Feedback

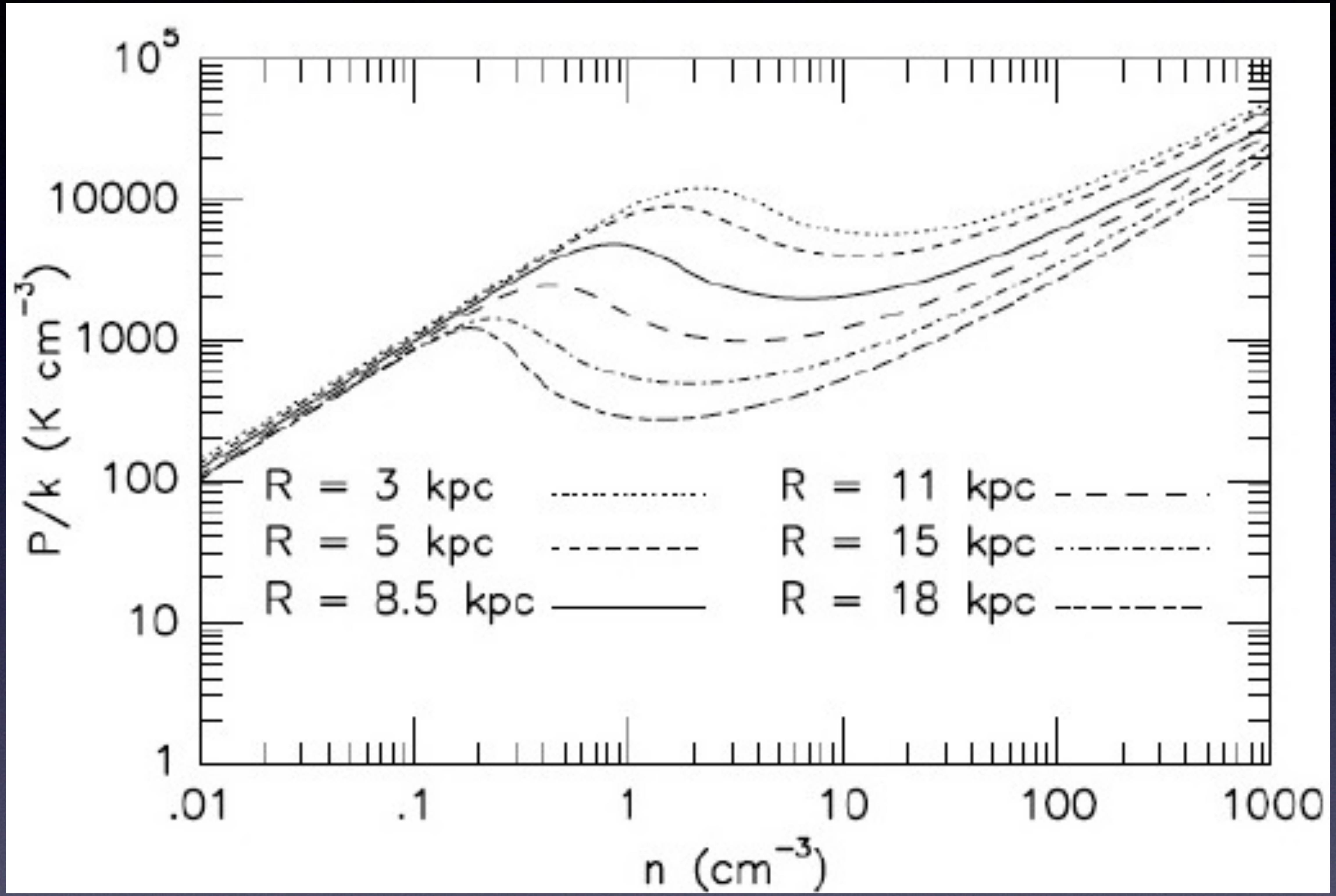
Xander Tielens on behalf of:

Nicola Schneider & the SOFIA Feedback Legacy Team

The ISM of Galaxies

Radiative & kinematic interaction of massive stars with their environment drives the evolution of the Interstellar Medium and the evolution of galaxies

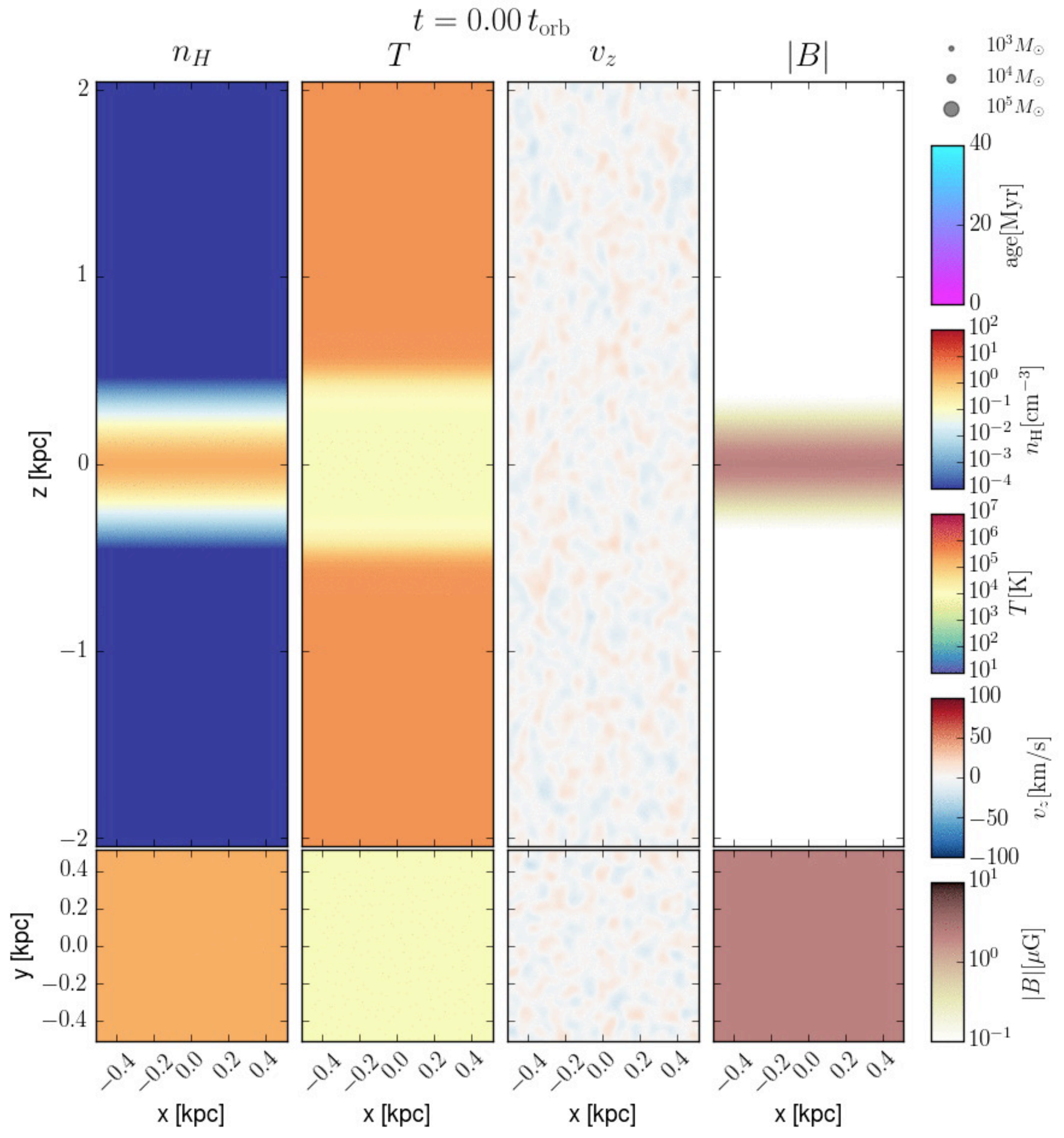
Phases of the ISM



Gas in thermal (radiative) & pressure equilibrium can exist in 2 stable phases: Warm Neutral Medium and Cold Neutral medium. The presence of a Hot Phase betrays the importance of kinetic energy input.

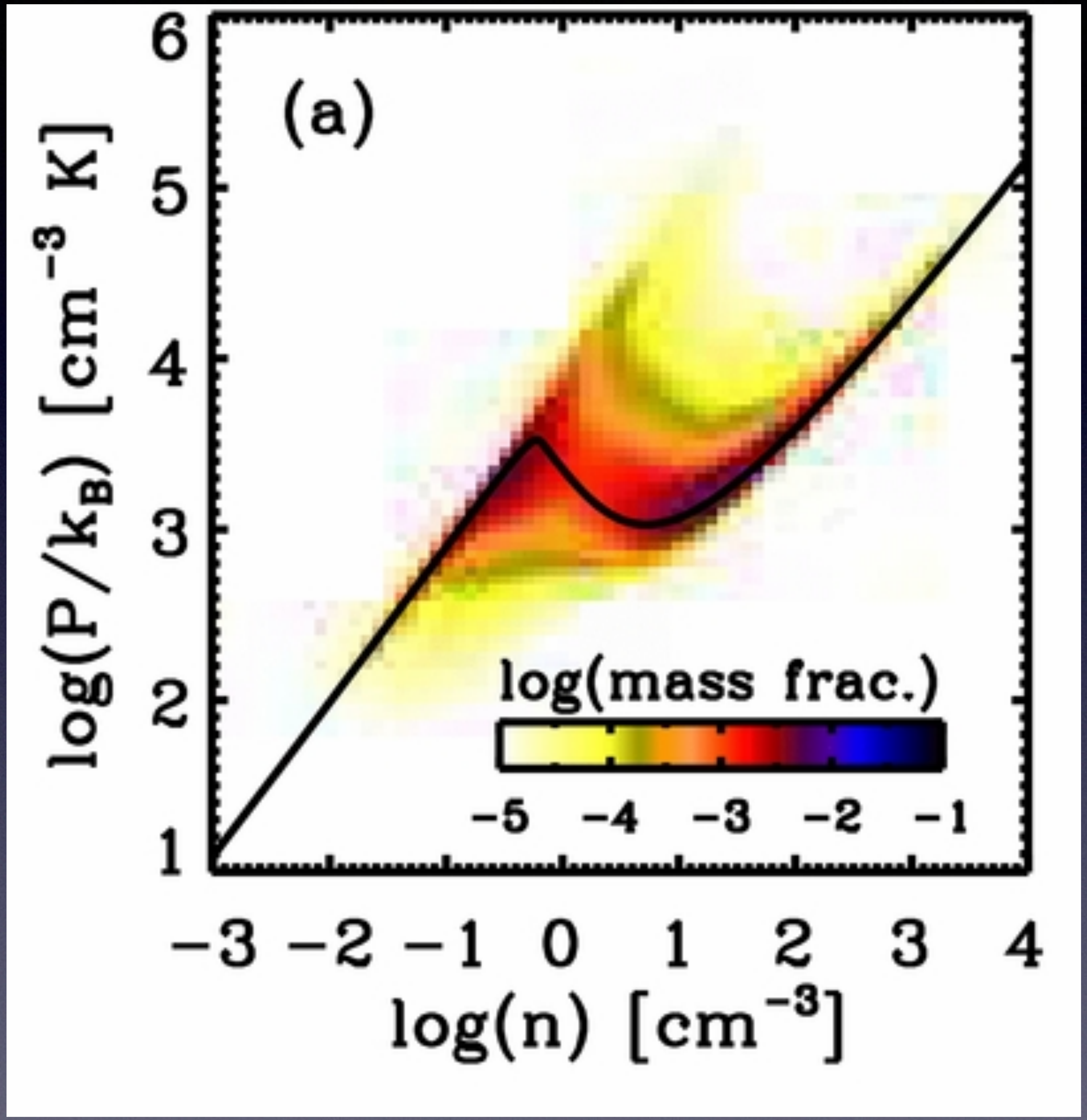
Field et al, 1969, ApJ, 155, L149
McCray & Snow, 1979, ARAA, 17, 213
Wolfire et al, 1995, ApJ, 443, 152

Feedback in the ISM



Kim & Ostriker 2013, ApJ, 776, 1 & 2015, ApJ, 802, 99

The Phases of the ISM and the role of Radiative and Mechanical Heating



C.-G. Kim & E.C. Ostriker 2013, ApJ, 776, 1

The cooling curve (CII versus OI/Lyα) sets the presence of phases
Radiative heating & mechanical energy input sets the pressure
Mechanical energy input sets the distributions over the phases

Key Questions in ISM Evolution

Radiative & kinematic interaction of massive stars with their environment drives the evolution of the Interstellar Medium and the evolution of galaxies

- What are the relative roles of ionization, radiation and mechanical feedback ?
- How do molecular clouds assemble and dissolve and how does this relate to star formation and nearby massive stars ?
- How did this vary over the history of the Universe ?

