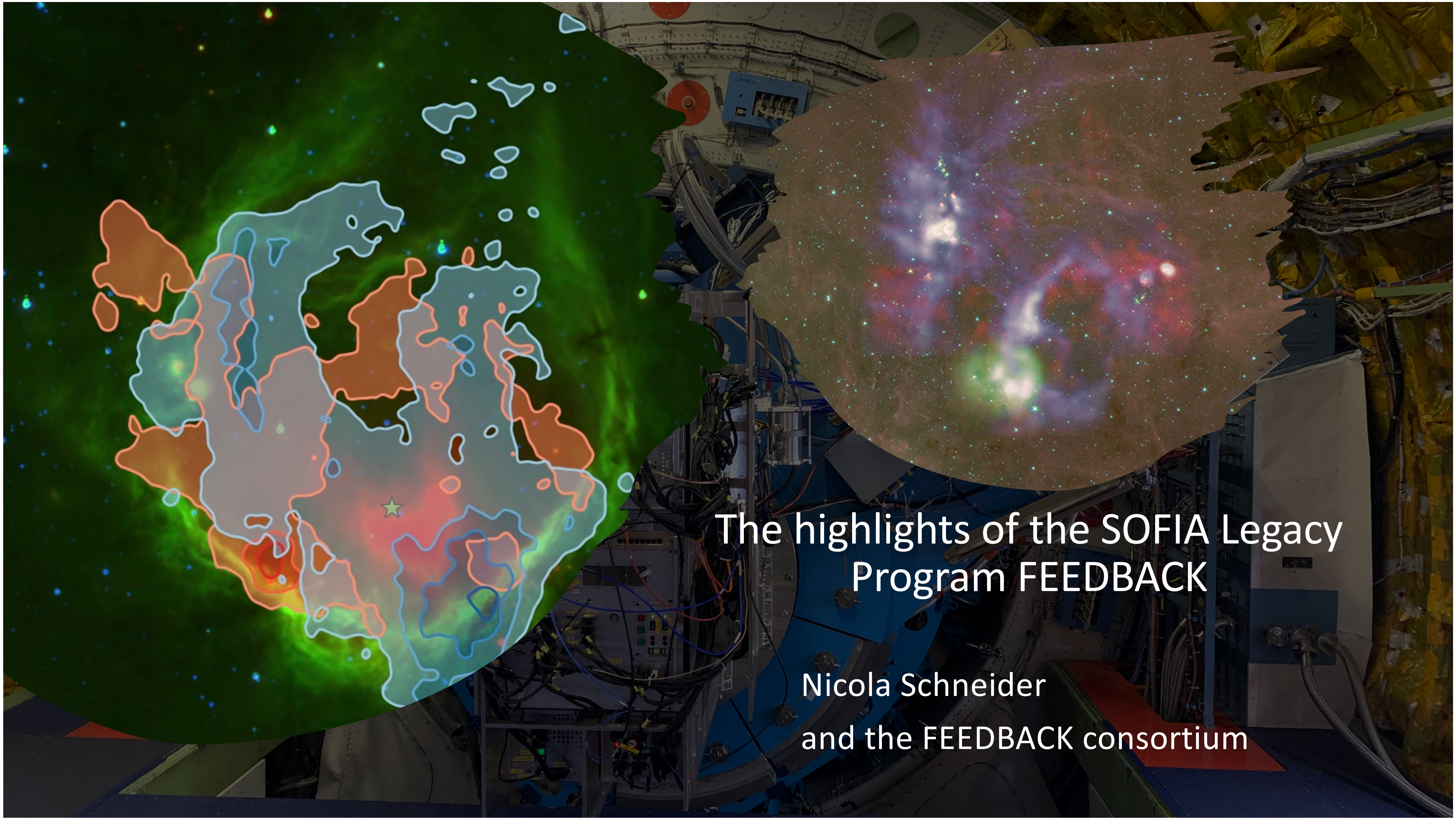

The highlights of the SOFIA Legacy Program FEEDBACK

Nicola Schneider

and the FEEDBACK consortium

SOFIA 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]

[1] I. Physik. Institut, University of Cologne, Zülpicher Str. 77, D-50937 Cologne, Germany; nschneid@ph1.uni-koeln.de
[2] Max-Planck Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[3] Department of Physics and Astronomy, West Virginia University, Morgantown WV 26506, USA
[4] Center for Astrophysics and Space Astronomy, University of Colorado, Colorado 80309, USA
[5] Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany
[6] LAB, University of Bordeaux, CNRS, B18N, F-33615 Pessac, France
[7] USRA/SOFIA, NASA Ames Research Center, Moffett Field, CA 94035-0001, USA
[8] LPENS, LERMA, Université PSL, CNRS, Sorbonne Université, Université de Paris, Paris, France
[9] Department of Astronomy, University of Maryland, College Park, MD 20742, USA
[10] Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India
[11] Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands
[12] Institute of Optical Sensor Systems, DLR, Rutherfordstr. 2, D-12489 Berlin, Germany
[13] Aix Marseille Université, CNRS, CNES, LAM, Marseille, France
[14] Institute for Astronomy, University of Hawaii, 640 N. Aohoku Place, Hilo, HI 96720, USA

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- Survey of 11 **galactic high mass star forming regions** in [CII] 158 μm and [OI] 63 μm
- Large diversity in geometry, SF activity etc. (W43, RCW120, RCW79, Cygnus X,…)
- Spectrally resolved data ((up-)GREAT), **dynamics and excitation conditions**
- ~ 100 h observing time (2019 – 2022), ~ 77% done

https://feedback.astro.umd.edu/

FEEDBACK
SOFIA C+LEGACY

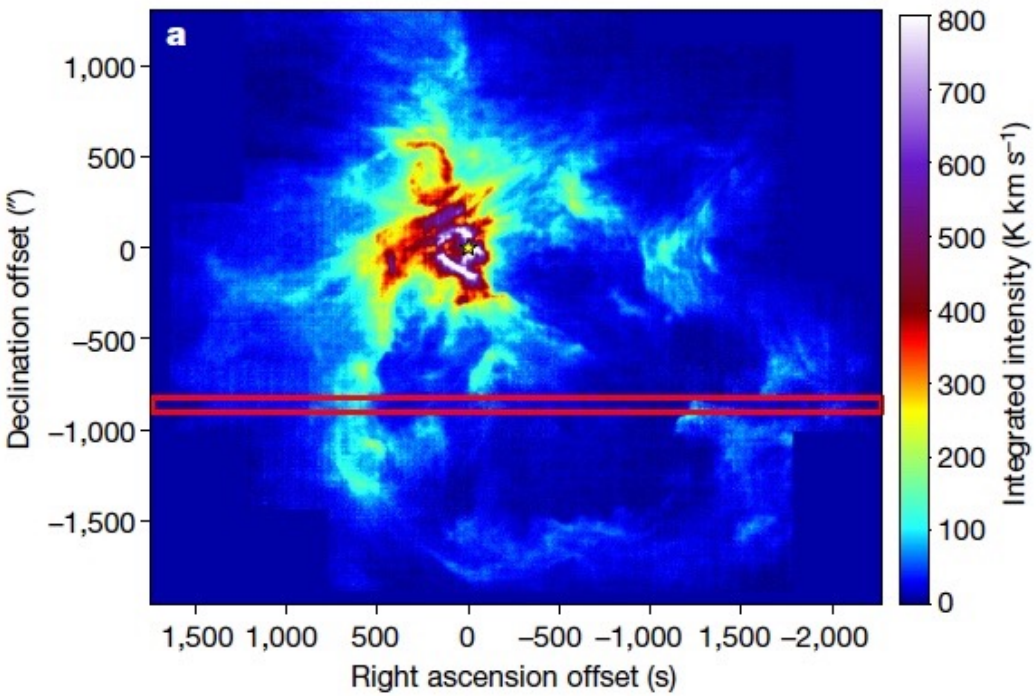
Highlights of FEEDBACK

- **Dynamics of [CII] emitting gas**
  - Expanding bubbles and a ring
  - Cloud erosion
- **Formation of molecular clouds**
- **The ‘CII-deficit’ caused by CII self-absorption**

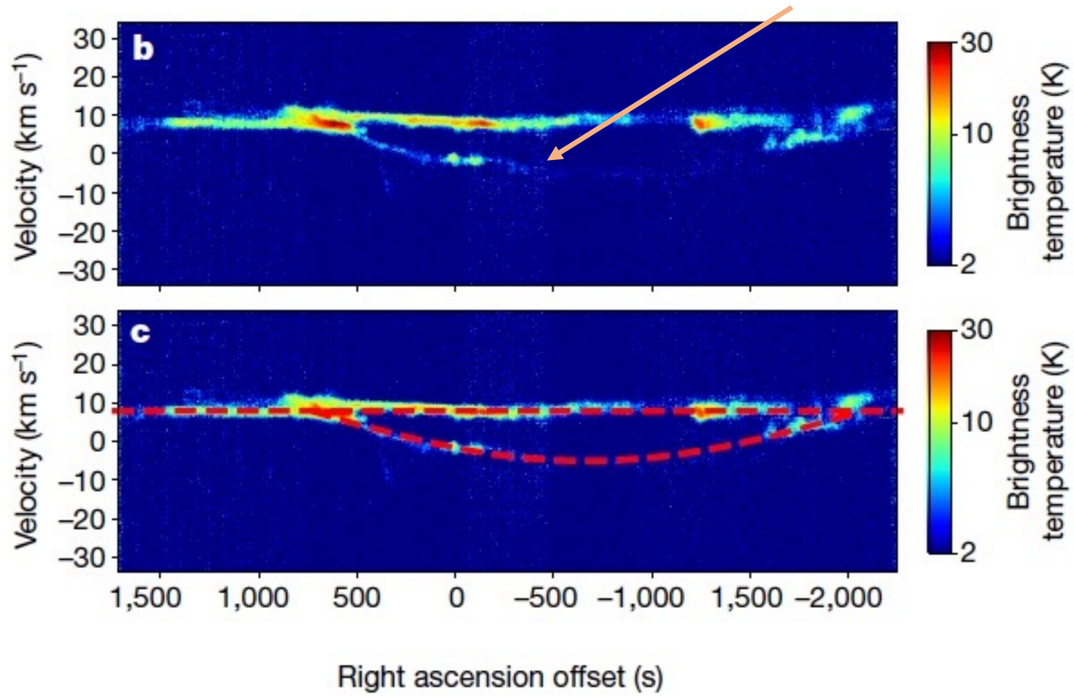
Dynamics of CII emitting gas:
expanding bubbles

