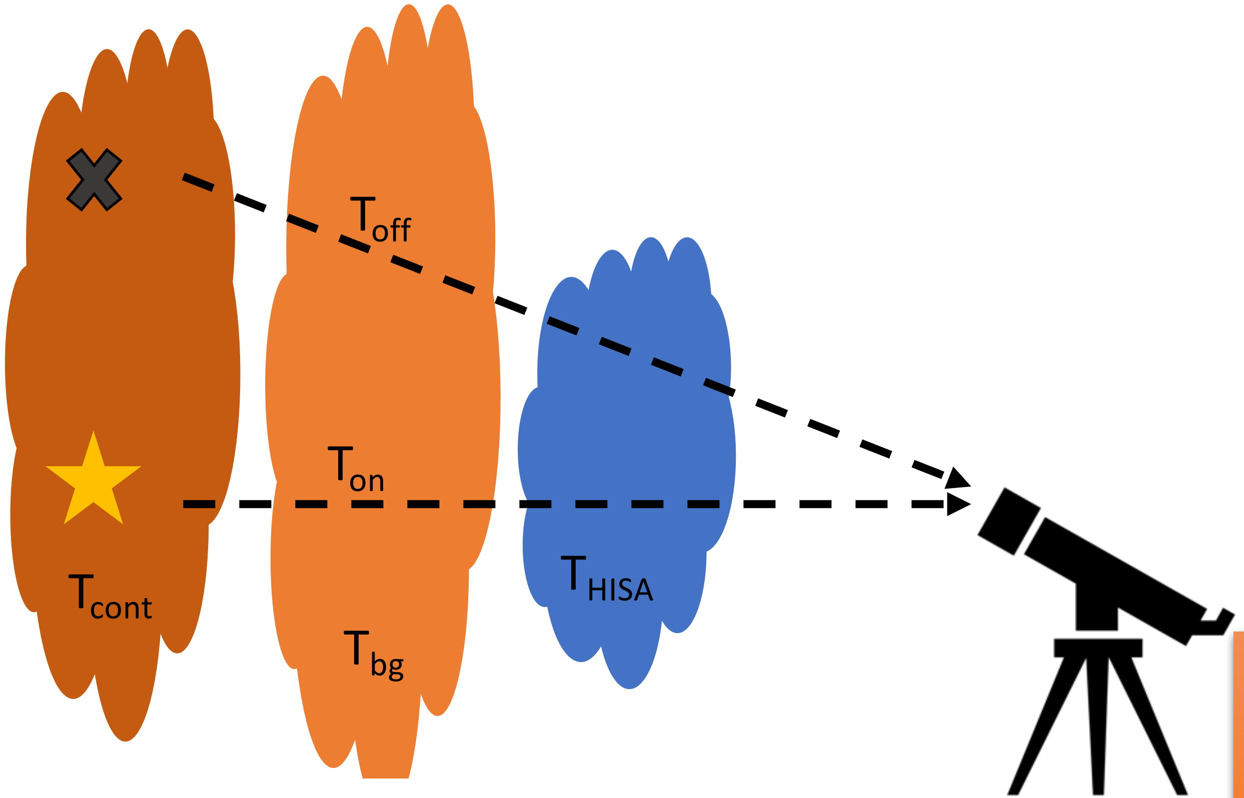
Components from the hot emitting layer:
T_{ex} ~ 60 K
$N_{[CII]}$ ~ 3 x 10^{18} cm^{-2}
M ~ 2000 $M_\odot$

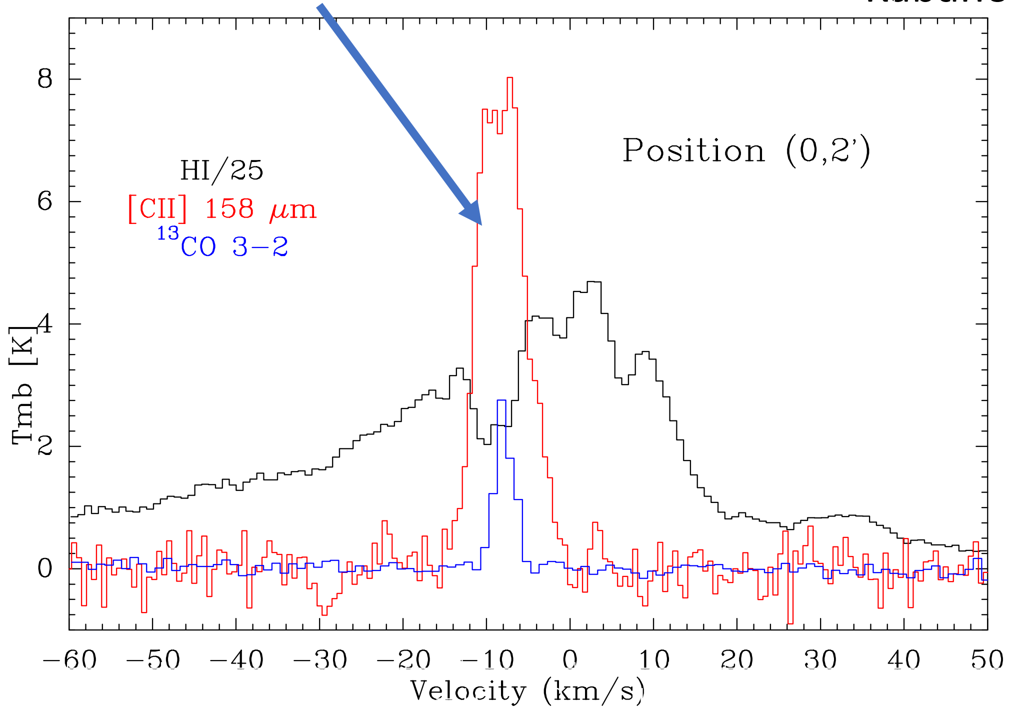
Components from the cold absorbing layer:
T_{ex} ~ 15 - 30 K
$N_{[CII]}$ ~ 2 x (5 - 10 x 10^{17})cm^{-2}
M ~ 2 x (340 – 680) $M_\odot$

HI self-absorption (HISA)

CII line 'peaks' in HI absorption dip but is also self-absorbed (flat-top spectrum)!