C+SQUAD: Orion [CII] SOFIA Large Program





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U Vienna

C+SQUAD team

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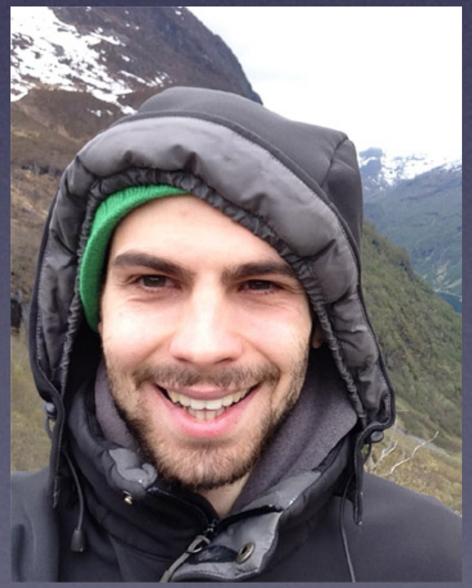




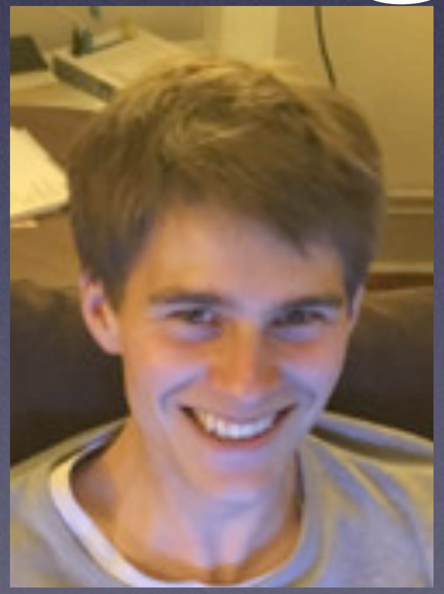

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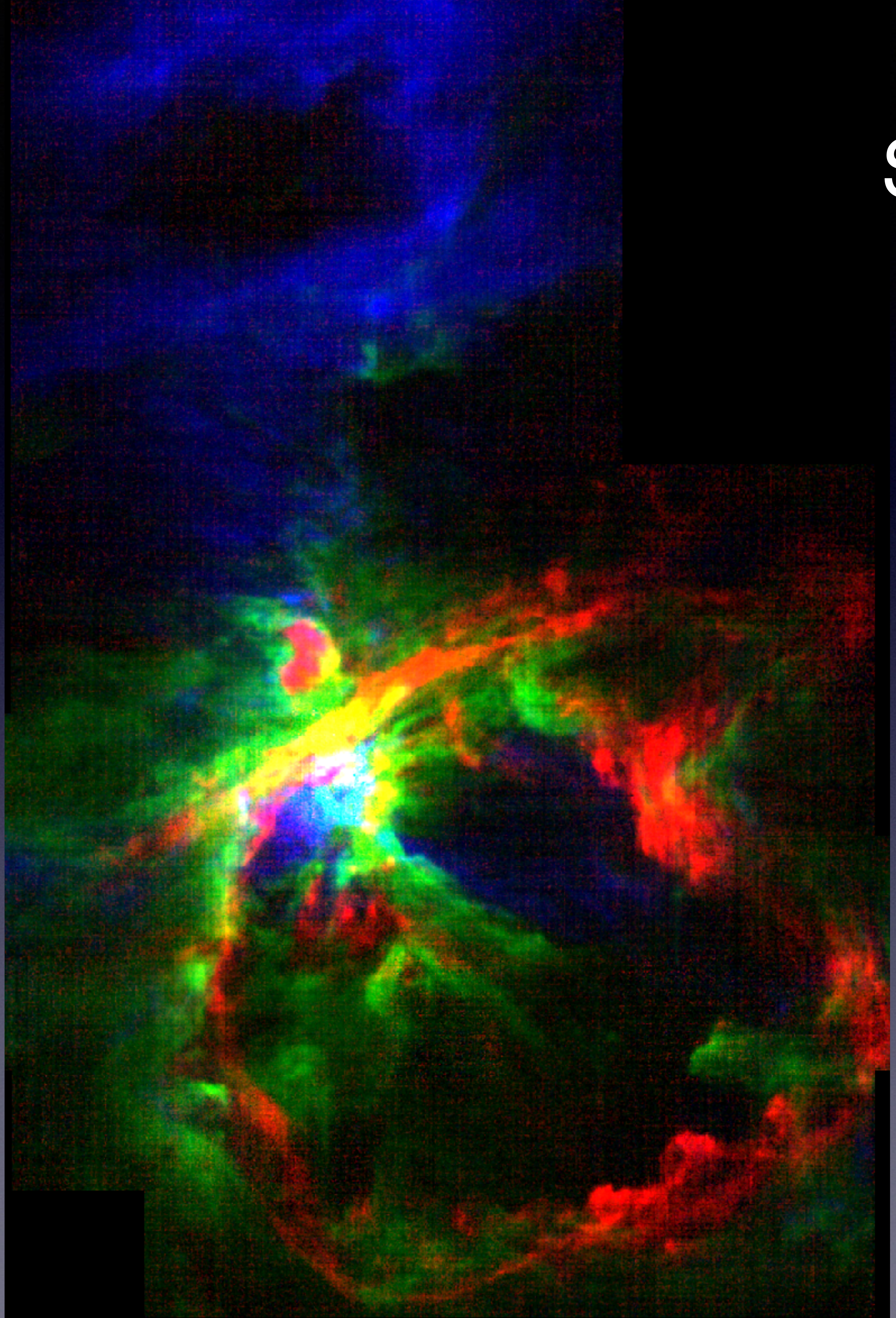
& Feedback team

Rolf Guesten, Juergen Stutzki
& upGREAT/SOFIA team

Monet meets Orion



[CII] 158 µm

See Cornelia Pabst's talk

Three bubbles:

- Orion Veil contains 1500 Msun, expands at 13 km/s and is driven by stellar wind
- M43 and NGC 1977 are thermally expanding HII regions
- Popping the Veil bubble: Poster by Umit Kavak

The SOFIA Legacy Program FEEDBACK

Science goal: How do massive stars regulate star formation ?

Survey of 11 regions of massive star formation in the [CII] 1.9 THz line using upGREAT on SOFIA. The sample spans a wide range in star formation characteristics and physical conditions

The data is non-proprietary

About 65% complete (February 2022)

Description of the program: Schneider et al 2020, PASP, 132, 4301

Goals & Objectives

Survey a broad sample of regions of massive star formation in the [CII] 1.9 THz line to measure the dynamic and radiative response of interstellar gas to massive stars

- Quantify the processes of feedback in the local Universe
  - Quantify the dissolution of molecular clouds
  - 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 physical, observational, and modeling framework to interpret studies of distant galaxies over cosmic time
- Provide benchmarks for theoretical simulations of galaxy evolution