Pioneering work of Cornelia Pabst (Nature 2019) and the Orion C+ squad (Higgins et al., Pabst et al. 2020, 2021)

Line integrated CII emission across the Veil in Orion



Position-velocity cuts indicating an expanding CII shell



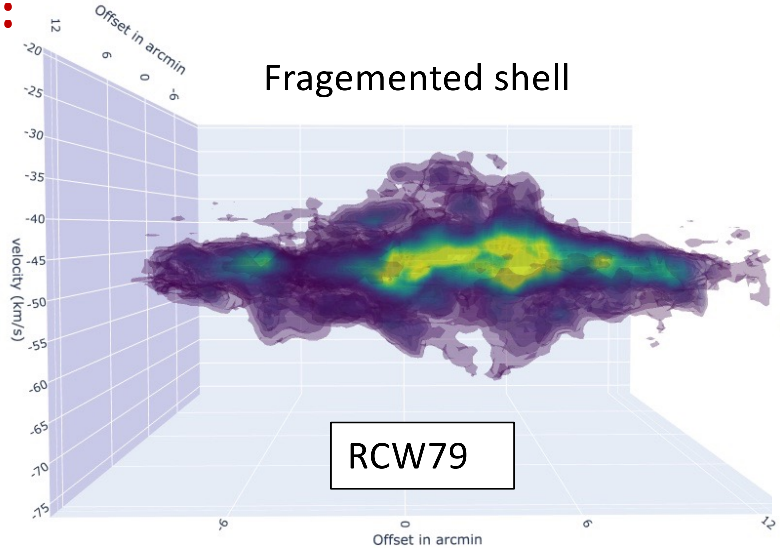
The **stellar wind** originating from the massive star θ1 Orionis C has swept up the surrounding material to create a **‘bubble’** of 4 pc in diameter with a 2600 M_{sun} shell, which is **expanding at 13 km/s.**

Dynamics of CII emitting gas:
expanding bubbles v > 10 km/s

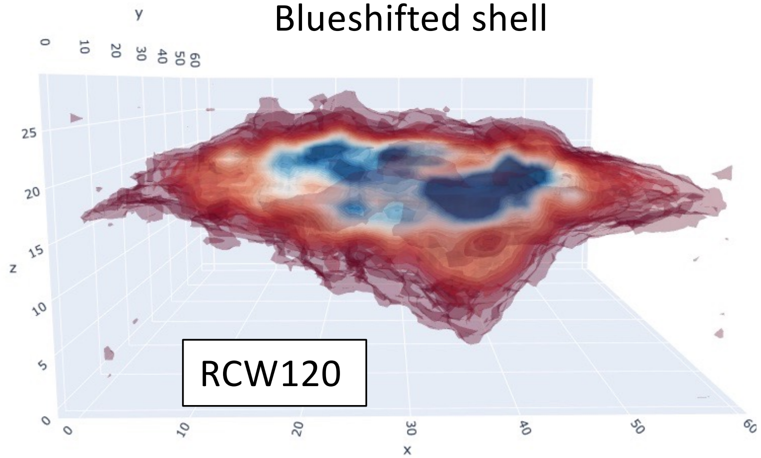
Seen in most of FEEDBACK sources

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)

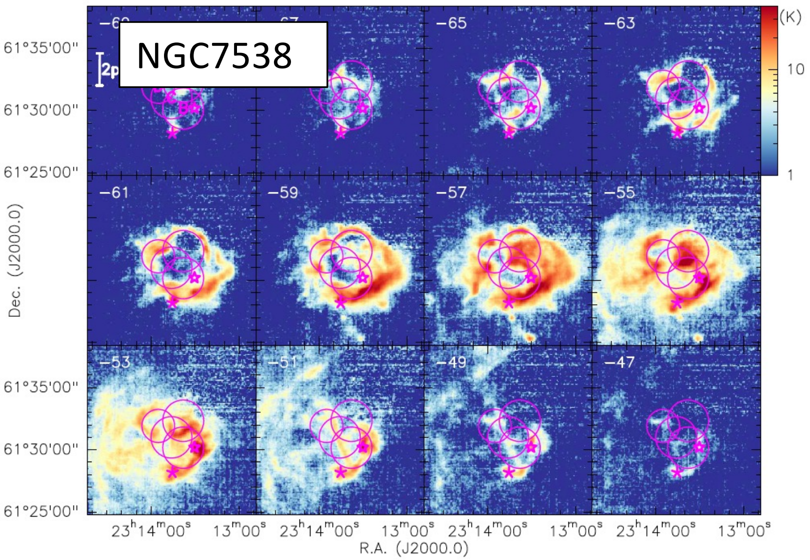
Fragemented shell



Blueshifted shell

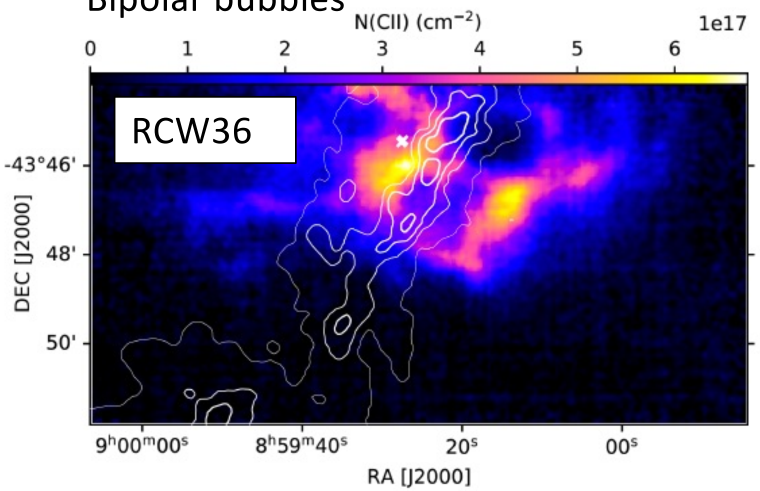


Multiple bubbles



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

Bipolar bubbles



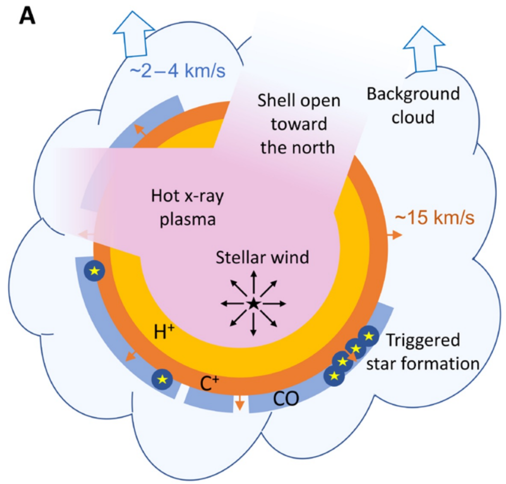
SCIENCE ADVANCES | RESEARCH ARTICLE

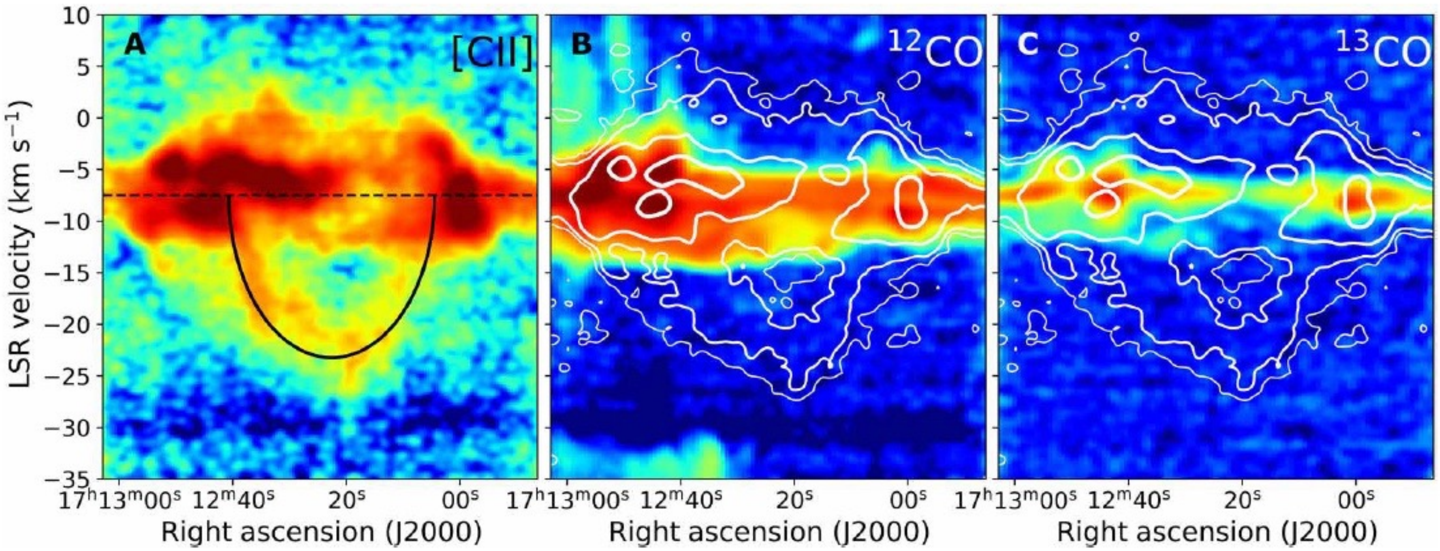
ASTRONOMY

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]

