Feedback

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Are we making progress?

Yes.

Observations: resolution (spatial, velocity) and sensitivity are game-changers.

Theory: multiple simulations now include multiple forms of feedback.

SILCC: **SI**mulating the **L**ife**C**ycle of molecular **C**louds

The SILCC project - IV. Impact of dissociating and ionizing radiation on the interstellar medium and Hα emission as a tracer of the star formation rate

Thomas Peters
Thorsten Naab
Stefanie Walch
Simon C. O. Glover
Philipp Girichidis
Eric Pellegrini
Ralf S. Klessen
Richard Wünsch
Andrea Gatto
Christian Baczynski

Peters et al., 2017, MNRAS 466, 3293

radiation, stellar winds and supernovae

Feedback

Fe01 How do the radiation, heat transfer, winds, (turbulent) flows, cosmic rays, and MHD/plasma waves produced during the SF process **affect** the **SF in the region**?

Fe02 In **low-mass** SF regions without a strong radiation field and SN shocks, which feedback process dominates (e.g., jets, outflows, stellar winds, turbulence, cosmic rays, etc.)?

Fe03 Co13 Cores near a forming cluster: will the radiation and winds **trigger** SF or **prevent** it?

Fe04 MC07 What effect has the feedback within one MC on **another MC** (e.g. during its destruction)?

Fe05 Fi16 Is the **feedback** of a massive star/cluster able to **form filamentary** structures in a nearby dense region?

Fe06 Can the numerous **B stars** compete with their wind feedback against the strong feedback of a few SNs?

→ posters:
P01 Ahmad Ali
P11 Wonju Kim
P13 Rolf Kuiper
P21 Alice Nucara

Je04 How much **turbulence** is injected by the jets and the outflows into the SF region?

General

Ge03 What is the fraction of stars being formed by **triggered SF**?

Ge07 In which phase is the SF process considerably affected by **cosmic rays**?

Ge08 In which phase and by which physical processes is the **multiplicity** of newly-formed stars determined?

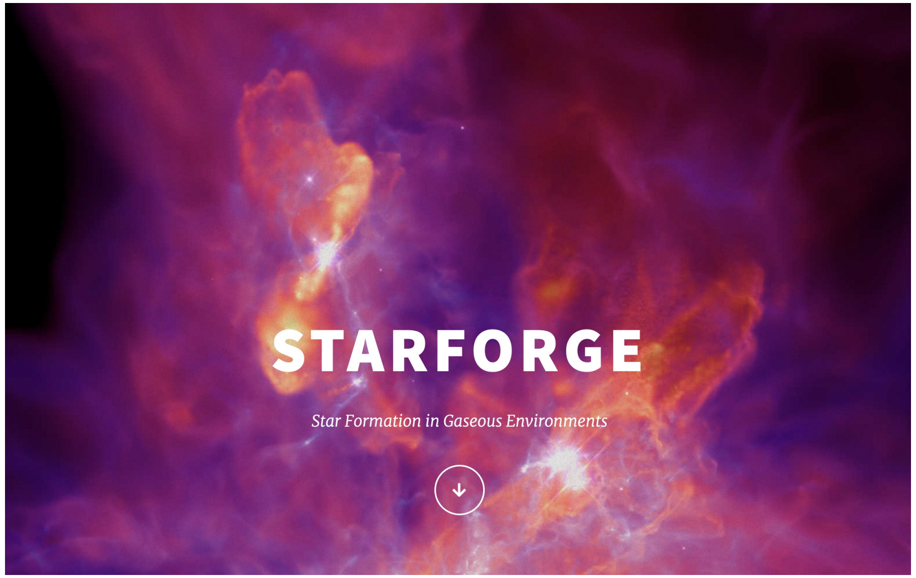
Ge09 Can radiation **stop** accretion?

Ge10 What is the main **driver** of the **turbulence** that is affecting SF regions?

Ge11 Is there a **limit** for the final **mass** of the formed star and how does it depend on the metallicity in the forming cloud?

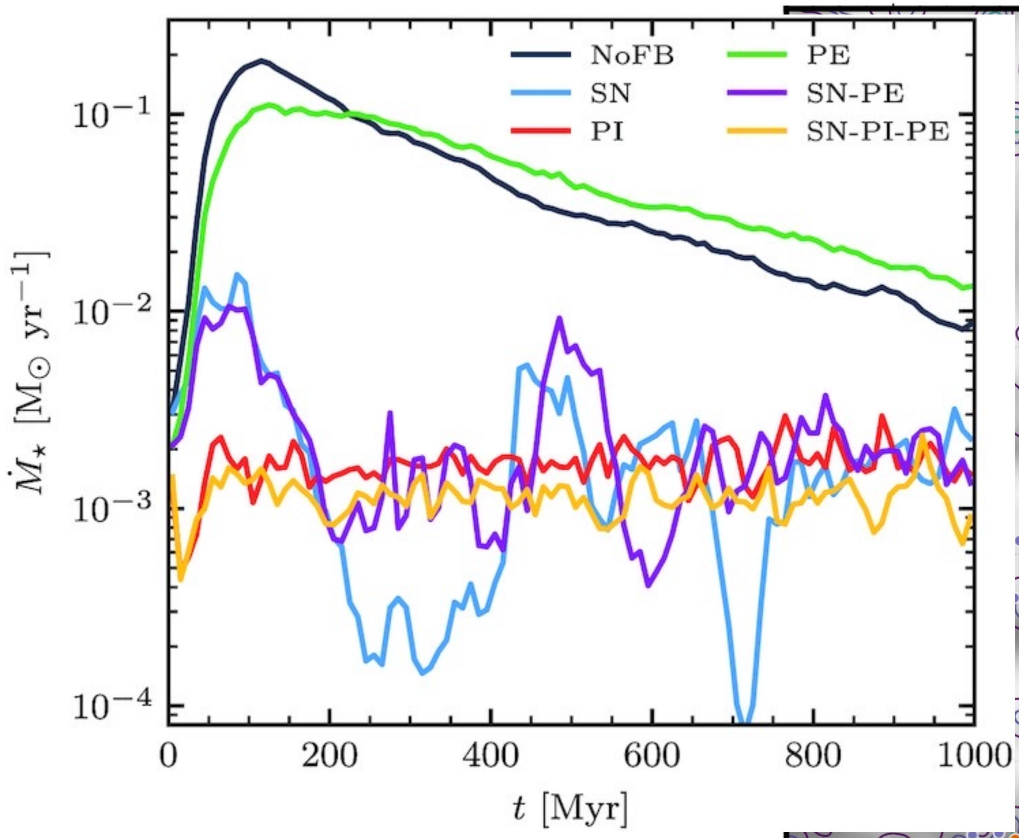
Ge12 What is the origin of the **initial mass functions** measured in different locations of the Galaxy?

Multiple simulations now include multiple forms of feedback – and not just star-formation simulations.

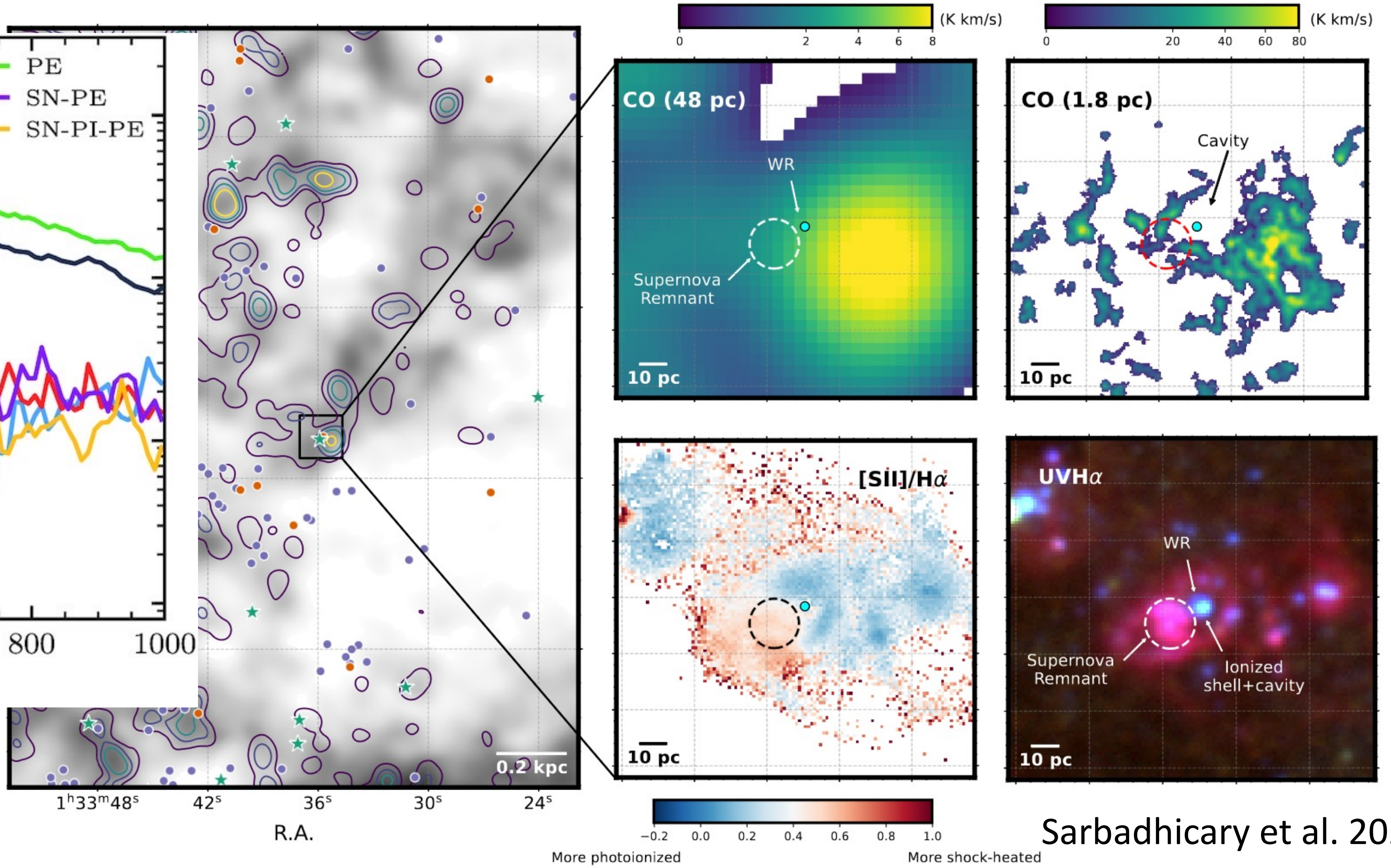


e.g., Hopkins et al. 2014; Walch et al. 2015; Wetzel et al. 2016; Seifried et al. 2017; Ali 2021; Grudić et al. 2021; Guszejnov et al. 2021; Mathew & Federrath 2021; Menon et al. 2022, 2023; Verliat et al. 2022; Polak et al. 2023; Andersson et al. 2024; …

Pre-SN feedback shapes the ISM that SNe explode into… and regulates the star formation that leads to the SN.

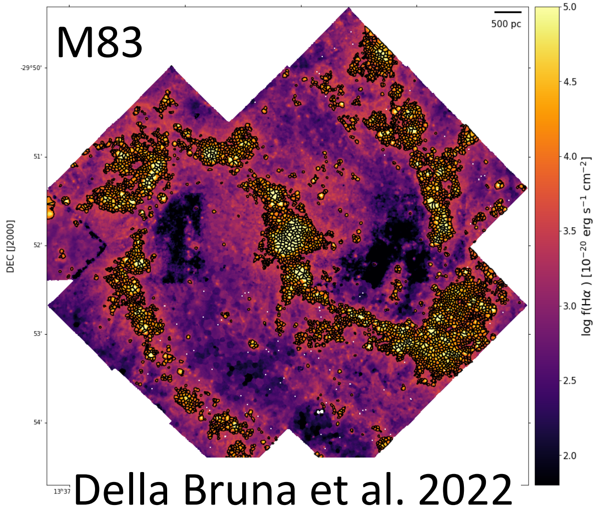


Smith et al. (2021)

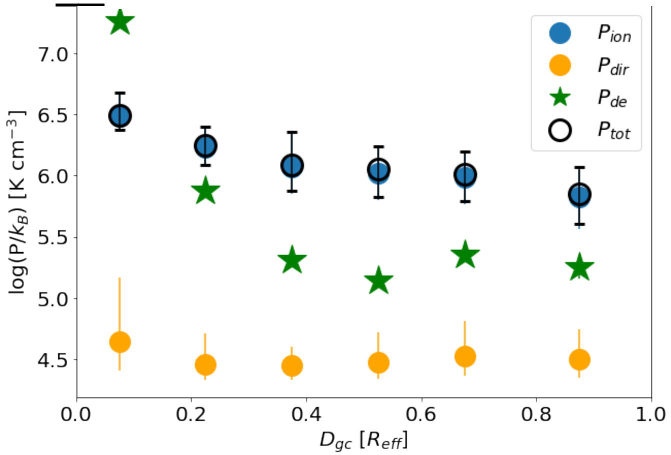


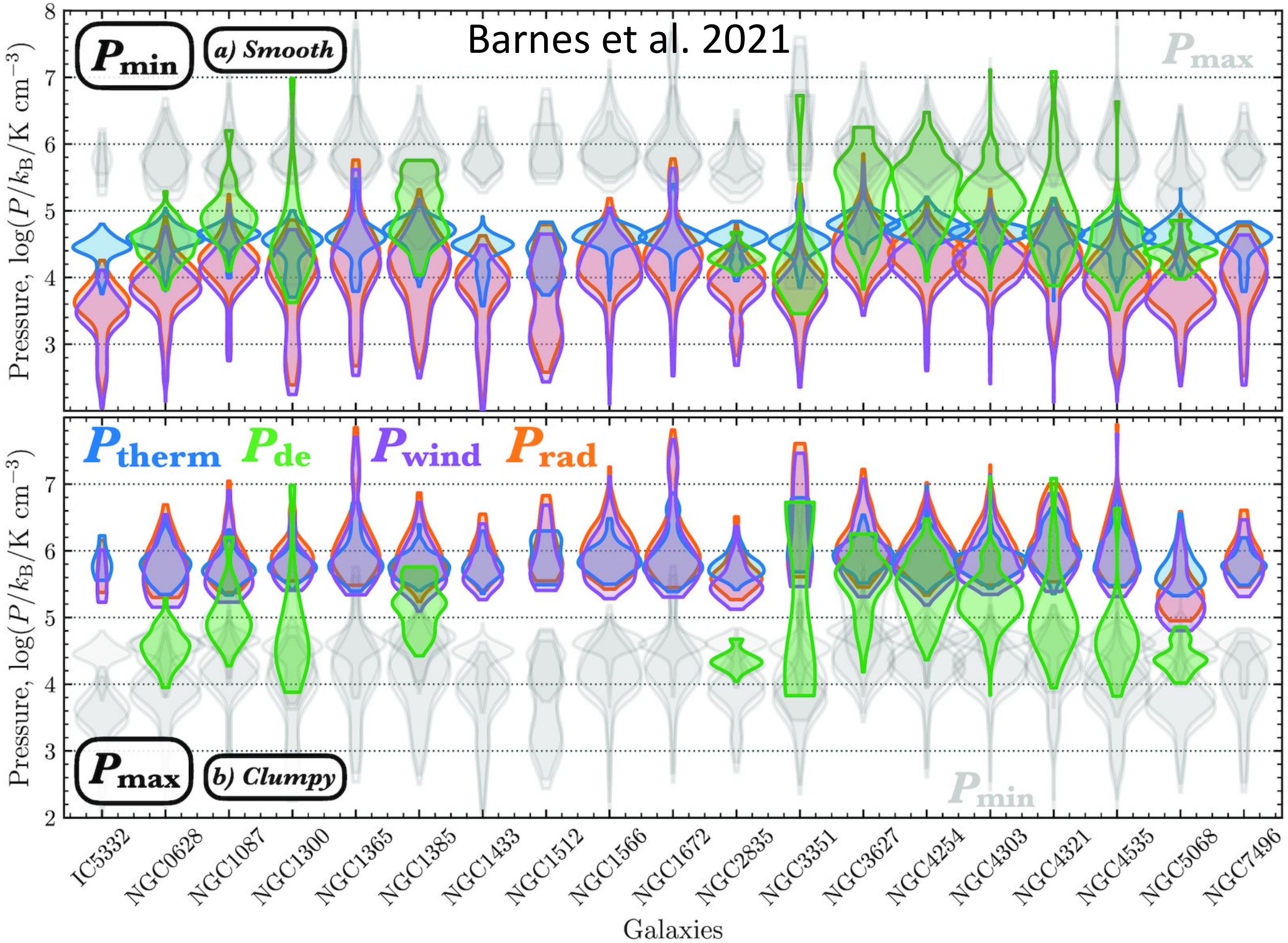
Sarbadhicary et al. 2024

Observations now constrain what form of feedback dominates at different ages, in different environments, and different galaxies.



