The future of *FEEDBACK* - Key findings and outlook

Simon Dannhauer on behalf of the FEEDBACK consortium

UNIVERSITÄT ZU KÖLN

SFB 1601

Max-Planck-Institut für Radioastronomie

SOFIA Legacy Project *FEEDBACK*

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

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]

Survey of 11 galactic, high-mass star-forming regions in [CII] 158µm and [OI] 63µm

- covering **diverse** environments (RCW120, Cygnus X, M17, W43..)
- **spectrally resolved** (up-)GREAT: tracing the dynamics of the gas
- ~100h observing time, 77% done

PI's:

Nicola Schneider

Xander Tielens

Image Credit: Jim Ross/NASA

FEEDBACK team

PI's: N. Schneider & A. Tielens

I. Physics U. of Cologne:

C. Buchbender, S. Dannhauer, R. Higgins, A. Jacob,
S. Kabanovic, E. Keilmann, Y. Okada,
V. Ossenkopf-Okada, M. Roellig, R. Simon, J. Stutzki, …

MPIfR Bonn:

R. Güsten, S. Neupane, K.Menten, M. Mertens,
O. Ricken, F. Wyrowski, …

and many more

L. Anderson , J. Bally, S. Bontemps, L. Bonne, H. Beuther,
T. Csengeri, A. Gusdorf, R. Karim, M. Luisi,
M. Pound, D. Russeil, M. Tiwari, M. Wolfire, A. Zavagno,
…

14 papers published + many more in prep.

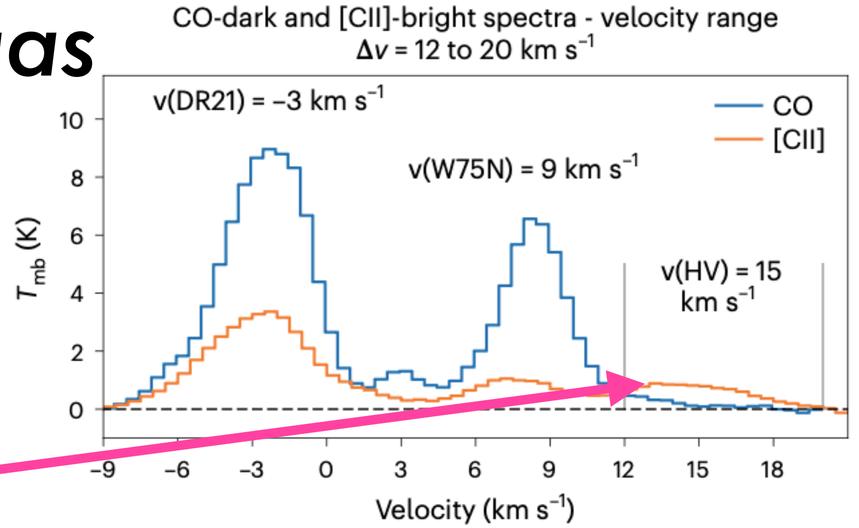
Name	Topic
Schneider et al. (2020)	FEEDBACK project paper
Luisi et al. (2021)	Expanding CII shells in RCW120
Tiwari et al. (2021)	Wind-driven shells in RCW49
Beuther et al. (2022)	Bubbles in NGC7538
Bonne et al. (2022)	Dynamics and mass ejection in RCW36
Tiwari et al. (2022)	PDR of RCW49
Kabanovic et al. (2022)	Self-absorption in RCW120
Schneider et al. (2023)	CII tracing cloud assembly
Bonne et al. (2023)	CII 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 CII
Bij et al. (2024)	CII and HAWK+ observations in RCW36
Keilmann et al. (2025.)	CII deficit in RCW79
Faerber et al. (subm.)	Expansion signatures in HII regions
Dannhauer et al. (in prep.)	The Diamond Ring in Cygnus X
Dannhauer et al. (in prep.)	The evolutionary sequence of CII bubbles
Keilmann et al. (in prep.)	PDR modelling in RCW79
Bonne et al. (in prep.)	High velocity wings around O starclusters
Karim et al. (in prep.)	The Eagle Nebula in CII and molecular lines
Neupane et al. (in prep.)	NGC6334
Bally et al. (in prep.)	W43
Jacob et al. (in prep.)	W40

Cloud Formation traced by [CII]

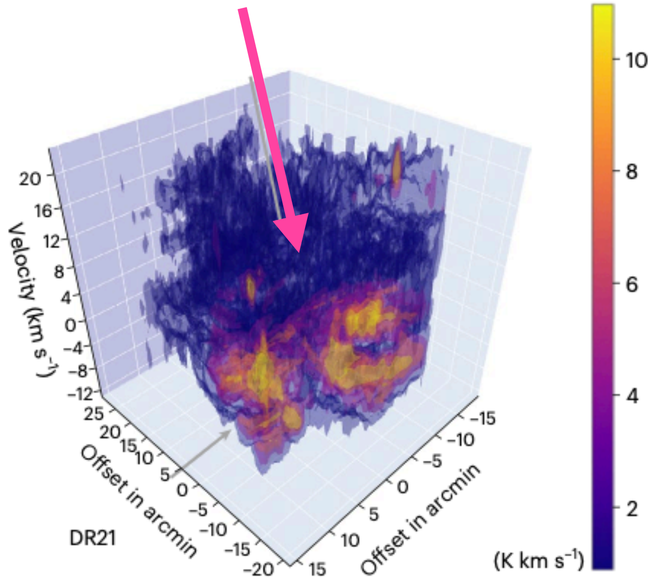
Ionized carbon as a tracer of CO-dark gas

