The highlights of the SOFIA Legacy Program FEEDBACK and future perspectives on Orion A

Slawa Kabanovic, Nicola Schneider

and the FEEDBACK consortium

SOFIA Legacy Program: FEEDBACK

(PIs N. Schneider and A. Tielens)

Maryland webpage:
http://feedback.astro.umd.edu/

Data access:
https://irsa.ipac.caltech.edu/applications/sofia

Survey of 11 galactic high mass star forming regions in [CII] and [OI], ~ 100 h observing time, ~ 75% done
+ APEX observation of the ^{12}CO and ^{13}CO lines

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

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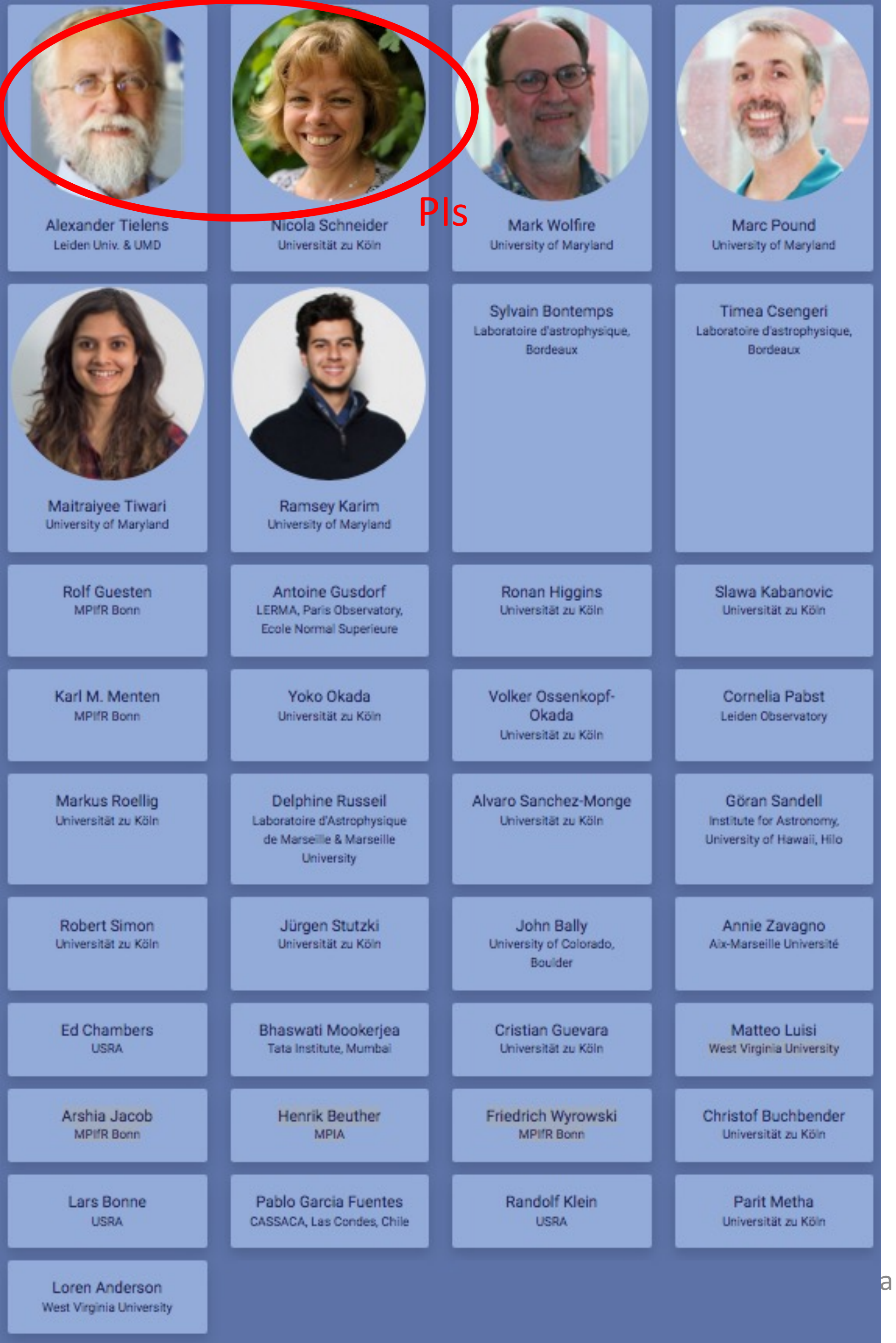


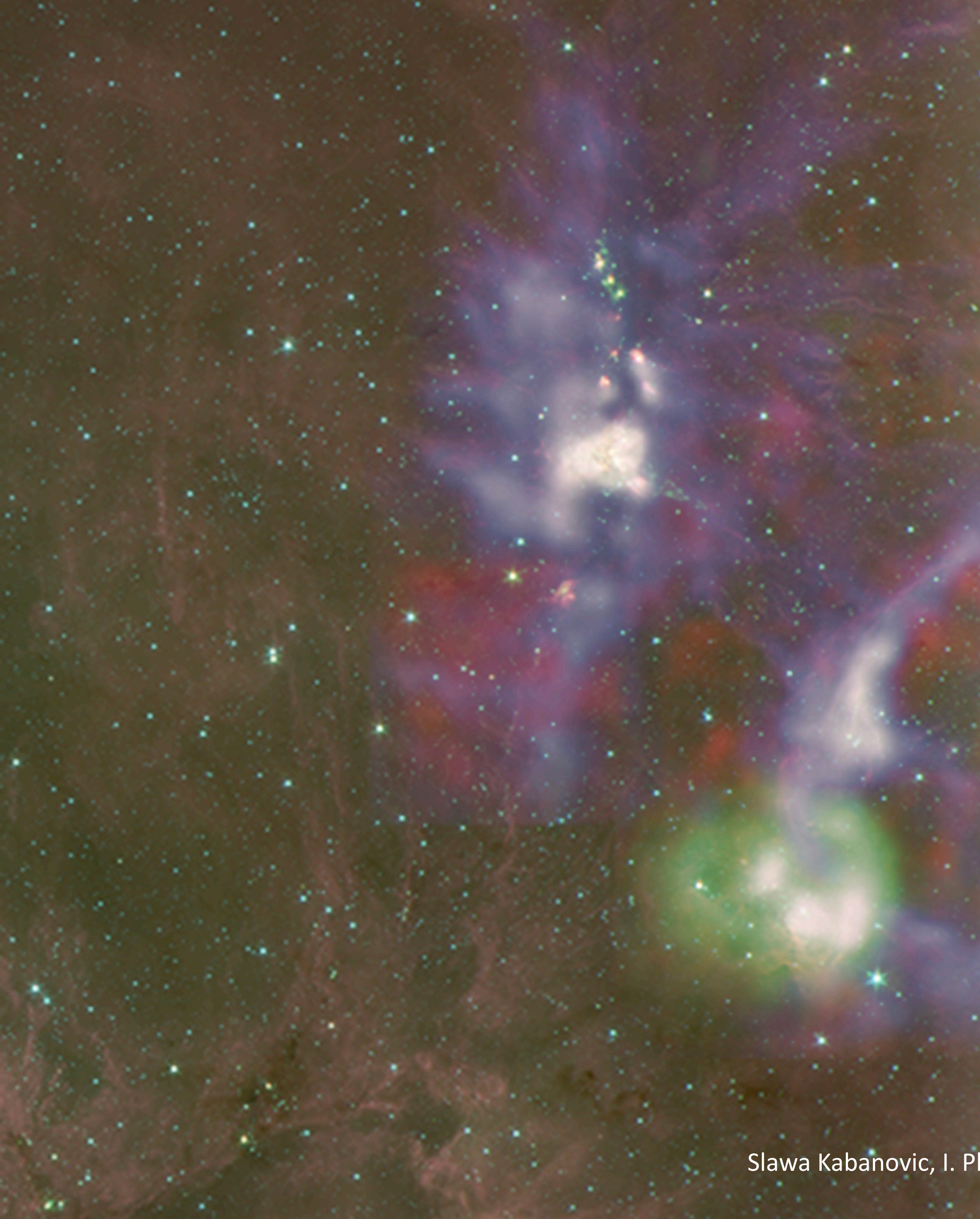
FEEDBACK team

Experts from all over the world with competences in submm observations, PDR modelling, shock modelling, HII regions, molecular cloud formation,….

12 paper published + >6 in prep. for 2024

Publications

Schneider et al. (2020)	FEEDBACK project
Luisi et al. (2021)	Expanding CII shells in RCW120
Tiwari et al. (2021)	Wind-driven shells in RCW49
Beuther et al. (2022)	Bubbles in NGC7538
Bonne et al. (2022)	Dynamics and mass ejection in RCW36
Tiwari et al. (2022)	PDR of RCW49
Kabanovic et al. (2022)	Self-absorption in RCW120
Schneider et al. (2023)	C^+ tracing cloud assembly
Bonne et al. (2023)	C^+ in DR21
Tiwari et al. (2023)	Gaussian Mixture model
Bonne et al. (2023)	Rapid anisotropic mass ejection in RCW79
Karim et al. (2023)	Pillars of creation in M16 in C^+
Bally et al. (in prep.)	W43
Keilmann et al. (in prep.)	PDR modelling of RCW79
Keilmann et al. (in prep.)	The compact HII region in RCW79
Metha et al. (in prep.)	Dynamics in M17
Neupane et al. (in prep.)	NGC6334
Dannhauer et al. (in prep.)	The Diamond Ring in Cygnus X



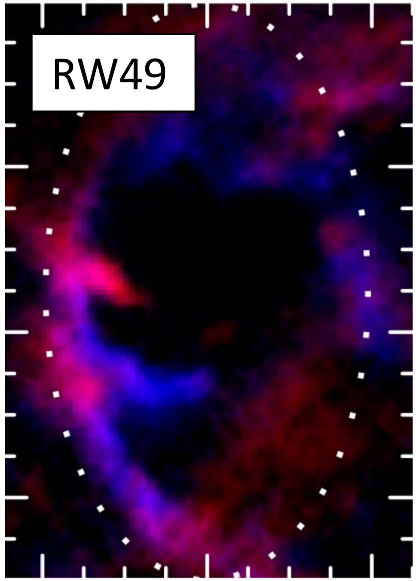
Highlights of FEEDBACK

- **Dynamics of [CII] emitting gas**
  - Expanding bubbles in [CII]
  - Cloud erosion seen in [CII]
- **Detection of large columns of cold [CII]**
- **Formation of molecular clouds seen in [CII]**

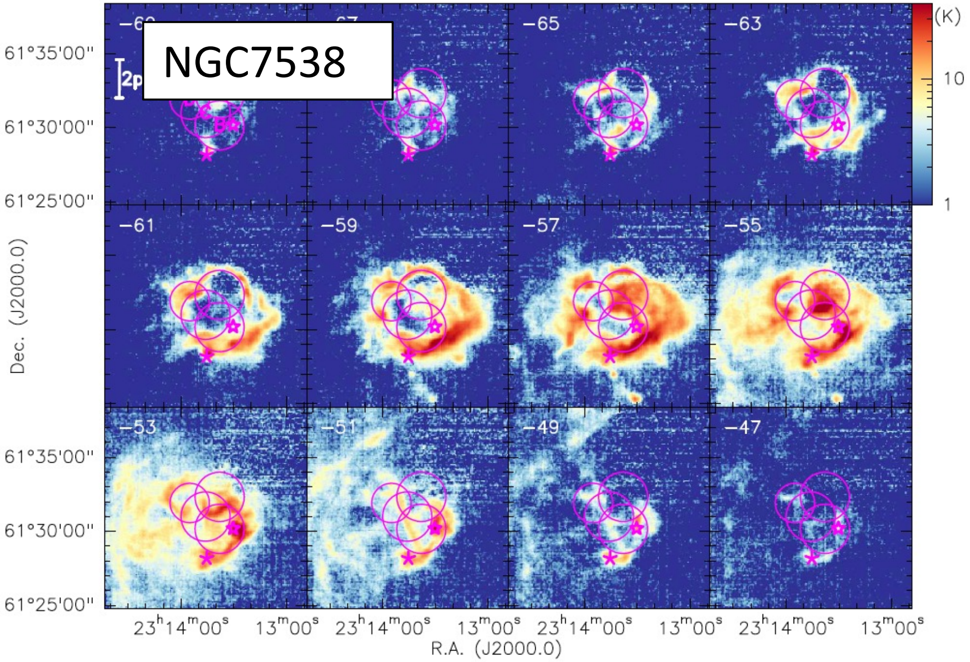
Dynamics of CII emitting gas

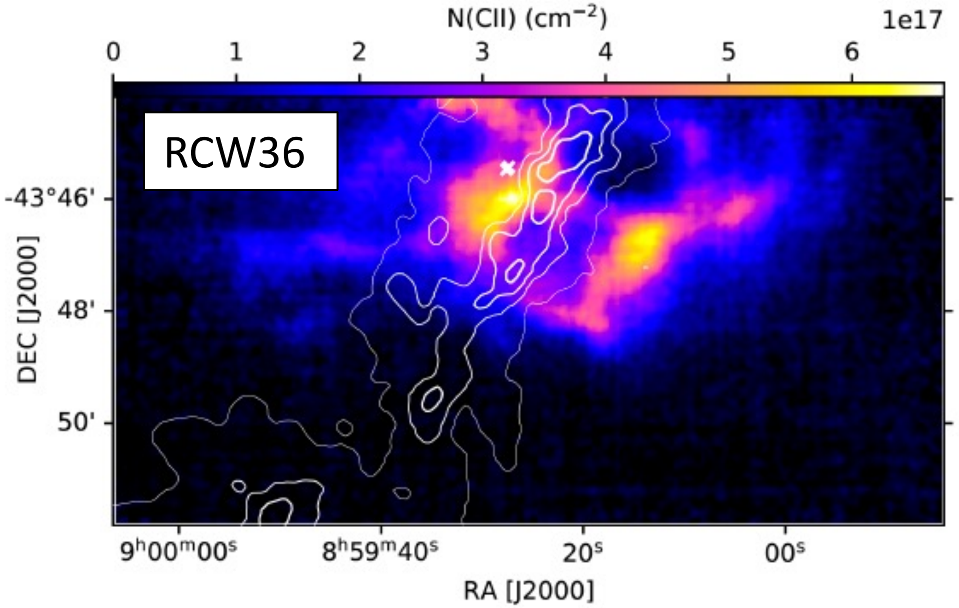
Expanding bubbles in CII

- First seen in Orion A (Pabst et al. 2019, 2020), then in nearly all FEEDBACK sources:
  RCW120 Luisi et al. (2021),
  RCW49 Tiwari et al. (2021),
  NGC7538 Beuther et al. (2022),
  RCW36 Bonne et al. (2022),
  RCW79 Bonne et al. (2023), Keilmann et al., in prep.