Della Bruna et al. 2022





e.g., Lopez et al. 2011, 2014; McLeod et al. 2019, 2020, 2021; Barnes et al. 2022, 2023; Olivier et al. 2021; Rosen et al. 2014; Rowland et al. 2024; Sirressi et al. 2024; Gerasimov et al. 2022, 2024; …

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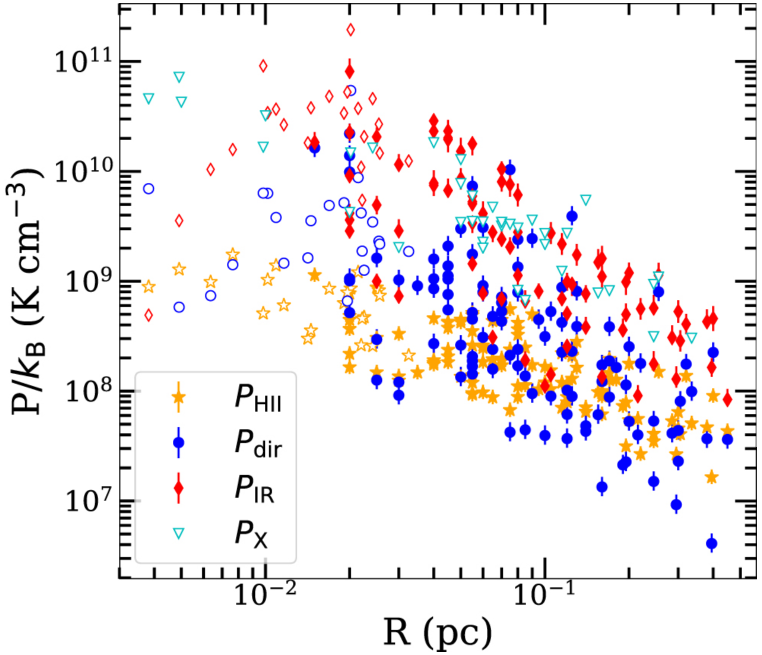
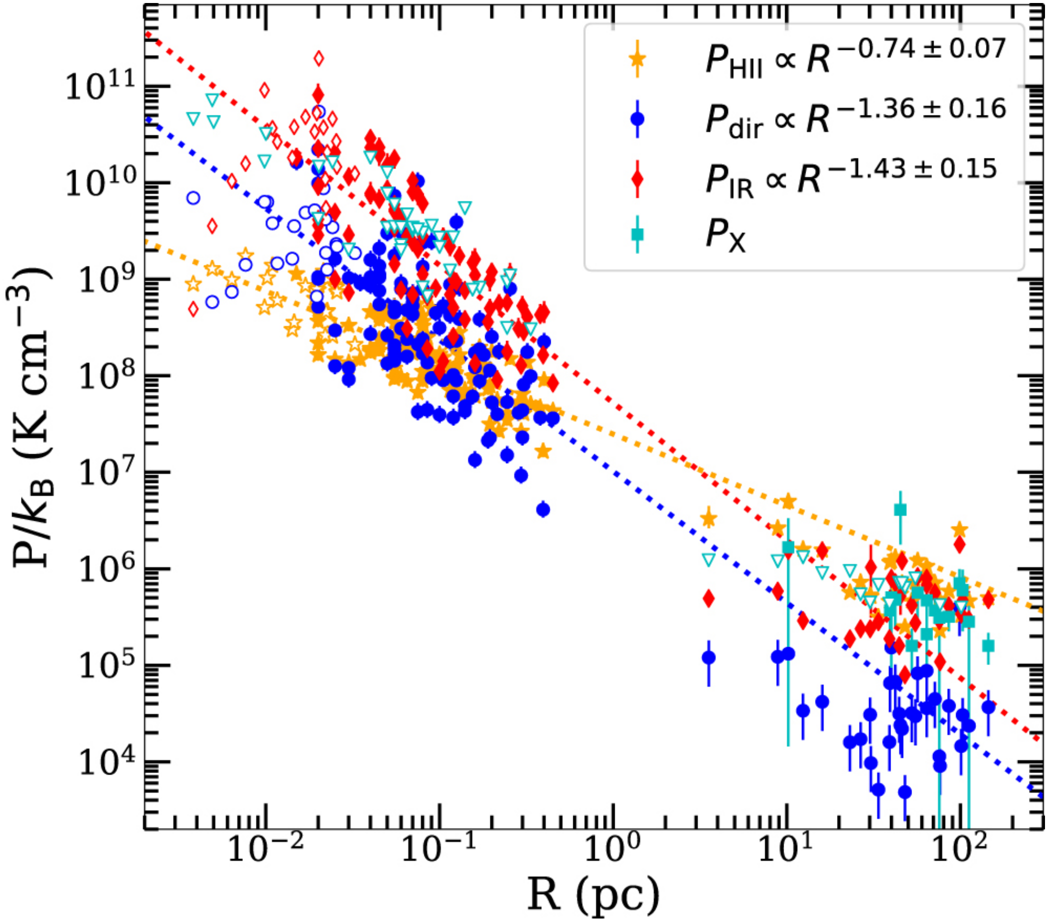
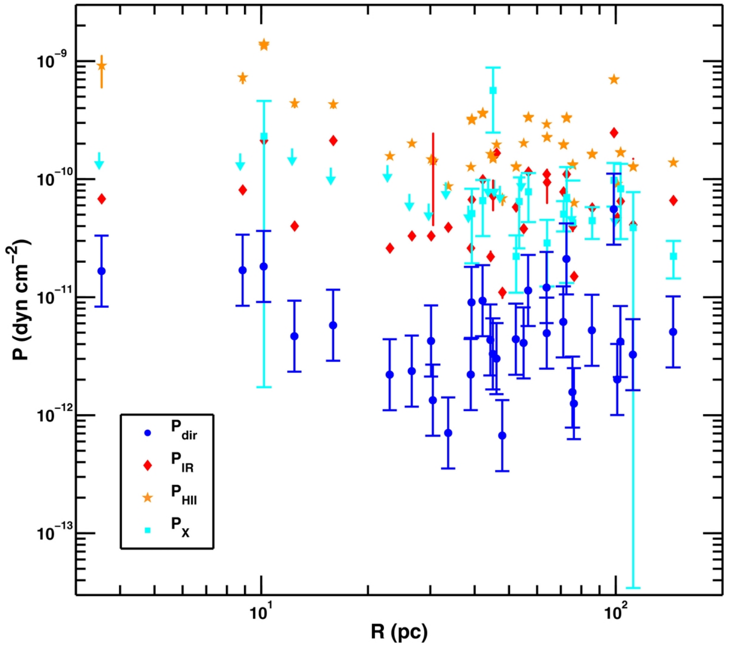
young H II region sample





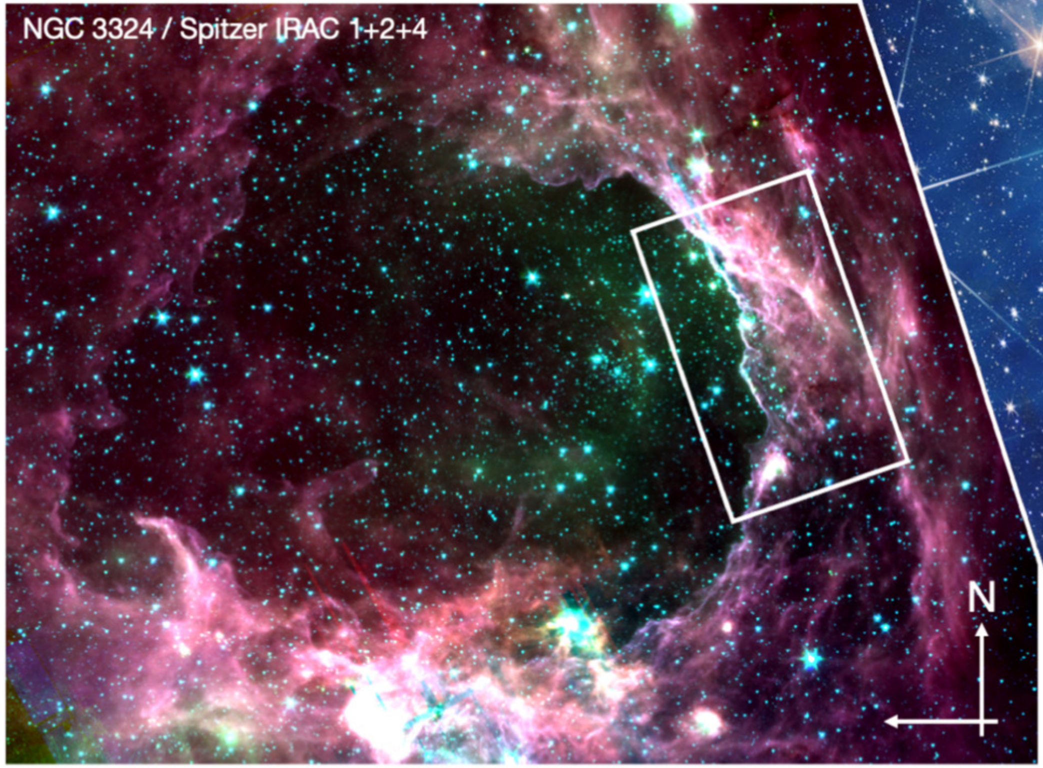
evolved H II region sample



Olivier et al. 2021; Lopez et al. 2014

We should also use our newfound resolution and sensitivity to study feedback locally.

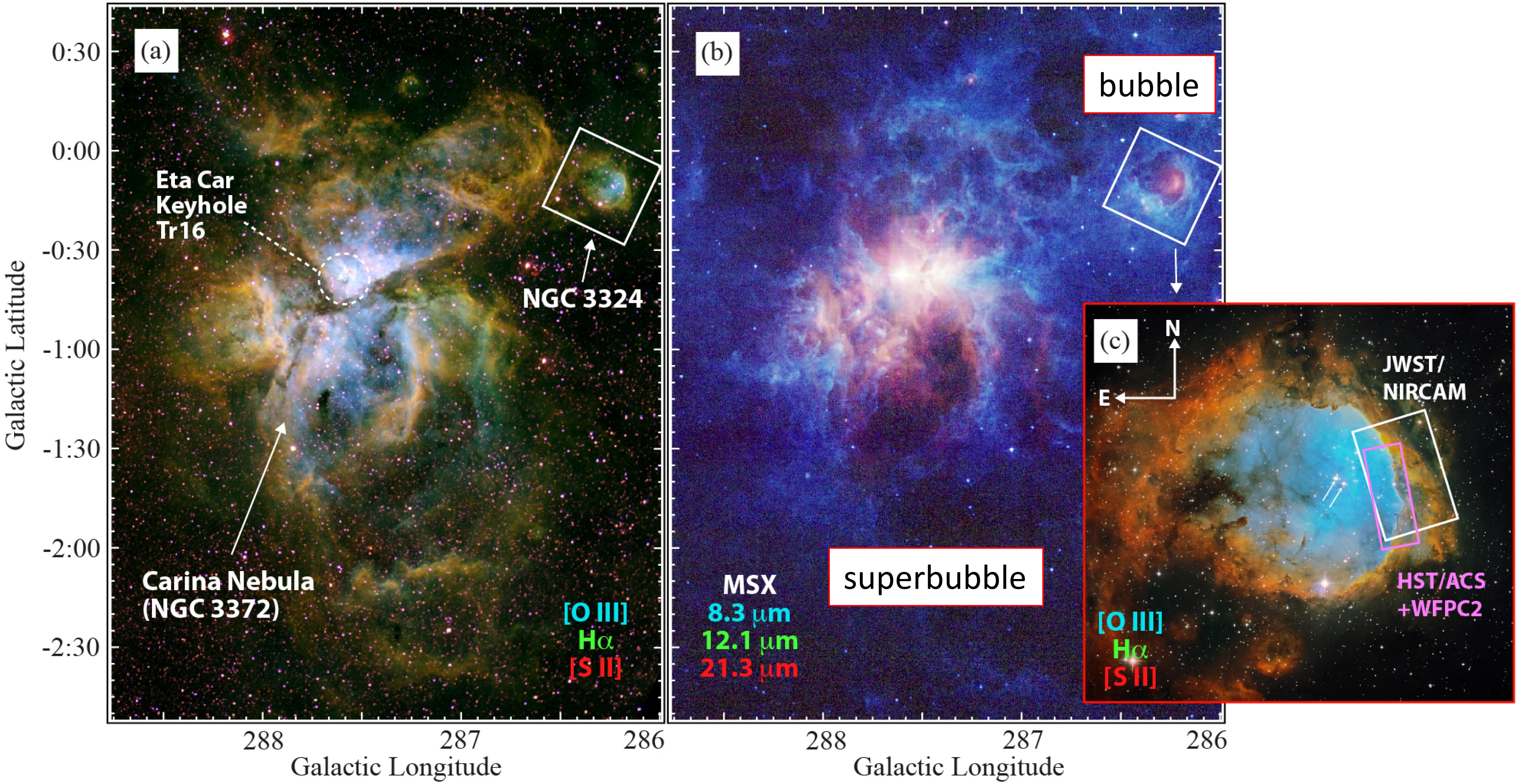
The ‘Cosmic Cliffs’ samples part of the molecular gas surrounding a bubble.



most active star formation…

Pontopiddan et al. 2022

NGC 3324 (the `Cosmic Cliffs') is next to the Carina star-forming complex but is ionized by different stars.



Reiter et al. 2022; adapted from Smith et al. 2000, 2007 and Telescope Live with permission (V. Unguru / Telescope Live)