Feedback Sampl

RCW 36
see Lars Bonne's talk

RCW 79

RCW 49
see Maitraiyee Tiwari's talk

RCW 120
see Luisi+
Science Adv, 7, 9511

NGC 6334
Wyrowski

M17
Stutzki

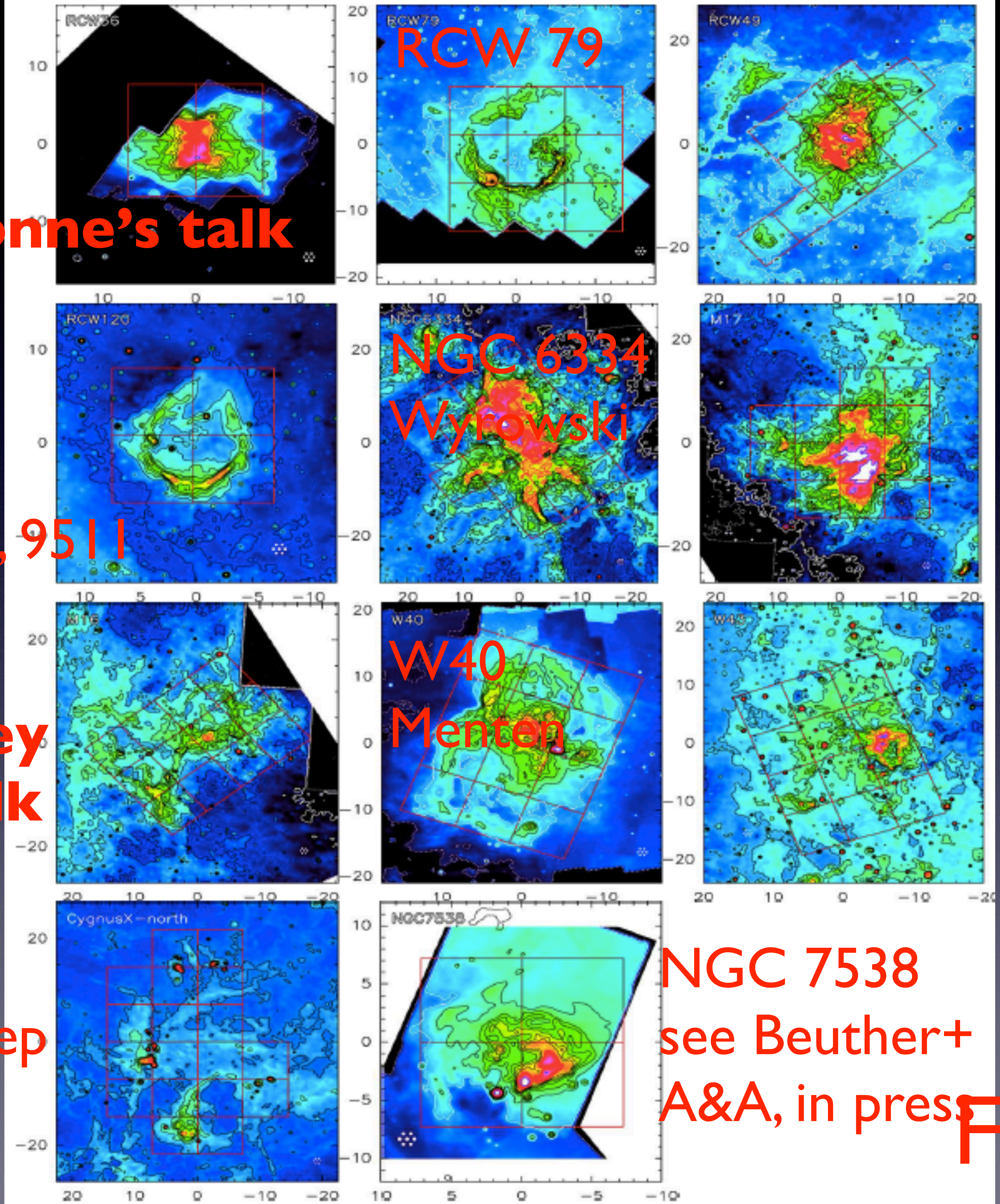
M16
see Ramsey Karim's talk

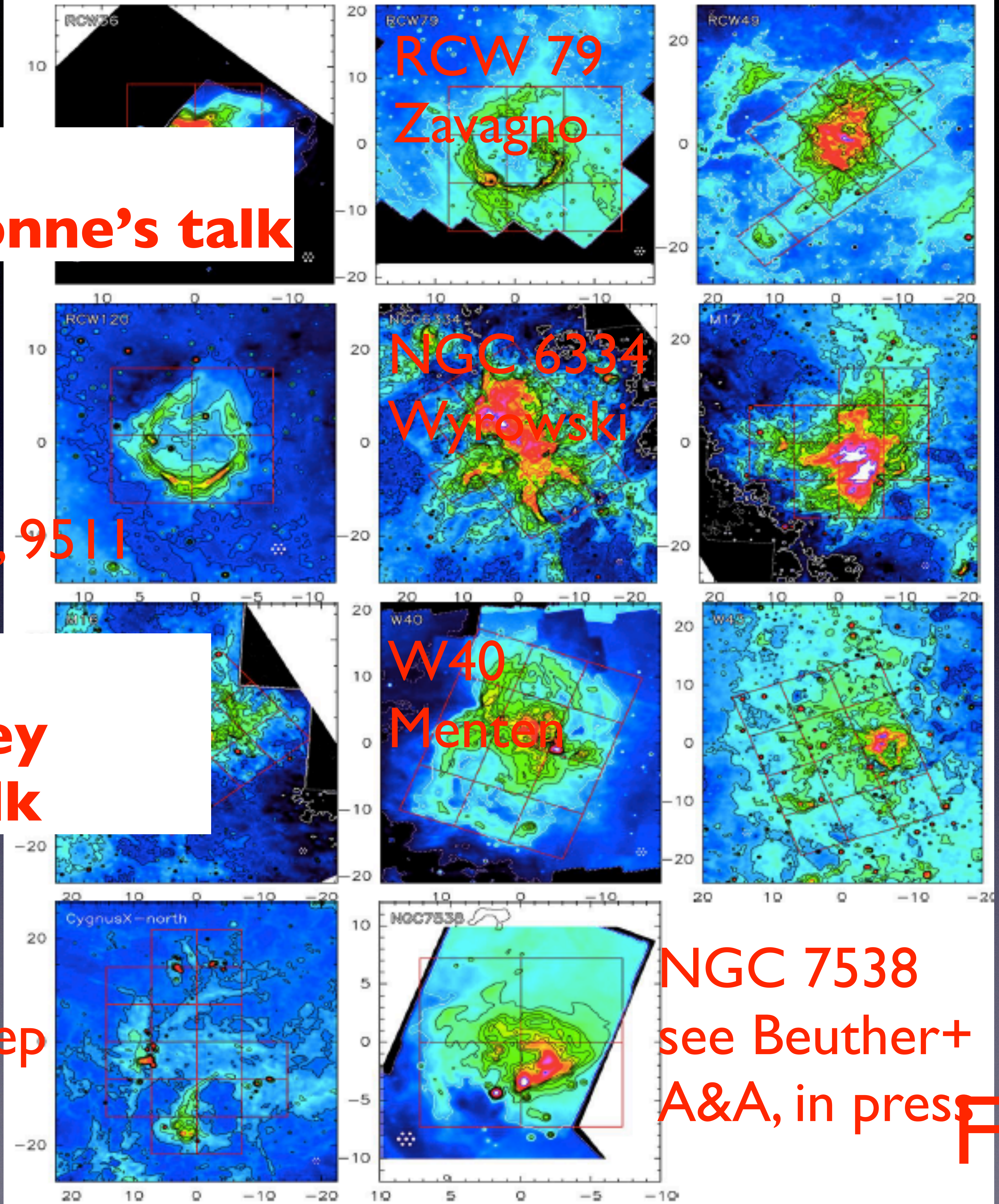
W40
Menten

W43
Bally+ in prep

Cyg X
Schneider+ in prep
Bonne+ in prep

NGC 7538
see Beuther+
A&A, in press





RCW 36
see Lars Bonne's talk

RCW 79
Zavagno

RCW 49
see Maitraiyee
Tiwari's talk

RCW 120
see Luisi+
Science Adv, 7, 9511

NGC 6334
Wyrowski

M17
To be done

M16
see Ramsey
Karim's talk

W40
Menten

W43
Bally+ in prep

Cyg X
Schneider+ in prep
Bonne+ in prep

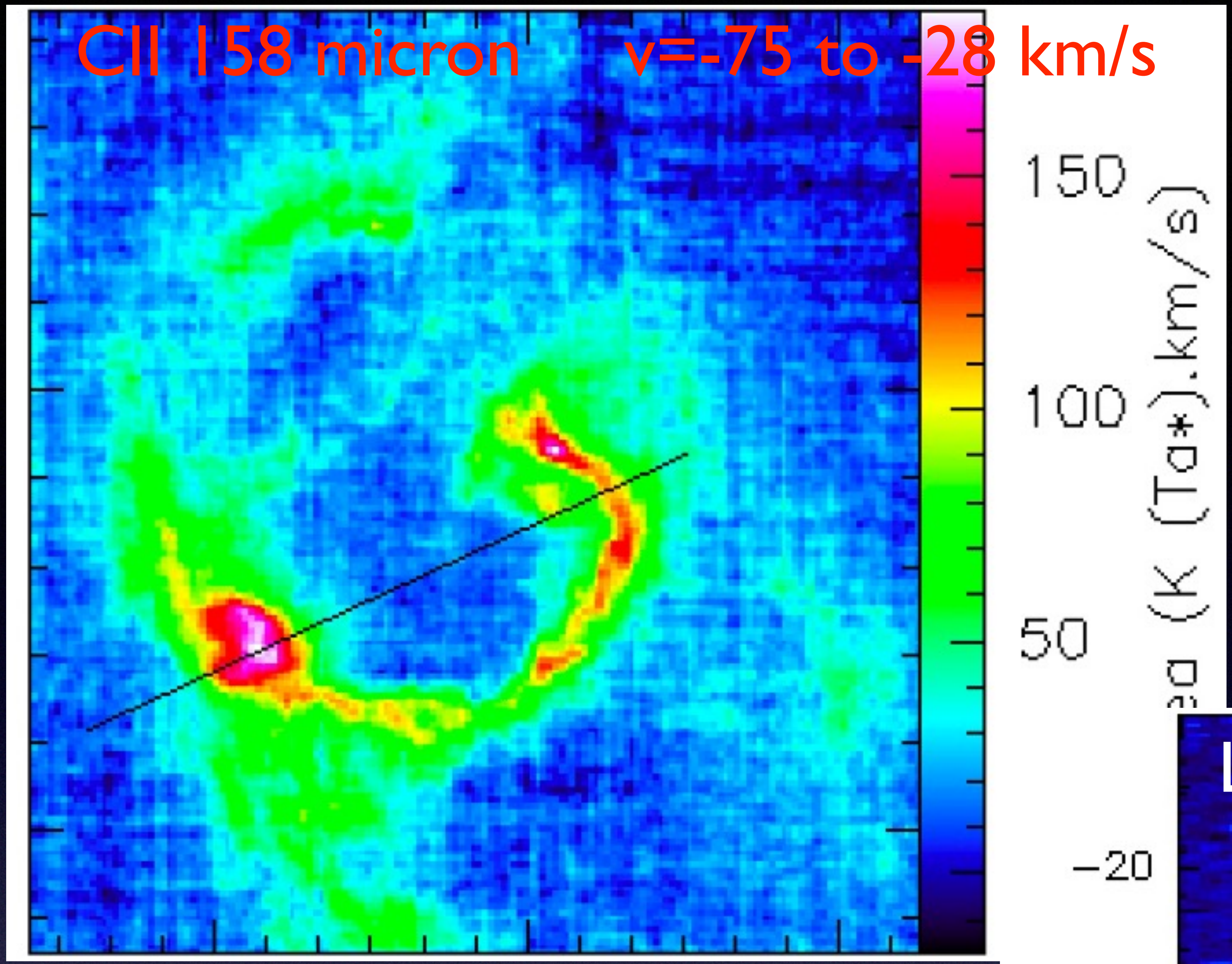
NGC 7538
see Beuther+
A&A, in press

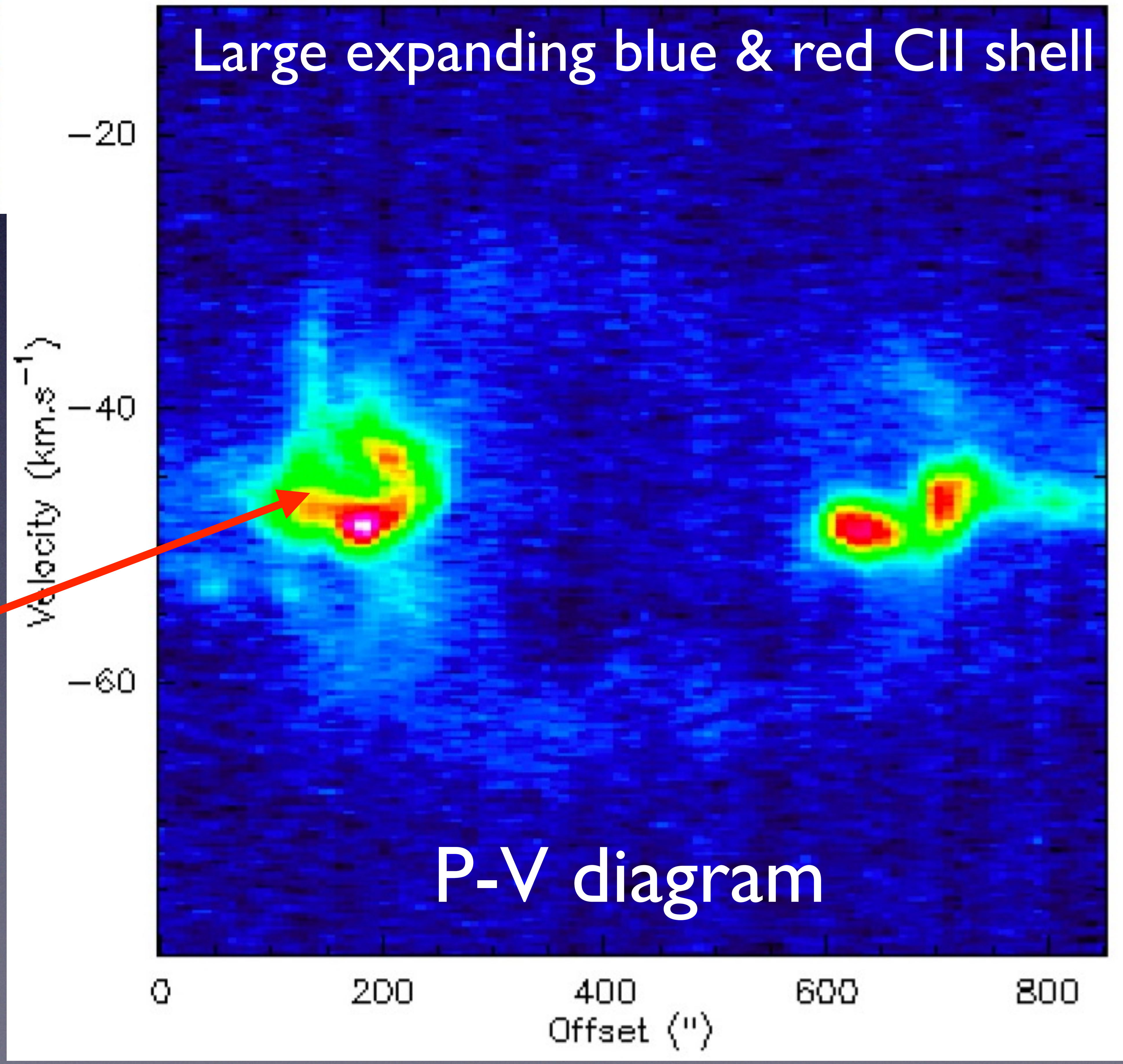
Feedback Sampl

Mechanical Feedback

Bottom line: All show (multiple) rapidly expanding shells driven by stellar wind from the main ionizing star(s)

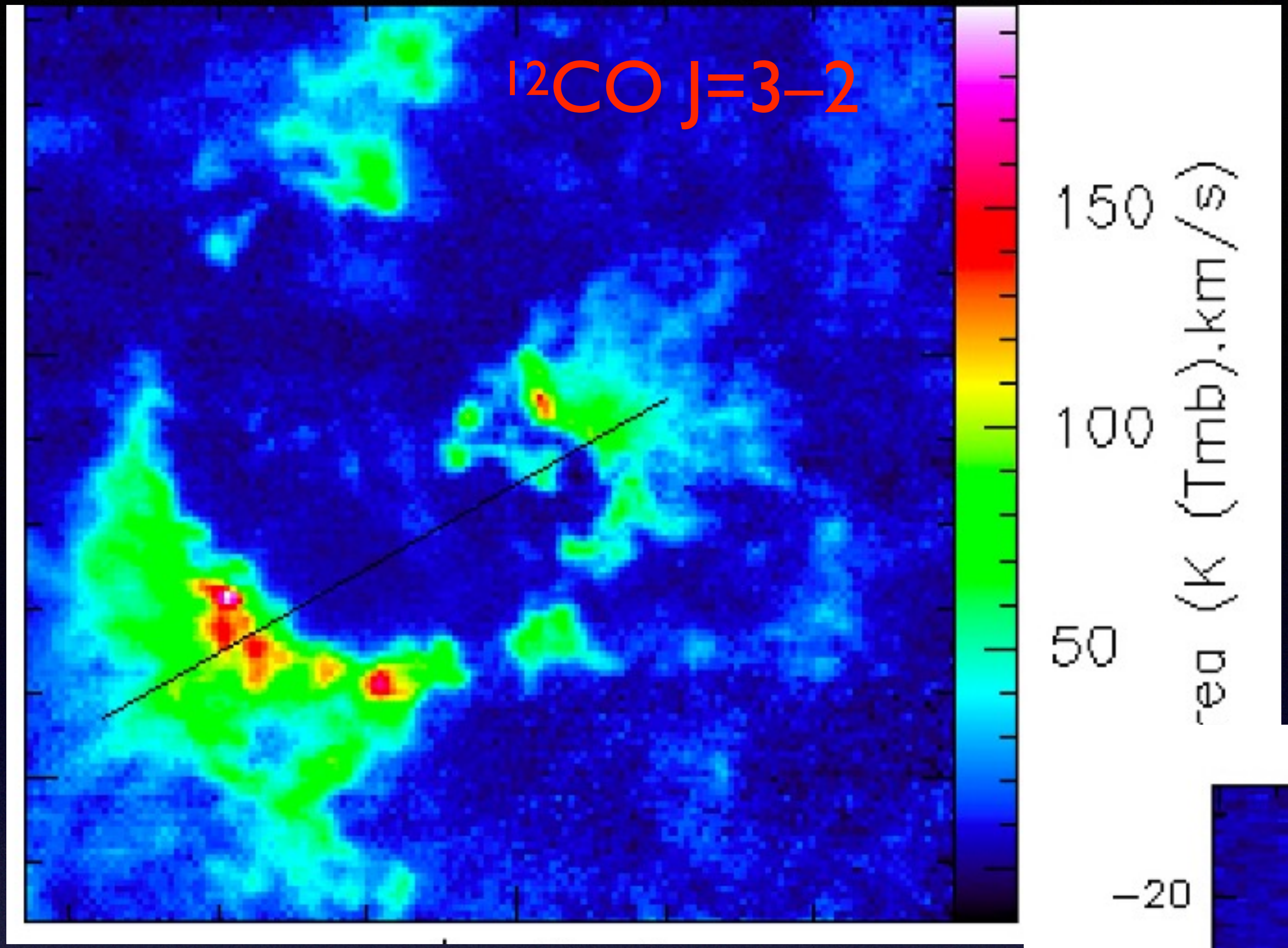
RCW 79



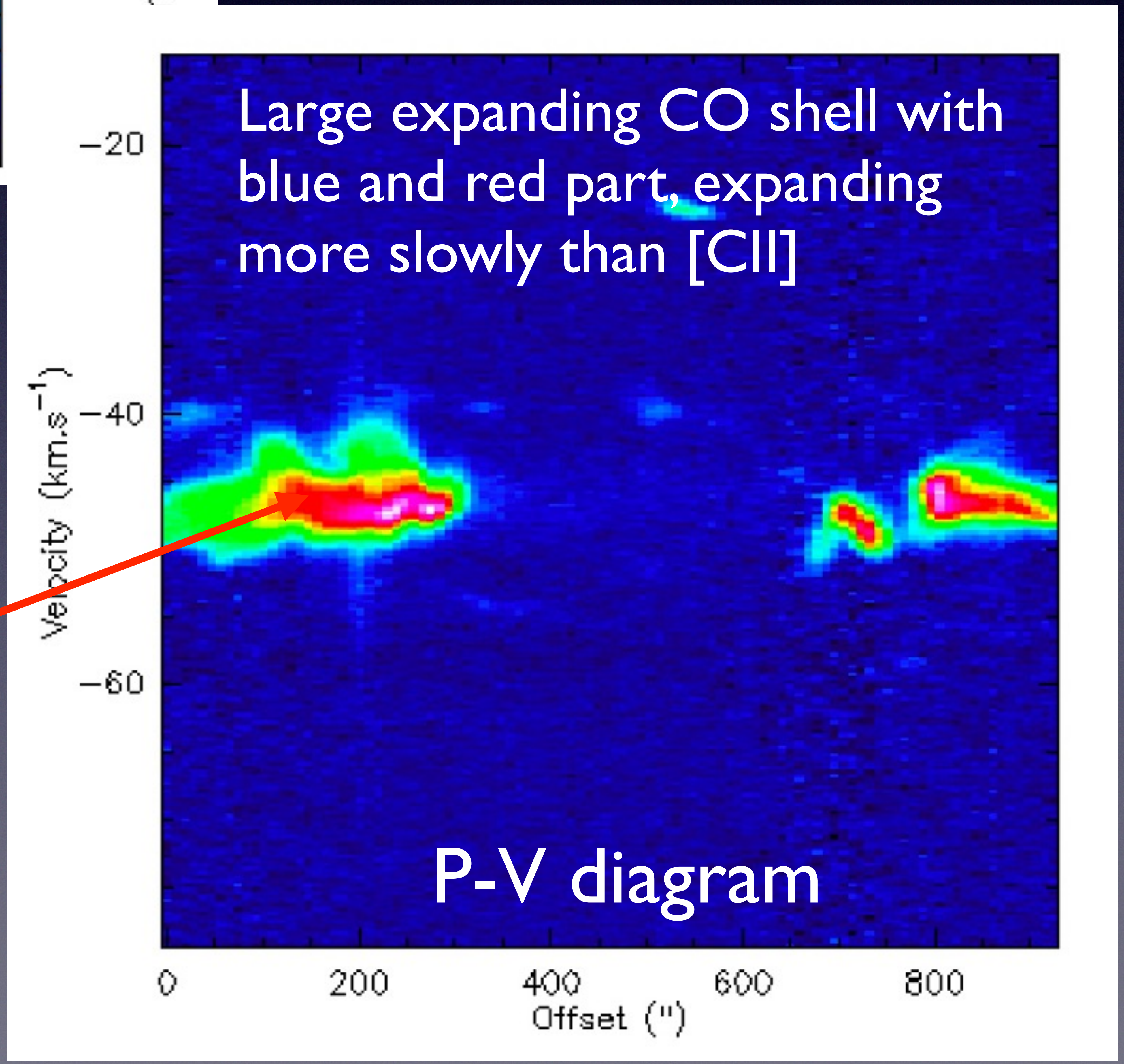


UC HII region with small expanding CII bubble, but bubble is filled with CII emission