Molecular Clouds in Cygnus X formed by mostly (80%) atomic colliding flows

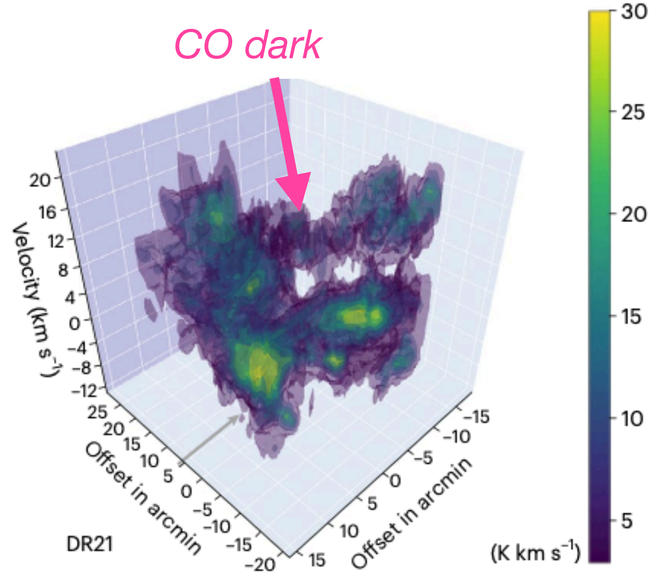
nH~100 cm^{-3}, T~100 K



Low intensity CII emission at high velocities



CO dark



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]

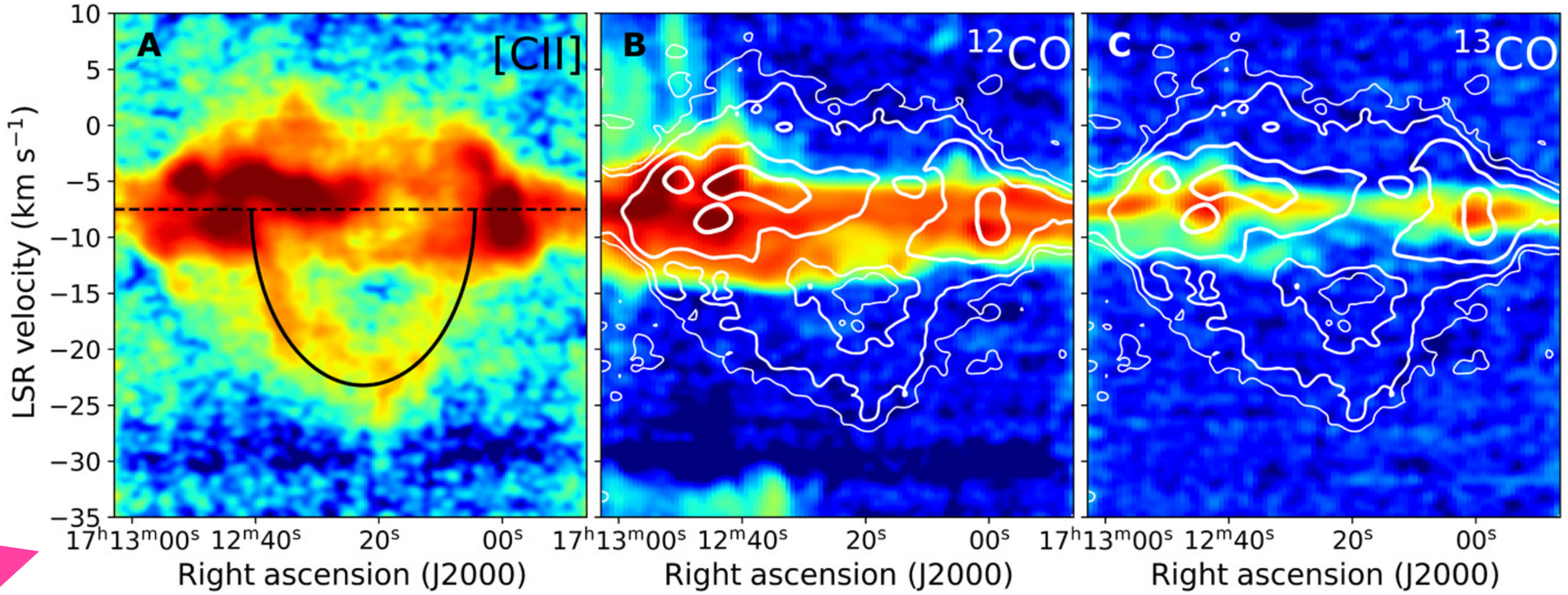
Schneider et al., 2023 (Nature)

Bonne et al., 2023

Fast expanding bubbles

(remember also Cornelia's talk + Pabst et al., 2019, Nature)

Fast (v>10km/s) expanding [CII] shells driven by stellar wind a common feature among most FEEDBACK sources