Face on





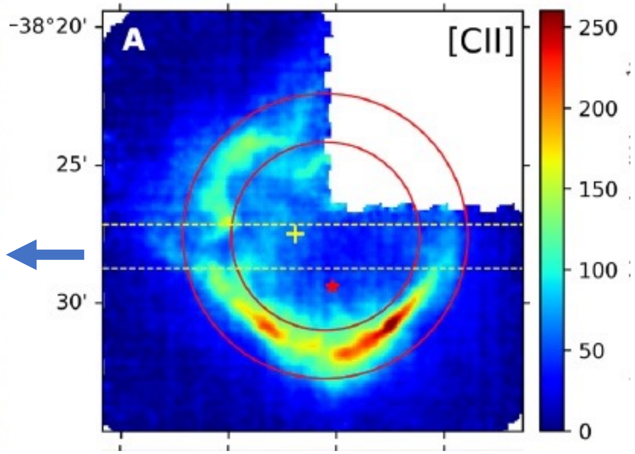
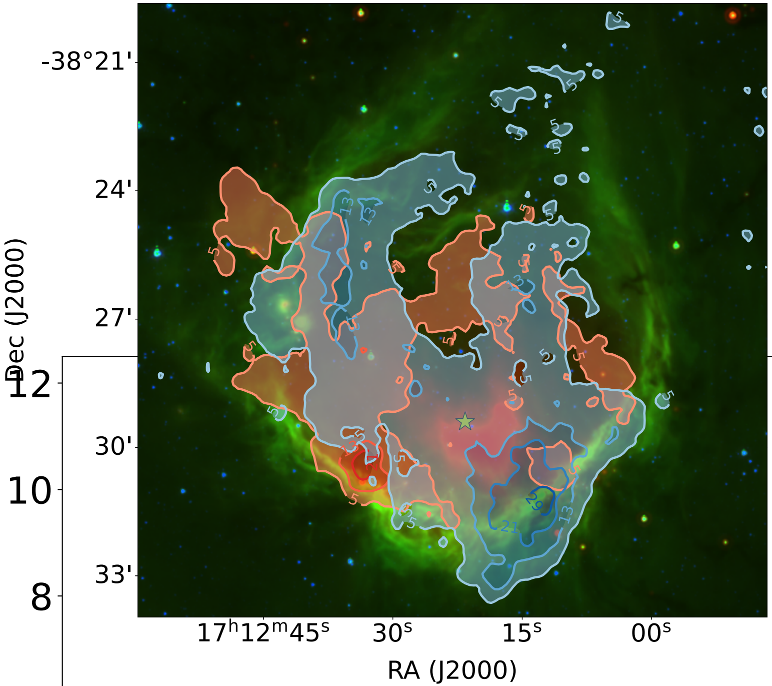
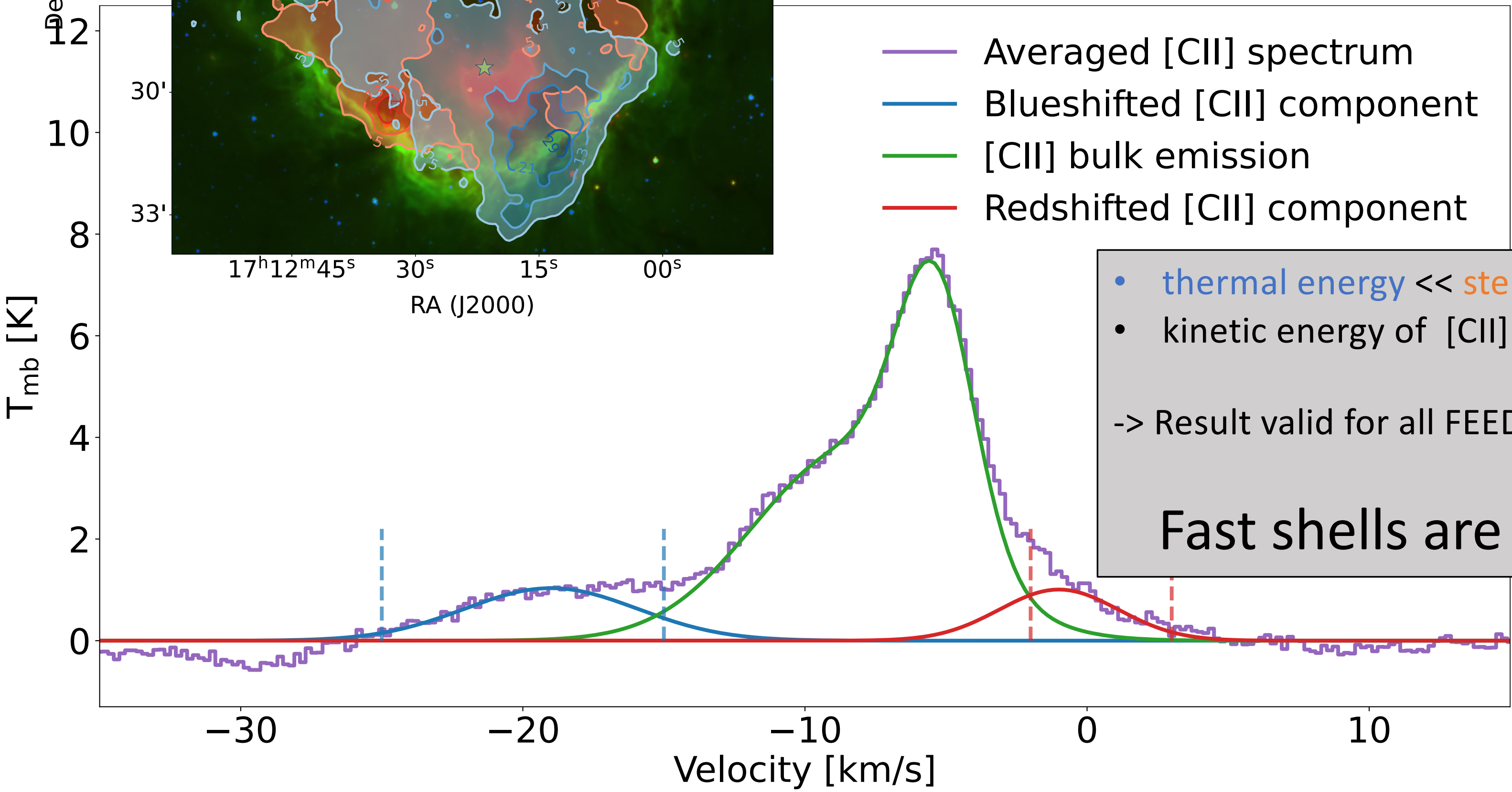


Table 1. Properties of the different components of RCW 120

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

-> Result valid for all FEEDBACK sources with v > 10 km/s

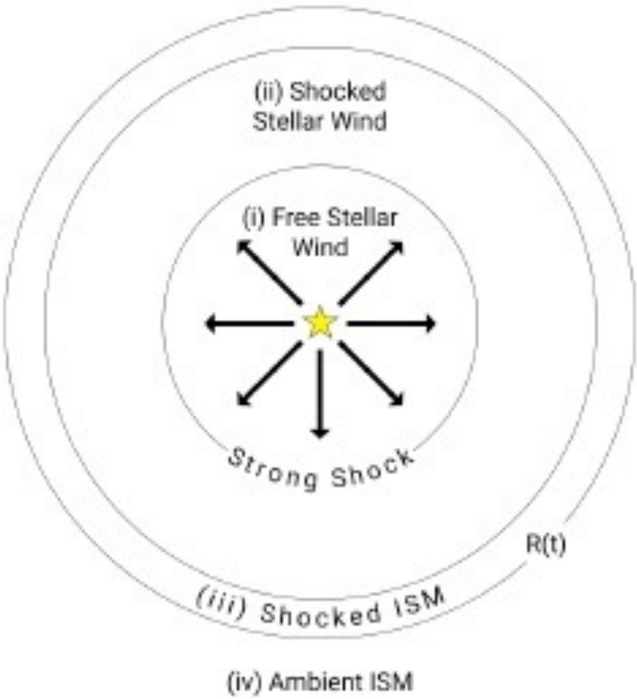
Fast shells are stellar wind driven!

