Feedback by Massive Stars and the Ecology of Galaxies

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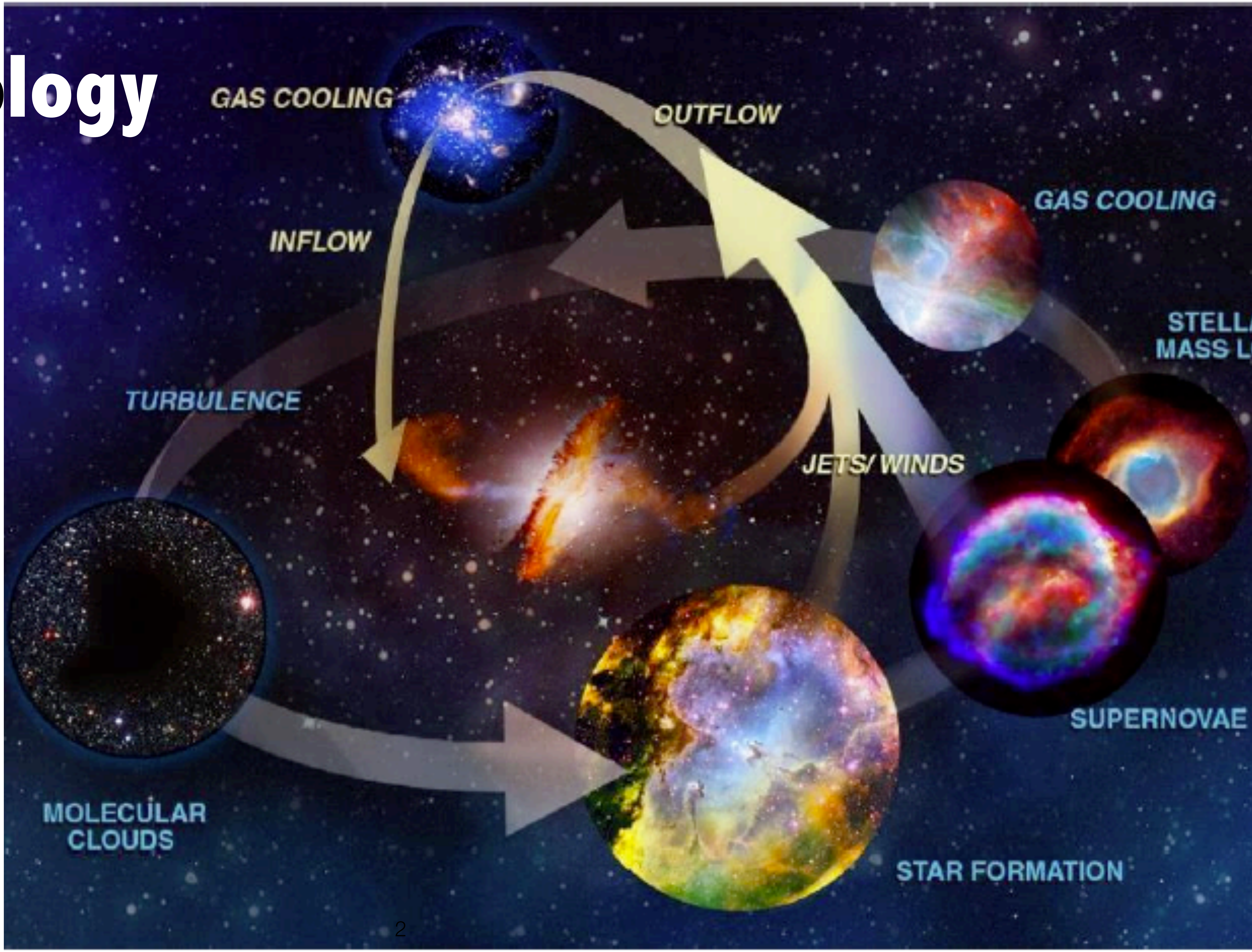
image credit: Kim Emig

Galactic Ecology

The lifecycle of material from stars to the ISM and back to stars & the interaction of stars with their environment determines the characteristics of the ISM and drives the evolution of galaxies



Mass Contributions to the ISM

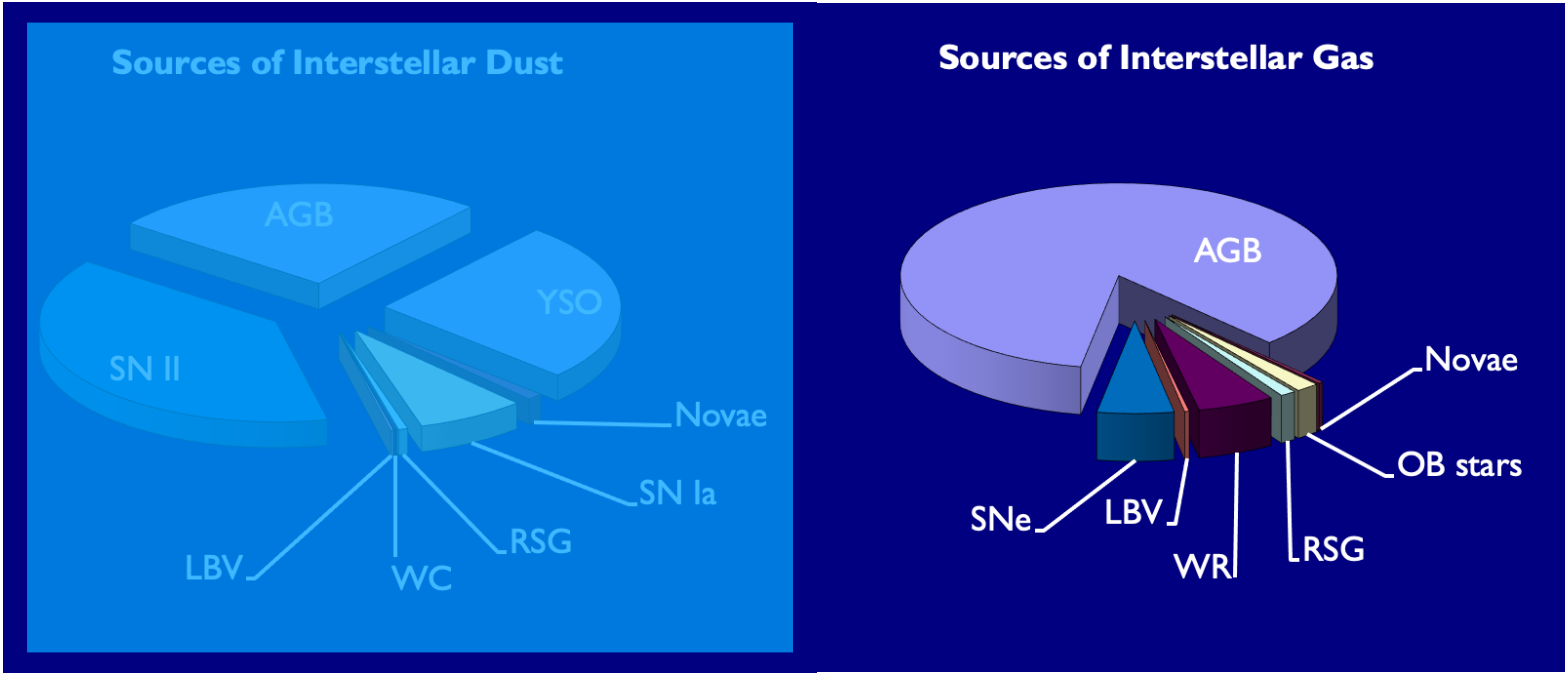


Table 1.4 in Tielens 2010

Mass Contributions to the ISM

Source	$\dot{M}_H^a$ [$M_\odot$ kpc^{-2} Myr^{-1}]	$\dot{M}_c^b$ [$M_\odot$ kpc^{-2} Myr^{-1}]	$\dot{M}_{sil}^c$ [$M_\odot$ kpc^{-2} Myr^{-1}]
C–rich giants	750	3	–
O–rich giants	750	–	5
Novae	6	0.3	0.03
SN type Ia	–	0.3^d	2^d
OB stars	30	–	–
Red supergiants	20	–	0.2
Wolf Rayet	100^e	0.06^f	–
SN type II	100	2^d	10^d
Star formation	–3000	-	-
Halo circulation[f]	7000		
Infall[g]	150		

[a] Total gas mass injection rate.
[b] Carbon dust injection rate.
[c] Silicate and metal dust injection rate.
[d] Fraction and composition of of dust formed in SN is presently unknown. These values correspond to upper limits.
[e] Dust injection only by carbon–rich WC 8–10 stars.
[f] Mass exchange between the disk and the halo estimated from HI in non-circular orbits and CIV studies.
[g] Estimated infall of material from the intergalactic medium and satellite galaxies.

Table 1.4 in Tielens 2010

Mass Contributions to the ISM

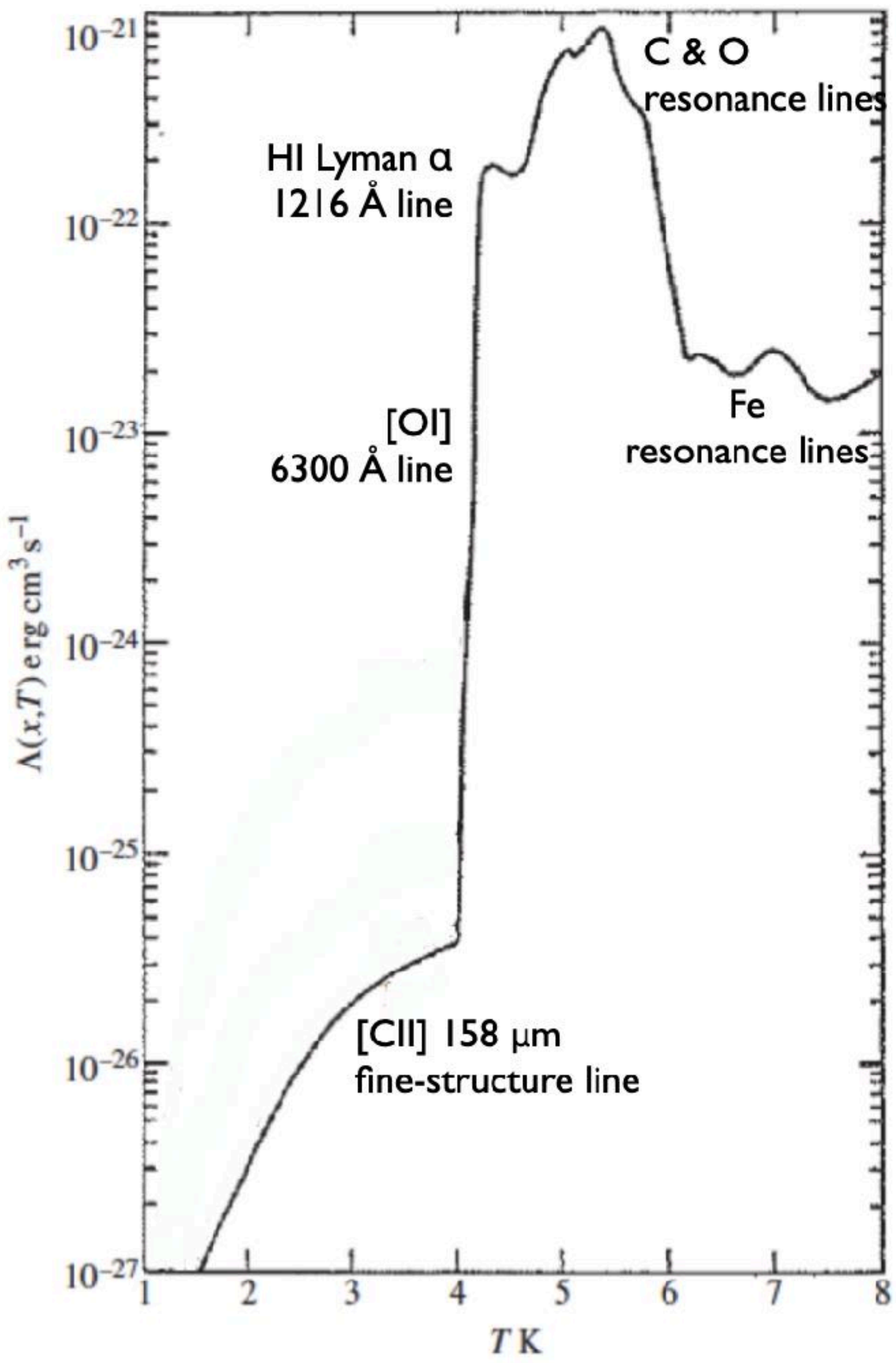
- Milky Way is in approximate steady state where formation of (low mass) stars (astration) is balanced by mass injection from (low) mass stars
- Circulation between the disk and halo is a major mixing process
- Stars are the nuclear caldrons:
  - Elemental enrichment mainly originates from type II SNe (core collapse of massive stars.
  - C has a large contribution from AGB stars (gentle winds from low mass stars)
  - s-process elements from AGB stars
  - r-process elements from neutron star mergers and type II SNe
  - p-process elements from type II SNe
- Many of the heavy elements are injected in the form of dust

Phases of the ISM

Thermal equilibrium: heating equals cooling

$$\mathscr{L} = n\Gamma(T) - n^2\Lambda(T) = 0$$

$$\frac{\Gamma(T)}{nkT} = \frac{\Lambda(T)}{kT}$$



Field et al, 1969, ApJ, 155, L149
Dalgarno & McCray 1972, ARAA, 10, 375

Phases of the ISM

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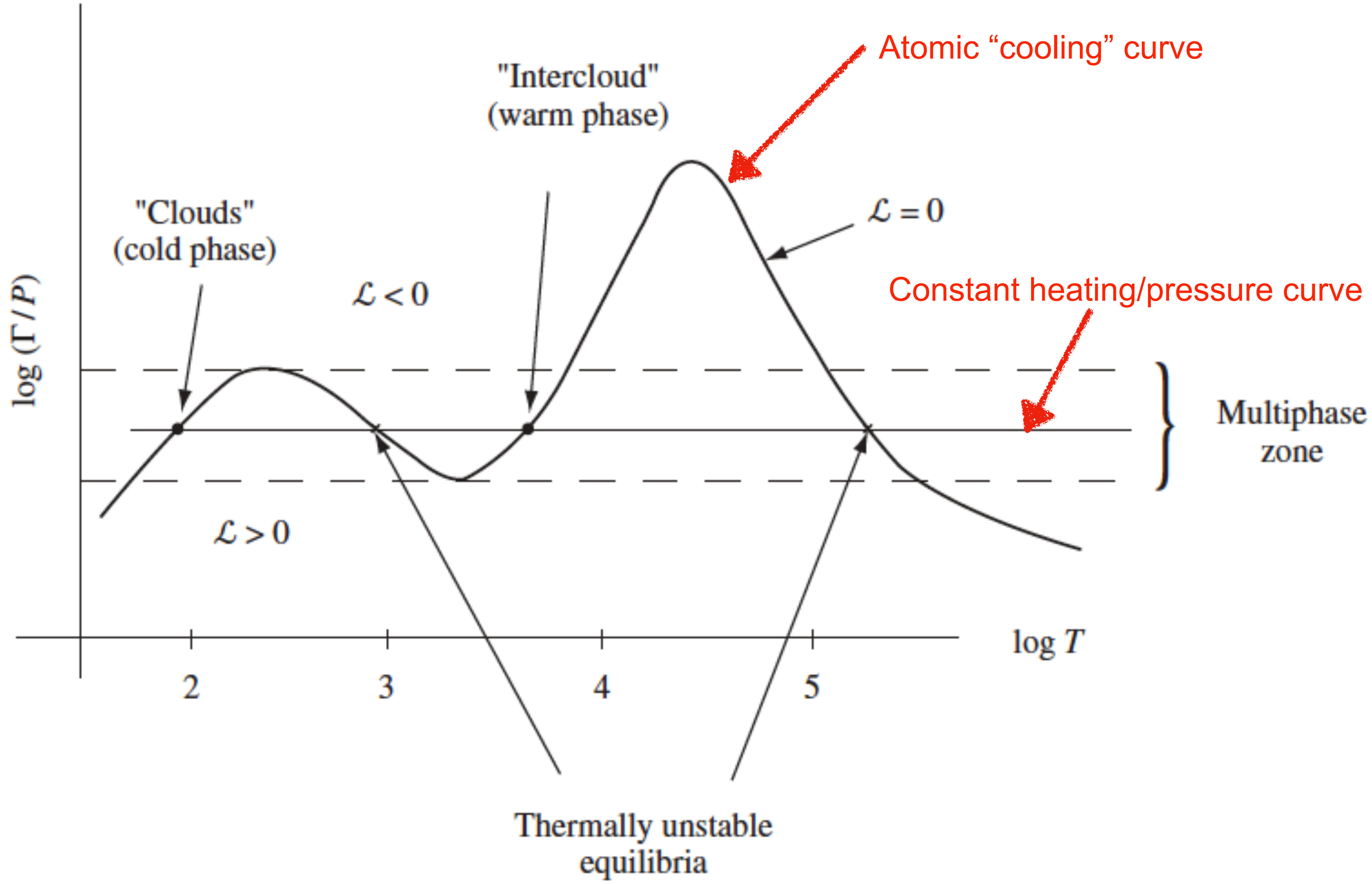


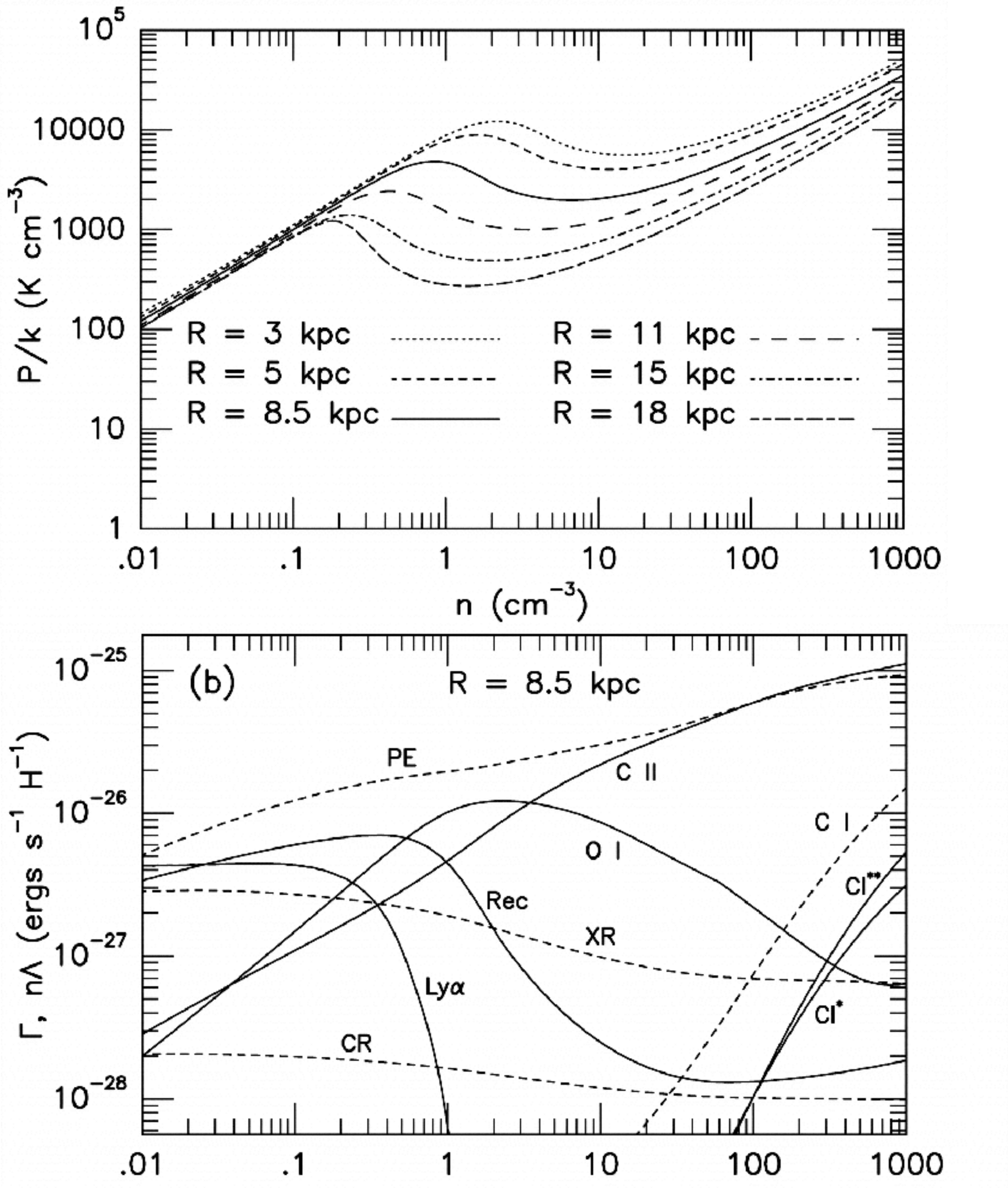
Field et al, 1969, ApJ, 155, L149

Phases of the ISM

Gas in thermal (radiative) & pressure equilibrium can exist in 2 stable phases: Warm Neutral Medium and Cold Neutral medium.

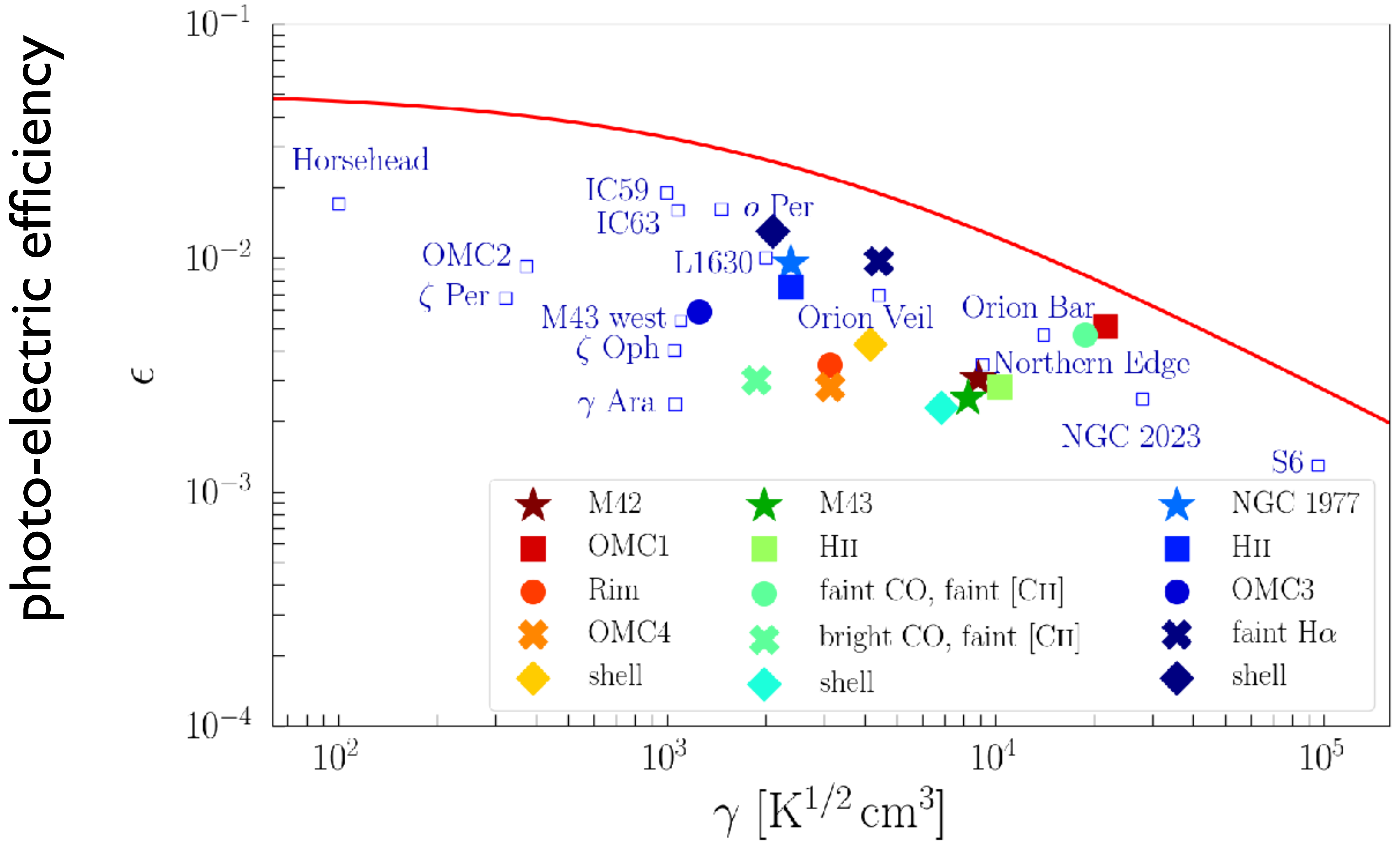
The presence of a Hot Intercloud Medium betrays the importance of kinetic energy input.

Molecular clouds are dominated by gravity.