-12 to -8 km/s
-8 to -4 km/s



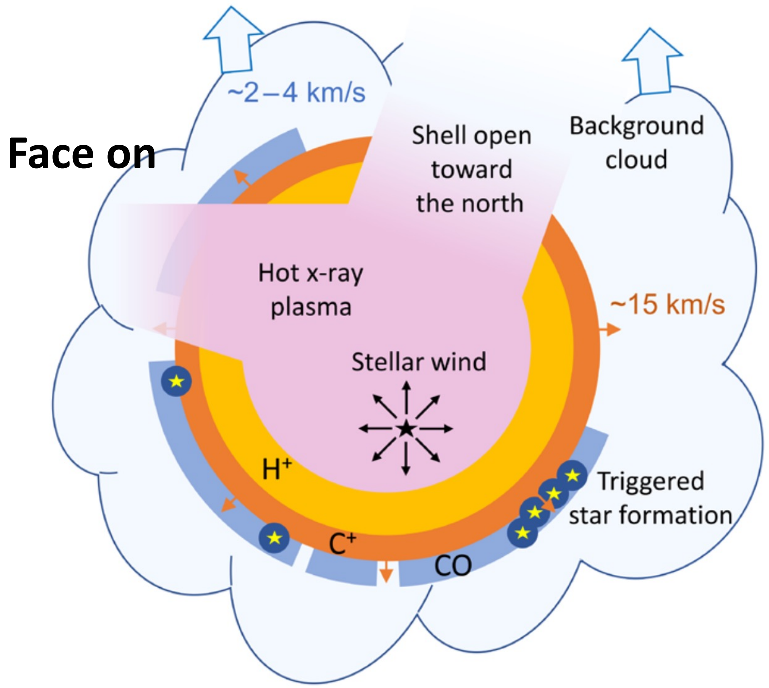


ASTRONOMY

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.



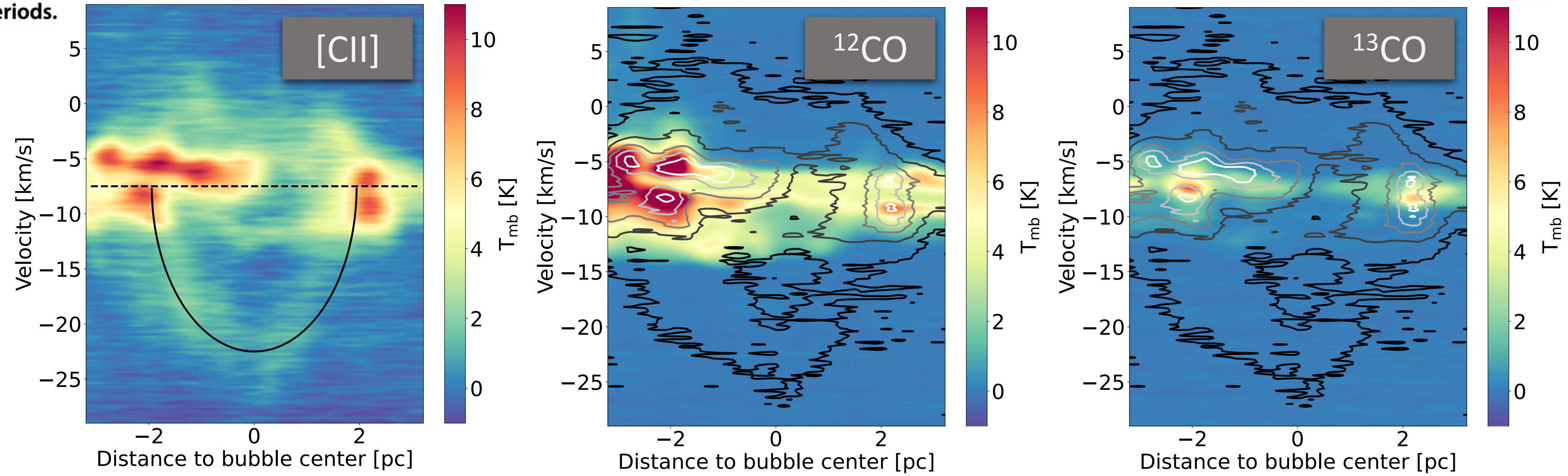
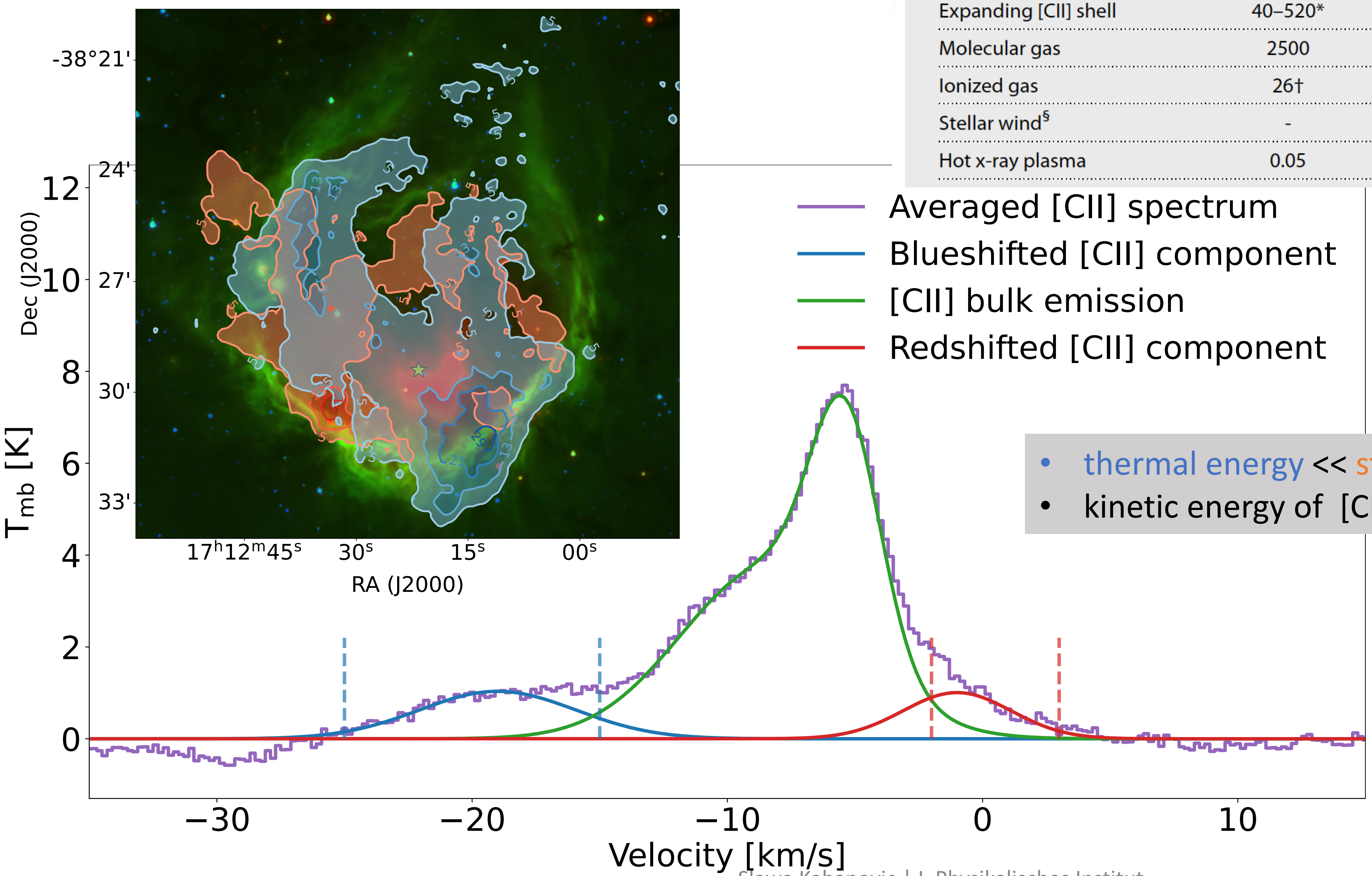


Table 1. Properties of the different components of RCW 120

Component	Mass ($M_\odot$)	Thermal energy (10^{46} erg)	Kinetic energy (10^{46} erg)
Expanding [CII] shell	40–520*	0.1–1.3	10–120
Molecular gas	2500	2.1	
Ionized gas	26†	5.1	-
Stellar wind§	-	-	150
Hot x-ray plasma	0.05	17	-

Luisi+2021



- thermal energy << stellar wind energy
- kinetic energy of [CII] bubble ≈ stellar wind energy

Dynamics of CII emitting gas

Cloud erosion seen in CII

- RCW79 Bonne et al. (2023)

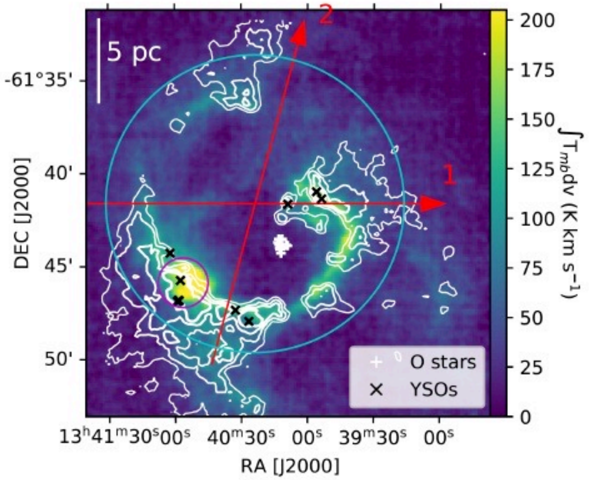
A&A 679, L5 (2023)
https://doi.org/10.1051/0004-6361/202347721

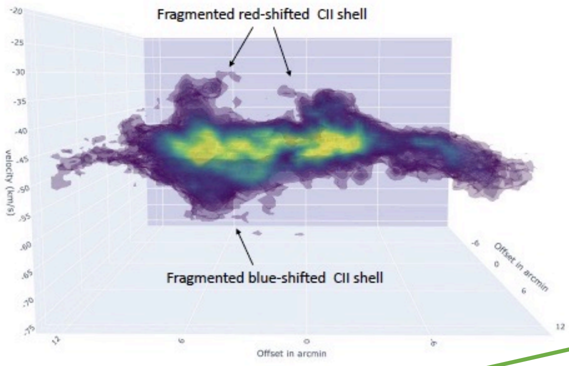
Astronomy & Astrophysics

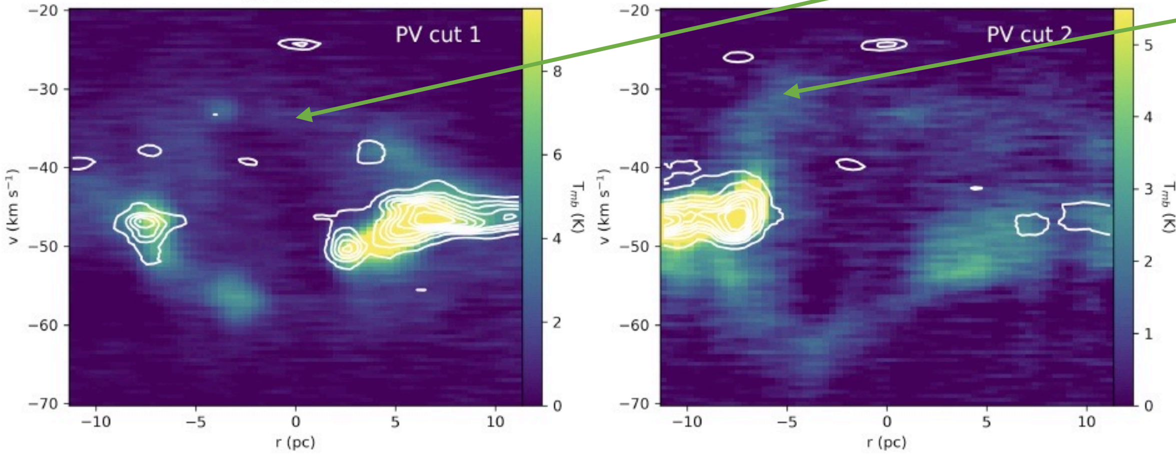
Letter to the Editor

The SOFIA FEEDBACK [CII] Legacy Survey: Rapid molecular cloud dispersal in RCW 79★

Bonne[1], S. Kabanovic[2], N. Schneider[2], A. Zavagno[3,4], E. Keilmann[2], R. Simon[2], C. Buchbender[2], R. Güsten[5], A. M. Jacob[5,6], K. Jacobs[2], U. Kavak[1], F. L. Polles[1], M. Tiwari[5], F. Wyrowski[5], and A. G. G. M. Tielens[7,8]



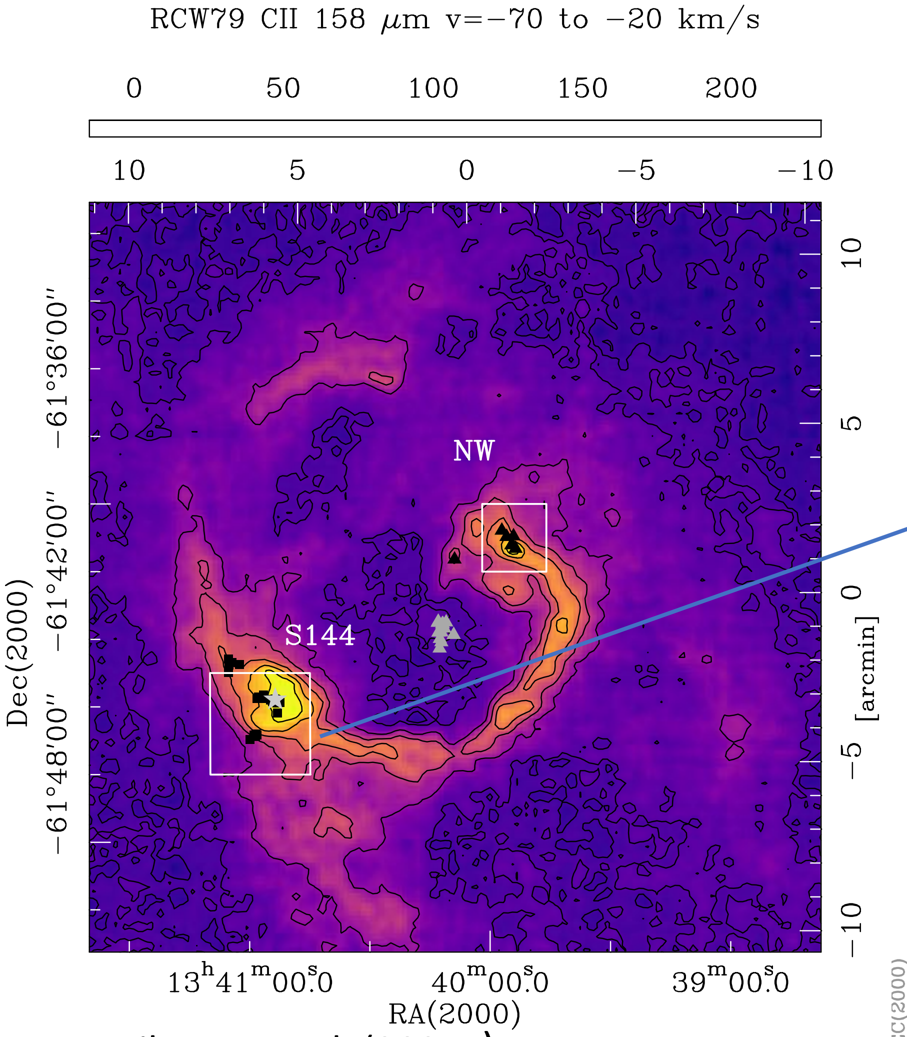




A fragmented [CII] shell and [CII] flows.