Dynamics of CII emitting gas:

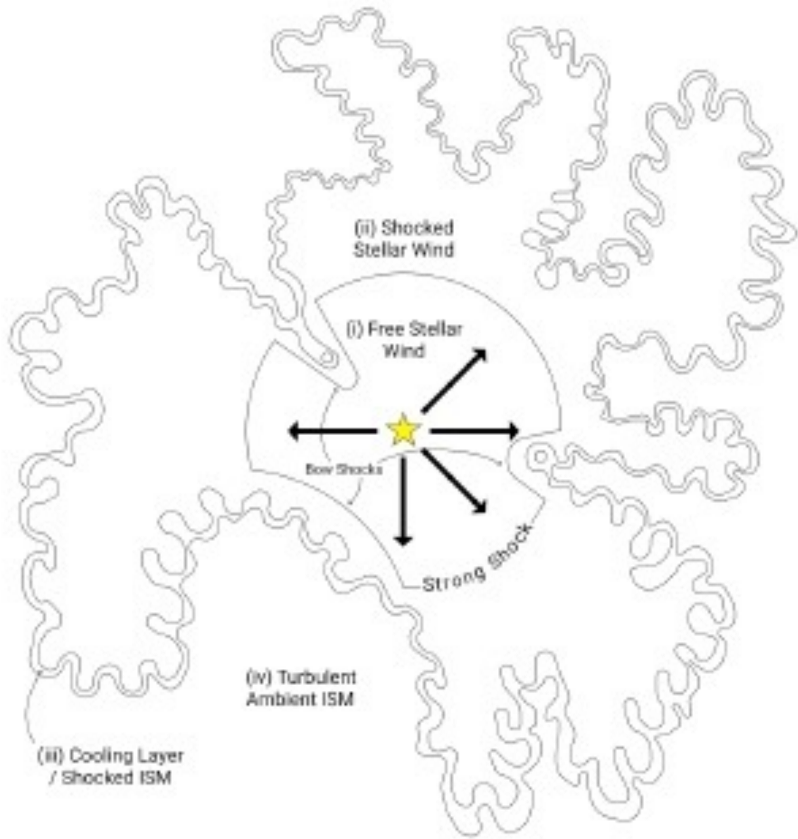
expanding bubbles

Schematic views of an HII region

Weaver et al. (1977)



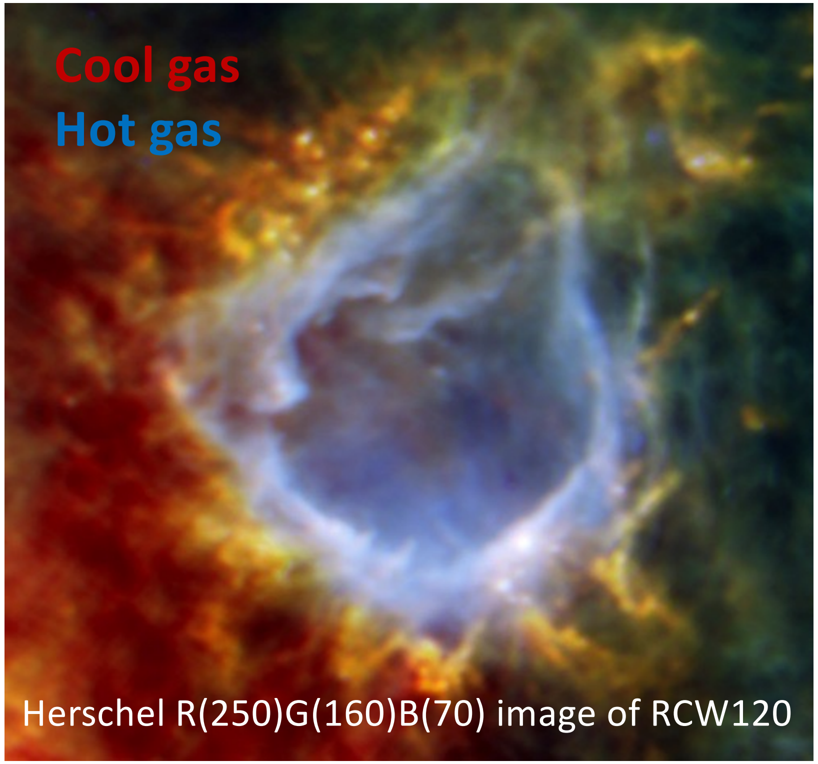
Lancaster et al. (2021)



FEEDBACK SOFIA C+LEGACY

Dynamics of CII emitting gas:

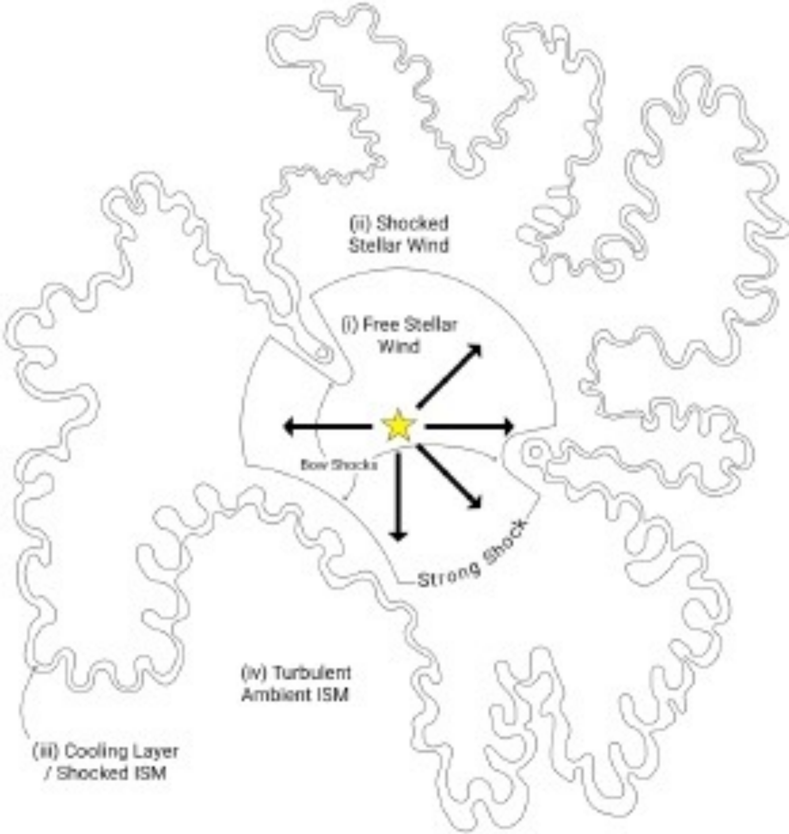
expanding bubbles



Herschel R(250)G(160)B(70) image of RCW120

Schematic views of an HII region

Lancaster et al. (2021)



-> a more realistic scenario?

Dynamics of CII emitting gas:

cloud erosion

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

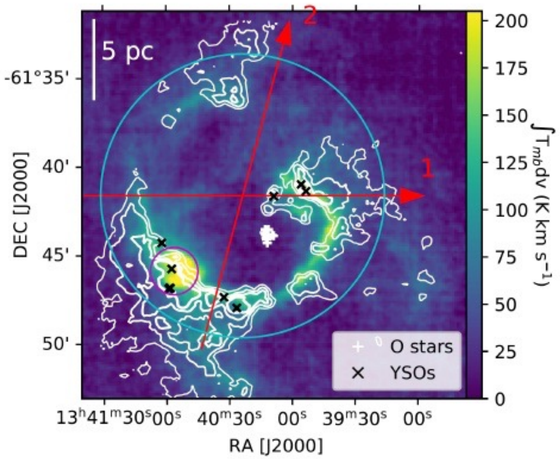
Astronomy & Astrophysics

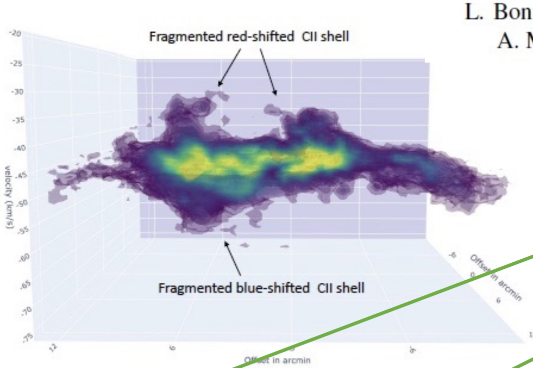
LETTER TO THE EDITOR

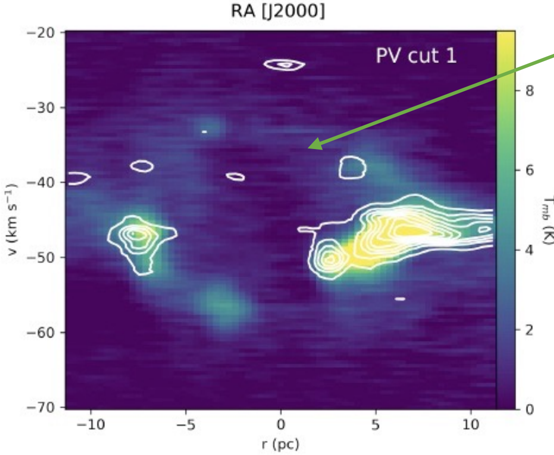
The SOFIA FEEDBACK [CII] Legacy Survey: Rapid molecular cloud dispersal in RCW 79★

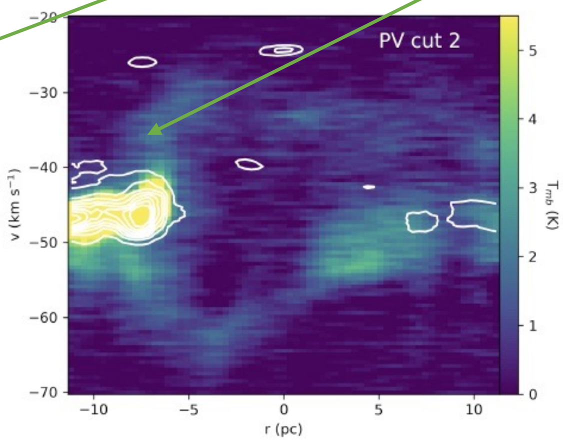
L. Bonne[1], S. Kabanovic[2], N. Schneider[2], A. Zavagno[3,4], E. Keilmann[2], R. Simon[2], C. Buchbender[2], R. Güsten[5], A. M. Jacob[5,6], K. Jacobs[2], U. Kavak[1], F. L. Polles[1], M. Tiwari[5], F. Wyrowski[5], and A. G. G. M. Tielens[7,8]