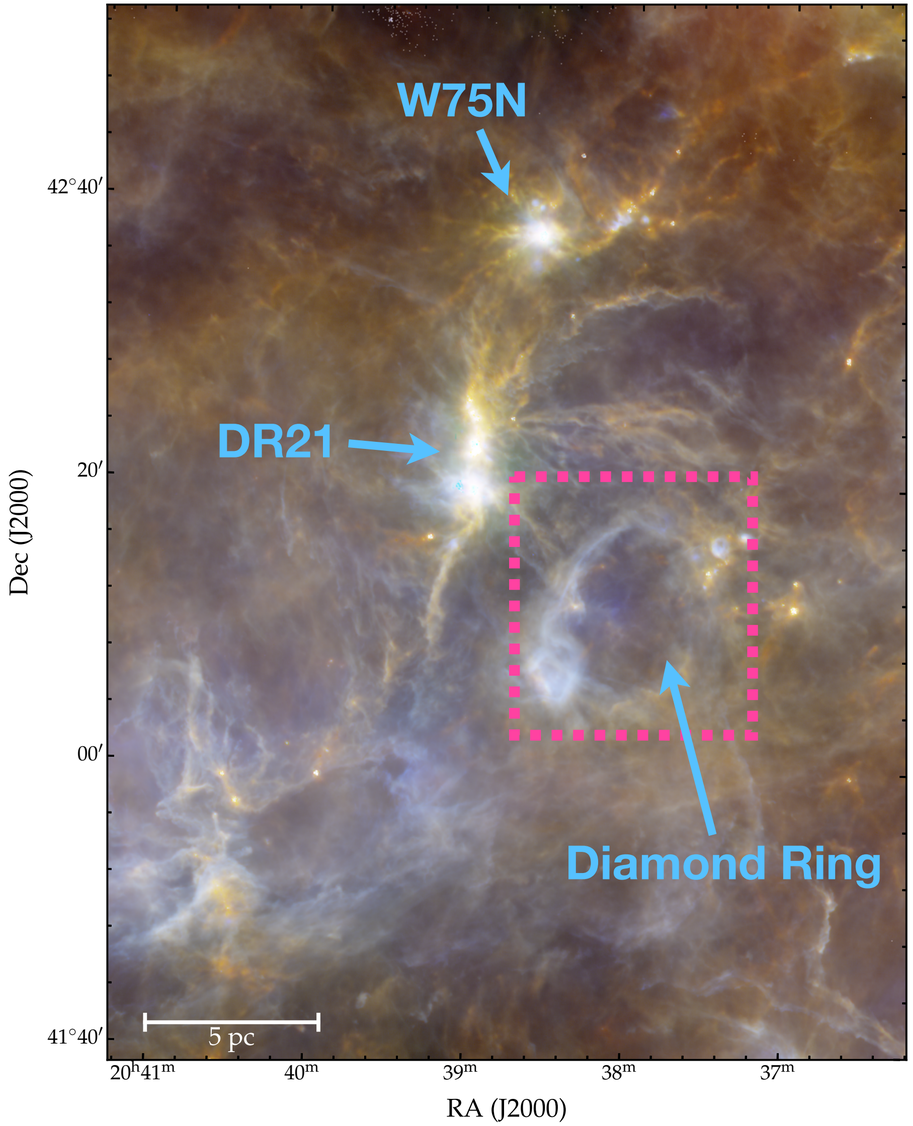


- RCW120 (Luisi et al., 2021)
- RCW49 (Tiwari et al., 2021)
- NGC7538 (Beuther et al., 2022)
- RCW36 (Bonne et al., 2022)
- RCW79 (Bonne et al., 2023
- …

Diverse sources: 'Bubble in a bubble', bi-polar shells,… and cloud dispersal (e.g., RCW79 Bonne et al., 2023)

How do they connect? There are some hints: flat clouds e.g., Beaumont & Williams, 2010 and Kabanovic et al., 2022

The ‘Diamond Ring’ in Cygnus X:
Environment shapes evolution



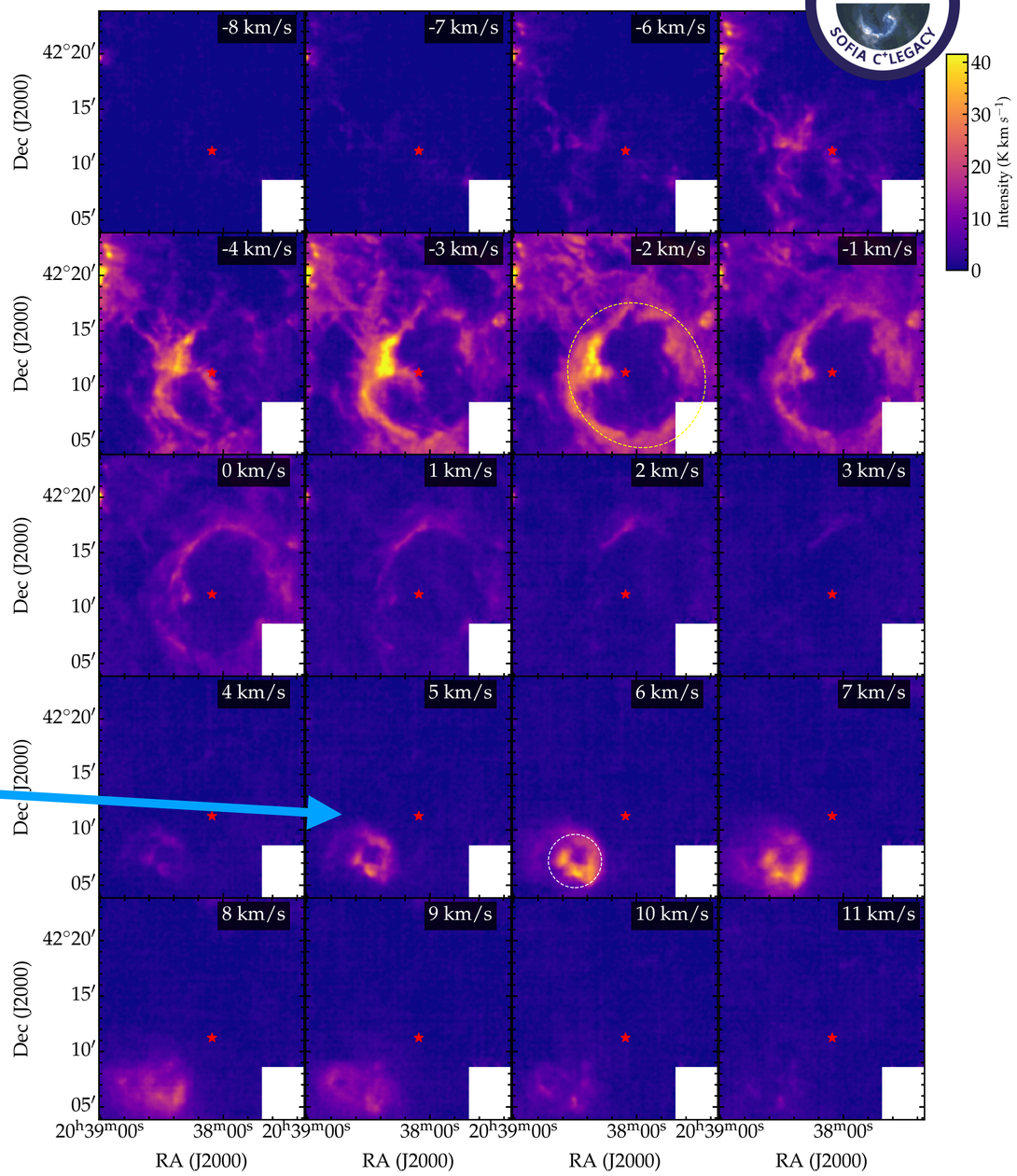
Herschel: 70µm/160µm/250µm
HOBYS program
(Schneider et al., 2021)