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

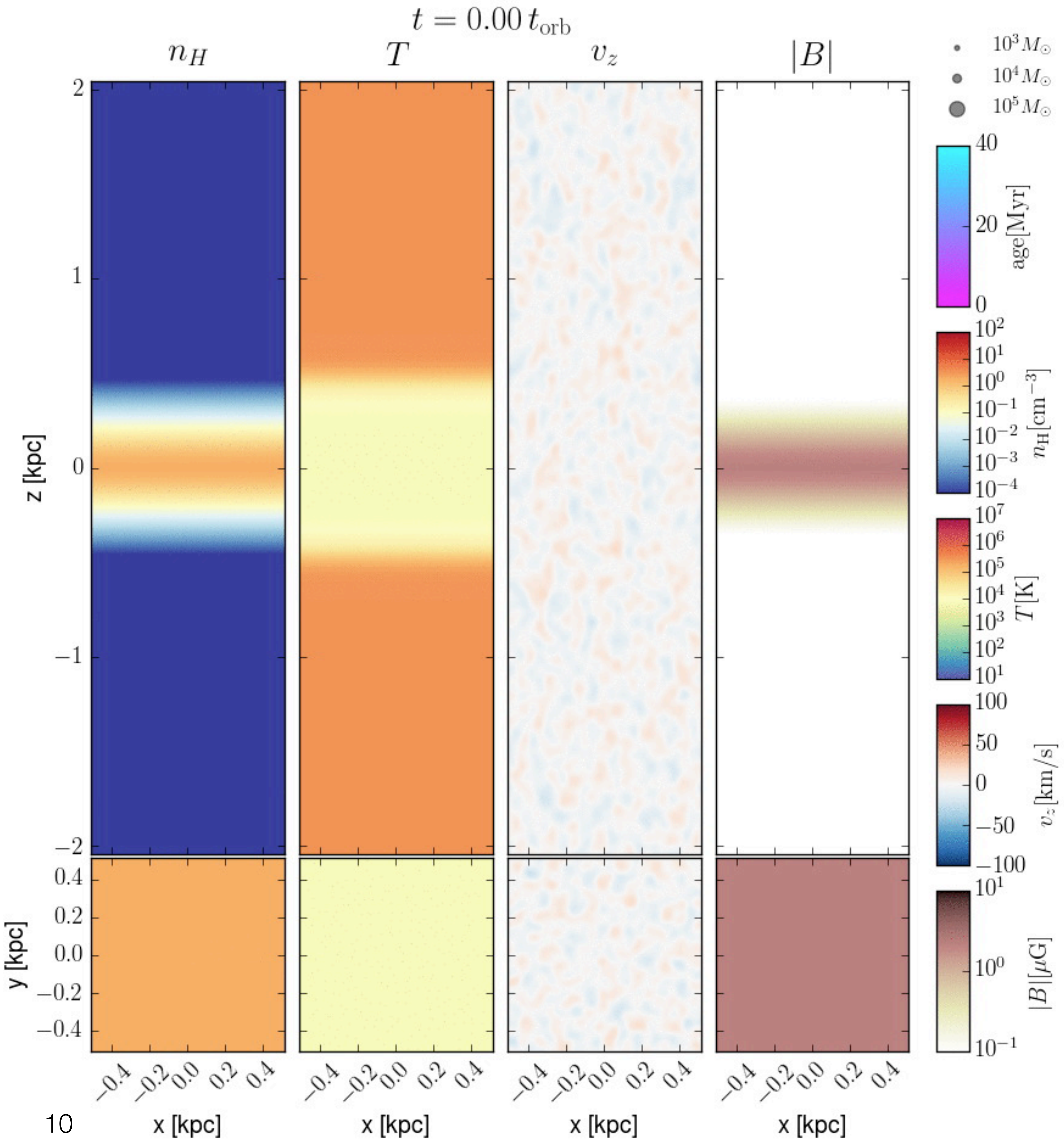
Photo-electric Heating



γ, the ionization parameter =
ionization rate over recombination rate

Salas et al., 2019, A&A, 626, A70
Pabst et al 2022, A&A, 658, A98
Bakes & Tielens 1994, ApJ, 427, 822

Feedback in the ISM



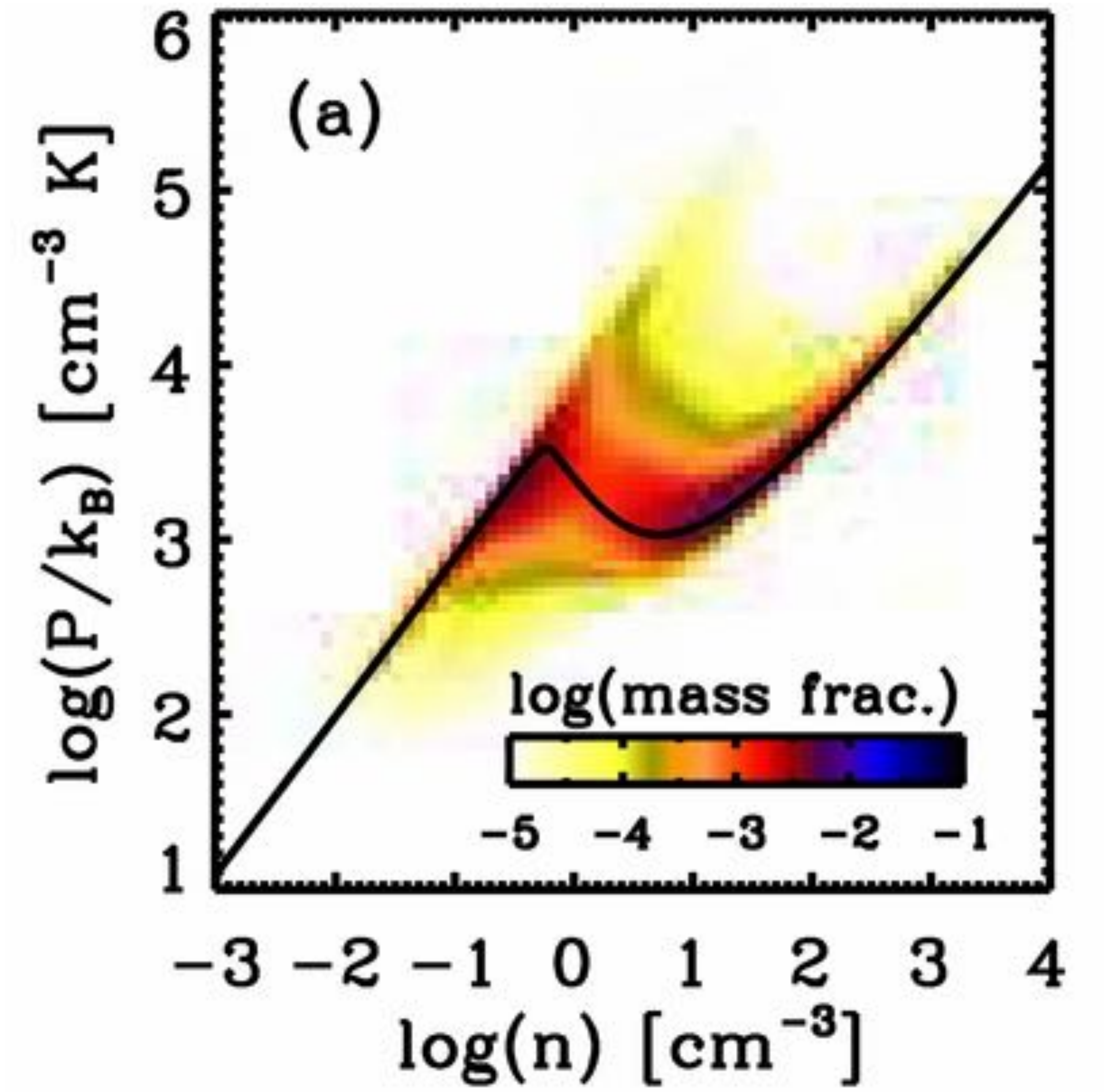
Kim & Ostriker 2013, ApJ, 776, 1 & 2015, ApJ, 802, 99

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

The cooling curve (CII versus OI/ Lyα) sets the presence of phases

Radiative heating & mechanical energy input sets the pressure

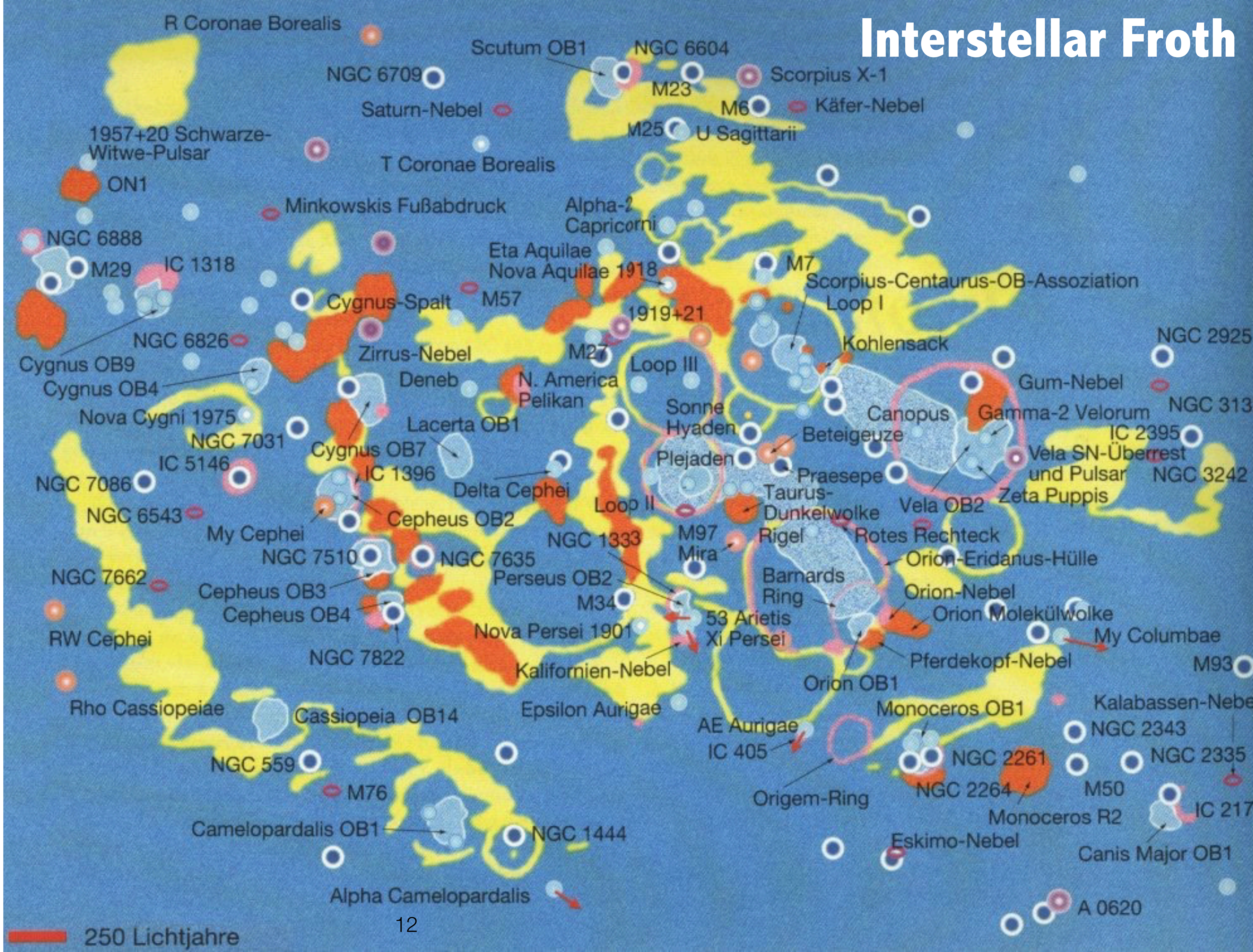
Mechanical energy input sets the distributions over the phases



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

Interstellar Froth

- Top-down view of a 1 kpc region around the sun containing many (super)bubbles
- The Sun is located in the local bubble at the center
- OB associations create superbubbles
  - That sweep up material in dense shells
  - That connect and form a foam-like network of tenuous gas
  - And the local star forming molecular clouds are in the bubble walls



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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Leiden U

Umit Kavak
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Olivier Berne

Javier Goicoechea

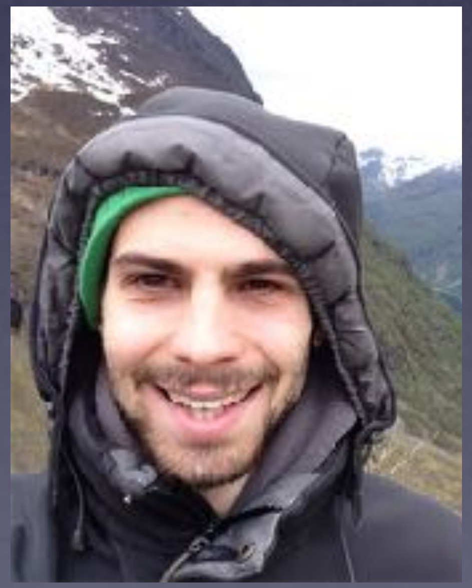
David Teyssier

Ronan Higgins

Ed Chambers

C+SQUAD team

Feedback SOFIA Legacy Program



Matteo Luisi
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Slawa Kabanovic
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Christian Guevara
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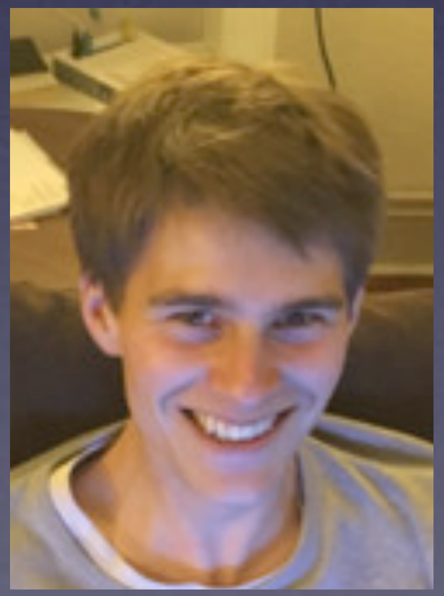

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Xander Tielens
& Feedback team

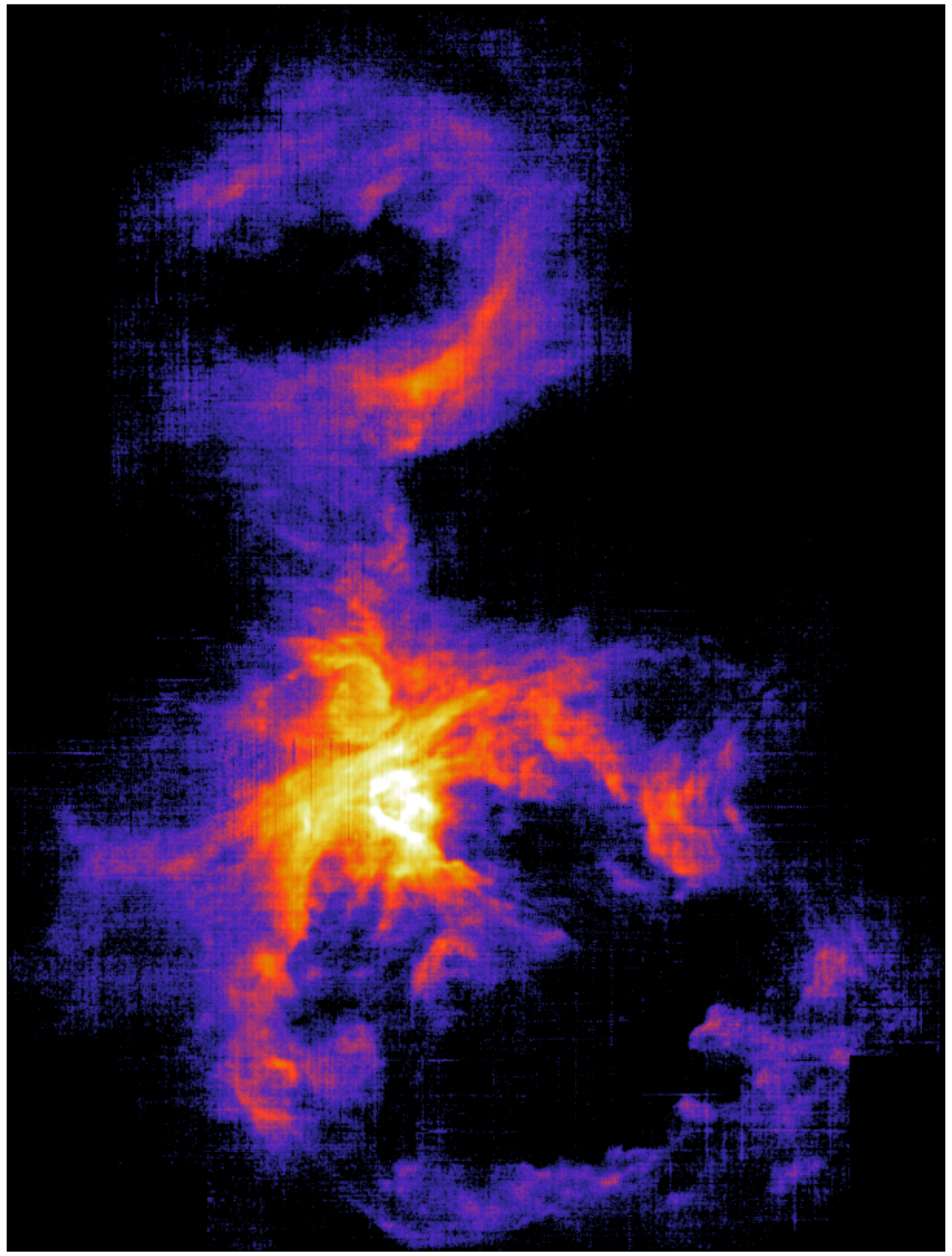
Rolf Guesten, Juergen Stutzki
& upGREAT/SOFIA team

SOFIA has provided a unique view of galactic feedback

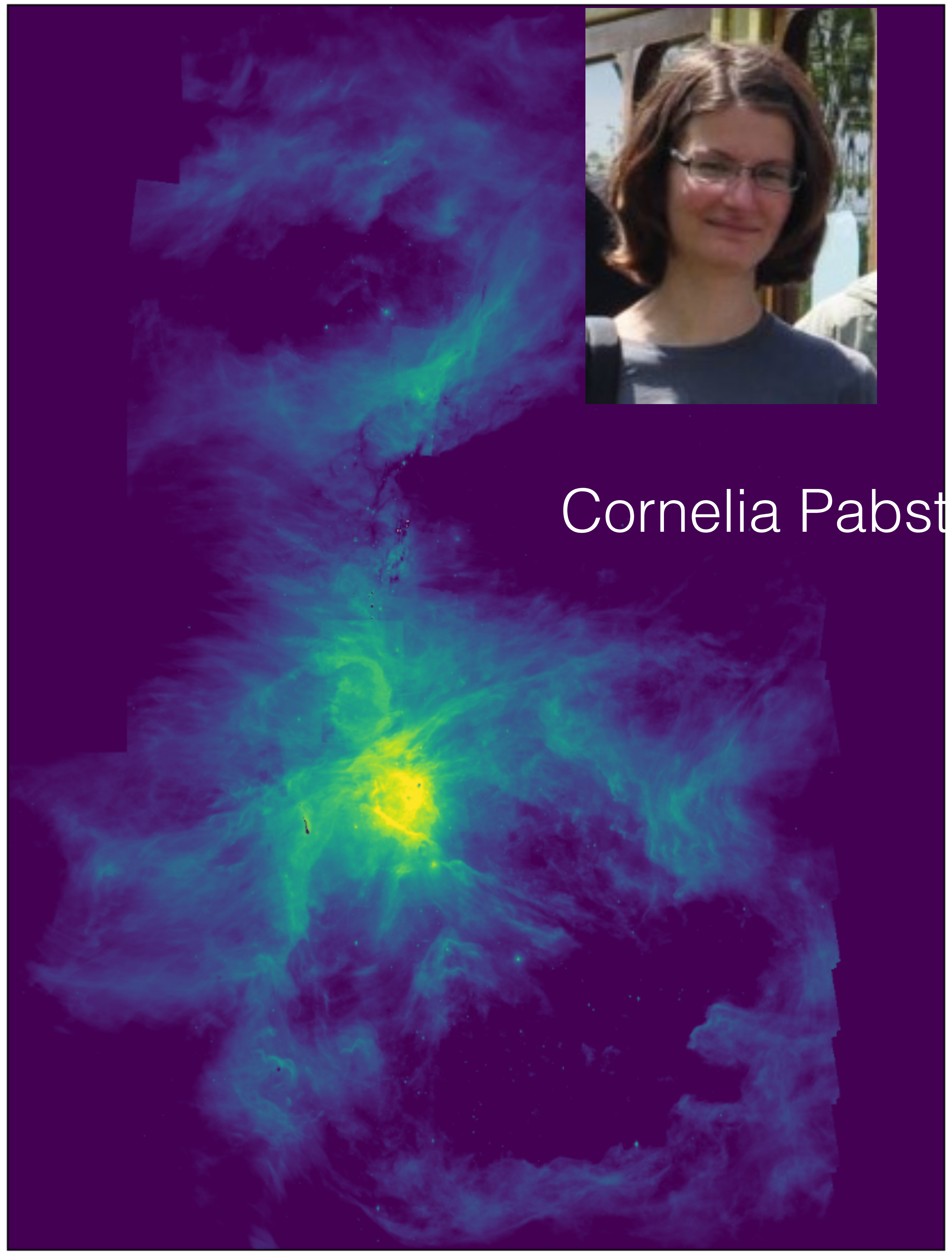
Three IR views of Orion

Herschel

SOFIA



Spitzer



PDRs & Radiative Feedback

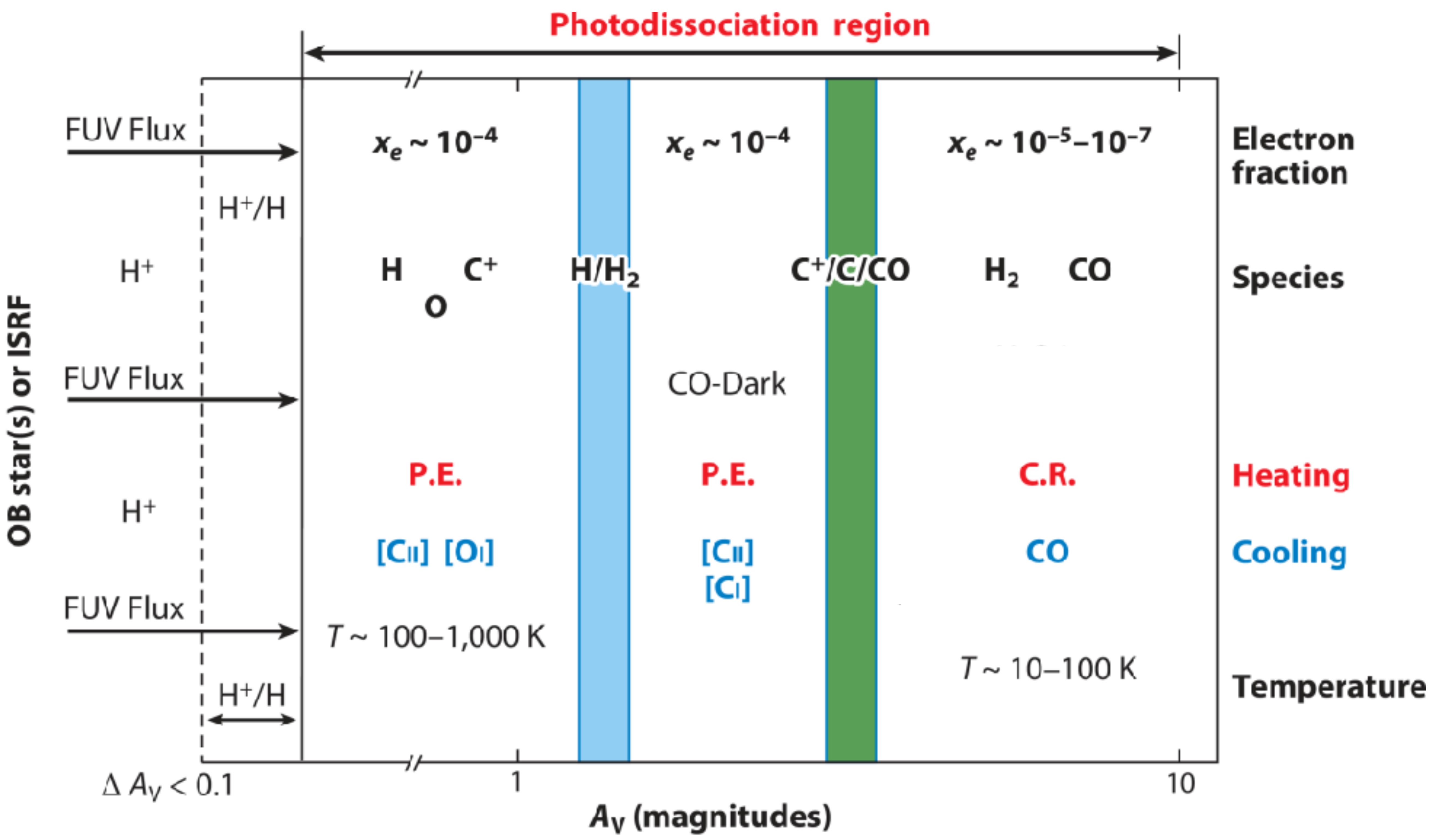
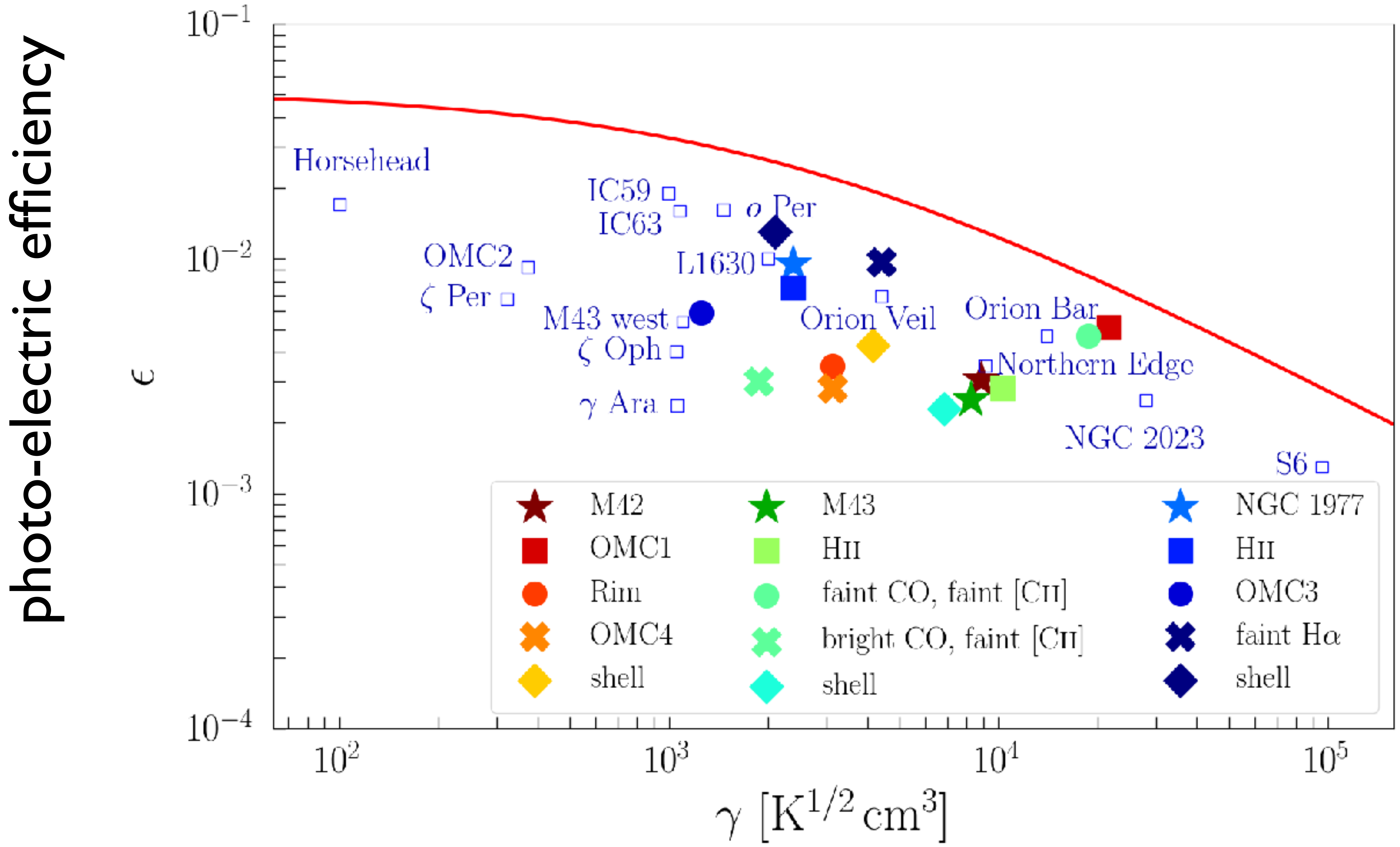