Kabanovic+2022





$$\tau_{\mathrm{HISA}}(v) = -\ln\left(1 - \frac{T_{\mathrm{on-off}}(v)}{T_{\mathrm{HISA}} - T_{\mathrm{off}}(v) - T_{\mathrm{cont}}}\right)$$

Wang+2020

Previous studies by:

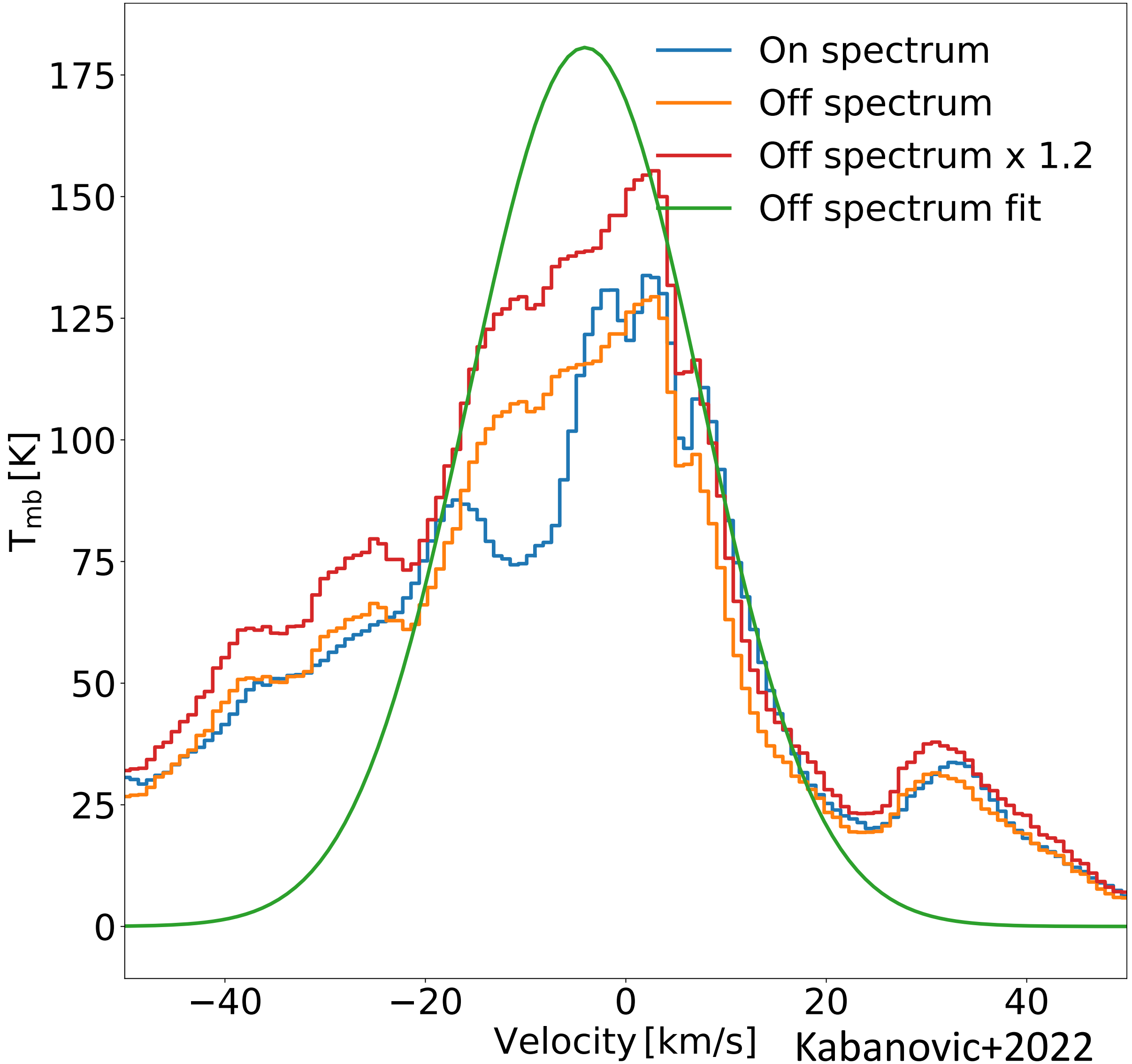
- Wannier+1991
- Andersson+1991
- Andersson+1992
- Andersson and Wannier 1993

indicate neutral atomic hallows around molecular clouds.

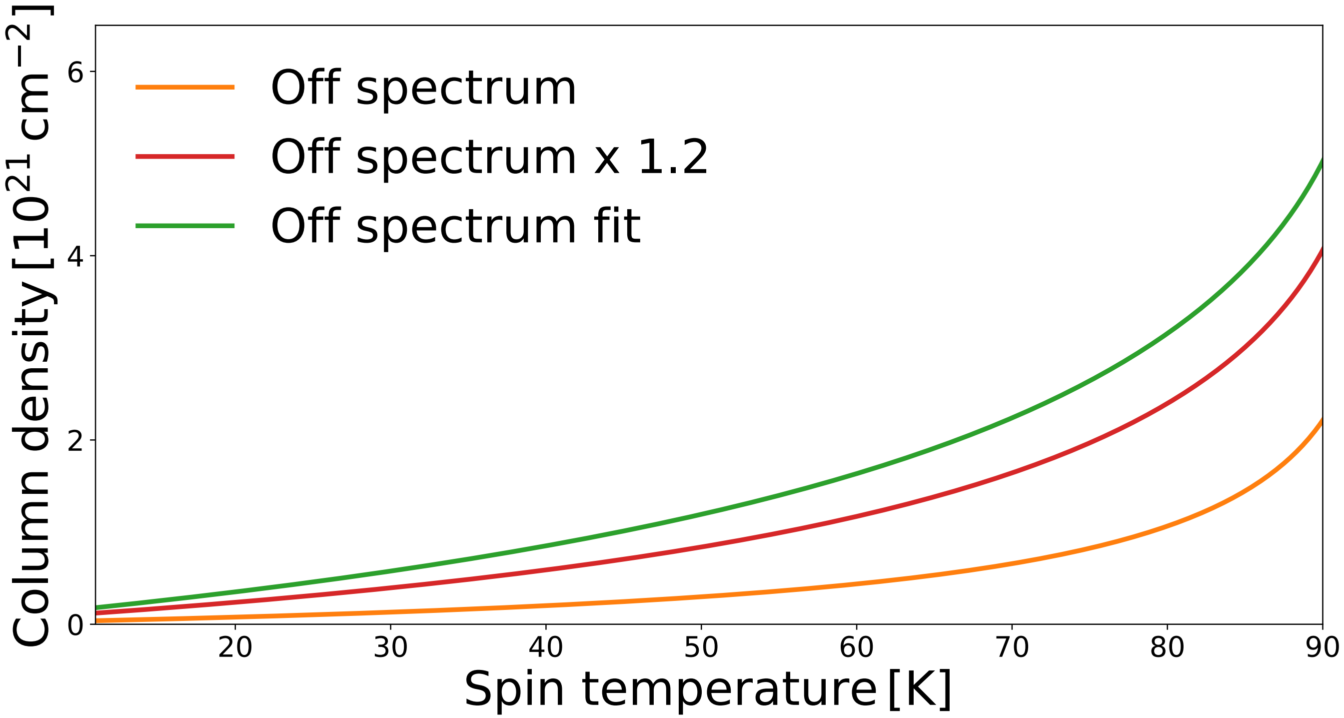
-> Possible origin for the large amounts of cold C^+?