Dannhauer et al., in prep

The ‘Diamond Ring’ in Cygnus X:
Environment shapes evolution

A ring in [CII] emission, shows only slow *radial* expansion, no shell structure as typically observed

- Ring mass ~1061$M_\odot$, v_{radial}~1.3 km s^{-1}
- Ionising source B0.5Ve star, as determined by our spectroscopy
- Associated HII region
- ‘Diamond’ (Cluster 13) just a LOS effect
- Final stage of a former bubble

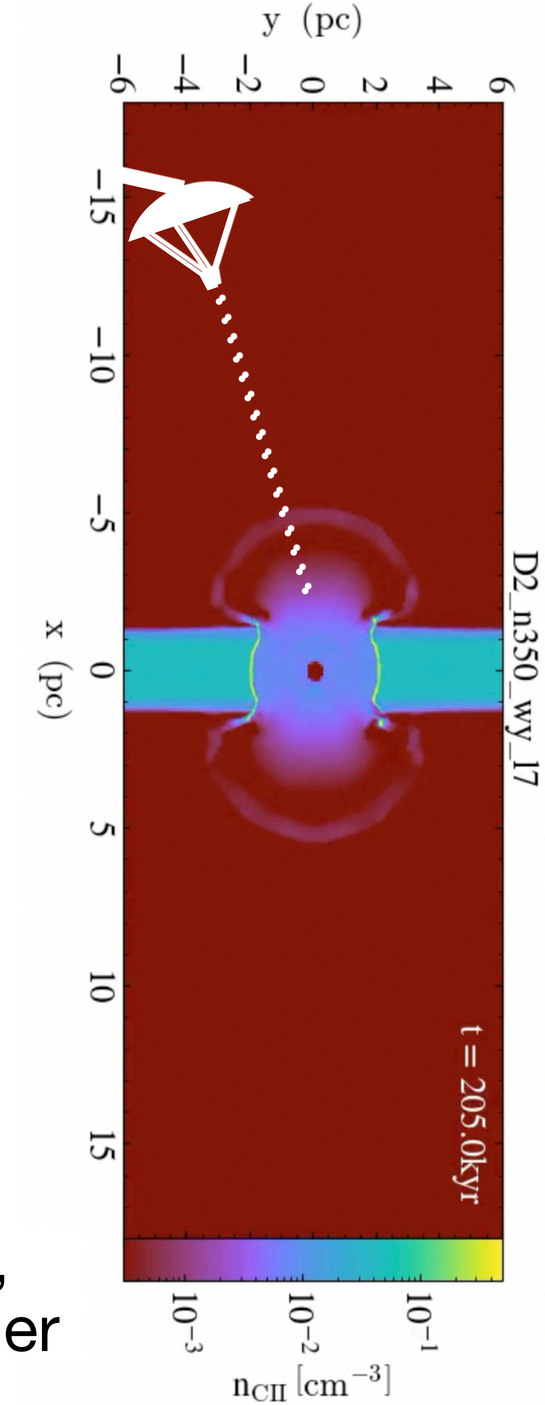


Dannhauer et al., in prep

The ‘Diamond Ring’ in Cygnus X:
Environment shapes evolution

Dynamics, morphology, [CII] intensity and HII region pressure can be reproduced by ionising feedback of a B0.5 star in a molecular *sheet*

- Idealised (no B-field, no turbulence) simulations
- Observations best explained by ~2 pc thick slab, nH=350 cm^{-3}
- Cloud dispersion taking over after ~100 kyr
- High velocity shell remains below our detection limit (synthetic observations)