RCW79 Bonne et al. (2023)









Fragmented CII shell

CII high-velocity gas streaming out of the cloud through holes

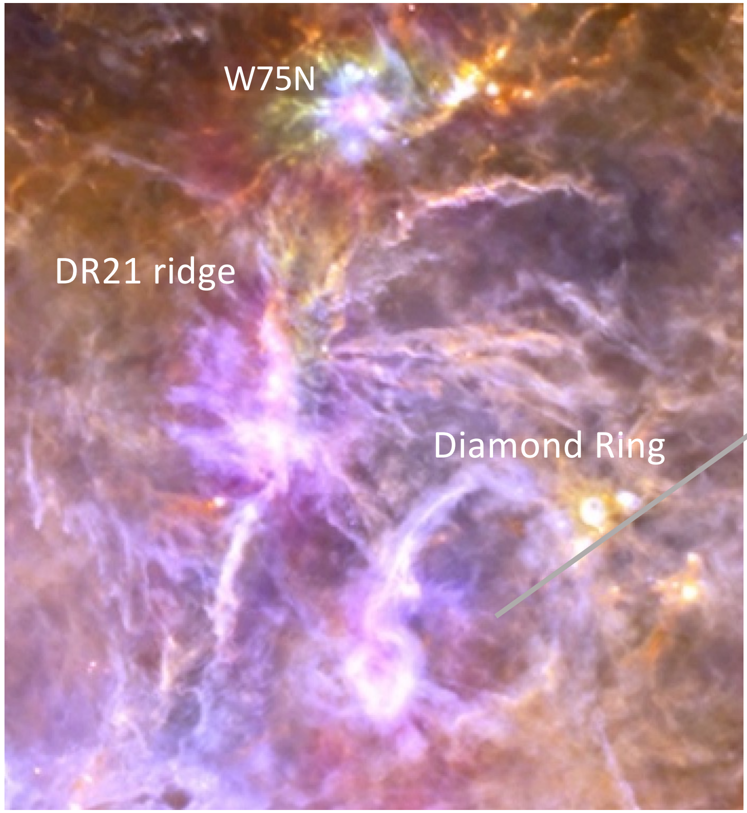
Dynamical timescales < 1.0 Myr, which is well below the 2.3 Myr age of the OB cluster.

Mass ejection rate 0.9–3.5 10^{-2} Msun/yr

-> short erosion timescales (<5 Myr) for the cloud

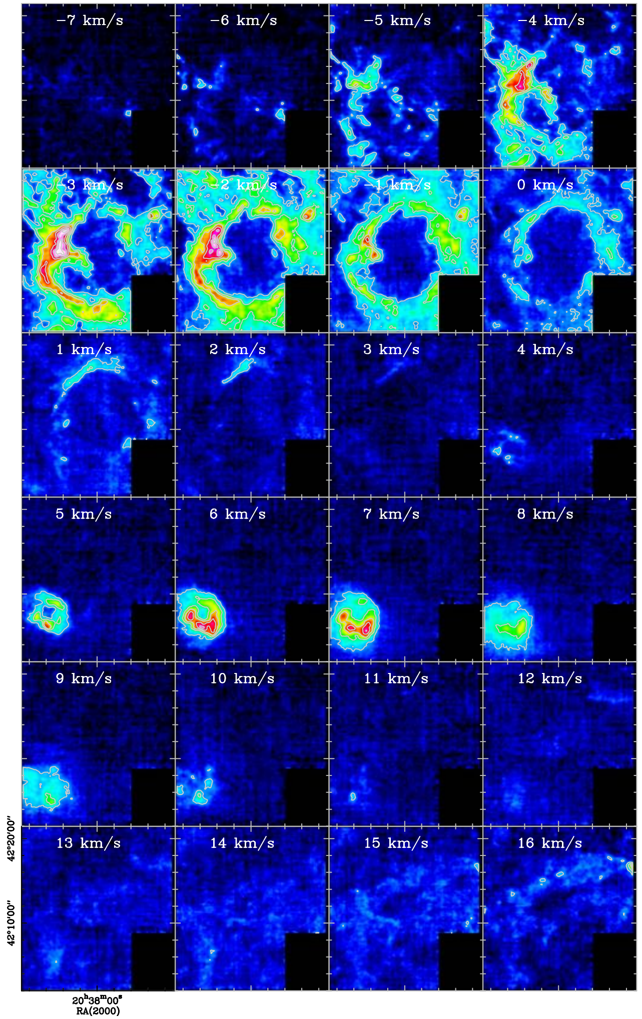
Dynamics of CII emitting gas:

a slowly expanding ring



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

Channel map of CII emission



Dannhauer et al. (2024)

- Tilted ring, but **no expanding CII shell.**
- One exciting **O-star.**
- What is this? Late evolutionary stage of an expanding bubble?

See Poster of Simon Dannhauer !

FEEDBACK SOFIA C+LEGACY

Formation of molecular clouds seen in CII

Schneider et al. (2023)

nature astronomy

Article https://doi.org/10.1038/s41550-023-01901-5

Ionized carbon as a tracer of the assembly of interstellar clouds

Received: 13 September 2022

Accepted: 20 January 2023

Published online: 16 February 2023

Nicola Schneider[1] ✉, Lars Bonne[2] ✉, Sylvain Bontemps[3], Slawa Kabanovic[1], Robert Simon[1], Volker Ossenkopf-Okada[1], Christof Buchbender[1], Jürgen Stutzki[1], Marc Mertens[1], Oliver Ricken[4], Timea Csengeri[3] & Alexander G.G.M. Tielens[5,6]

Bonne et al. (2023)

The Astrophysical Journal, 951:39 (26pp), 2023 July 1 https://doi.org/10.3847/1538-4357/acd536

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]

[1] SOFIA Science Center, NASA Ames Research Center, Moffett Field, CA 94045, USA; lbonne@usra.edu

[2] Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, F-33615 Pessac, France

[3] I. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, D-50937 Köln, Germany

[4] Academia Sinica, Institute of Astronomy and Astrophysics, Taipei, Taiwan

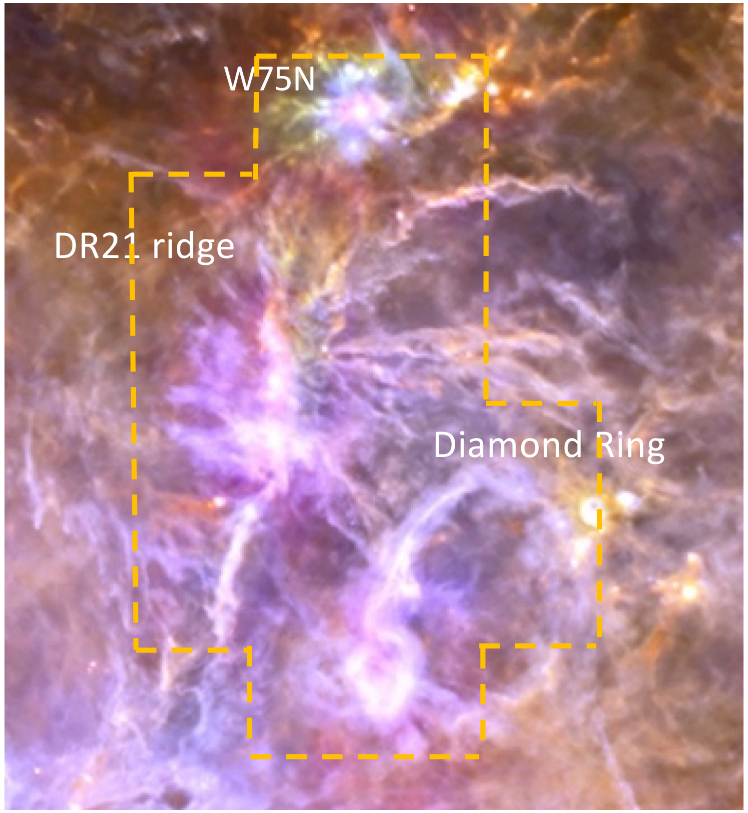
[5] Green Bank Observatory, P.O. Box 2, Green Bank, WV 24944, USA

[6] University of Maryland, Department of Astronomy, College Park, MD 20742-2421, USA

[7] Leiden Observatory, P.O. Box 9513, 2300 RA Leiden, The Netherlands

Received 2022 October 28; revised 2023 May 2; accepted 2023 May 12; published 2023 July 10

Cygnus X *Herschel RGB image*



FEEDBACK SOFIA C+LEGACY

Formation of molecular clouds seen in CII

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

n ~ 100 cm^{-3}
T ~ 100 K **-> 80% atomic, 20% molecular**
v = 4 - 20 km/s

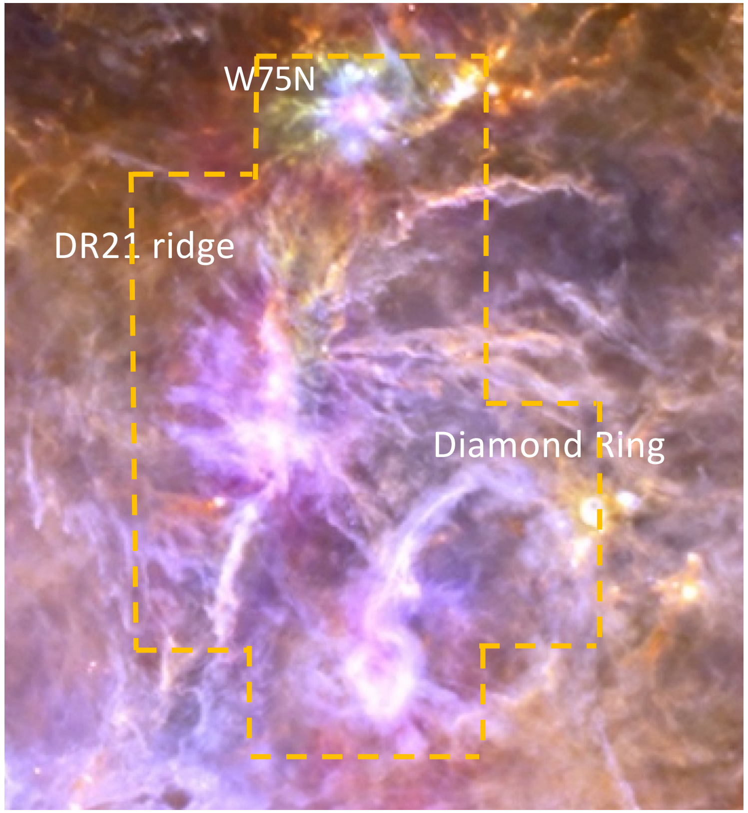
The molecular clouds in Cygnus X form by interaction of mostly **atomic colliding flows**, traced in CII.