- 12pc bubble expanding at ~15 km/s
- powered by 12 O stars
- ~ 1Myr old



RCW 79



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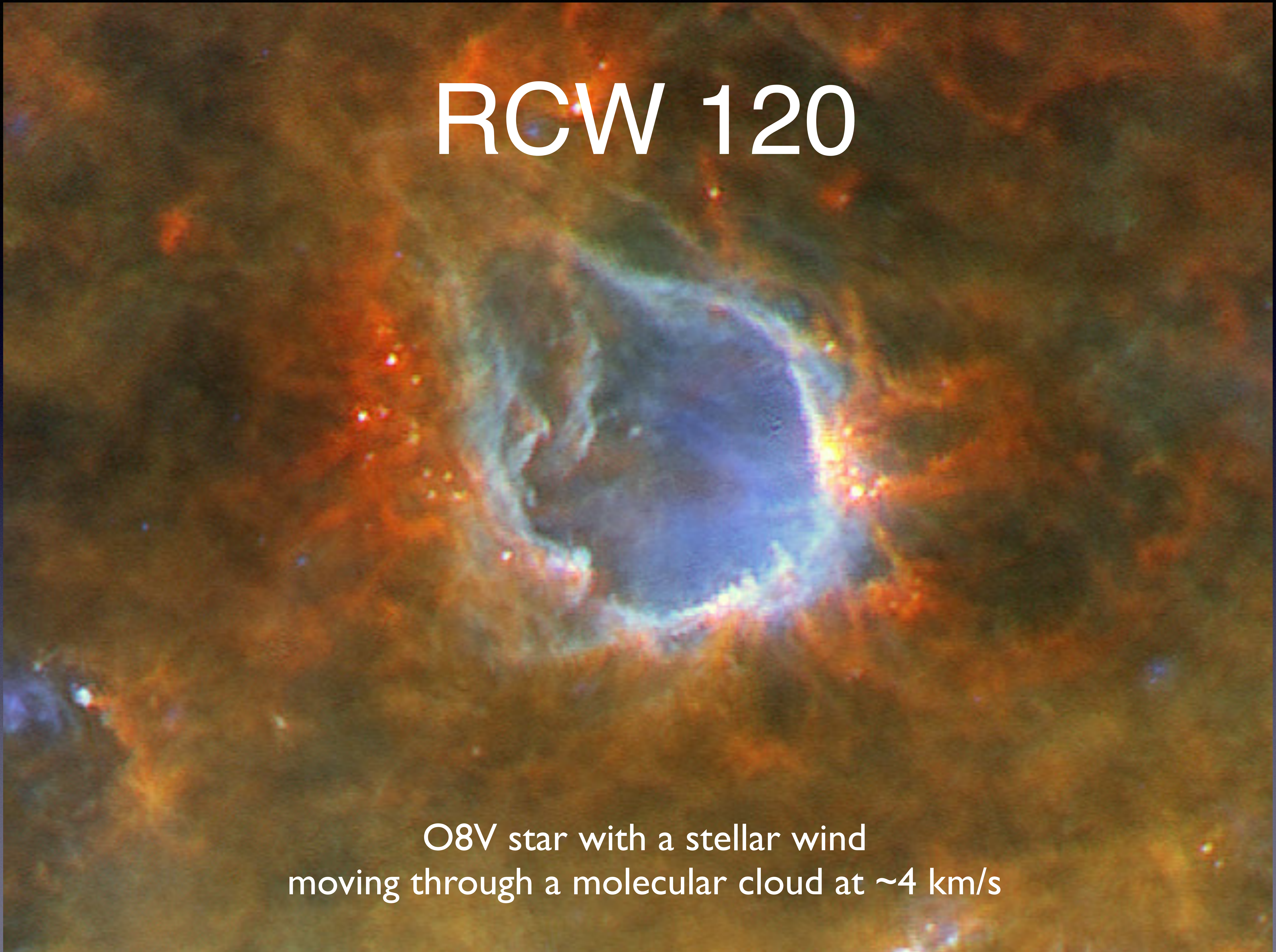
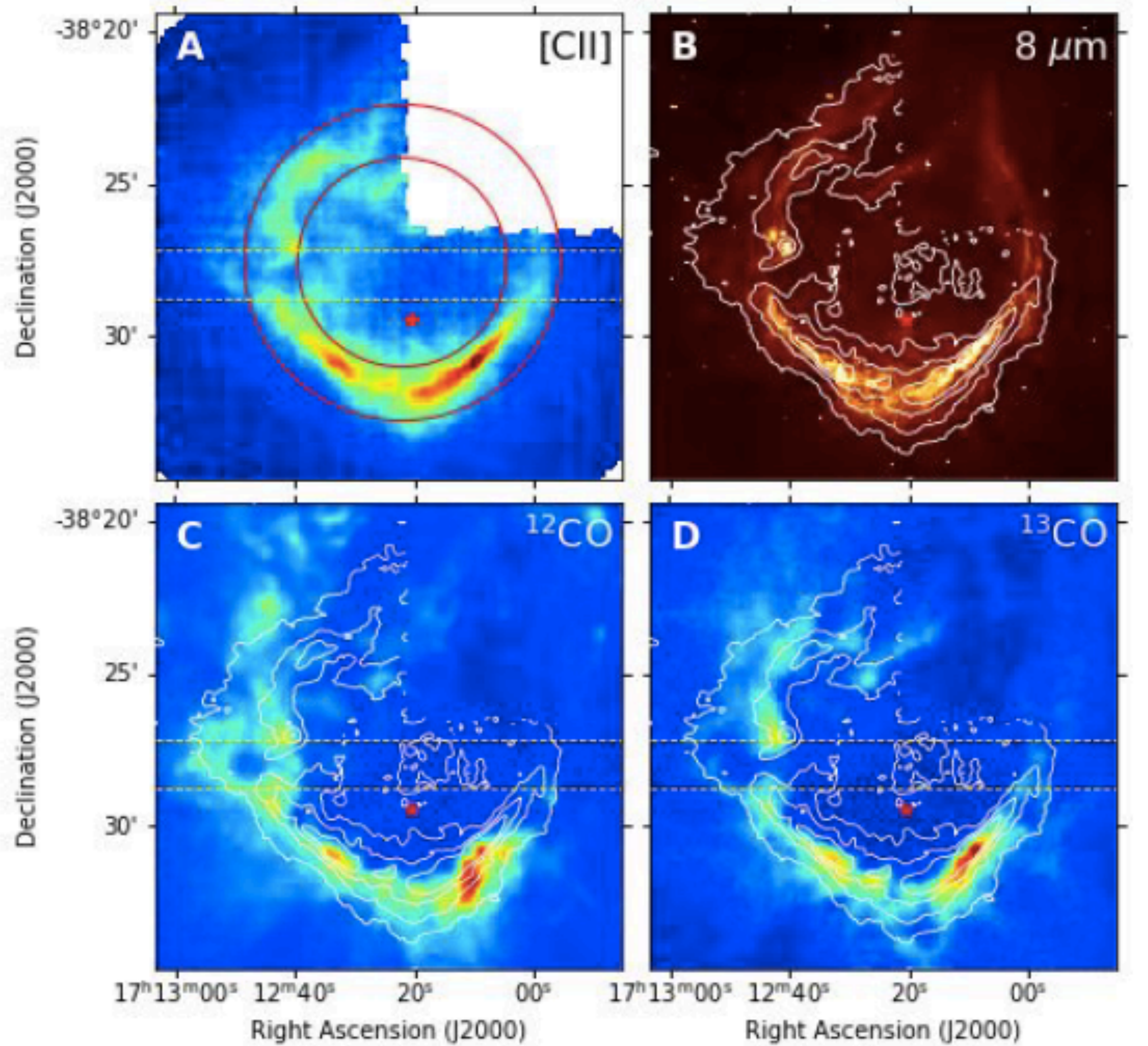
RCW 120



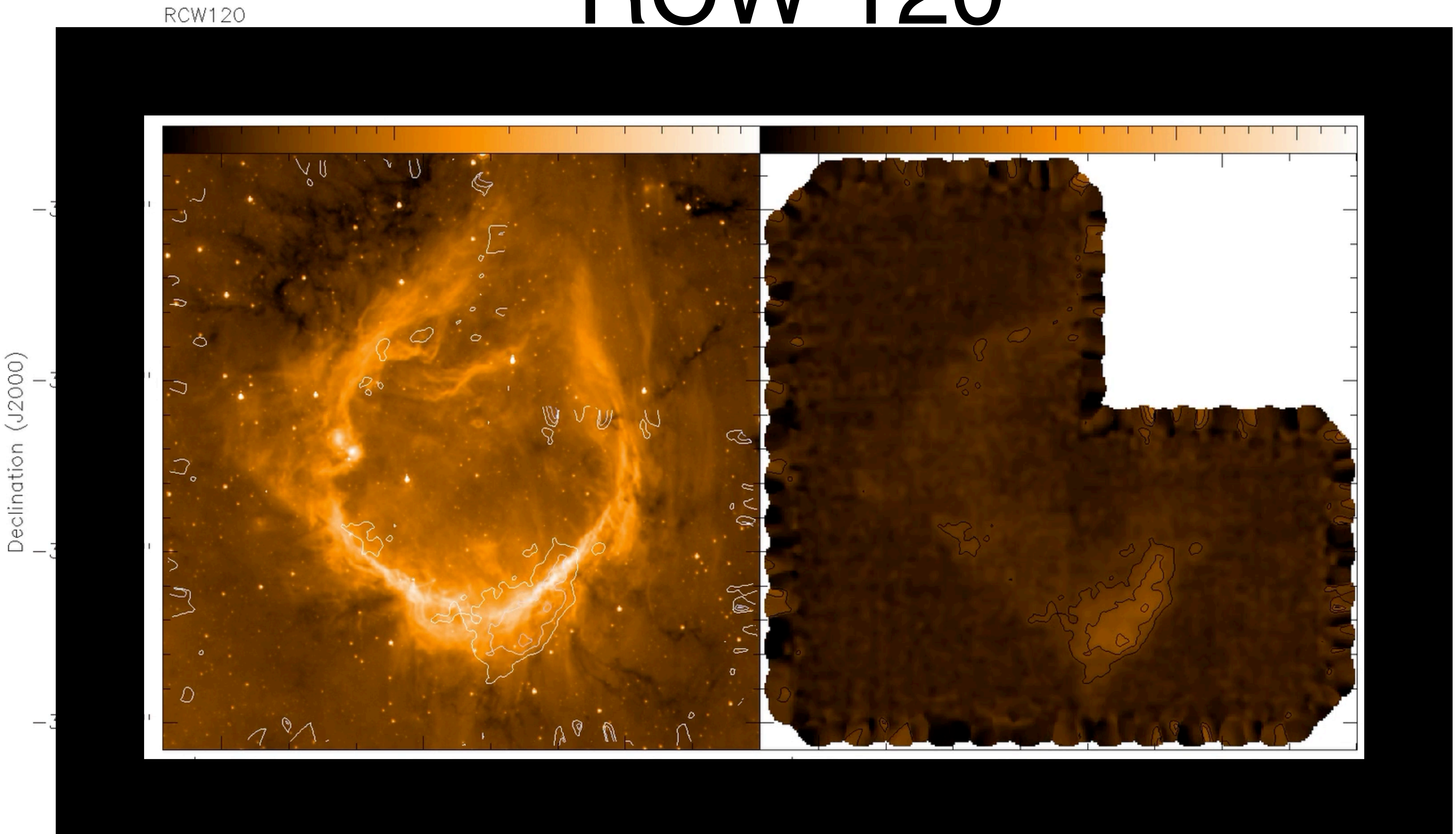
O8V star with a stellar wind
moving through a molecular cloud at ~4 km/s