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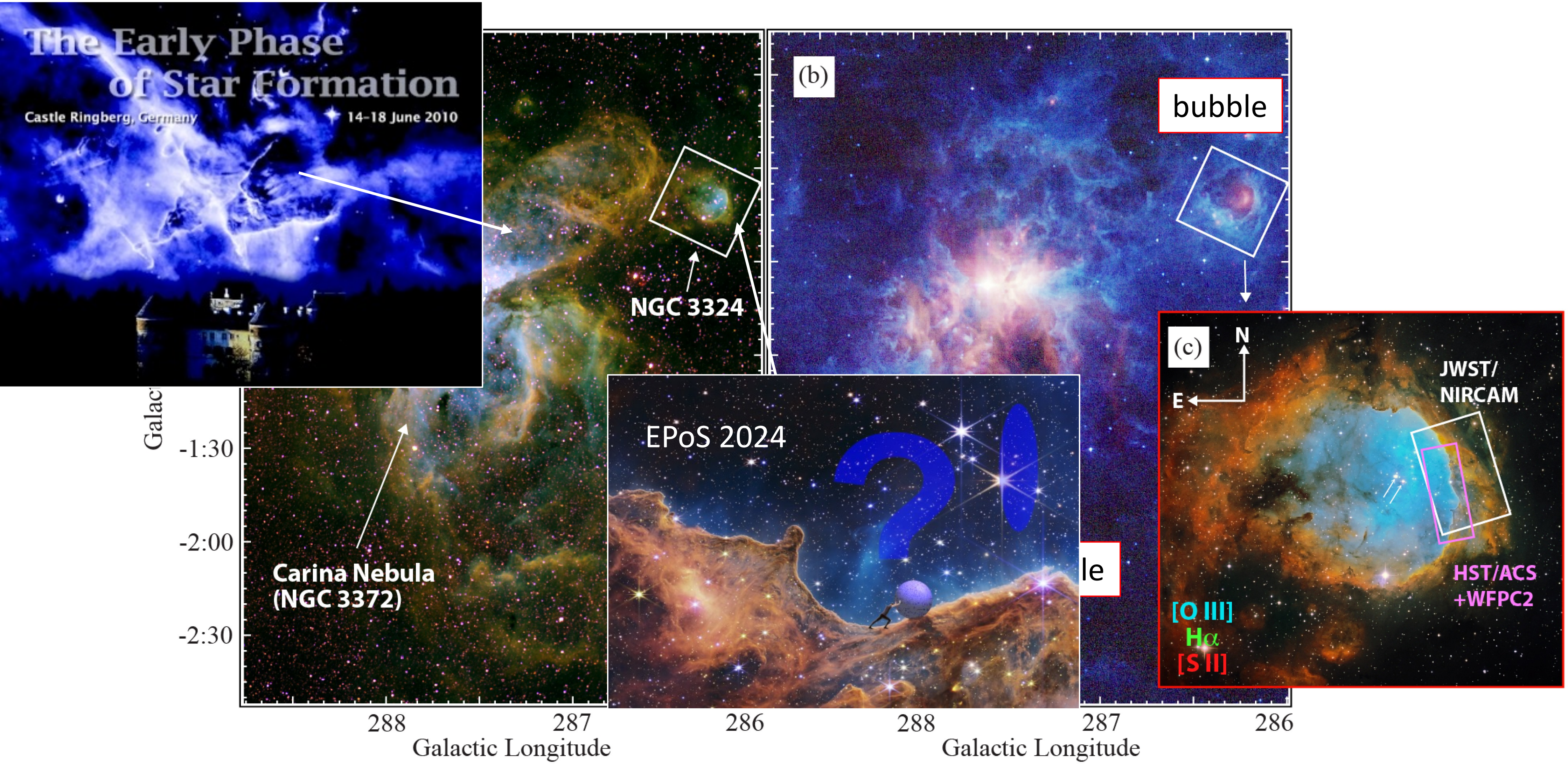
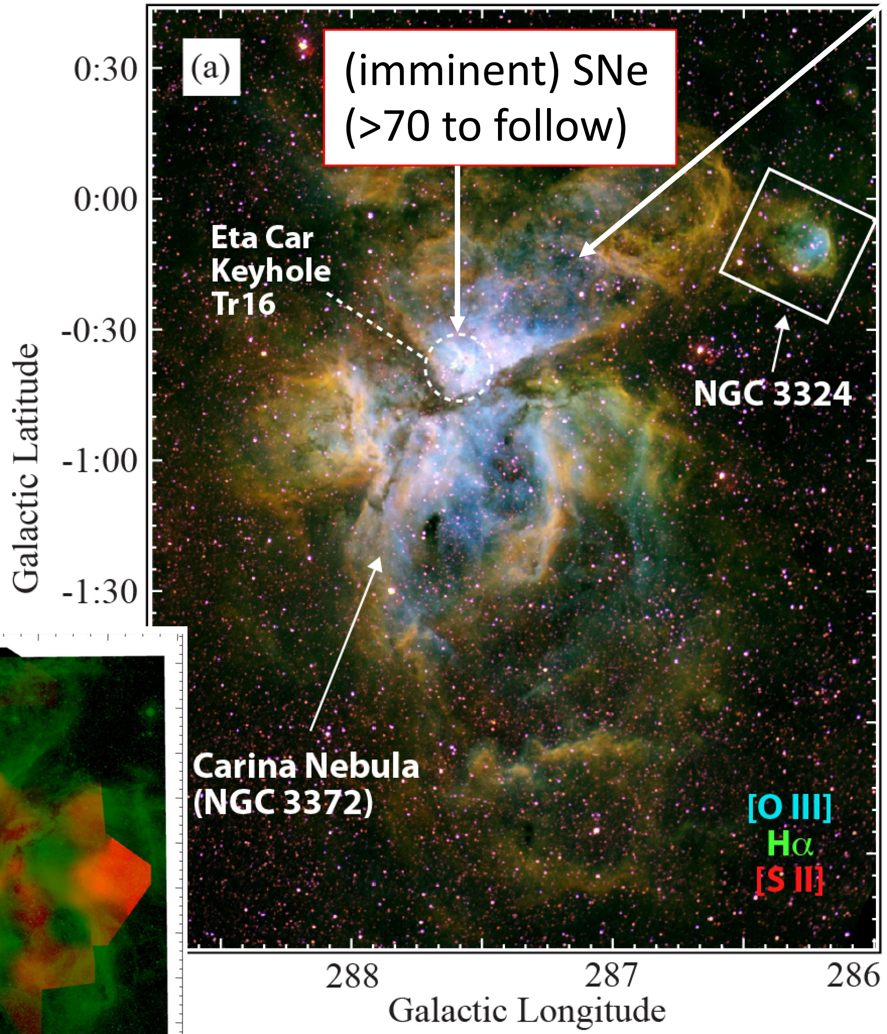
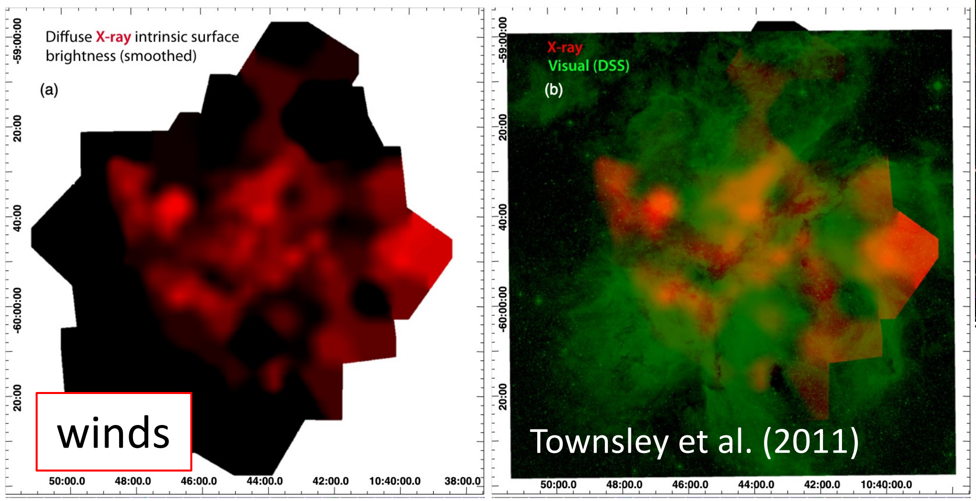


Reiter et al. 2022; adapted from Smith et al. 2000, 2007 and Telescope Live with permission (V. Unguru / Telescope Live)

Carina-like regions (many O stars) sample all forms of feedback and are close enough to study how they interact.





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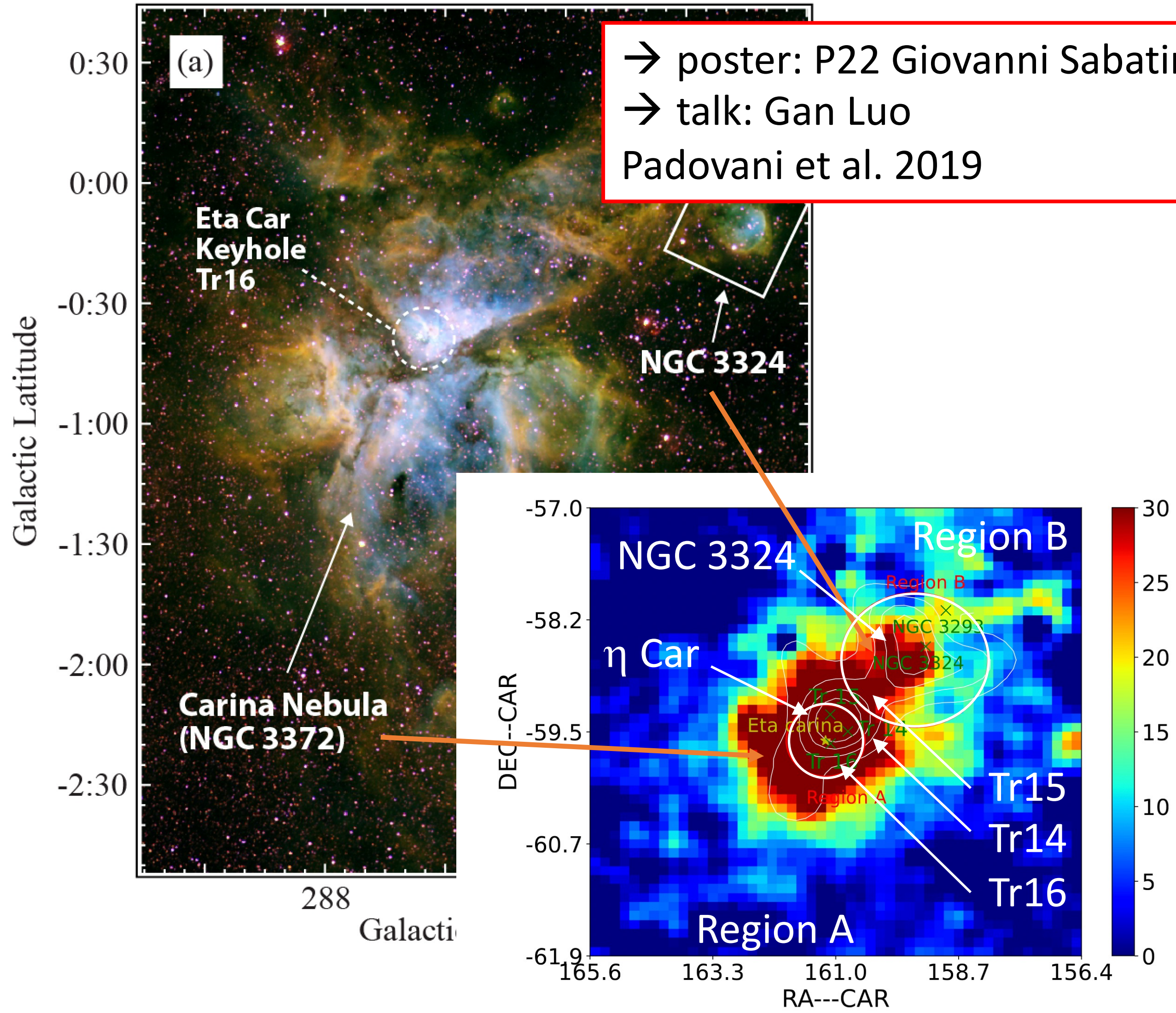
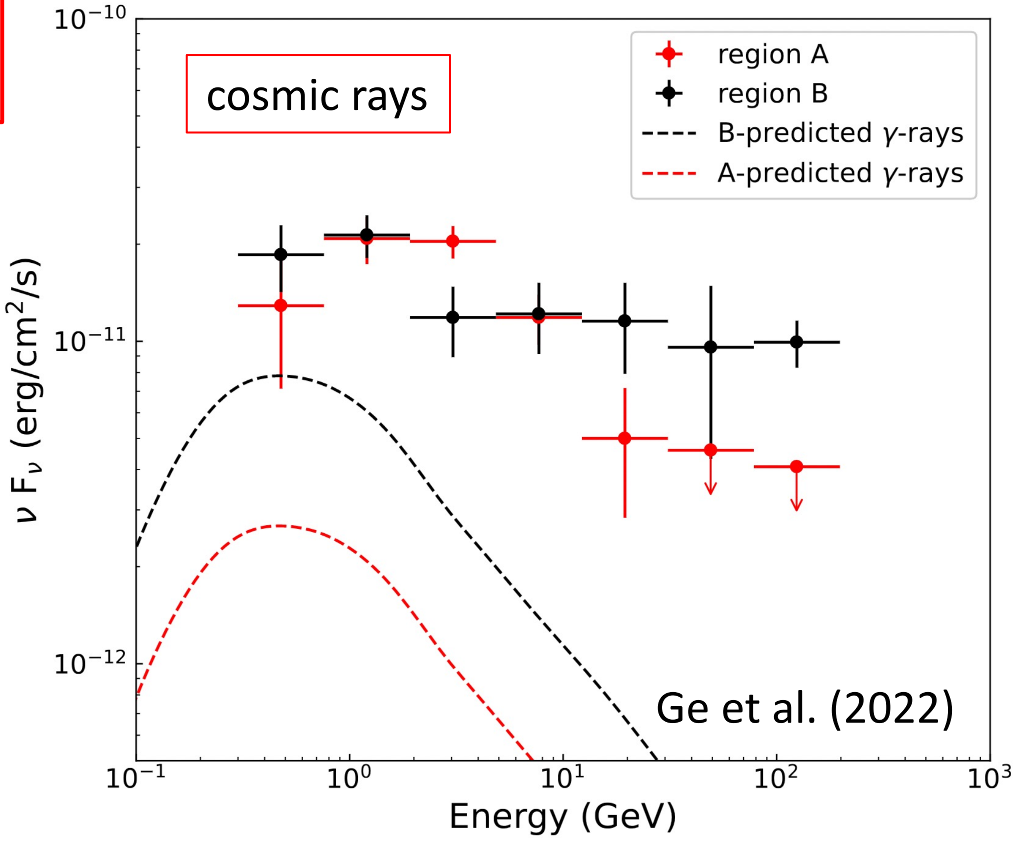
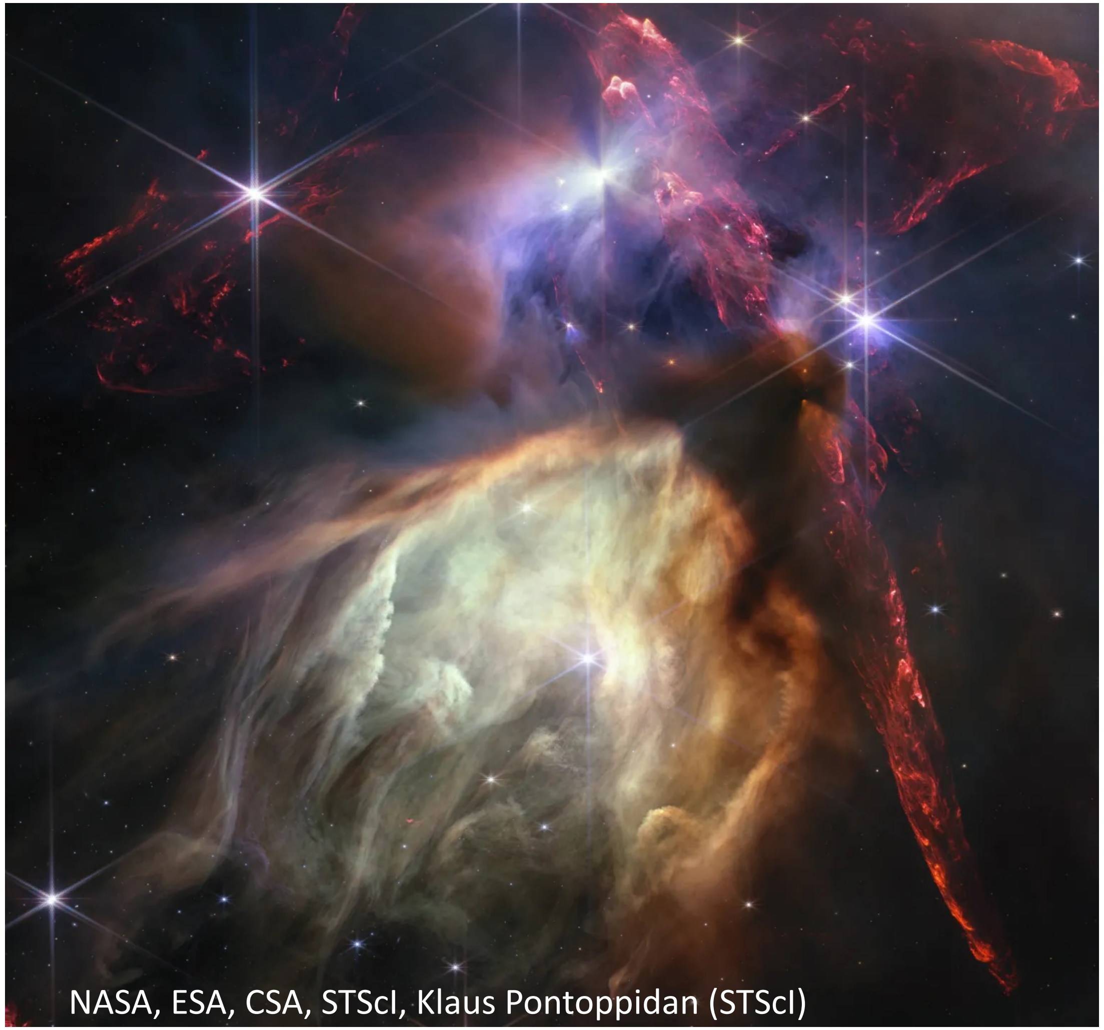


→ poster: P22 Giovanni Sabatini
→ talk: Gan Luo
Padovani et al. 2019



assuming local CR flux (ISS)