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.

Schneider et al. (2023) Bonne et al. (2023)

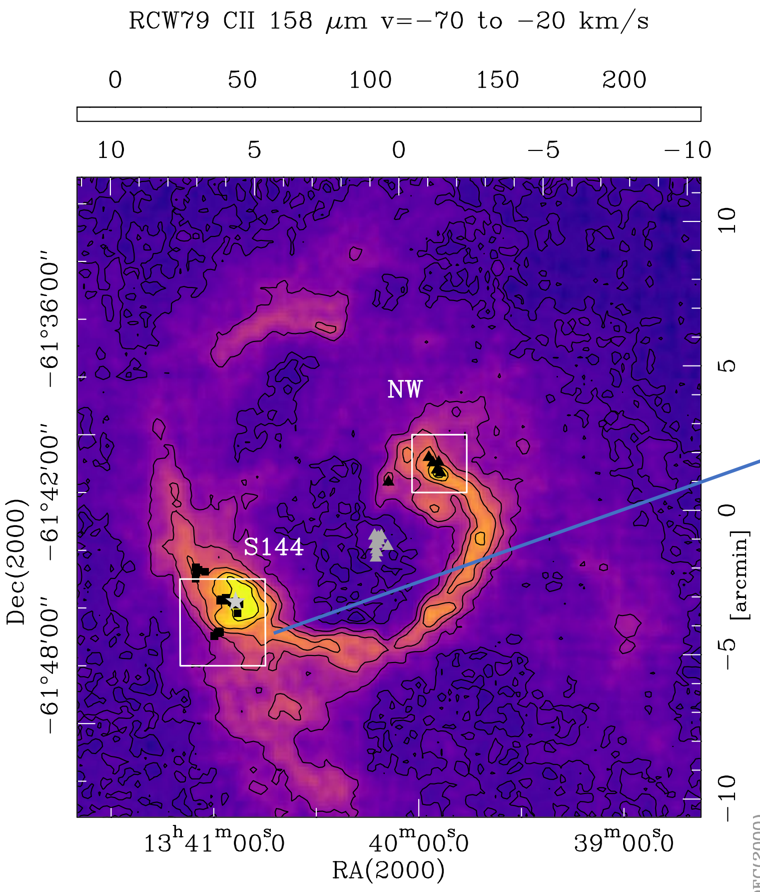
Cygnus X *Herschel RGB image*



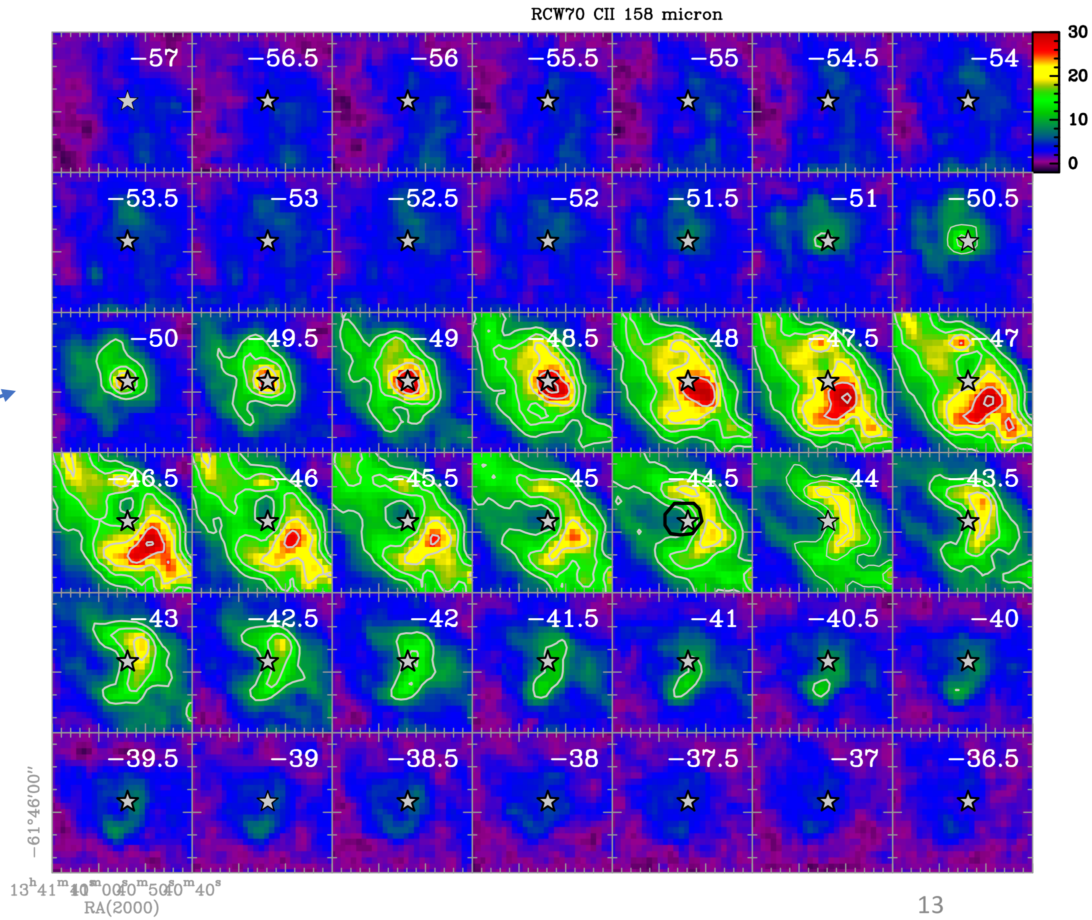
The 'CII-deficit'

a bubble in a bubble in RCW79

Is the compact HII region filled with C⁺and the 'hole' is due to self-absorption? -> Early evolutionary stage ?



Keilmann, Dannhauer et al. (2024)

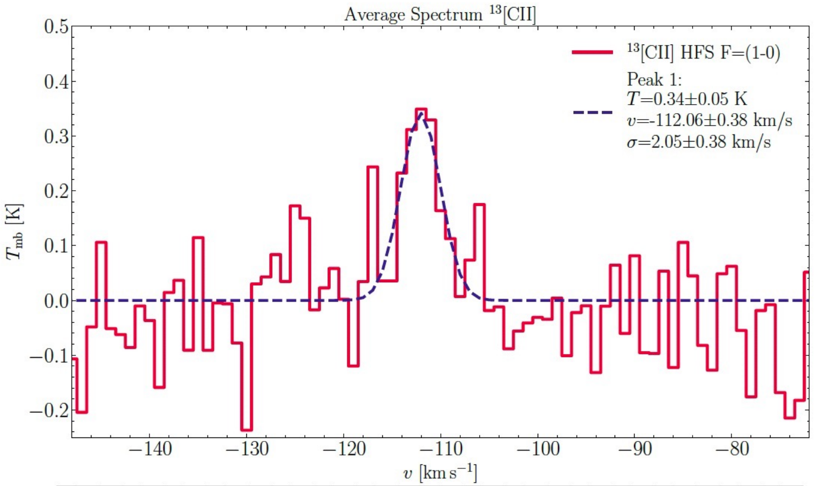


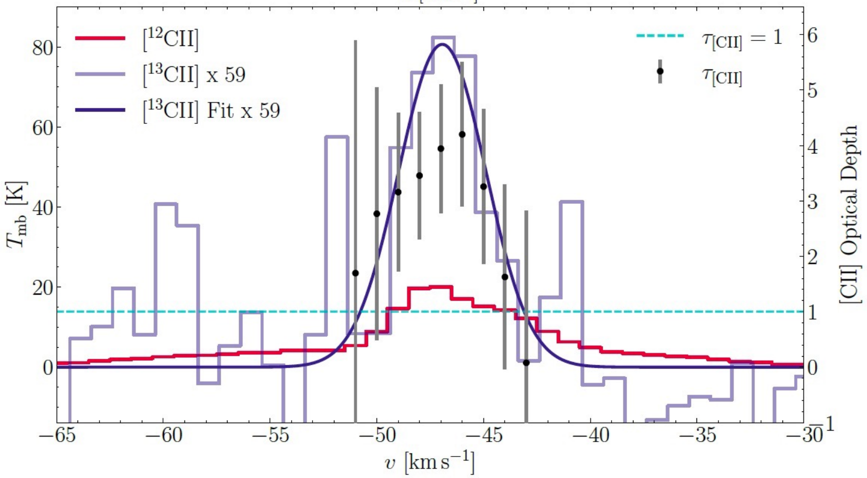
The 'CII-deficit'