RCW 120



Luisi et al 2021, Sci Adv, 7, 9511

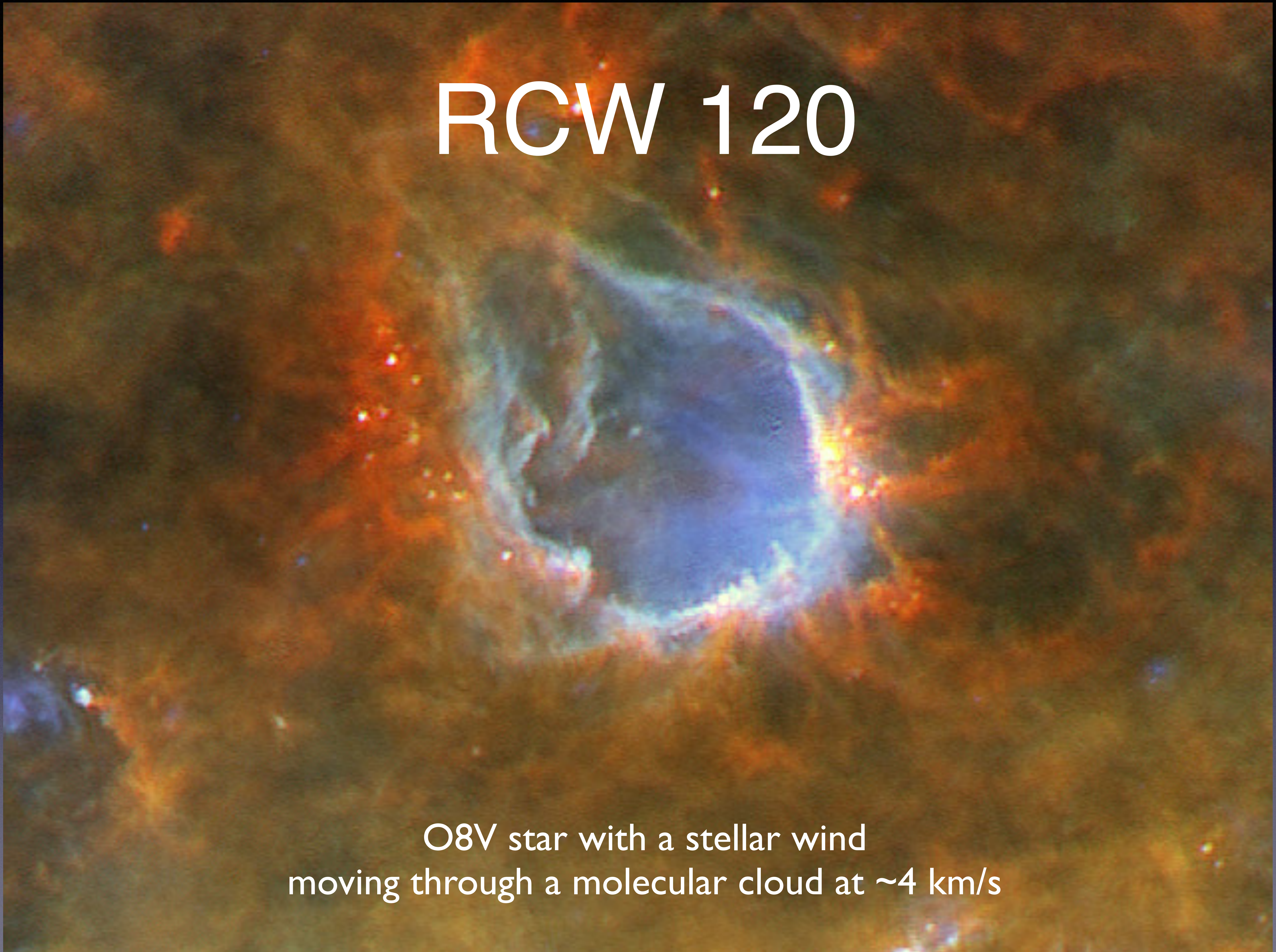
RCW 120



RCW 120

- Rapidly expanding bubble (15 km/s)
- Driven by the stellar wind
- ~150,000 yr old
- Breached toward the Northeast and toward the North
- Star formation has been triggered in the swept-up shell
- Mass of the shell: 2000 $M_{\odot}$ dust; 500 $M_{\odot}$ [CII]; 1500 $M_{\odot}$ CO

RCW 120



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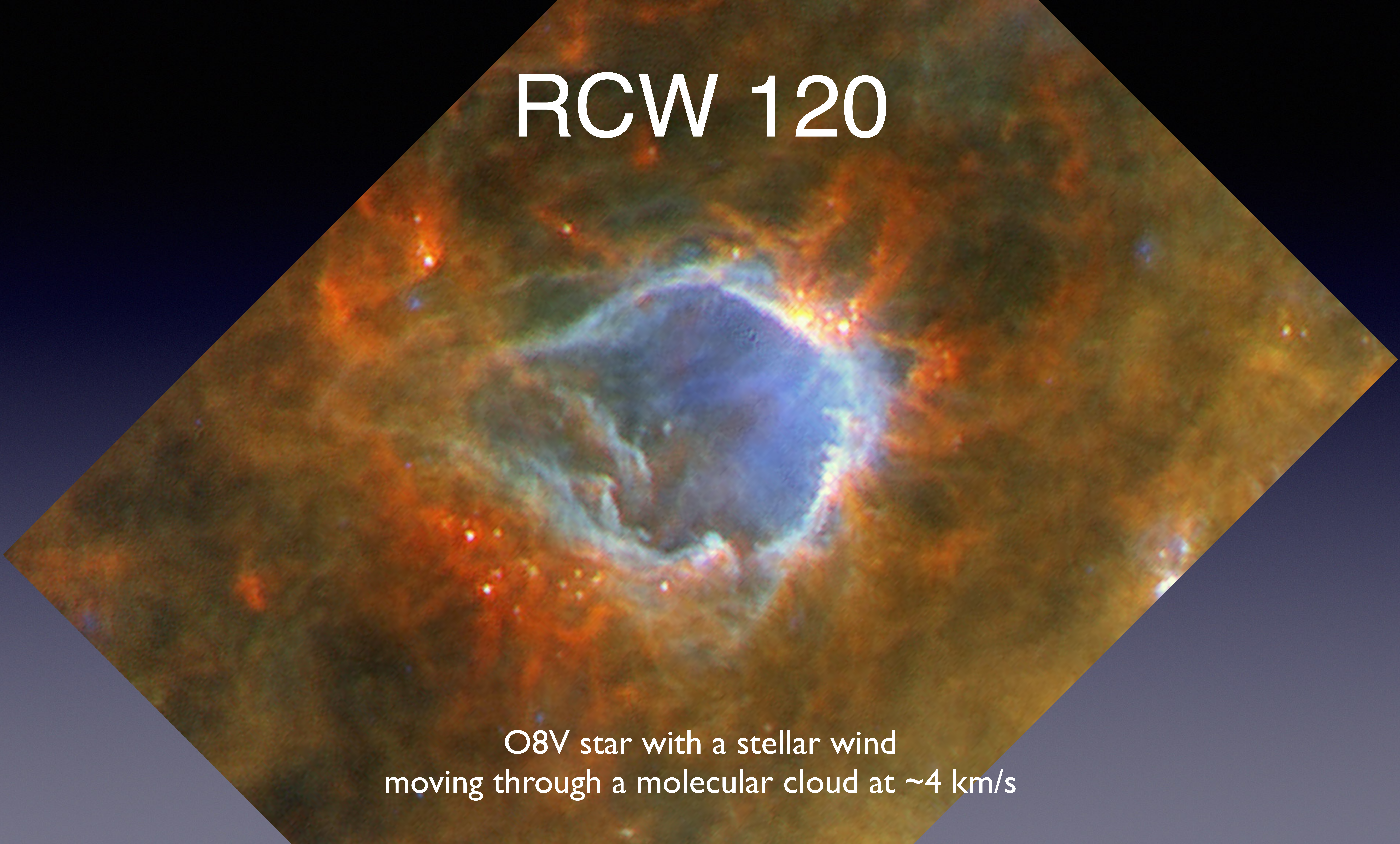

O8V star with a stellar wind
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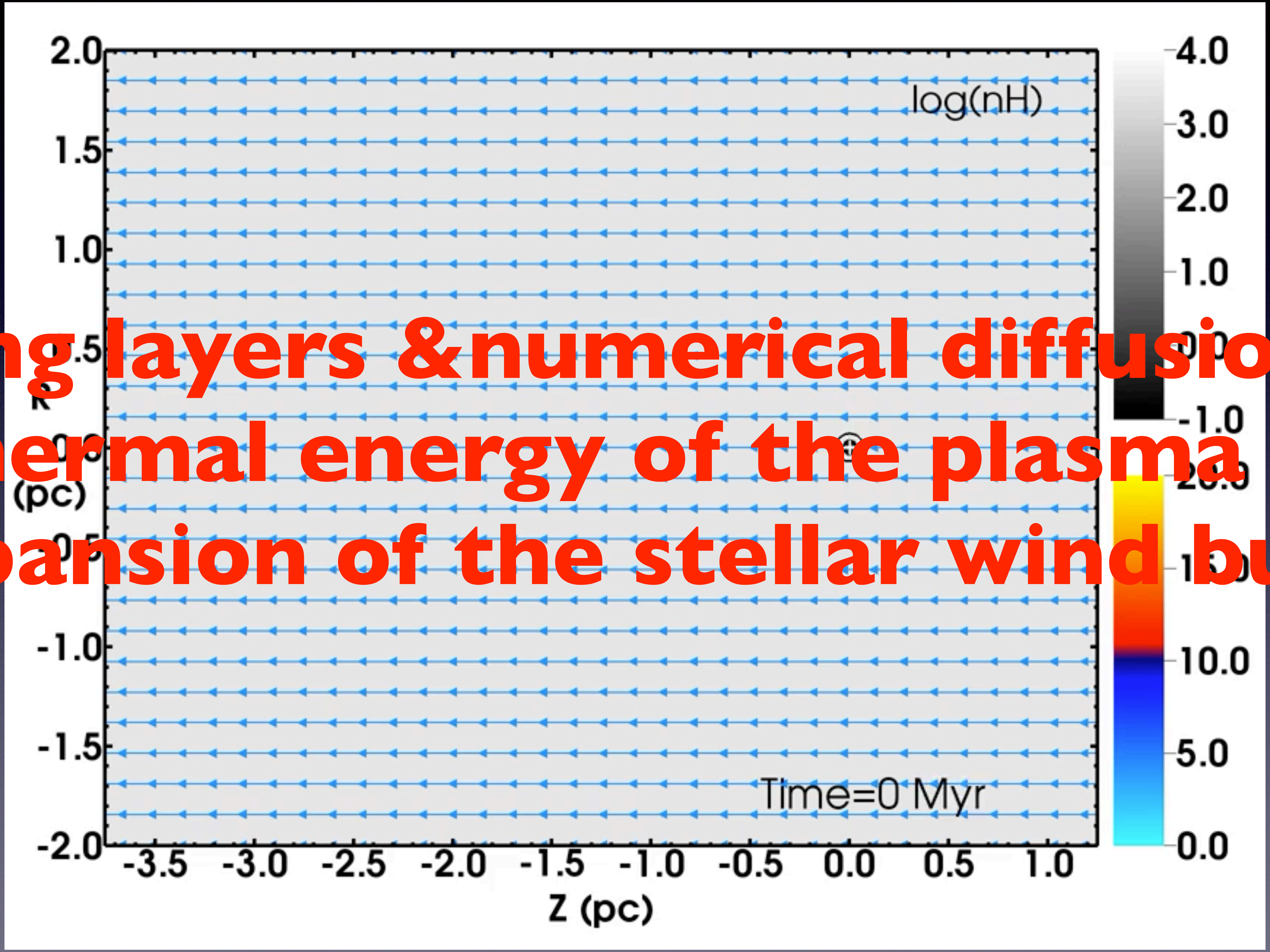
RCW 120 Simulation



Mixing layers &numerical diffusion limit the thermal energy of the plasma and the expansion of the stellar wind bubble

Mackey et al, 2015, A&A, 573, A10

“like a hell-broth boil and bubble”

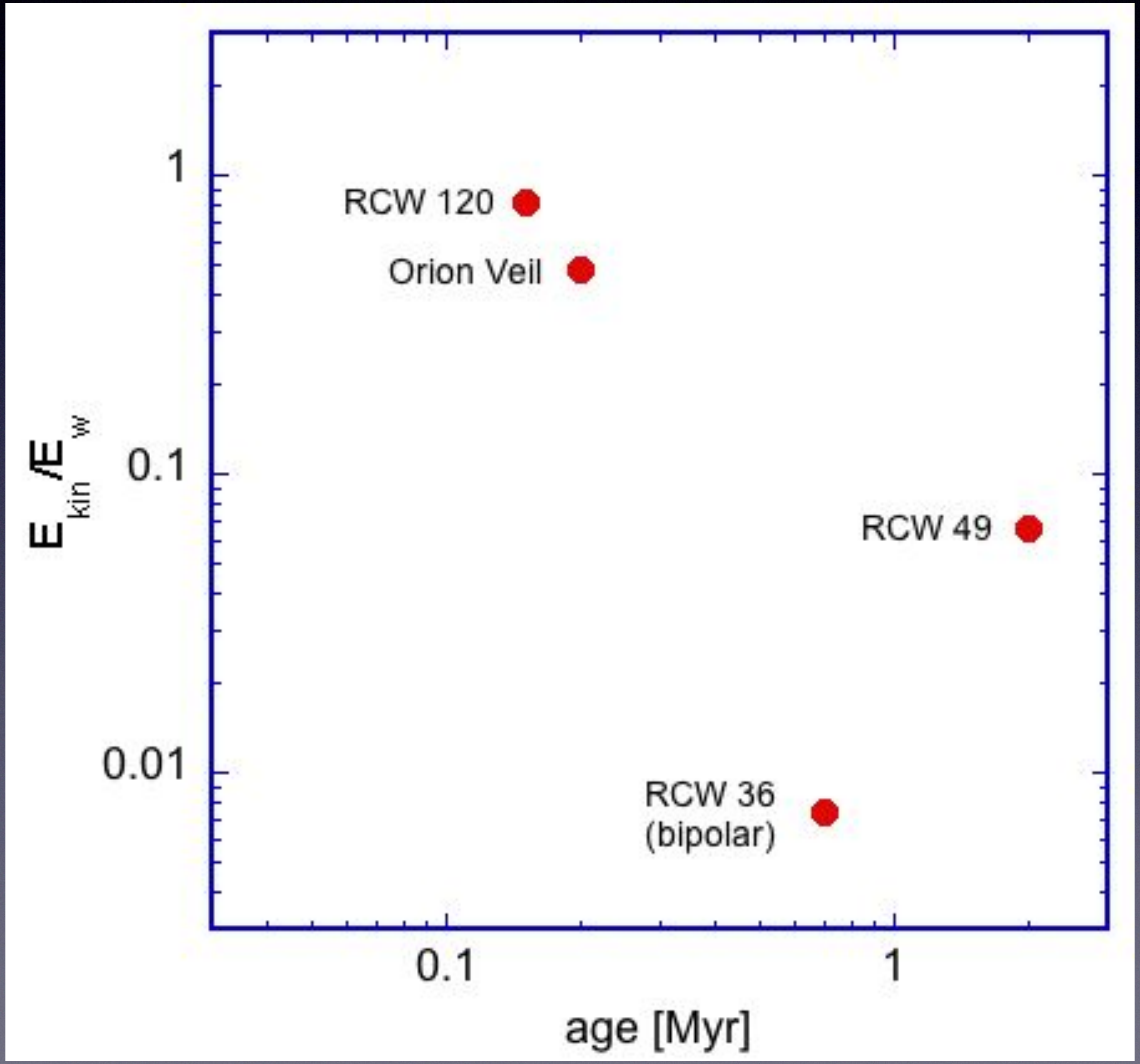
Component		NGC 1977	M43	RCW 36	RCW 120	M42 (Veil)	RCW 49
Spectral Type		B1V	B0.5V	O9V & O9.5V	O8V	O6.5V	40OB & 2WR
N_{Lyc}	10^{47} s^{-1}	1	1.5	6	38	70	3,900
L_{wind}	$L_\odot$	0.02	0.02	350	80	210	2,500
neutral mass	$M_\odot$	700	7	1000	500	1500	24,000
ionized mass	$M_\odot$	16	0.3	20	26	24	470
v neutral	km/s	1.5	6	bipolar	15	13	13
E_{kin}, neutral	10^{46} erg	2	0.3	22	120	250	4000
$E_{thermal}$, ionized	10^{46} erg	5	0.7	3.5	5	3	95
$E_{thermal}$, plasma	10^{46} erg	–	–	13	17	10	280
L_{FIR}	10^4 $L_\odot$	1.5	1.6	13	9.1	3.2	1200
L_{CII}	10^4 $L_\odot$	0.014	0.004	0.03	0.07	0.017	0.009
age	Myr	0.4	0.02	0.7	0.15	0.2	2
Expansion		Spitzer	Spitzer	stellar wind	stellar wind	stellar wind	stellar wind