Photo-electric Heating



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γ, the ionization parameter =
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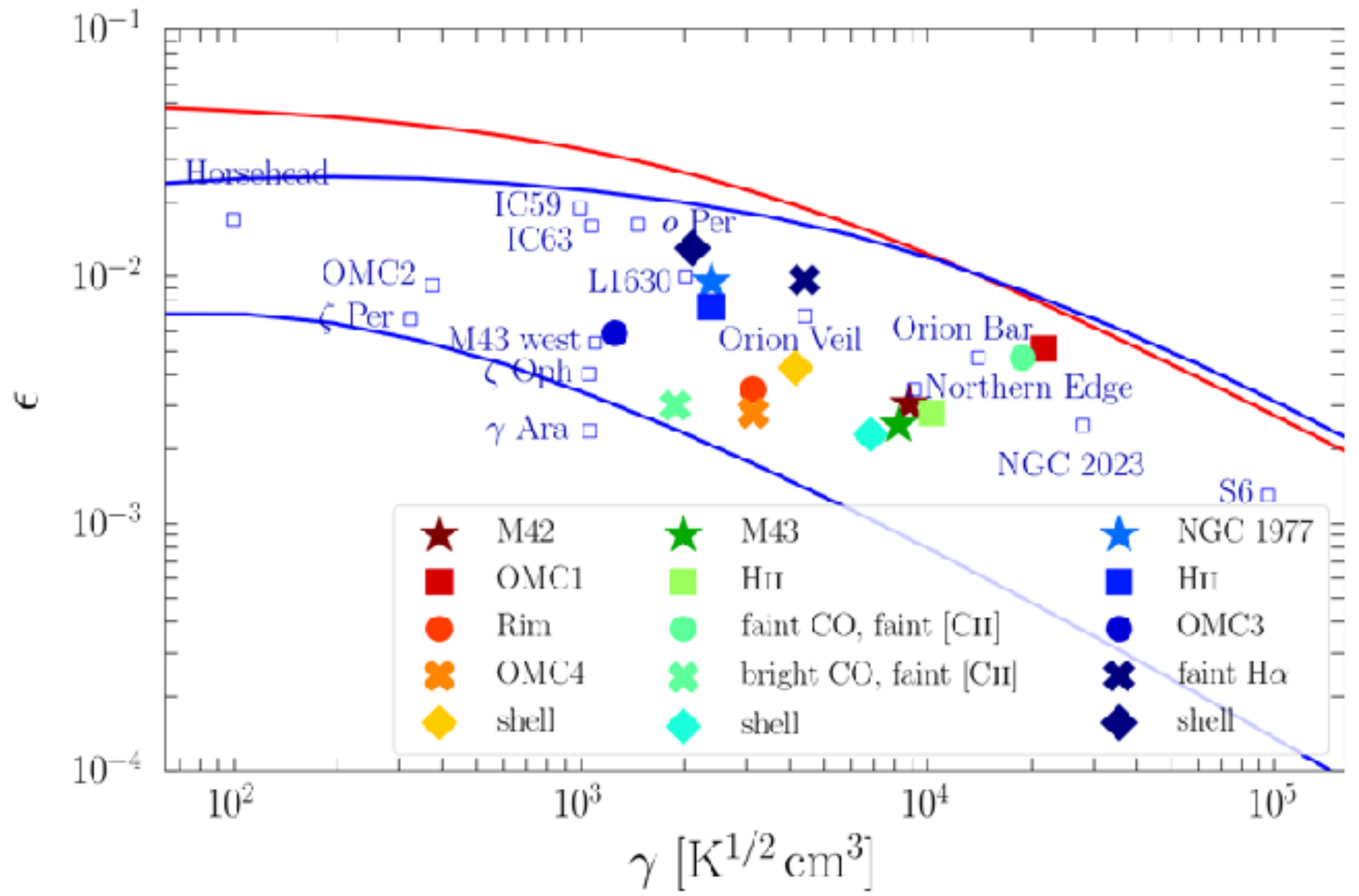
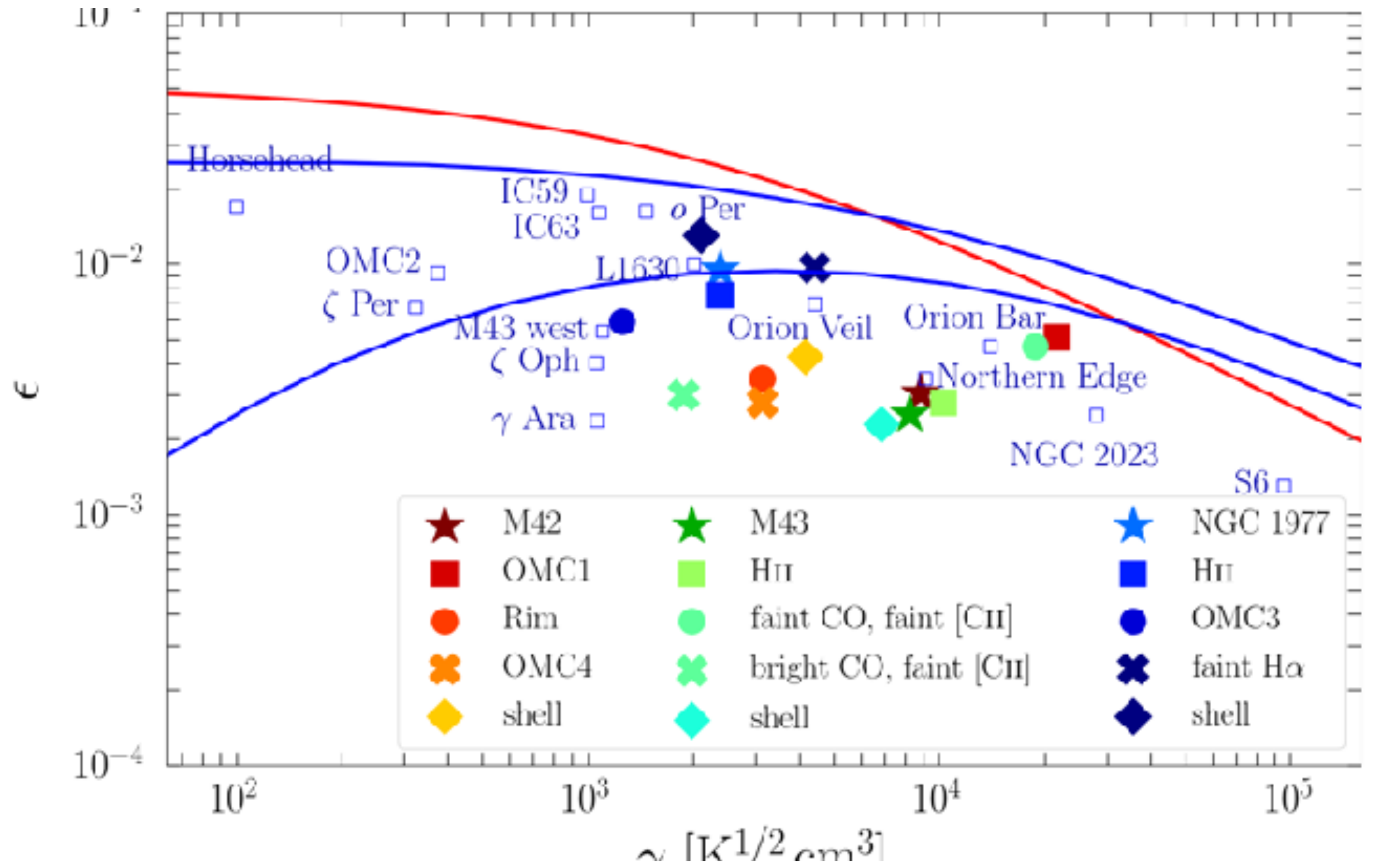
Salas et al., 2019, A&A, 626, A70
Pabst et al 2022, A&A, 658, A98
Bakes & Tielens 1994, ApJ, 427, 822

Photo-Electric Heating

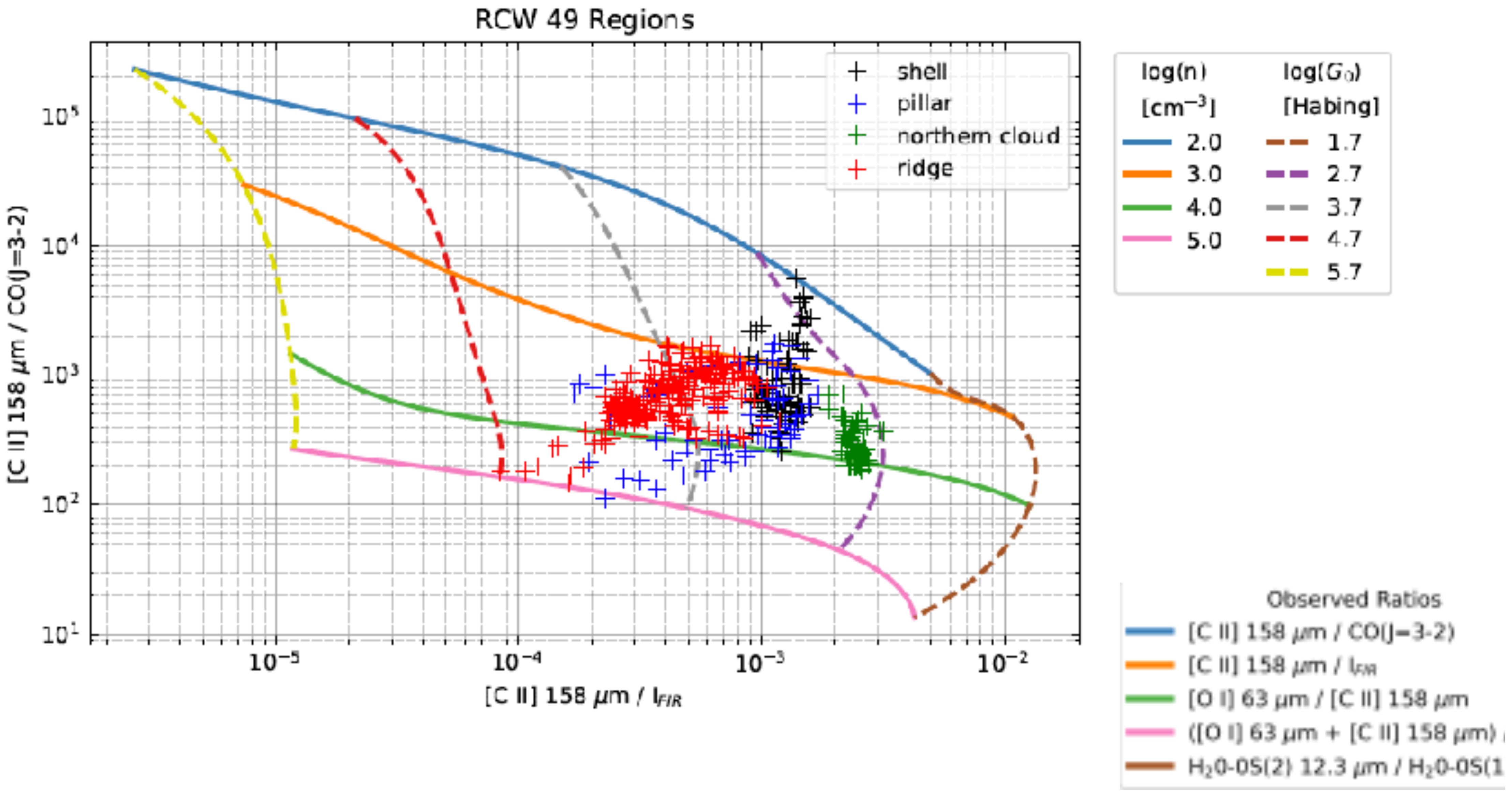
- Additional coolants besides [CII]
- Lower/variable PAH abundance
- Variation in the PAH family



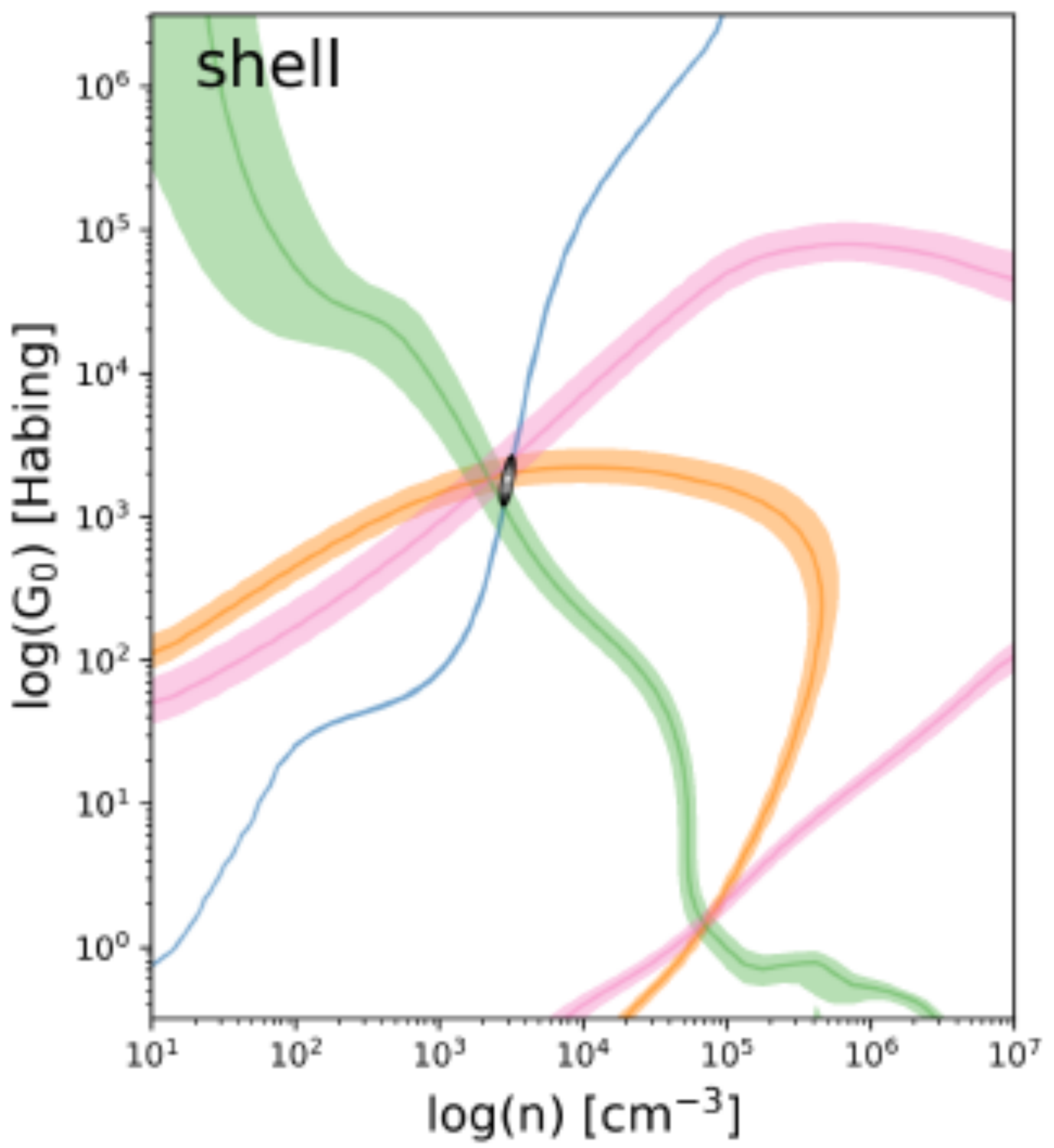


Salas et al., 2019, A&A, 626, A70
Pabst et al 2022, A&A, 658, A98
Bakes & Tielens 1994, ApJ, 427, 822
Wolfire, 2024, in prep

PDR Toolbox



Diagnostic diagram for RCW 49



Spaghetti diagram

PDR toolbox: https://dustem.astro.umd.edu/
Pound & Wolfire, 2022, AJ, 165, 25

Tiwari+, 2022, AJ, 164, 150

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PDR Characteristics

Maitraiyee Tiwari

Different relationships for reflection nebulae, HII regions, and dense star forming clumps

Strömgren relation gives:

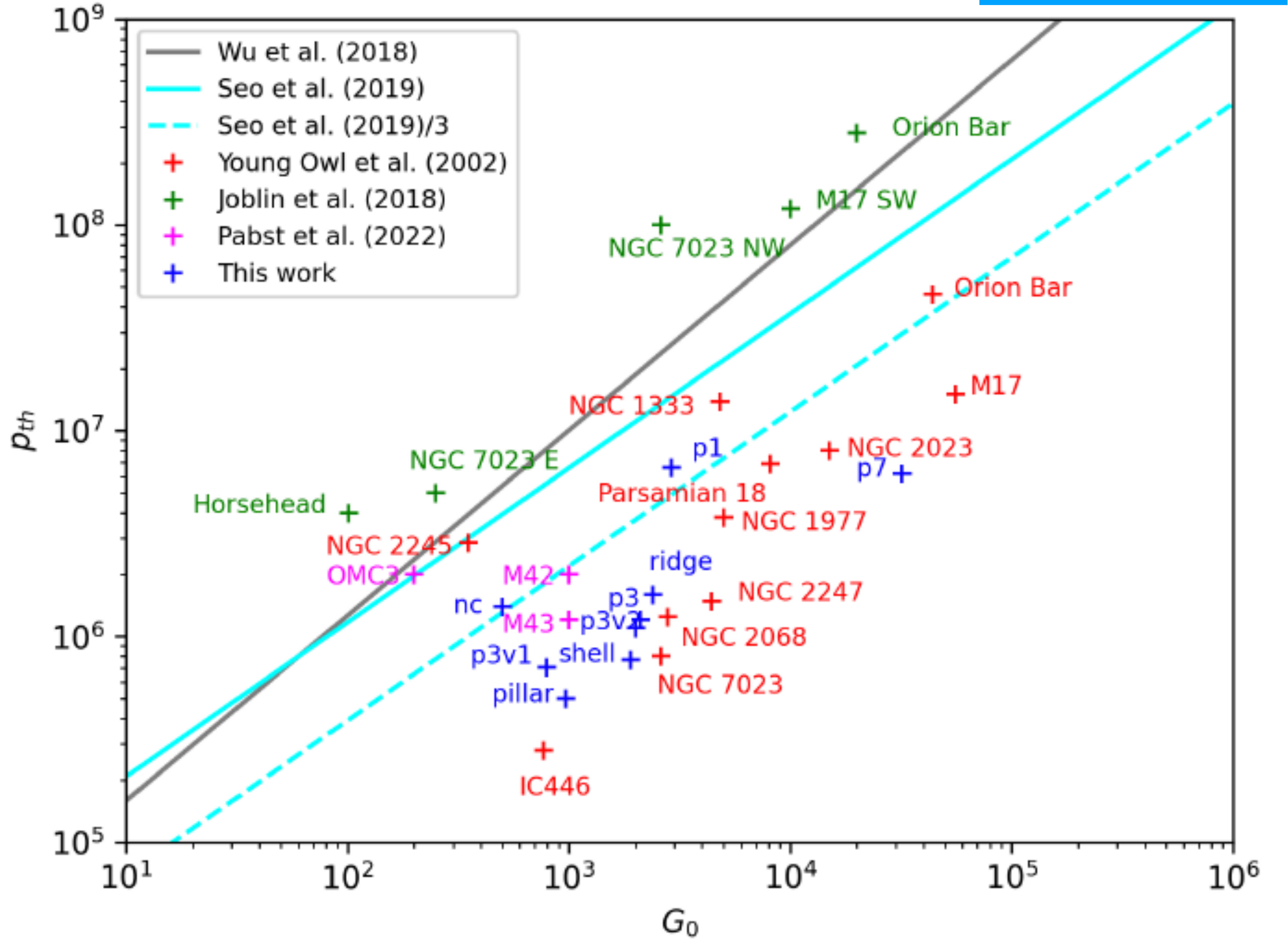
$$\frac{G_0}{n_H} \propto n_H^{1/3}$$

and

$$T \propto G_0^{1/4}$$

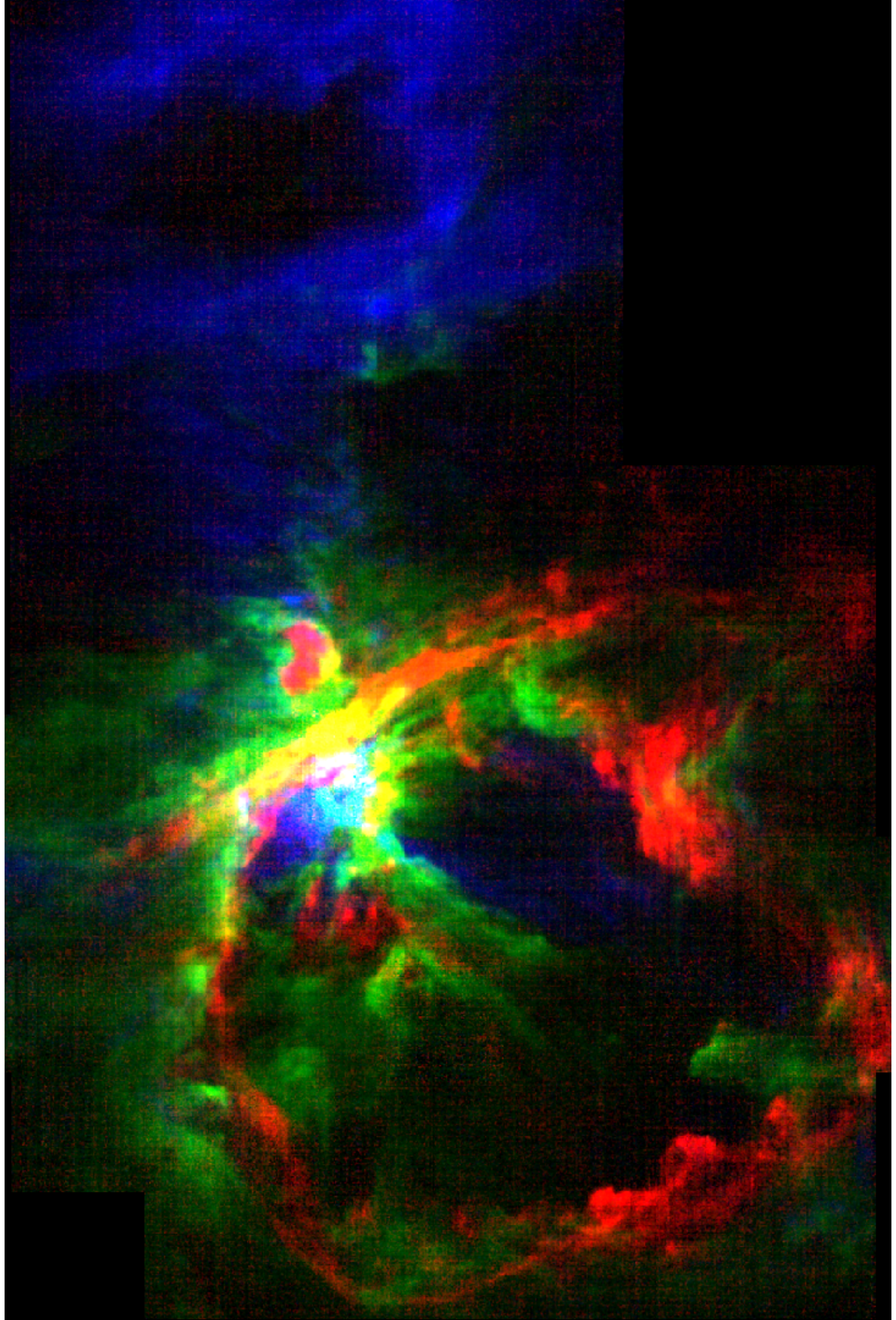
Thus, for HII regions: $P_{th} \propto G_0$

PDR pressure versus radiation field



Tiwari+, 2022, AJ, 164, 150
Pabst+, 2022, A&A, 658, 98
Joblin+, 2018, A&A, 615, 129
Seo+, 2019, ApJ, 878, 120
Young Owl+, 2002, ApJ, 578, 885

Mechanical Feedback



[CII] 158 μm

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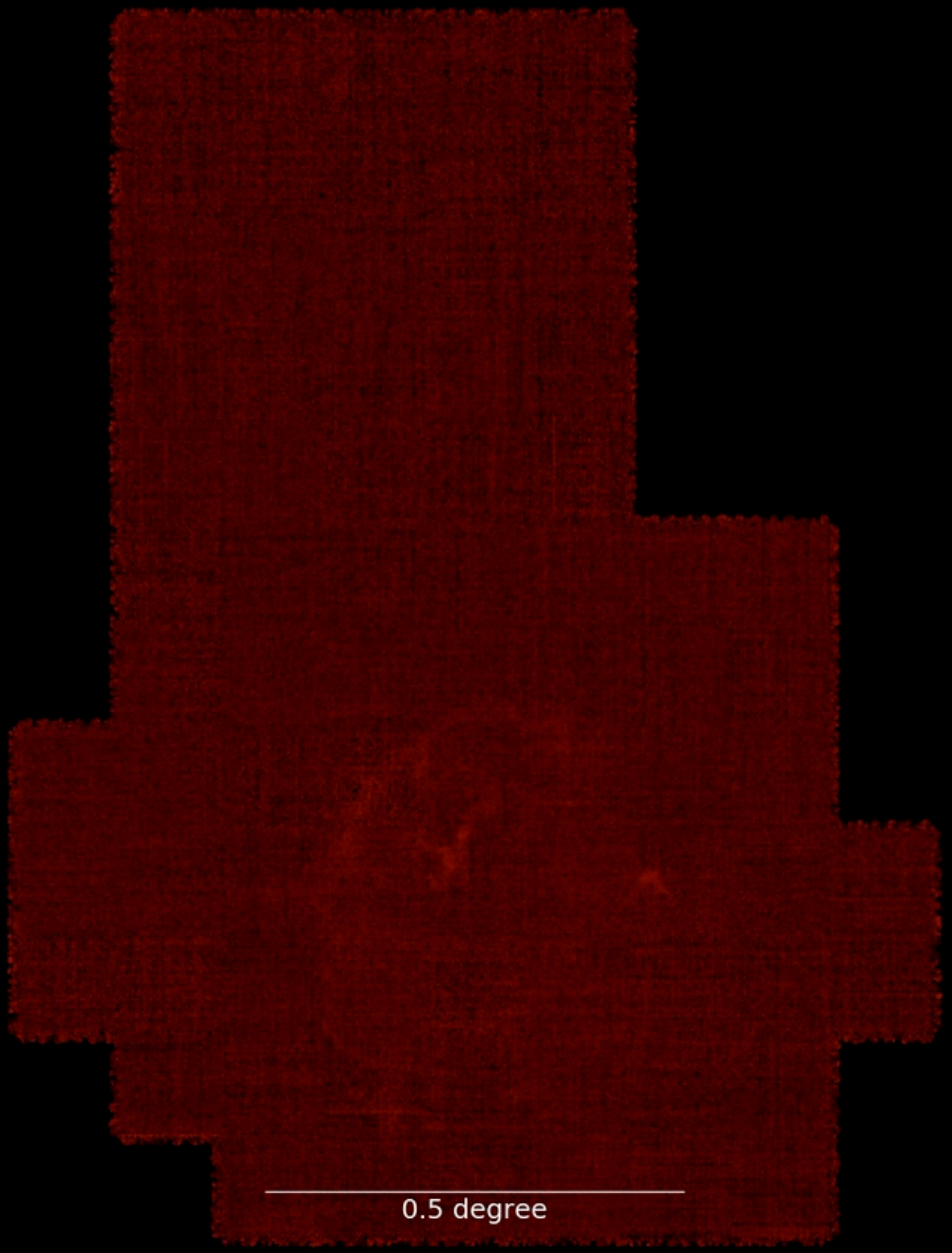
Orion: the movie



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Pabst et al 2019, Nature, 565, 618

- [CII] traces the Orion Veil consisting of 1500 $M_\odot$ expanding at 13 km/s toward us

- The stellar wind of θ^1 Ori C creates hot plasma bubble observed at X-ray wavelengths