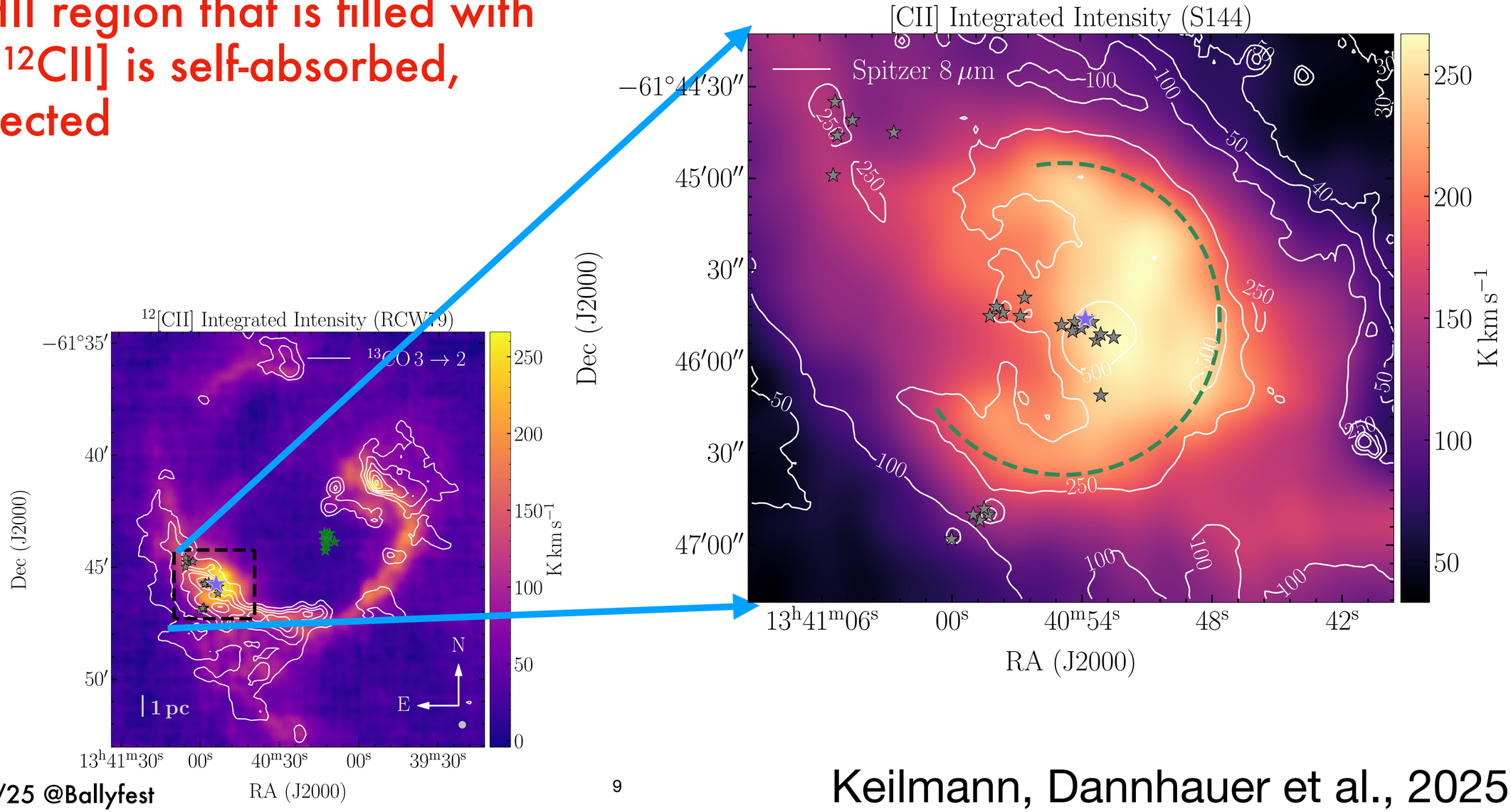


Dannhauer et al., in prep

Simulations by Sebastian Vider, group of Stefanie Walch-Gassner

[CII]/FIR deficit by [CII] self-absorption
A bubble (S144) in a bubble (RCW79)

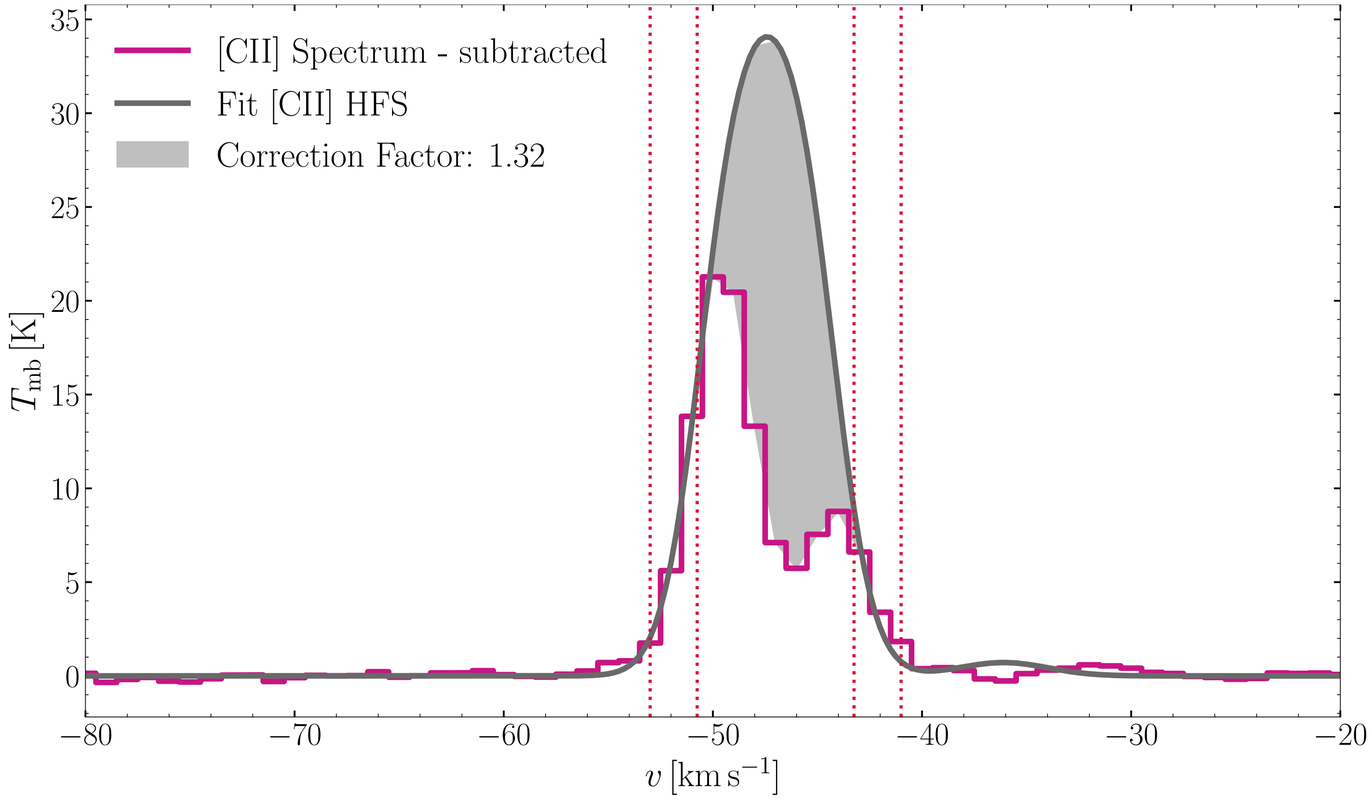
S144 is a cHII region that is filled with C^+ and the [^{12}CII] is self-absorbed, [^{13}CII] is detected

