The Dynamics and Mass Ejection in RCW 36

L. Bonne

SOFIA Tele-Talk

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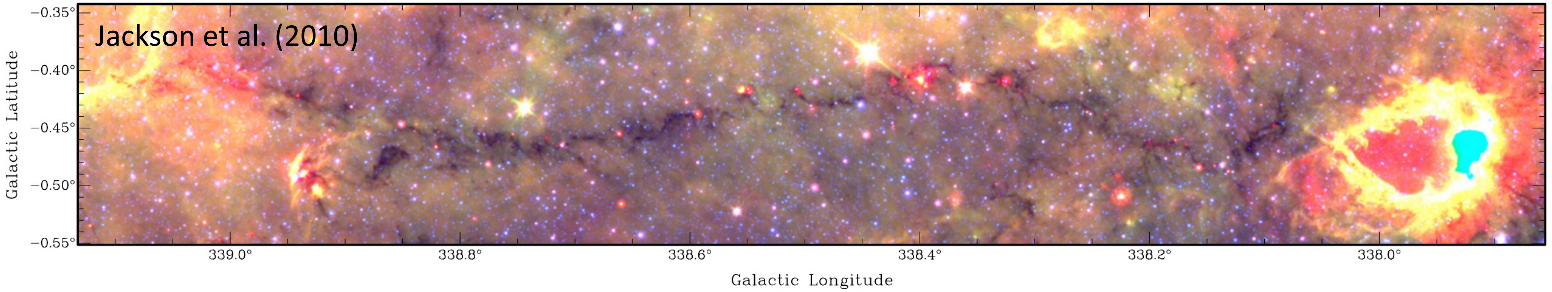
With many thanks to: N. Schneider, P. García, A. Tielens, R. Simon, A. Bij, L. Fissel, L. Townsley, P. Broos, J. Jackson, R. Guesten, A. Zavagno and the FEEDBACK team

Feedback in molecular clouds

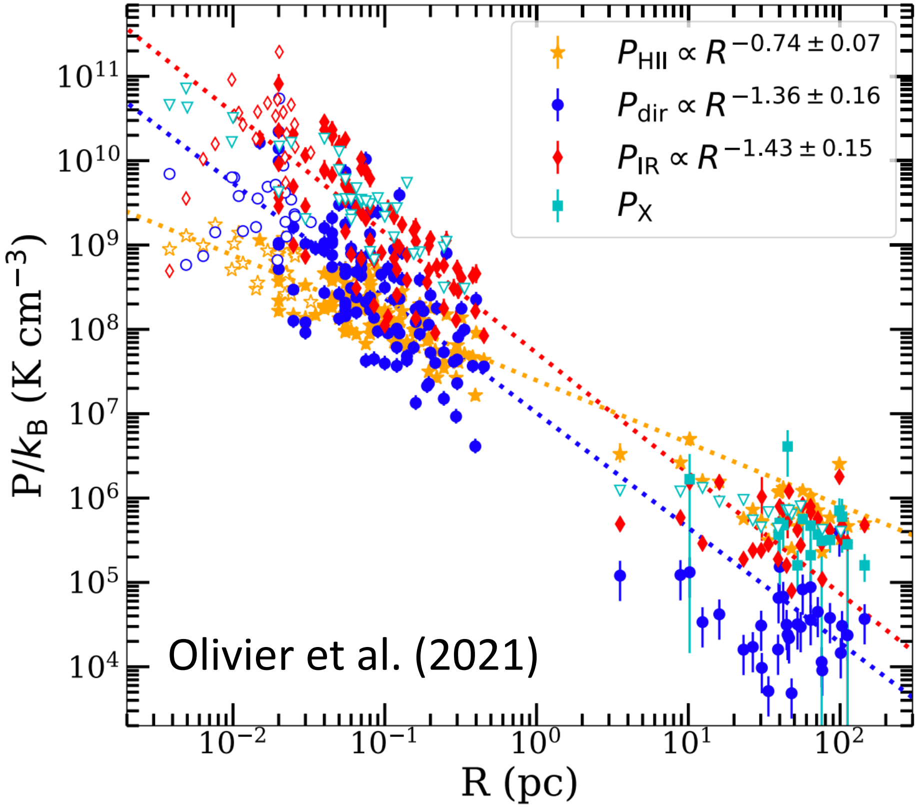
- Stellar feedback shapes the interstellar medium (ISM) (e.g. Churchwell et. 2006)
- Drives galactic and molecular cloud evolution
  - Quasi-static or rapid molecular cloud evolution? (e.g. Shu et al. 1987; Elmegreen 2000)



Feedback in molecular clouds

- ➢ Which feedback mechanism drives the expansion of HII regions?

- ➢ Many uncertainties
  - Stellar models?
  - Hot plasma dissipation?
  - Leakage?
  - Filling factors?

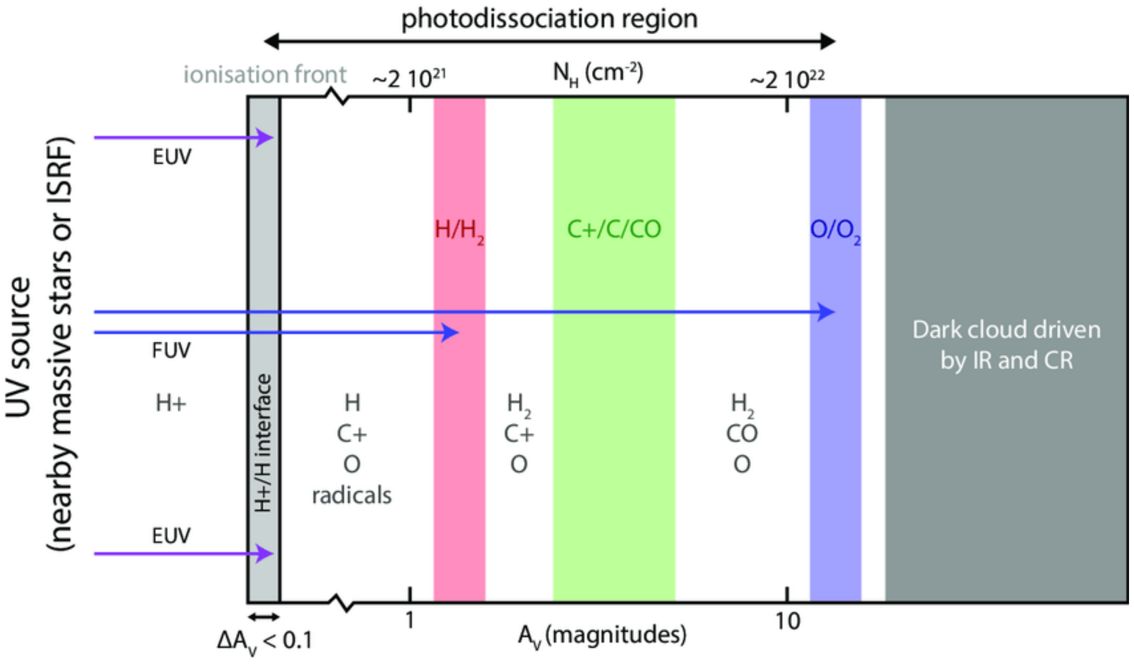


Olivier et al. (2021)

The FEEDBACK legacy program

- ➢ Large upGREAT spectral data cubes (Schneider et al. 2020)
  - [CII] at 158 µm and [OI] at 63 µm
  - Traces photodissociation regions (PDRs)
  - High spectral resolution (R > 1 000 000)

- ➢ 11 high-mass star forming regions
  - Diverse regions
  - Complementary data: $^{12/13}$CO, Herschel, Chandra,…

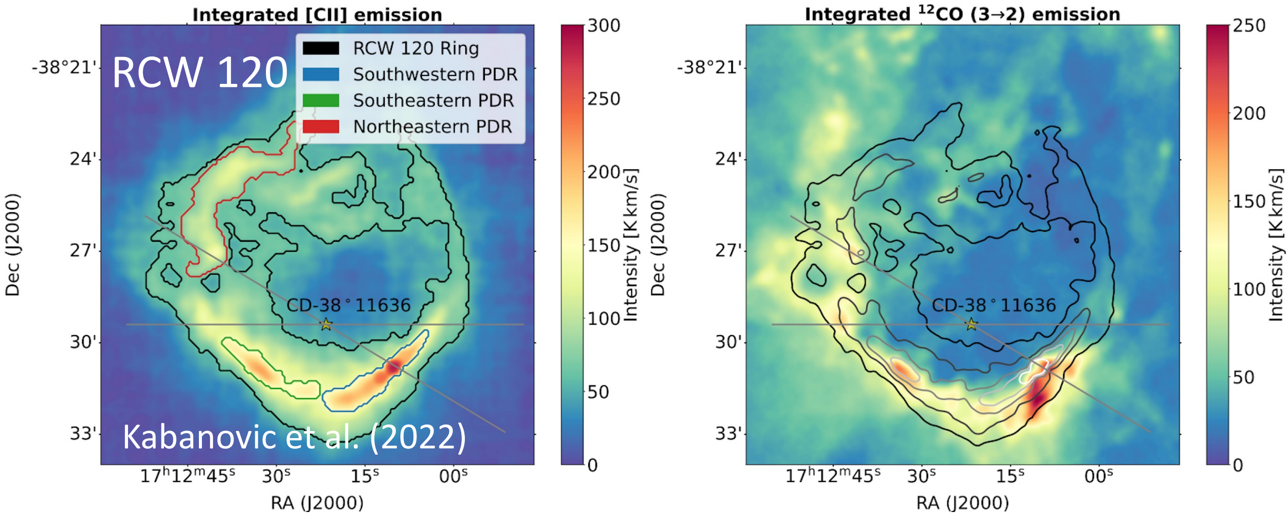


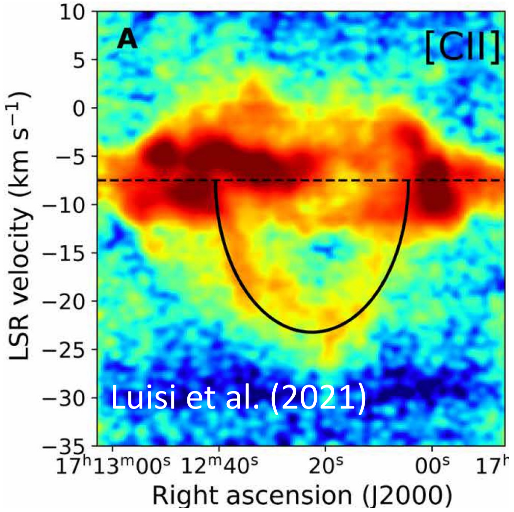
Outline

- The first FEEDBACK results
- Introduce RCW 36 and the observed dynamics
- Magnetic field observations
- Which feedback mechanisms drive the observed dynamics?

Early FEEDBACK results

- ➢High-velocity expanding shells (Luisi et al. 2021; Tiwari et al. 2021; Beuther et al. 2022)
- ➢[CII] self-absorption (Kabanovic et al. 2022)
- ➢Expansion in a sheet (Kabanovic et al. 2022)
- ➢PDR modeling (Tiwari et al. 2022)





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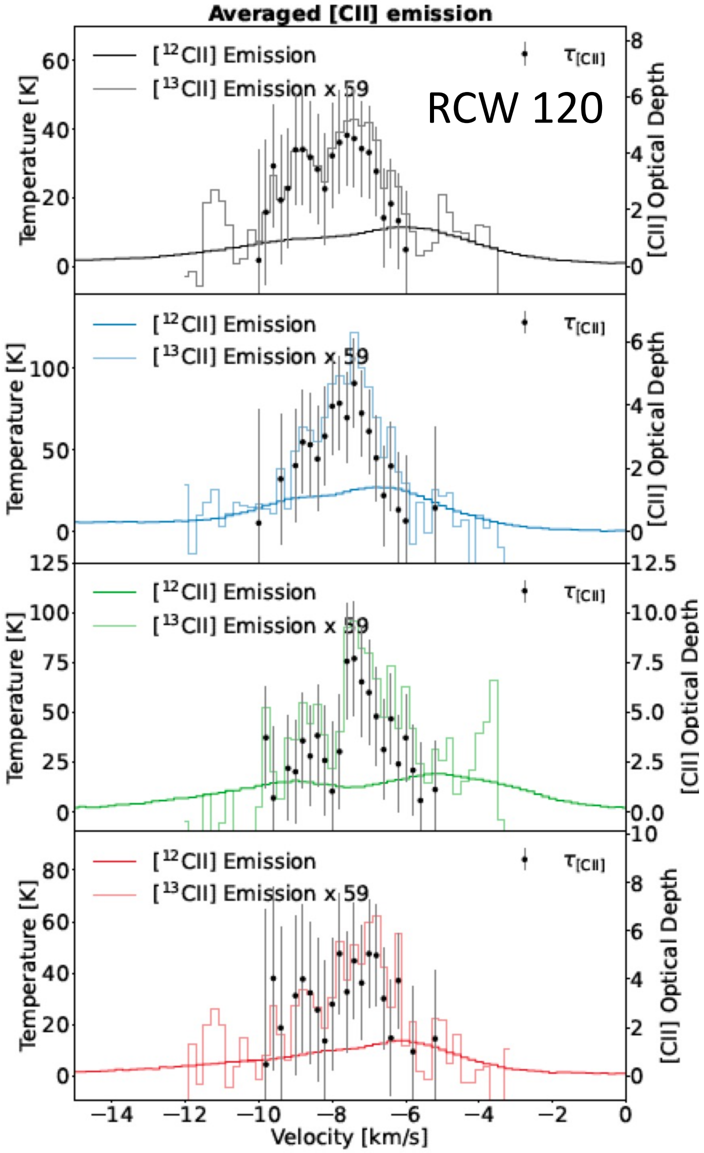