- Overpressure of hot plasma drives expansion

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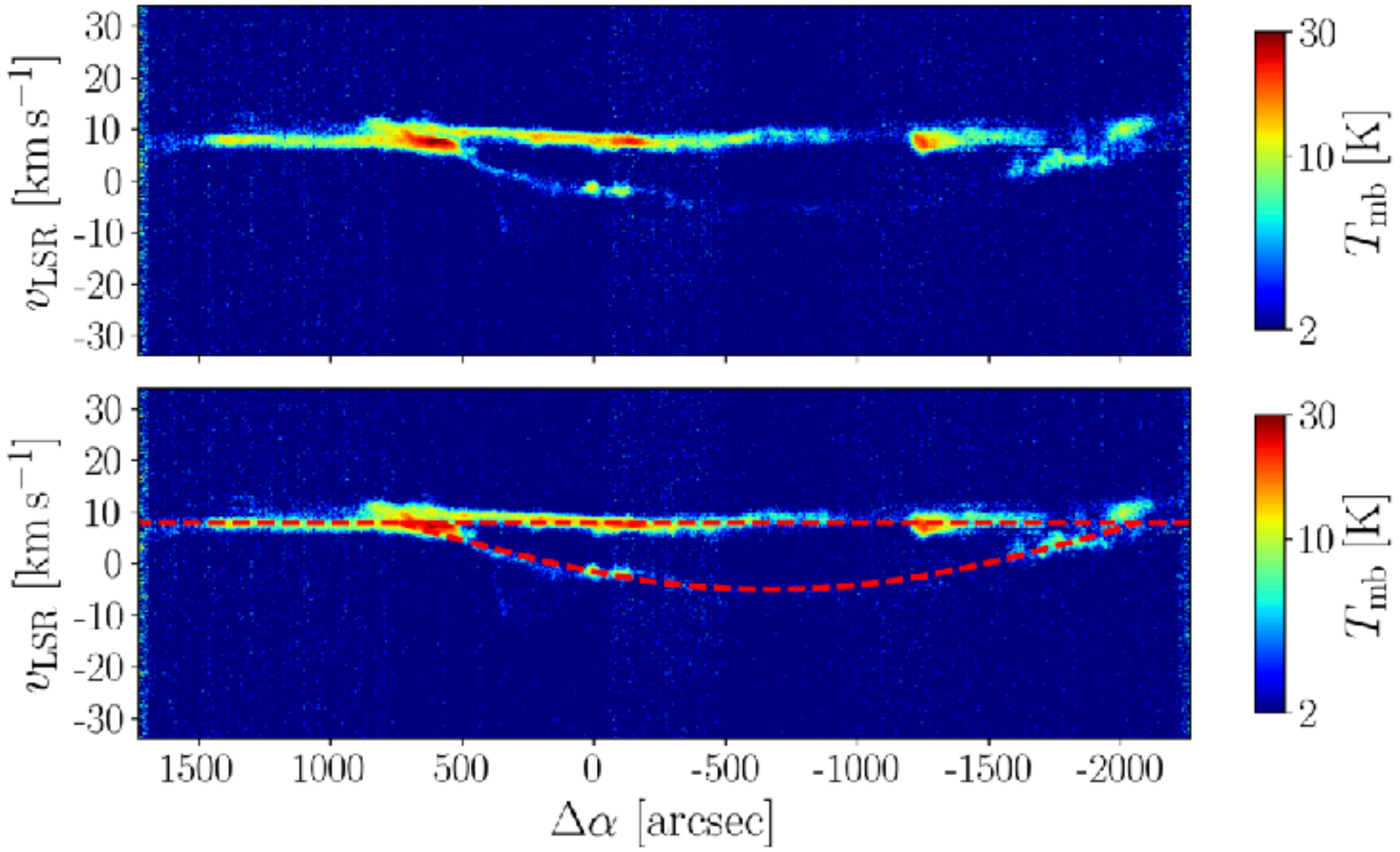
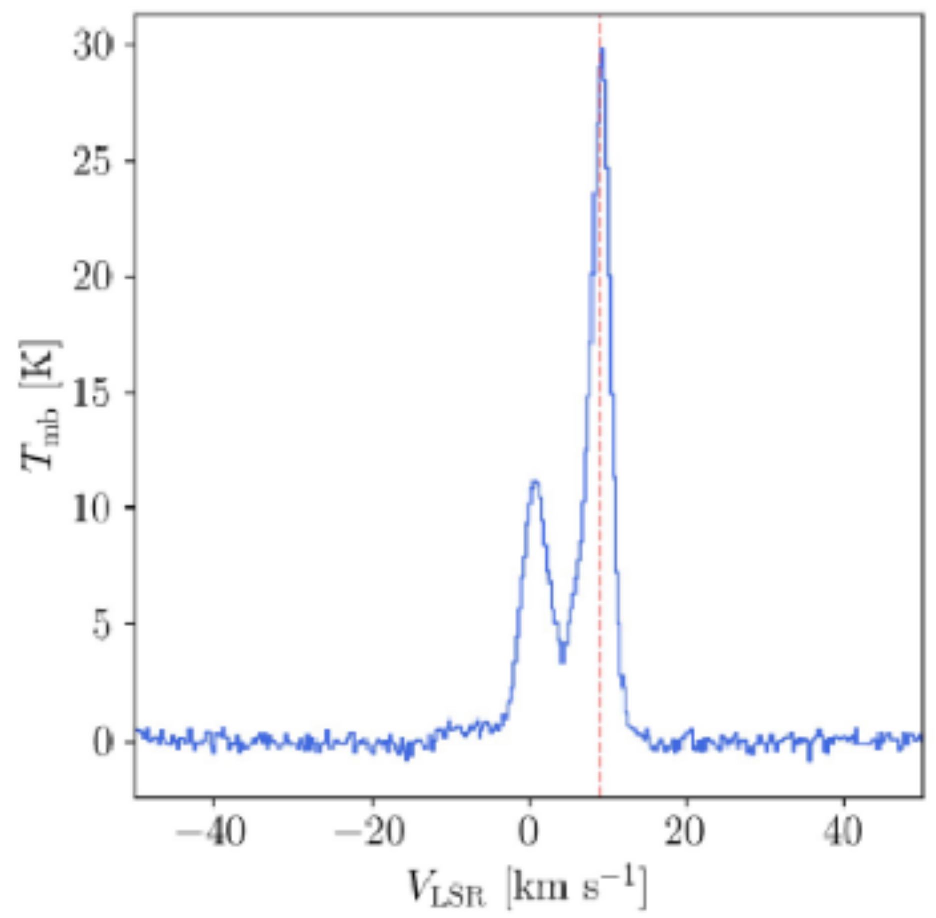


p-v diagram of expanding shell

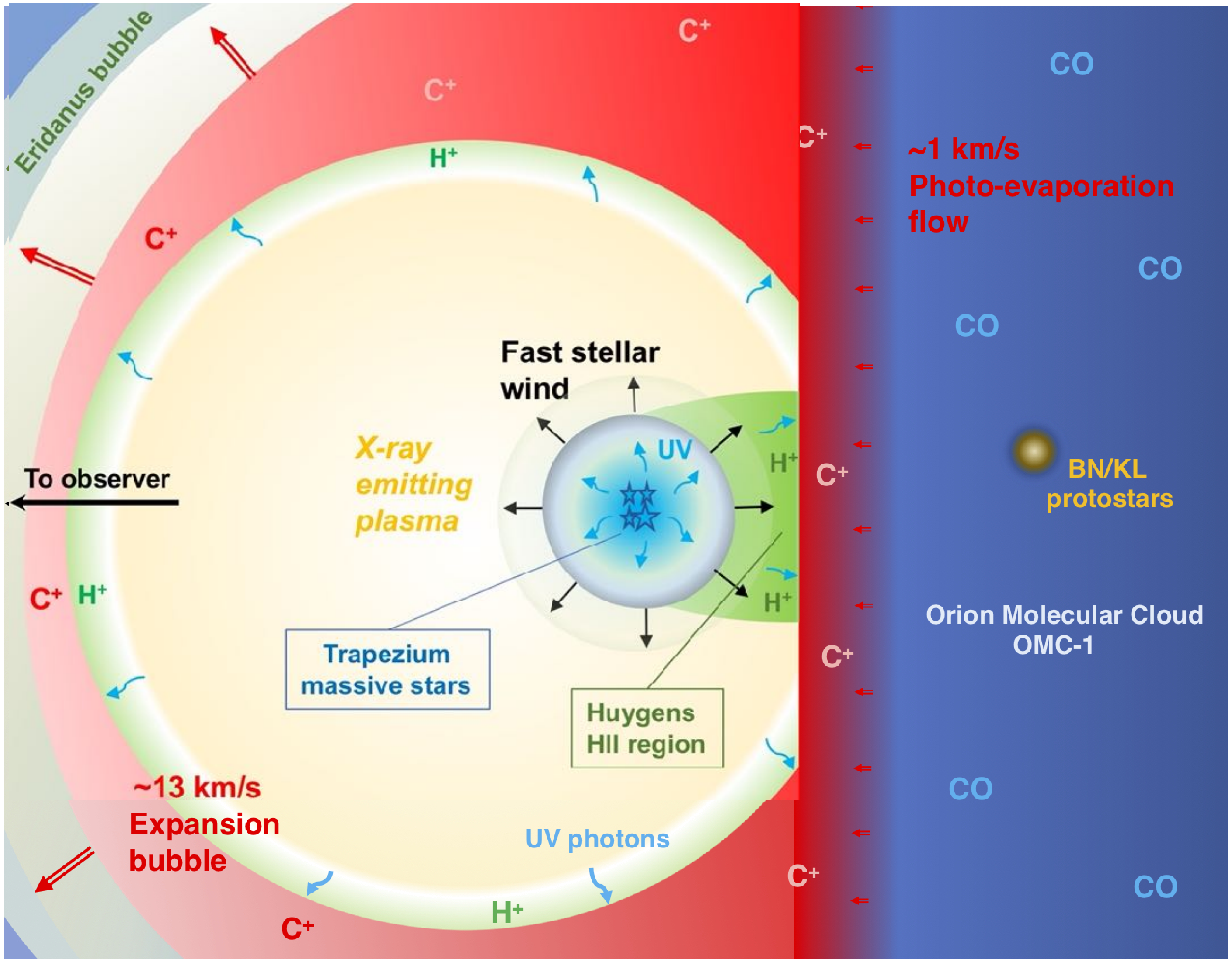
Sample spectrum



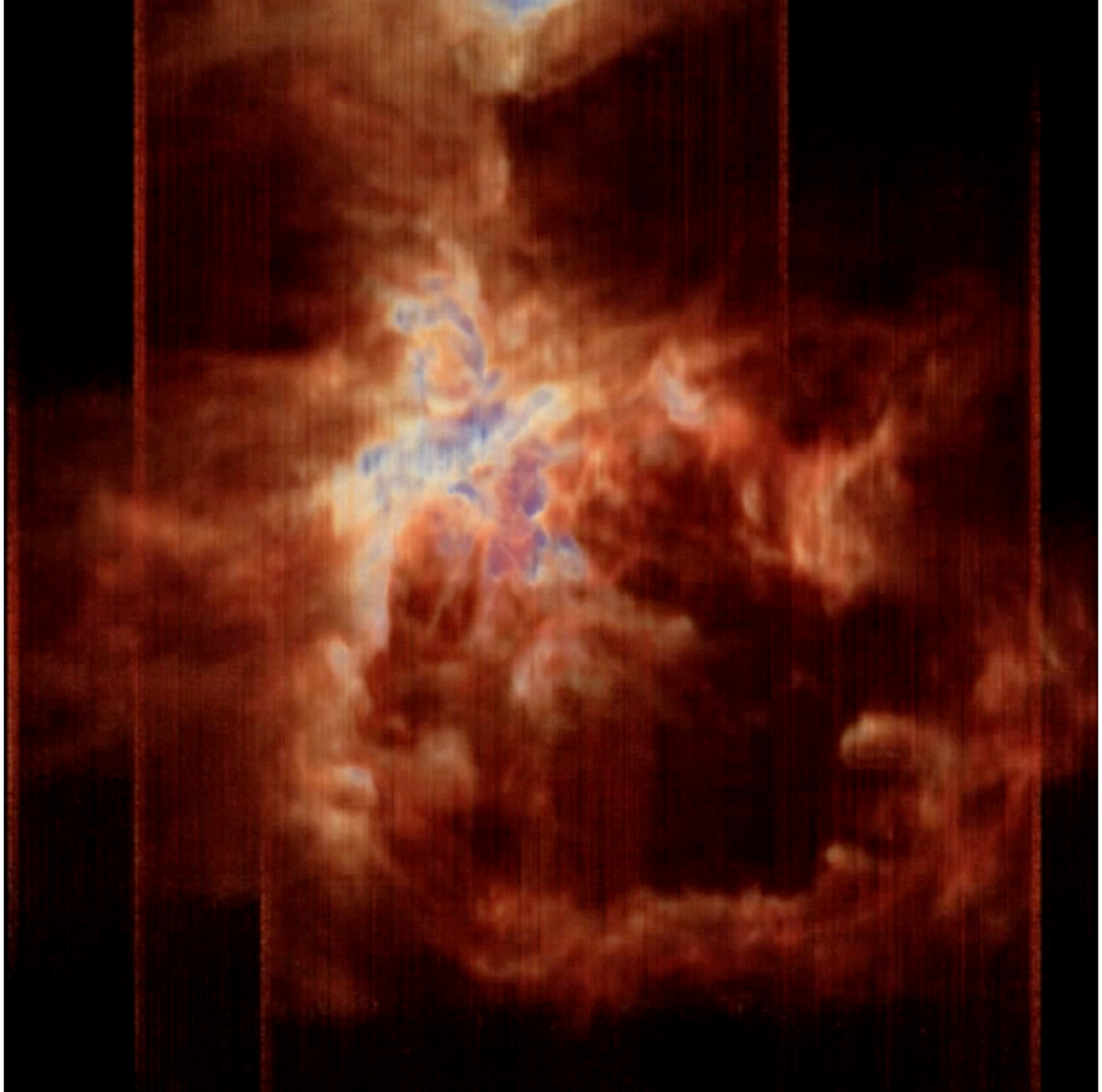
Pabst et al 2019, Nature, 565, 618

Orion Veil

The stellar wind from θ[1] Ori C shocks and creates a hot (~10^6 K) plasma. Because of the large pressure gradient, this plasma bubble expands primarily toward us, sweeping up part of the molecular core into a shell: the Veil. The high pressure of the Huygens region drives an ionized flow into this cavity