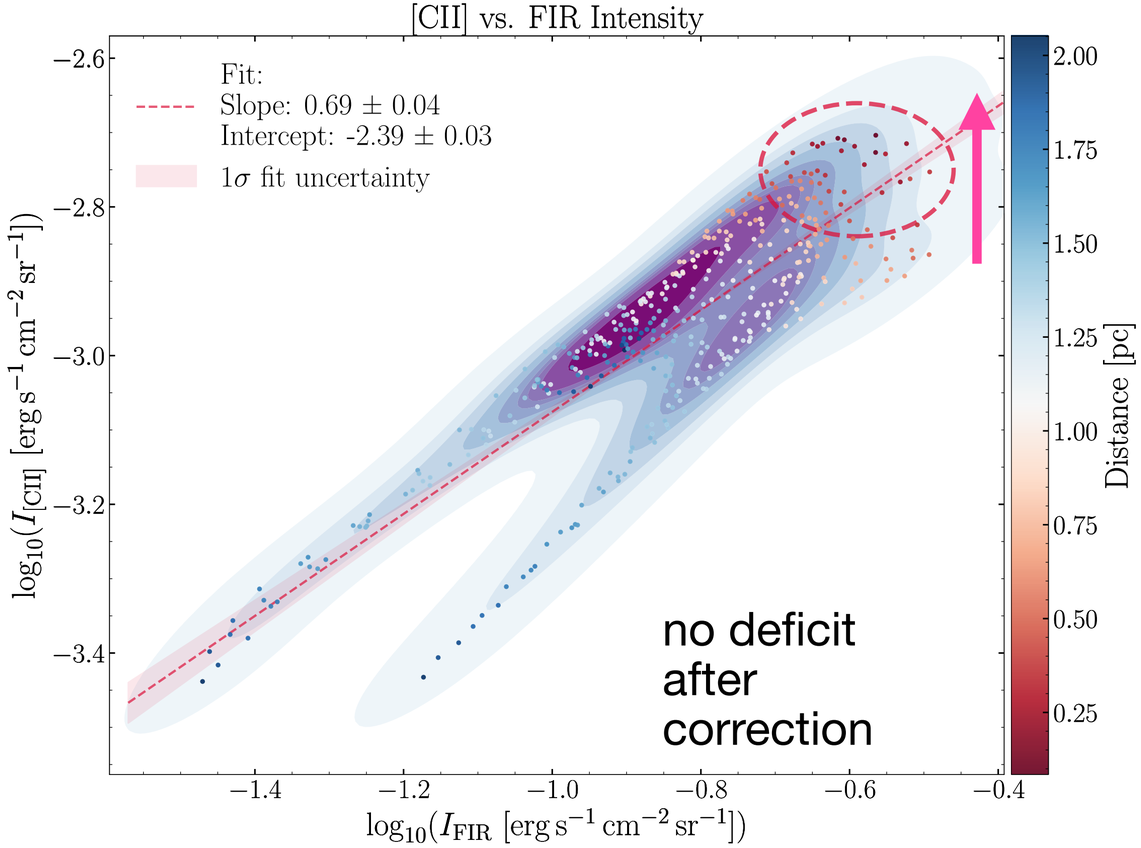


Keilmann, Dannhauer et al., 2025

[CII]/FIR deficit by [CII] self-absorption
A bubble (S144) in a bubble (RCW79)

If we correct for the missing [CII] flux, the deficit vanishes in *this* early Galactic bubble





Keilmann, Dannhauer et al., 2025

for the details see poster by Eduard Keilmann!