HI self-absorption (HISA)

$$\tau_{\mathrm{HISA}}(\mathrm{v}) = -\ln\left(1 - \frac{T_{\mathrm{on-off}}(\mathrm{v})}{T_{\mathrm{HISA}} - T_{\mathrm{off}}(\mathrm{v}) - T_{\mathrm{cont}}}\right)$$

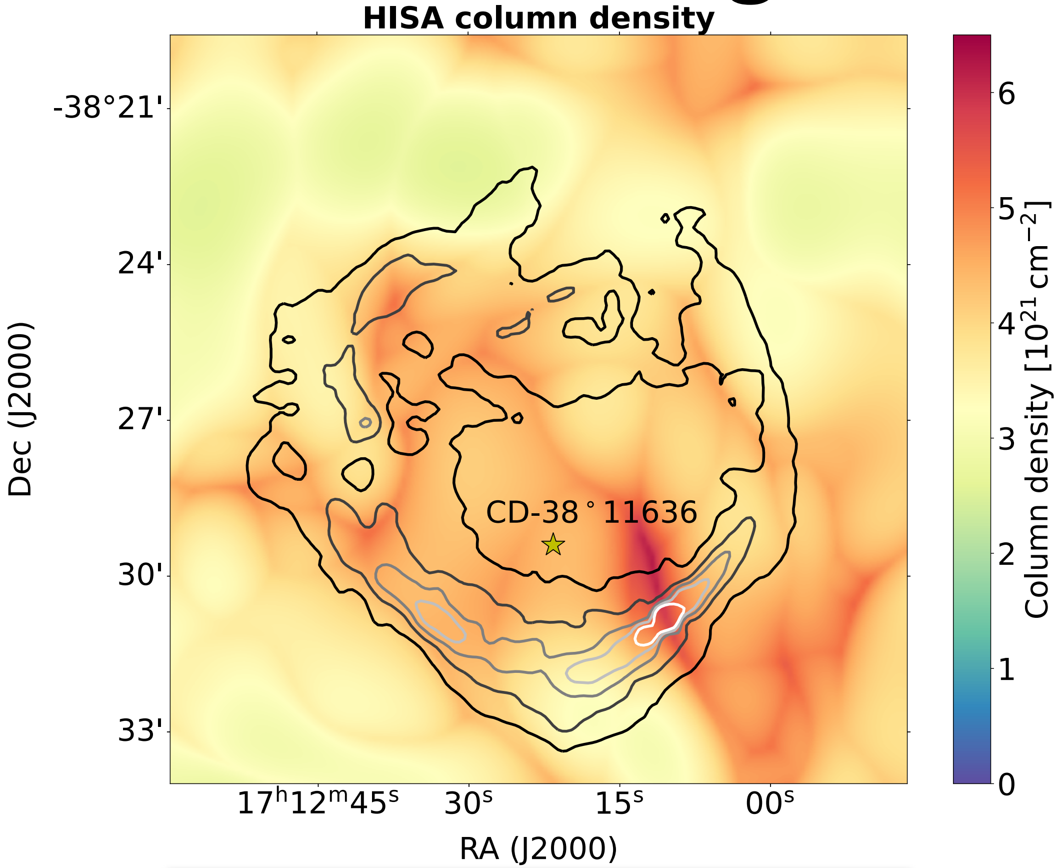


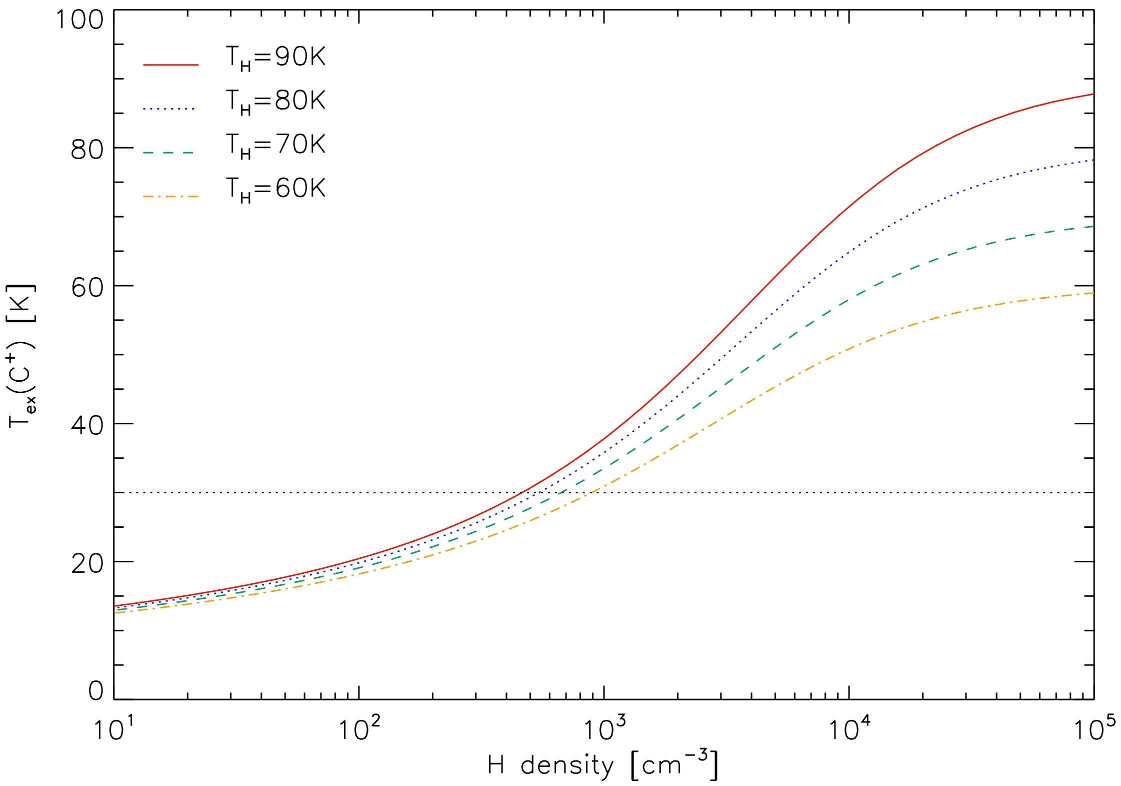
Kabanovic+2022



- The HISA column density is sensitive to the spin temperature.
- Seifried+2022 showed, utilizing SILCC-ZOOM simulations, that the “true” column density is best determined using the absorption dip temperature

HISA: the origin of the cold C+ emission





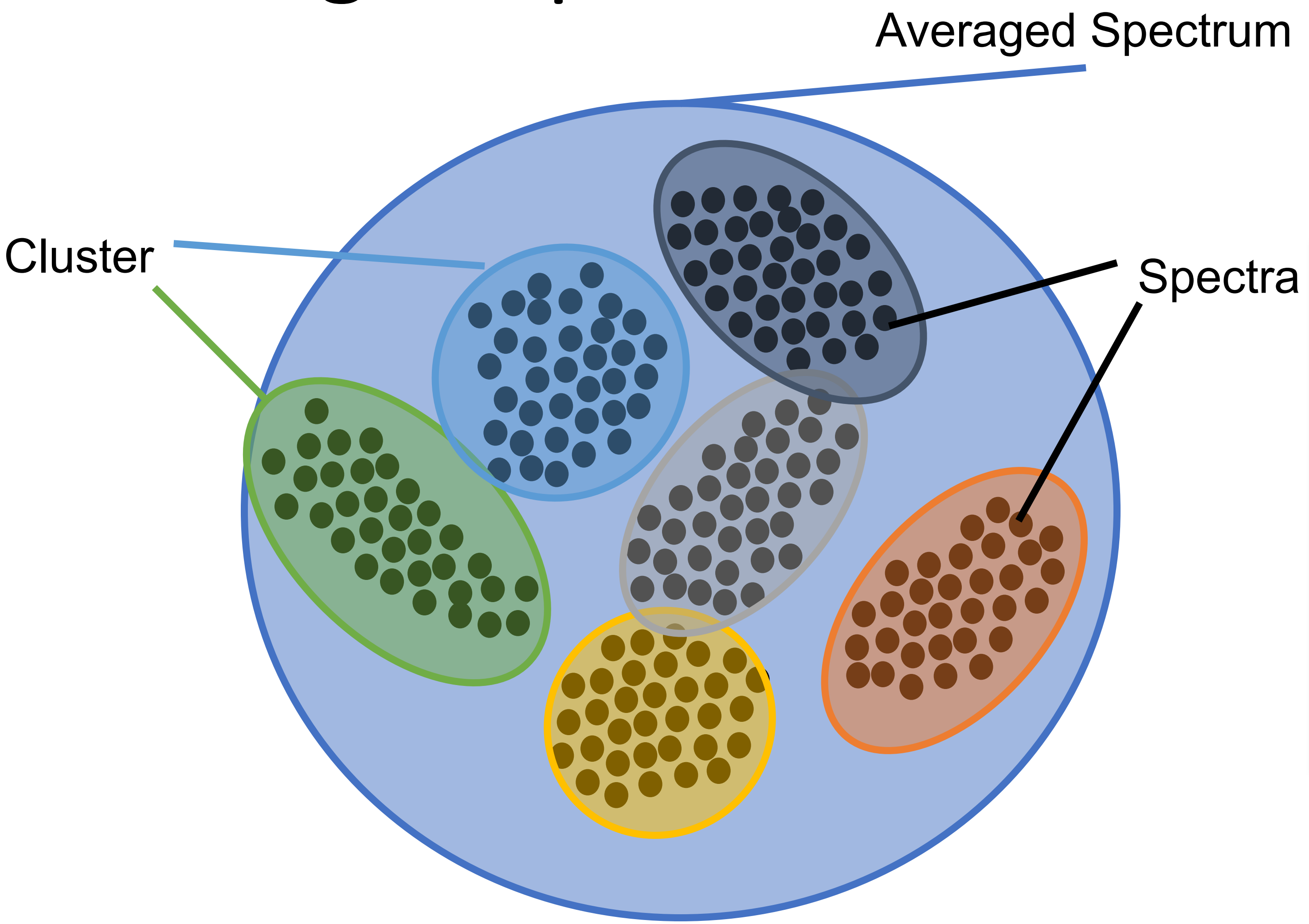
Kabanovic+2022

The determined column densities of the cold layer of HI self-absorption (HISA) are similar to the large column densities determined of the cold absorbing C^+.

Combination of the C^+ and HISA analysis confines the physical properties of the cold atomic layer in front of RCW 120:

- **HI density ~ 100-500 cm^{-3}**
- **HI-layer extension ~5-10 pc**

Clustering of Spectra



- We need a new approch to solve the radiative transfer equations for an entire data cube of more than 40000 spectra!
- Spectral shape is confined by local physical conditions.
- Spectra can be grouped into clusters.

Gaussian Mixture Model

Probability distribution

$$P(\vec{x}) = \sum \phi_i N(\vec{x}|\vec{x_i}, \Sigma_i)$$

A Gaussian mixture model is parameterized by the mixture **component weights** $\boldsymbol{\phi}$ and the component **means** $\boldsymbol{\mu}$ and **variances** $\boldsymbol{\Sigma}$.