Weaver et al 191977, ApJ, 218, 337
Pabst et al 2019, Nature, 565, 618

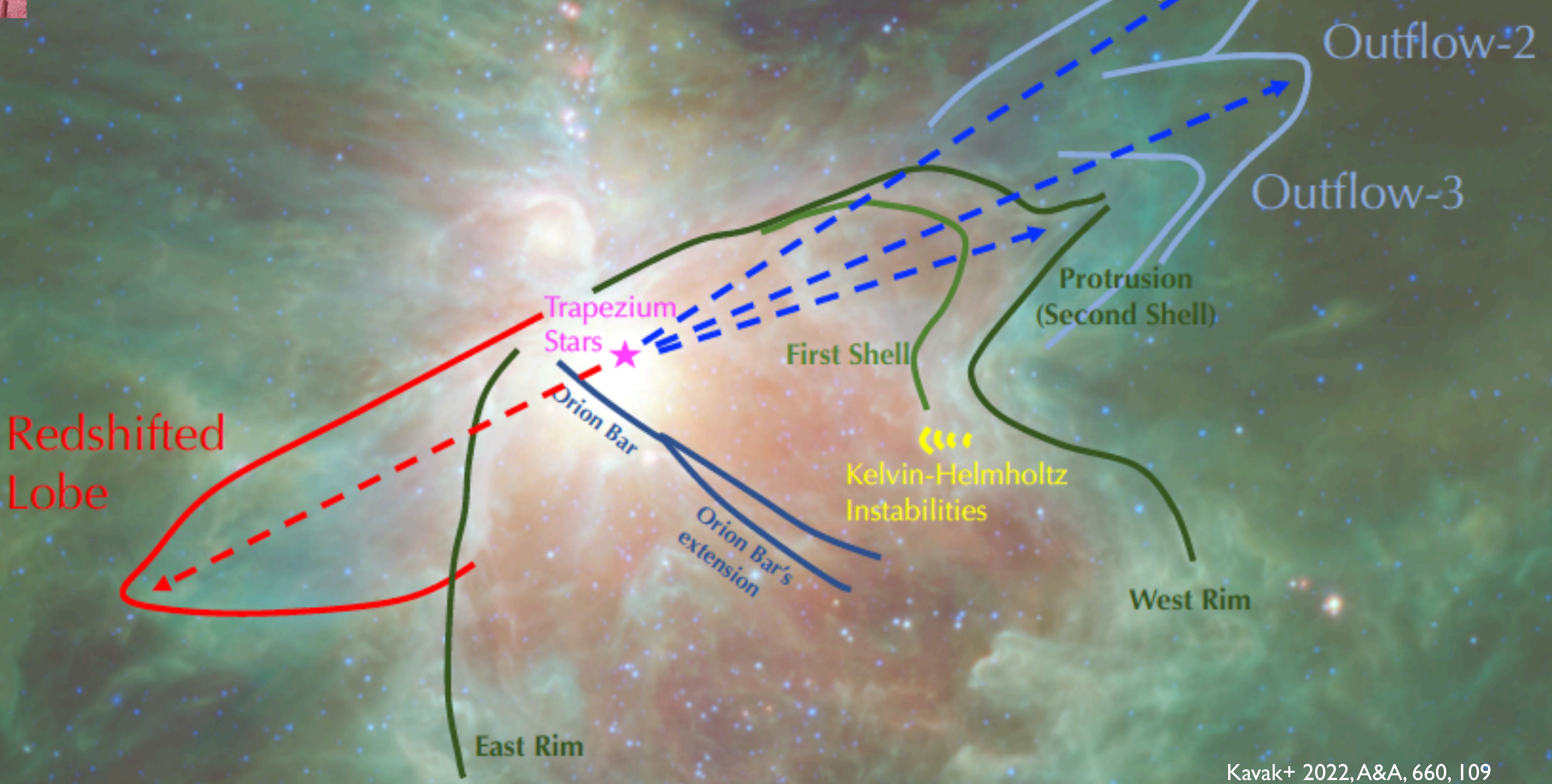


Cornelia Pabst

Pabst et al 2019, Nature, 565, 618

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

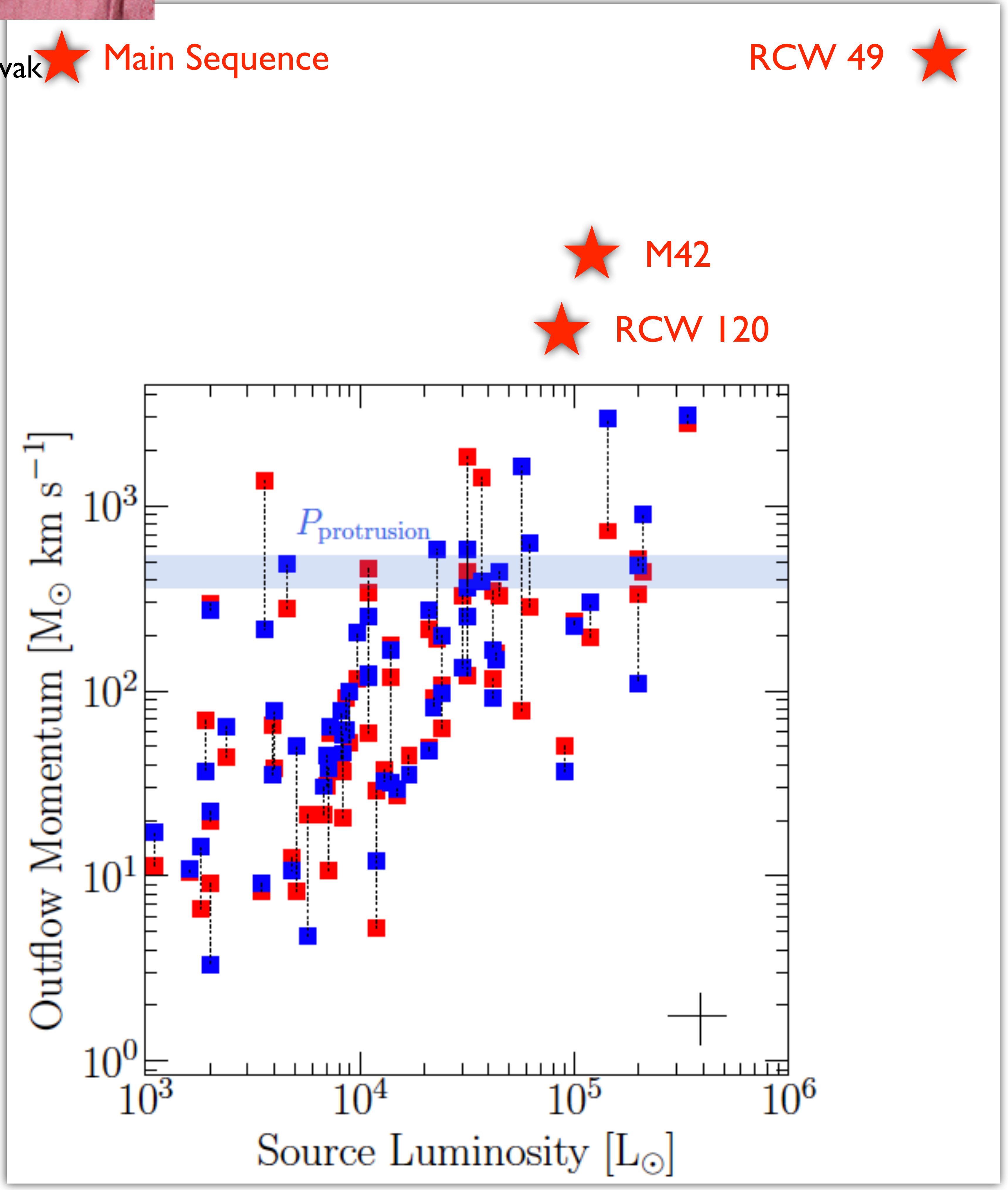
Umit Kavak

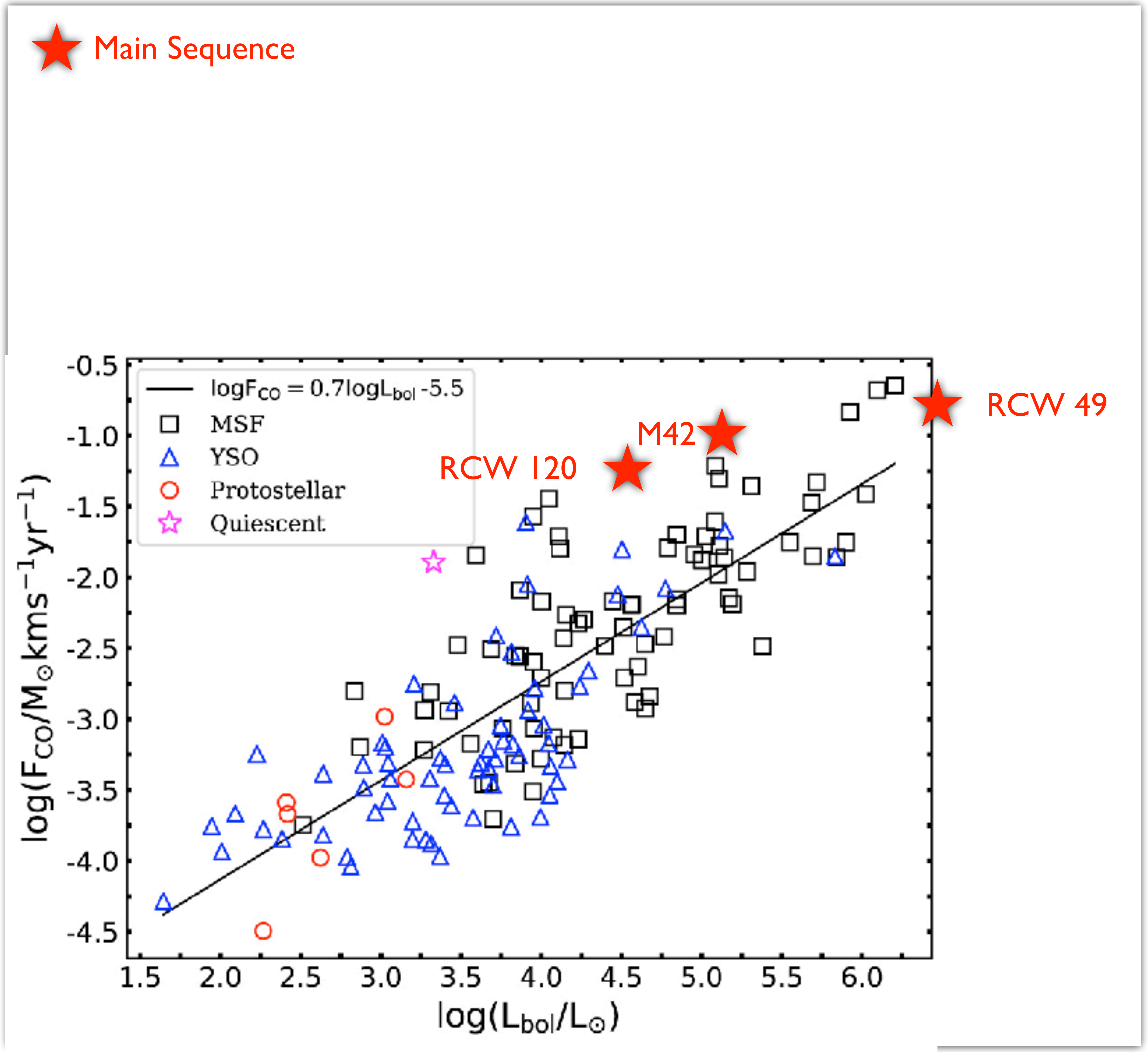


Kavak+ 2022, A&A, 660, 109

otostellar & Main Sequence Feedback

Umit Kavak



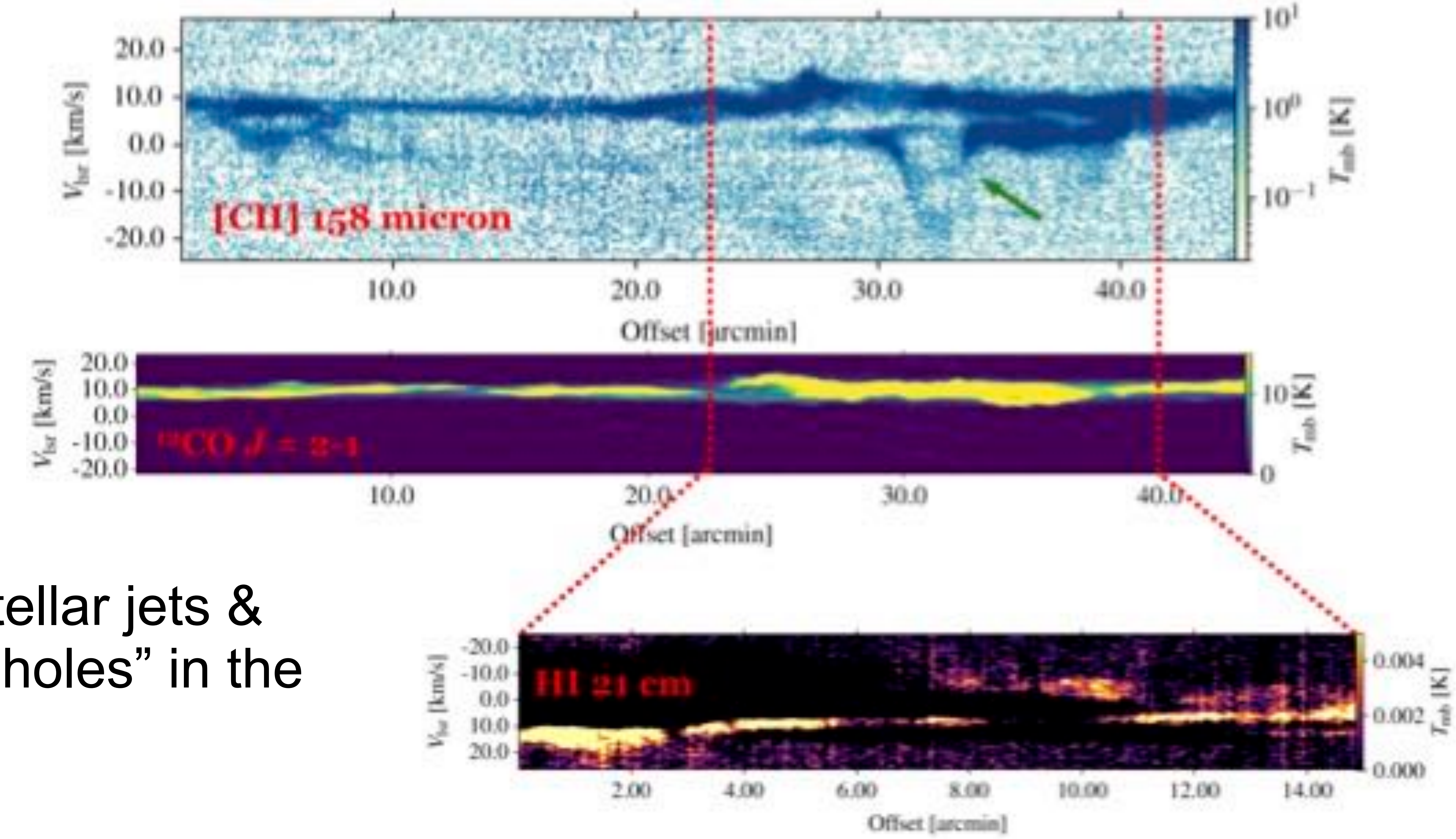


See also: Kavak presentation

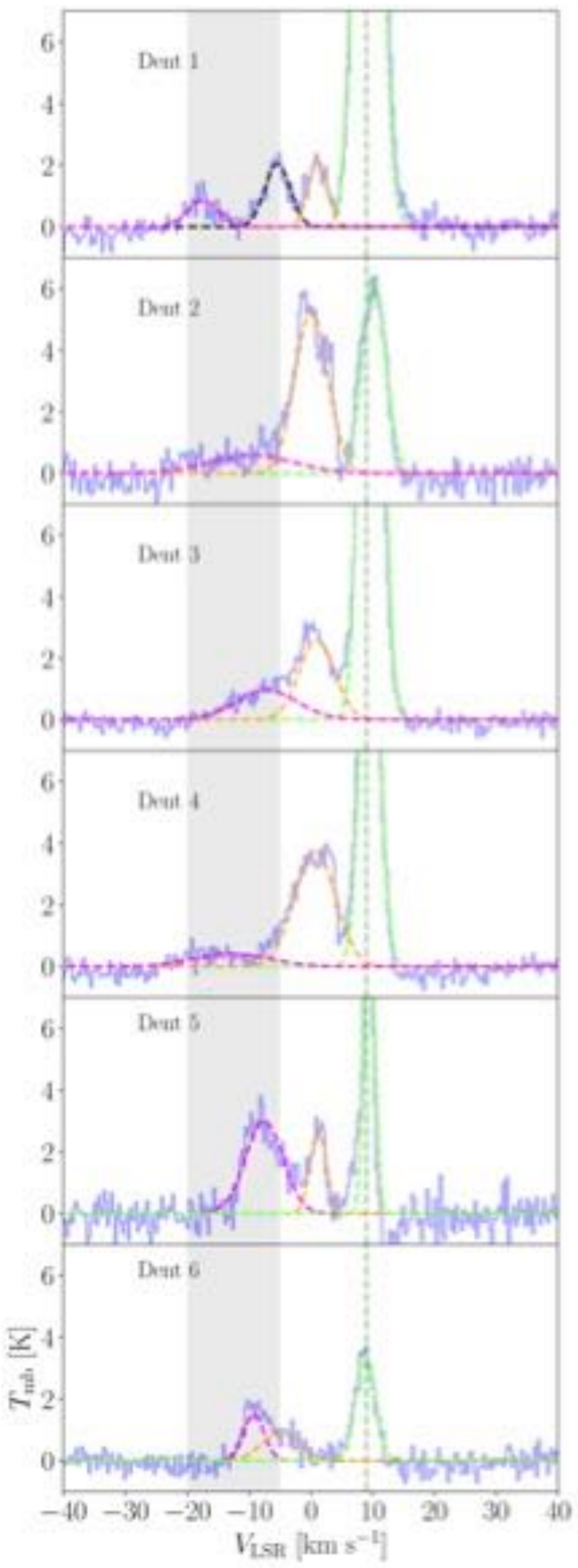
Kavak+ 2022, A&A, 660, 109
Yang+ 2018, ApJS, 235, 3

Umit Kavak

Piercing the Veil



- Multiple protostellar jets & outflows poke "holes" in the veil
- Rayleigh-Taylor instabilities will also break the shell open
- timescale ~200,000 yr



Kavak+ 2022, A&A, 663, 117

The Demise of OMC1

Stellar wind dominated phase

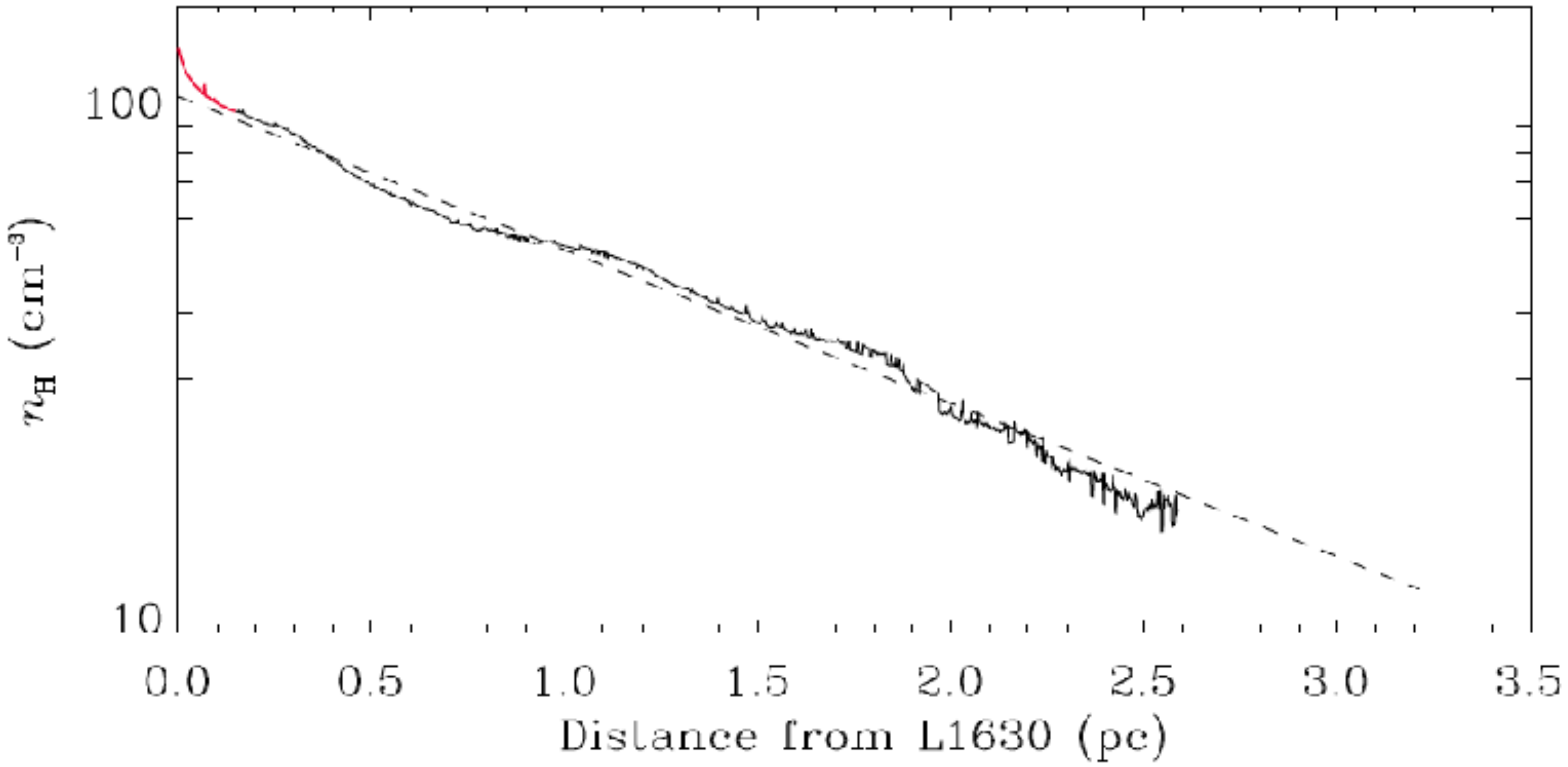
- Stellar wind removes ~1500 $M_\odot$ from OMC1
- Molecular mass OMC1 ~3000 $M_\odot$
- Stellar mass OMC1 ~1800 $M_\odot$

Photo-ionized gas dominated phase

- θ^1 Ori C moves away at ~5 km/s (25 pc in 5 Myr)
- Late stage photo-ionized flow will remove ~1000 $M_\odot$

Bram Ochsendorf

Photo-Ionized Evaporative Flow

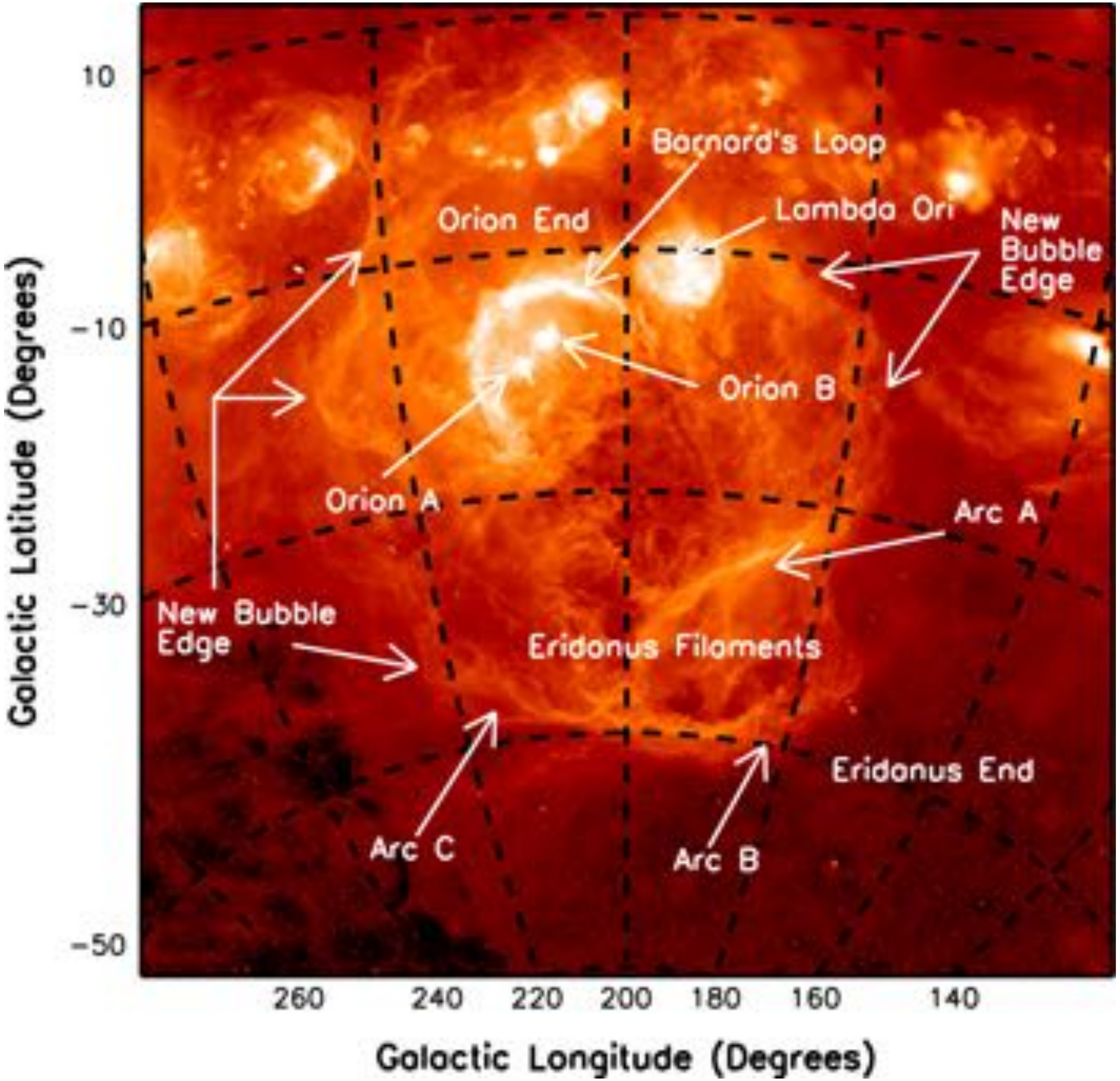


- Sigma Ori (O9.5 + B0.5) is moving into an old, emptied out bubble, GS206-17+13
- Photo-ionizes L1630
- Setting up a stationary flow: $v \simeq 20$ km/s $H \simeq 1$ pc $M \simeq 100$ M$_\odot$
- Total mass lost: $M \simeq 10^3$ M$_\odot$

The Bigger Picture

Bram Ochsendorf

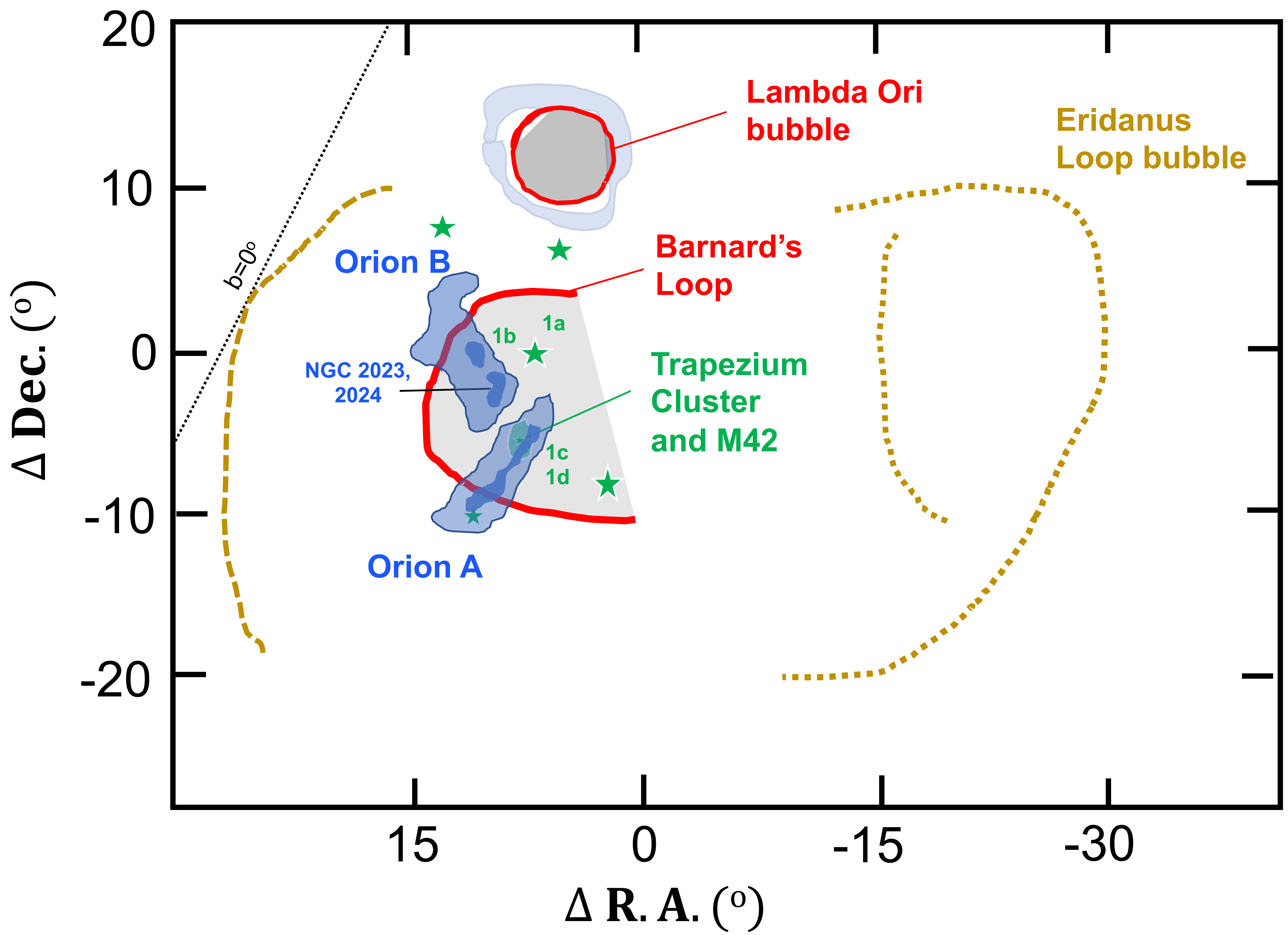
The Orion-Eridanus Superbubble



Ochsendorf et al, 2015, ApJ, 808, 111

Bram Ochsendorf

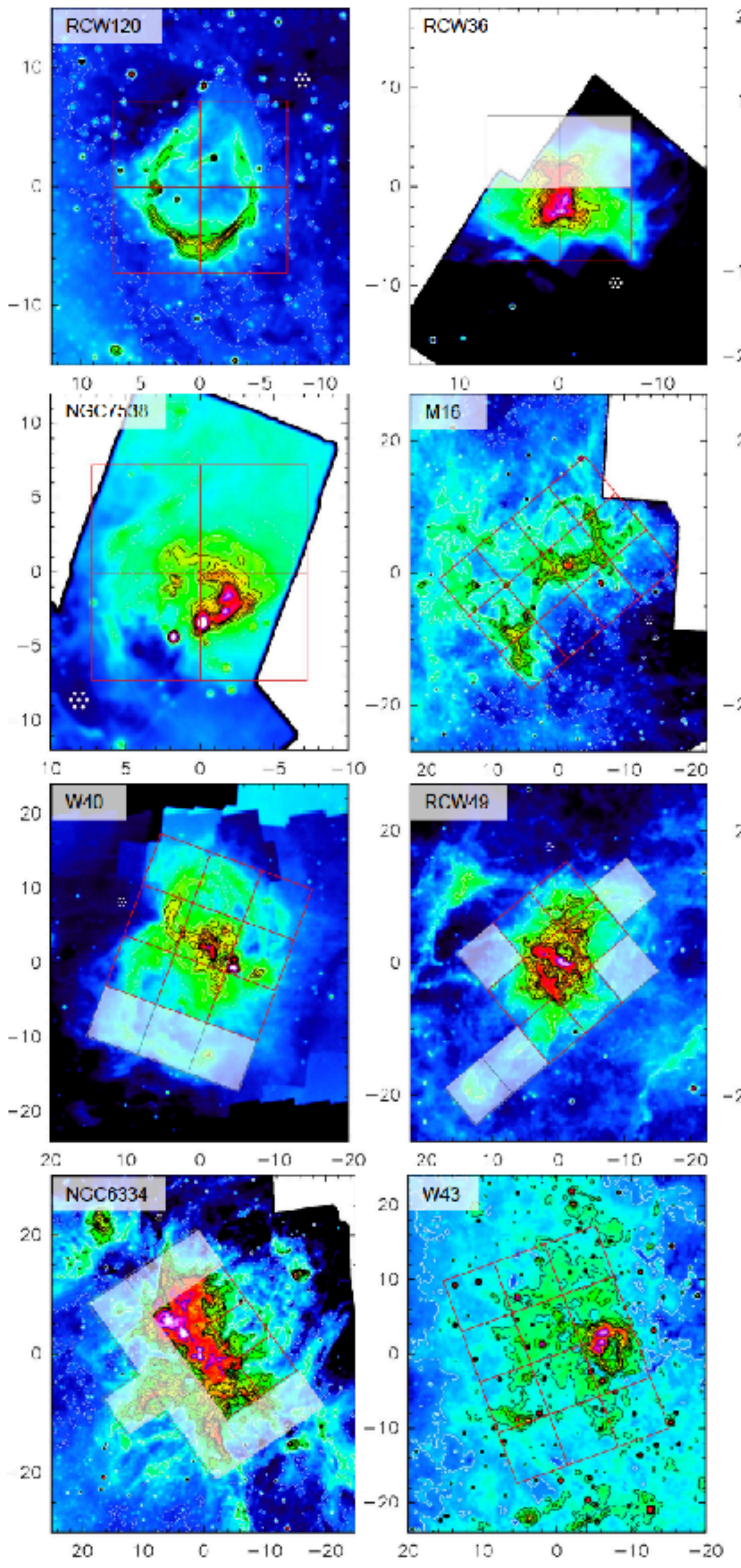
The Veil & the Ecology of the Galaxy



The SOFIA Feedback Legacy Program

Science goal: How do massive stars interact with their environment ?

- Survey of 11 regions of massive star formation in the [CII] 1.9 THz line using upGREAT on SOFIA
- Typical size surveyed 25x25’
- The data is non-proprietary and available through the IRSA SOFIA Archive
- About 80% complete
- ancillary data: 8µm IRAC, 70-160 µm Herschel, CO J=3-2, X-ray
- Description of the program: **Schneider et al 2020, PASP, 132, 4301**



Beuther+ A&A, 659, A77
Bonne+ 2022, ApJ, 935, 171
Bonne+ 2023, ApJ, 951, 39
Bonne+ 2023, A&A, 679, L5
Kabanovic+, 2022, A&A, 659, A36
Karim+, 2023, AJ, 166, 240
Luisi+, 2021, Science Advance, 7, 951
Schneider+ 2023, Nature Astronomy, 7, 546
Tiwari+ 2021, ApJ, 914, 117
Tiwari+ 2022, AJ, 164, 150
Tiwari+ 2023, ApJ, 958, 136

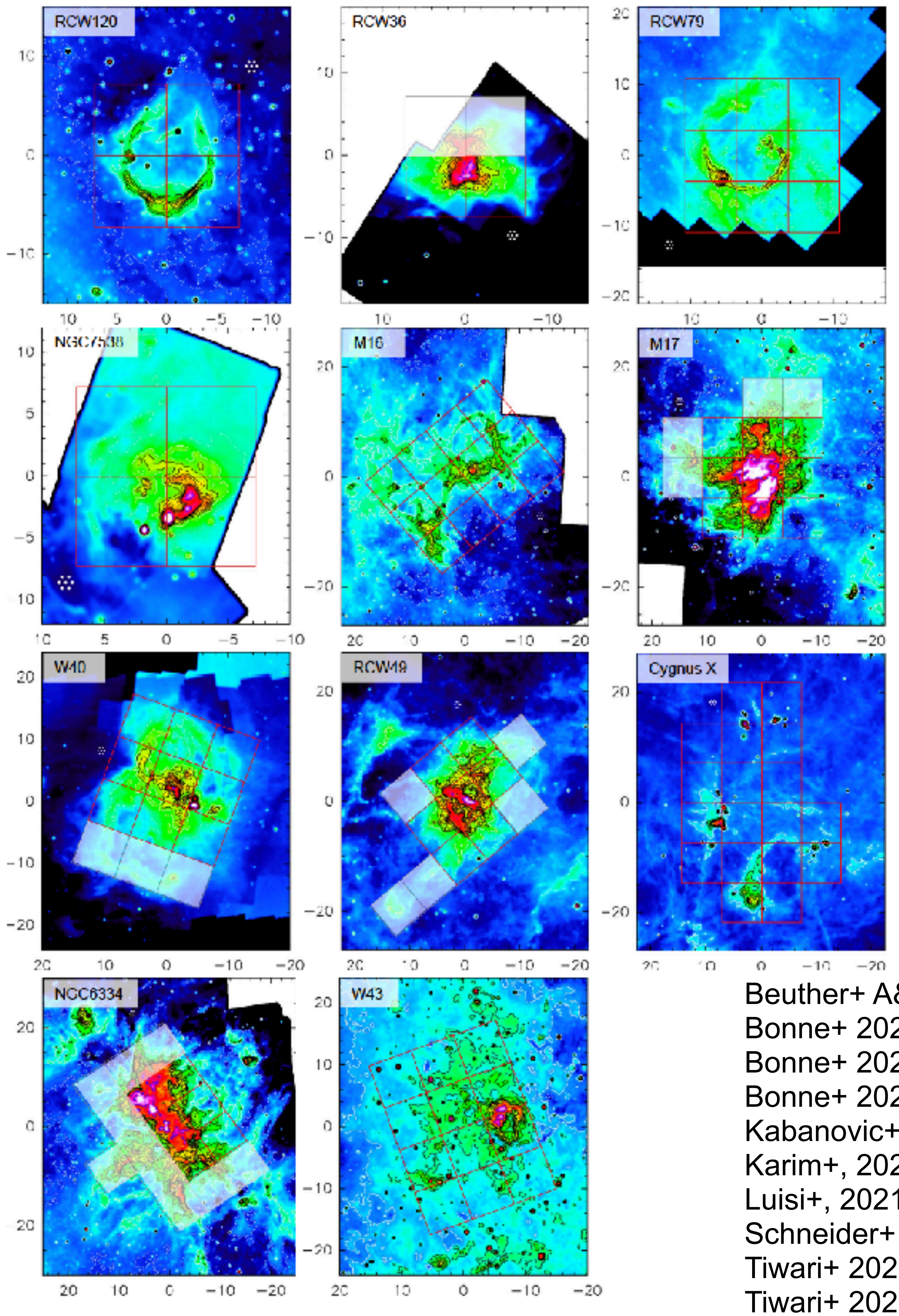
The SOFIA Feedback Legacy Program

Science goal: How do massive stars interact with their environment ?