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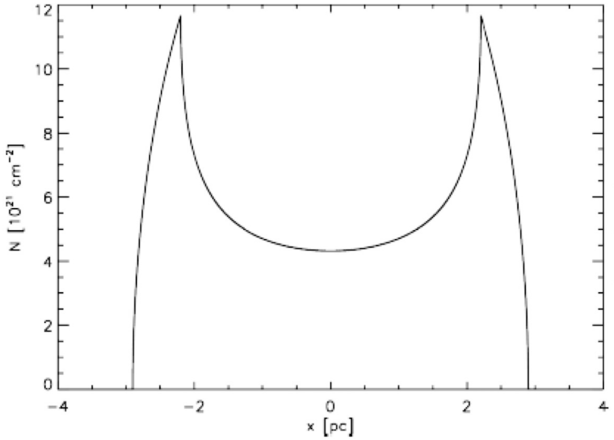

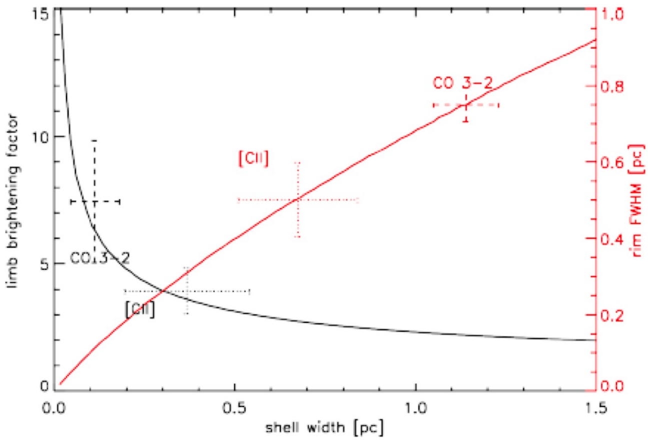

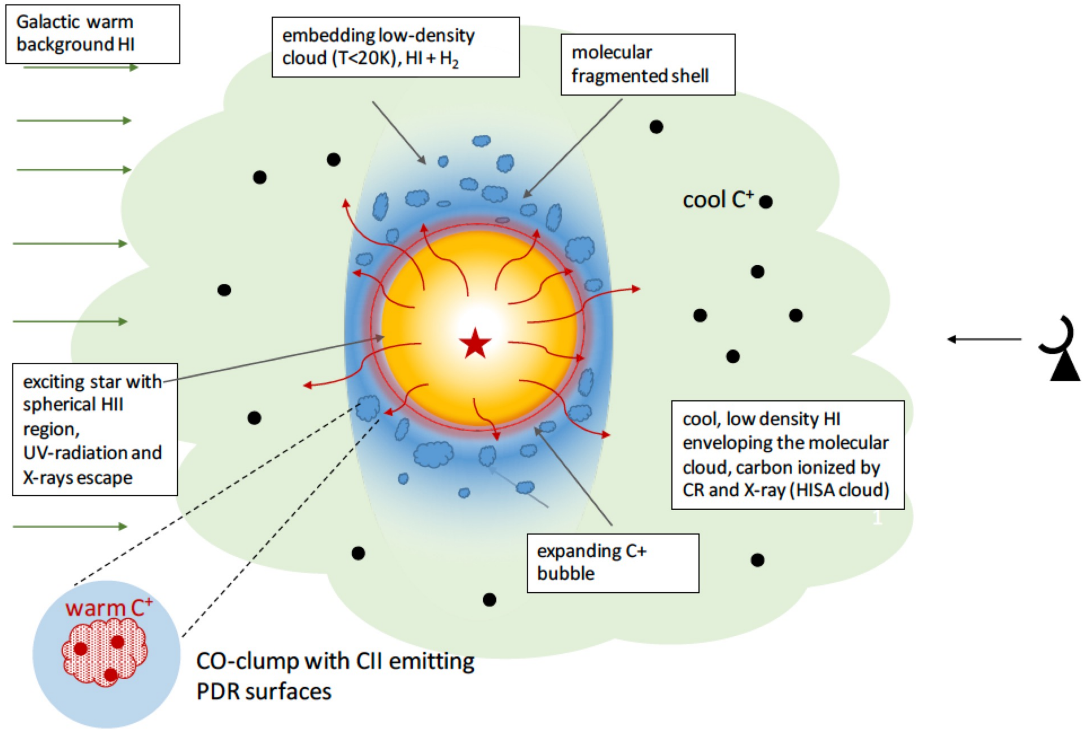

Galactic warm background HI

embedding low-density cloud (T<20K), HI + H_2

molecular fragmented shell

cool C^+

exciting star with spherical HII region, UV-radiation and X-rays escape

cool, low density HI enveloping the molecular cloud, carbon ionized by CR and X-ray (HISA cloud)

expanding C+ bubble

warm C^+

CO-clump with CII emitting PDR surfaces

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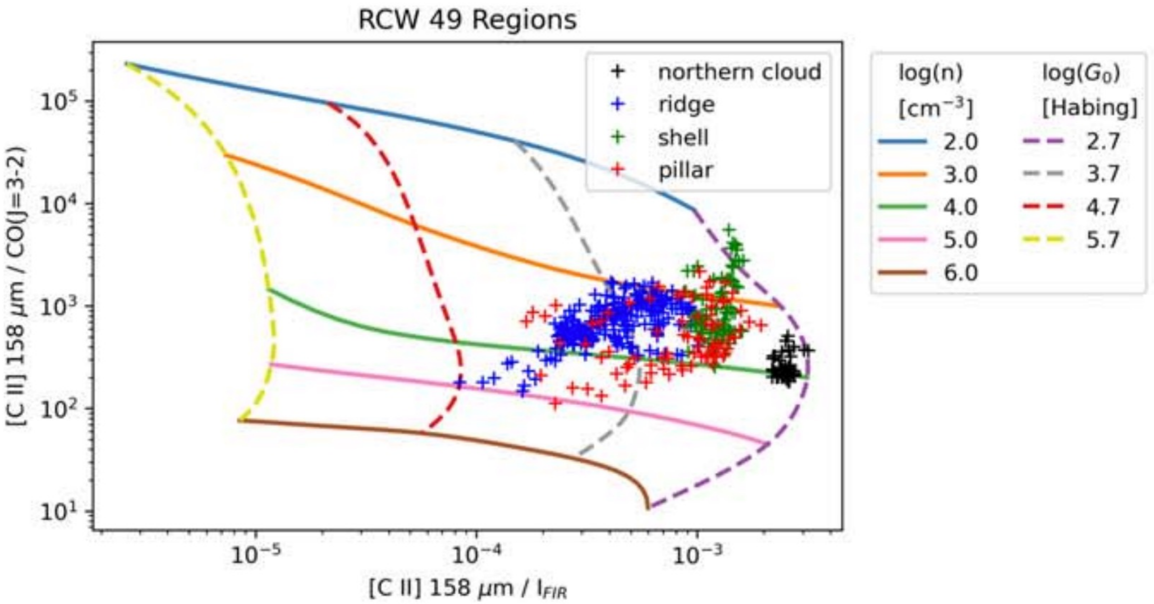
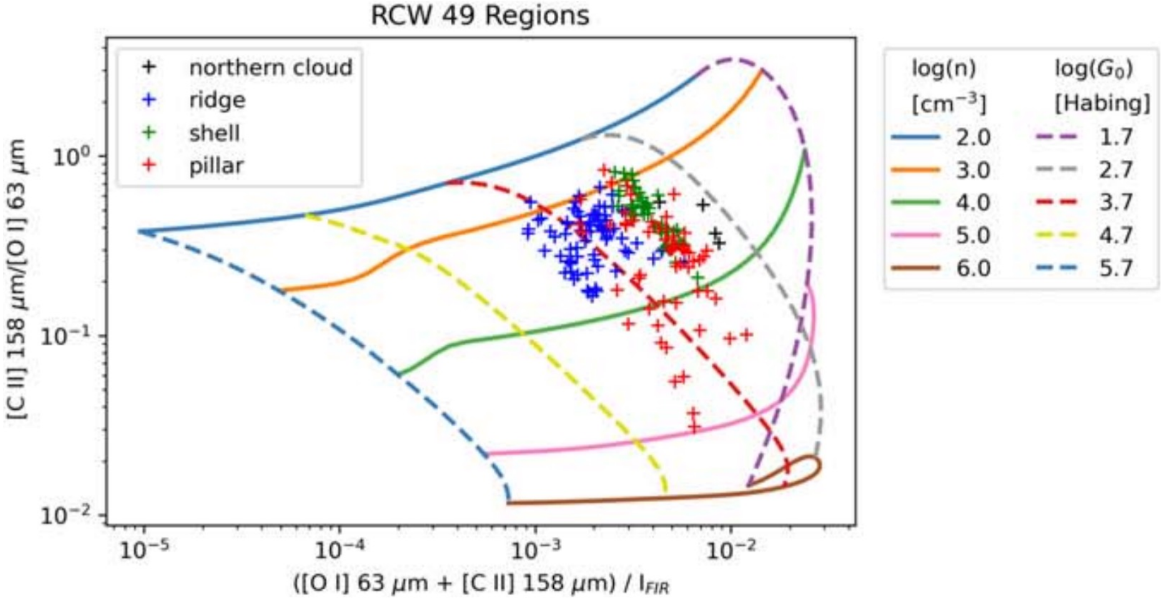
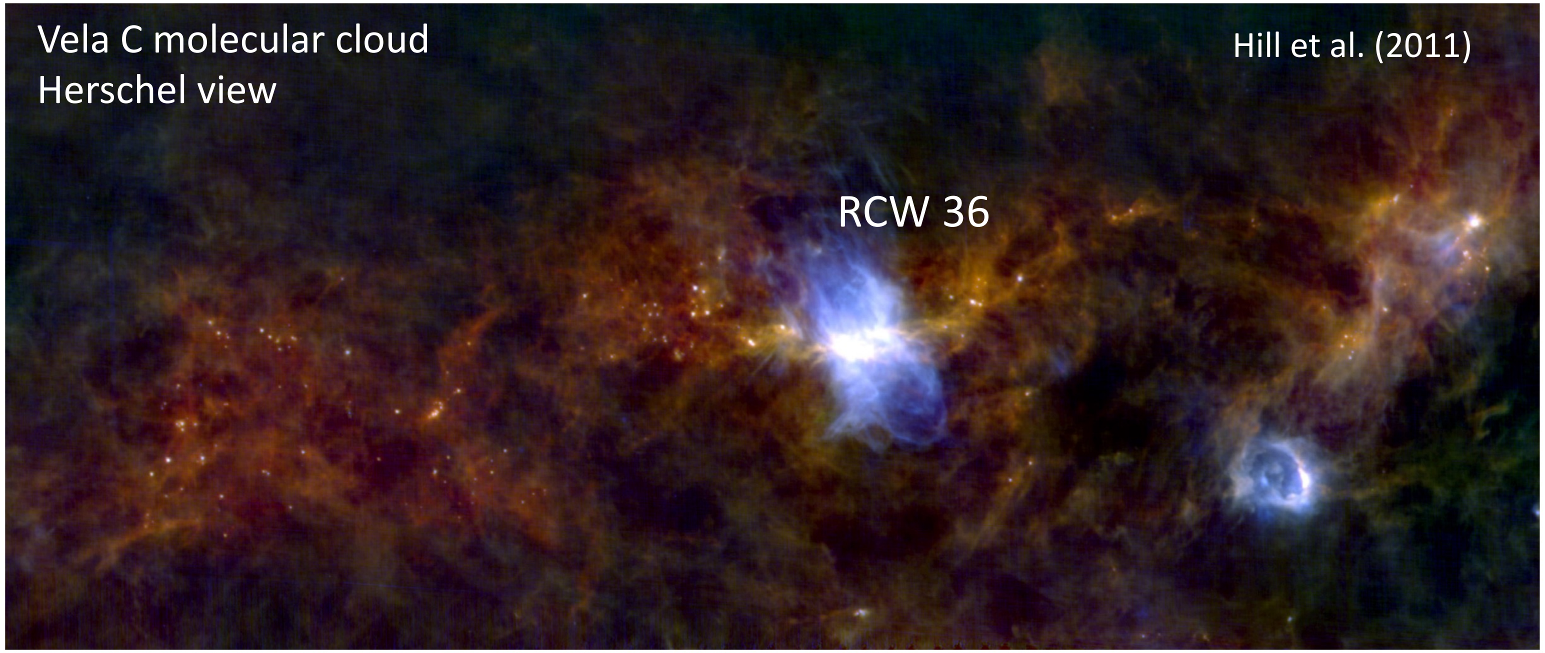
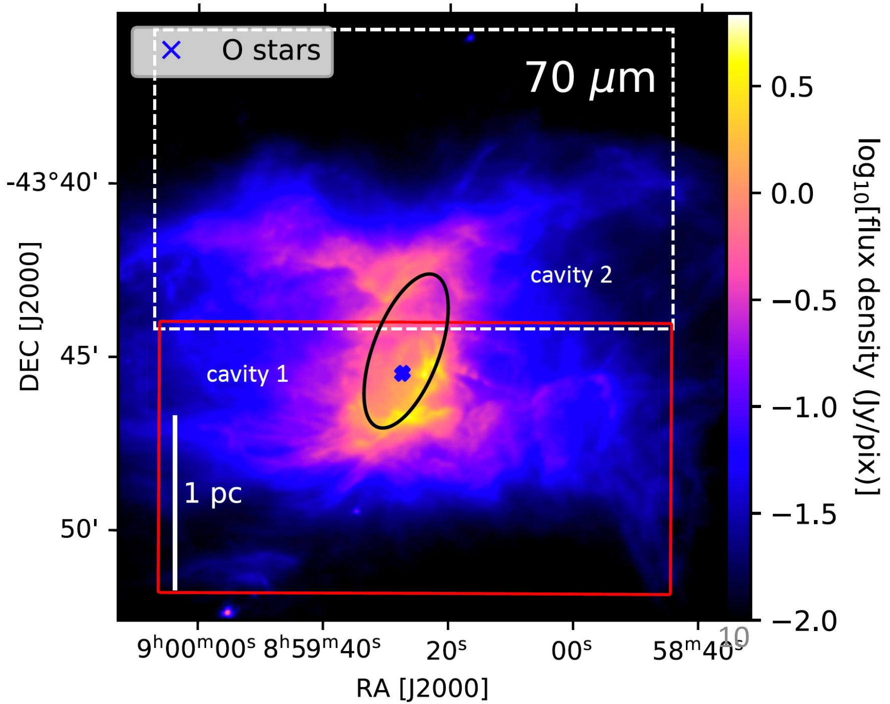