Gaussian distribution

$$N(\vec{x}|\vec{\mu_i}, \Sigma_i) = \frac{1}{\sqrt{(2\pi)^K |\Sigma_i|}} \exp(-\frac{1}{2}(\vec{x} - \vec{\mu_i})^T \Sigma_i^{-1} (\vec{x} - \vec{\mu_i}))$$

Weights

$$\sum_i \phi_i = 1$$

1) Expectation Step

$$\gamma_{ik} = \frac{\phi_k N(x_i|\mu_k \sigma_k)}{\sum_j^K \phi_j N(x_i|\mu_j \sigma_j)}$$

Probability that spectrum x_i is in cluster C_k.

2) Maximization Step

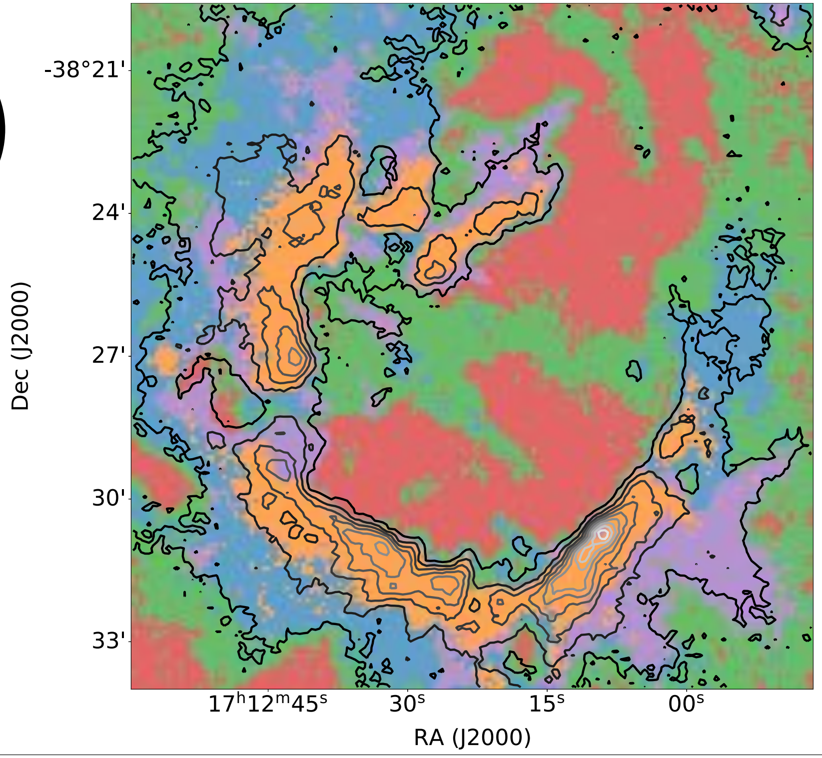
$$\phi_k = \sum_i^N \frac{\gamma_{ik}}{N}$$

Update of the model parameter.

$$\mu_k = \frac{\sum_i^N \gamma_{ik} x_i}{\sum_i^N \gamma_{ik}}$$

$$\sigma_k^2 = \frac{\sum_i^N \gamma_{ik}(x_i - \mu_k)^2}{\sum_i^N \gamma_{ik}}$$

Bayesian Information Criterion (BIC)



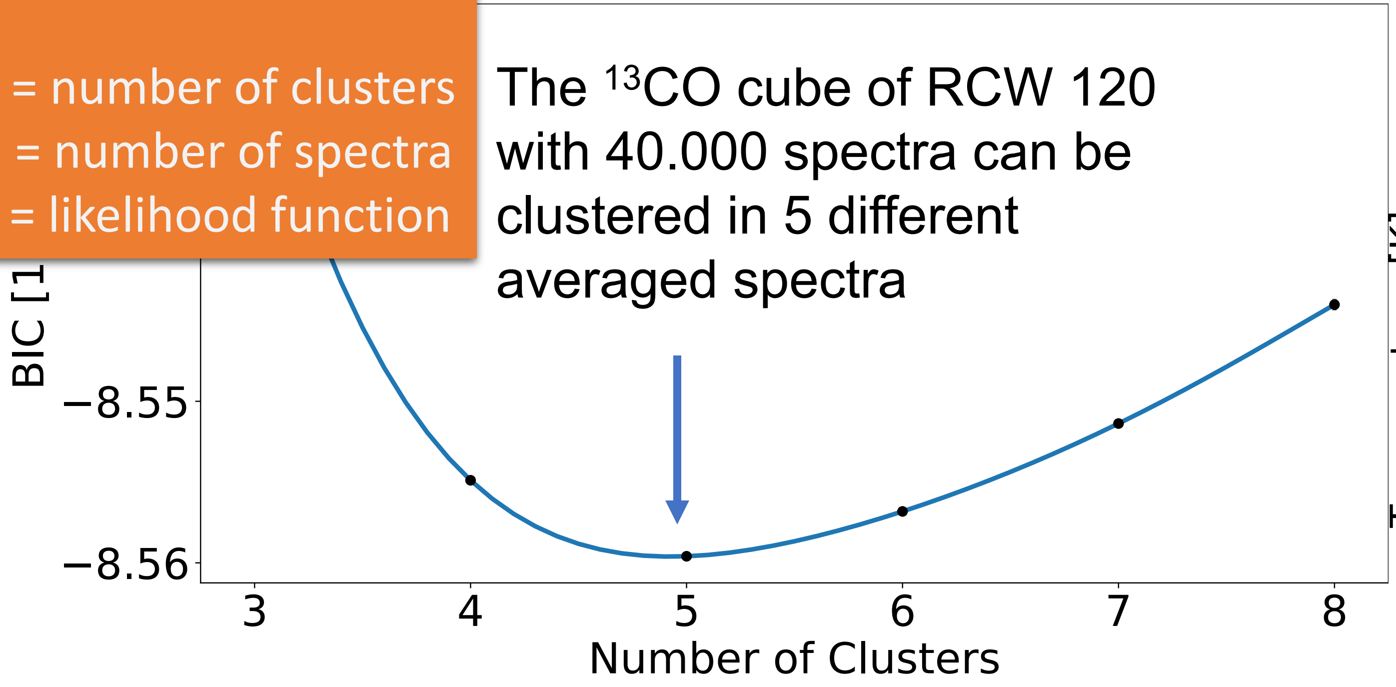
The BIC is a criterion for model selection among a finite set of models, based on the likelihood function.