- 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
  - Stellar characteristics
  - Time/evolution
  - Environment/Molecular cloud structure

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



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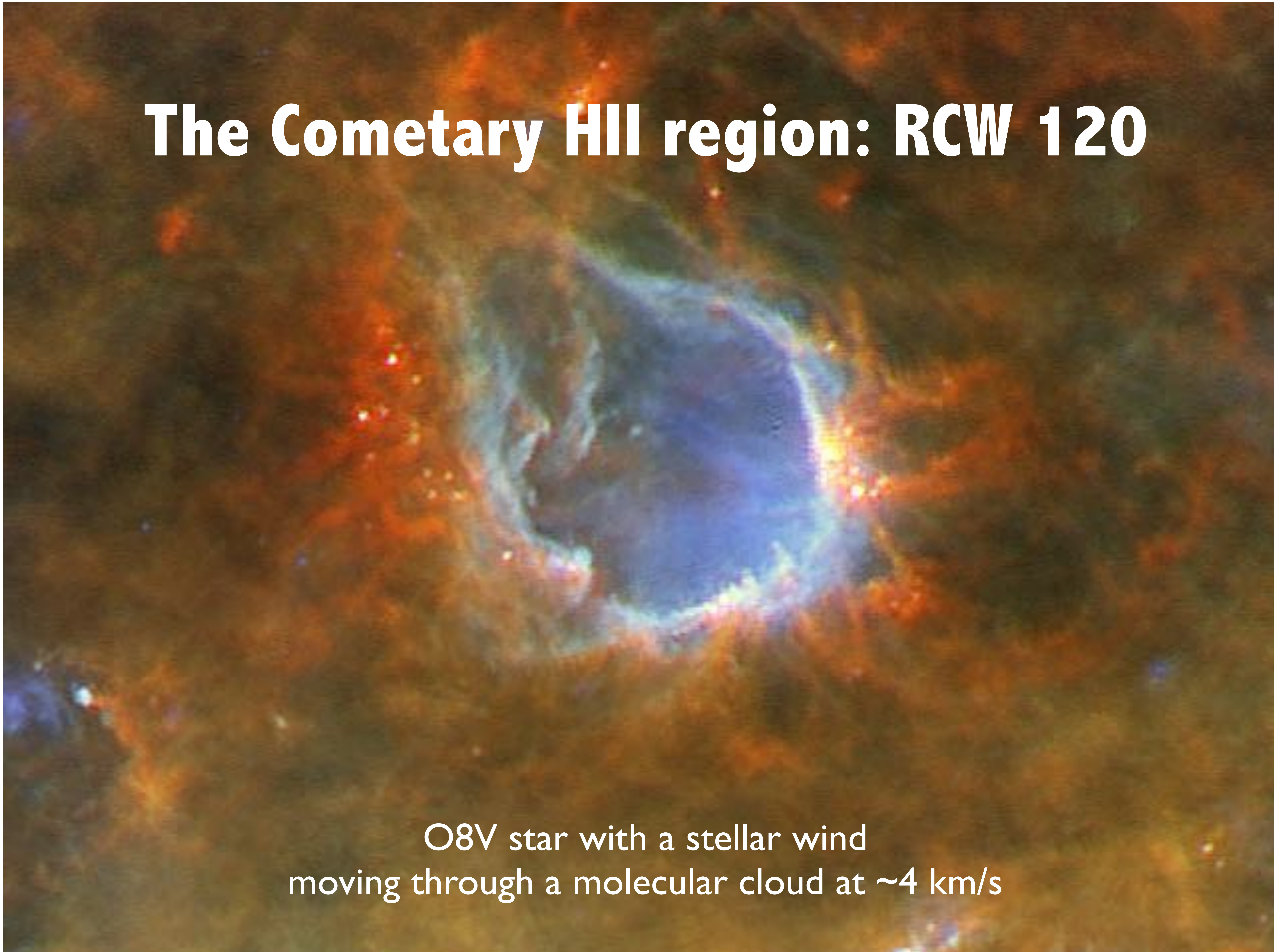
Tiwari+ 2021, ApJ, 914, 117
Tiwari+ 2022, AJ, 164, 150
Tiwari+ 2023, ApJ, 958, 136

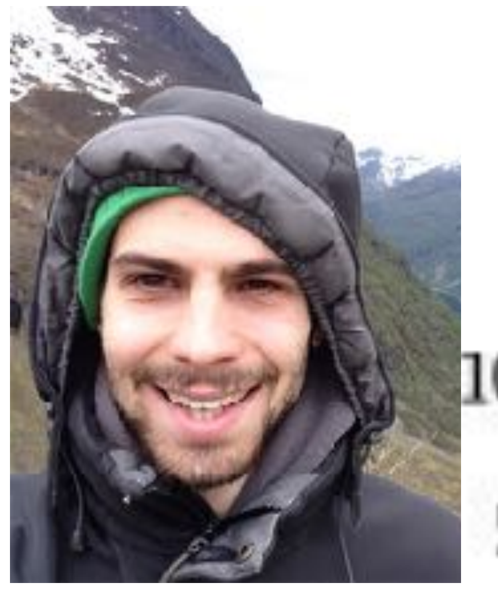
Matteo Luisi
U West Virginia

The Cometary HII region: RCW 120



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

Slawa Kabanovic
U Cologne



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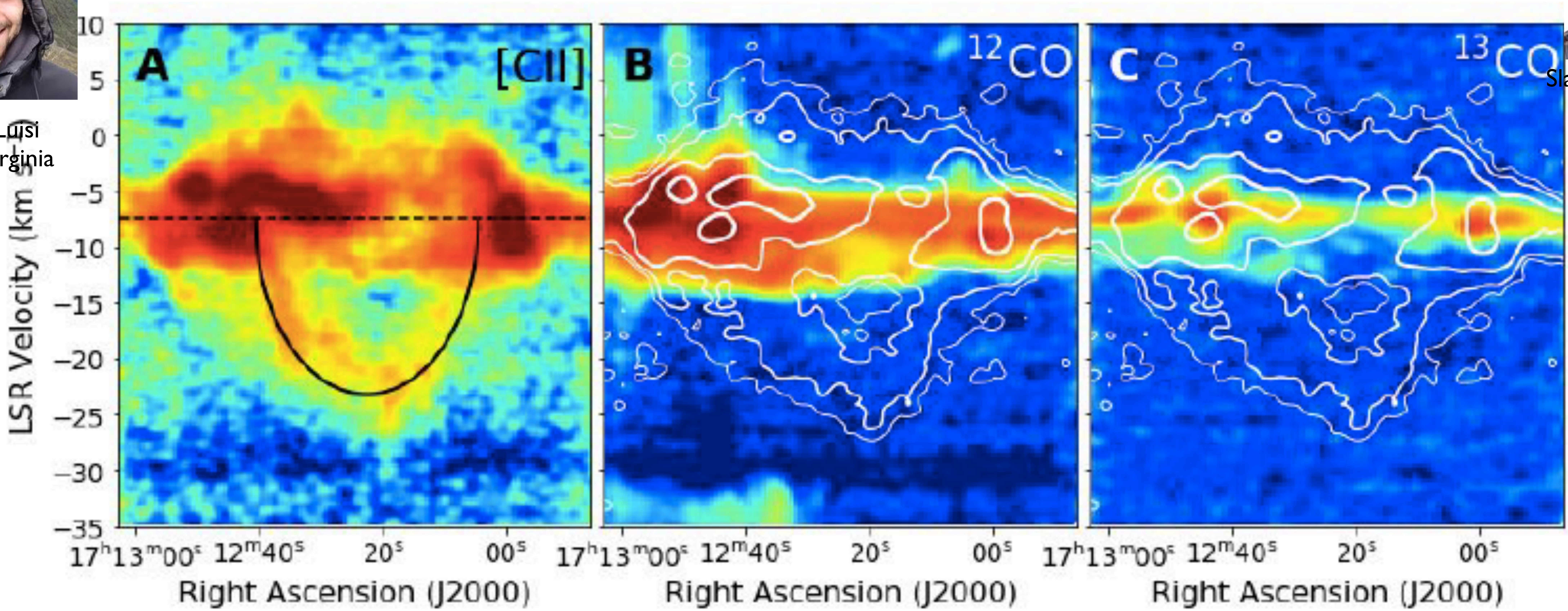
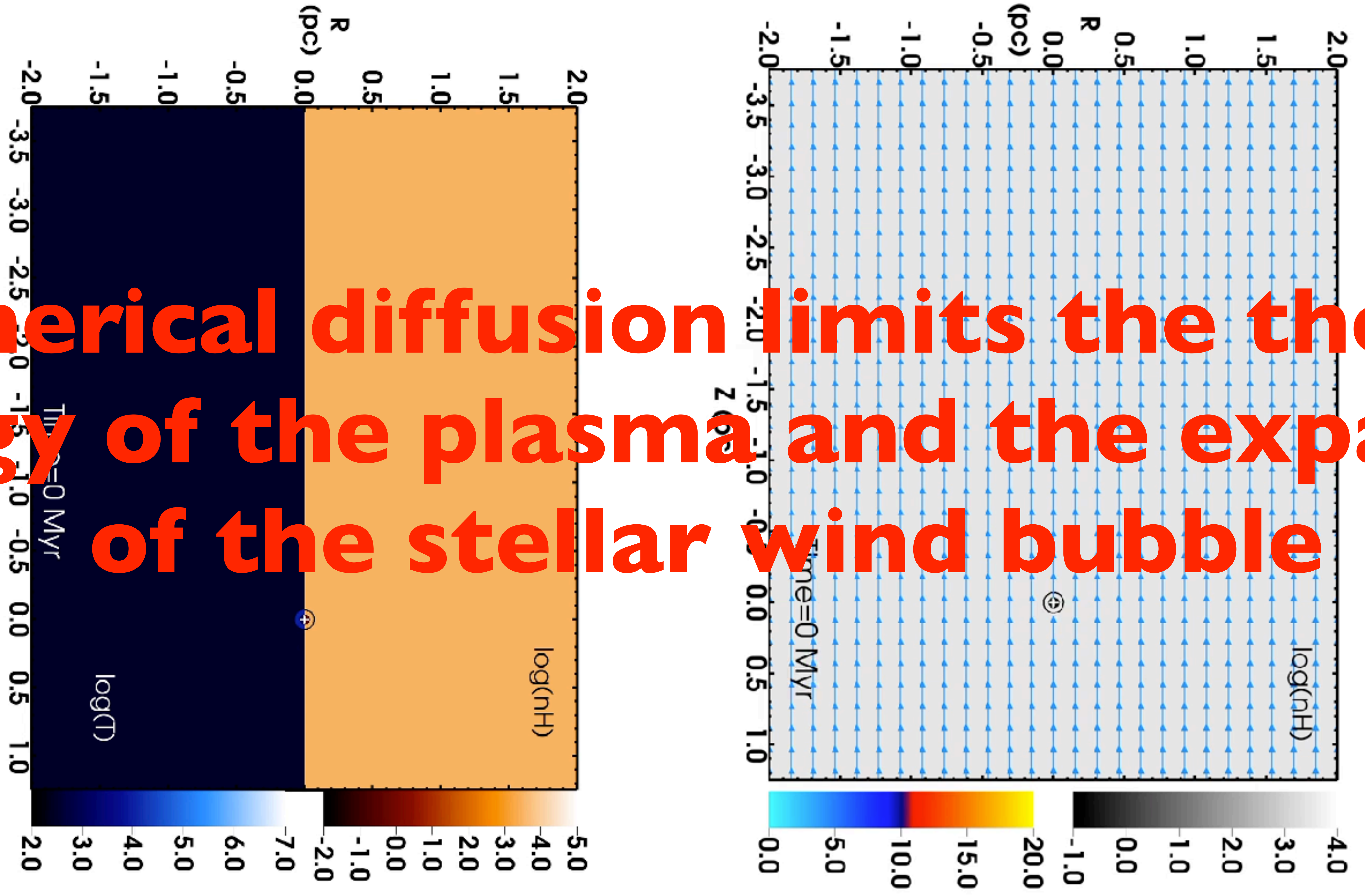


Slawa Kabanovic
U Cologne

Bubble expanding toward us. The rear is denser, fragmented, and expands slower

Luisi+, 2021, Science Advance, 7, 951

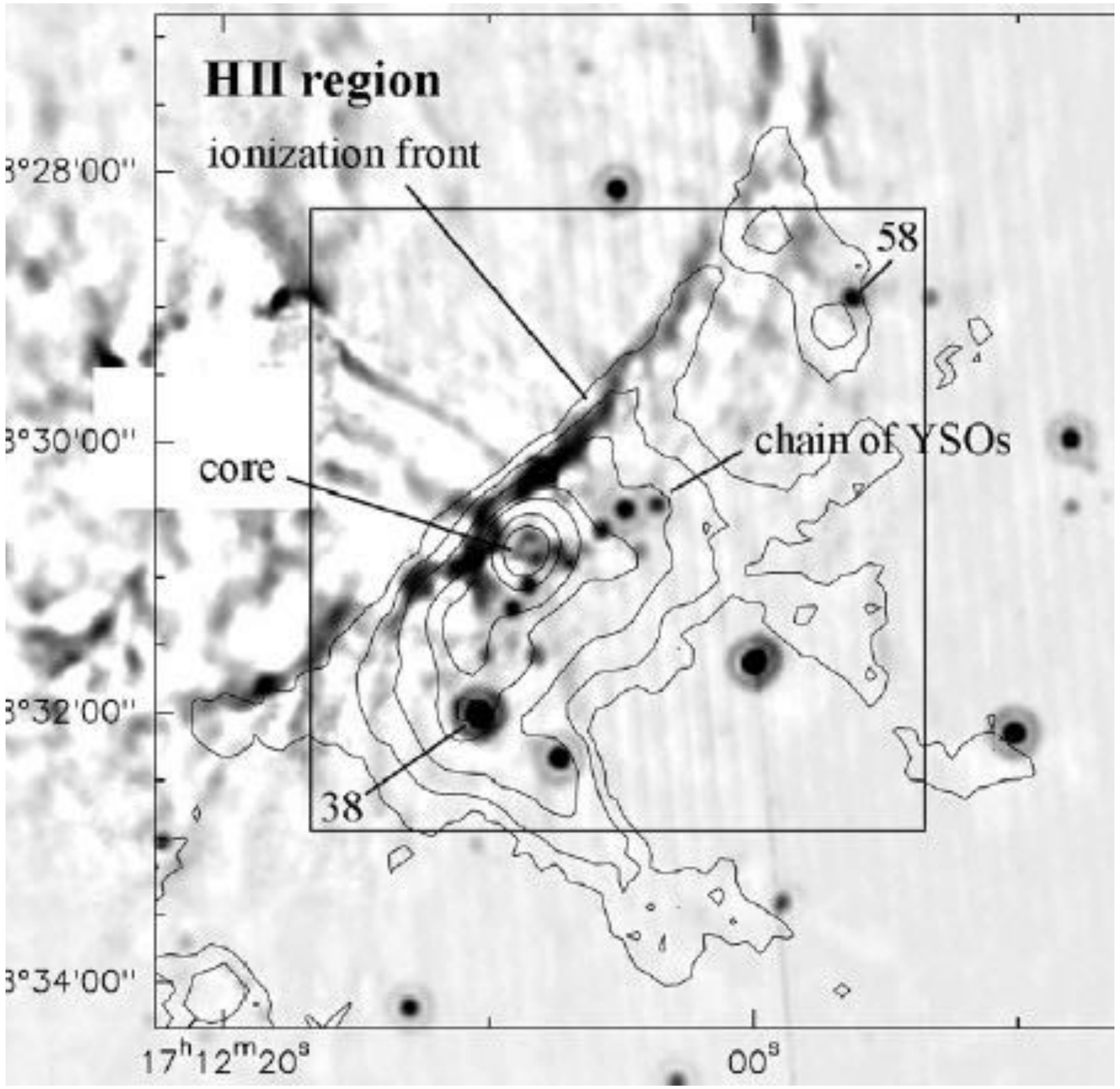
RCW 120 Simulation



Numerical diffusion limits the thermal energy of the plasma and the expansion of the stellar wind bubble