RCW 36 in the Vela C molecular cloud

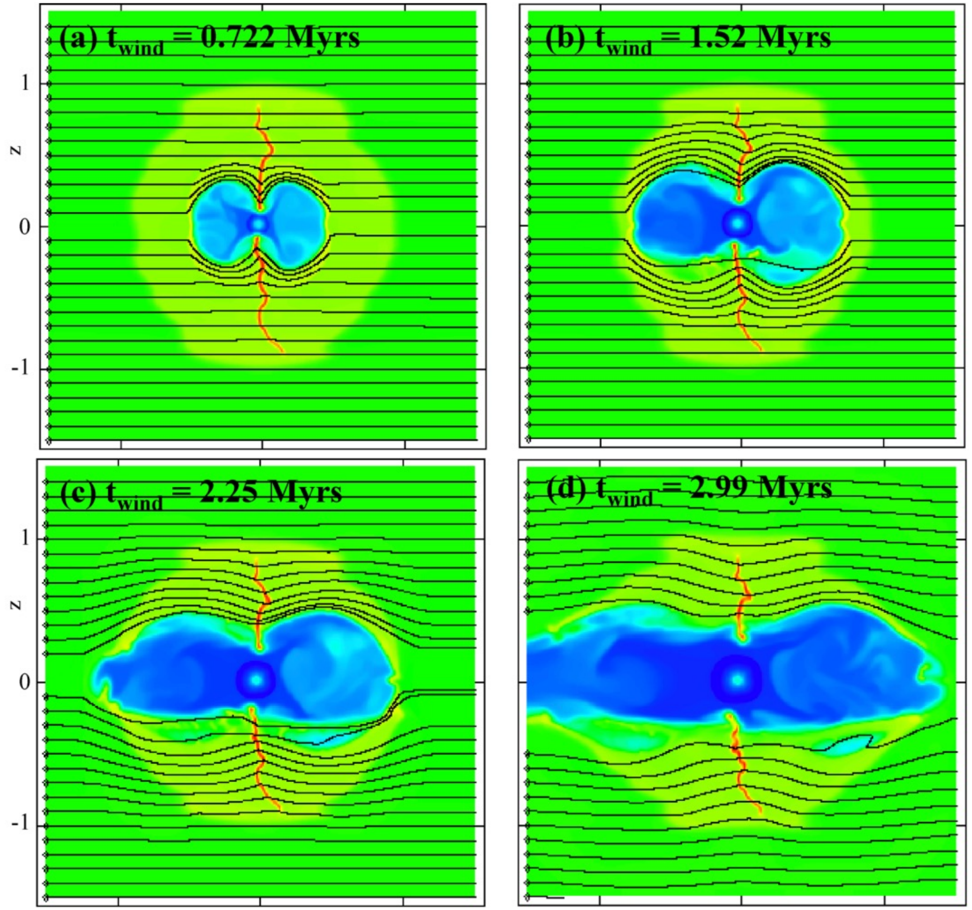
- RCW 36: A bipolar HII region
  - Distance: 900 – 950 pc (Zucker et al. 2020)
  - 1.1 ± 0.6 Myr old OB cluster (Ellerbroek et al. 2013)
  - A dense molecular ring and bipolar cavities





Bipolar HII regions

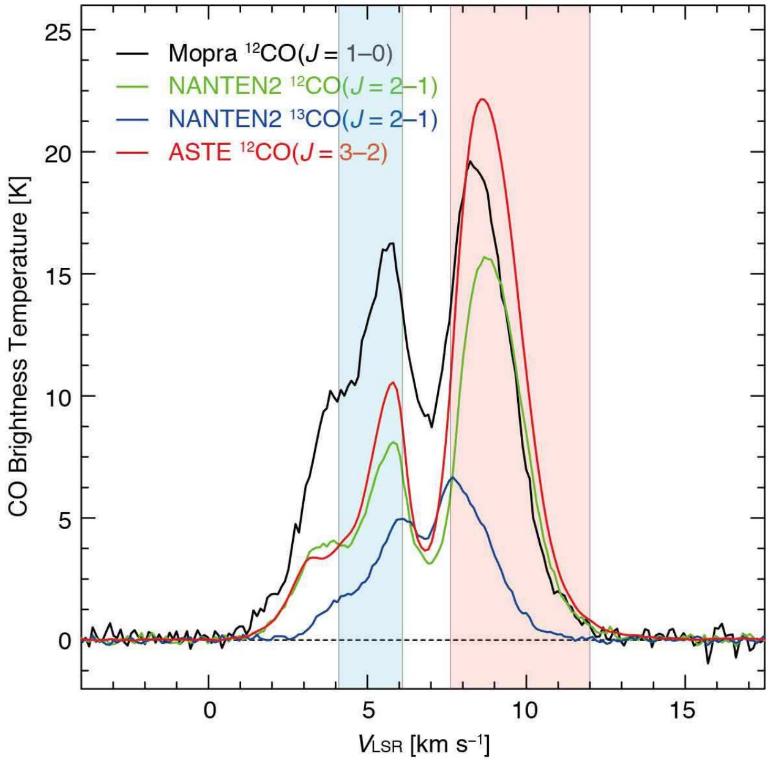
- ➢Bipolar HII regions are rare (Samal et al. 2018)
  - ≤ 10%
  - Projection effects?
- ➢Limited number of studies
  - Theoretical and observational
- ➢Generally proposed to form in a sheet (e.g. Bodenheimer et al. 1979)
  - Simulations: bipolar morphology remains over time (e.g. Wareing et al. 2017)



Wareing et al. (2017)

Proposed cloud-cloud collision in RCW 36

- RCW 36: Proposed to have formed in a cloud-cloud collision (Sano et al. 2018)



- Detailed investigation of higher density tracers raises questions (Fissel et al. 2019)

- [$^{(13)}$CII] unveils self-absorption
  - Raises further uncertainty on the proposed collision

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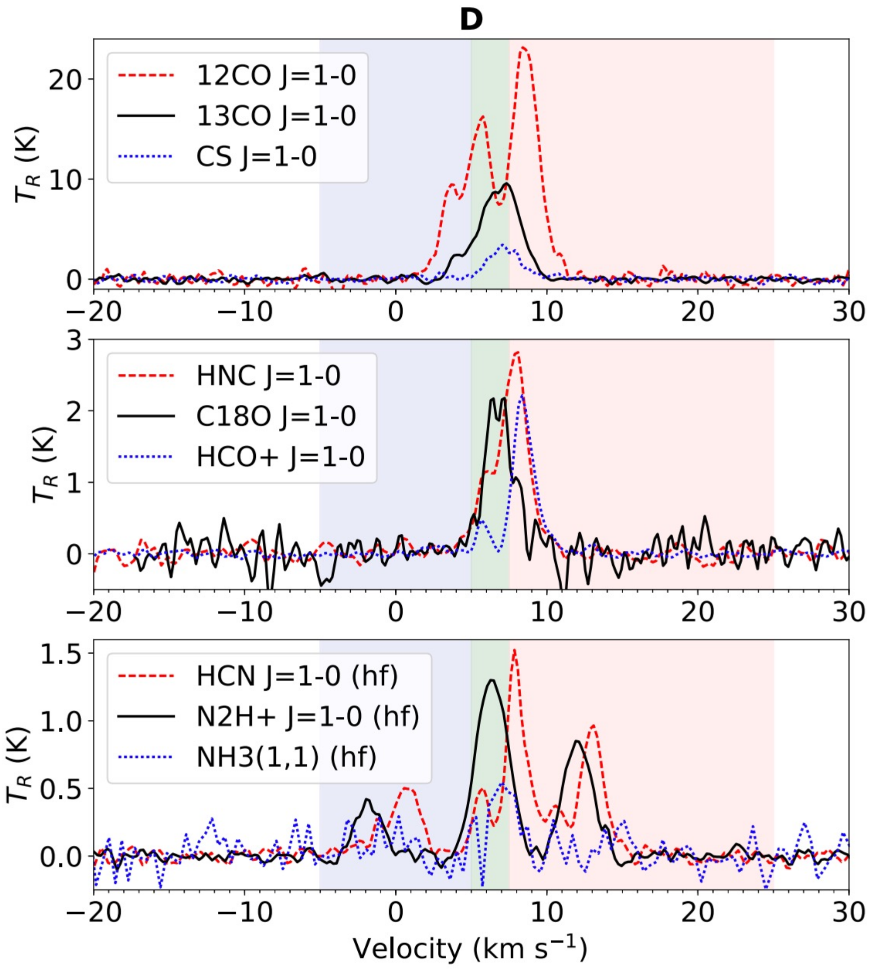

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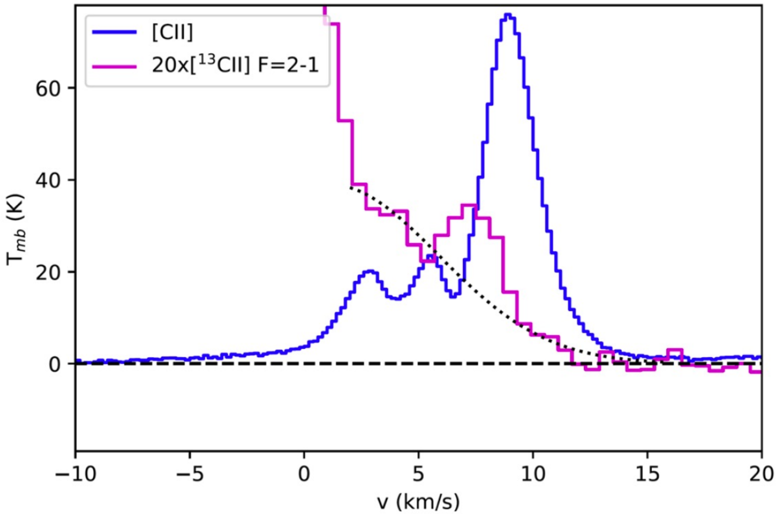
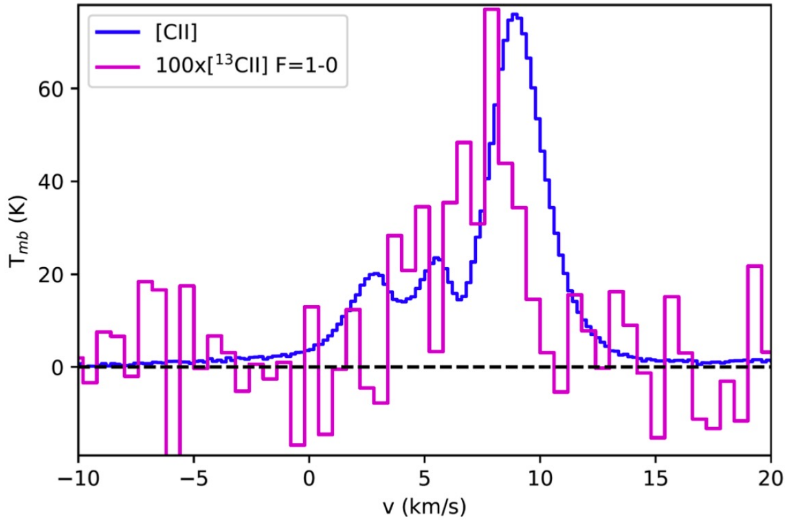
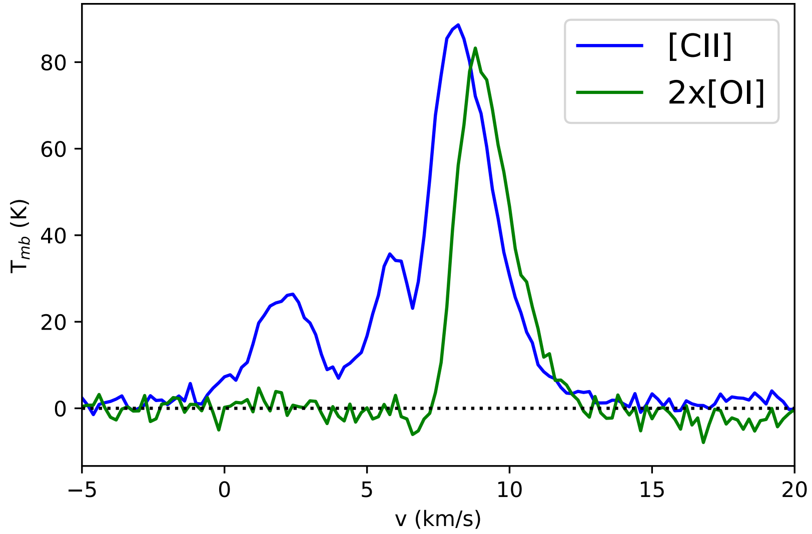
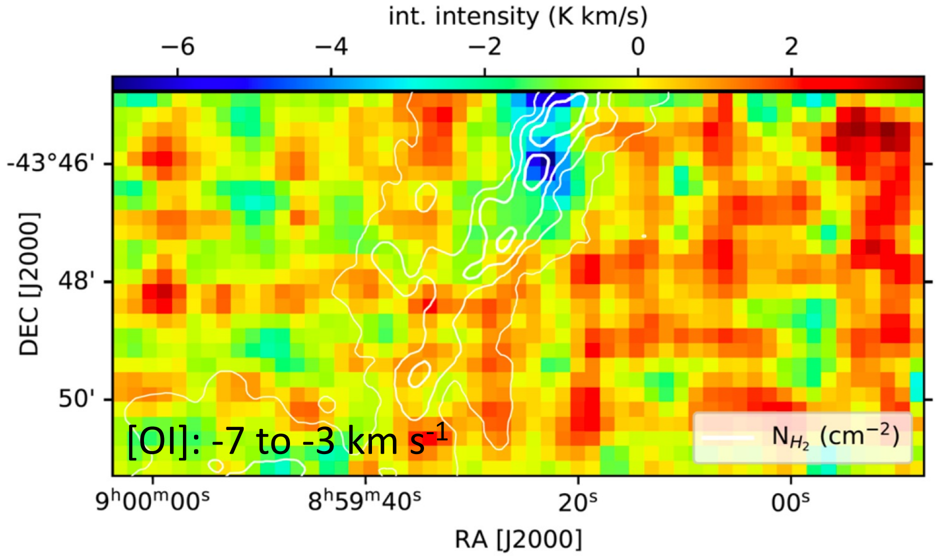