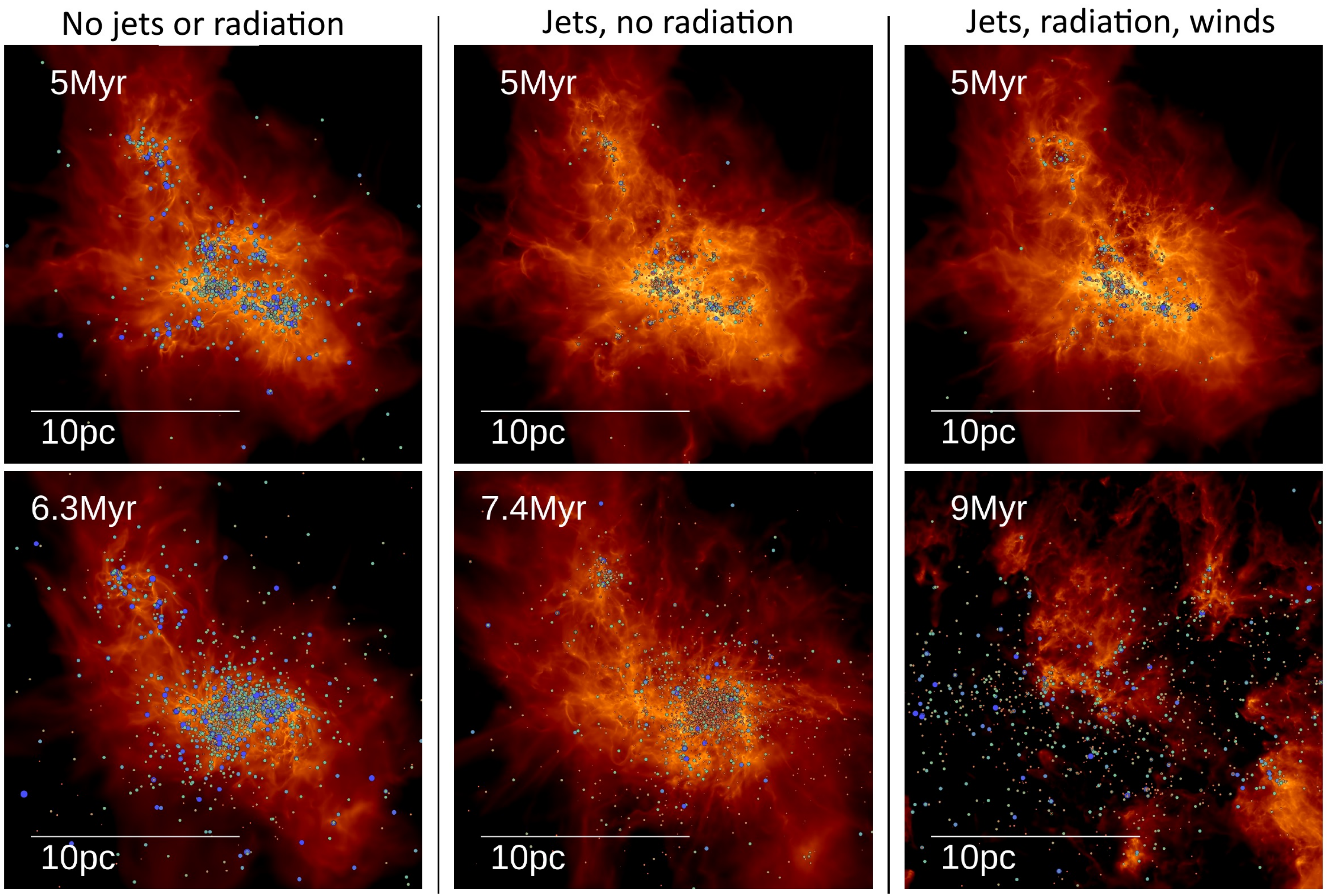
Jets / outflows affect smaller scales than radiation and winds but may be important early.



→ talks:
- Seamus Clarke
- Alessio Trificante

→ posters:
- P09 Katharine G. Johnston
- P20 Luca Moscadelli

Origin of the IMF? Masses of stars set by outflows and radiative feedback more than environment.



Guszejnov et al. 2022

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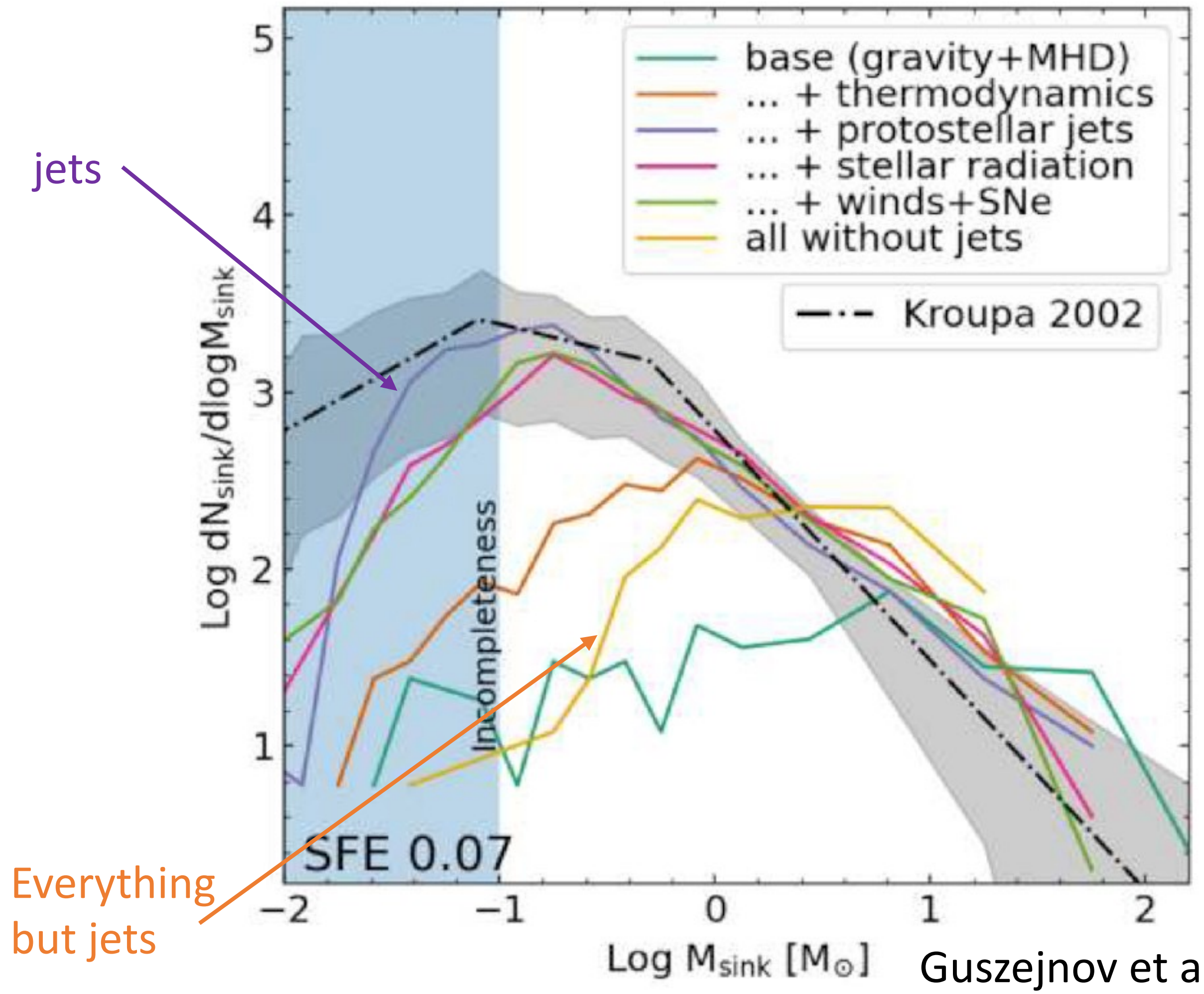
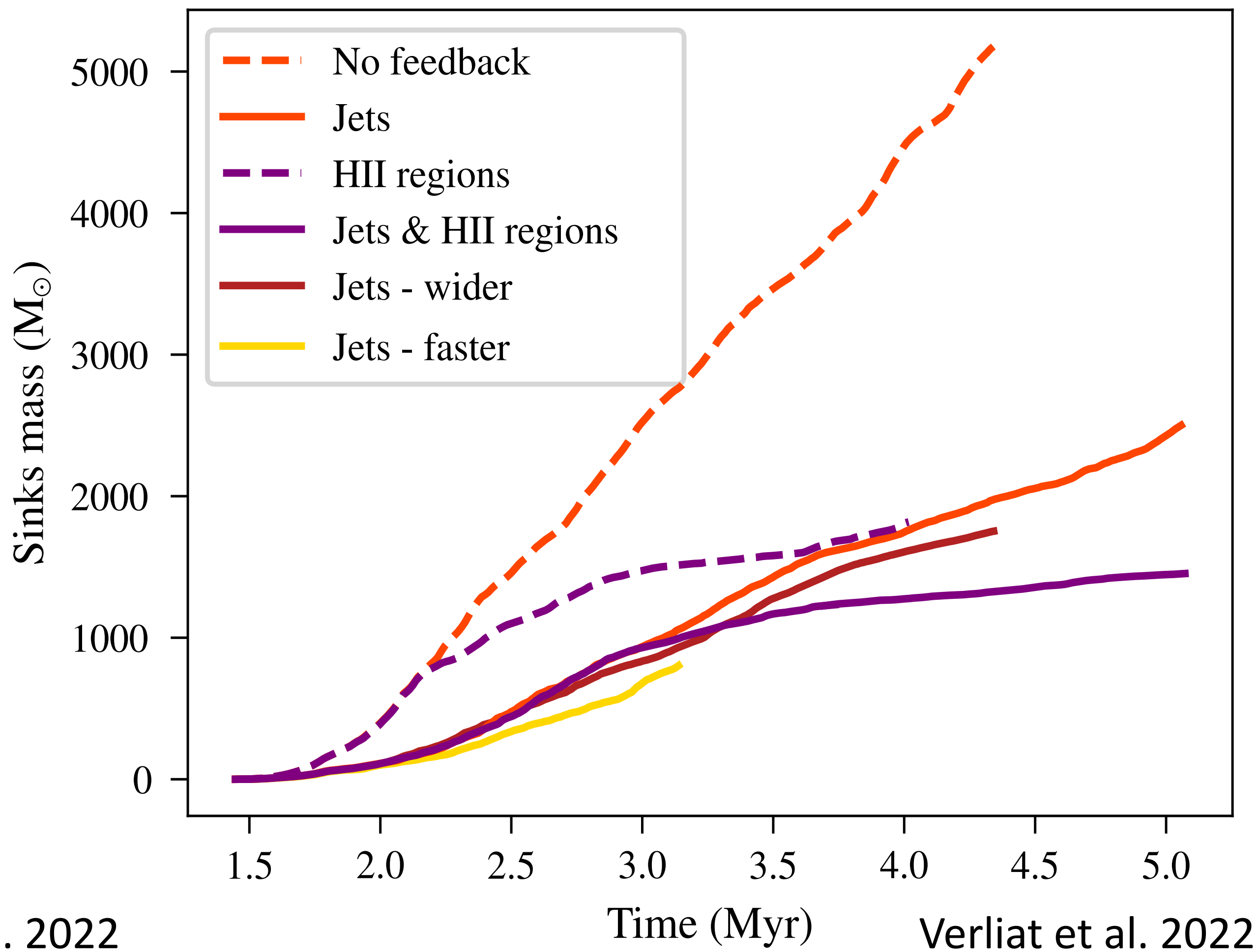


Guszejnov et al. 2022

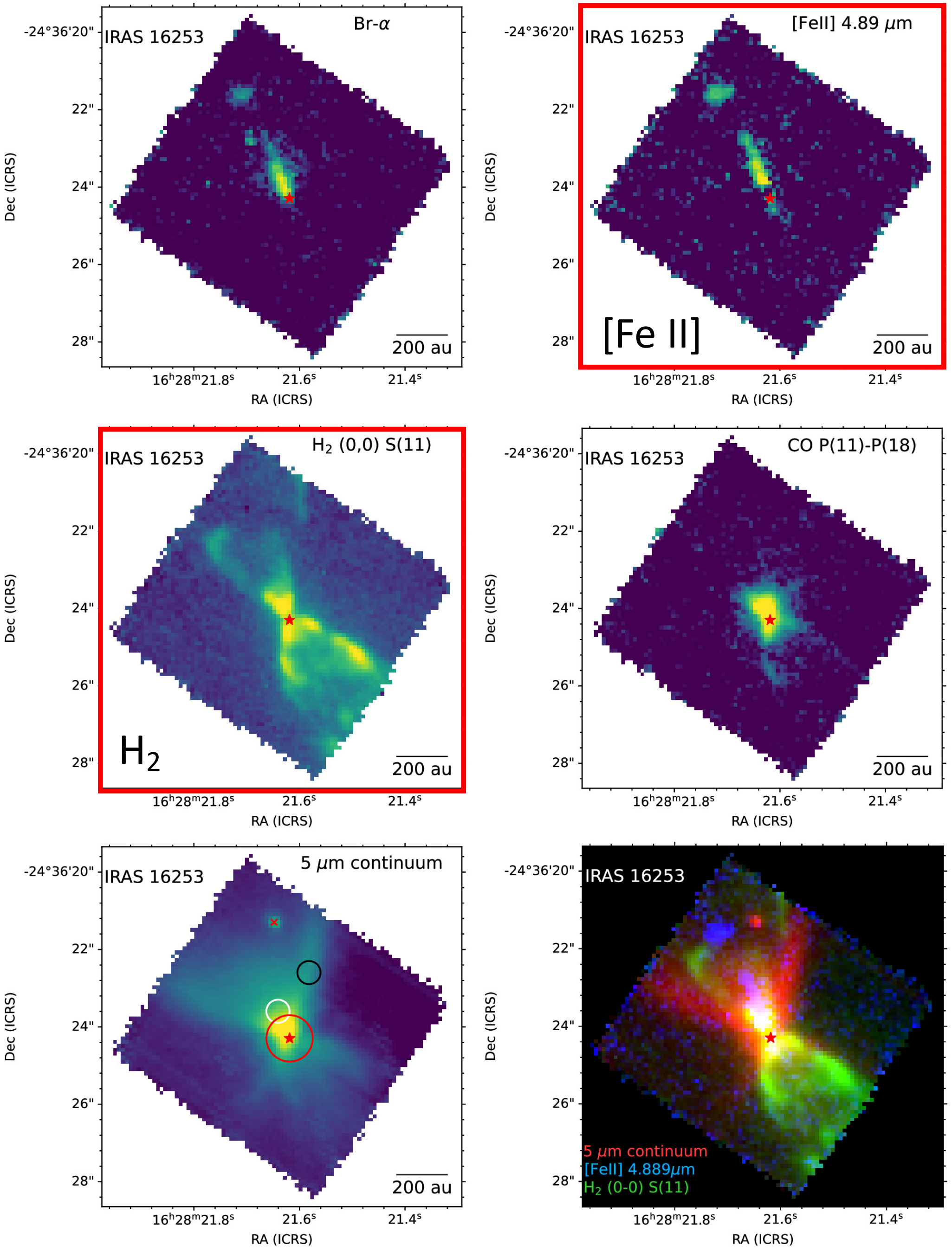


Verliat et al. 2022

JWST: excellent resolution over large FOV – quantify jet impact on local and large scales.