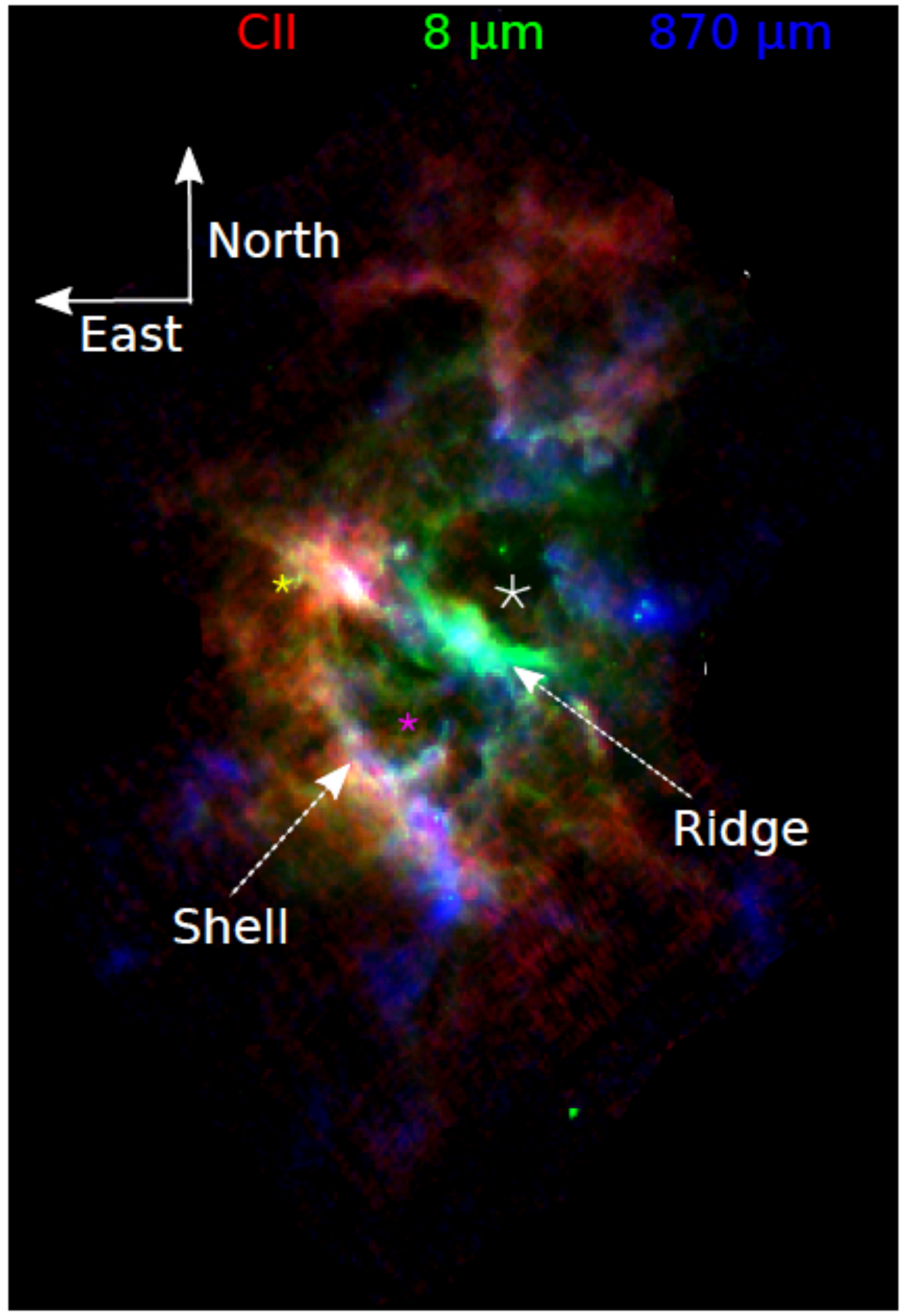
Mackey et al, 2015, A&A, 573, A10

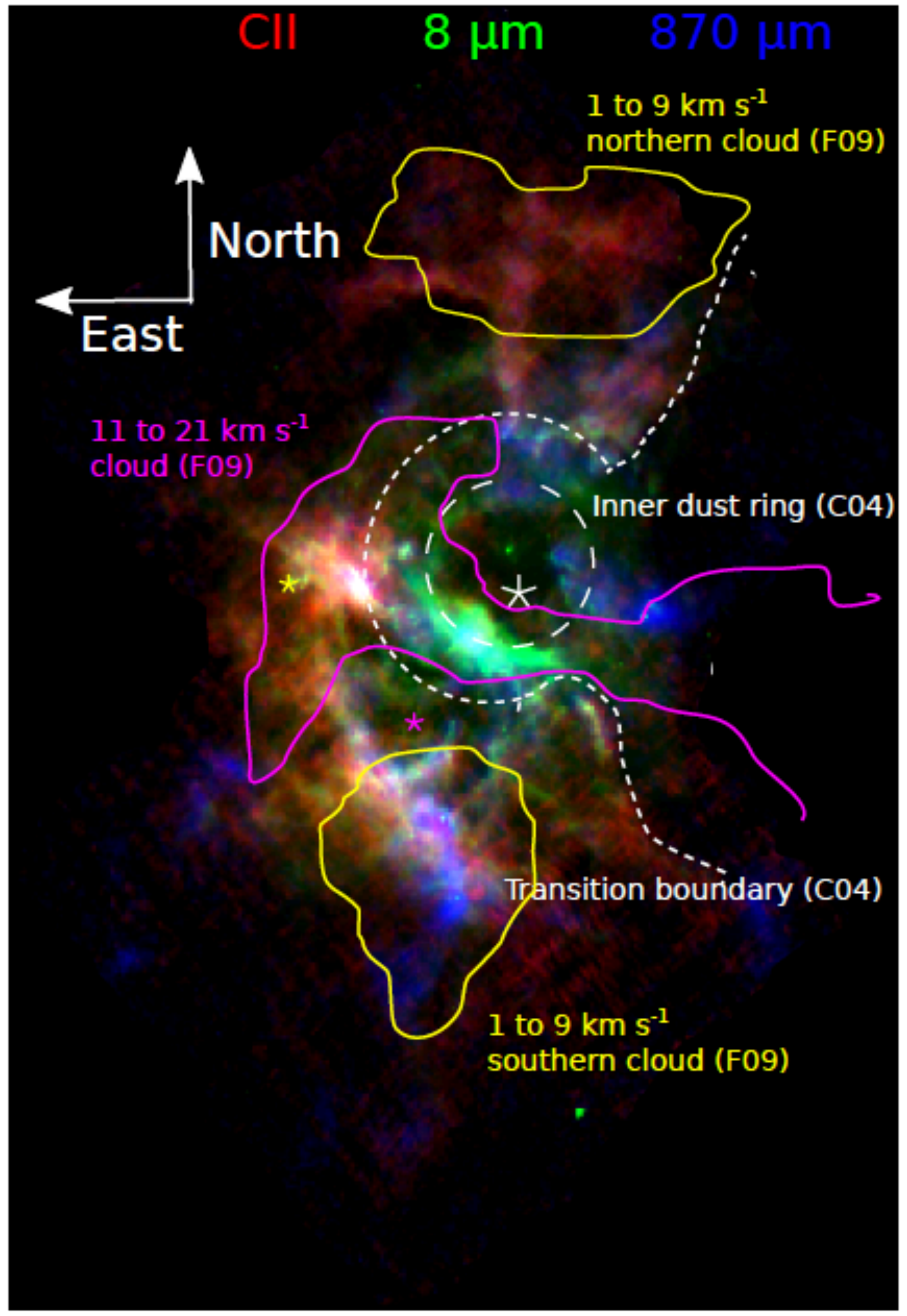
Triggered Starformation

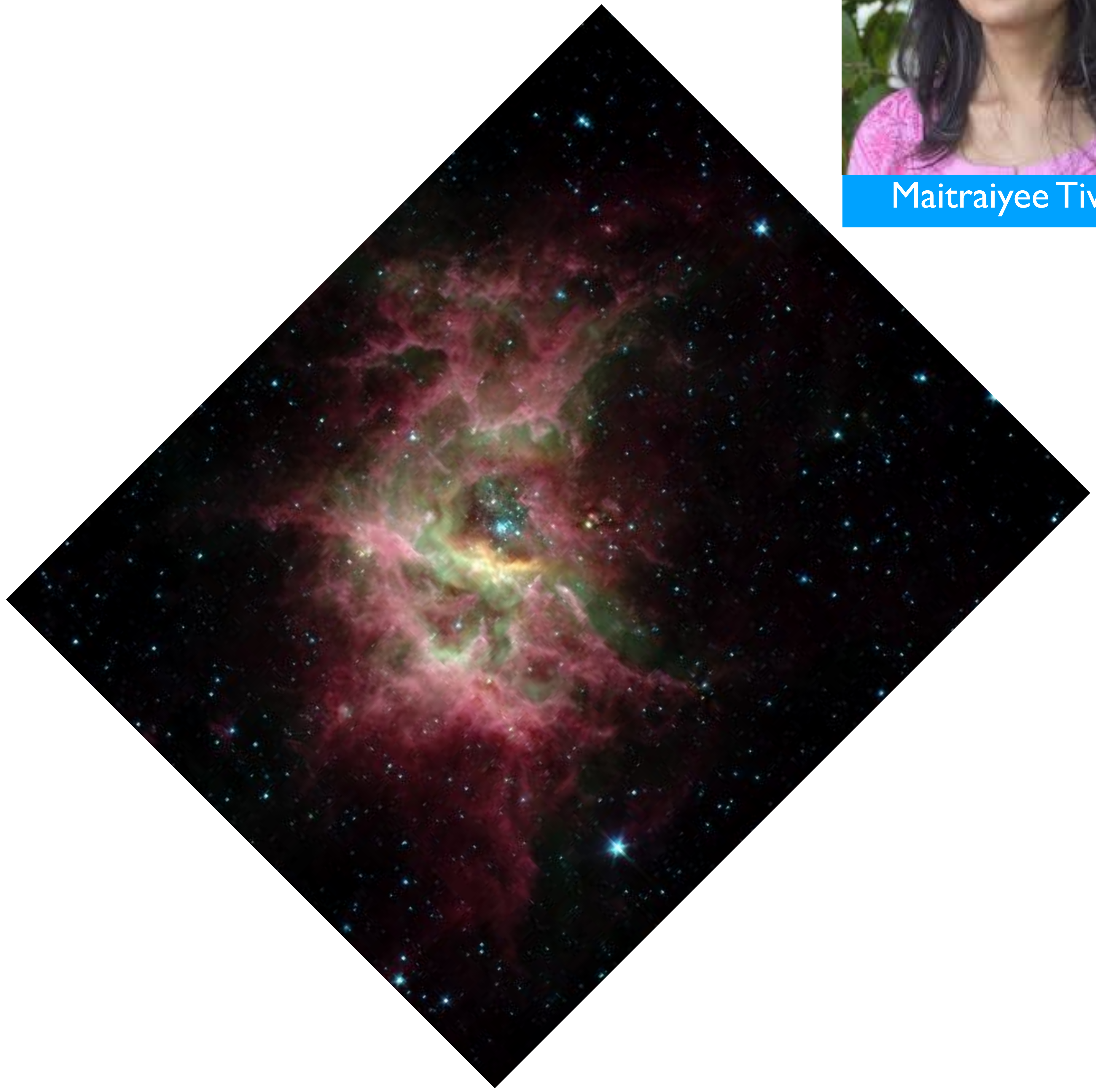


Zavagno+ 2010, A&A, 518 , L81

SOFIA's & Spitzer's View of RCW 49



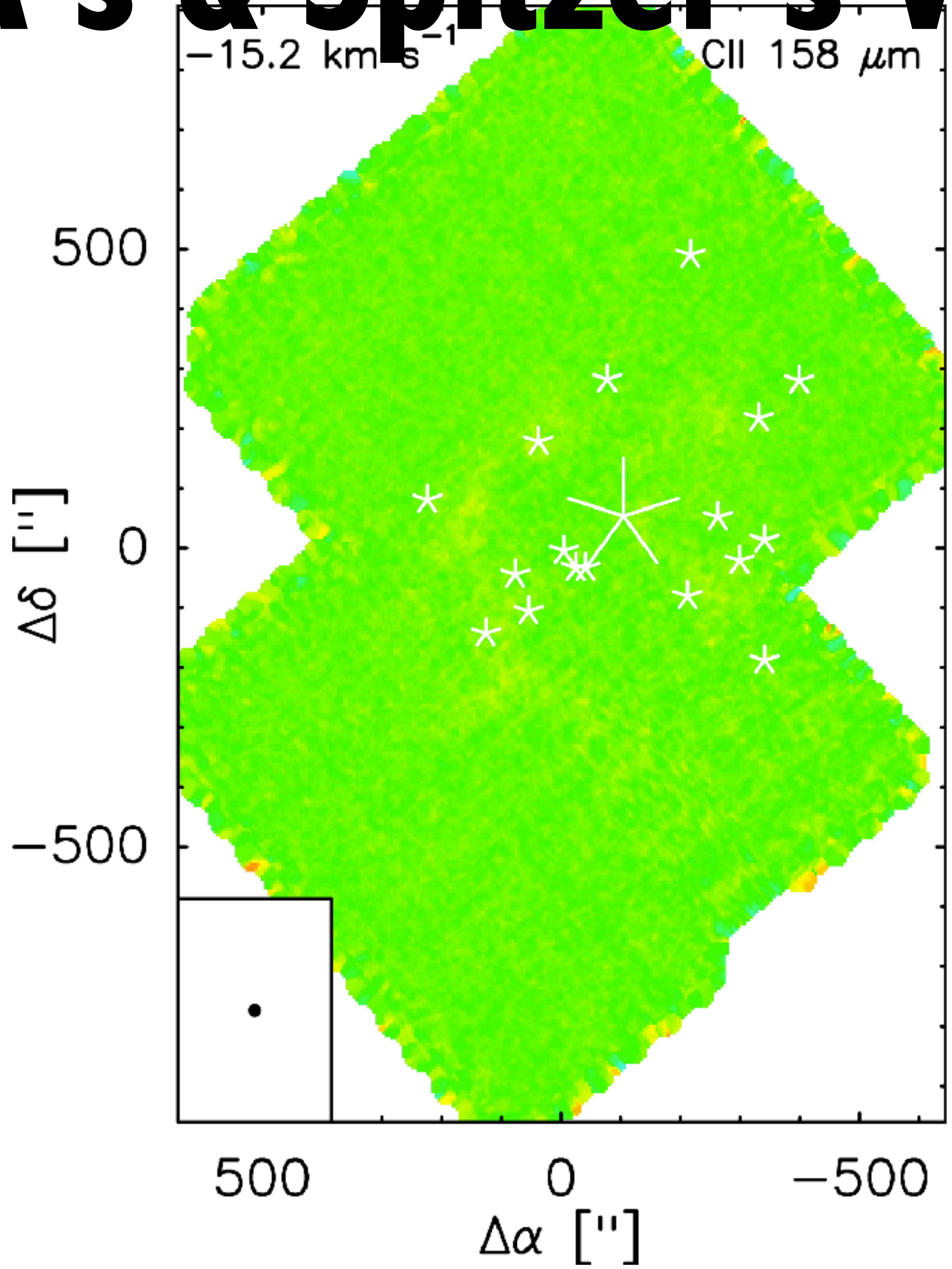


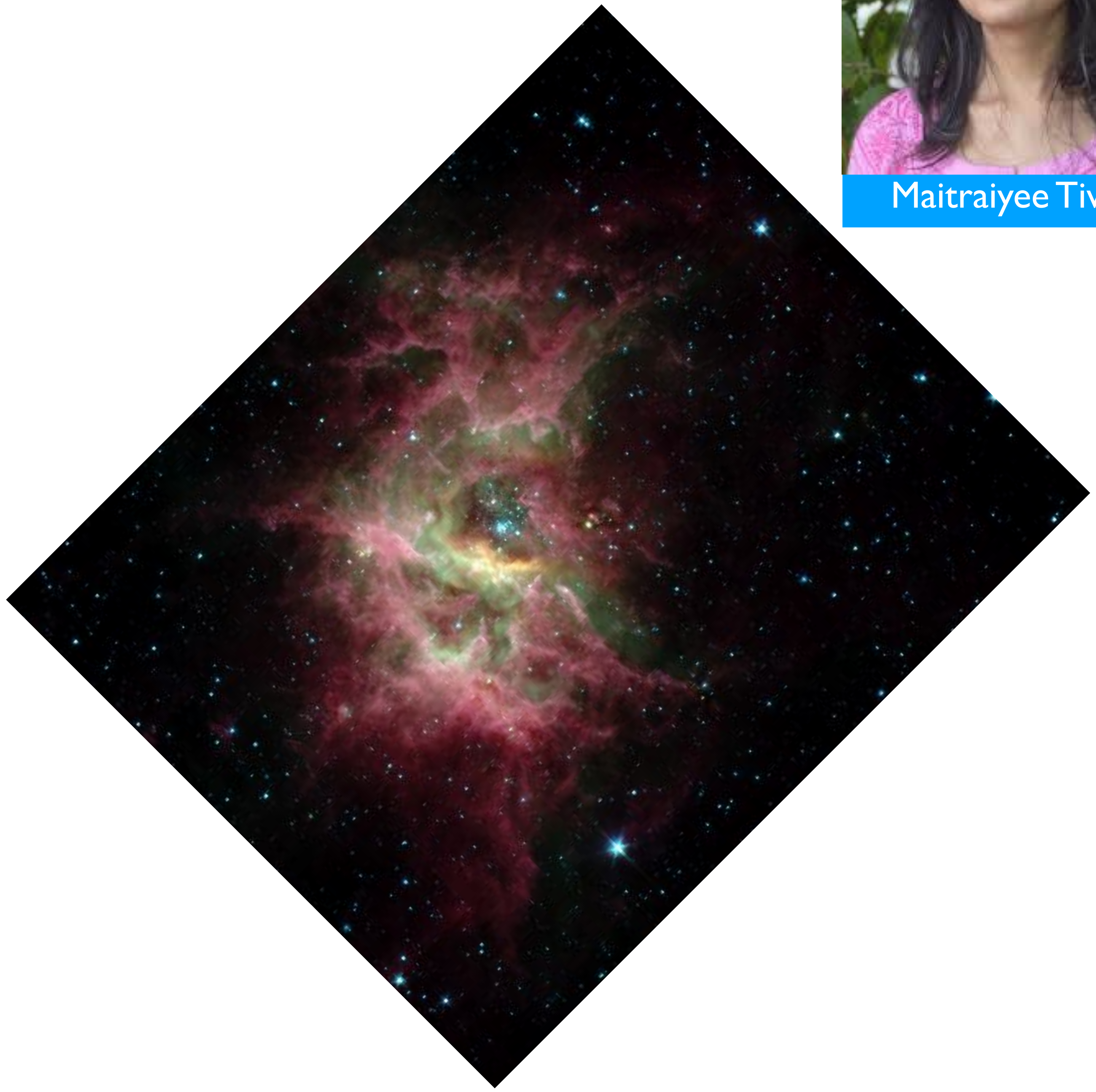


- Westerlund 2 cluster: 37 OB stars, 2WR
- Bubble ruptured to the West
- Expanding shell to the East
- X-ray plasma "escaping" to the West

Tiwari+ 2021, ApJ, 914, 117

SOFIA's & Spitzer's View of RCW 49





- Westerlund 2 cluster: 37 OB stars, 2WR
- Bubble ruptured to the West
- Expanding shell to the East
- X-ray plasma "escaping" to the West

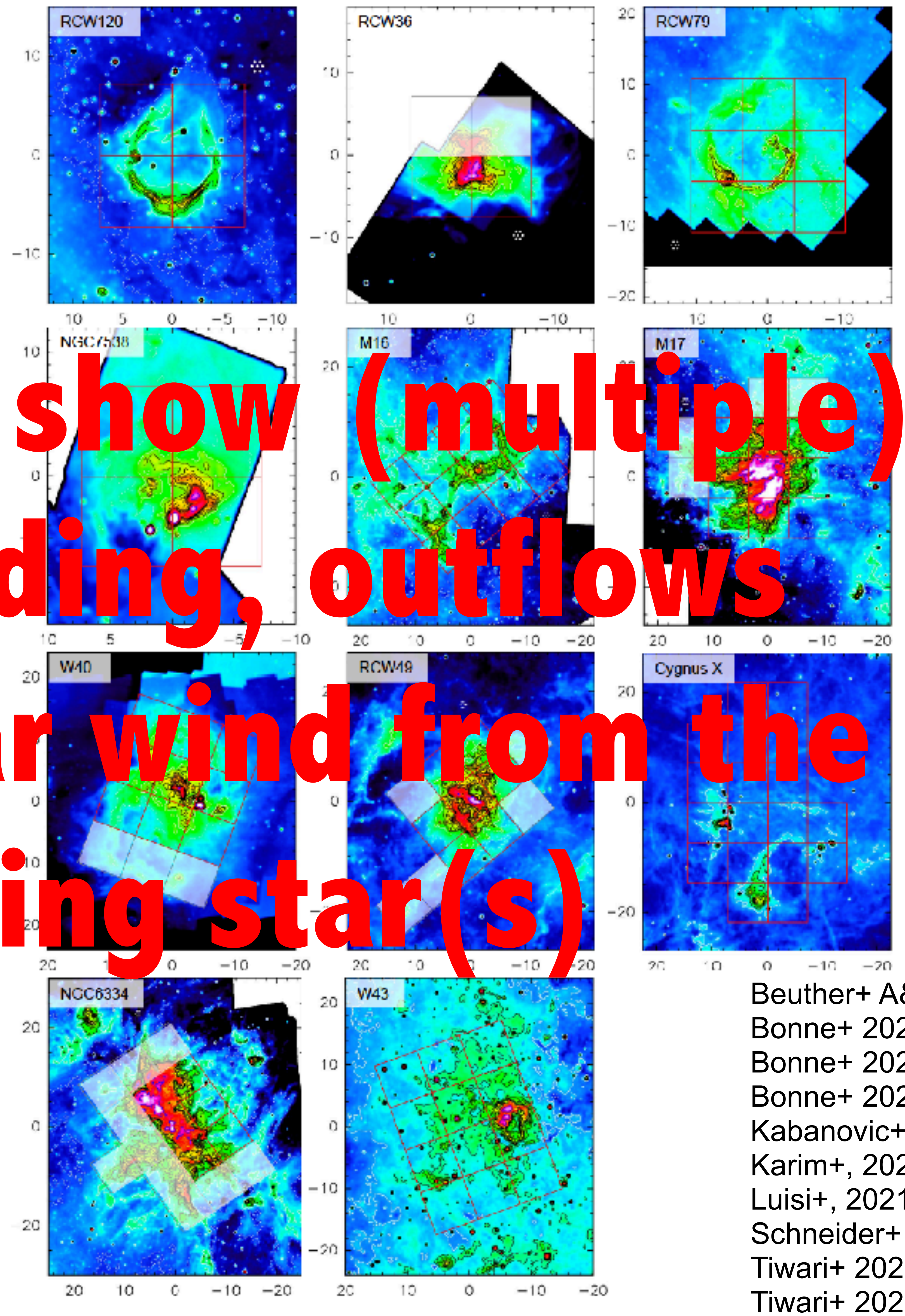
Tiwari+ 2021, ApJ, 914, 117

The SOFIA Feedback Legacy Program

Science goal: How do massive stars interact with their environment ?

- Survey of 11 regions of massive star formation in the [CII] 1.9 THz line using upGREAT on SOFIA
- Typical size surveyed 25x25’
- The sample spans a wide range in star formation characteristics and physical conditions
- The data is non-proprietary and available through the IRSA SOFIA Archive
- About 80% complete
- ancillary data: 8µm IRAC, 70-160 µm Herschel, CO J=3-2, X-ray
- Description of the program: **Schneider et al 2020, PASP, 132, 4301**

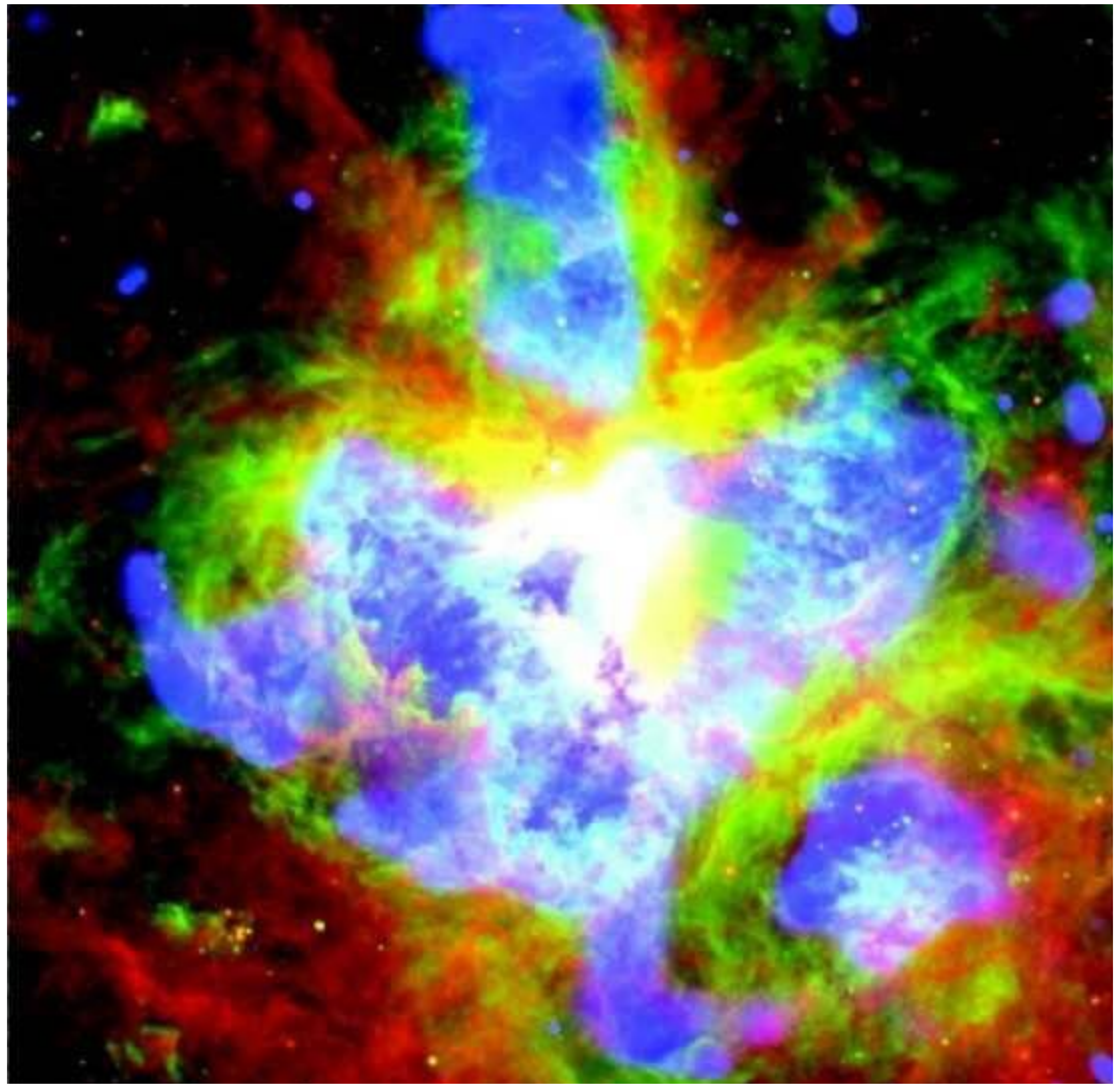
Bottom line: All show (multiple) rapidly expanding, outflows driven by stellar wind from the main ionizing star(s)



Beuther+ A&A, 659, A77
Bonne+ 2022, ApJ, 935, 171
Bonne+ 2023, ApJ, 951, 39
Bonne+ 2023, A&A, 679, L5
Kabanovic+, 2022, A&A, 659, A36
Karim+, 2023, AJ, 166, 240
Luisi+, 2021, Science Advance, 7, 951
Schneider+ 2023, Nature Astronomy, 7, 546
Tiwari+ 2021, ApJ, 914, 117
Tiwari+ 2022, AJ, 164, 150
Tiwari+ 2023, ApJ, 958, 136

Cornelia Pabst

The Super Star Cluster 30 Dor



X-ray
IRAC 8μm
Hα

- Super star cluster: 1100 OB stars, 30 WR
- Compact (pc-scale) star clusters (R136)
- Distributed star formation over ~100pc
- “Burst” of star formation peaking ~4Myr

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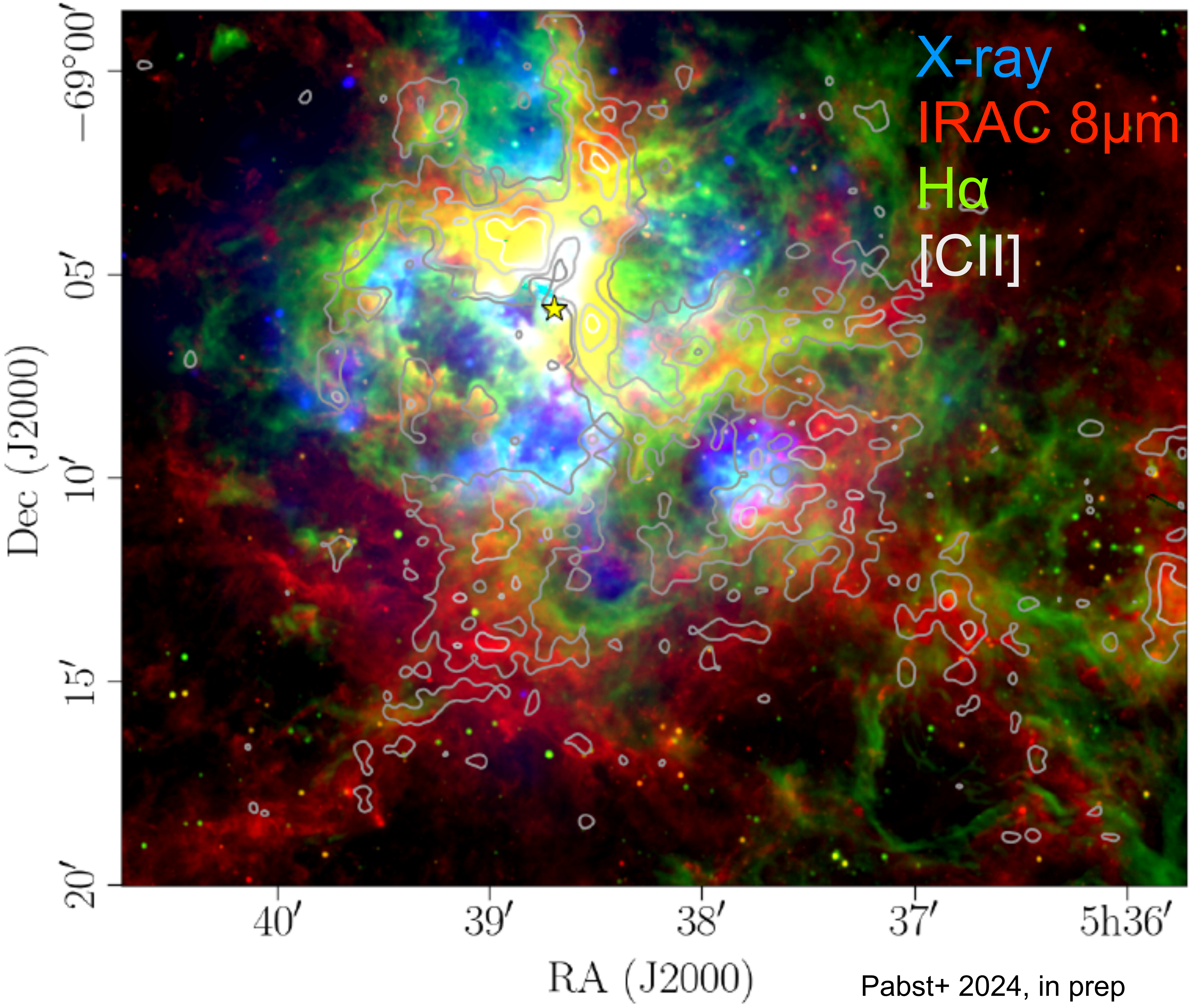


Pabst+ 2024, in prep

Where has all the energy gone, long time passing ?

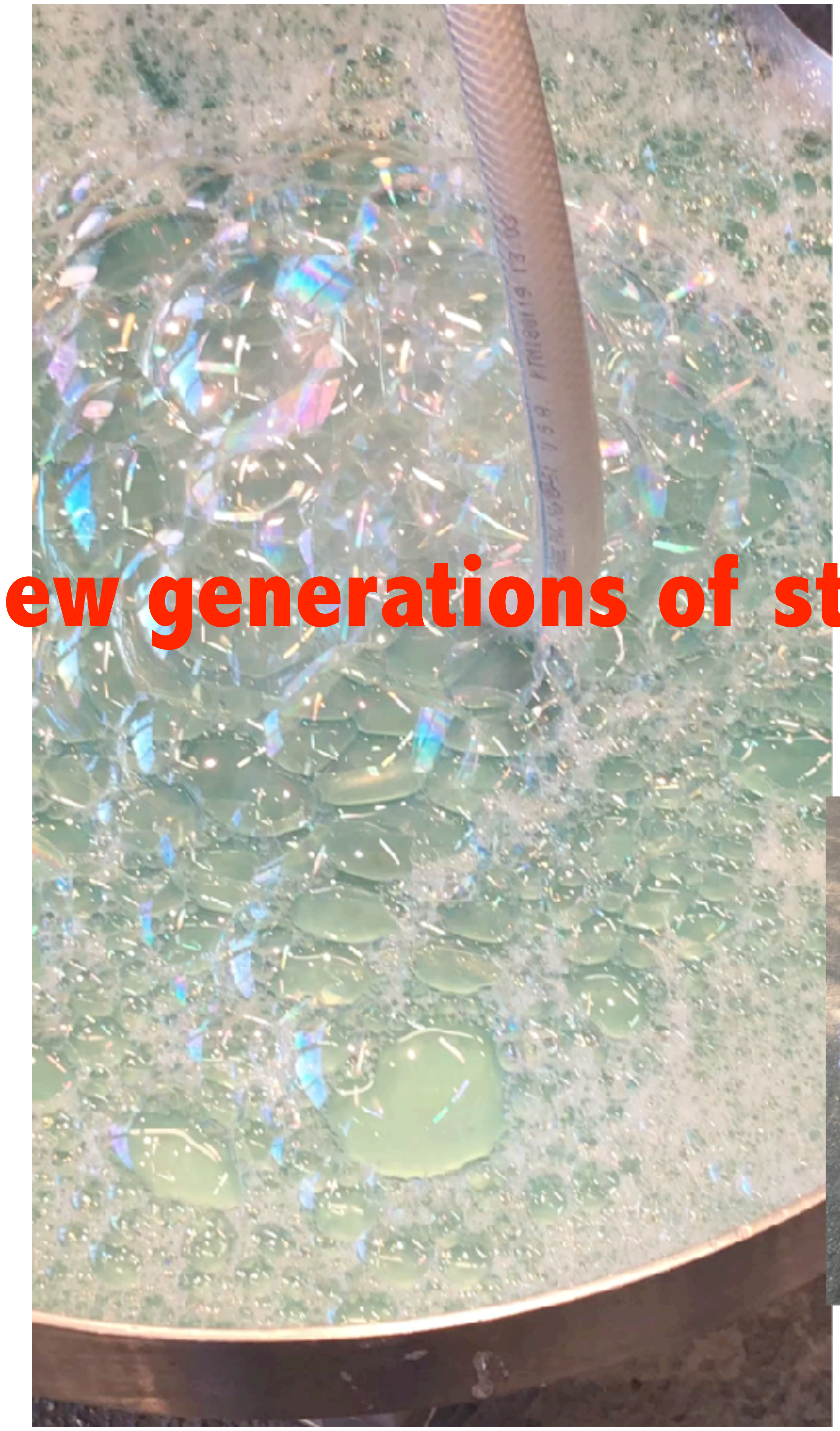
- Stellar wind feedback energy: $E_w \simeq 2.8 \times 10^{53}$ erg
- Kinetic/turbulent energy ionized gas: $E_{kin} \simeq 8.4 \times 10^{51}$ erg
- Kinetic/turbulent energy PDR gas: $E_{kin} \simeq 4 \times 10^{51}$ erg
- Thermal energy plasma: $E_{th} \simeq 3.6 \times 10^{52}$ erg
- Kinetic energy HI shells: $E_{kin} \simeq 3 \times 10^{51}$ erg

Pabst+ 2024, in prep

Where has all the energy gone, long time passing ?

- No large-scale expanding shells
- Stirring up the ionized gas without “moving" it
- Stellar winds sweep up hot plasma, compress, (photo-ionize), and “cool” the gas
- Stellar winds create fast-moving, dense ($\sim 50\ cm^{-3}$), (ionized) gas shells (like RCW 49/Wd2) with typical kinetic energy of 5×10^{50} erg
- This energy is dissipated by shell-shell collisions and does not couple well to drive large scale expansion of a neutral shell
- This triggers “distributed” star formation

Passed on to form new generations of stars



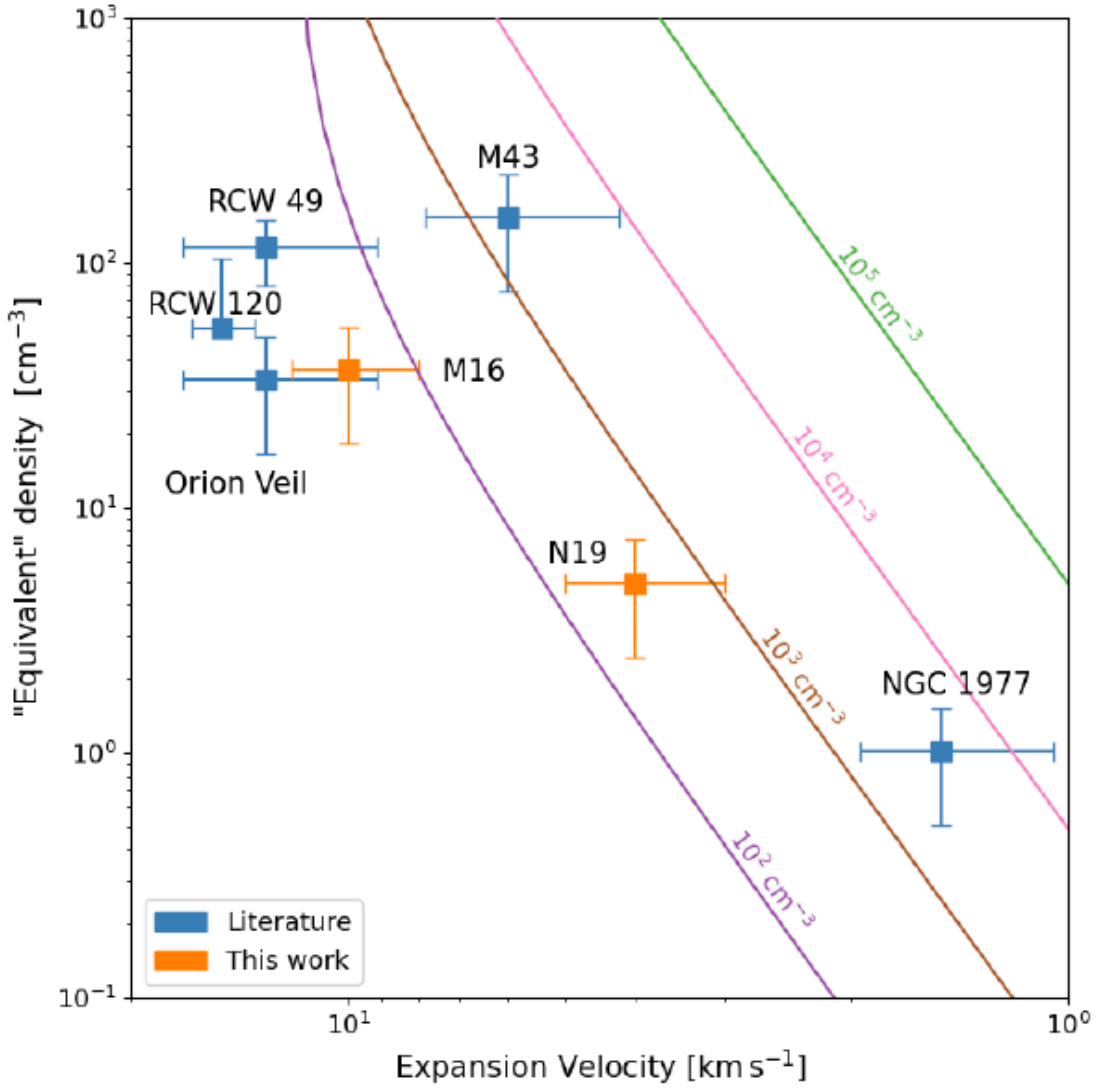
Gracie Phelps 2022
Children Museum Denver