Indications of [OI] absorption

- [OI] also absorbed away
    - Appears to go below the baseline
- At 70 µm continuum and column density peak
- Creates a red asymmetry
    - Indicates expansion

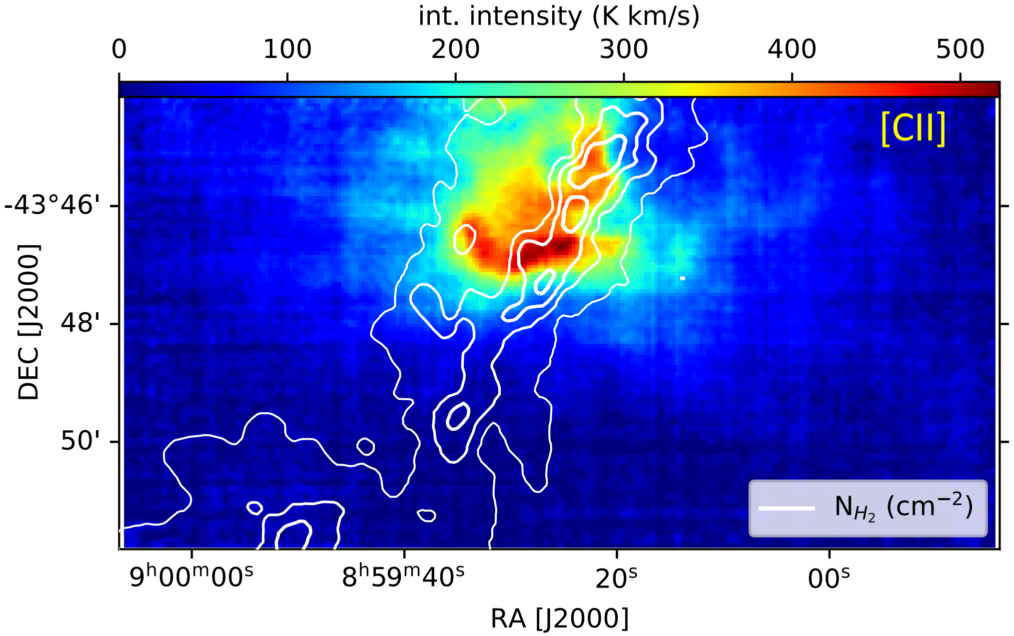


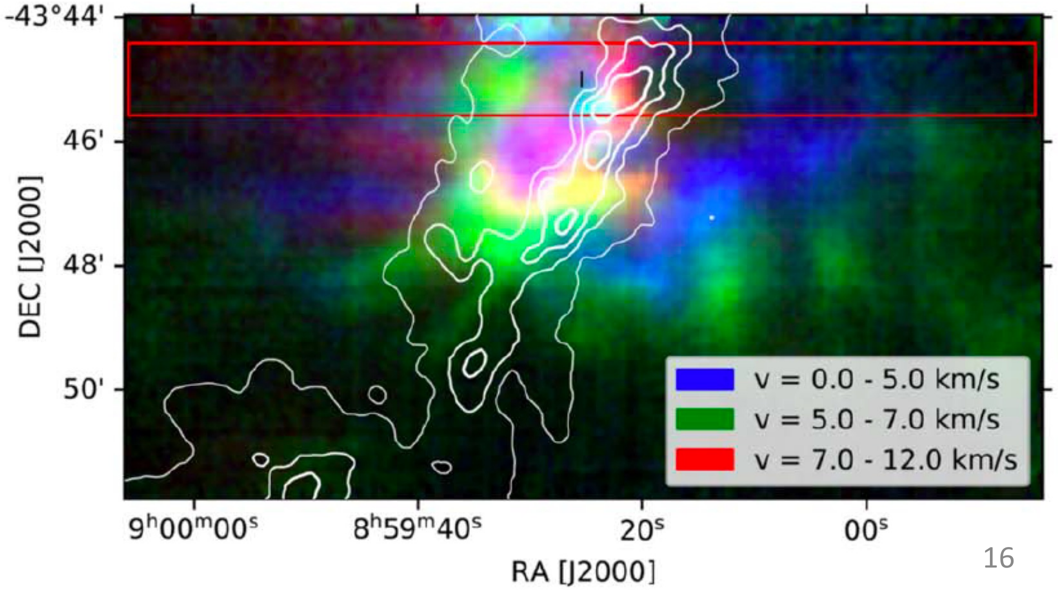


The [CII] map of RCW 36

- Bright [CII] emission in the molecular ring

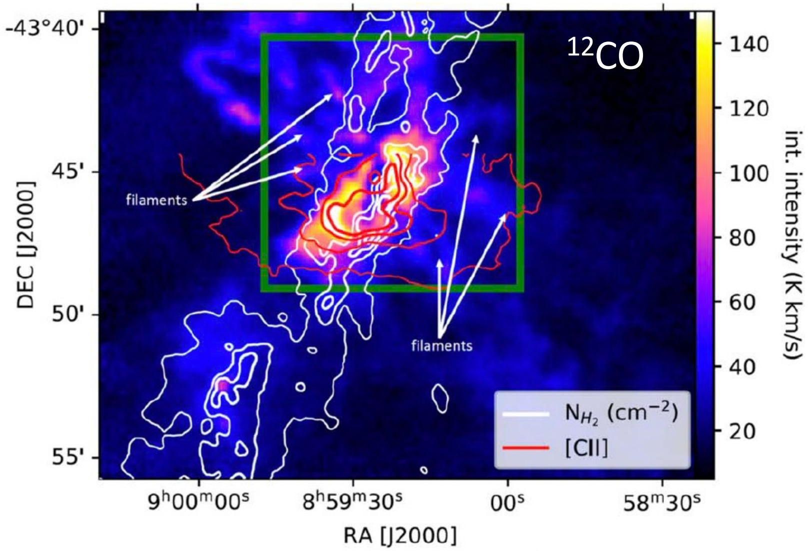
- Ring expands at 1-2 km s^{-1}
  - Also seen in molecular lines (Minier et al. 2013; Bij et al. in prep.)

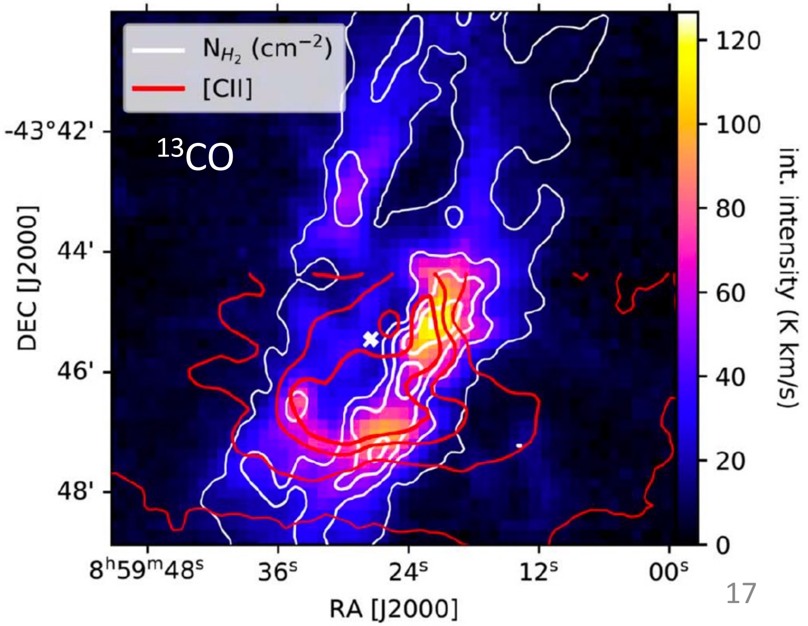




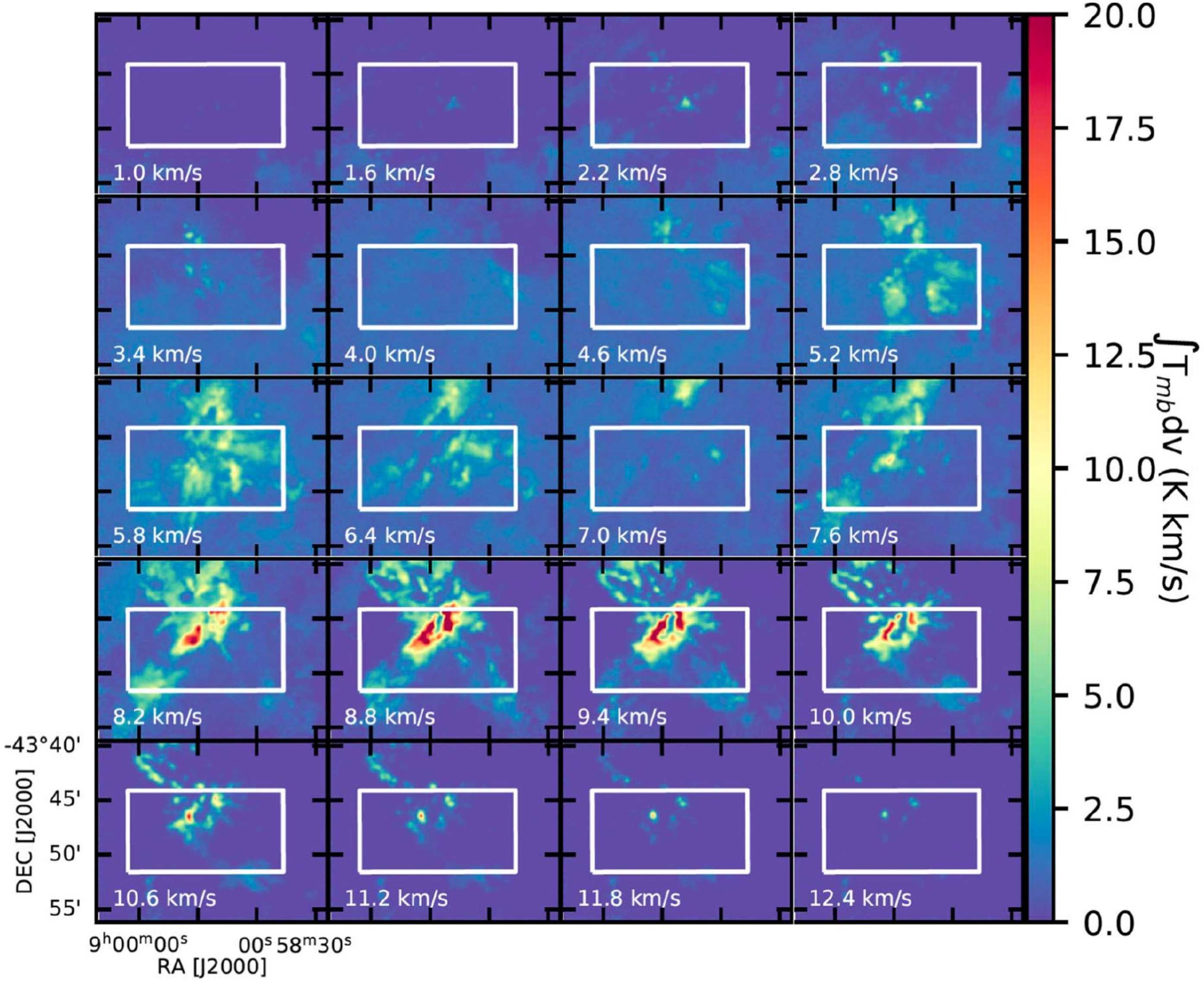
The $^{12/13}$CO map of RCW 36

- APEX observations of $^{12/13}$CO(3-2) with the LAsMA receiver
- ^{13}CO highlights the dense ring
- ^{12}CO highlights filamentary structures
    - Perpendicular to ring
    - Curved morphology





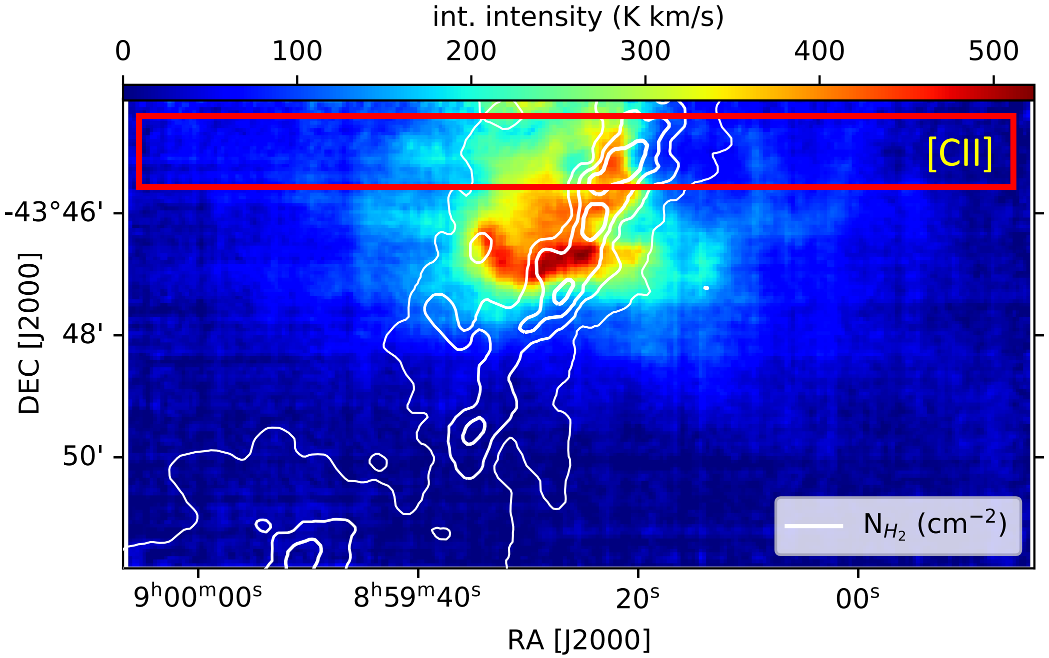
Filaments in ^{12}CO(3-2)