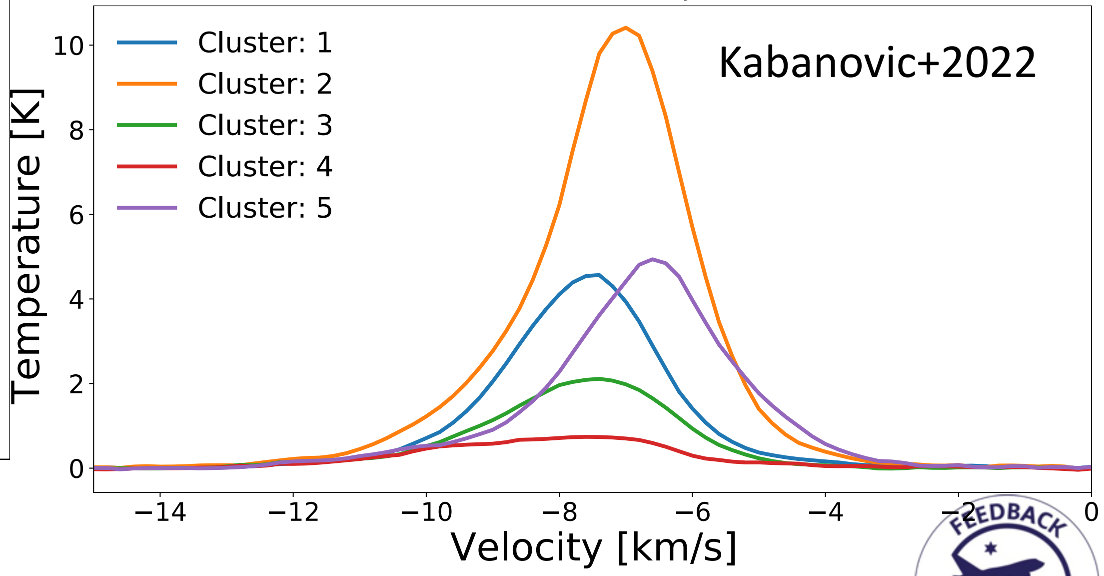
The likelihood function measures the goodness of fit of a statistical model to a sample of data.

$BIC = k \ln(n) - \ln(L)$

k = number of clusters
n = number of spectra
L = likelihood function

The ^{13}CO cube of RCW 120 with 40.000 spectra can be clustered in 5 different averaged spectra