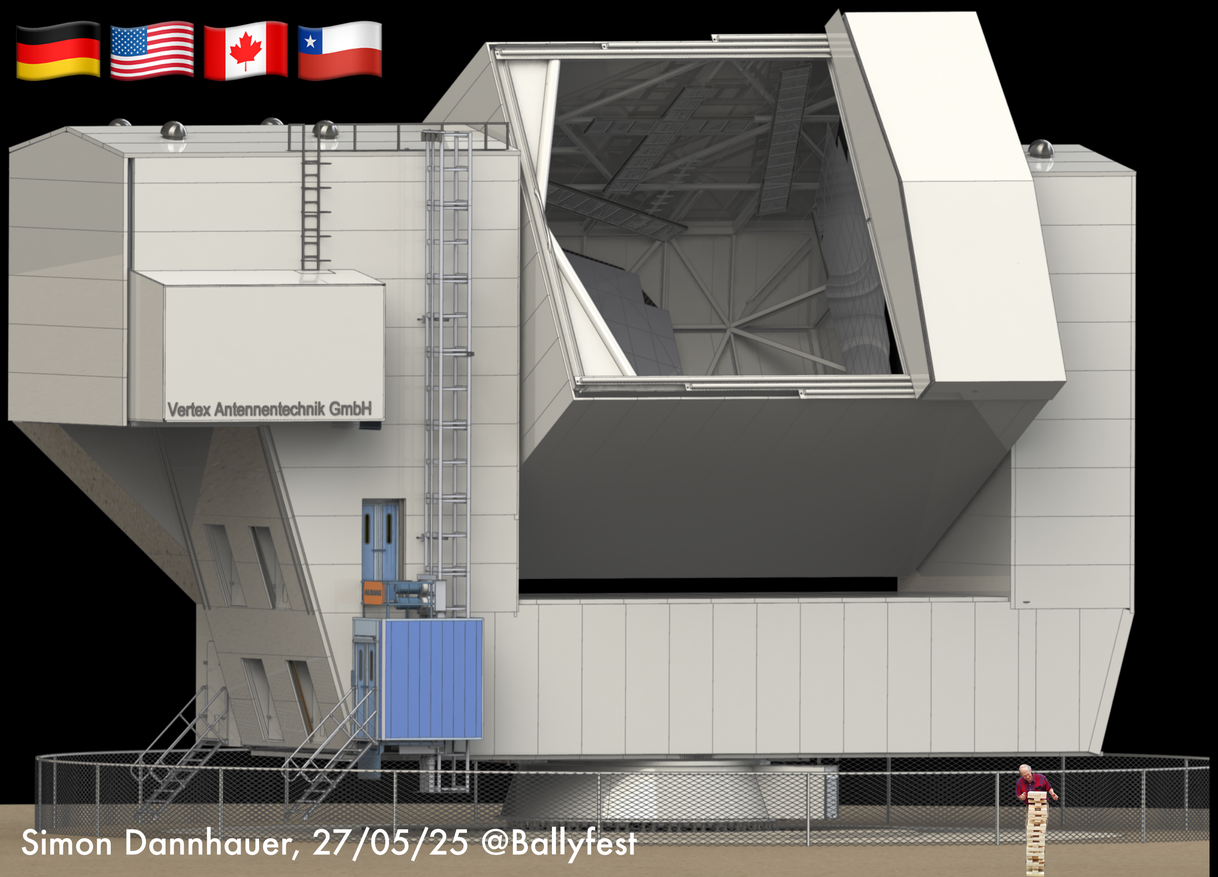
Next steps

- Establish an **evolutionary sequence** of [CII] bubbles
- Quantify the coupling of FUV radiation to interstellar gas, determine the **photoelectric heating efficiency** of atomic and molecular carbon
- Investigate **[CII]-FIR deficit** in further bubbles
- How good is [CII] as a **star-formation tracer?**
- **'Triggered star-formation'**, CO, [CII] linewidths and velocity gradients
- **[OI] 63µm,** at 6" it allows connection to smaller scales
- **[CII] vs CRRLs** (SKAO pathfinder)
- **[CII] vs [CI]** (CCAT/FYST synergies)

CCAT/FYST Galactic Ecology* (GEco)

**a term coined by John Bally*

PI: R. Simon



- Fred Young Submilimeter Telescope
- Summit of Cerro Chajnantor (5600m, Chile)
- Large FOV, survey instrument
- First light in Q1 2026
- One of the Key Science Projects: *GEco survey*
- CO (4-3), [CI] (1-0) @~26” and CO (7-6), [CI] (2-1) @~15”
- Highly complementary to *FEEDBACK*

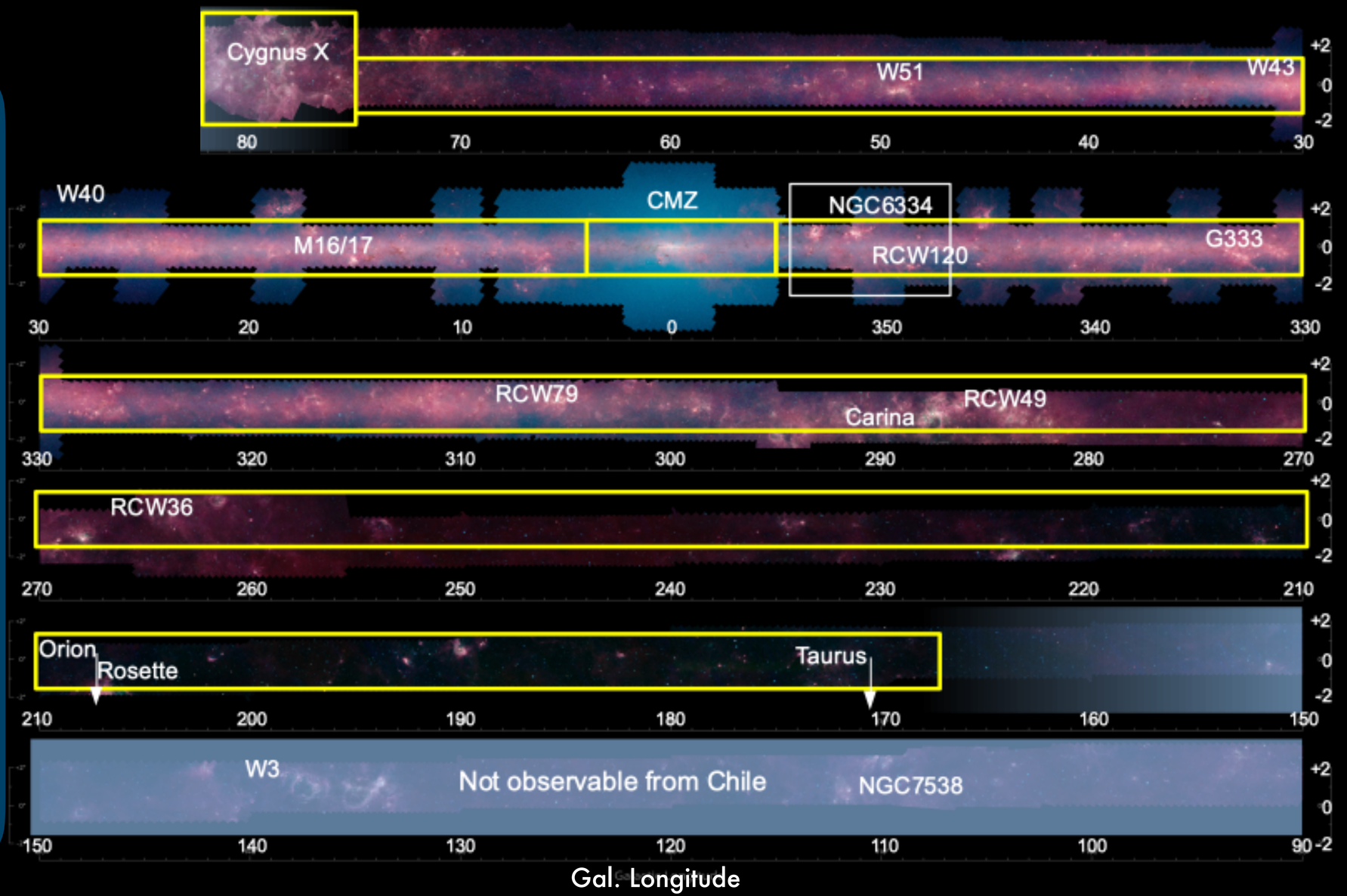
FYST Galactic Ecology* (GEco)