→ talk: Henrik Beuther

Ray et al. 2023



Federman et al. 2023

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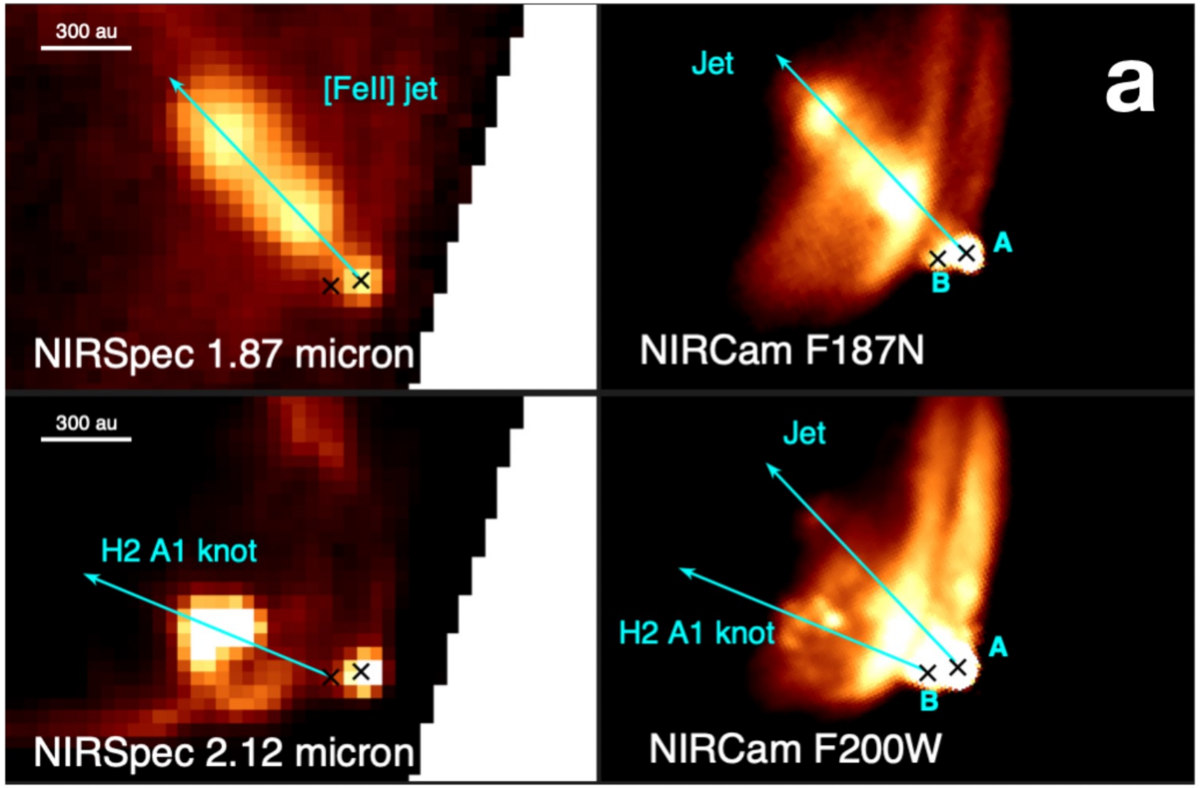
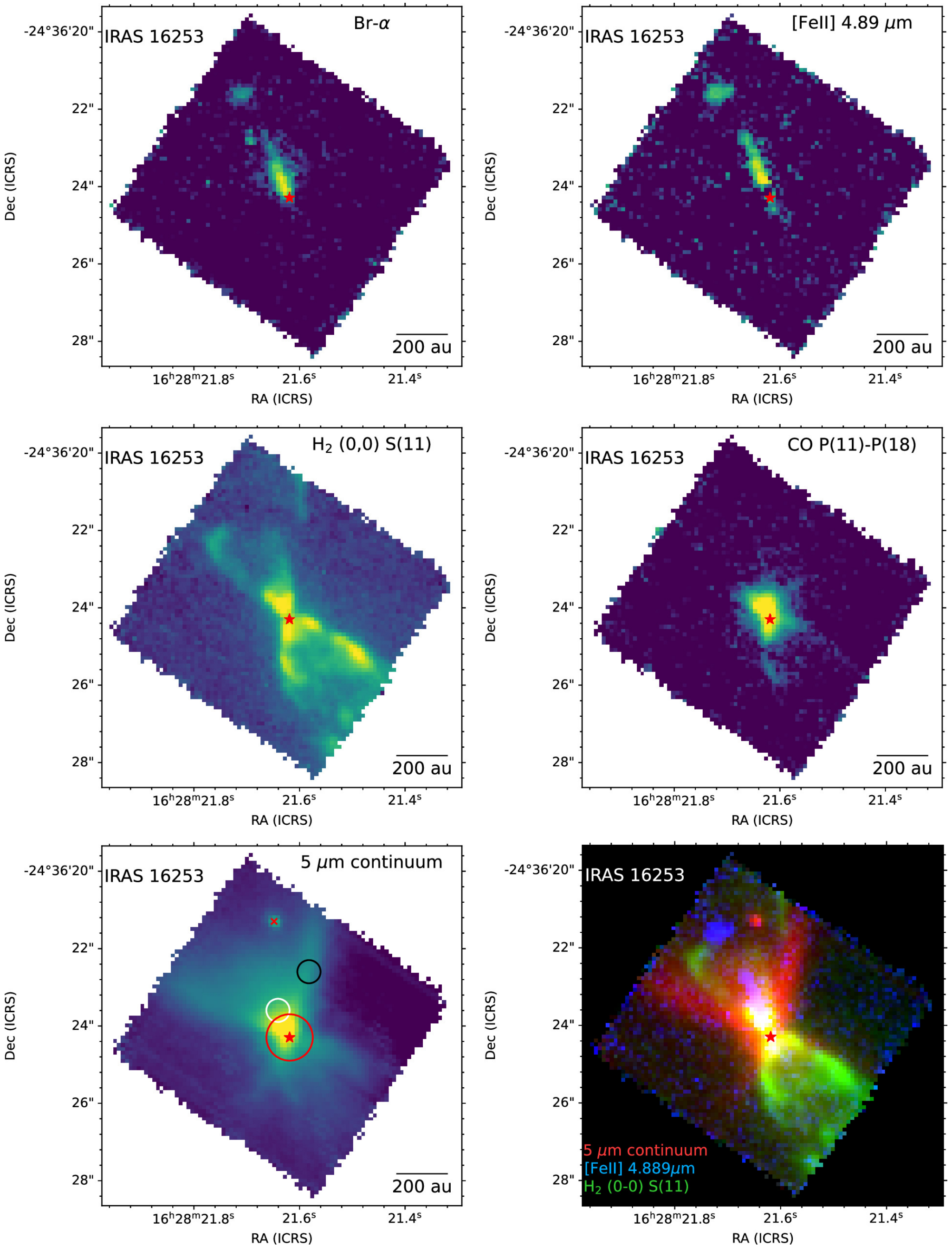


→ talk: Henrik Beuther

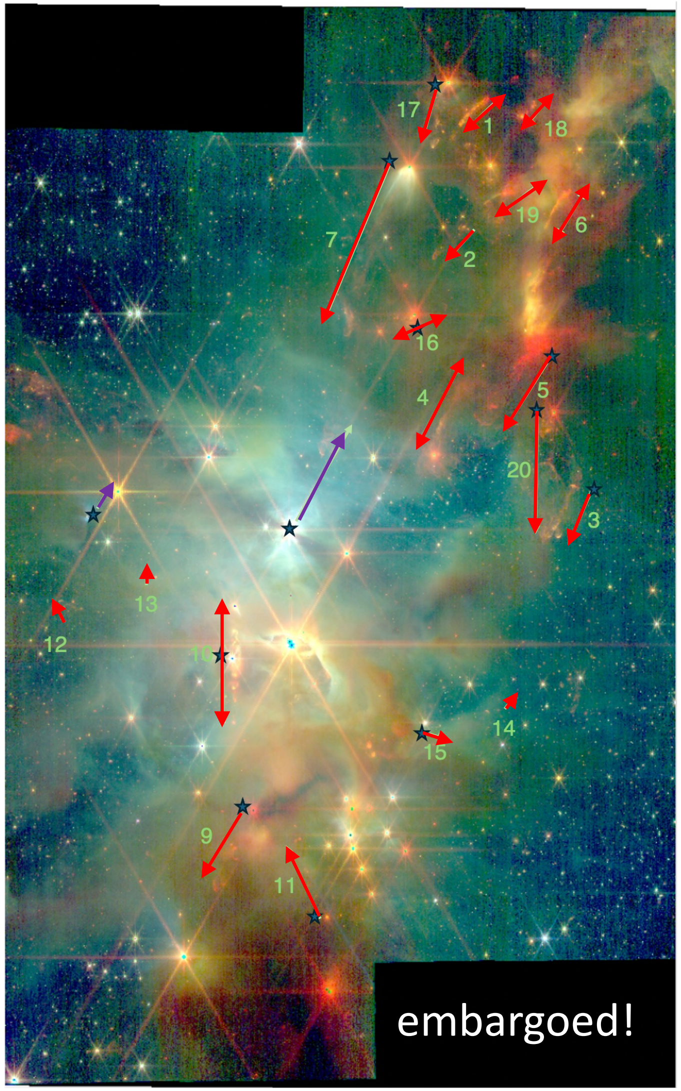
Nisini et al. (2024)

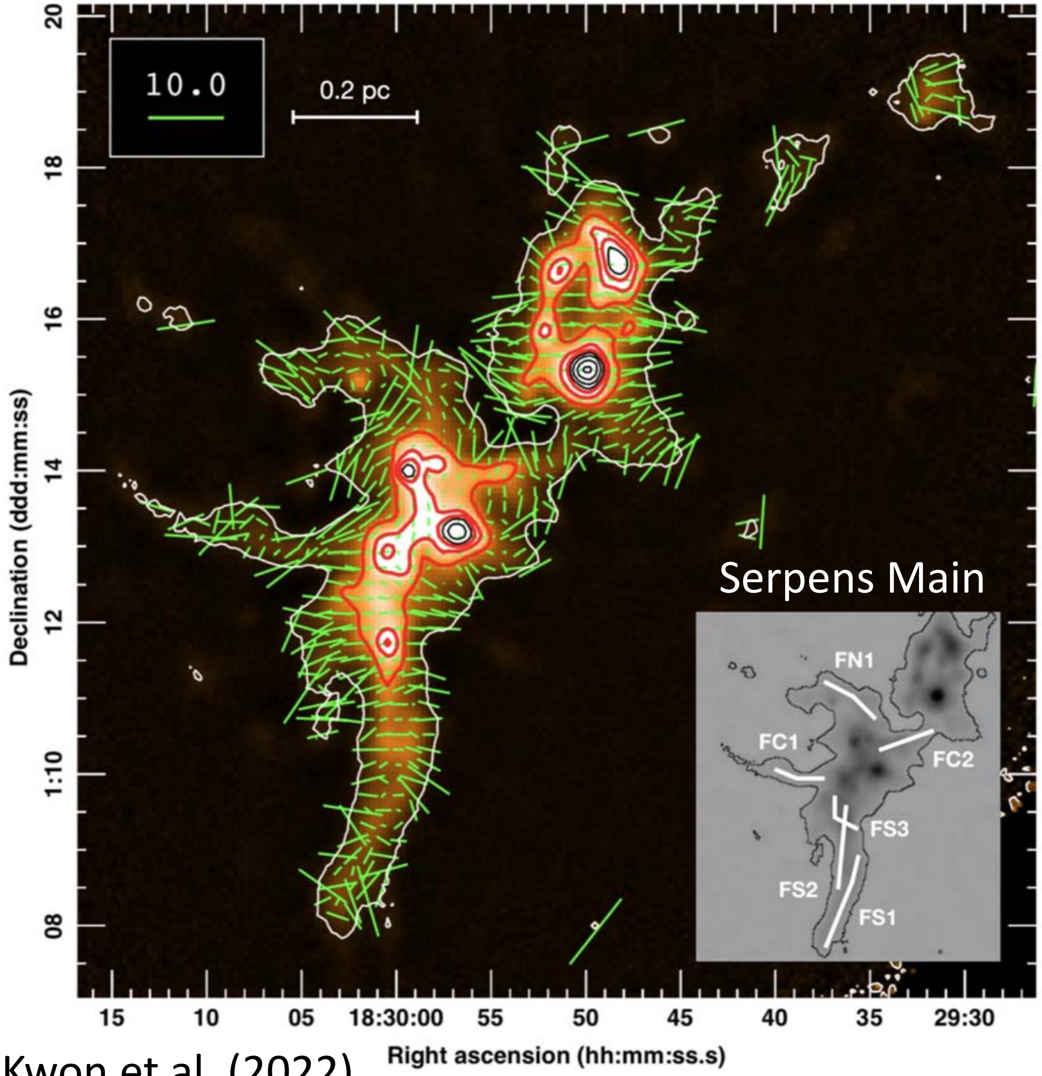


Federman et al. 2023

Some hints for outflow alignment in young regions but too few examples to constrain how long alignment persists.

→ strong outflow alignment in Serpens Main (Green et al. subm)





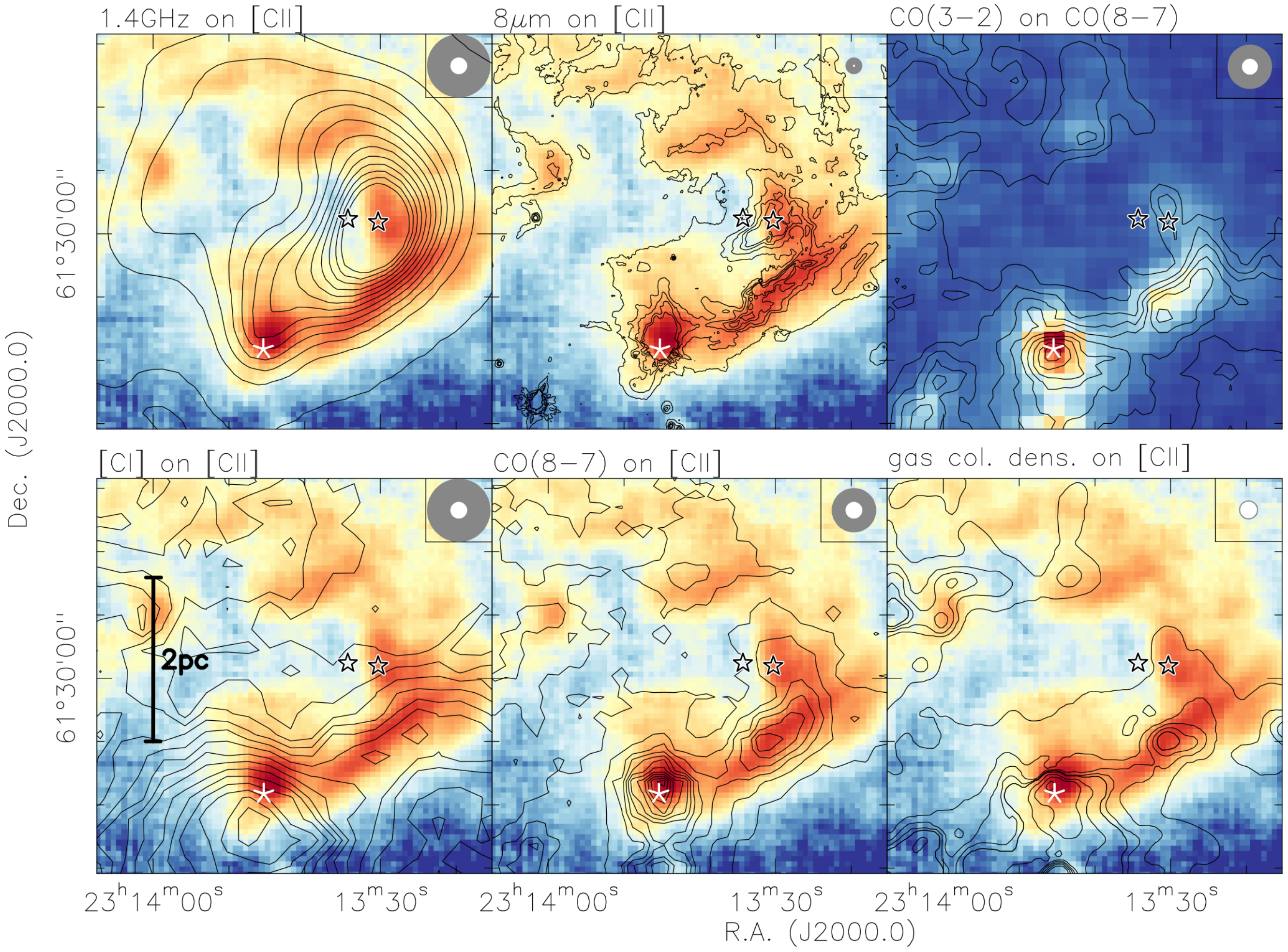
Kwon et al. (2022)