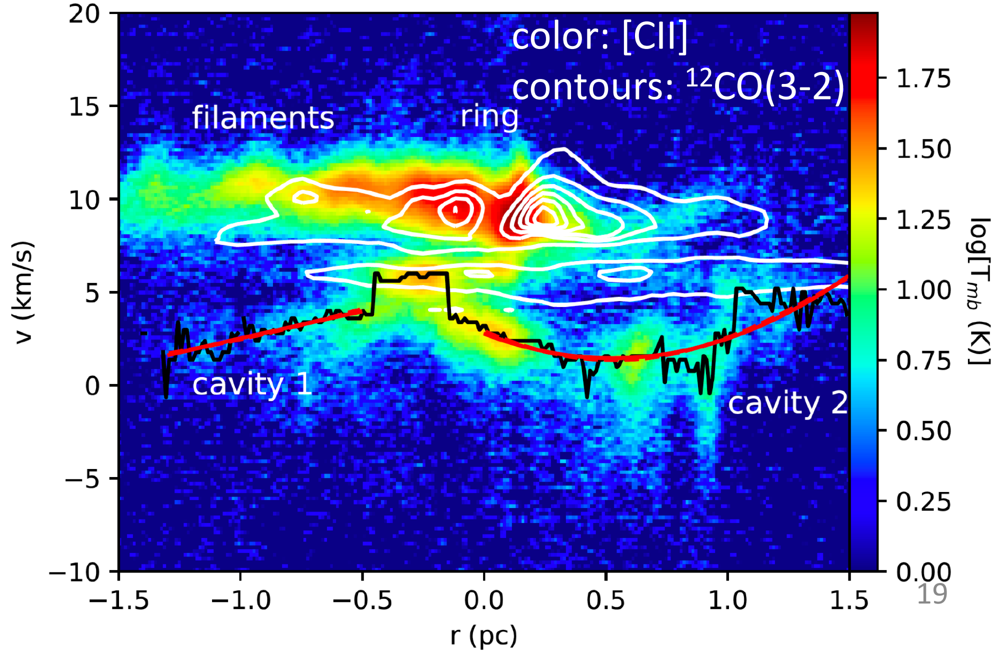


The dynamics of RCW 36 in [CII]

- [CII] emission: expanding shells in the cavity
  - Estimated expansion velocity: 5.2 ± 0.5 ± 0.5 km s^{-1}

- Short dynamic timescale ~0.2 Myr: lifetime of the cavities?

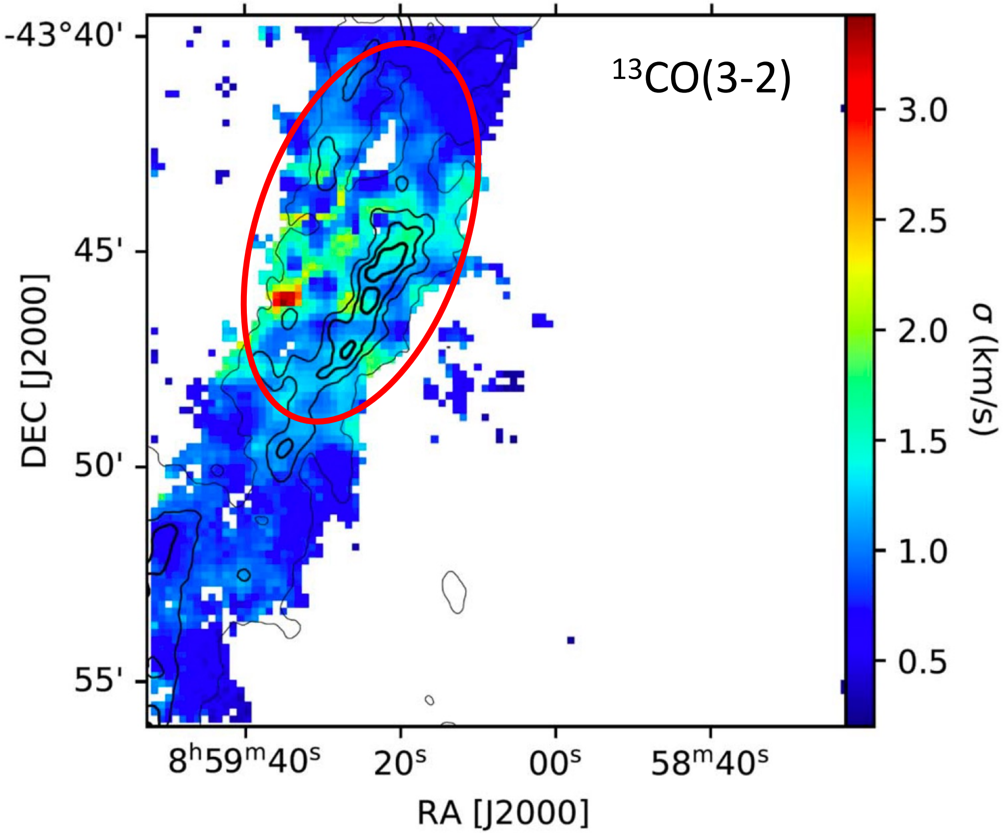




Turbulence in the ring

- Increased molecular linewidth in the ring
  - Some opacity effects, but minimal
  - Required energy injection rate: 2.4×10^{33} erg s^{-1}

- Might alter outcome of ongoing star formation activity
  - In competition with ring erosion

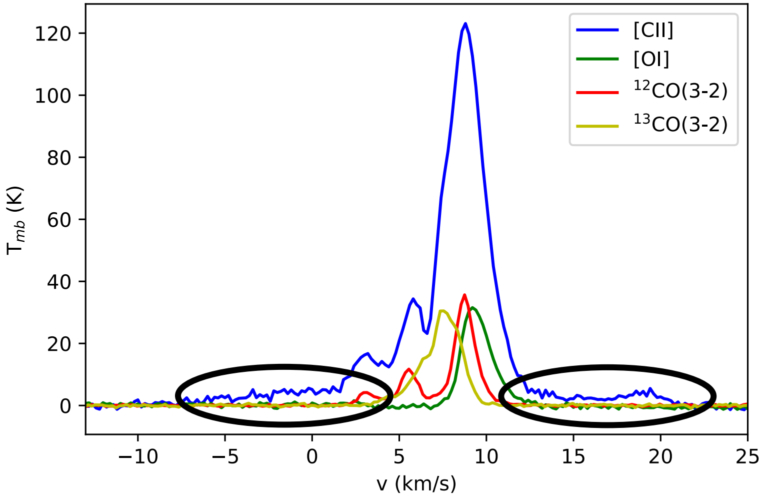


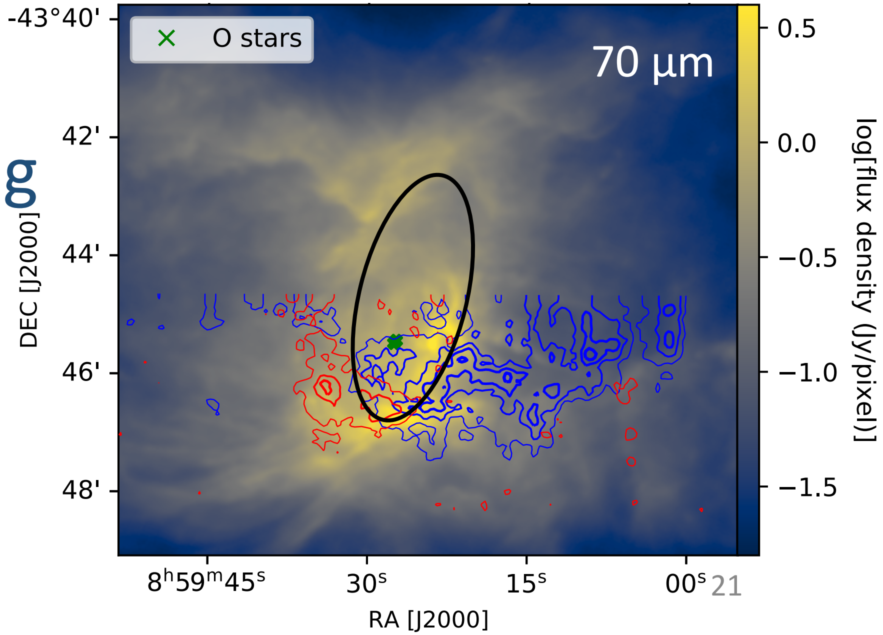
The [CII] high-velocity wings in RCW 36

- [CII] high-velocity wings: ~15 km s^{-1}
  - S/N > 10 in individual channel

- No evident shell morphology
  - No protostellar objects

- Bipolar mass ejection originating from the ring
  - Dynamic timescale < 0.1 Myr
  - Mass ejection rate: ~4-7x10^{-4} M$_{sun}$ yr^{-1}
  - Can disperse the dense ridge in ~1-2 Myr
  - Required energy rate: 1-1.6x10^{35} erg s^{-1}





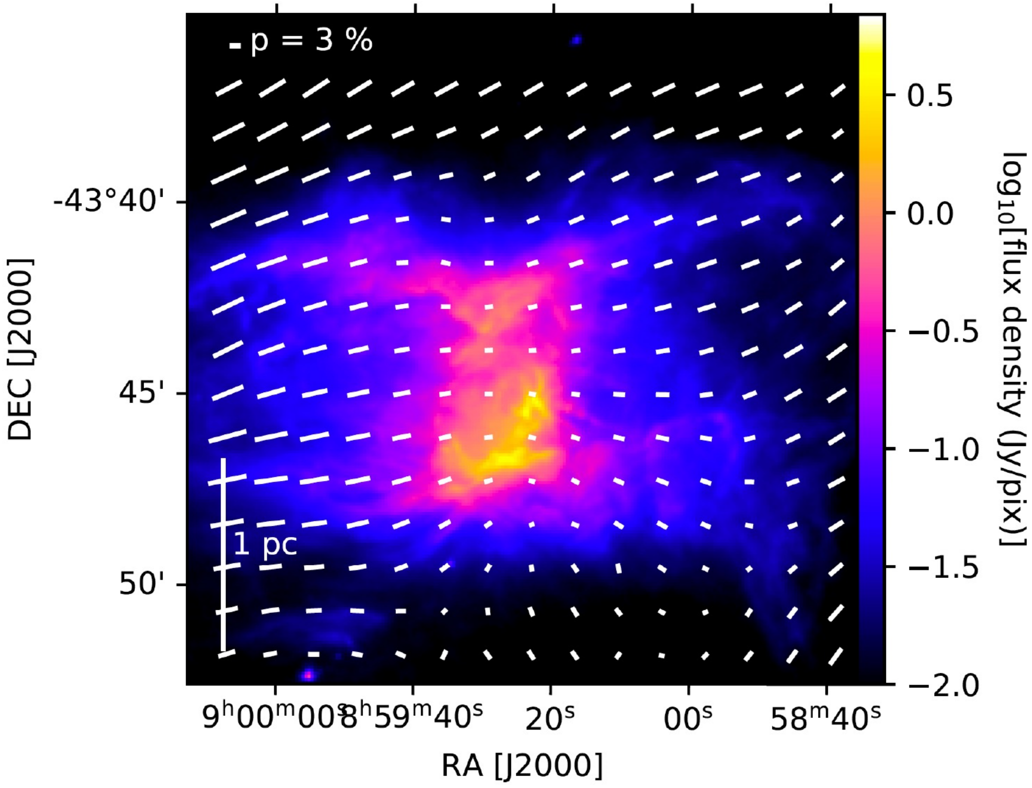
The magnetic field around RCW 36

- Magnetic field at 500 µm with BLASTPol
  - Perpendicular to the ring

- Curves along the cavities

- Sheet or magnetically favored direction?

70 µm + BLASTPol magnetic field (Fissel et al. 2016; 2019)

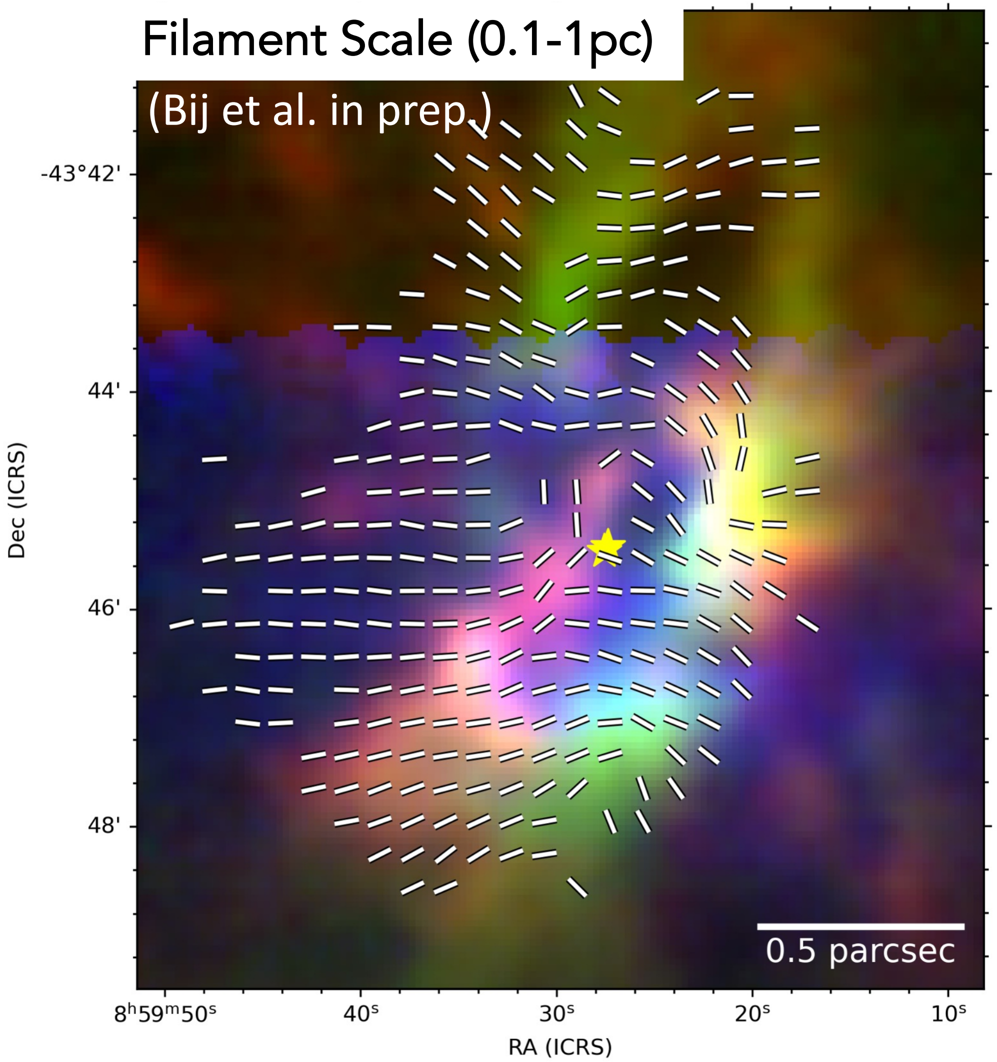


High-resolution magnetic field in the ring

- HAWC+ observations (Bij et al. in prep.)
  - Band C (79 μm) & E (214 μm)

- More detailed analysis of ‘the ring’ (Bij et al. in prep.)