Mass ejection rate 0.9 – 3.5 10^{-2} M_{sun}/yr
-> short erosion timescales (<5 Myr) for the cloud

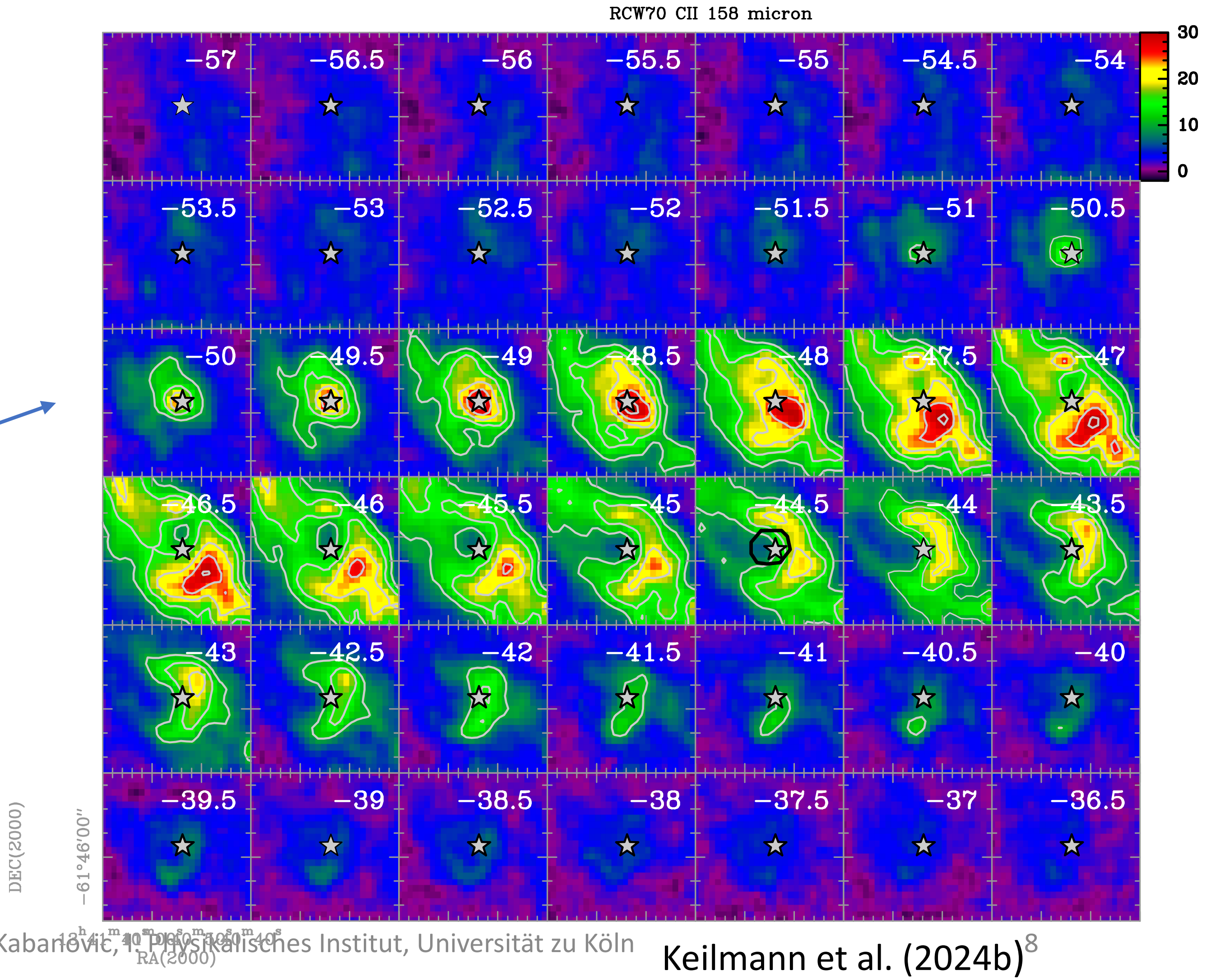
Outlook: RCW79 (Expanding large bubble and [CII] filled compact HII region)



Keilmann et al. (2024a)

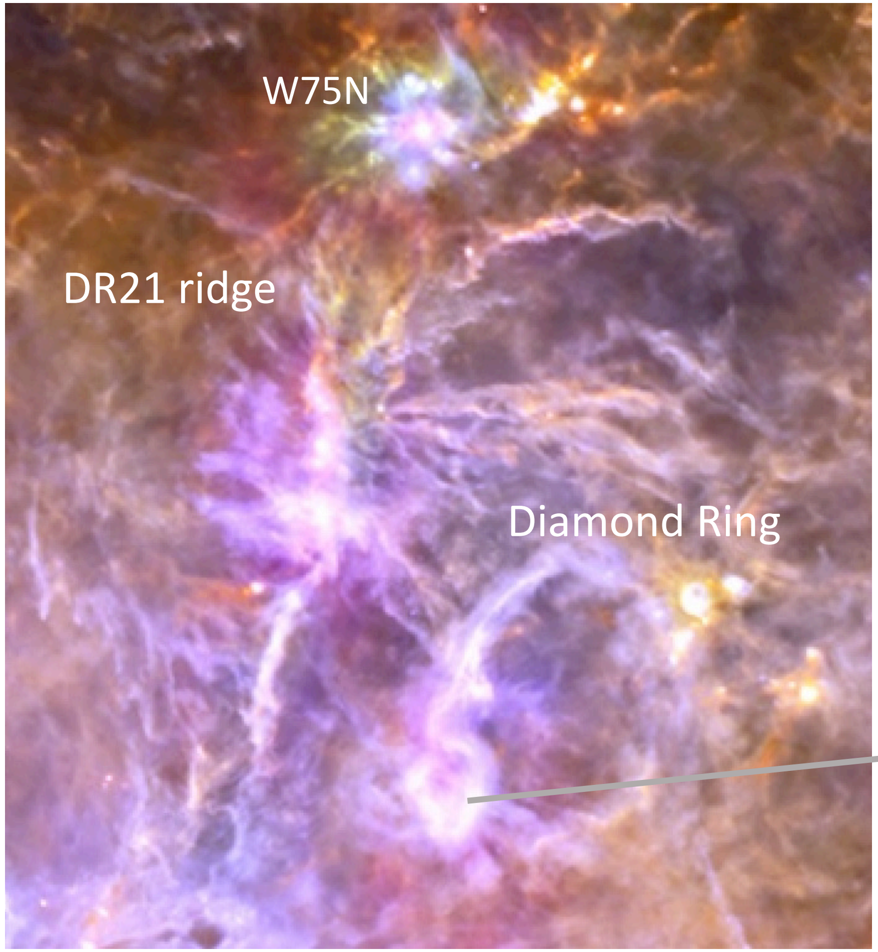
(Squares indicate APEX-proposed areas)

The compact HII region is filled with C⁺. The 'hole' is due to self-absorption. Early evolutionary stage? The central star is an O-star.

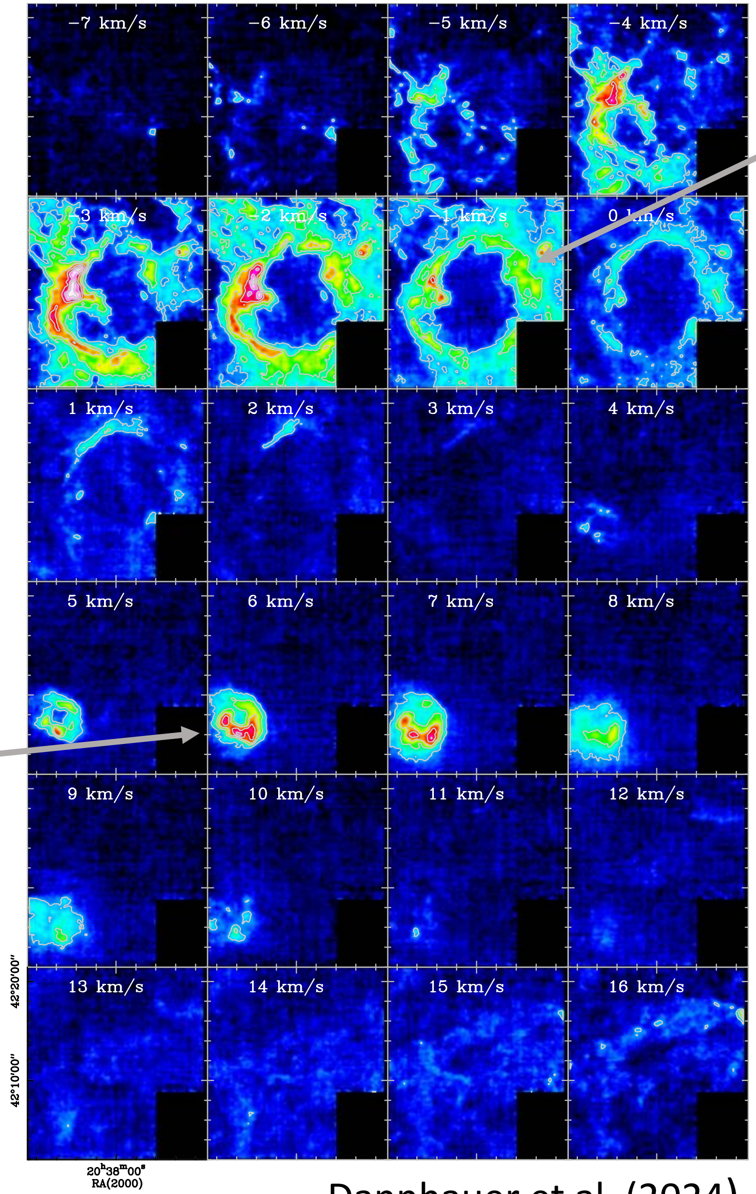


Keilmann et al. (2024b)

Outlook: a non-expanding CII ring in Cygnus X - the Diamond Ring



The '**diamond**' (Marston et al. (2004) is not part of the Diamond ring!



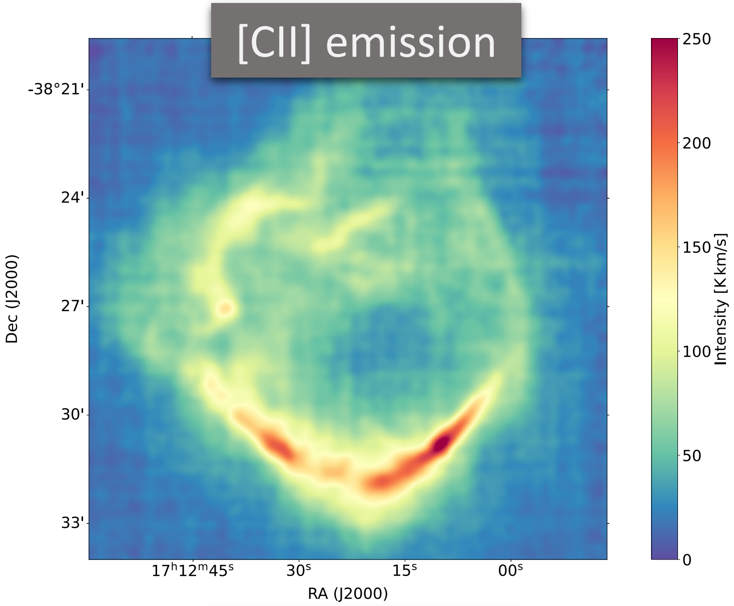
Dannhauer et al. (2024)

- Tilted ring, but no expanding CII shell.
- No obvious exciting star(s).
- What is this?

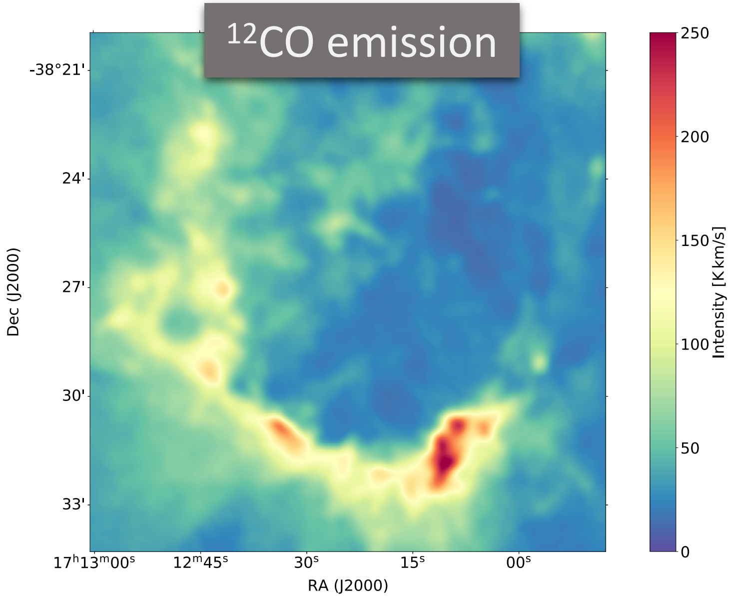
See poster by S. Dannhauer for more information!

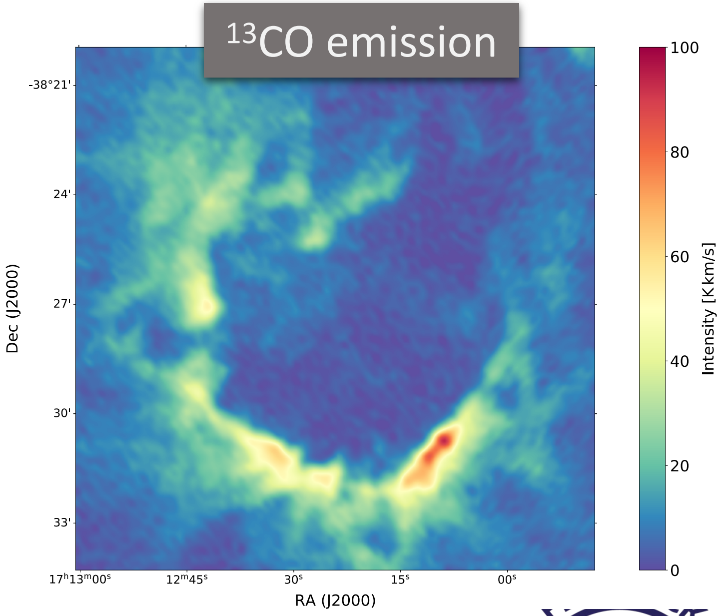
Detection of large columns of cold [CII]

Velocity resolved observations of RCW 120 with SOFIA and APEX

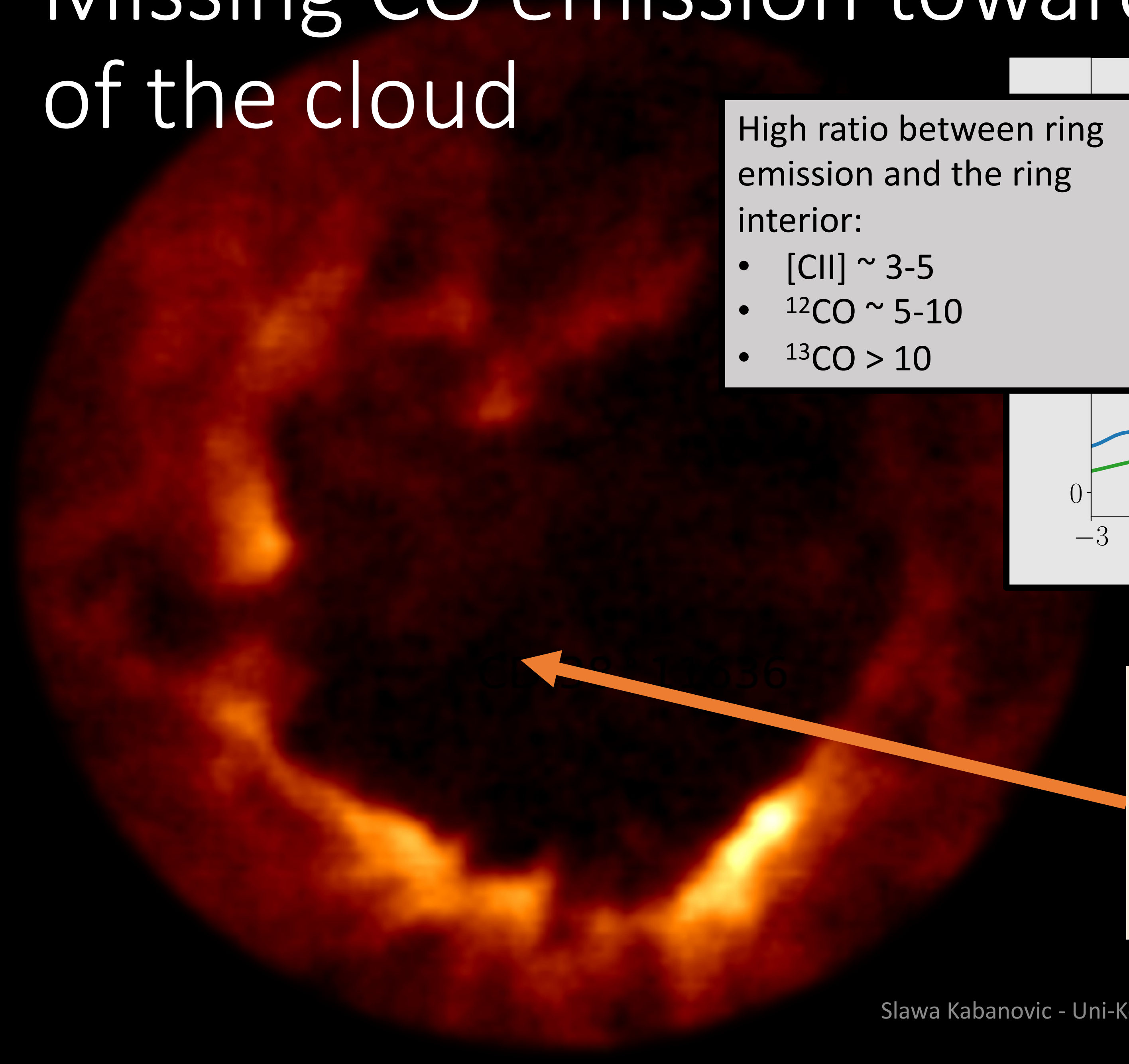


- [CII]: confined ring with an opening in the north and west.
- CO (3-2): fragmented ring with a deficit in the central HII region.