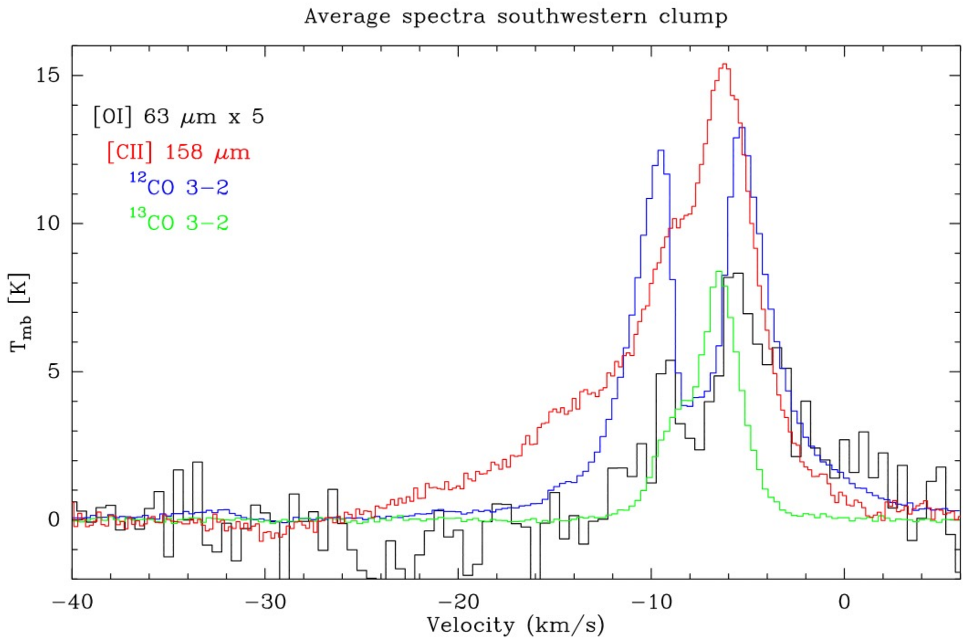
→ talk: Seamus Clarke

→ see also Stephens et al. 2017; Xu et al 2022; …

Winds: the potato chip bag model of an H II region

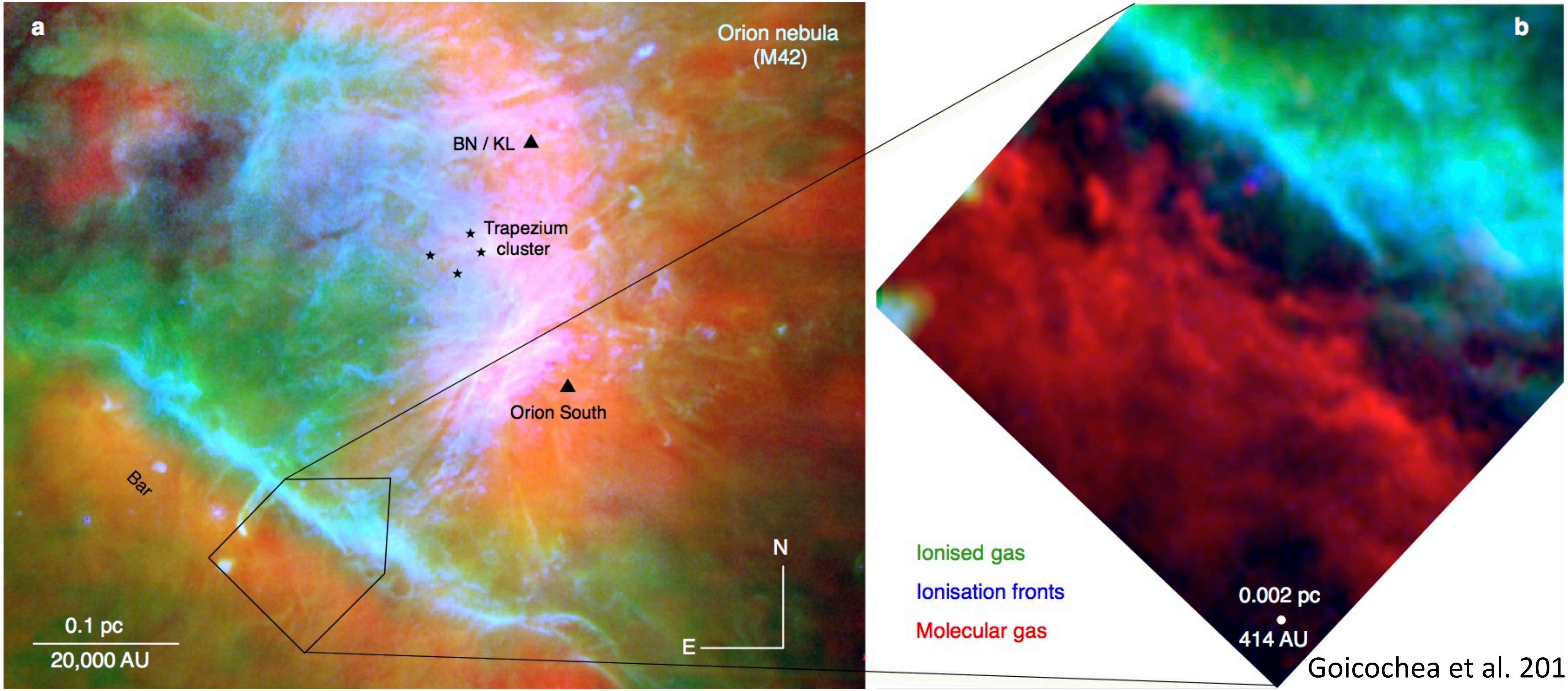
FEEDBACK: SOFIA legacy survey to quantify interaction of high-mass stars with their environment.





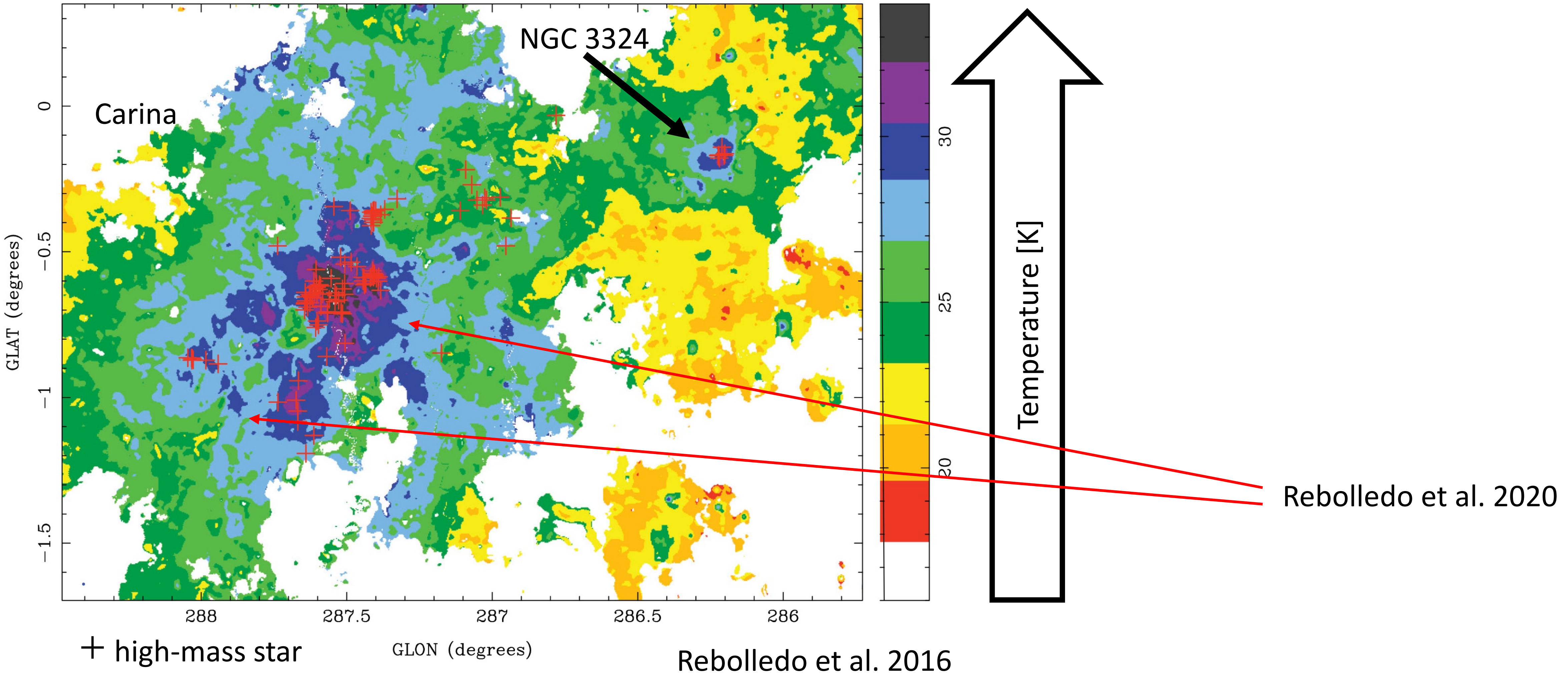
e.g., Schneider et al. 2020; Luisi et al. 2021; Tiwari et al. 2021; Beuther et al. 2022; Bonne et al. 2022; Kabanovic et al. 2022; …

Photoevaporating PDR models may better explain the structure in PDRs; dynamical effects are important.



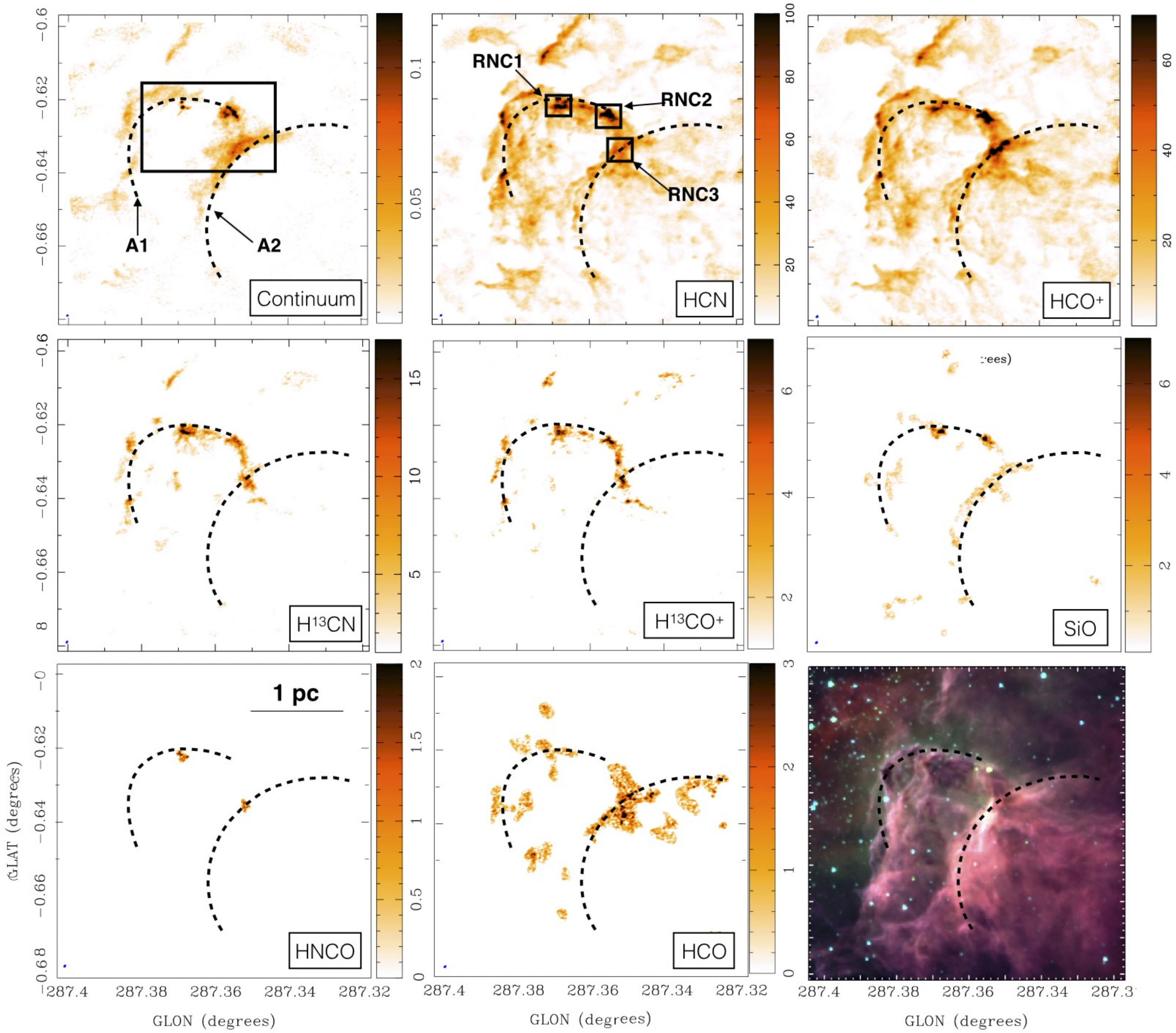
Goicochea et al. 2016

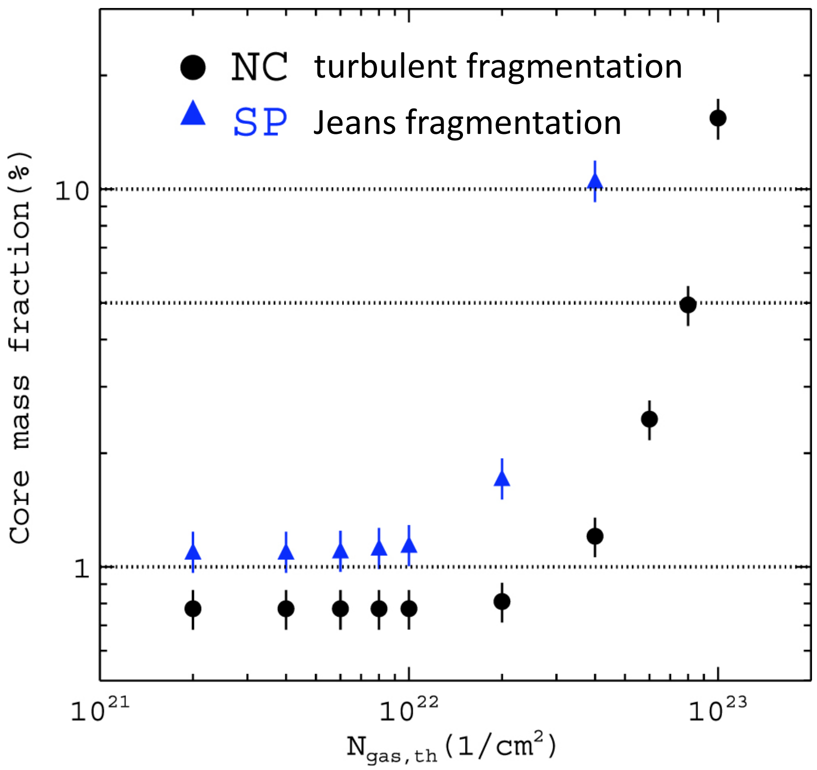
Radiation from high-mass stars heats and reshapes surrounding cloud, may affect fragmentation, chemistry, …



Rebolledo et al. 2016

Comparing dust and gas properties in two regions with an order of magnitude difference in the incident UV radiation.





Rebolledo et al. 2020

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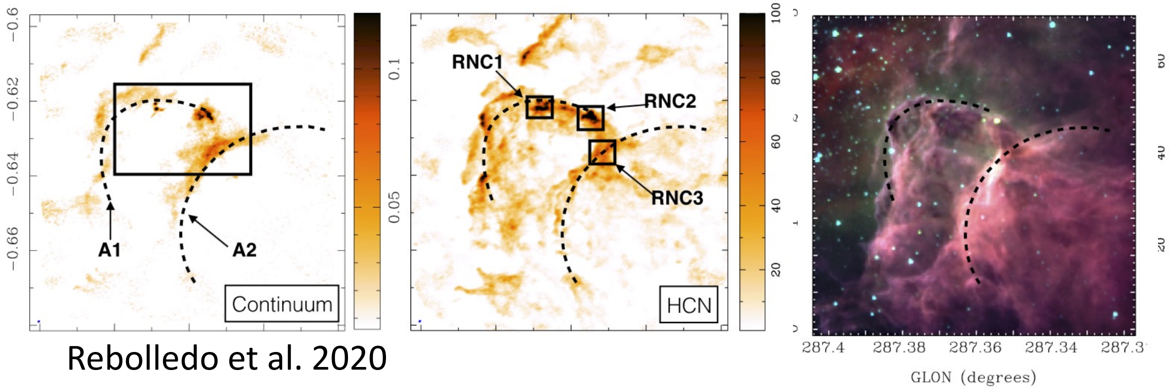
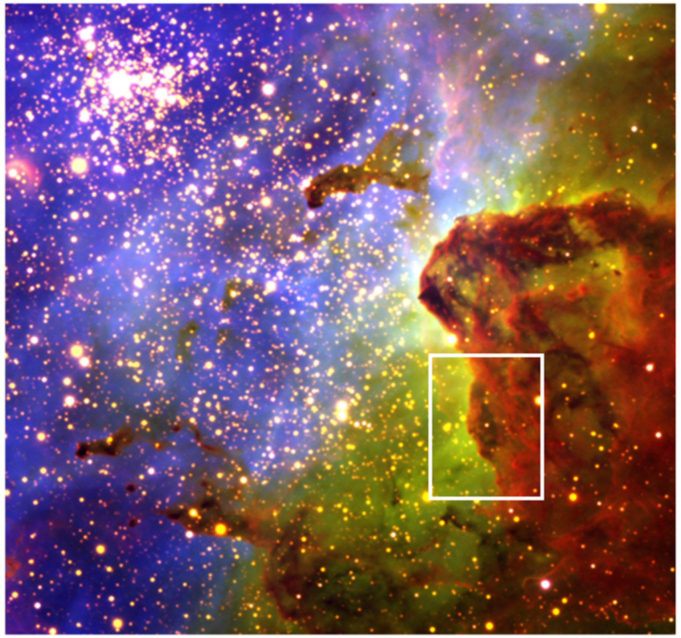
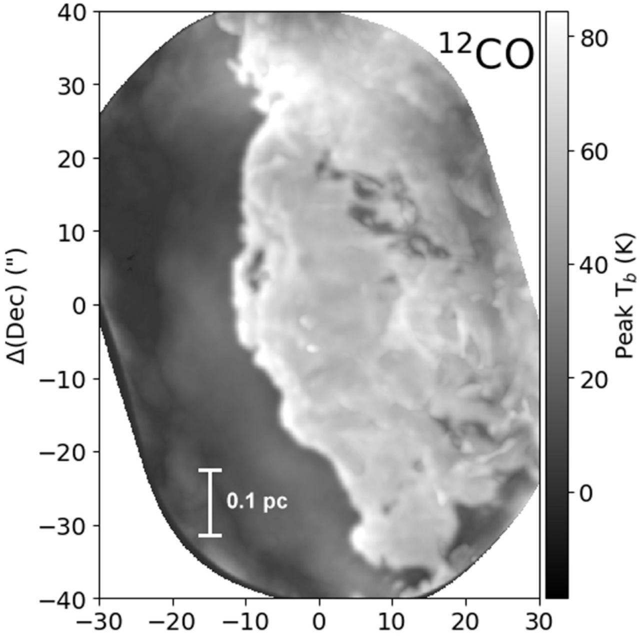
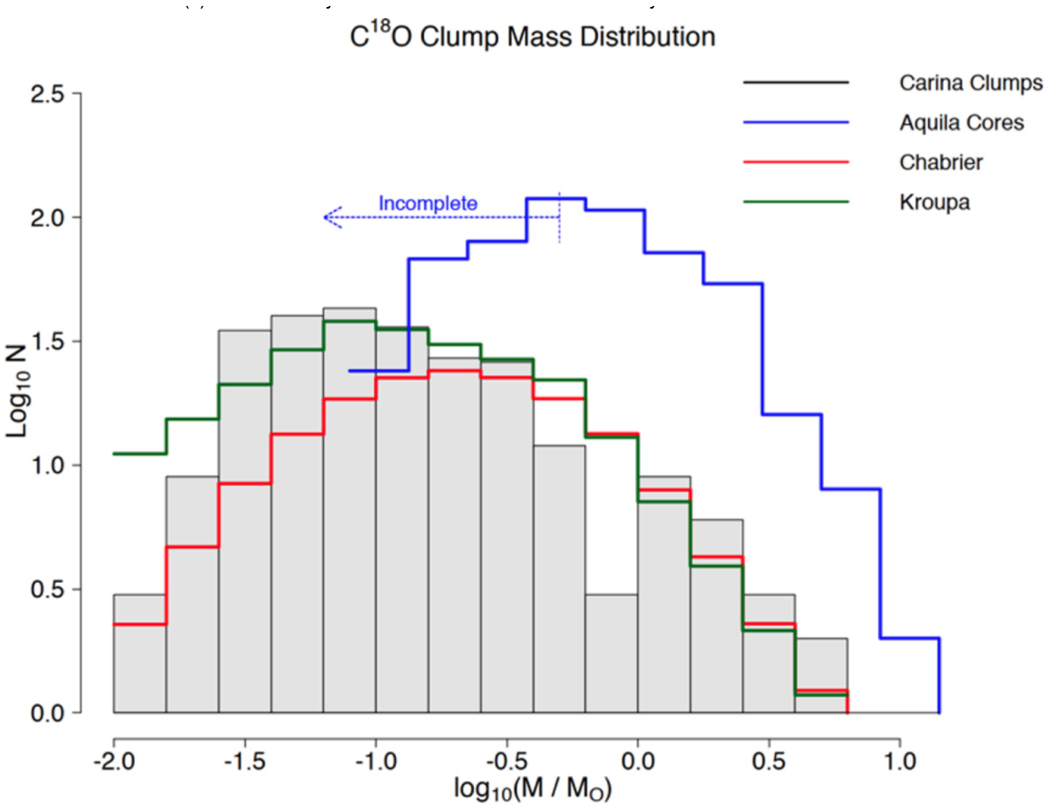