**a term coined by John Bally*

PI: R. Simon

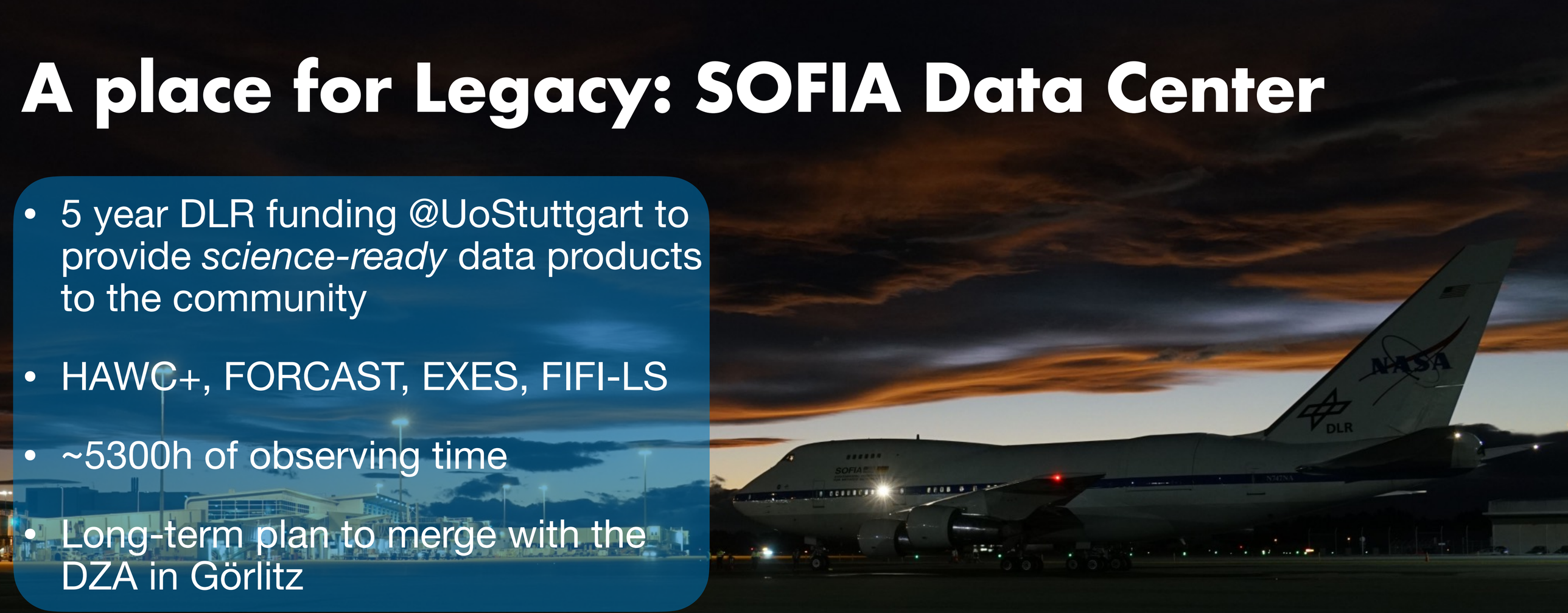
Science Topics:

- cloud and dense structure formation
- stellar feedback
- carbon budget, CO-dark gas
- extended to nearby galaxies (low Z), gal. low-mass SF regions



A place for Legacy: SOFIA Data Center

- 5 year DLR funding @UoStuttgart to provide *science-ready* data products to the community
- HAWC+, FORCAST, EXES, FIFI-LS
- ~5300h of observing time
- Long-term plan to merge with the DZA in Görlitz



… and don't forget GREAT support at UoC!

Universität Stuttgart

DLR

SDC SOFIA DATA Center

Image Credit: Greg Perryman/USRA

Take-home messages

- stellar feedback and cloud formation must be understood together
- still lots of work to be done!
- current efforts aimed at providing science-ready [CII] data to the community, bridging the gap until new instruments come available
- CCAT/FYST will provide additional complementary lines for large regions

Thank you for your attention.

dannhauer@ph1.uni-koeln.de