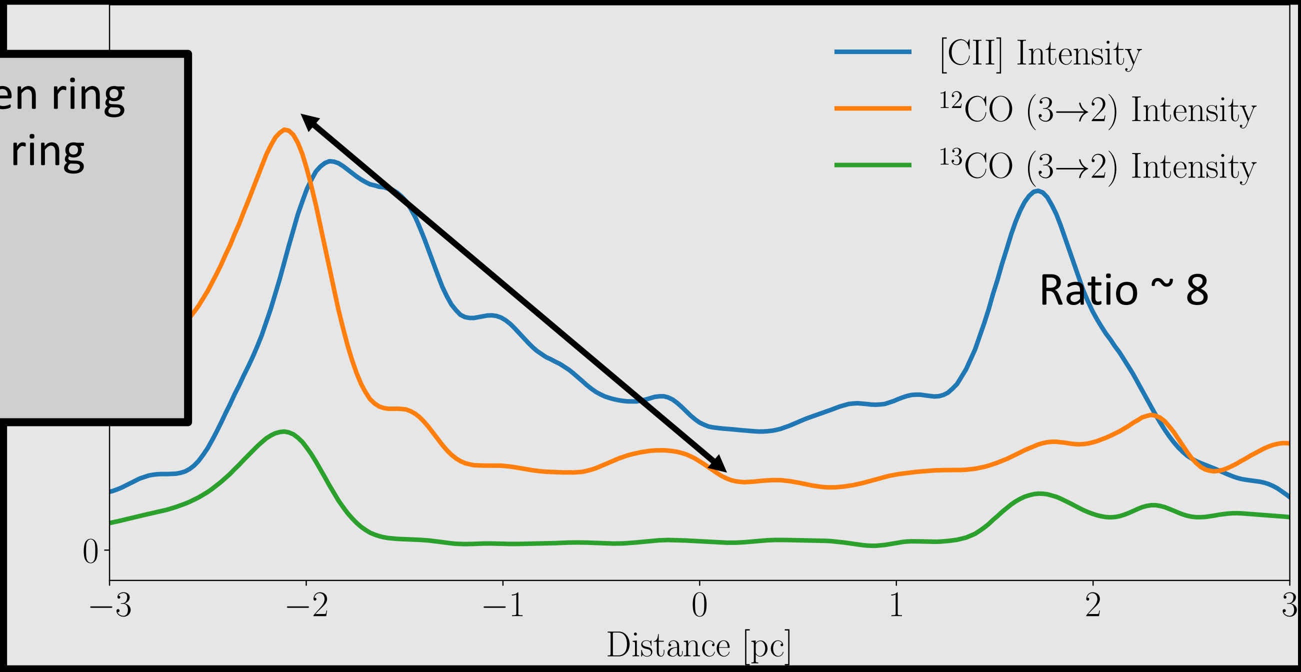


Missing CO emission toward the center of the cloud



High ratio between ring emission and the ring interior:

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

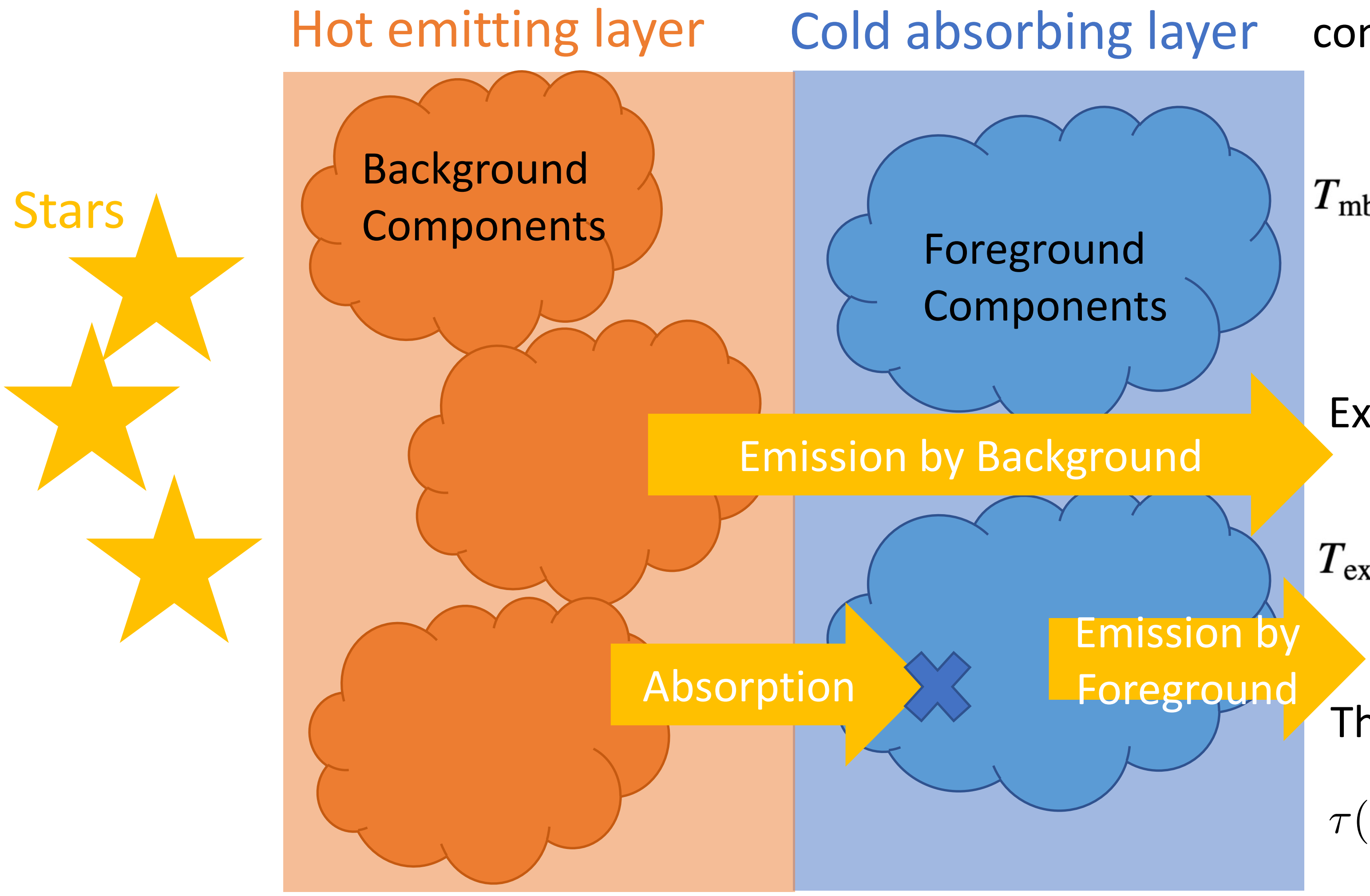


Missing CO emission :

- Observations cannot be explained by spherical geometry!
- Are we tricked by self-absorption effects?

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

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

Two-Layer Multicomponent Model

(Guevara+2020, Kabanovic+2022)

Components from the hot emitting layer:

$T_{ex} \sim 60$ K

$N_{[CII]} \sim 3 \times 10^{18}$ cm^{-2}

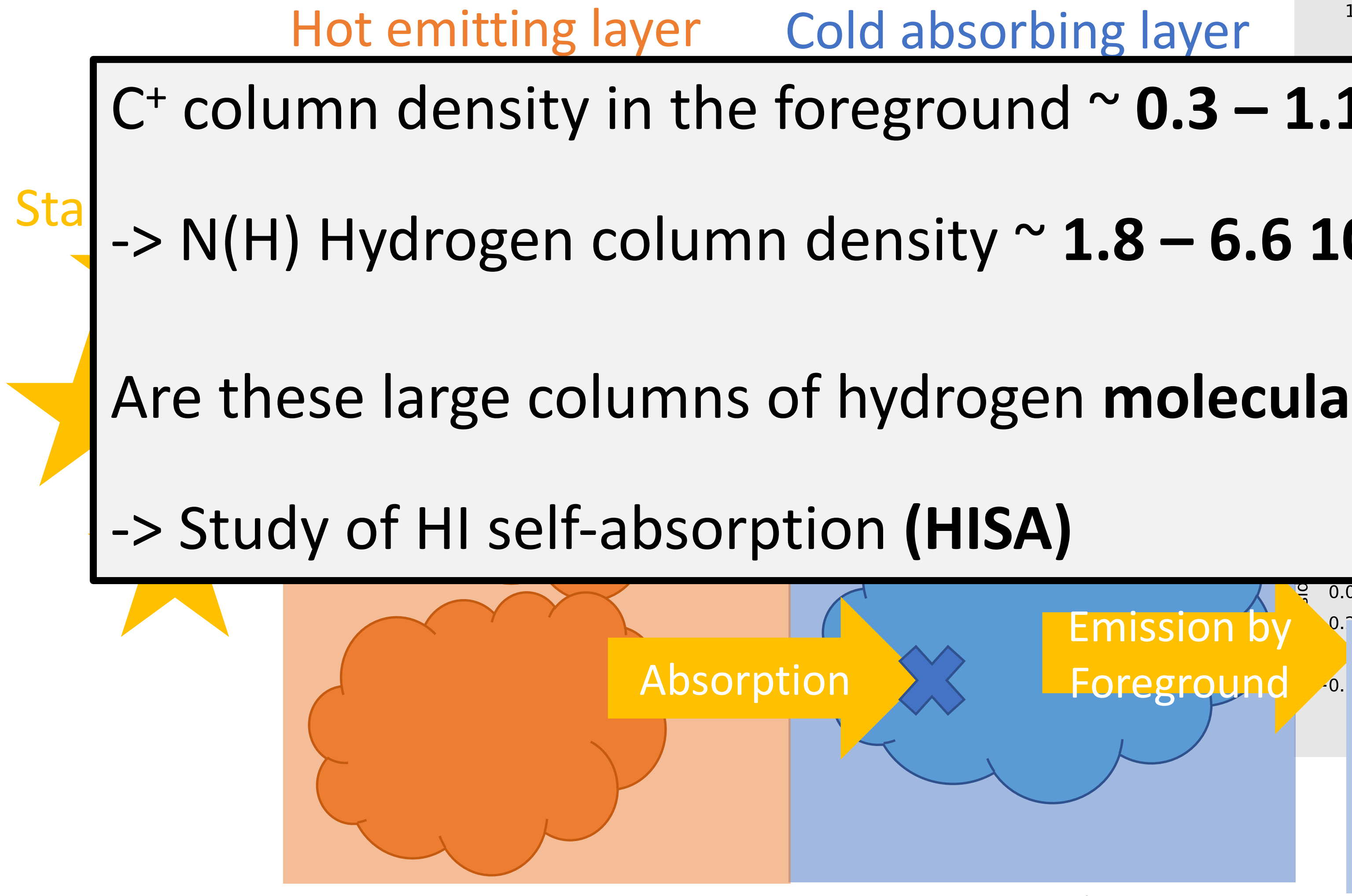
M ~ 2000 $M_{\odot}$

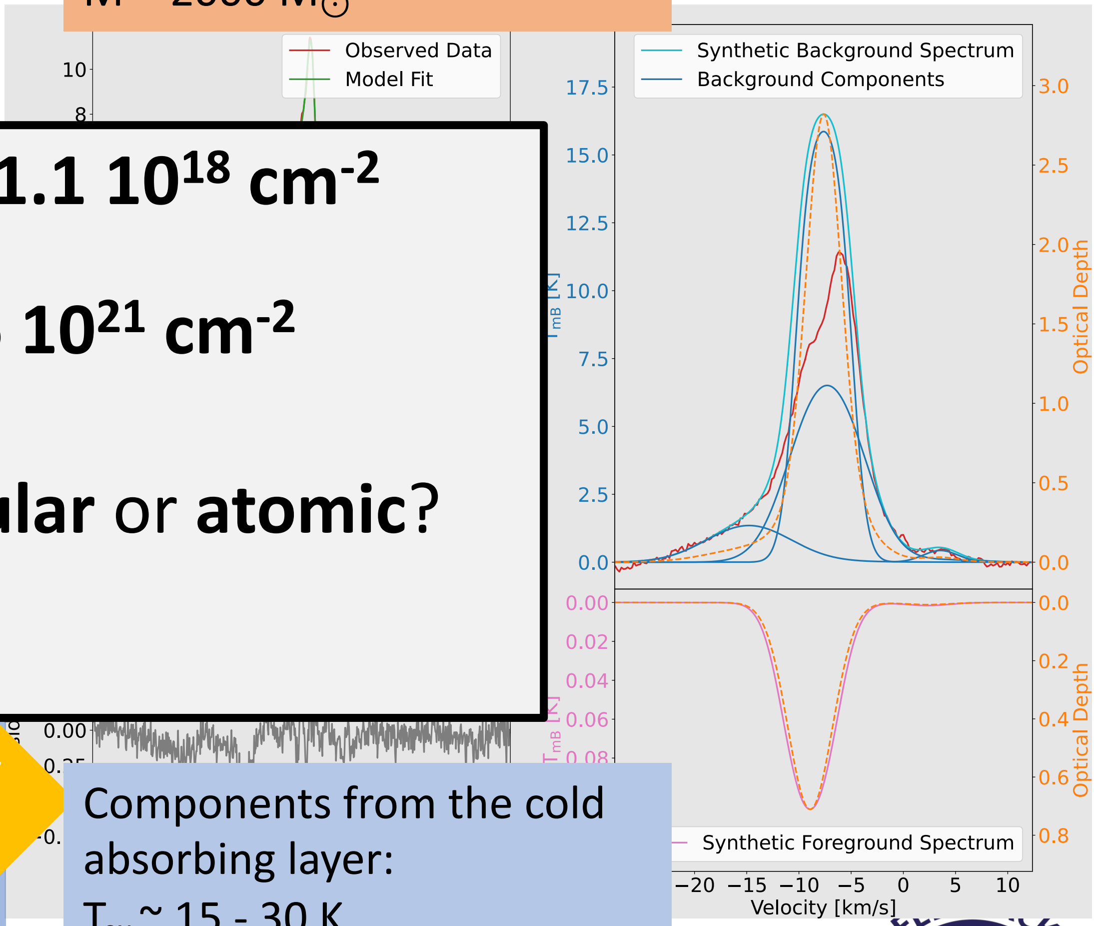
C^+ column density in the foreground ~ **0.3 – 1.1 10^{18} cm^{-2}**

-> N(H) Hydrogen column density ~ **1.8 – 6.6 10^{21} cm^{-2}**

Are these large columns of hydrogen **molecular** or **atomic**?