Pabst+, 2019, Nature, 565, 618; 2020, A&A, 639, 2: Luisi+, 2021, Sci Adv, 7, 9511; Tiwari+, 2021, ApJ, 914, 117; Bonne+, 2022, in press

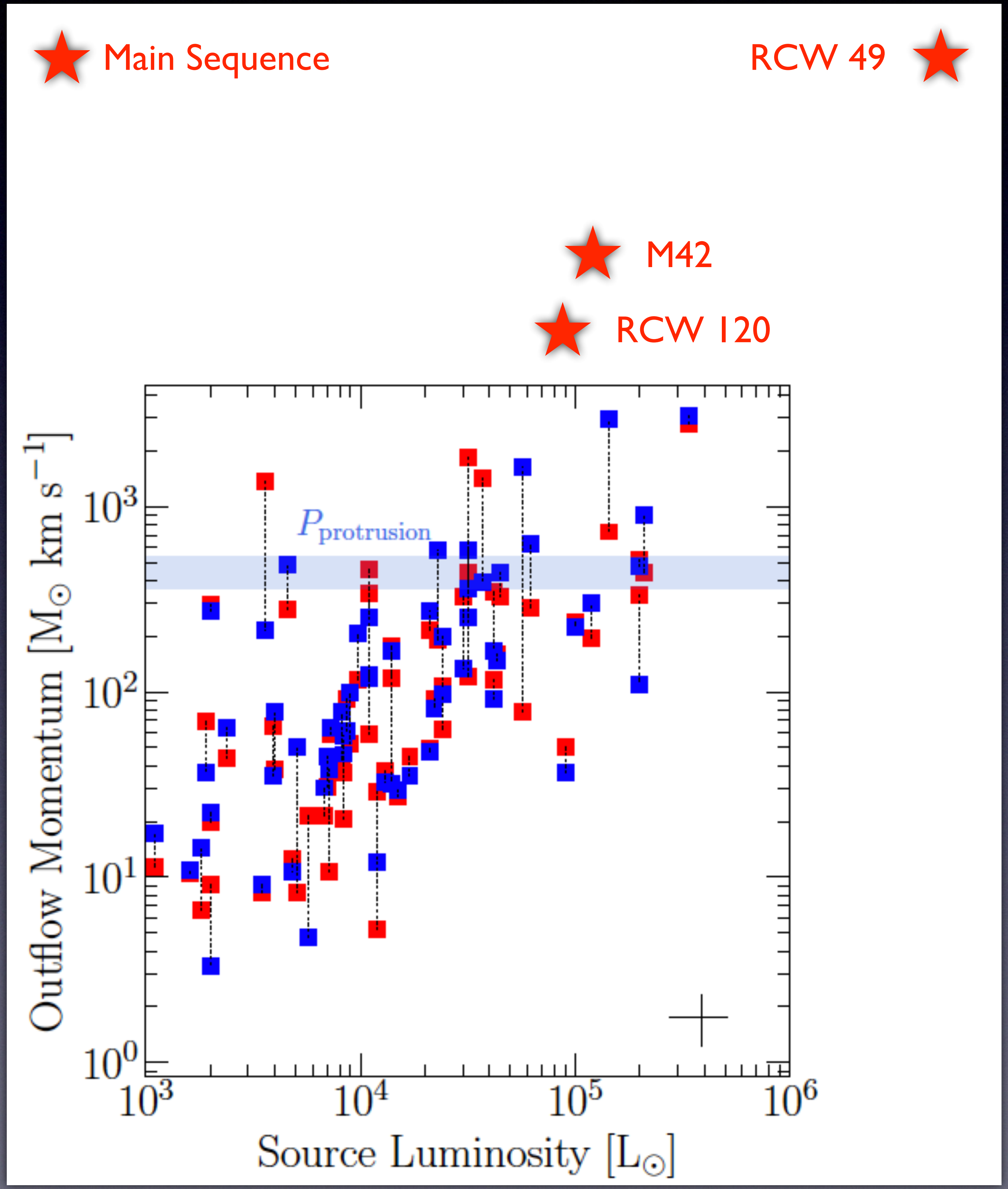
Feedback Energetics

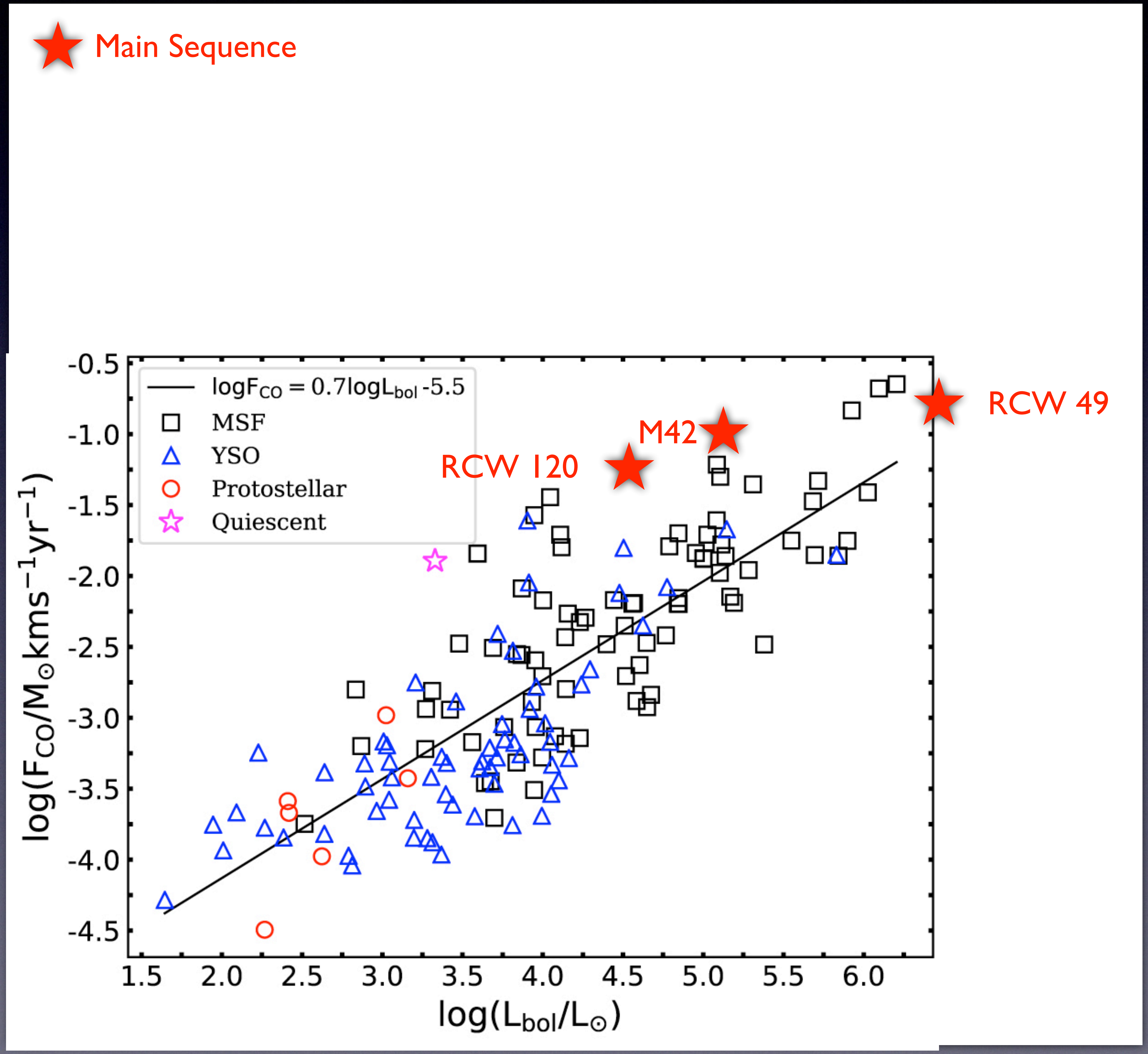
Initial phase: stellar wind energy drives expansion

After 300,000 yr (?), bubble burst and shell coasts



Protostellar & Main Sequence Feedback





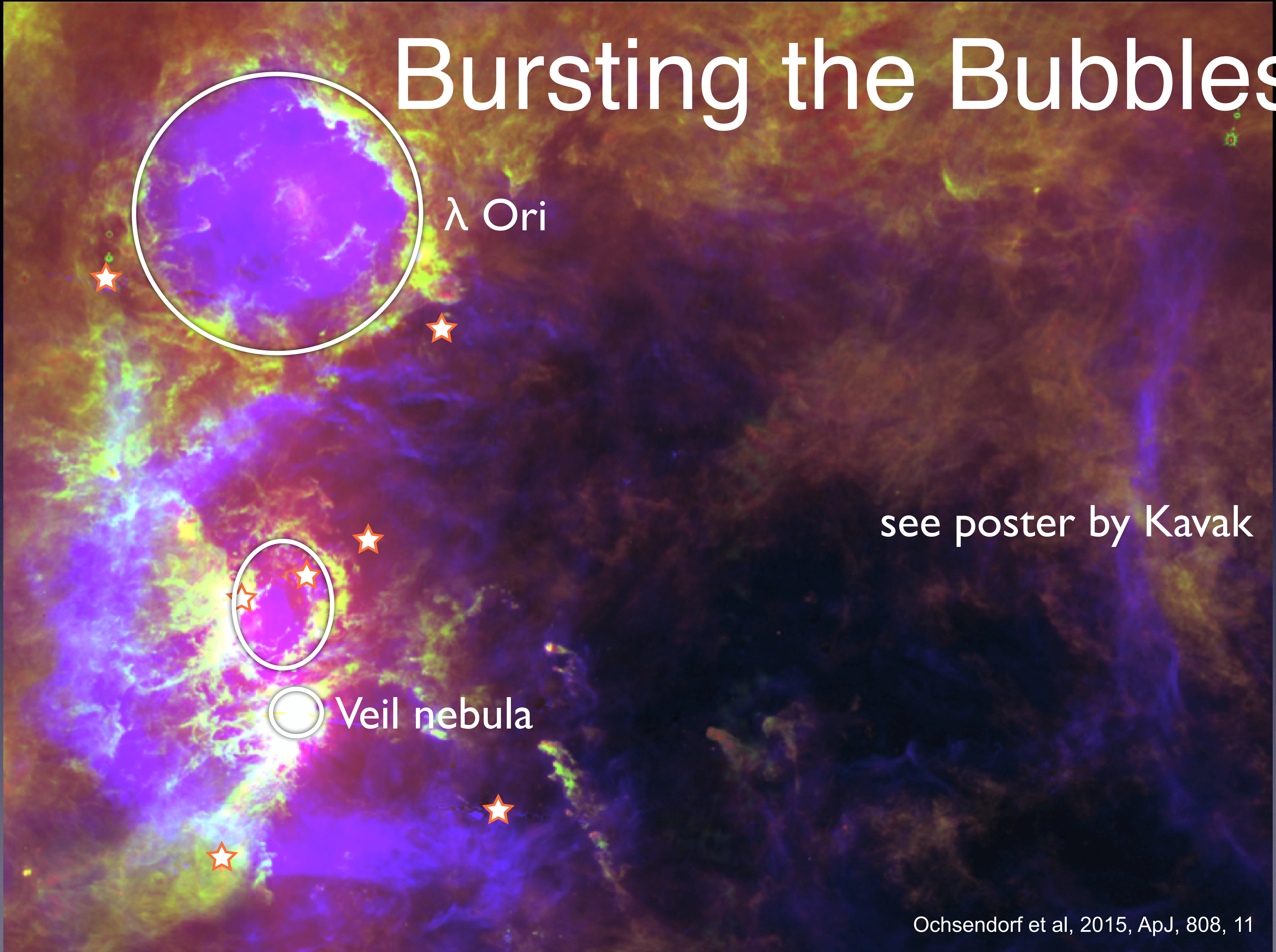
See also: Poster by Kavak

Kavak+ 2022, in press
Yang+ 2018, ApJS, 235, 3

Energetically, main sequence feedback dominates but protostellar feedback sets the stage