$\tau\ (^{12}\mathrm{CII}) \sim 4$

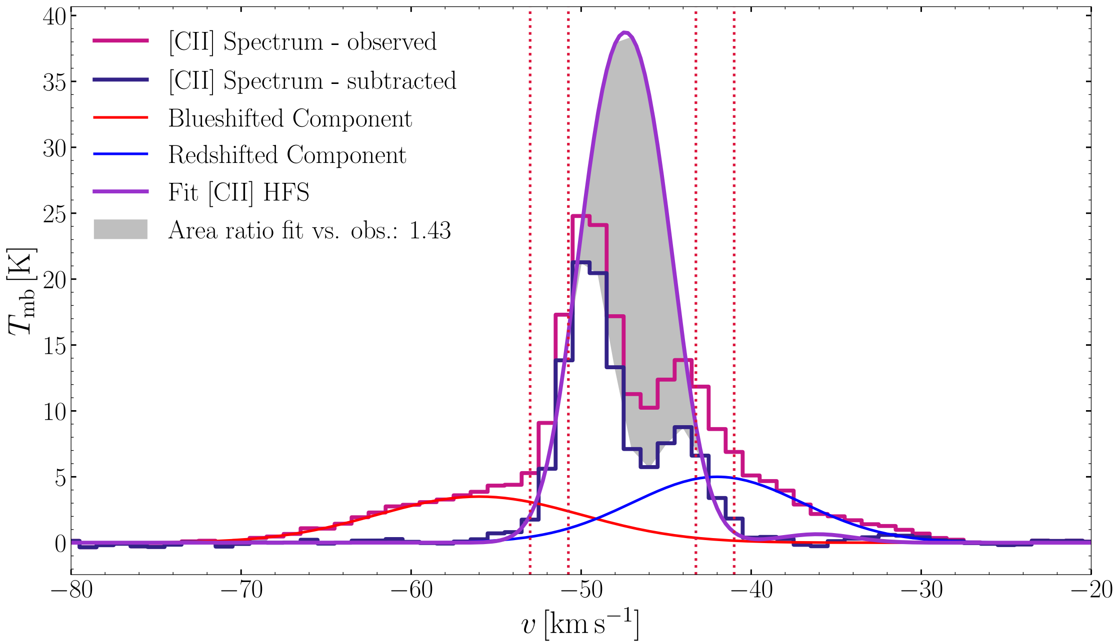
-> CII line is optically thick -> self-absorption!

Detection of 1-0 HFS line of ^{13}CII





Gausssian fit to the CII line wings to derive the 'missing' emision.

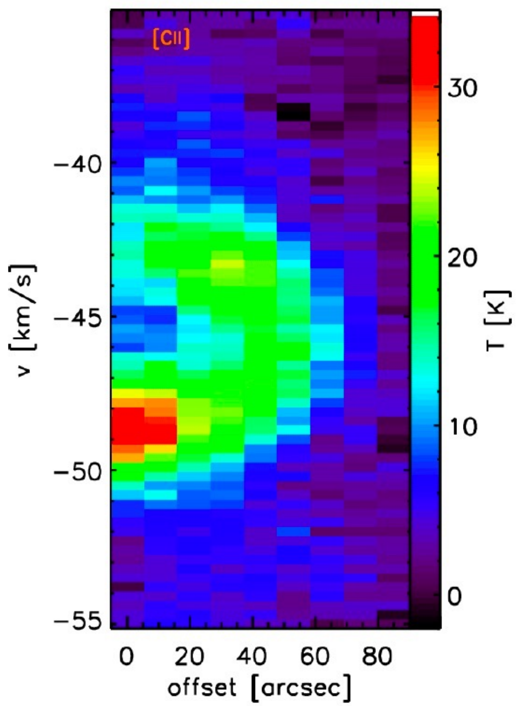


The 'CII-deficit'

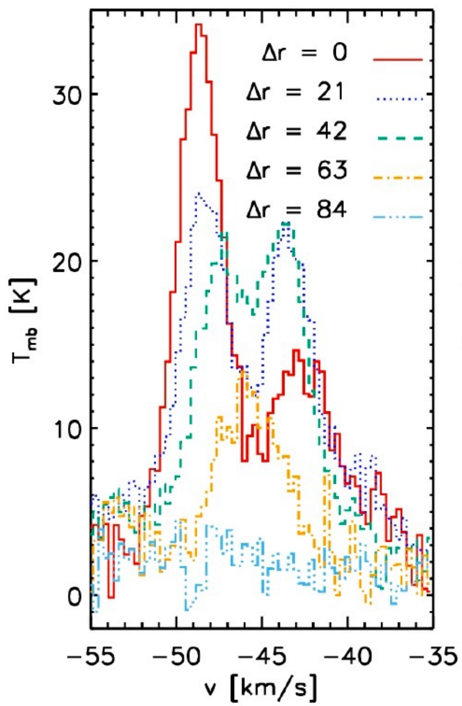
first time detection of a C^+ filled bubble -> early stage !?

Observations

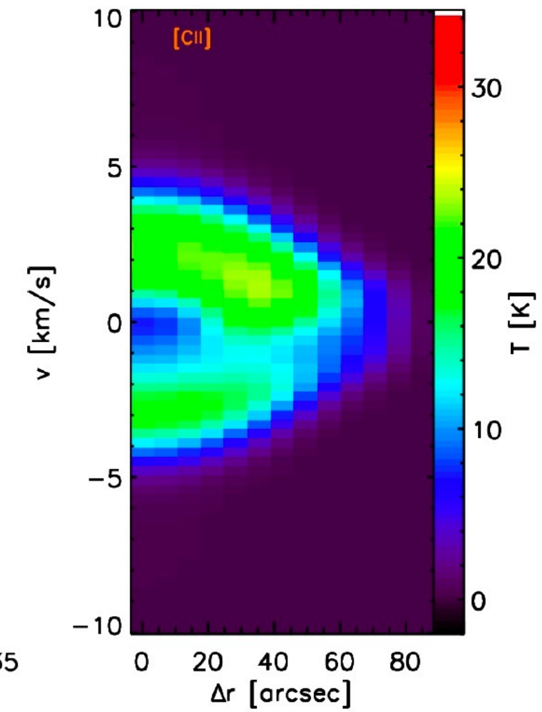
1D (SimLine) modelling with 3 shells,
T- and v-gradients