-> Study of HI self-absorption **(HISA)**





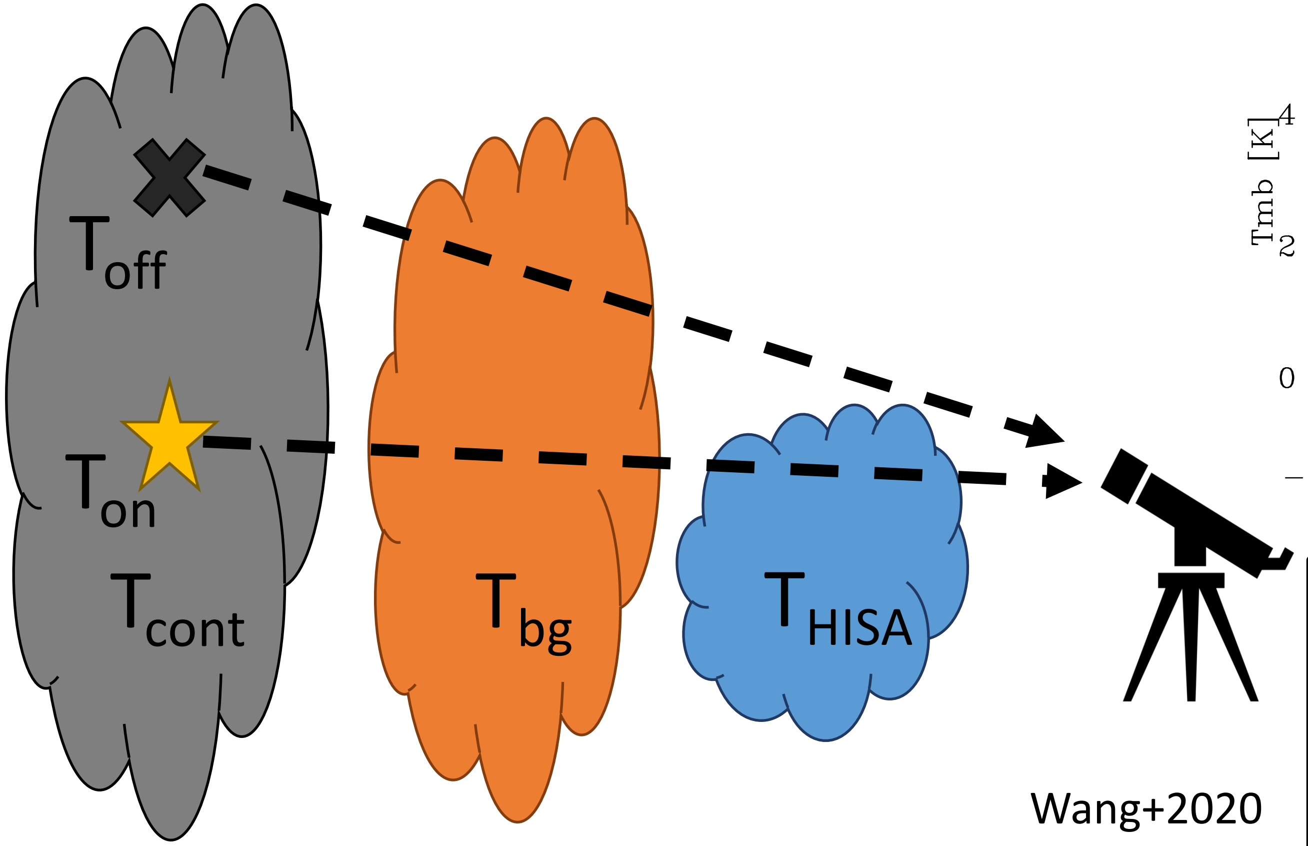
Components from the cold absorbing layer:

$T_{ex} \sim 15 - 30$ K

$N_{[CII]} \sim 2 \times (5 - 10 \times 10^{17})$cm^{-2}

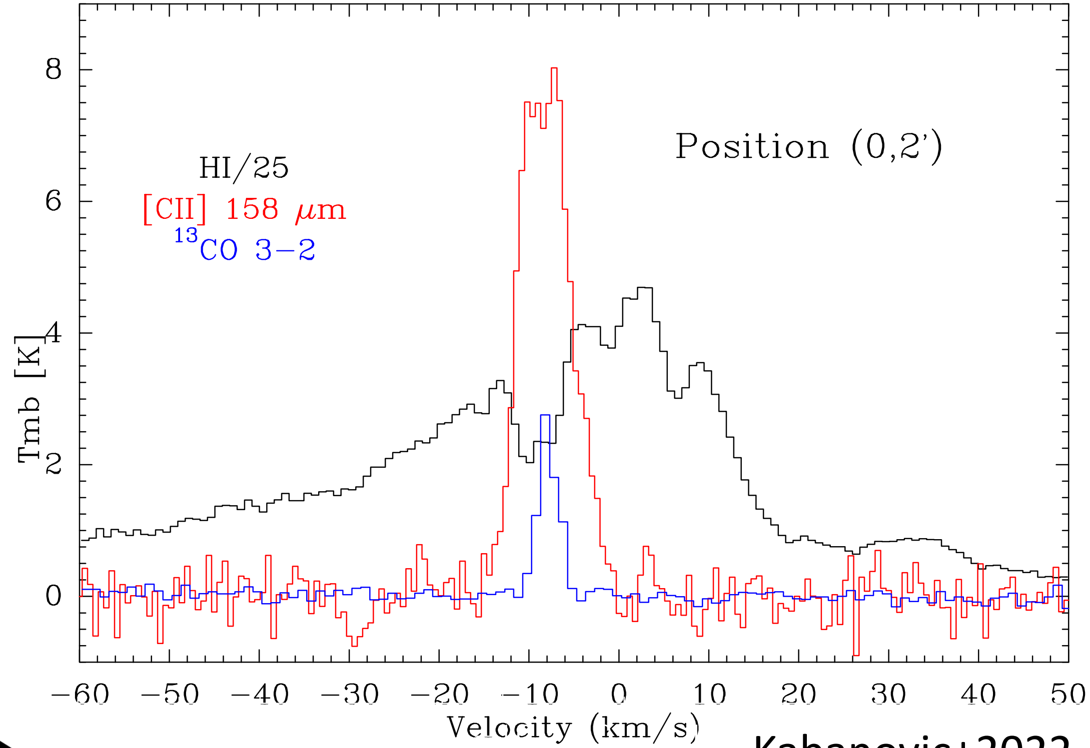
M ~ 2 x (340 – 680) $M_{\odot}$

HI Self-Absorption (HISA)



Wang+2020

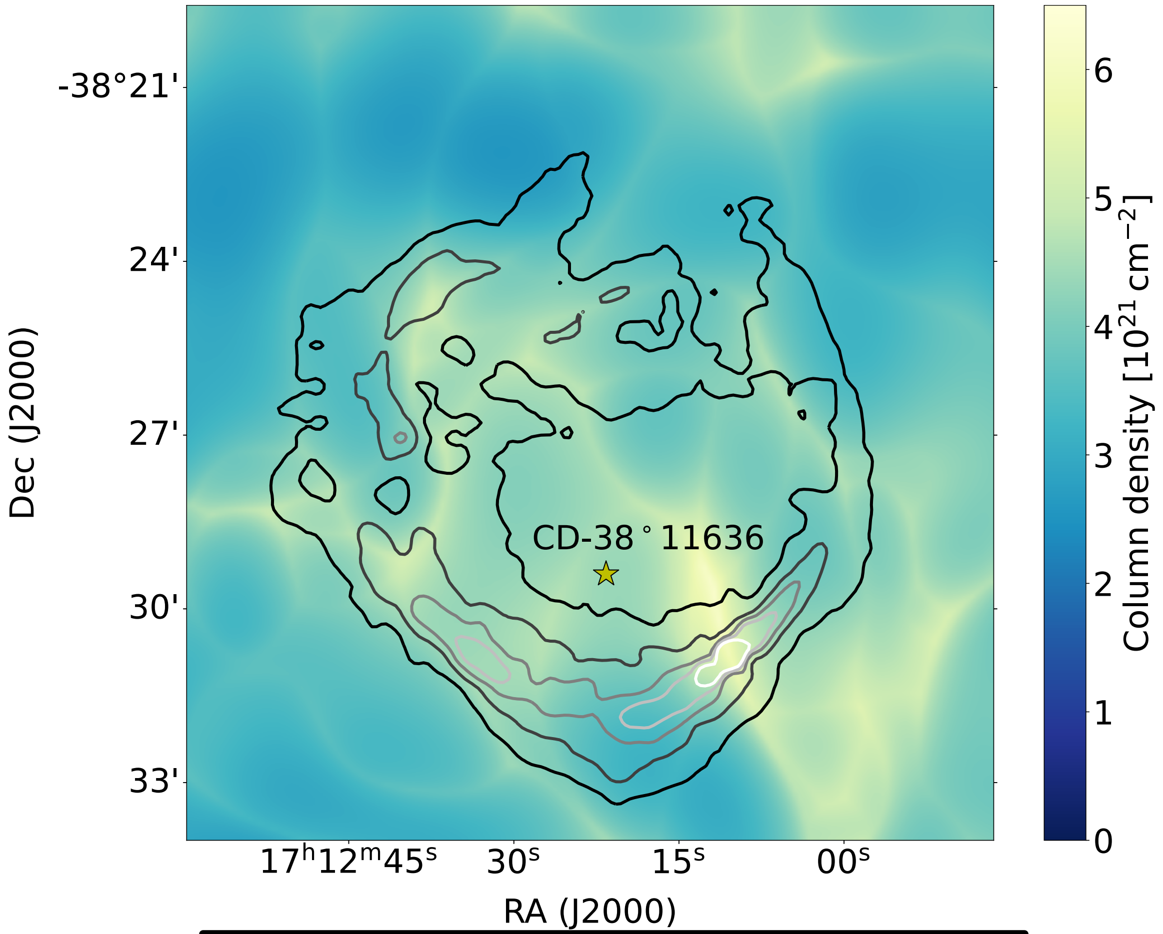
$$\tau_{HISA}(v) = -\ln\left(1 - \frac{T_{on-off}(v)}{T_{HISA} - T_{off}(v) - T_{cont}}\right)$$

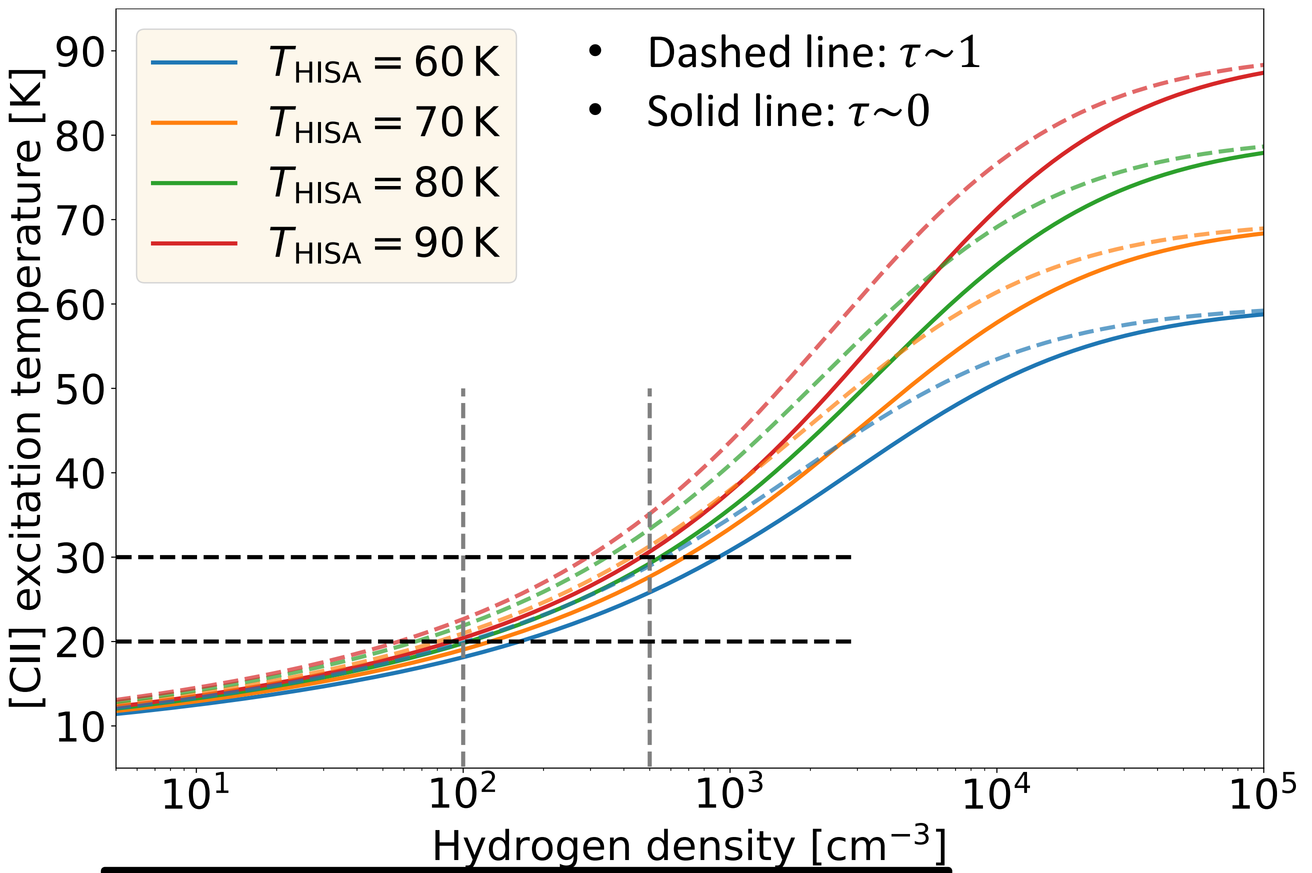


Kabanovic+2022

- [CII] and CO line 'peaks' in HI absorption dip but is also self-absorbed!
- Indicates neutral atomic halo around molecular clouds.
- Possible origin for the large amounts of cold C⁺?