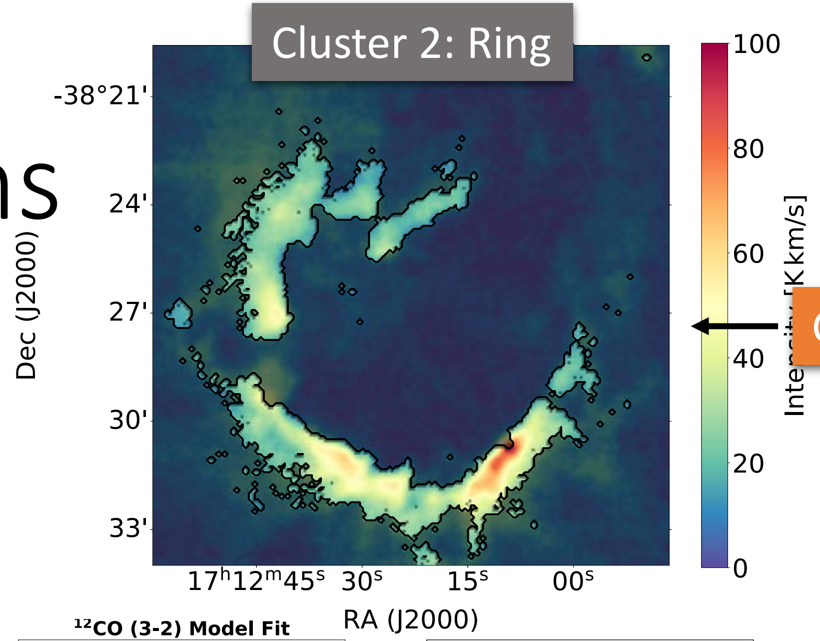




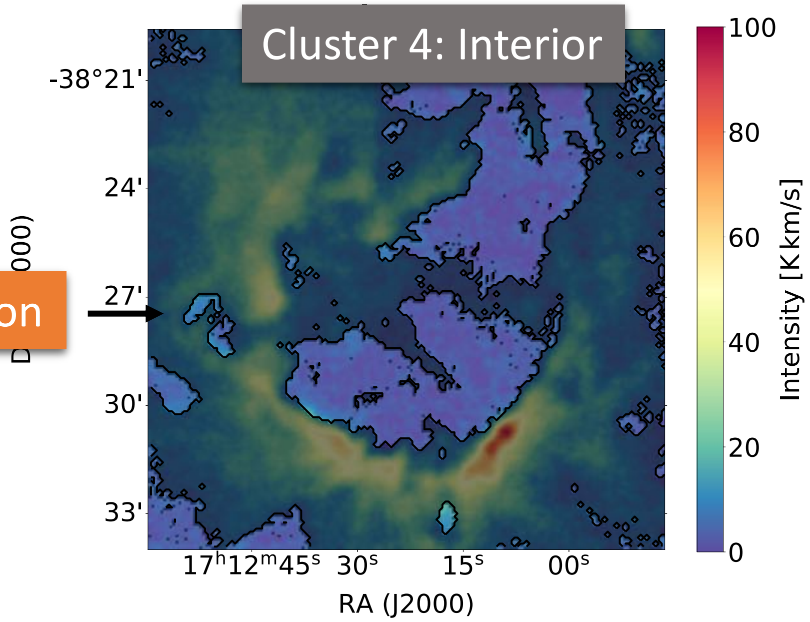
FEEDBACK SOFIA C+LEGACY

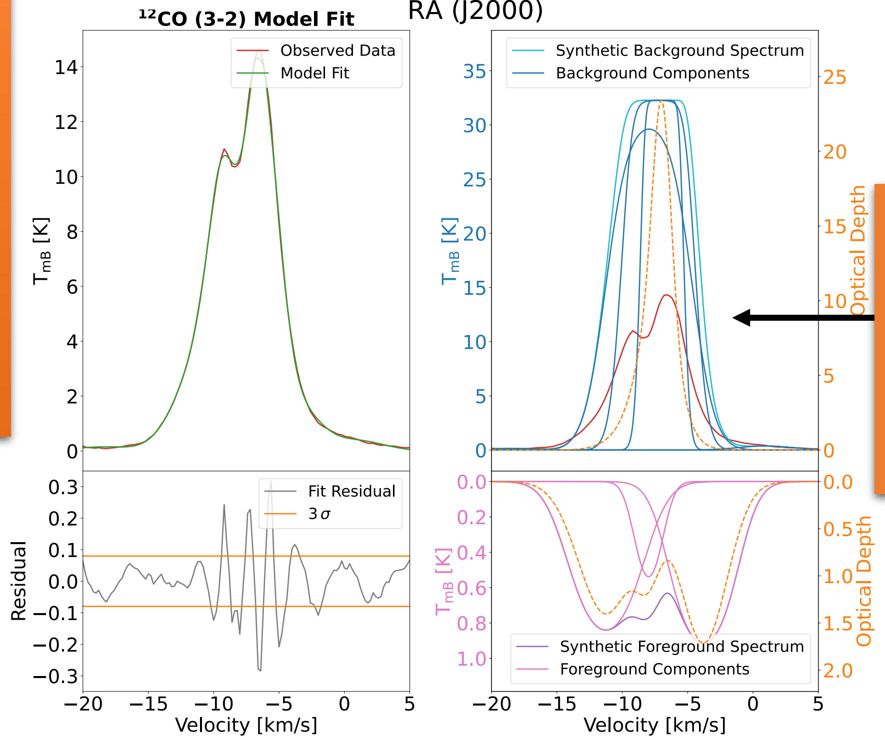
Initial Conditions

- The initial conditions are determined by solving the two-layer model for the average spectrum of each cluster.
- Foreground best described by three components.