- Complex morphology
  - Aligned and perpendicular to density structures



^{12}CO, ^{13}CO, [CII], vectors: SOFIA 214 μm

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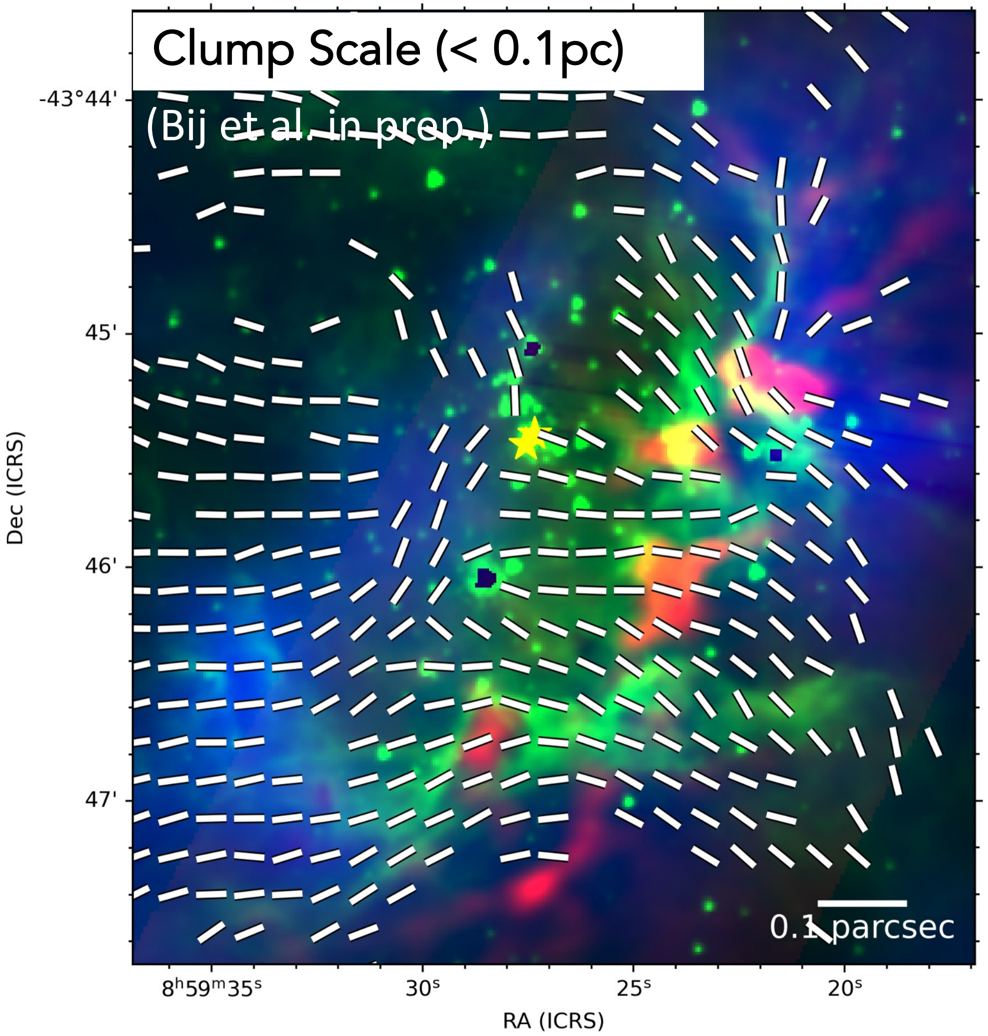
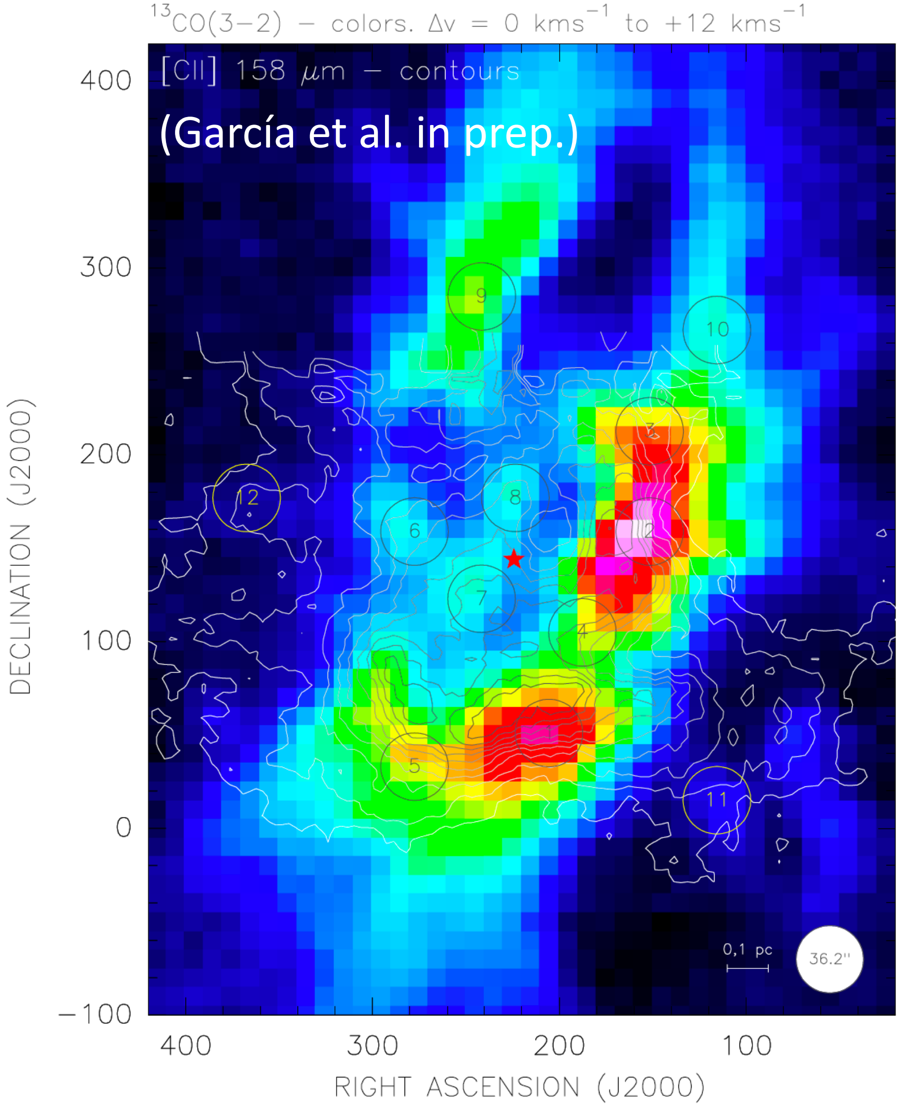


ALMA 1.1mm, 3.6 μm, ^{12}CO, vectors: SOFIA 79 μm

PDR and XDR modeling of the ring

- 12 pointed observations with a variety of lines (García et al. in prep.)
  - $^{12/13}C^{(18/17)}O$(2-1,3-2,4-3,6-5)
  - HCO^+(2-1,3-2,4-3)
  - [CI](1-0), [CII], [OI]
- PDR modeling (Röllig et al. 2013; Pound & Wolfire 2022)
- XDR modeling (Meijerink et al. 2007)
- [$^{18}O/^{17}O$] abundance ratio

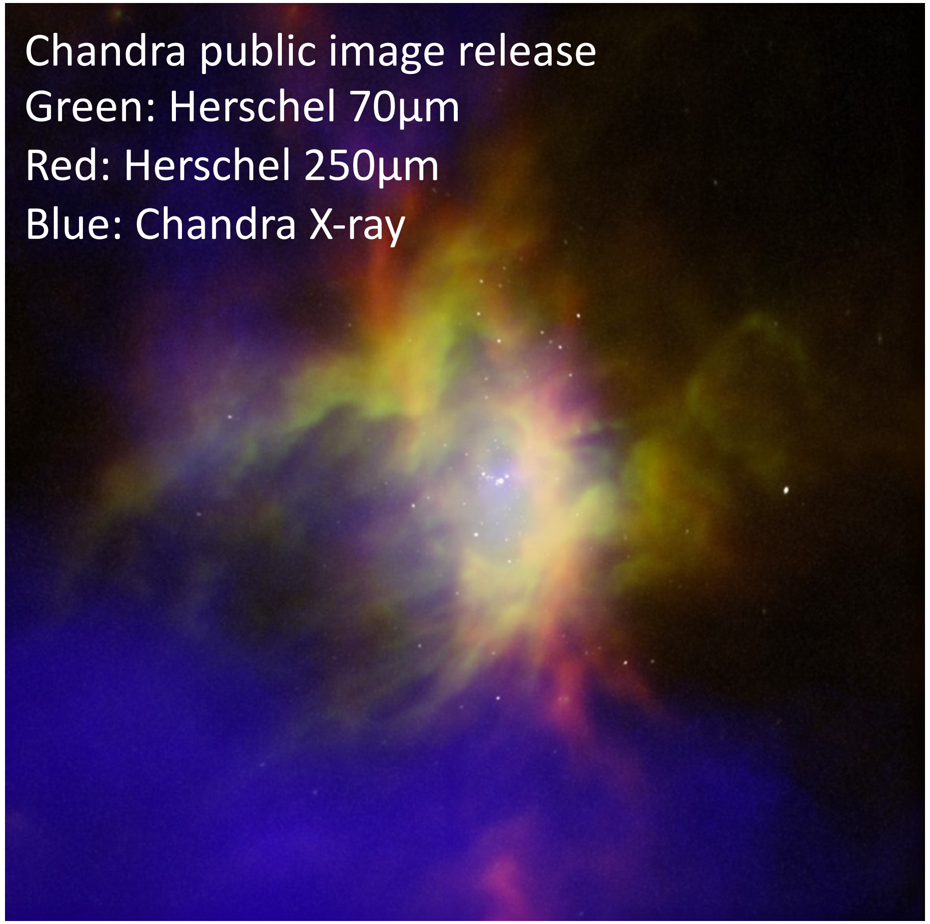


Chandra observations of RCW 36

- Point sources
  - Members of the stellar cluster

- Extended X-ray emission
  - Weak in the cavities (extinction)
  - Extended around the cavities

0.5-7 keV (see also Townsley et al. 2014)



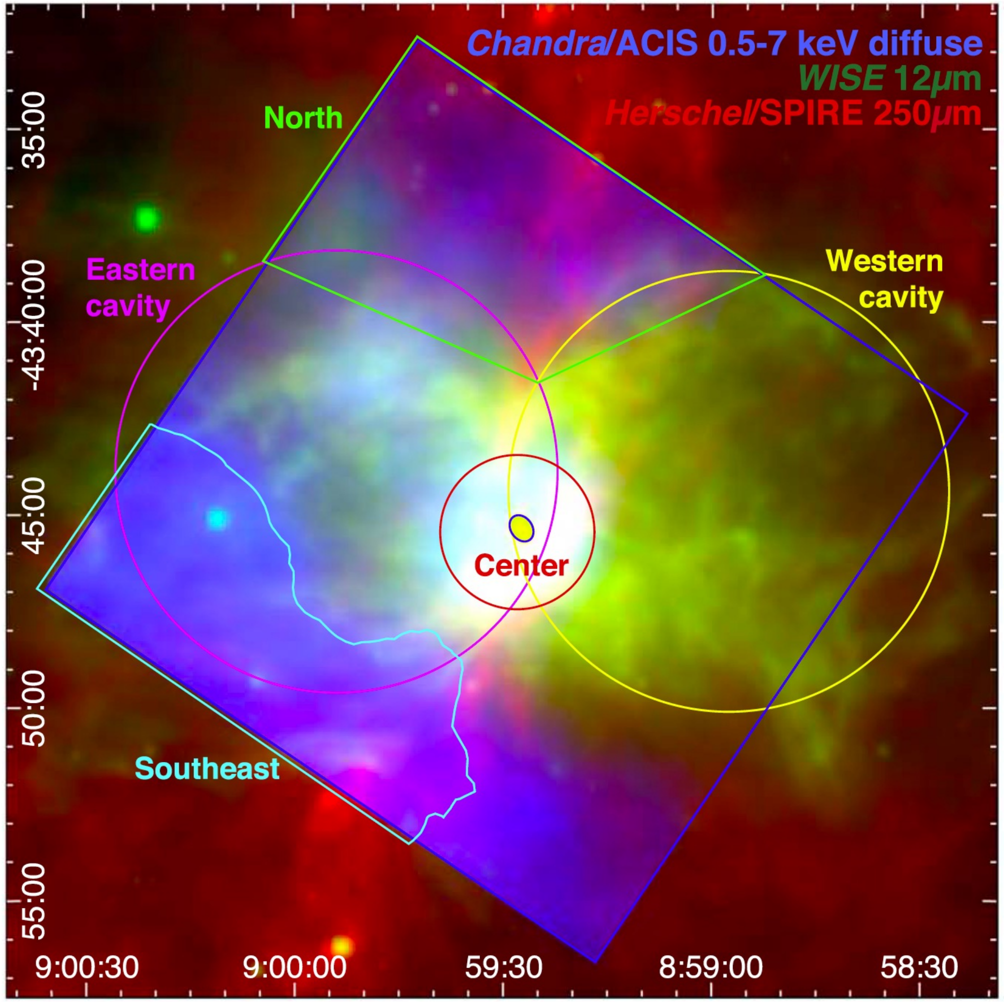
Chandra public image release
Green: Herschel 70µm
Red: Herschel 250µm
Blue: Chandra X-ray

https://www.nasa.gov/mission_pages/chandra/news/astronomers-see-stellar-self-control-in-action.html