HISA: The Origin of the Cold C+ Emission

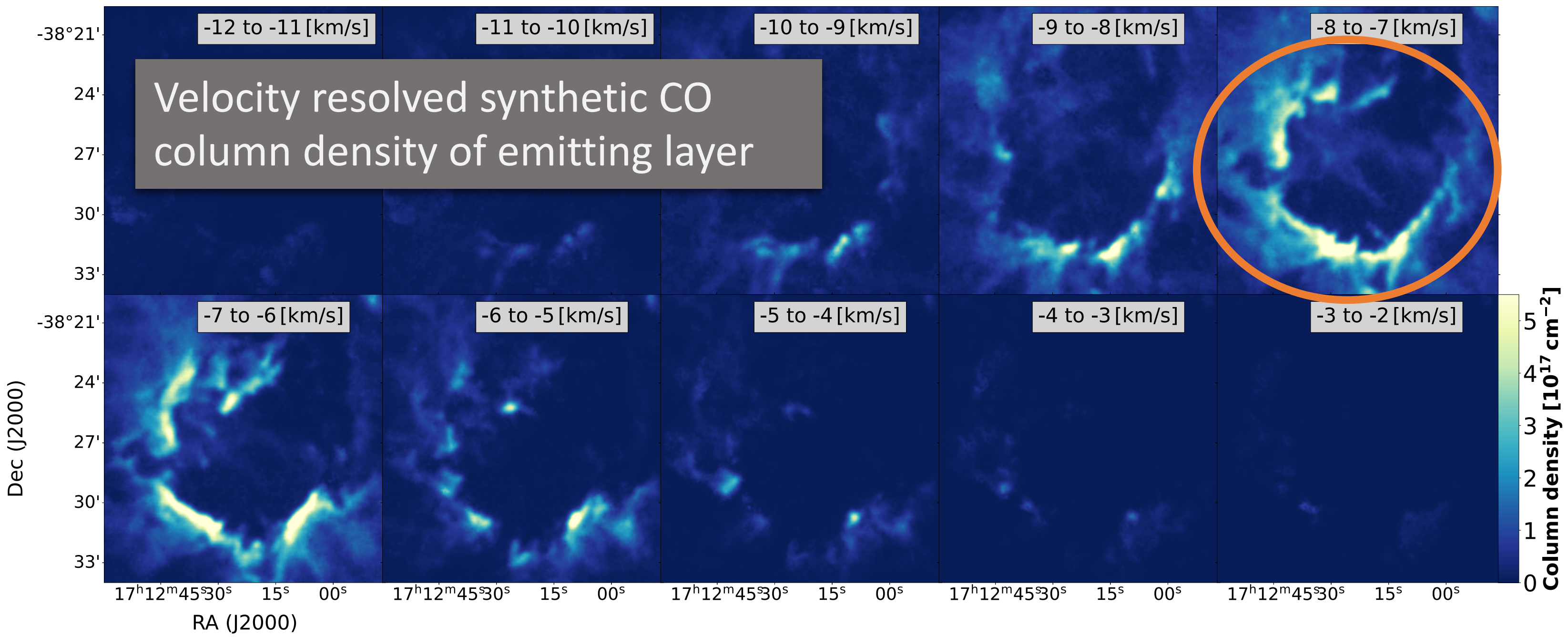


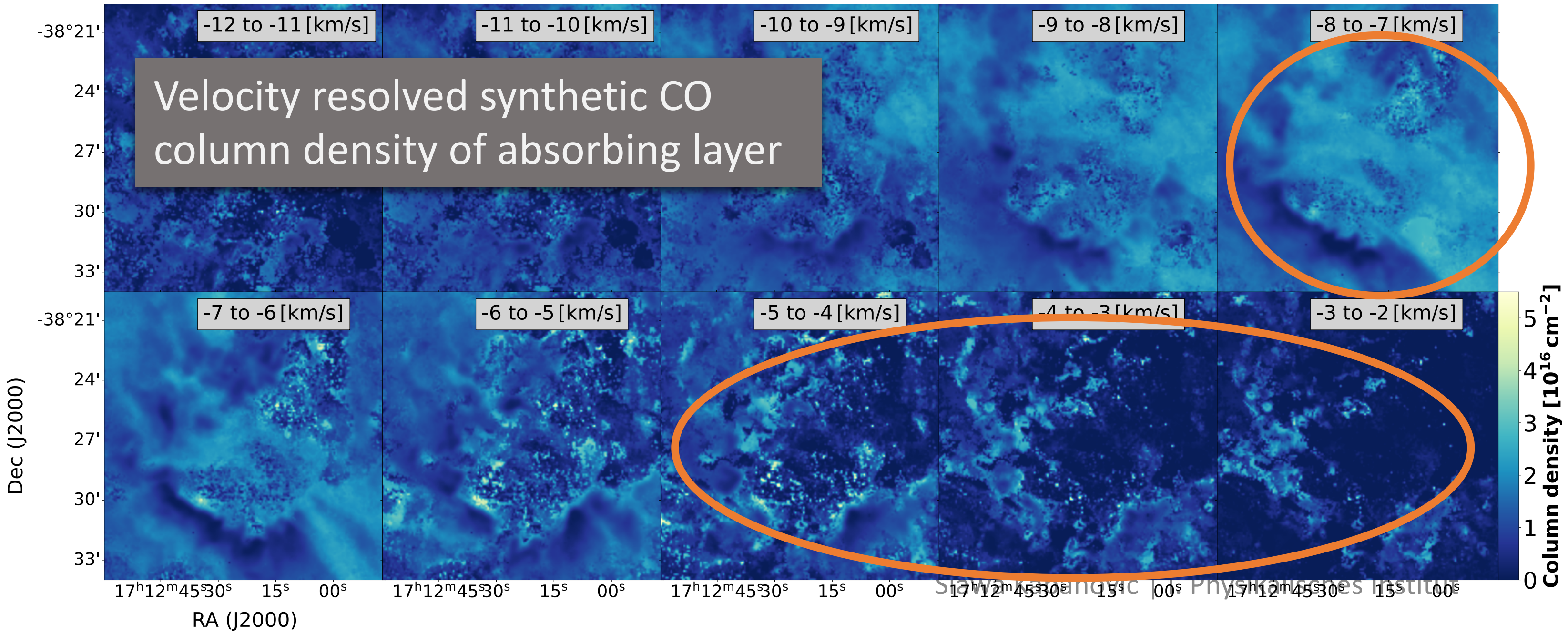


column densities of cold HI self-absorption layer ≈
column densities of cold absorbing C^+.

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**

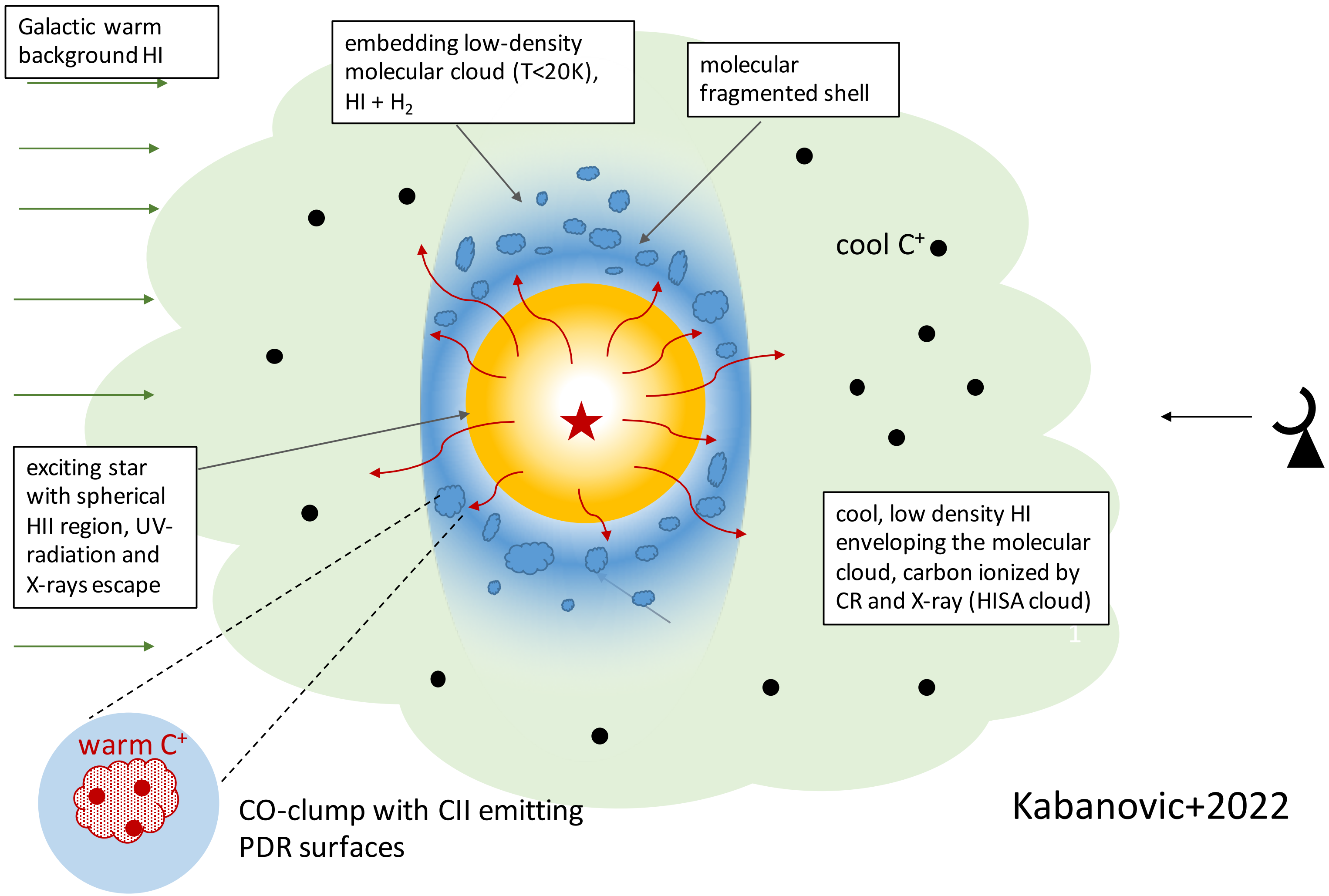




- The warm emitting layer traces the **fragmented dense ring**.
- Increasing foreground column density towards the interior. But not enough to explain the emission deficit!
- Sudden change in morphology indicates **global infall**.

A new View on RCW 120

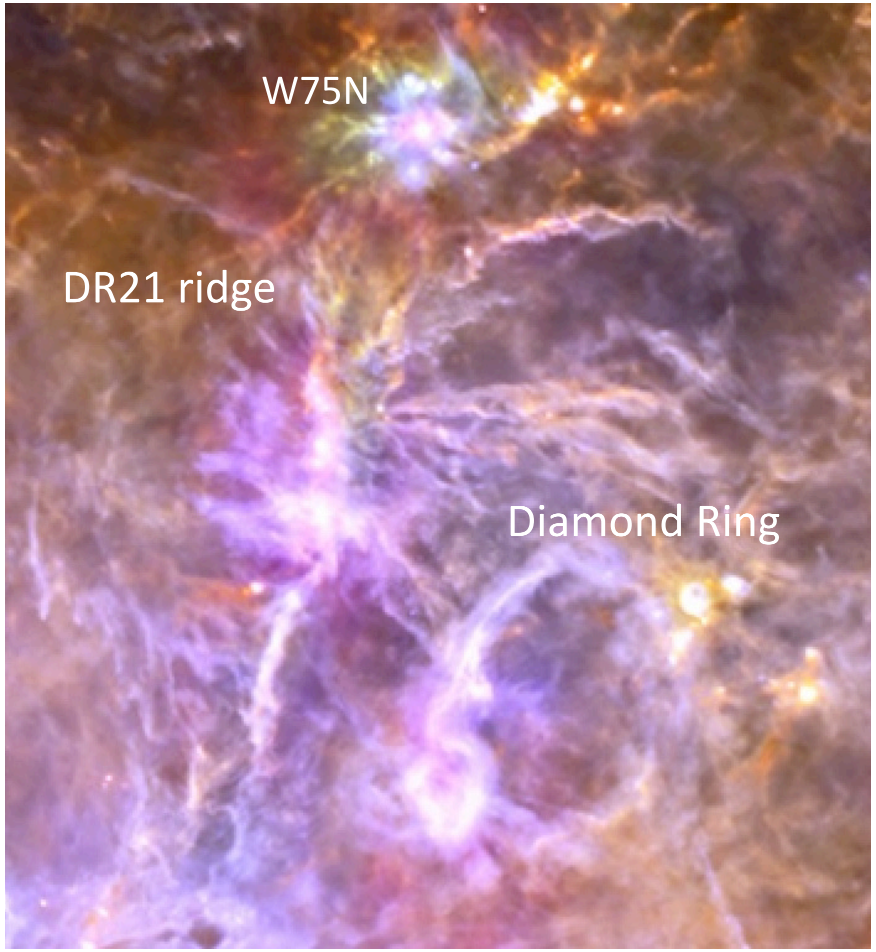
- Stellar wind drives an expanding C^+ bubble (Luisi+2021).
- The expansion compresses the surrounding molecular cloud to a torus.
- The HII bursts out of a sheet-/ filament-like molecular cloud.
- The flat molecular cloud is surrounded by a cold atomic layer.



Kabanovic+2022

Formation of molecular clouds seen in CII

Cygnus X



Schneider et al. (2023)

nature astronomy

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Ionized carbon as a tracer of the assembly of interstellar clouds

Received: 13 September 2022

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Nicola Schnei
Slawa Kabano
Christof Buchl
Timea Csenge

See poster by E. Keilmann on the first [CII] detection of the high latitude intermediate velocity cloud Draco and talk by V. Ossenkopf.

See poster by E. Keilmann on the **first [CII] detection** of the high latitude intermediate velocity cloud **Draco**

and talk by V. Ossenkopf.

Bonne et al. (2023)

The Astrophysical Journal, 951:39 (26pp), 2023 J

Unveiling the Formation of the Massive DR21 Ridge

L. Bonne[1], S. Bontemps[2], N. Schneider[3], R. Simon[3], S. D. Clarke[4], T. Csengeri[2], E. Chambers[1], U. Graf[3], J. M. Jackson[1,5], R. Klein[1], Y. Okada[3], A. G. G. M. Tielens[6,7], and M. Tiwari[6]

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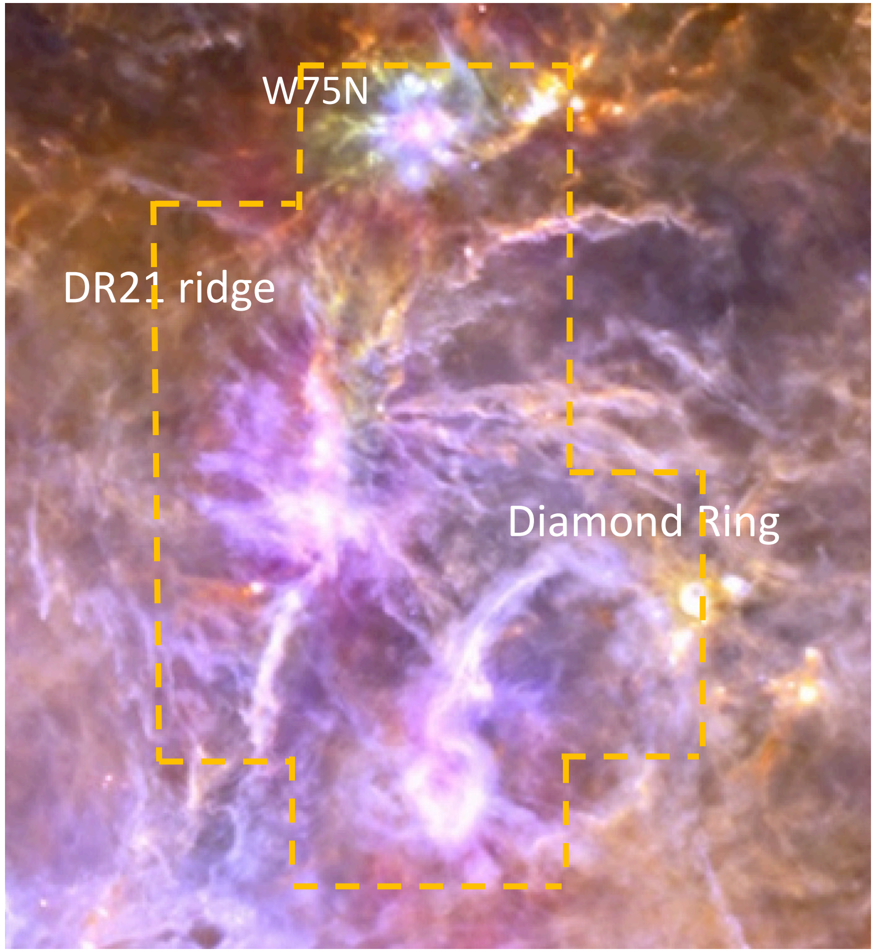
FEEDBACK SOFIA C+LEGACY