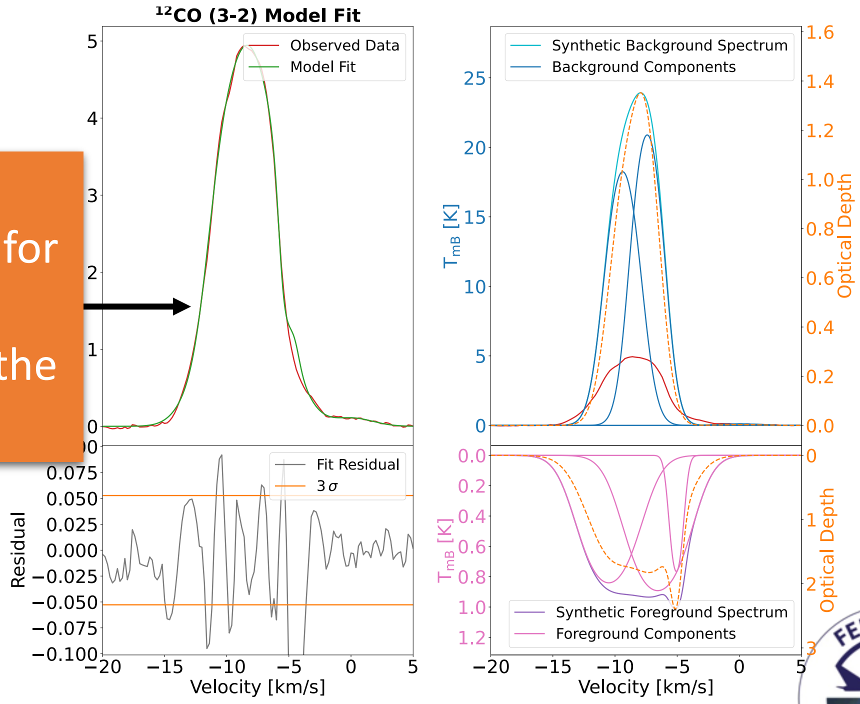


Cluster location

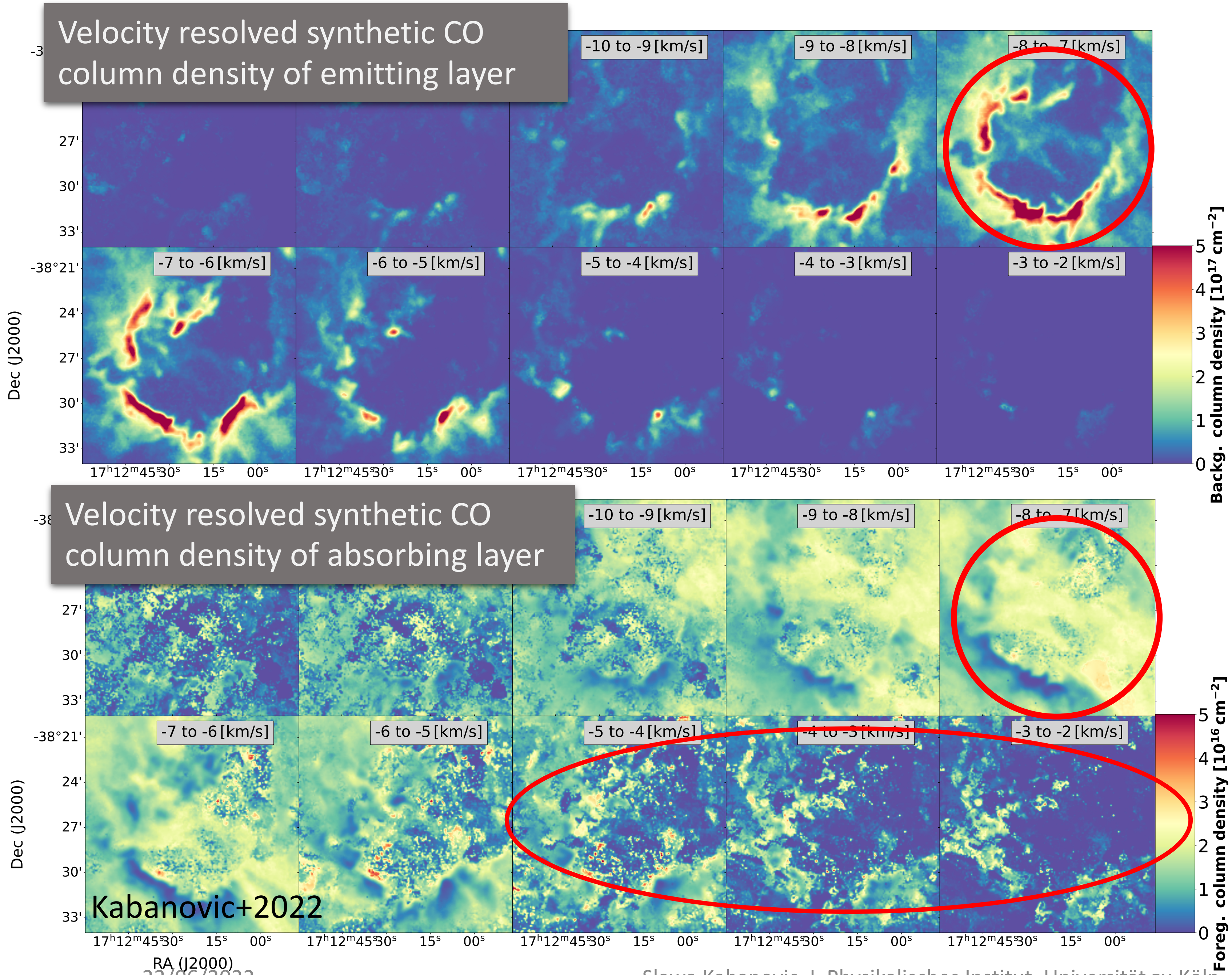




Two-layer model result for the average spectrum of the cluster



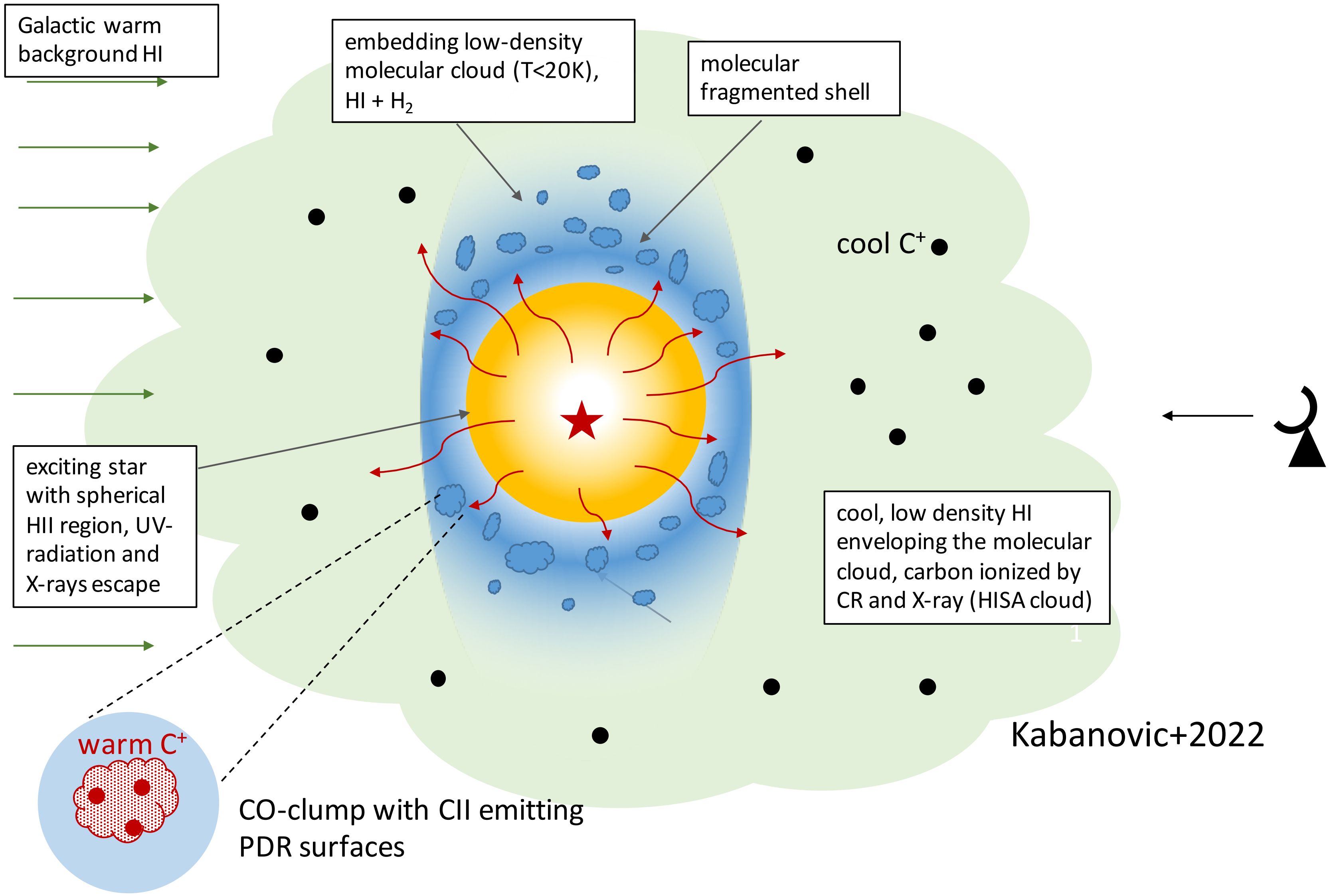
Kabanovic+2022



- The warm emitting layer traces the **fragmented dense ring**.
- We find increasing column density towards the interior. But not enough foreground is found to explain the emission deficit!
- We detect self-absorption along the ring at red-shifted velocities, thus a sudden change in morphology, probably indicating **global infall**.

A new view on RCW 120

- Stellar wind drives an expanding C^+ bubble (Luisi+2021).
- The expansion compresses the surrounding molecular cloud to a torus.
- The HII bursts out of a sheet/filament like molecular cloud.
- The flat molecular cloud is surrounded by a cold atomic layer.



Kabanovic+2022

Summary

FEEDBACK

- **C+** is a **unique tracer of gas kinematic**s.
- **Stellar wind driven expanding shells** in C^+ are observed in RCW 120, RCW49, RCW 79, NGC7538 and Orion A
- The compression leads to a molecular shell that fragments. **Star-formation is triggered** on short time scales.

RCW120

- The large column densities of **cold** absorbing **C^+** can be explained by a low-density (~100-500 cm^{-3}) , diffuse **HI layer.**
- Carbon in this layer can be ionized by **cosmic rays,** X-rays and/or UV radiation leaking out of the HII region.
- The deficit in CO emission along central sightlines can not be explained by CO self-absorption, which is modelled and explained by a temperature gradient.
- The associated **molecular cloud is flat**.
- We tentatively see global **infall of gas onto the molecular ring**.