Rebolledo et al. 2020

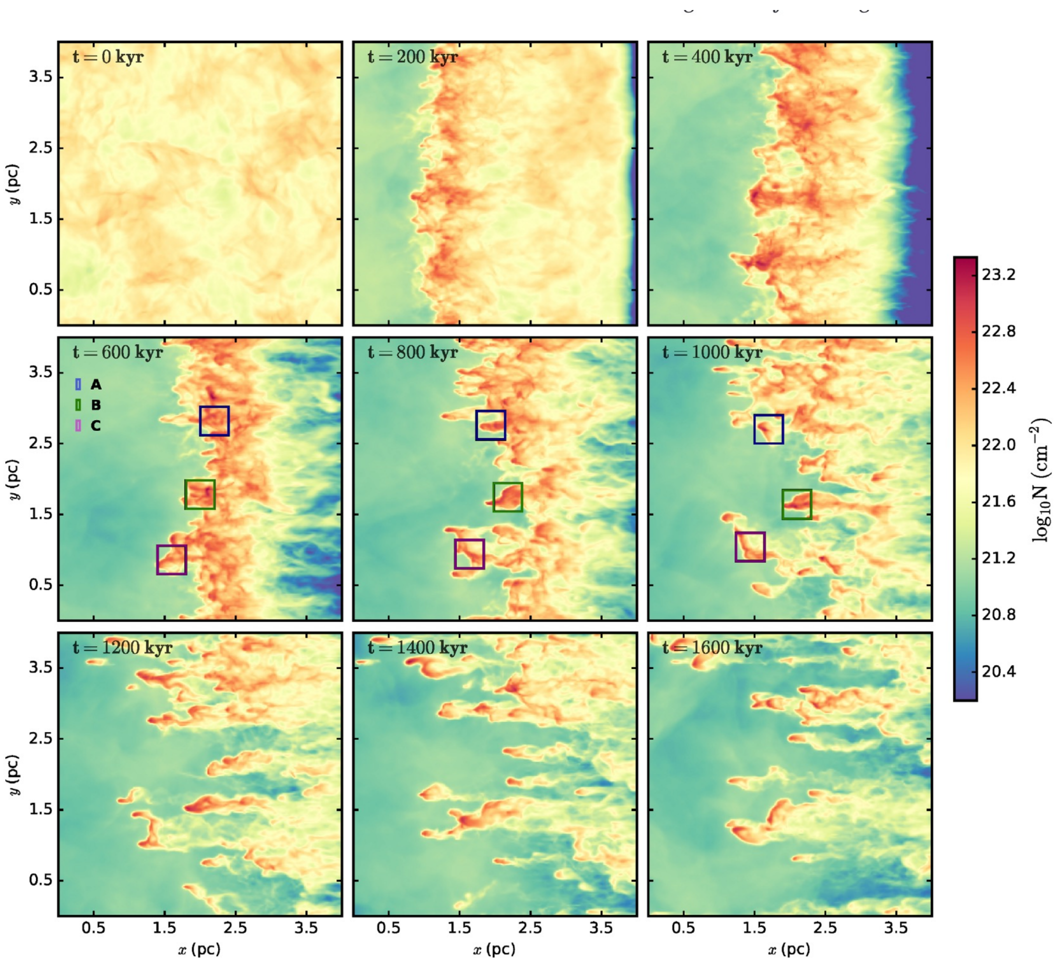




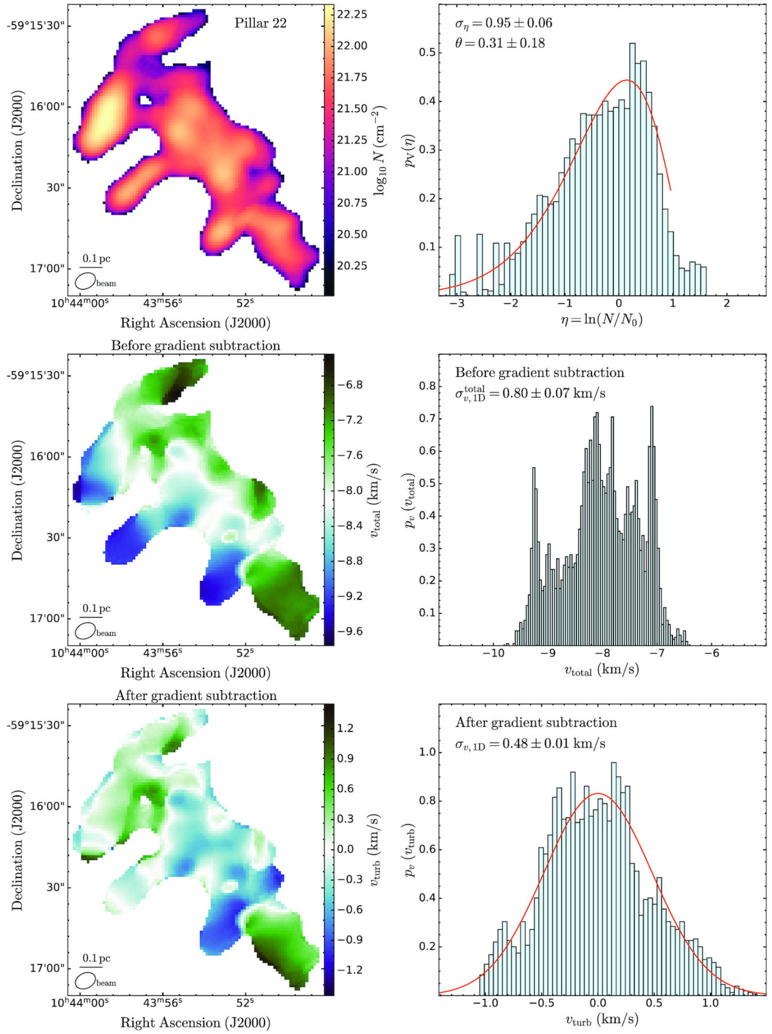


Hartigan et al. 2022; Downes et al. 2023

Ionization-driven compression may trigger star formation – observations can now resolve relevant scales.



Gritschneder et al. 2010; Dale et al. 2012; Tremblin et al. 2012a,b; Walch et al. 2012, 2013; **Menon et al. 2020**



Klaassen et al. 2020; Menon et al. 2021; Reiter et al. 2023

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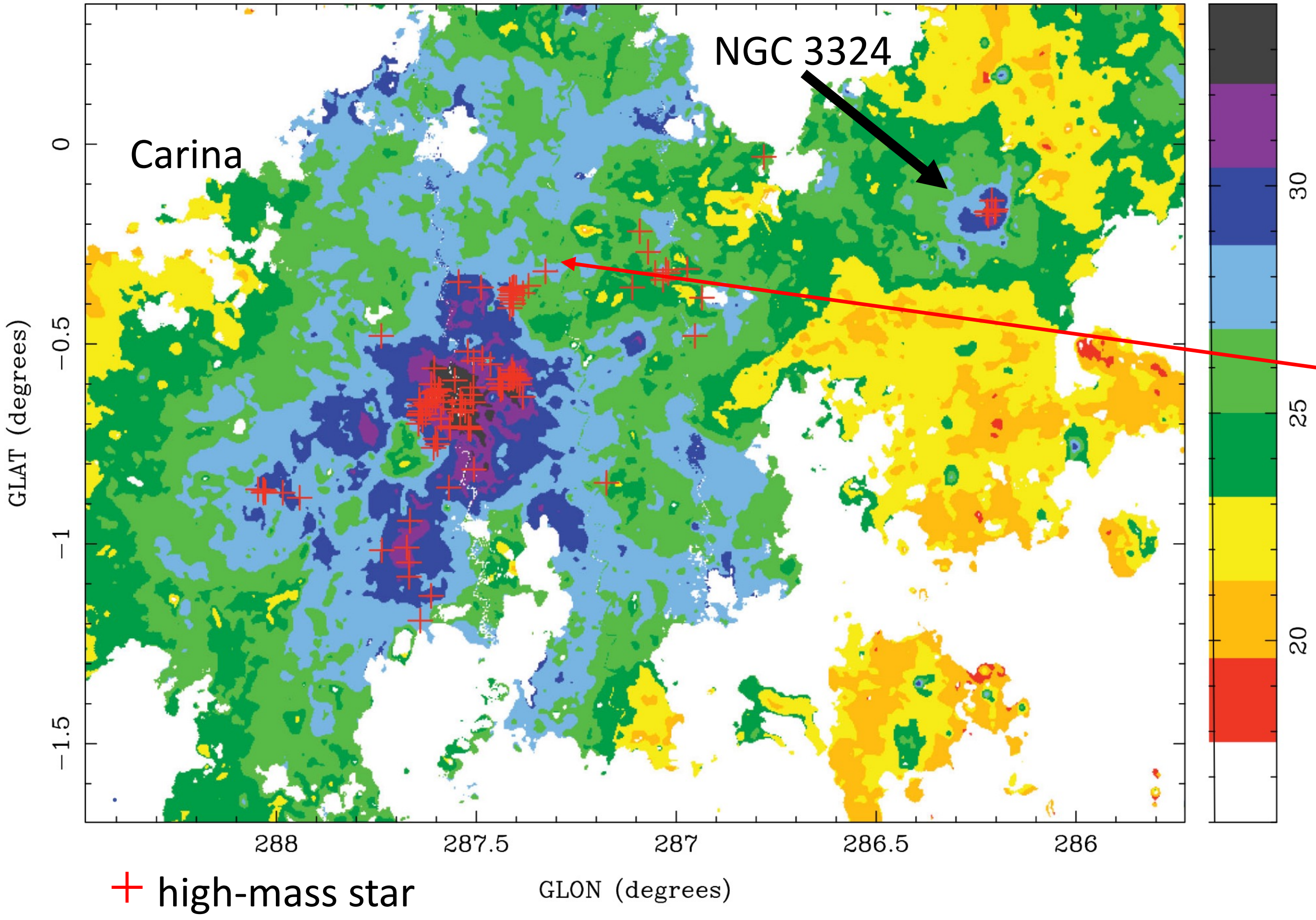
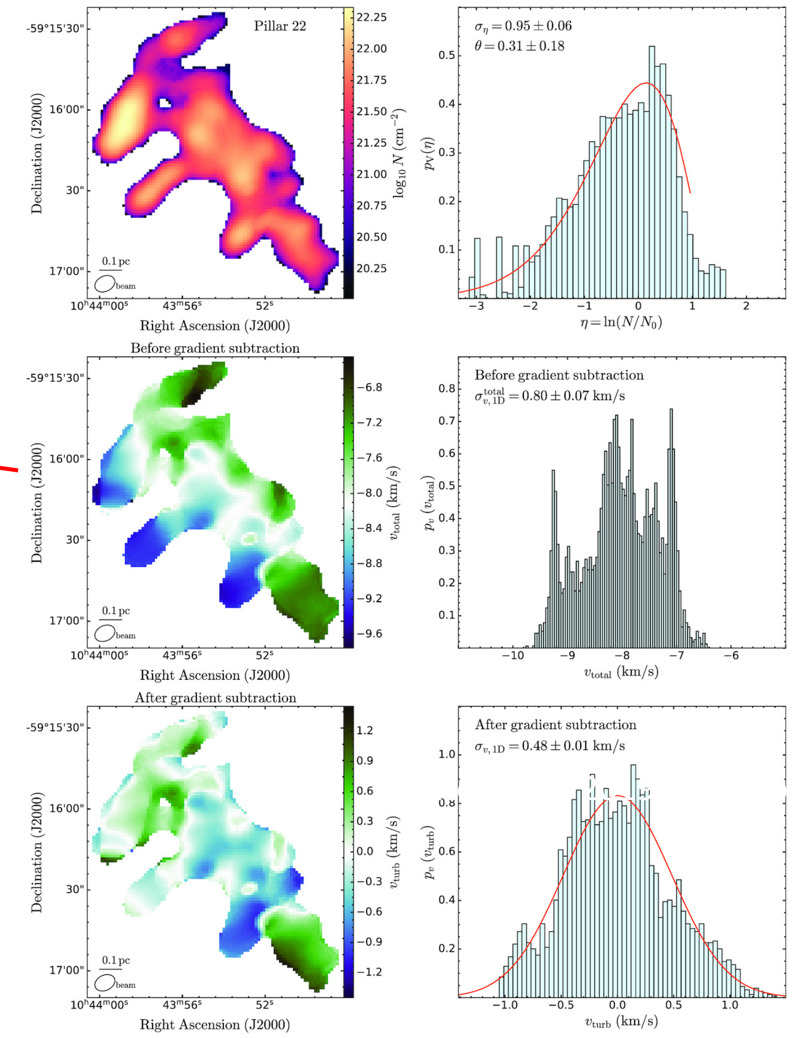