Formation of molecular clouds seen in CII

Cygnus X



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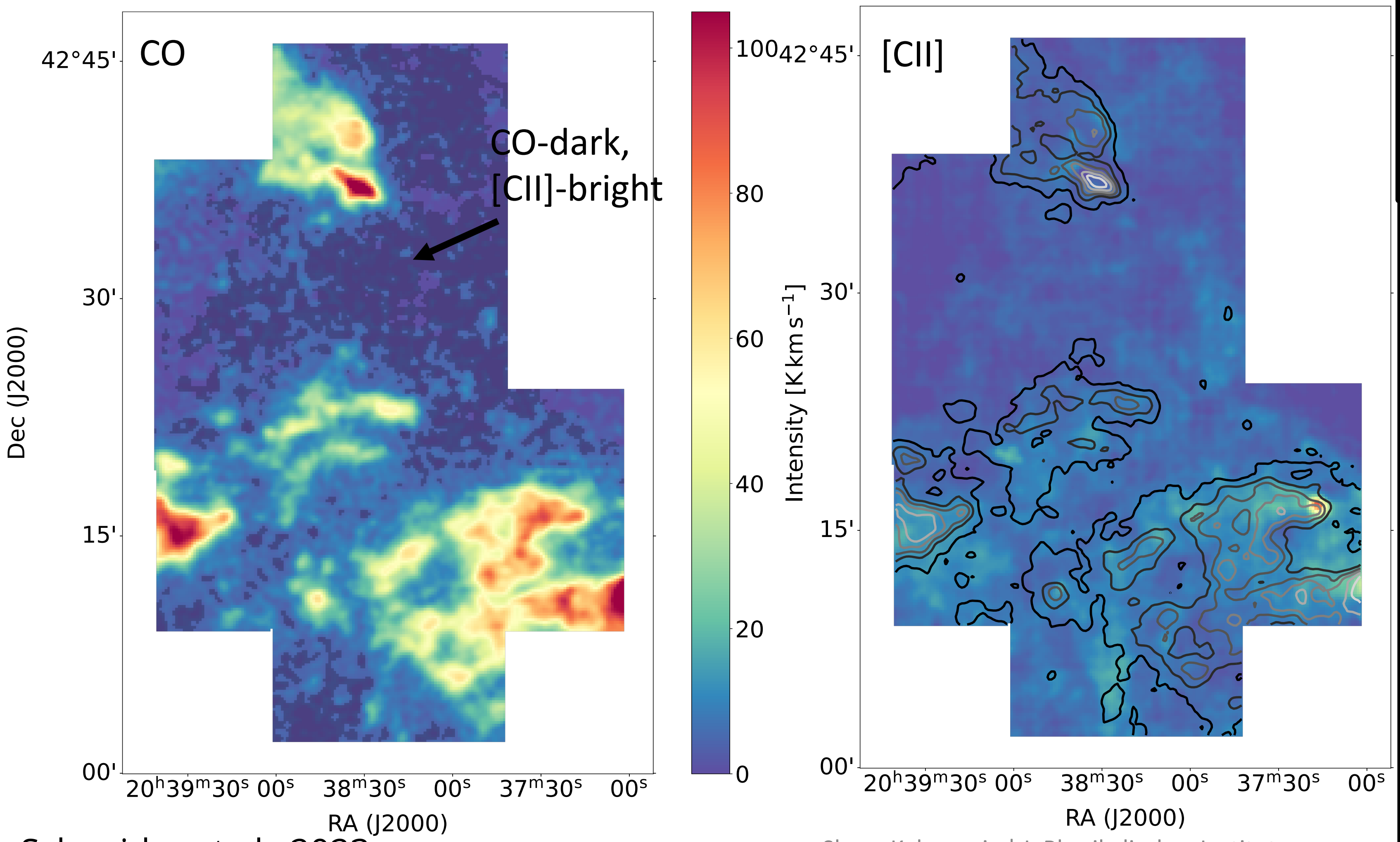
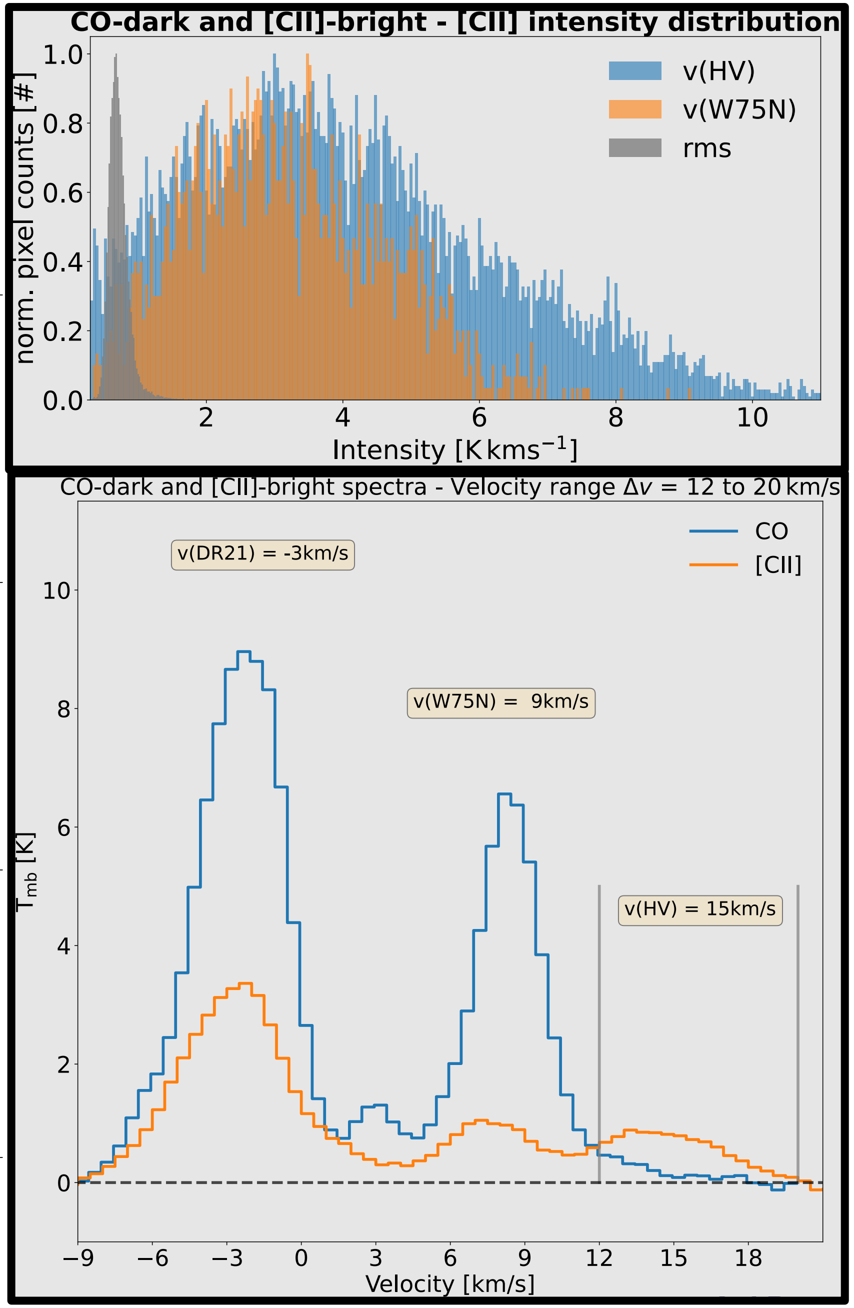
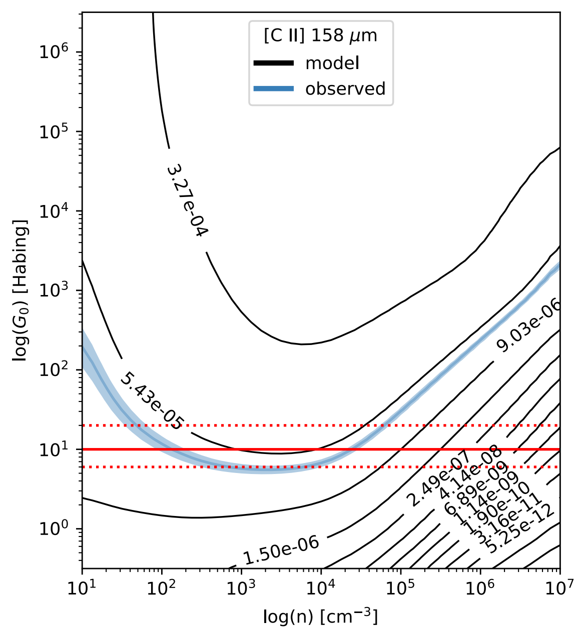
[CII] reveals CO dark gas at high velocities

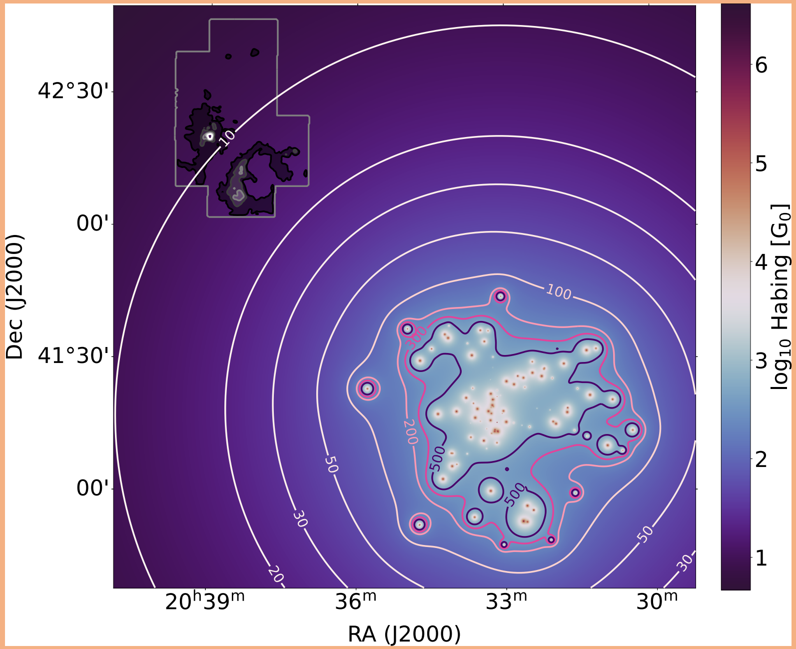




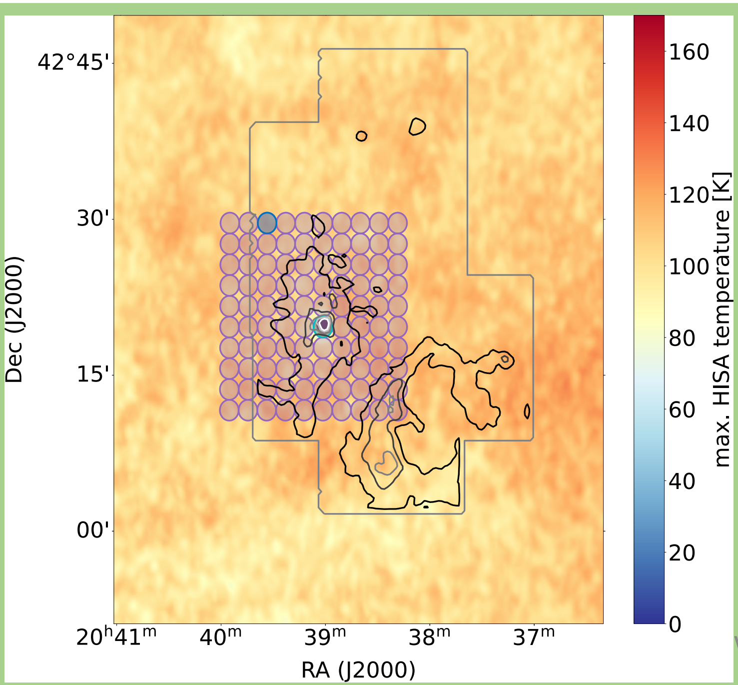
Schneider et al., 2023

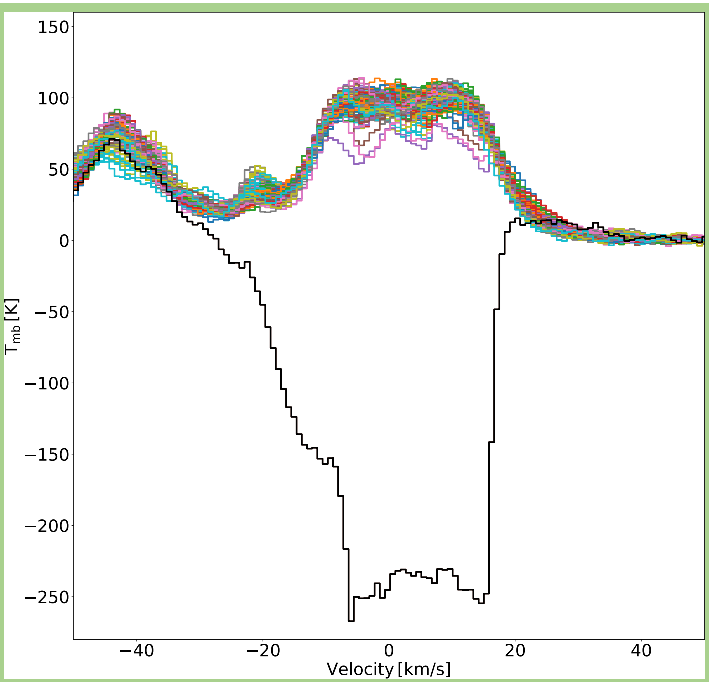
PDR analysis





HISA analysis





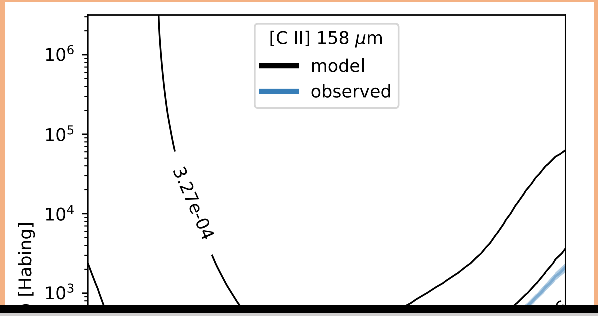
Properties of the [CII]-bright, CO-dark atomic flow from PDR modelling and HISA analysis:

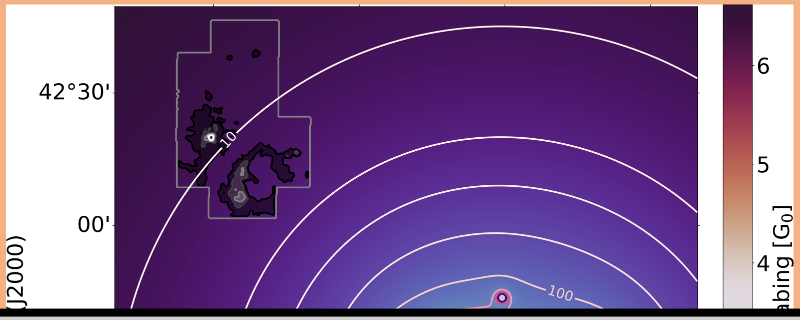
$n \sim 100$ cm^{-3},
$T \sim 100$ K,
v = 4- 20 km/s,

-> 80% atomic and
20% molecular

Schneider et al., 2023

PDR analysis



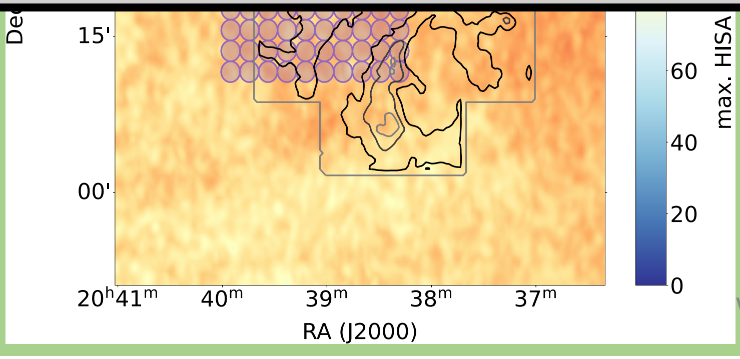


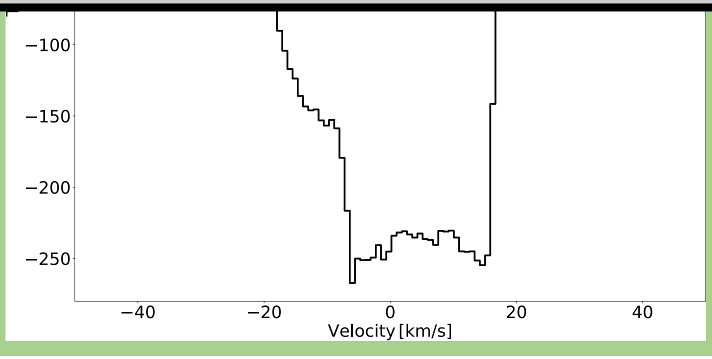
The molecular clouds in Cygnus X form by interaction of mostly **atomic colliding flows**, traced in CII.