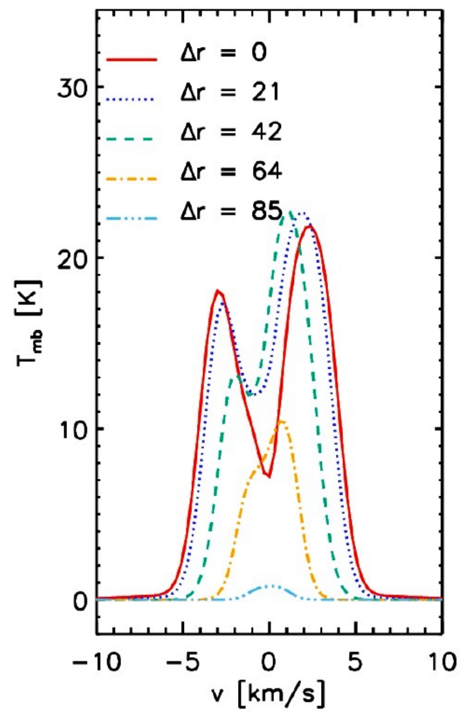


PV cut



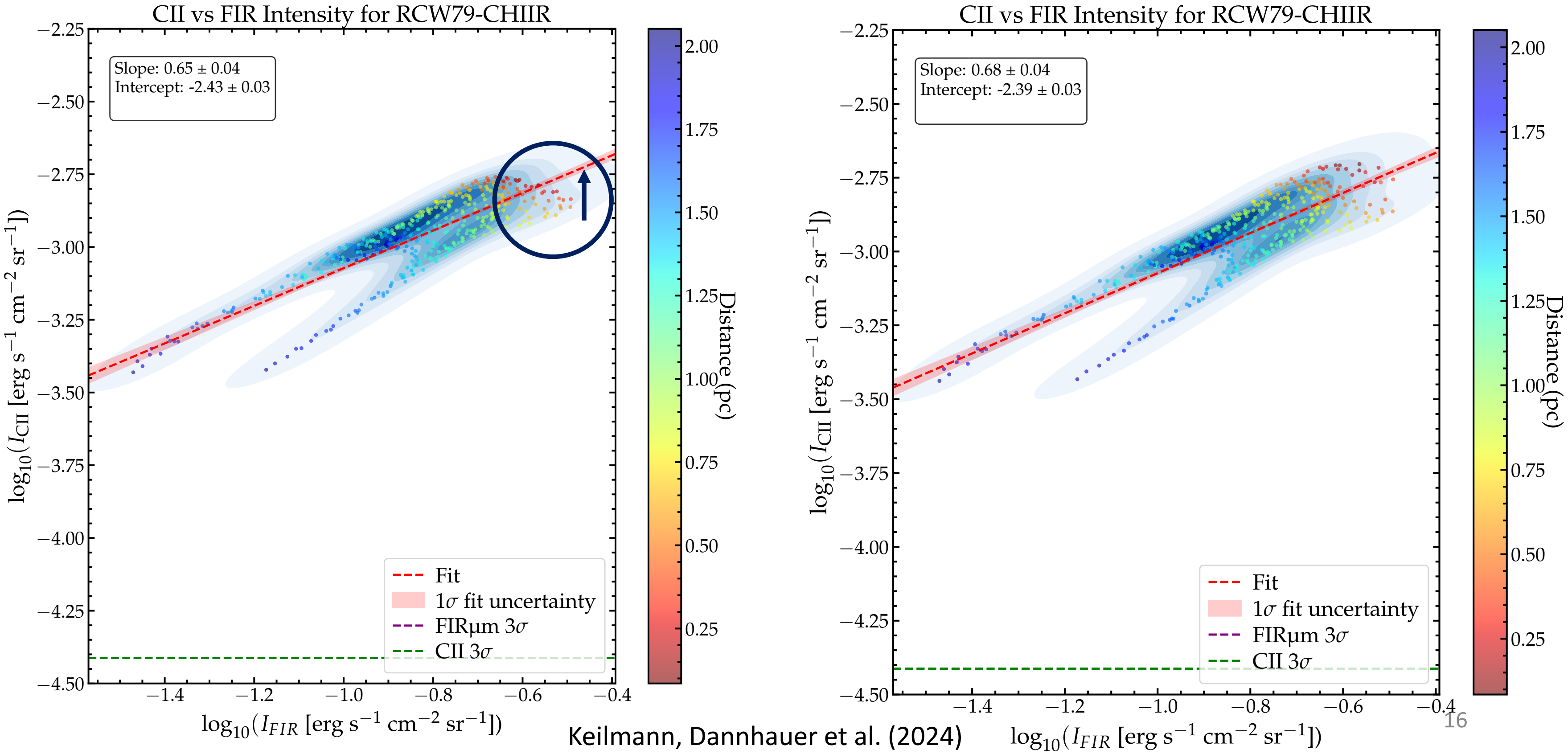
Spectra at different positions





The 'CII-deficit': low CII/total FIR ratio

- High optical depth of the CII line /self-absorption
- High dust optical depth
- High ionization parameter
- More efficient heating of dust grains over gas
- Radiation Field Strength and Hardness
- High gas densities causing collisional de-excitation.
- Metallicity variations
- Geometrical effects and observational resolution limits



Keilmann, Dannhauer et al. (2024)

More to come and to do

- Quantify the radiative coupling of interstellar gas to the FUV photons of massive stars and determine the **heating efficiency** of neutral atomic and CO-dark gas.

-> Derive from CII luminosity the heating efficiency.
-> Heating efficiency depends on the ionization parameter, $\gamma = G_o T^{0.5}/n_e$ with G_o the Habing field (to be determined from GAIA for example) .

- Continue to investigate the **CII-deficit** in other FEEDBACK bubbles.

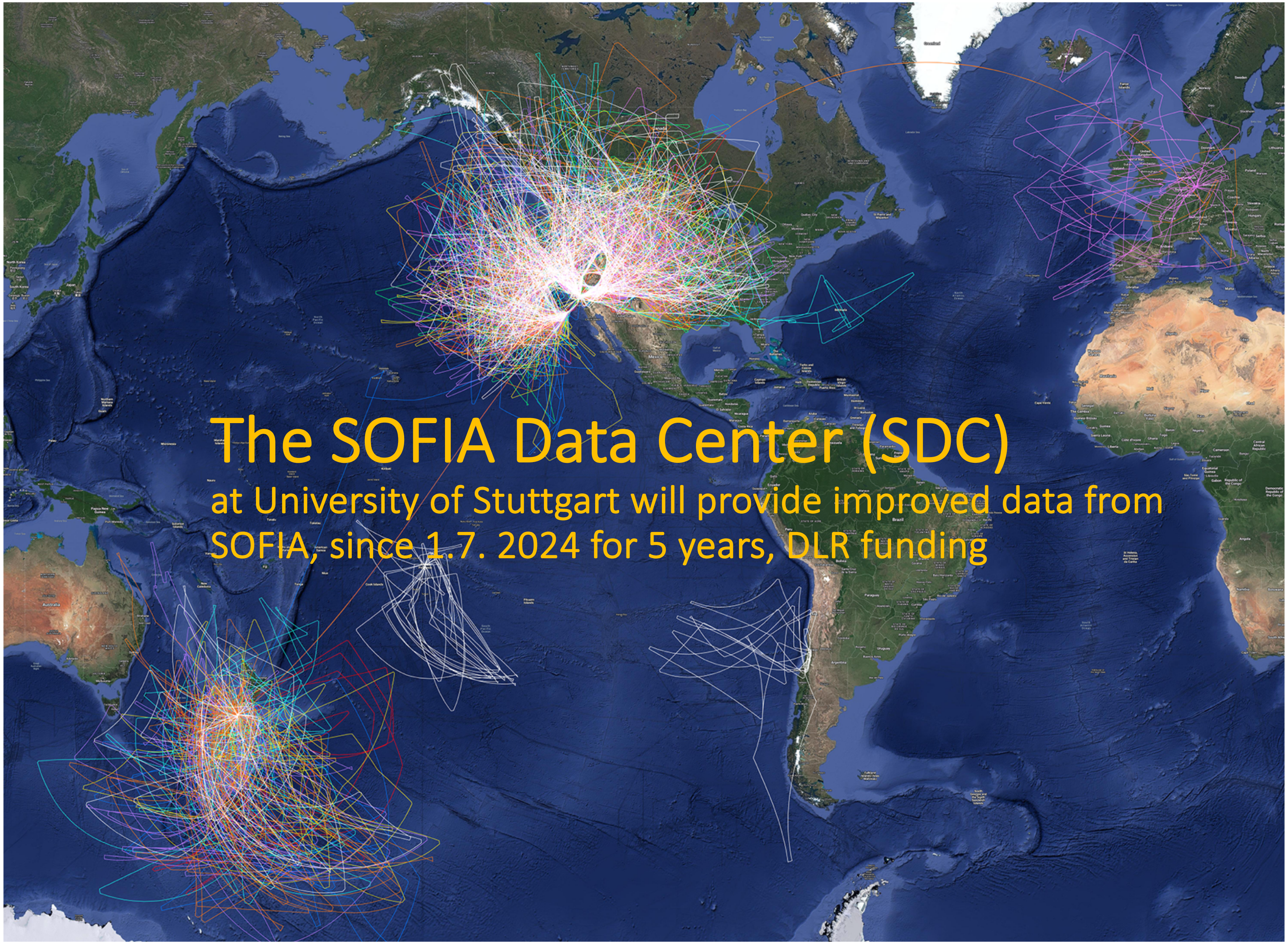
- '**Triggered star-formation**': compare CO and CII linewidths, velocities etc.

- How good is the CII line as a **star-formation rate** tracer ?

- Compare CII/CO observations with **simulations** of expanding HII regions including stellar wind.

- What about the **OI 63 μm** line?

- ……



The SOFIA Data Center (SDC)

at University of Stuttgart will provide improved data from SOFIA, since 1.7. 2024 for 5 years, DLR funding

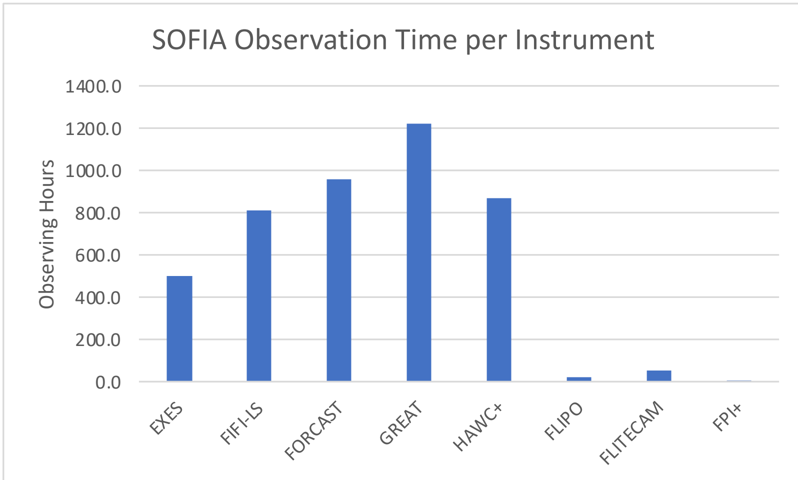
The SOFIA Data Vault

- Science Data **~24 TB**
- Total about **5300 h**
- Telescope guider cameras were always active **(>5300 h)**.
- Data so far at NASA/IPAC Infrared Science archive (IRSA)

Data Volume in DCS

Daten

Archive		LEVEL_0	LEVEL_1	LEVEL_2	LEVEL_3	LEVEL_4	Total
SDC/IRSA	**EXES**	46.6	2013.9	819.6	43.7	0.0	**2923.7**
SDC/IRSA	**FIFI-LS**	0.0	972.4	21.1	125.7	35.9	**1155.1**
IRSA	**FLITECAM**	0.3	31.1	46.8	38.2	0.0	**116.3**
SDC/IRSA	**FORCAST**	5.6	94.3	548.7	148.0	1.2	**797.8**
IRSA	**FPI_PLUS**	0.0	22.4	43.4	0.3	1.1	**67.3**
Cologne/IRSA	**GREAT**	0.0	2494.6	0.0	3056.7	75.7	**5627.0**
SDC/IRSA	**HAWC_PLUS**	13334.1	0.7	18.5	10.1	4.9	**13368.3**
IRSA	**HIPO BLUE**	0.0	46.8	0.0	0.0	0.0	**46.8**
IRSA	**HIPO RED**	0.0	74.8	0.0	0.0	0.0	**74.8**
	Total	**13386.5**	**5751.1**	**1498.0**	**3422.7**	**118.8**	**24177.0**



Credit: Bernhard Schulz, DSI Uni Stuttgart