Pabst+ 2024, in prep

Thermal Expansion

Ramsey Karim

- The excess thermal pressure of ionized gas will drive expansion of the HII region
- The "equivalent" density takes into account differences in the ionizing radiation field
- Curves are labeled by the initial cloud density
- Time increases to the right from about 50,000 yr for M43 to 200,000 yr for NGC 1977
- Sources to the left of the curves expand much faster than thermal expansion can explain and are driven by stellar winds

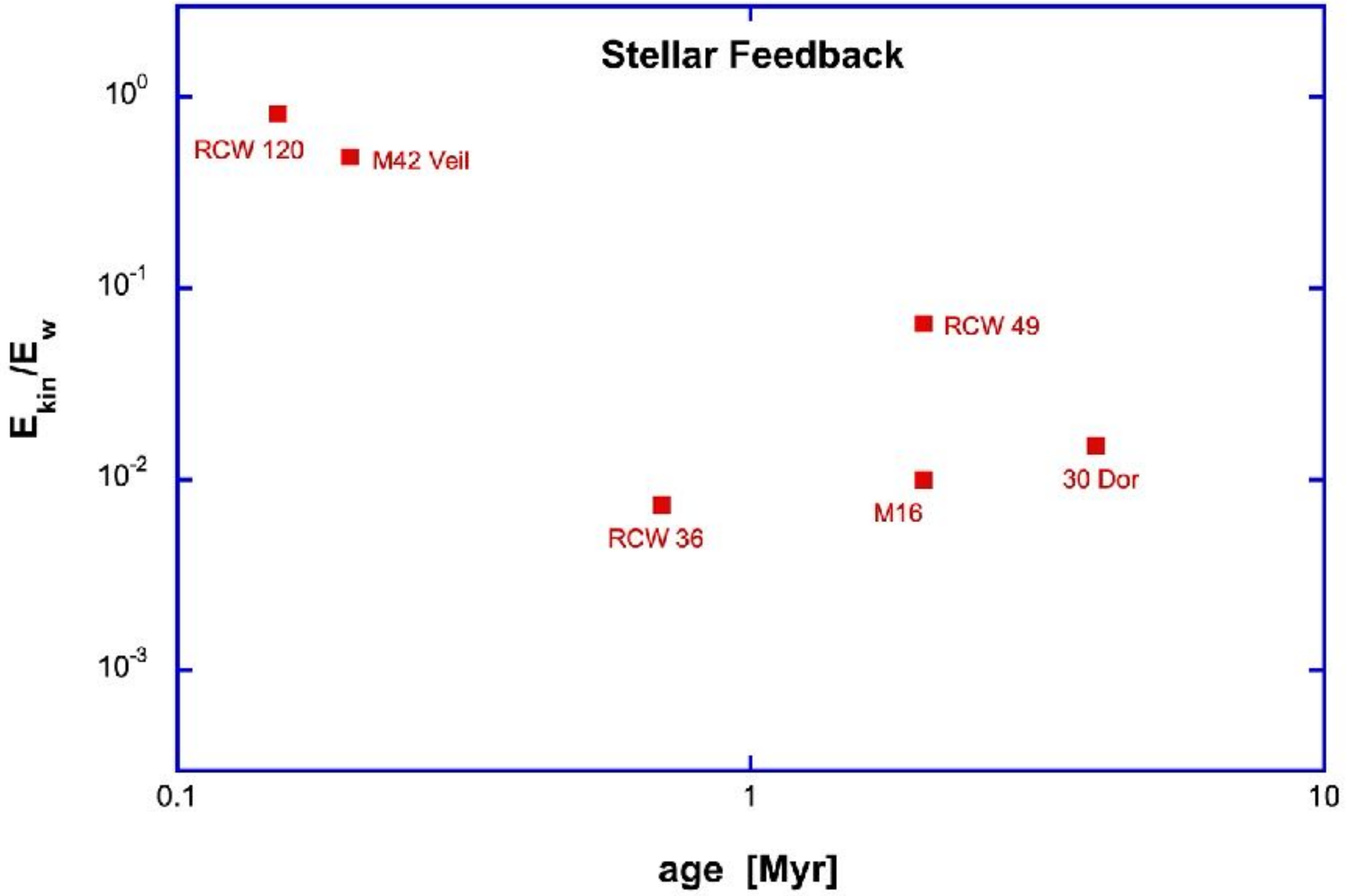


Karim+ 2024

Kinetic Feedback: Mechanical Energy

OB associations:

- Initial phase: stellar wind energy drives expansion
- Depending on environment, after 100,000–300,000 yr, bubble bursts, energy escapes, and shell “coasts”
- Energy rejuvenates superbubbles



Pabst+ 2024, in prep

Summary

- Radiative & mechanical feedback regulates the structure and evolution of galaxies
- The macroscopic structure of the galaxy is intimately linked to the microscopic properties of the gas
- FUV radiation heats the gas through the photo-electric effect and controls the thermal structure of the ISM
- Mechanical energy input sets the pressure and the distribution of the gas over the ISM phases
- Initially, mechanical feedback destroys molecular cloud cores. In later stages, photo-ionization takes over.
- For typical OB associations, coupling of mechanical energy to gas kinetic energy is only efficient until the bubble bursts (first ~200,000 yr)
- Rejuvenation and mass loading of SNe creates superbubbles that vent material into the halo and transport material over large distances. Coupling of mechanical energy is fairly efficient.
- In super star clusters, mechanical energy is used to drive prolonged star formation. This limits the efficient coupling to galactic winds

Future

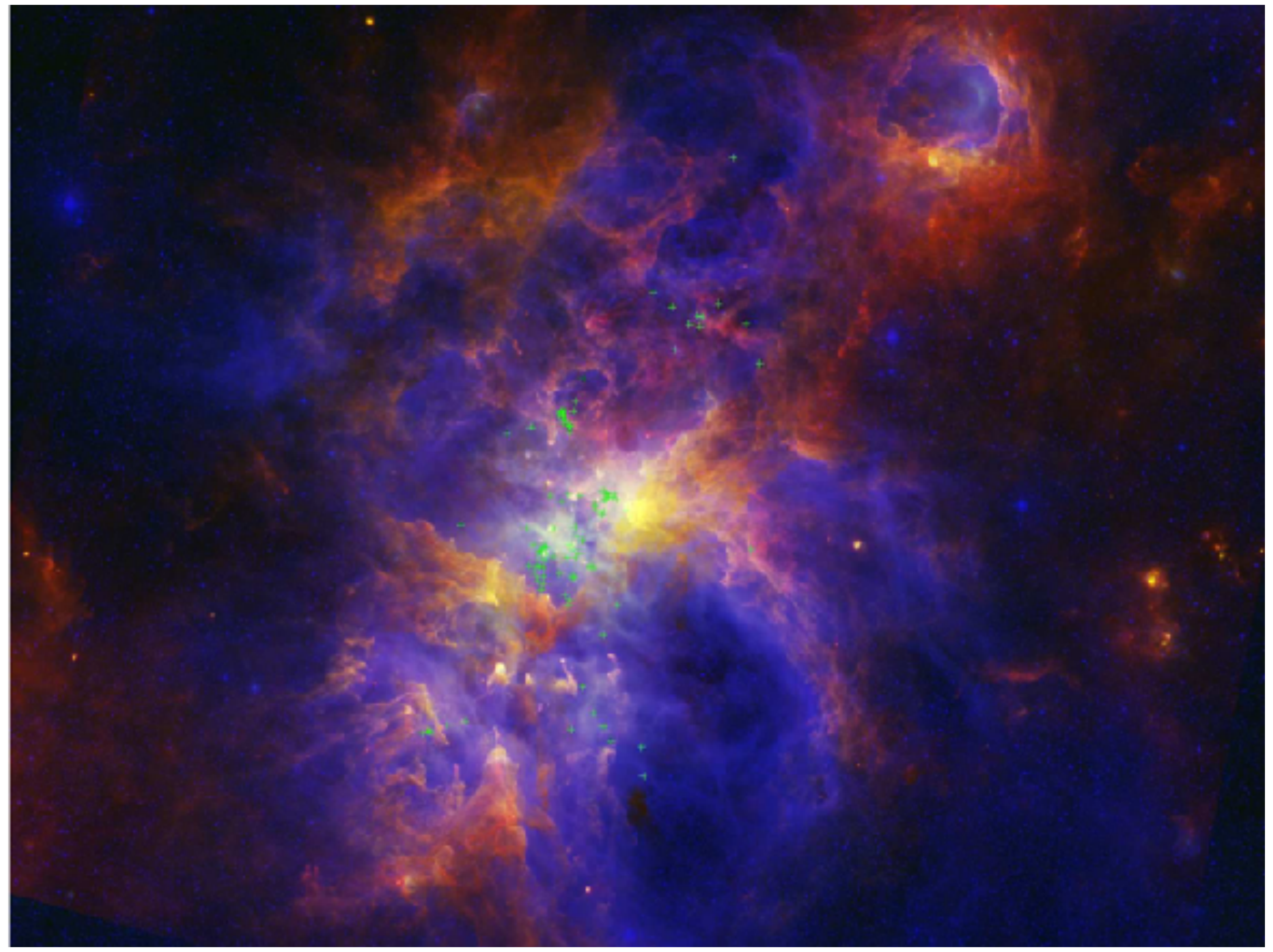
Balloon Surveys

GUSTO

- Surveyed ~50 square degrees of the inner galactic plane at 45” spatial resolution in the [CII] 1.9 THz line (& [NII])
- Surveyed ~1 square degree of the 30 Dor molecular ridge in the LMC
- Some 100 stellar bubbles
- Stellar feedback on large scales

ASTHROS

- will survey ~1 square degree of SOFIA/ Feedback sources in [NII] and [OIII] at comparable spatial resolution



Carina Nebula

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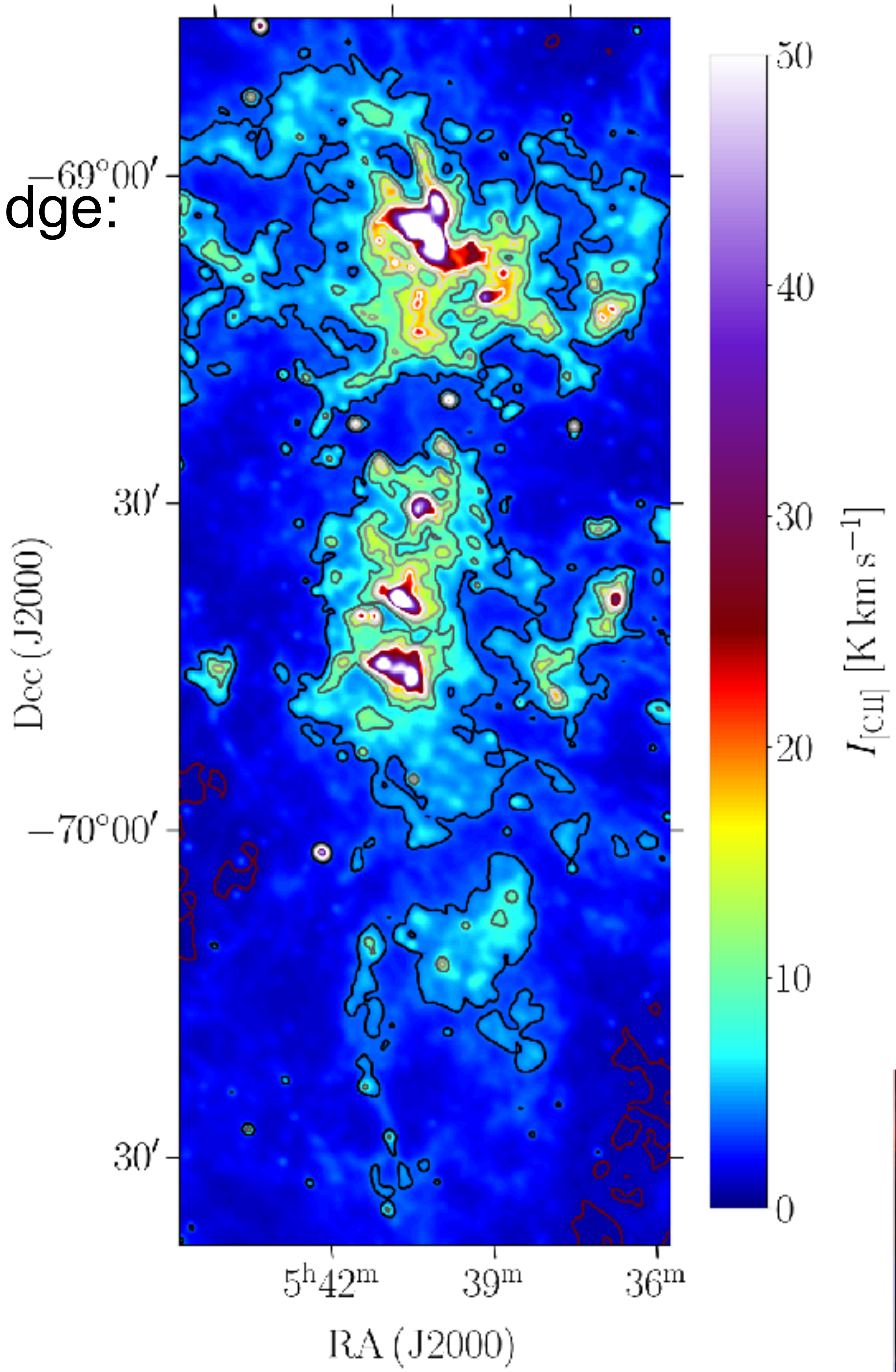
30 Dor molecular ridge:

What GUSTO may have seen

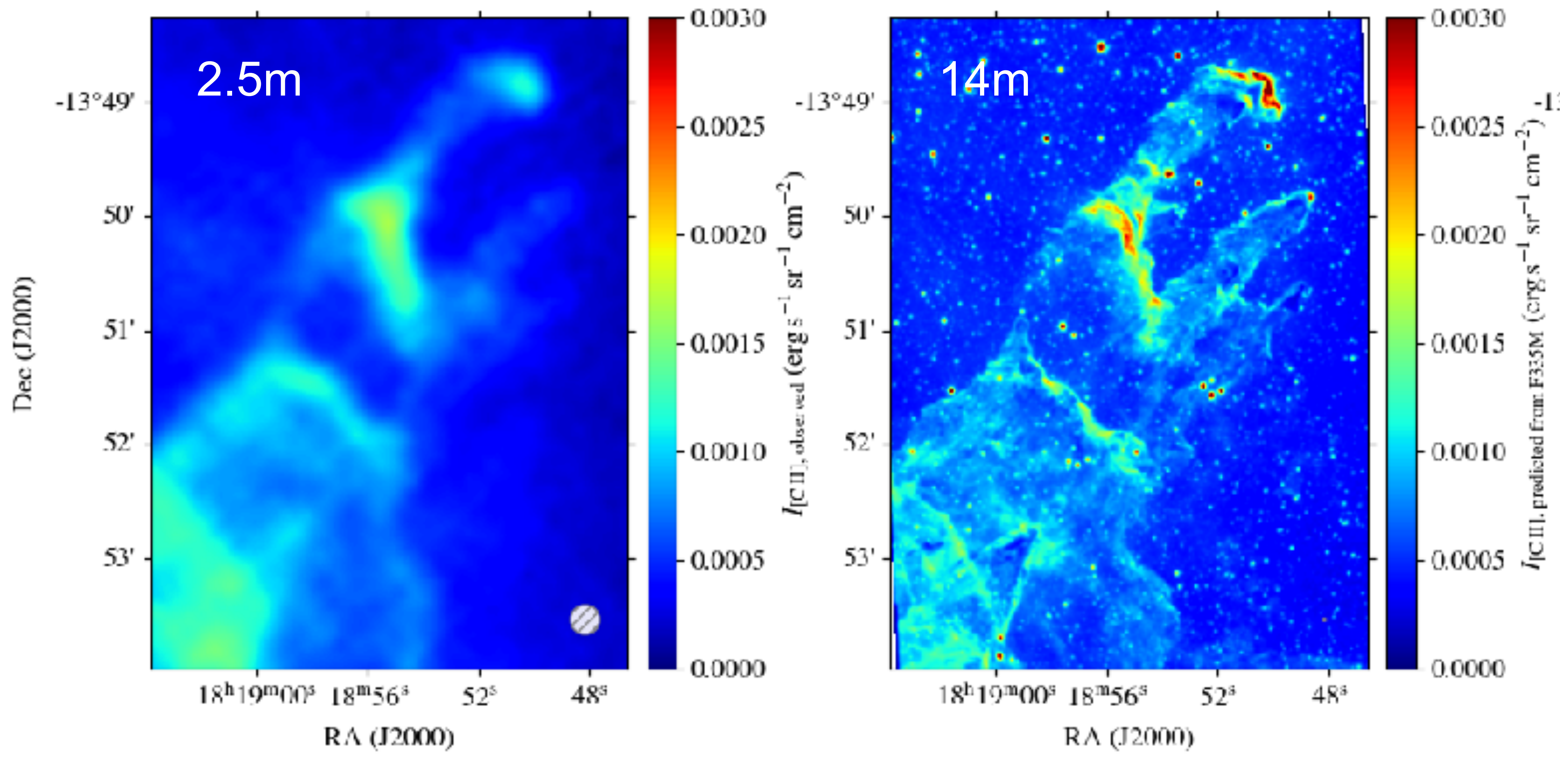


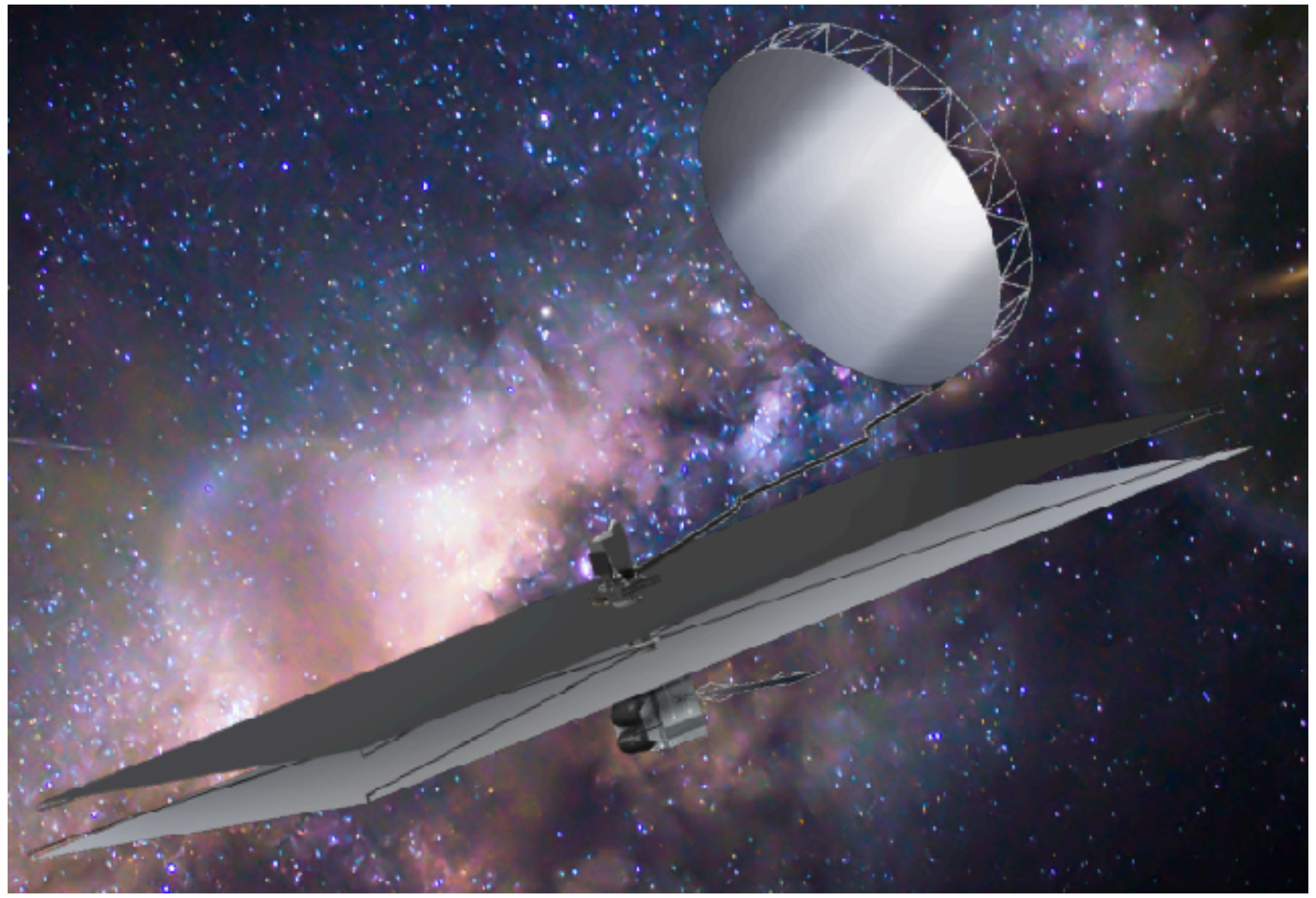
Future

Proposed NASA Far-IR probe

SALTUS

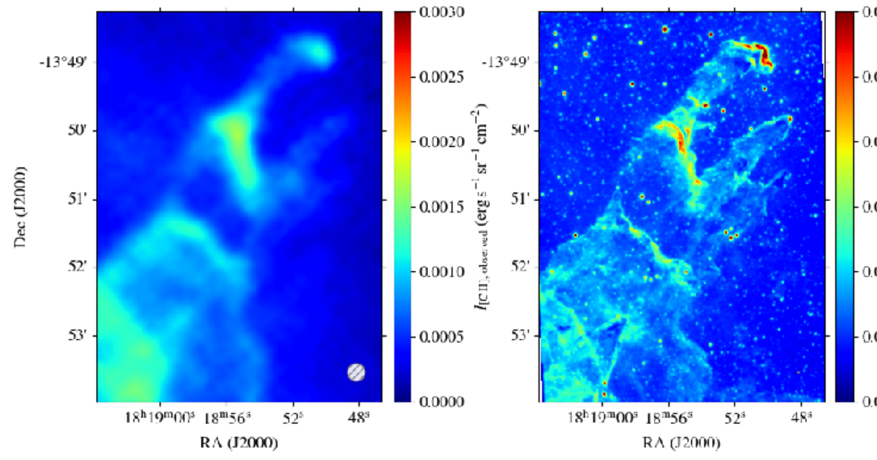
- inflatable 14 m aperture with 34-230 μm spectrometer at R=300 and heterodyne receivers at a.o. [CII] 1.9 THz and a wealth of H_2O lines
- Steerable secondary allows mapping of 5 square arc minutes without repointing: well matched to JWST mapping capabilities
- With [CII] at 2.5” spatial resolution, SALTUS promises close-up view of radiative and mechanical feedback





SALTUS

Future



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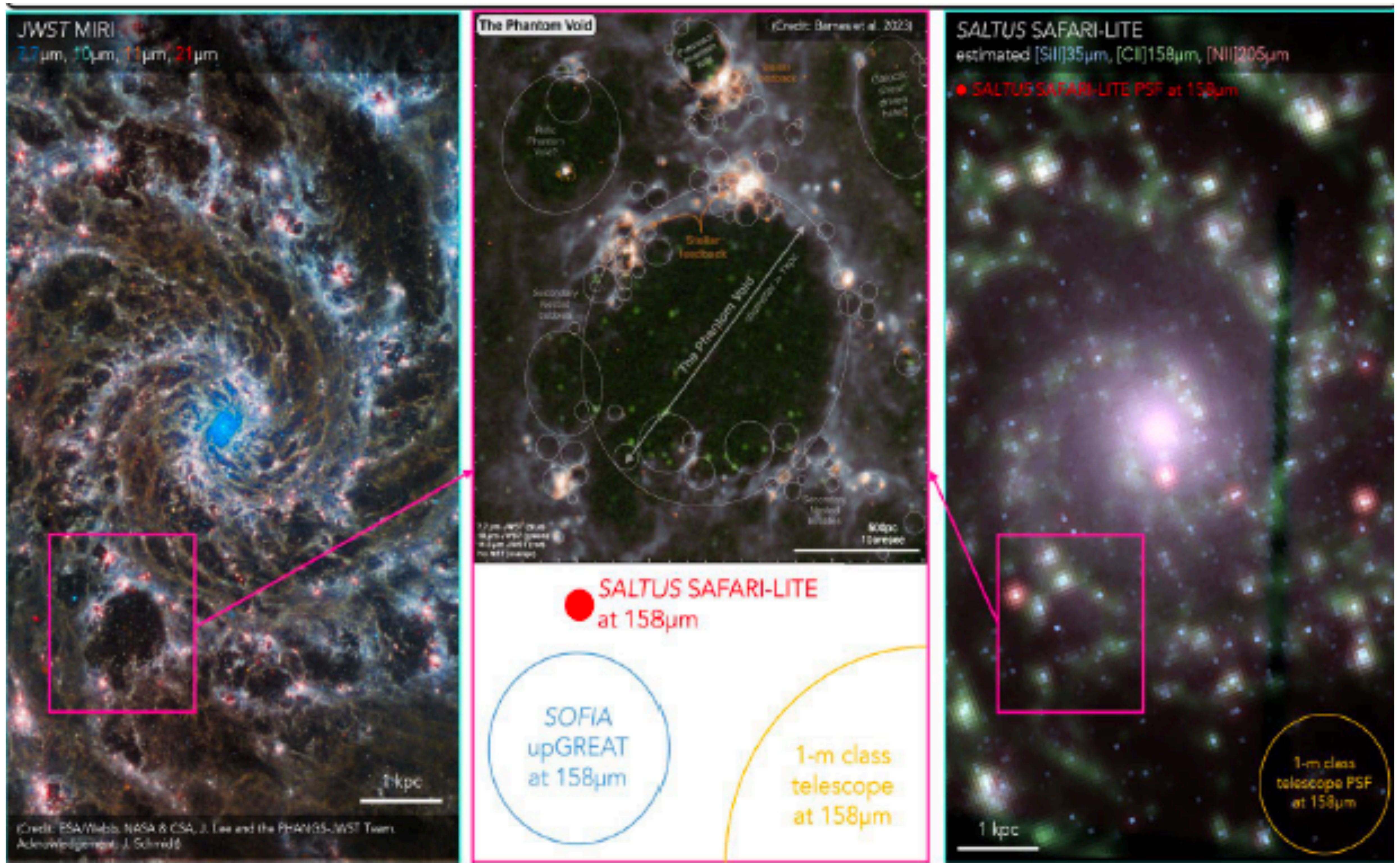

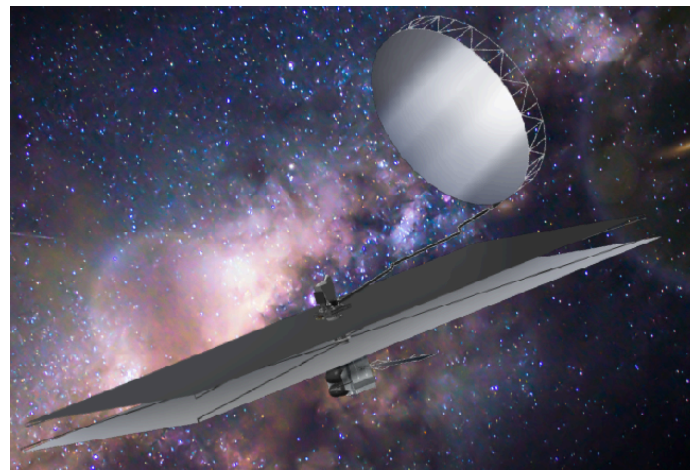

SALTUS