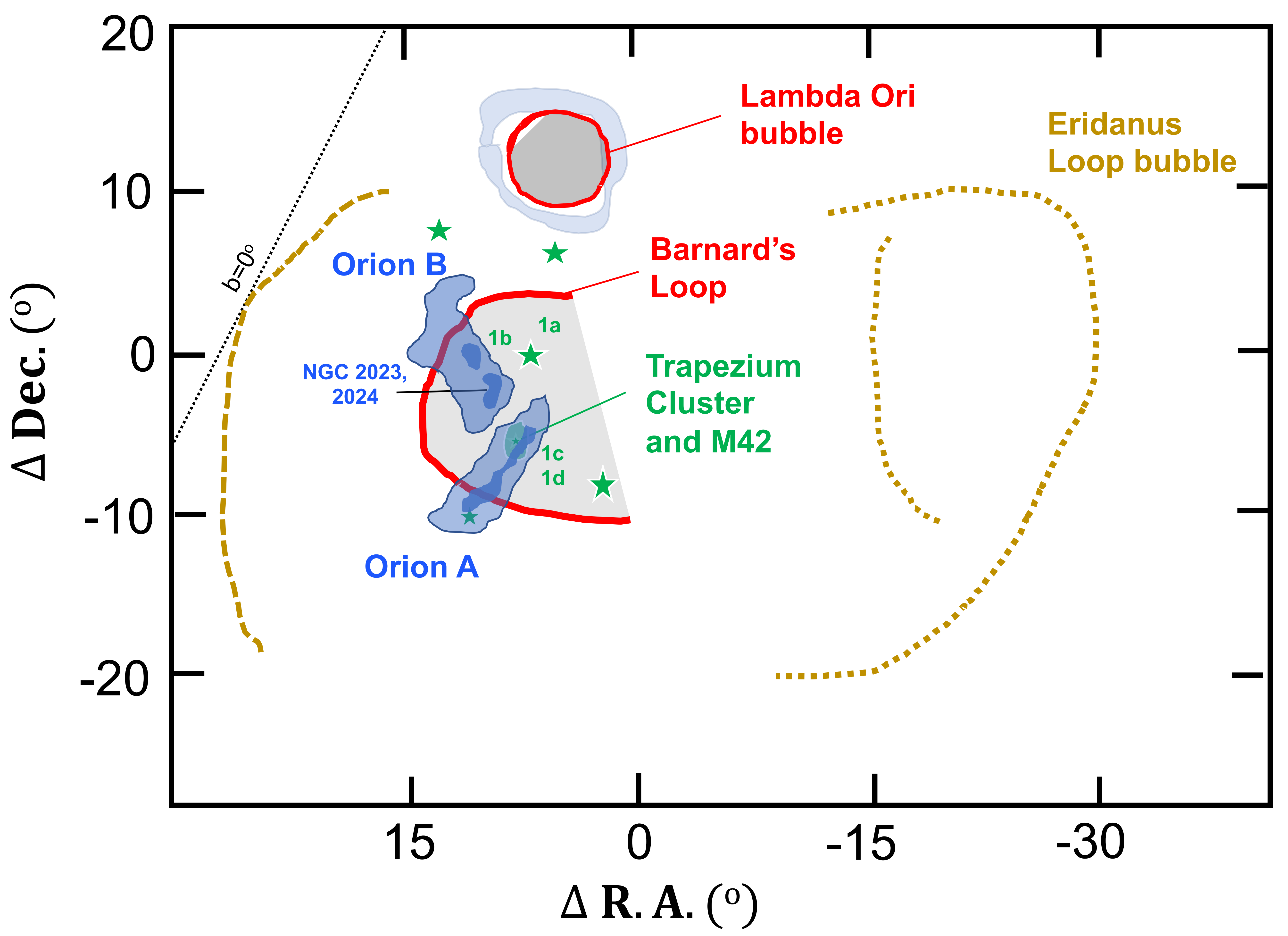
Kavak+ 2022, in press

Bursting the Bubbles



Ochsendorf et al, 2015, ApJ, 808, 11

The Veil & the Ecology of the Galaxy



Radiative Feedback

PDRs Galore

Orion & Feedback studies:

Orion: Pabst+, 2022, A&A, 658, 98
RCW 120: Kabanovic+, 2022, A&A, in press
Tiwari+, 2022, in prep

See Poster by Marc Pound on the PDRtoolbox

PDR review: Wolfire, Vallini & Chevance, 2022, ARAA, in press

Photo-electric Heating

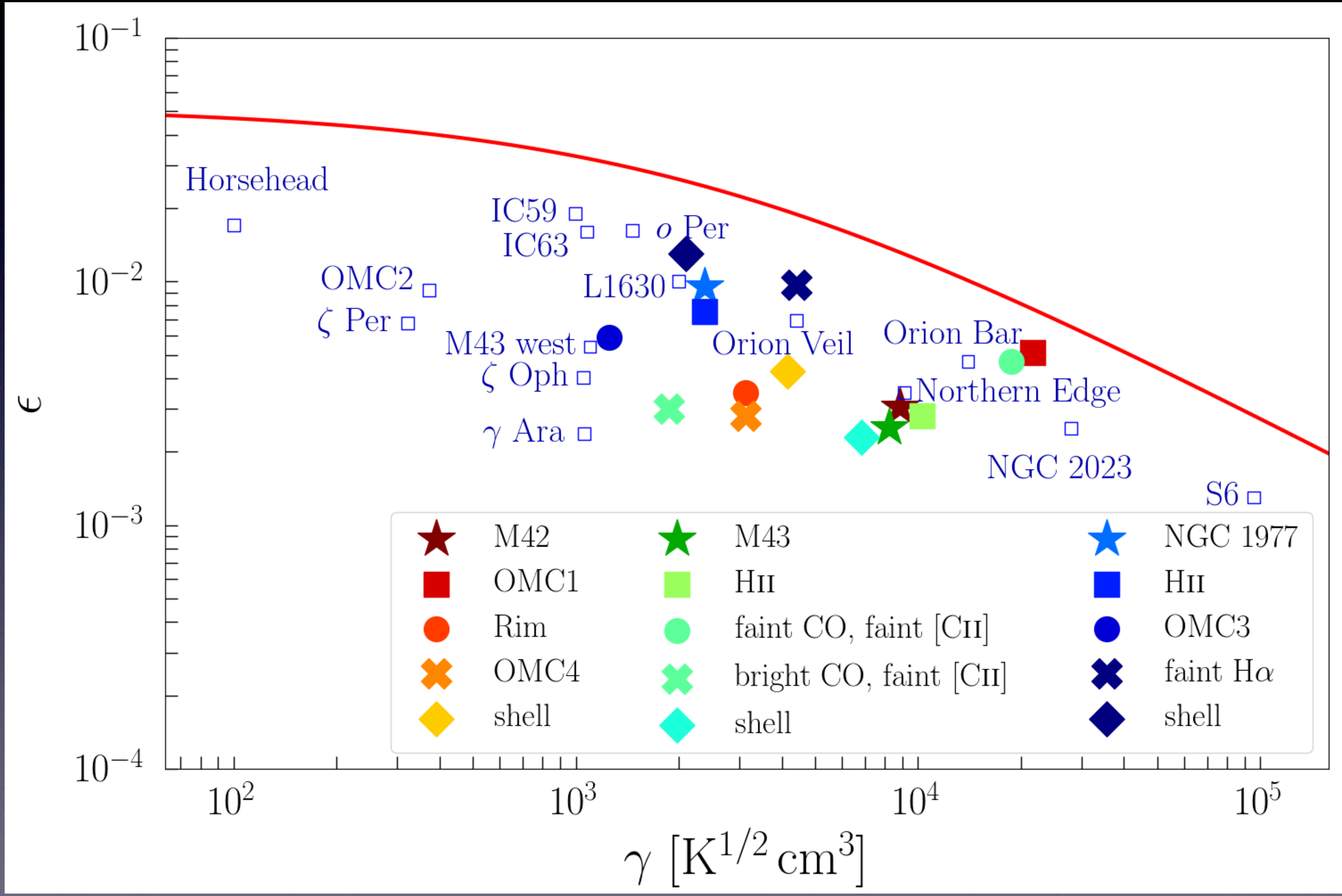
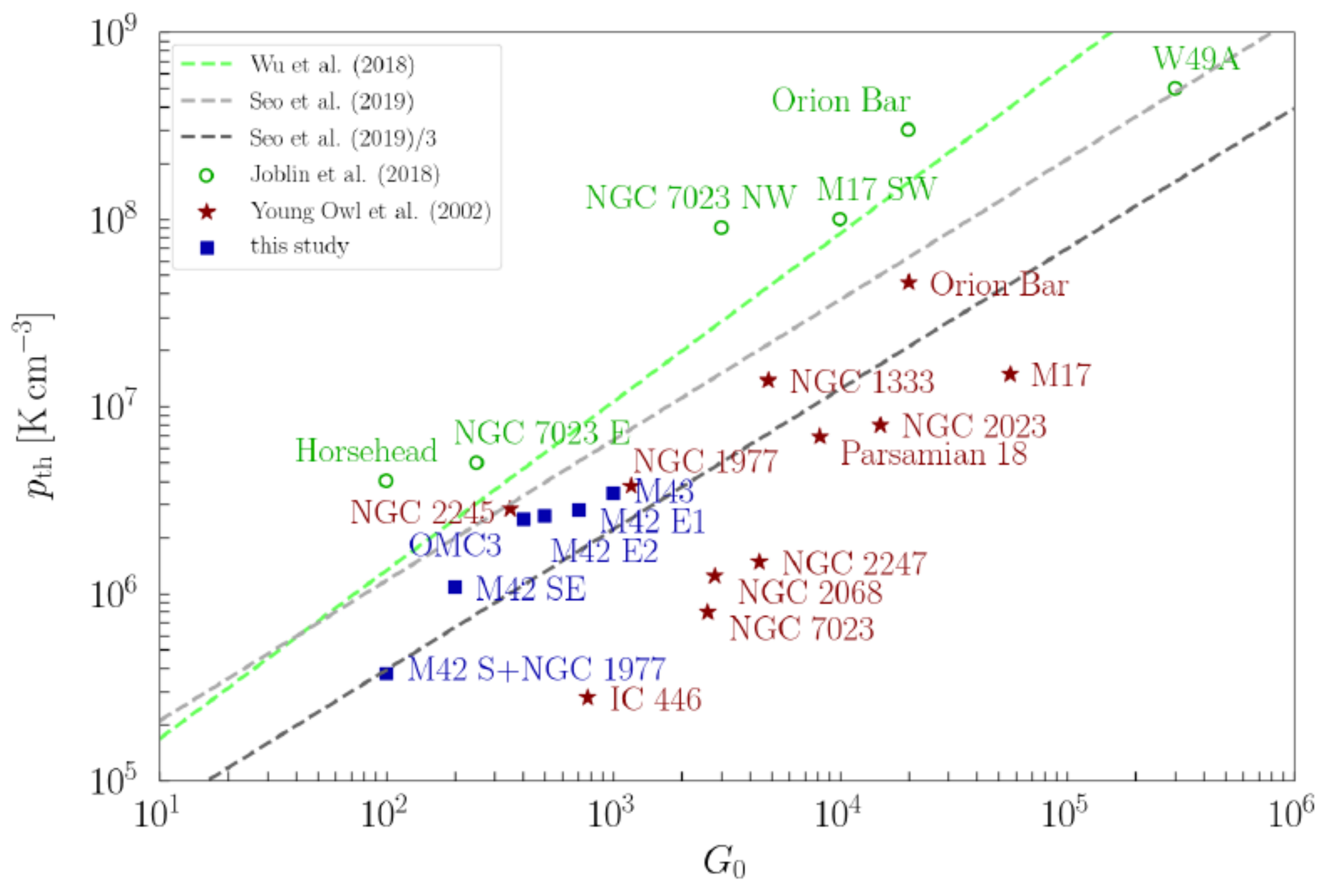


photo-electric efficiency

ionization parameter

Pabst+, 2022, A&A, 658, 98
Bakes+, 1994, ApJ, 427, 822

Characteristics of PDRs



Stromgren relation & pressure equilibrium ?

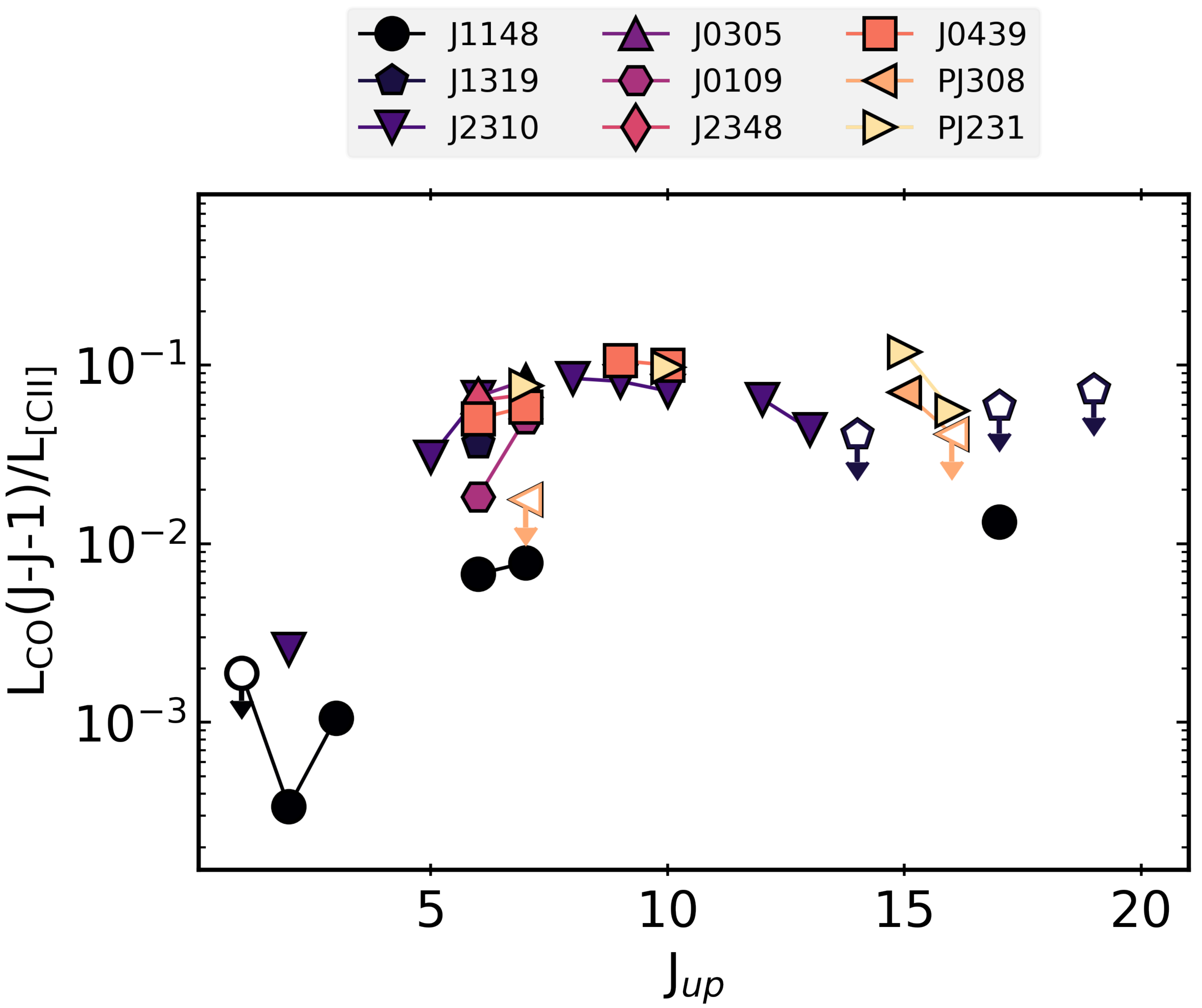
Pabst+, 2022, A&A, 658, 98
Young Owl+2002, ApJ, 578, 885
Seo+, 2019, ApJ, 878, 120