Formation time scale ~ 1 Myr, much **faster** than in quasi-static cloud formation scenarios.

Purely molecular head-on **cloud-cloud collisions** are not supported by our observations.

HISA analysis





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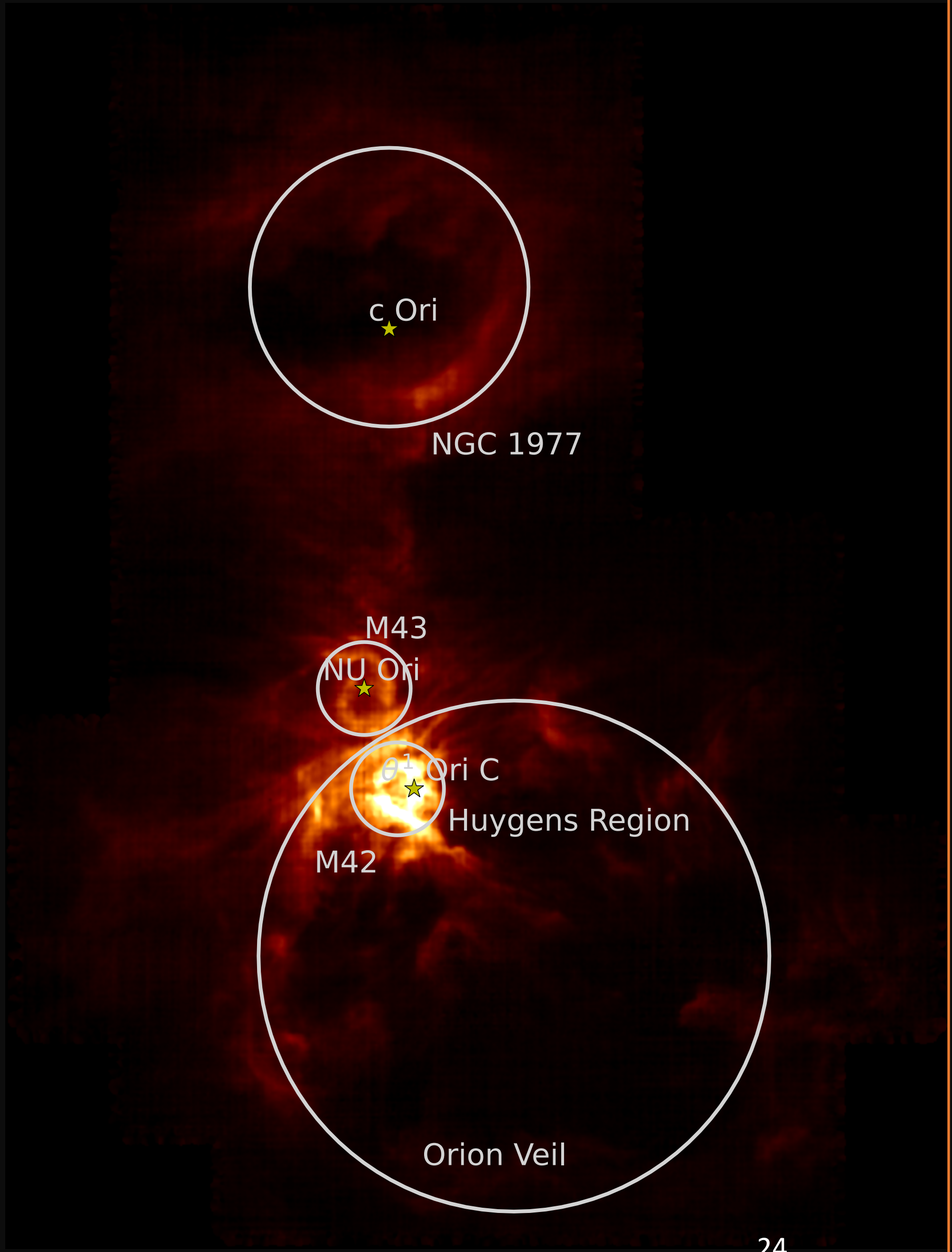
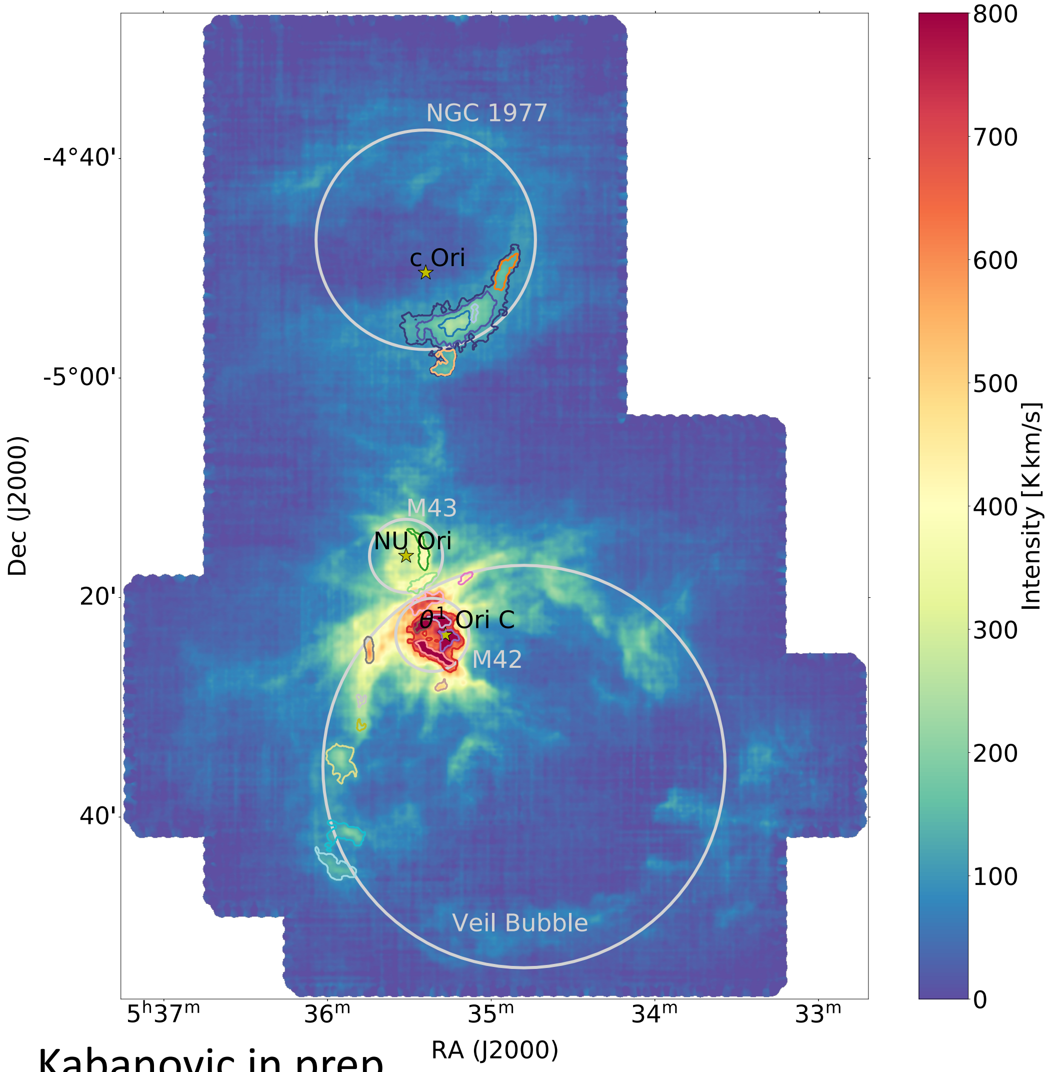
Schneider et al., 2023

Orion A Legacy



Optical Depth along Orion A



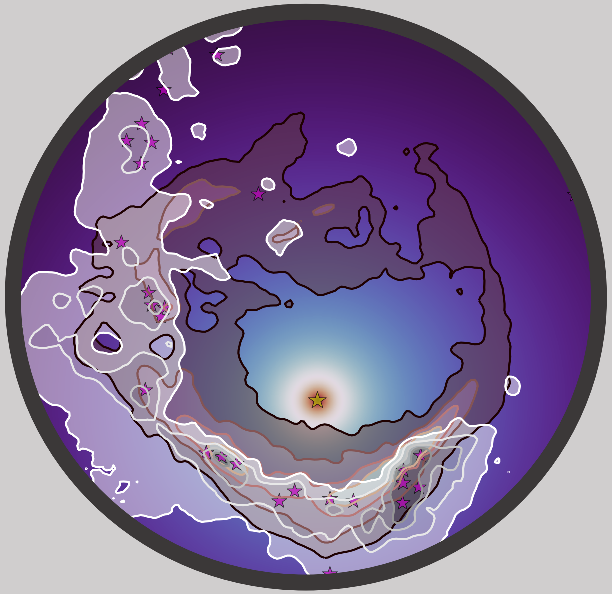
Kabanovic in prep.

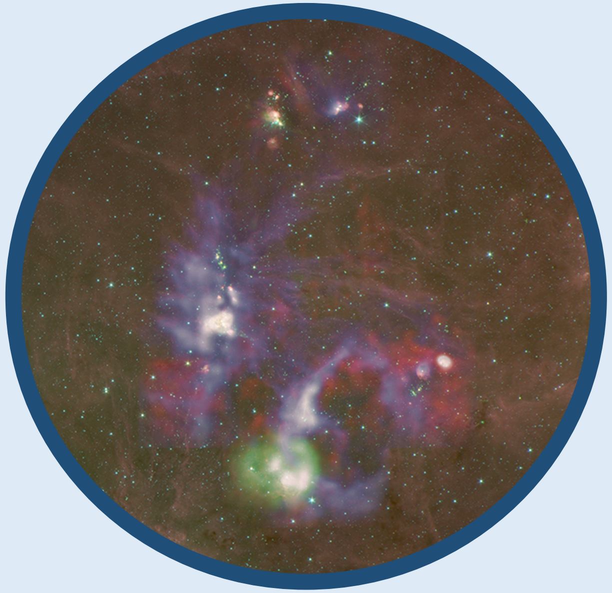
- NGC 1977, $\langle\tau_{[CII]}\rangle = 2.6 \pm 0.2$
- NGC 1977 - Rim, $\langle\tau_{[CII]}\rangle = 3.2 \pm 0.3$
- NGC 1977 - Large Clump, $\langle\tau_{[CII]}\rangle = 3.8 \pm 0.3$
- NGC 1977 - Small Clump, $\langle\tau_{[CII]}\rangle = 4.0 \pm 0.6$
- NGC 1977 - N. Rim, $\langle\tau_{[CII]}\rangle = 2.3 \pm 0.6$
- NGC 1977 - S. Rim, $\langle\tau_{[CII]}\rangle = 2.8 \pm 0.9$
- M43 - West, $\langle\tau_{[CII]}\rangle = 1.4 \pm 0.3$
- M43 - South, $\langle\tau_{[CII]}\rangle = 2.9 \pm 0.2$
- M42, $\langle\tau_{[CII]}\rangle = 1.2 \pm 0.2$
- M42 - Orion Bar, $\langle\tau_{[CII]}\rangle = 1.6 \pm 0.3$
- M42 - Ridge, $\langle\tau_{[CII]}\rangle = 1.6 \pm 0.2$
- M42 - BN/KL, $\langle\tau_{[CII]}\rangle = 1.8 \pm 0.3$
- M42 - E. PDR, $\langle\tau_{[CII]}\rangle = 1.5 \pm 0.4$
- M42 - S. Clump, $\langle\tau_{[CII]}\rangle = 0.2 \pm 0.8$
- Veil Buble - N. Stream, $\langle\tau_{[CII]}\rangle = 1.3 \pm 0.6$
- Veil Buble - N. Rim, $\langle\tau_{[CII]}\rangle = 3.3 \pm 0.2$
- Veil Buble - N.E. Clump, $\langle\tau_{[CII]}\rangle = 1.8 \pm 0.3$
- Veil Buble - Small E. Clump I, $\langle\tau_{[CII]}\rangle = 4.1 \pm 0.6$
- Veil Buble - Small E.Clump II, $\langle\tau_{[CII]}\rangle = 3.2 \pm 0.6$
- Veil Buble - Large E.Clump, $\langle\tau_{[CII]}\rangle = 2.2 \pm 0.4$
- Veil Buble - S.E. Crescent I, $\langle\tau_{[CII]}\rangle = 1.7 \pm 0.7$
- Veil Buble - S.E. Crescent II, $\langle\tau_{[CII]}\rangle = 2.3 \pm 0.6$

Strong optical depth effect along the bubbles in Orion A!

$$\frac{1 - e^{-\tau_{[CII]}}}{\tau_{[CII]}} = \alpha_{F\rightarrow F'} \frac{T_{mb,12}(v)}{T_{mb,13}(v - \Delta v_{F\rightarrow F'})}$$

Conclusion





- **C+** is a **unique tracer of gas kinematics** tracing **stellar wind driven expanding shells** and the **dispersal of molecular clouds.**

- The deficit in CO emission along central sightlines cannot be explained by CO self-absorption.
- The associated **molecular cloud is flat**.

- The molecular clouds in Cygnus X form by interaction of mostly **atomic colliding flows**, traced in CII.

The compression leads to the **formation of a torus** surrounding the HII region.

The origin of the **cold C^+** can be explained by a low-density (~100 cm^{-3}, T_{kin}~100 K), diffuse **HI layer.**