Chandra observations of RCW 36

- Fitting the X-ray spectra (using XSPEC; Arnaud 1996)
  - Five regions
  - Hot plasma (created by stellar winds)

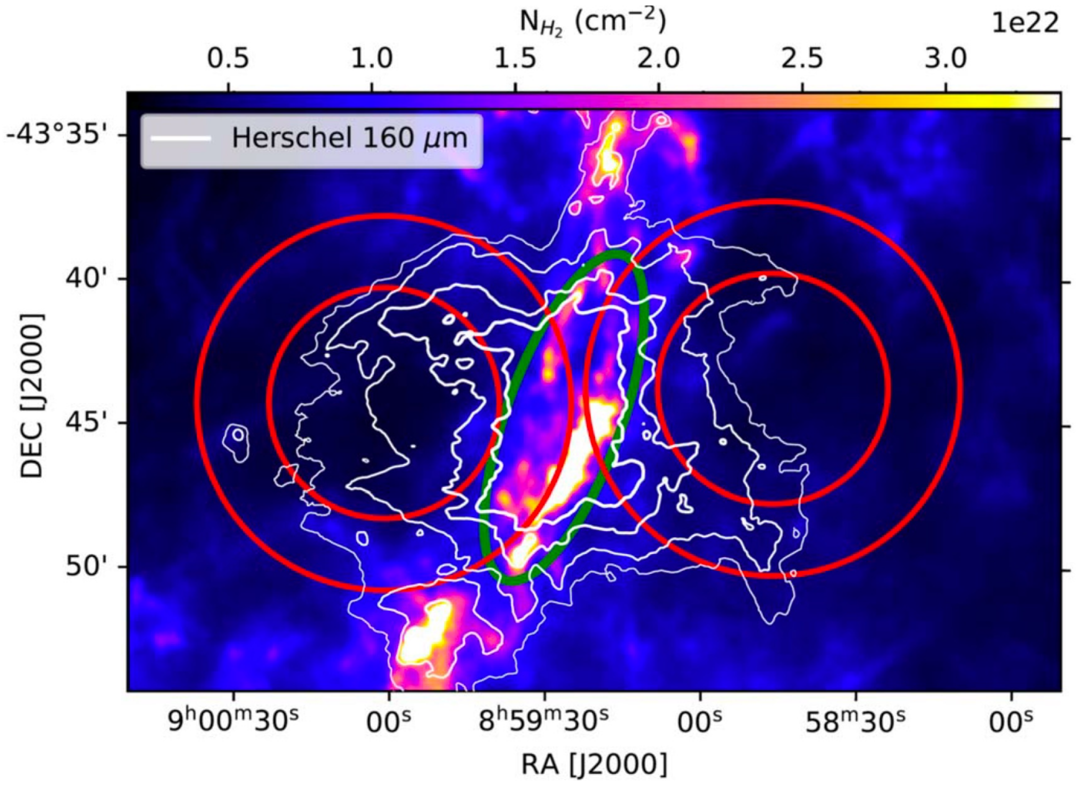
- Similar hot plasma properties in- and outside the cavities
  - Leakage from RCW 36



Expansion of the ring and cavities

- Energy and mass of the expanding structures?
  - Define with Herschel or [CII]

- Define:
  - Ring (green)
  - Cavities (red) – include limb brightening

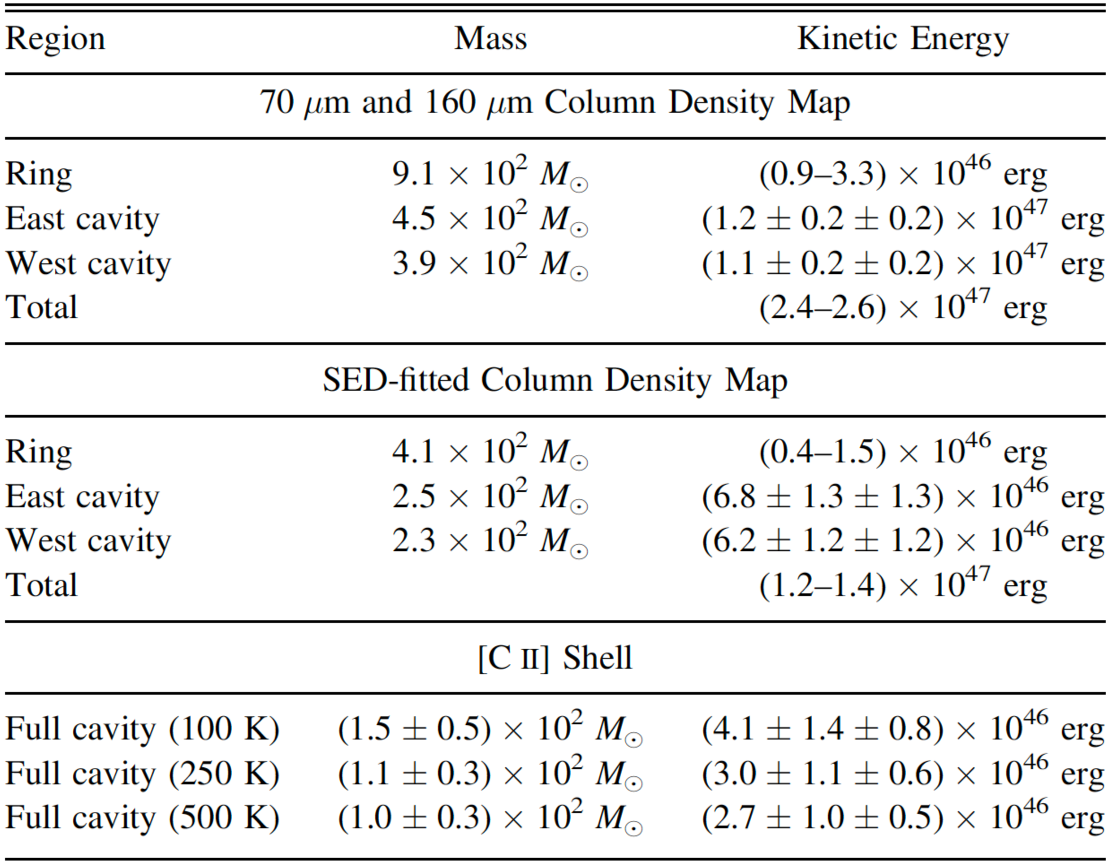


Expansion of the ring and cavities

- What drives the expansion?

- Hot plasma energy
  - East cavity: 7.2x10^{46} erg
  - West cavity: 5.4x10^{46} erg
  - Ring: \

- Requires adiabatic expansion



Region	Mass	Kinetic Energy
70 μm and 160 μm Column Density Map		
Ring	$9.1 \times 10^2\ M_\odot$	$(0.9\text{–}3.3) \times 10^{46}$ erg
East cavity	$4.5 \times 10^2\ M_\odot$	$(1.2 \pm 0.2 \pm 0.2) \times 10^{47}$ erg
West cavity	$3.9 \times 10^2\ M_\odot$	$(1.1 \pm 0.2 \pm 0.2) \times 10^{47}$ erg
Total		$(2.4\text{–}2.6) \times 10^{47}$ erg
SED-fitted Column Density Map		
Ring	$4.1 \times 10^2\ M_\odot$	$(0.4\text{–}1.5) \times 10^{46}$ erg
East cavity	$2.5 \times 10^2\ M_\odot$	$(6.8 \pm 1.3 \pm 1.3) \times 10^{46}$ erg
West cavity	$2.3 \times 10^2\ M_\odot$	$(6.2 \pm 1.2 \pm 1.2) \times 10^{46}$ erg
Total		$(1.2\text{–}1.4) \times 10^{47}$ erg
[C II] Shell		
Full cavity (100 K)	$(1.5 \pm 0.5) \times 10^2\ M_\odot$	$(4.1 \pm 1.4 \pm 0.8) \times 10^{46}$ erg
Full cavity (250 K)	$(1.1 \pm 0.3) \times 10^2\ M_\odot$	$(3.0 \pm 1.1 \pm 0.6) \times 10^{46}$ erg
Full cavity (500 K)	$(1.0 \pm 0.3) \times 10^2\ M_\odot$	$(2.7 \pm 1.0 \pm 0.5) \times 10^{46}$ erg

Expansion of the ring and cavities

- Ionizing radiation over 1.1 Myr (from Hα)
  - East cavity: 6.2×10^{49} erg
  - West cavity: 6.6×10^{49} erg
  - Ring: 7.6×10^{50} erg

- Coupling efficiency for ionizing radiation is low
  - ~10^{-4} (e.g. Haid et al. 2018)
  - Cavities: driven by hot plasma
  - Ring: can be driven by radiation

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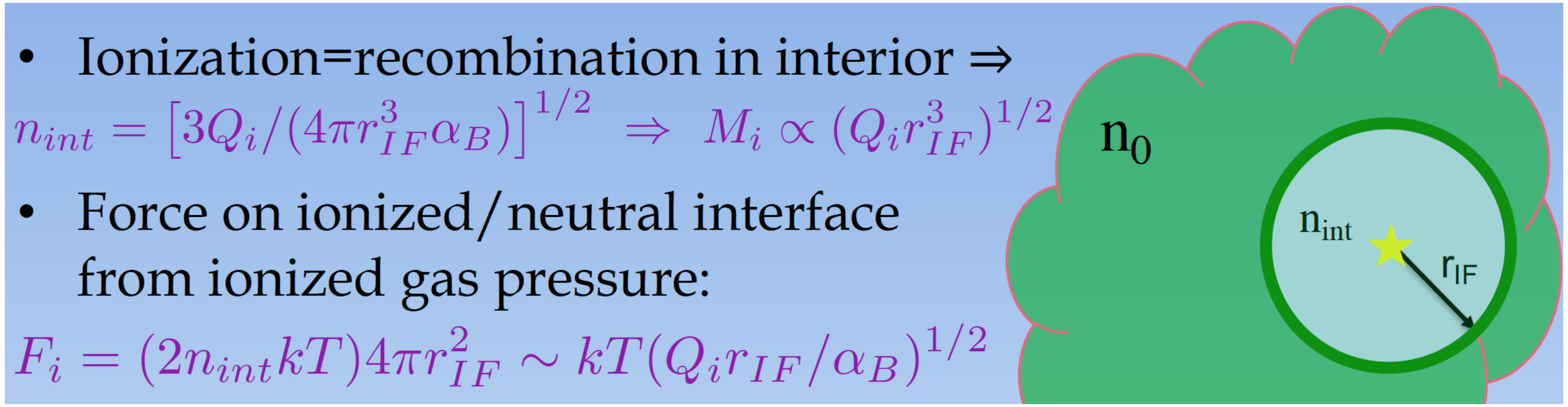
Expansion of the ring and cavities

- But…

E. Ostriker: Ascona conference 2022



- Ionization=recombination in interior ⇒

$n_{int} = \left[3Q_i/(4\pi r_{IF}^3 \alpha_B)\right]^{1/2} \Rightarrow M_i \propto (Q_i r_{IF}^3)^{1/2}$

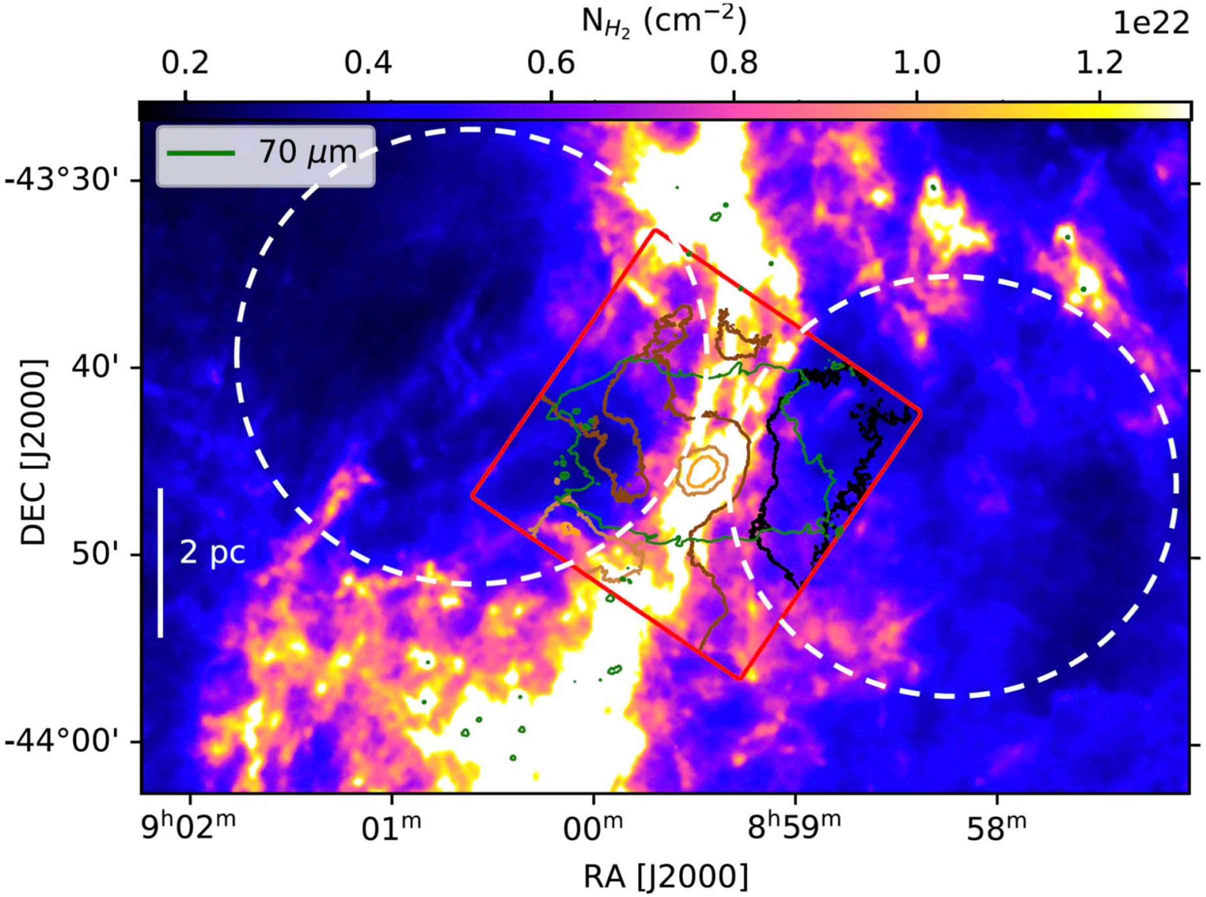
- Force on ionized/neutral interface from ionized gas pressure:

$F_i = (2n_{int} kT) 4\pi r_{IF}^2 \sim kT(Q_i r_{IF}/\alpha_B)^{1/2}$

- Injected momentum in the cavities: 2.3-2.5x10^3 $M_\odot$ km s^{-1}
  - Sufficient for 0.5-2.3x10^3 $M_\odot$ km s^{-1} expansion momentum of the cavities

Leakage from RCW 36

- ➢Hot plasma indicates leakage
- ➢Larger cavities centered on RCW 36
  - Tentative correlation with hot plasma emission
- ➢Hot plasma leakage (Harper-Clark & Murray 2009)
  - Could be as high as -2.0x10^{35} erg s^{-1}

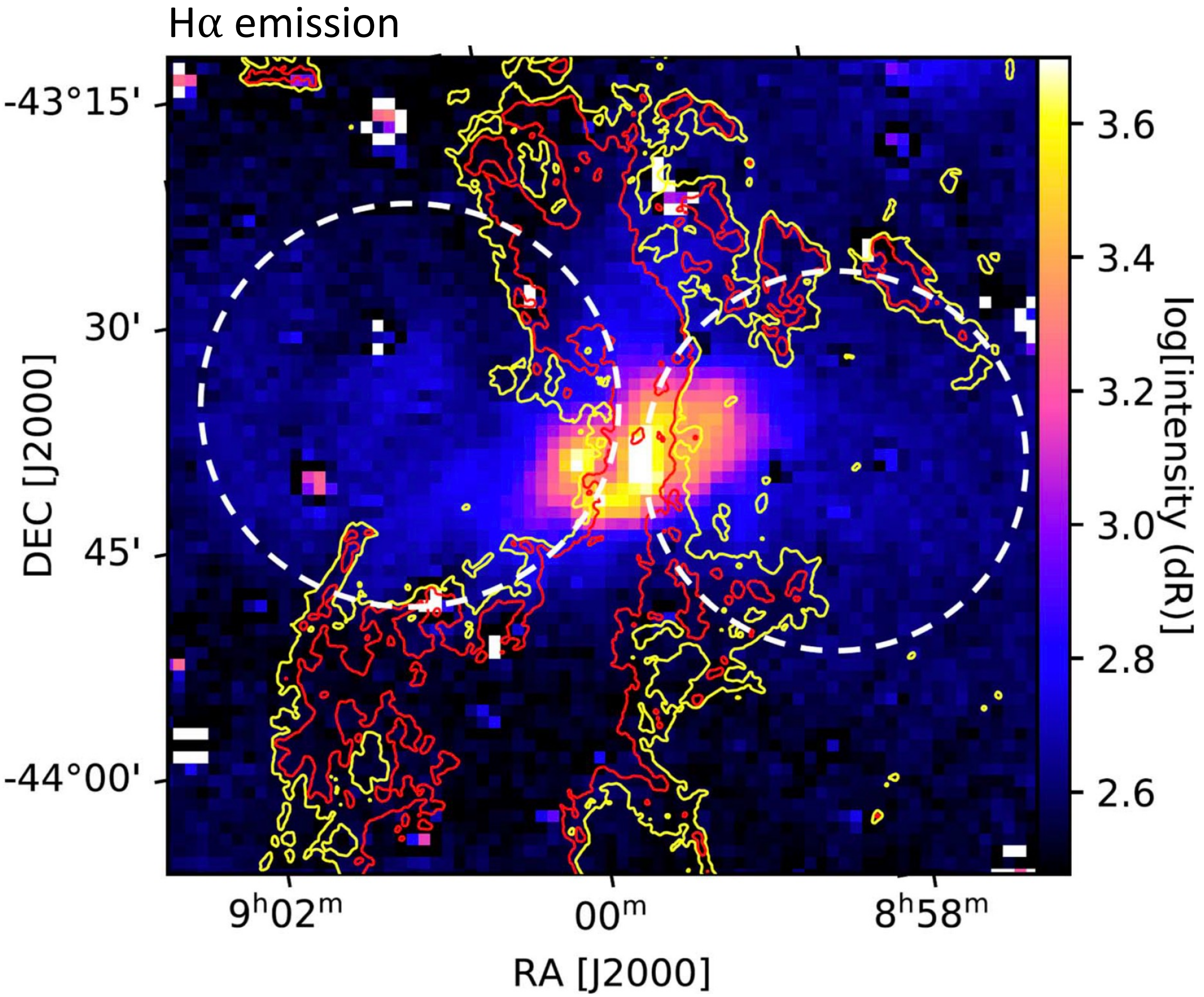


Leakage from RCW 36

- Leakage also seen in Hα
  - Confirms hot plasma leakage

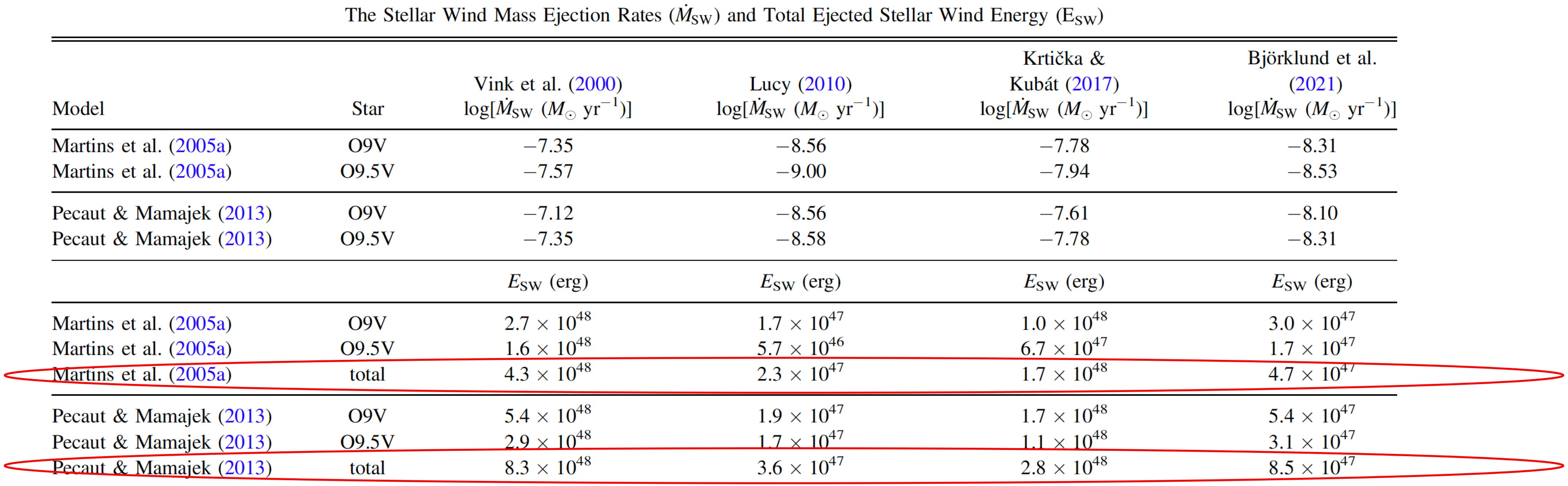
- Disturbs the GMC on larger scales

- Estimated ionizing photon leakage
  - 1.4×10^{36} erg s^{-1} (≤ 10%)



High-velocity mass ejection: stellar winds

- Uncertainties in the stellar models
  - Energy injection rate: 0.7-24x10^{34} erg s^{-1}
  - Needed to drive high-velocity wings: 1.0-1.6x10^{35} erg s^{-1}



The Stellar Wind Mass Ejection Rates ($\dot{M}_{\mathrm{SW}}$) and Total Ejected Stellar Wind Energy (E_{SW})

Model	Star	Vink et al. (2000) $\log[\dot{M}_{\mathrm{SW}}\ (M_\odot\ \mathrm{yr}^{-1})]$	Lucy (2010) $\log[\dot{M}_{\mathrm{SW}}\ (M_\odot\ \mathrm{yr}^{-1})]$	Krtička & Kubát (2017) $\log[\dot{M}_{\mathrm{SW}}\ (M_\odot\ \mathrm{yr}^{-1})]$	Björklund et al. (2021) $\log[\dot{M}_{\mathrm{SW}}\ (M_\odot\ \mathrm{yr}^{-1})]$
Martins et al. (2005a)	O9V	-7.35	-8.56	-7.78	-8.31
Martins et al. (2005a)	O9.5V	-7.57	-9.00	-7.94	-8.53
Pecaut & Mamajek (2013)	O9V	-7.12	-8.56	-7.61	-8.10
Pecaut & Mamajek (2013)	O9.5V	-7.35	-8.58	-7.78	-8.31
		E_{SW} (erg)	E_{SW} (erg)	E_{SW} (erg)	E_{SW} (erg)
Martins et al. (2005a)	O9V	2.7×10^{48}	1.7×10^{47}	1.0×10^{48}	3.0×10^{47}
Martins et al. (2005a)	O9.5V	1.6×10^{48}	5.7×10^{46}	6.7×10^{47}	1.7×10^{47}
Martins et al. (2005a)	total	4.3×10^{48}	2.3×10^{47}	1.7×10^{48}	4.7×10^{47}
Pecaut & Mamajek (2013)	O9V	5.4×10^{48}	1.9×10^{47}	1.7×10^{48}	5.4×10^{47}
Pecaut & Mamajek (2013)	O9.5V	2.9×10^{48}	1.7×10^{47}	1.1×10^{48}	3.1×10^{47}
Pecaut & Mamajek (2013)	total	8.3×10^{48}	3.6×10^{47}	2.8×10^{48}	8.5×10^{47}

High-velocity mass ejection: ionizing radiation

- Injected momentum rate by the O stars: 6.8×10^{-3} $M_\odot$ km s^{-1} Myr^{-1}
  - Needed to drive high-velocity wings: $1.1\text{-}1.6\times10^{-2}$ $M_\odot$ km s^{-1} Myr^{-1}

- Both stellar wind and ionizing radiation models pushed to the limit

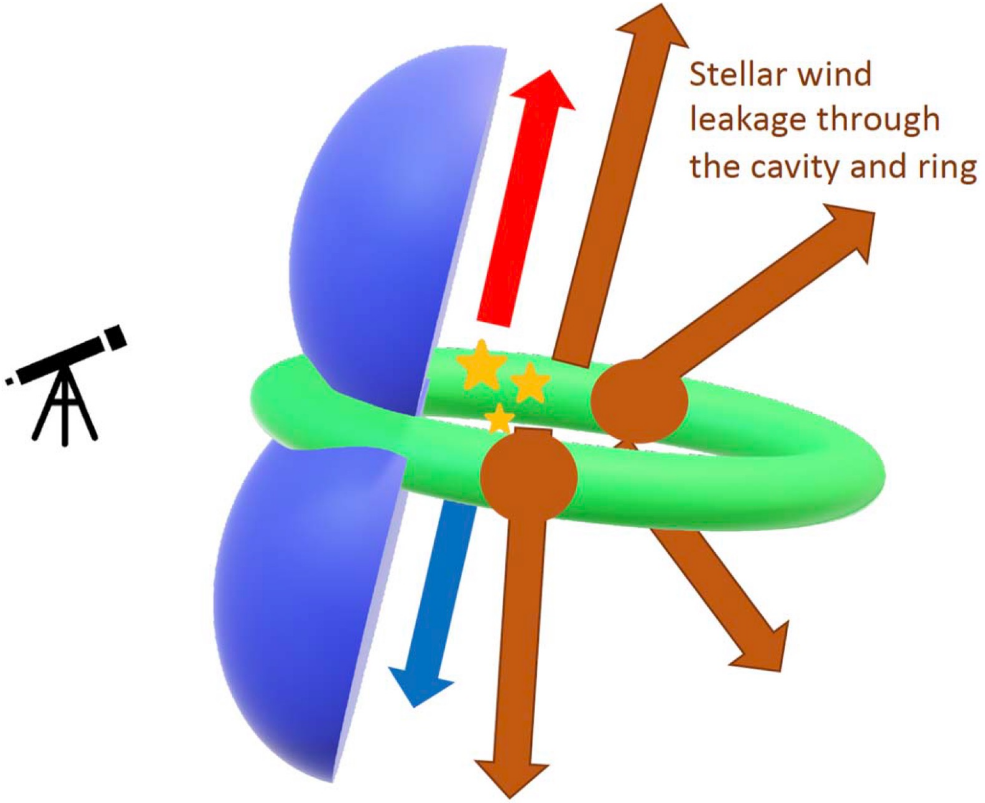
- Many uncertainties in calculation mass ejection rate
  - C^+ abundance
  - Inclination angle
  - Temperature
  - …

Conclusion

- Inhomogeneous expansion in the Vela C molecular cloud

- High-velocity mass ejection and leakage
  - Rapid molecular cloud erosion once high-mass stars have formed

- Significant uncertainties to pin down the process that drives rapid cloud dispersal



Future

- ➢A lot of FEEDBACK work still to be done
  - High-velocity gas is ubiquitous, morphology
  - More in-depth studies of feedback mechanisms
  - [CII] self-absorption
  - Constraining PDR models
  - [OI]
  - …

- ➢Not so distant future:
  - Balloon missions?

(Bonne et al. to be subm.)