PDRs in the high-z Universe

AGN versus star formation (XDRs vs PDRs) Traced through high J CO vs [CII]

- Large colored symbols: Quasars at z>6

-



Vallini+, 2022, in prep
Vallini+, 2019, MNRAS, 490, 4502

PDRs in the high-z Universe

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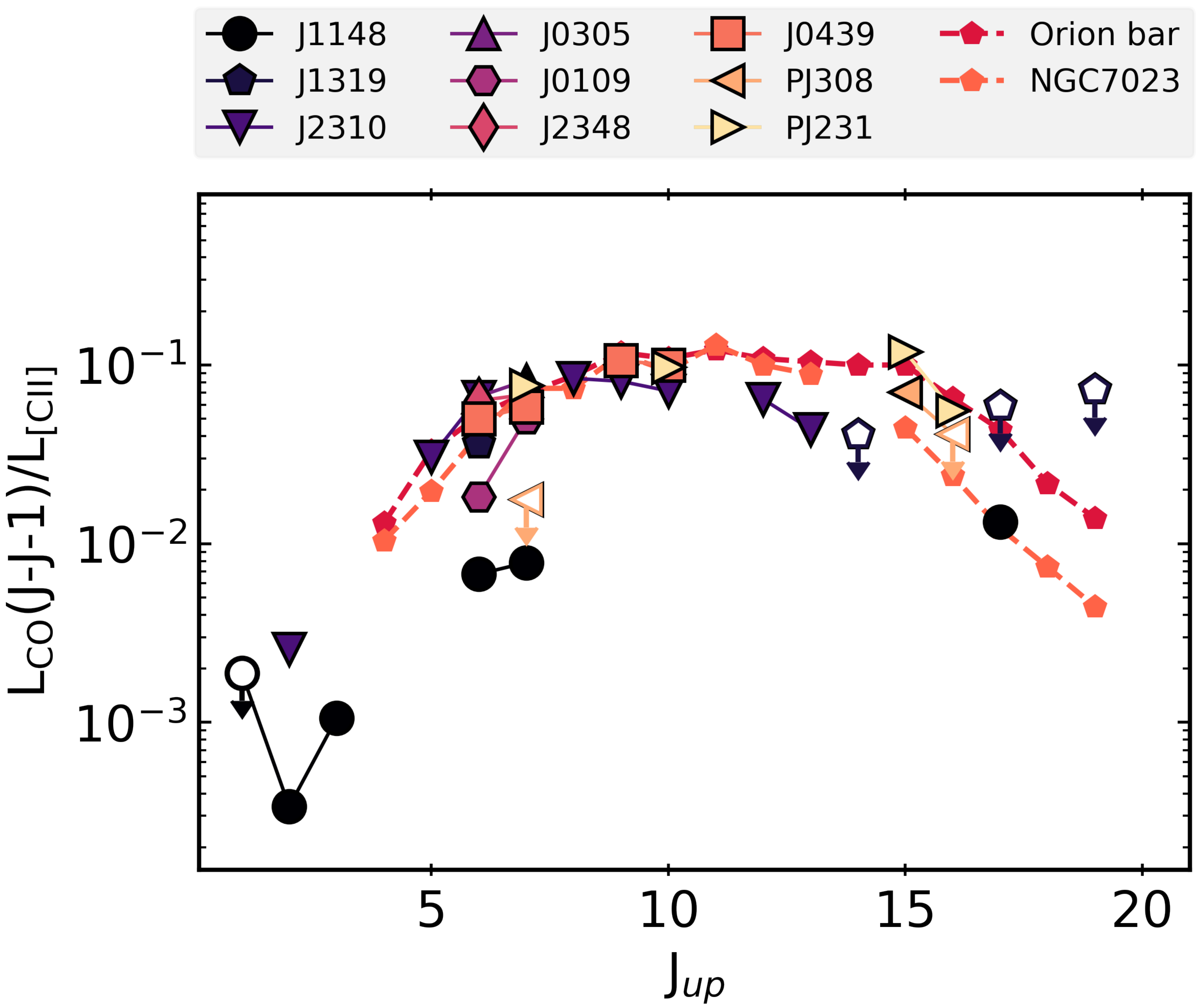
- Orange/red dots: galactic PDRs
-



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- colored shading: (U)LIRG CO ladder classification
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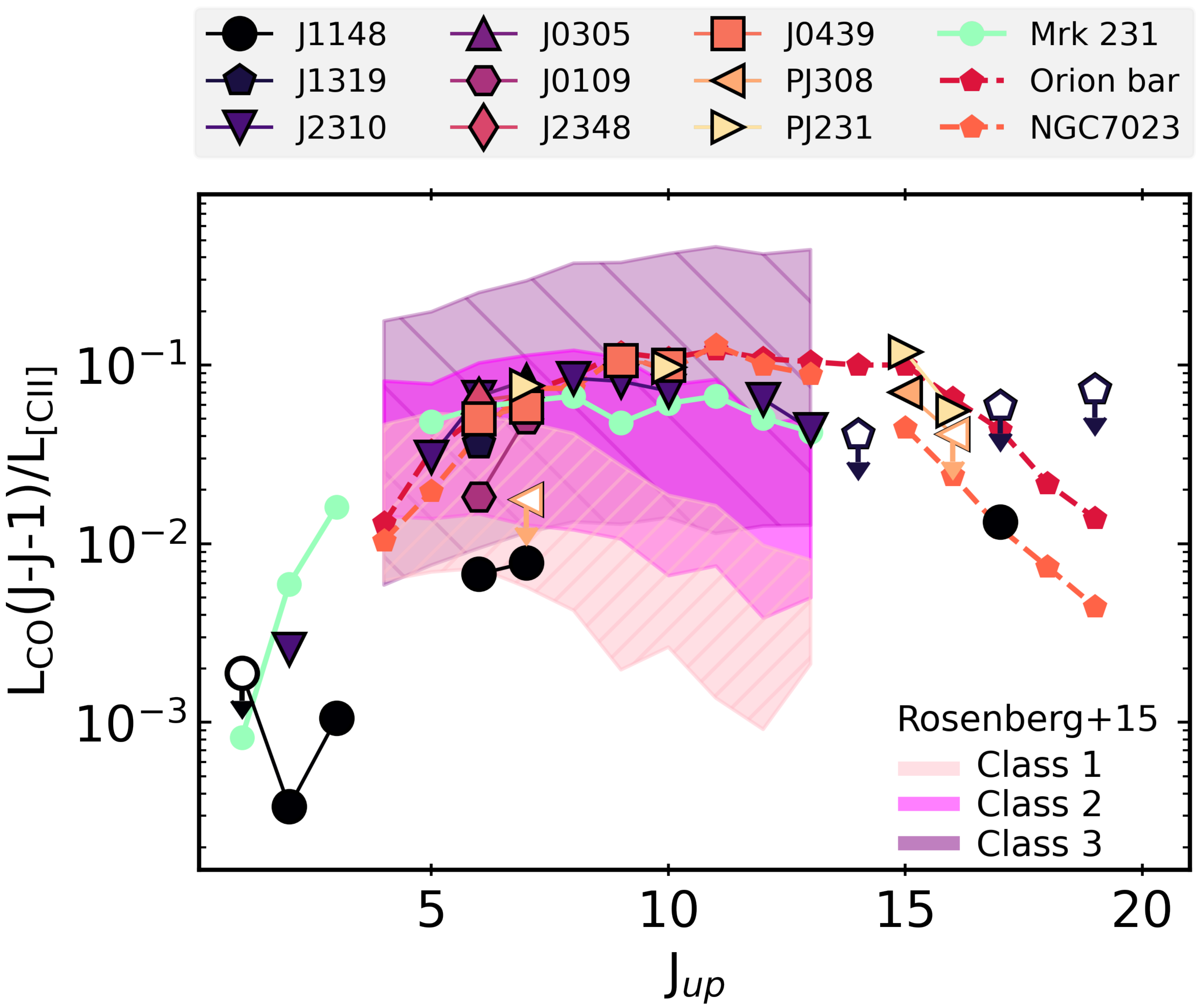

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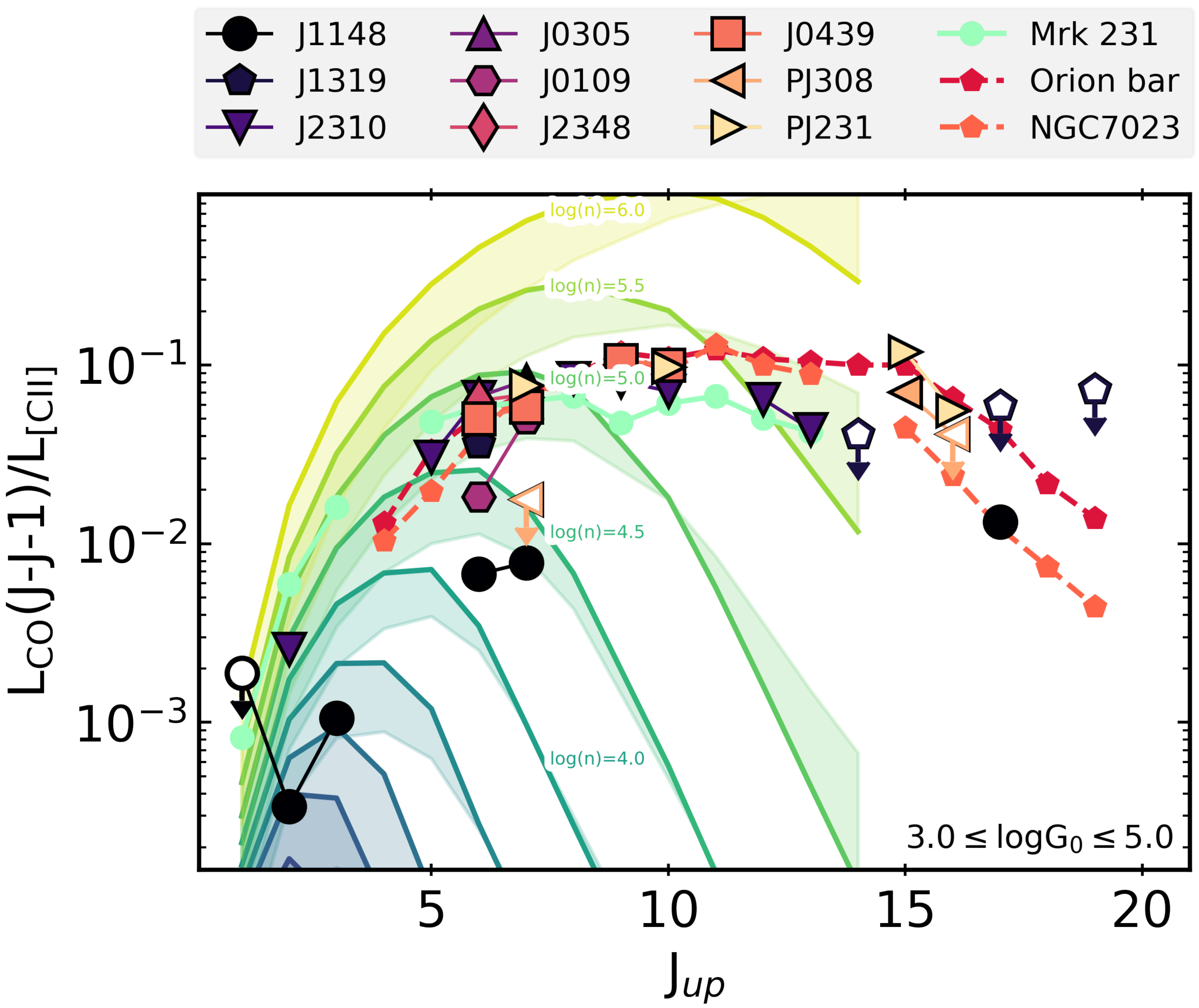
- PDR models



Vallini+, 2022, in prep
Vallini+, 2019, MNRAS, 490, 4502

Summary

- **Early on, mechanical feedback is dominated by stellar winds**
  - **Early B stars: Spitzer type expansion**
  - **O stars: Stellar wind mechanical energy couples efficiently to shell until the bubble bursts**
- **Disruption of molecular core/triggered star formation depends on environment**
- **How important are magnetic fields ? When does radiation pressure become important ?**
- **SNe are the “street sweepers” of the Milky Way: key to large scale structures and circulation to the halo**
- **Radiative feedback: We will provide a broad sample of well-studied galactic PDRs and much insight in their characteristics**

SOFIA is “heaven-made” for feedback studies

A big thanks to the SOFIA team, the upGREAT team, and the students & postdocs revealing the [CII] Universe