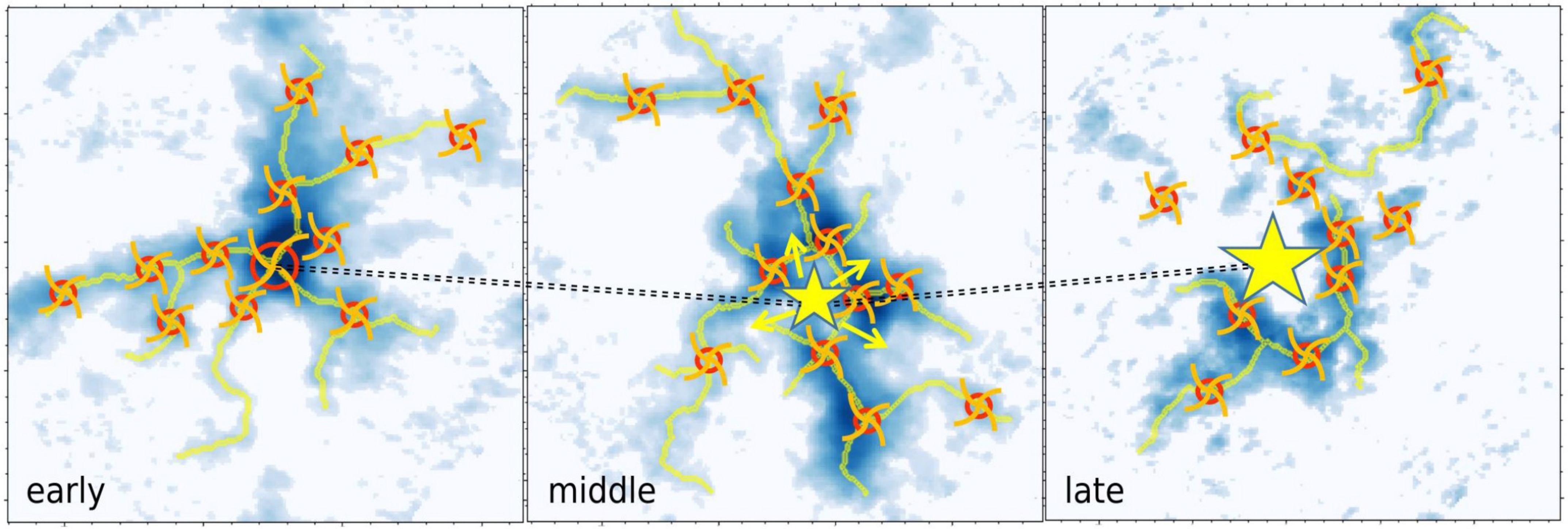
Menon et al. (2020)

Rebolledo et al. 2016



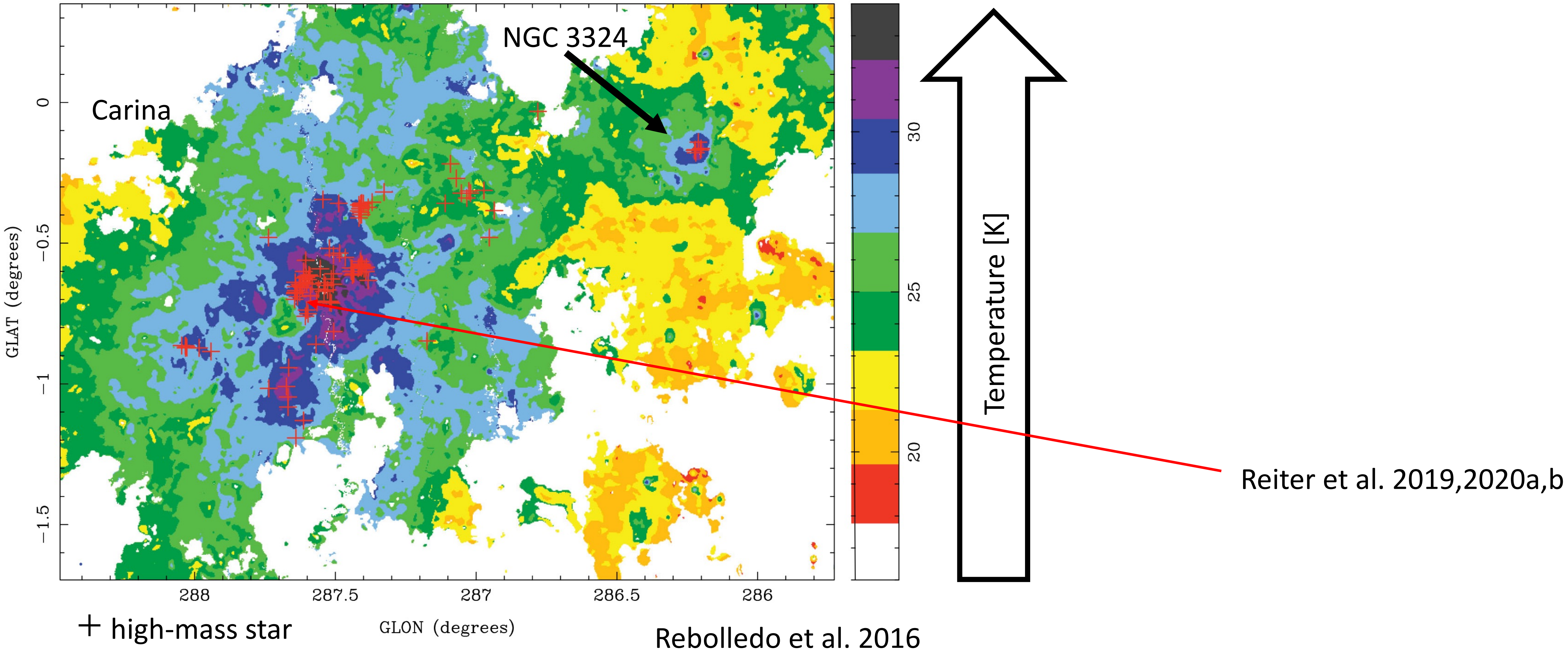
Klaassen et al. 2020; Menon et al. 2021; Reiter et al. 2023

Feedback doesn't significantly change kinematic properties of embedded dense gas structures.



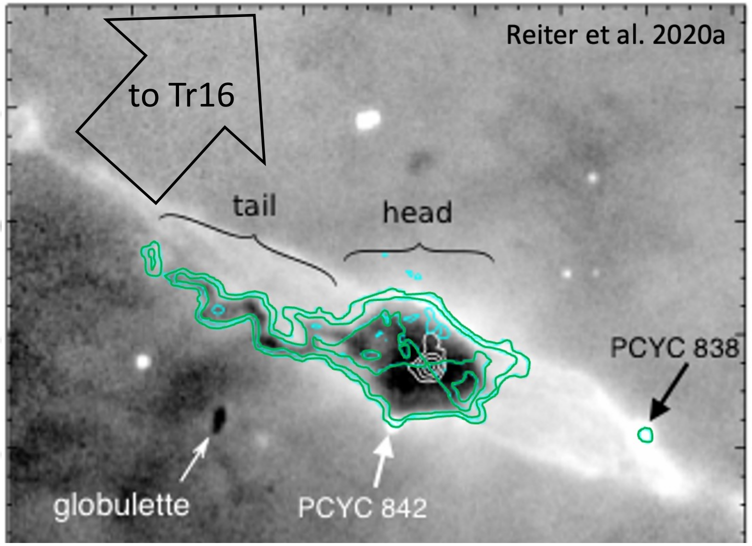
Zhou et al. 2024

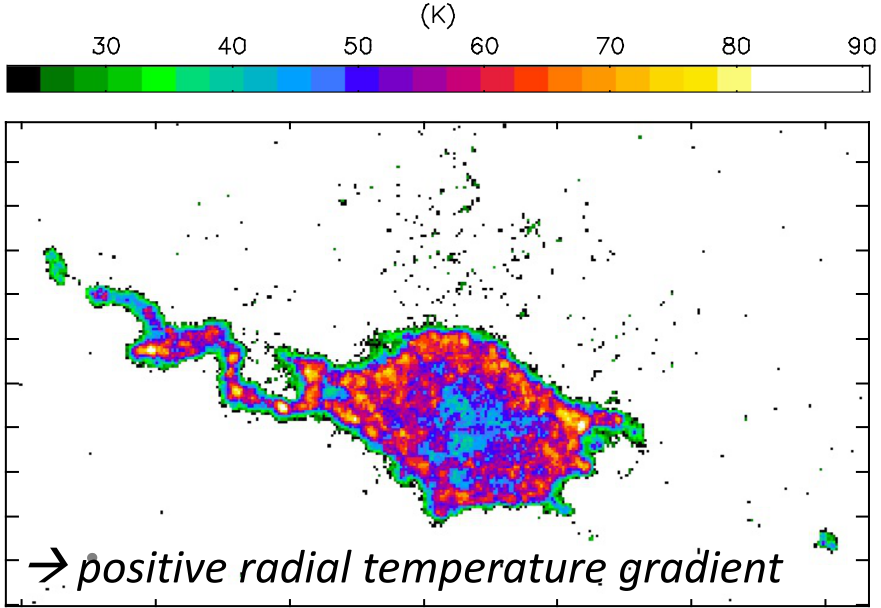
Feedback from high-mass stars heats and reshapes surrounding cloud, may affect fragmentation, chemistry, …

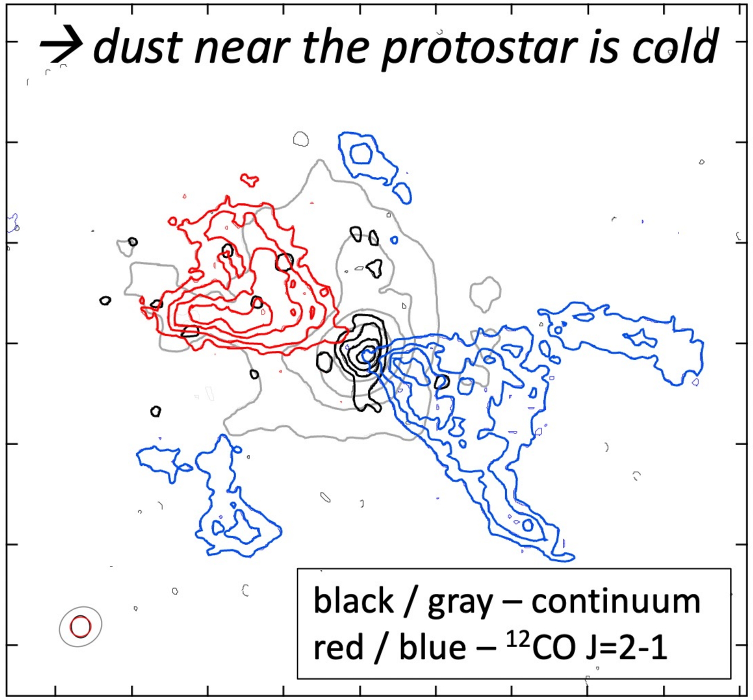


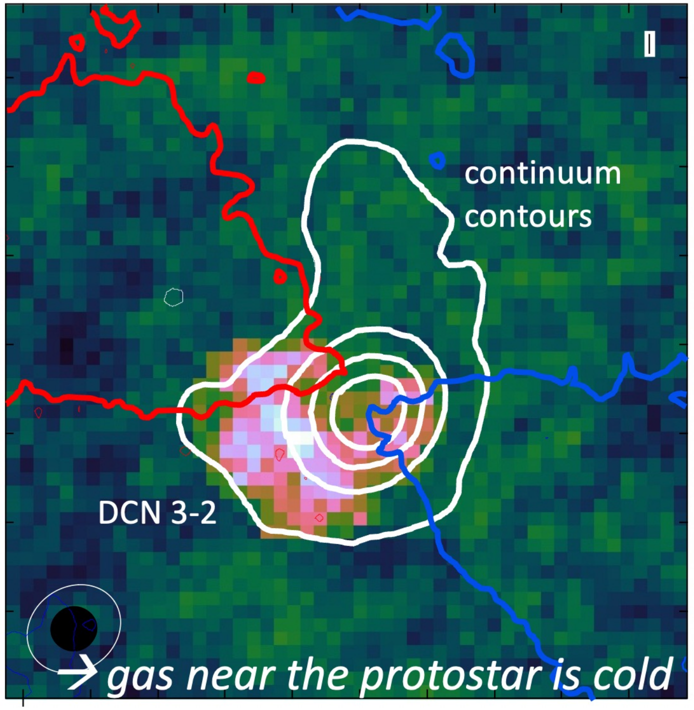
Rebolledo et al. 2016

Quantify the impact of external heating: the surface of the star-forming cocoon is hot but the inside remains cold.





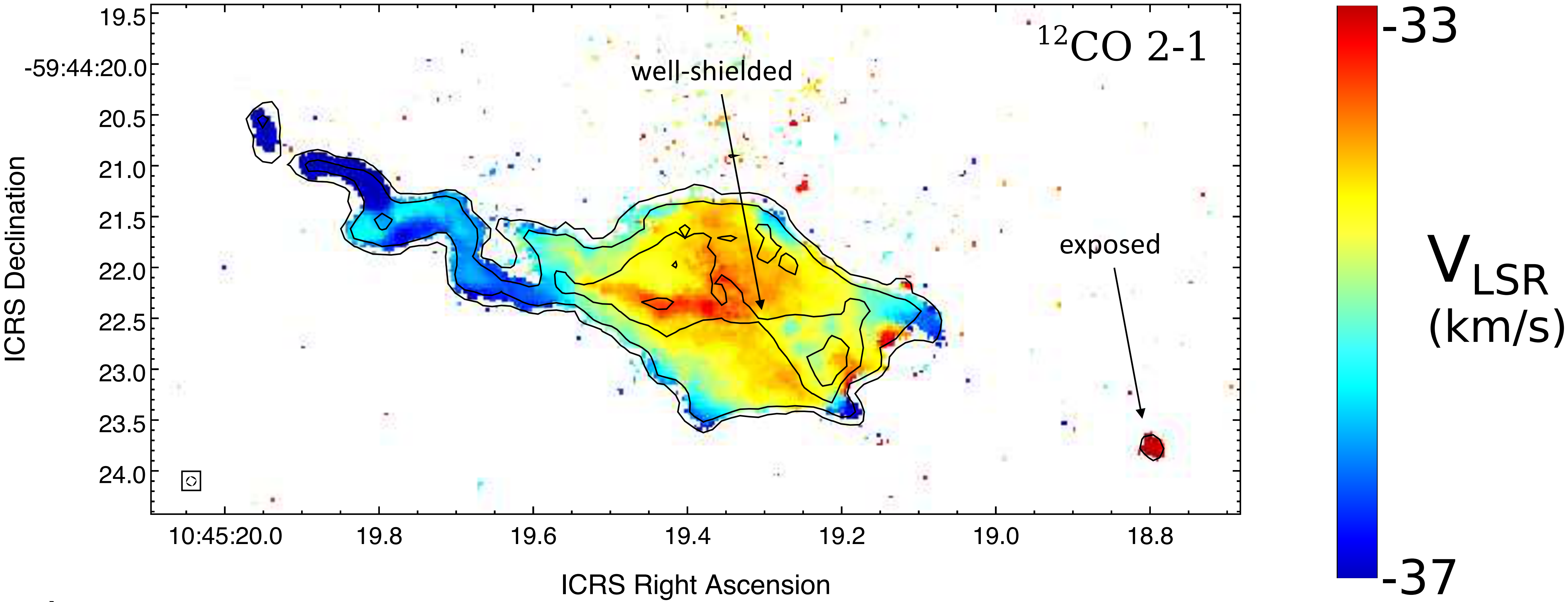




→poster: P25 Kamber Schwarz

Reiter et al. 2020

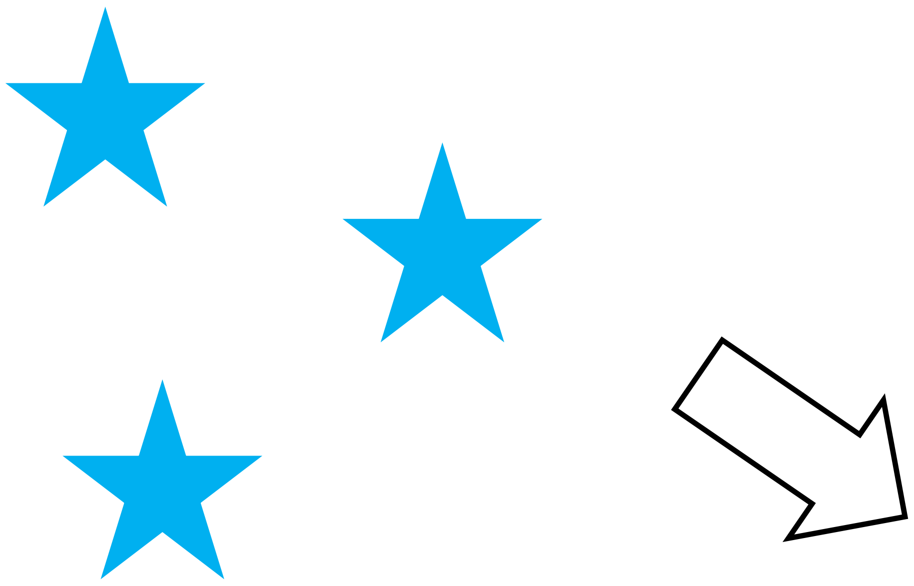
Protostars embedded in dense cocoons may not notice their environment; exposed YSOs absolutely will.



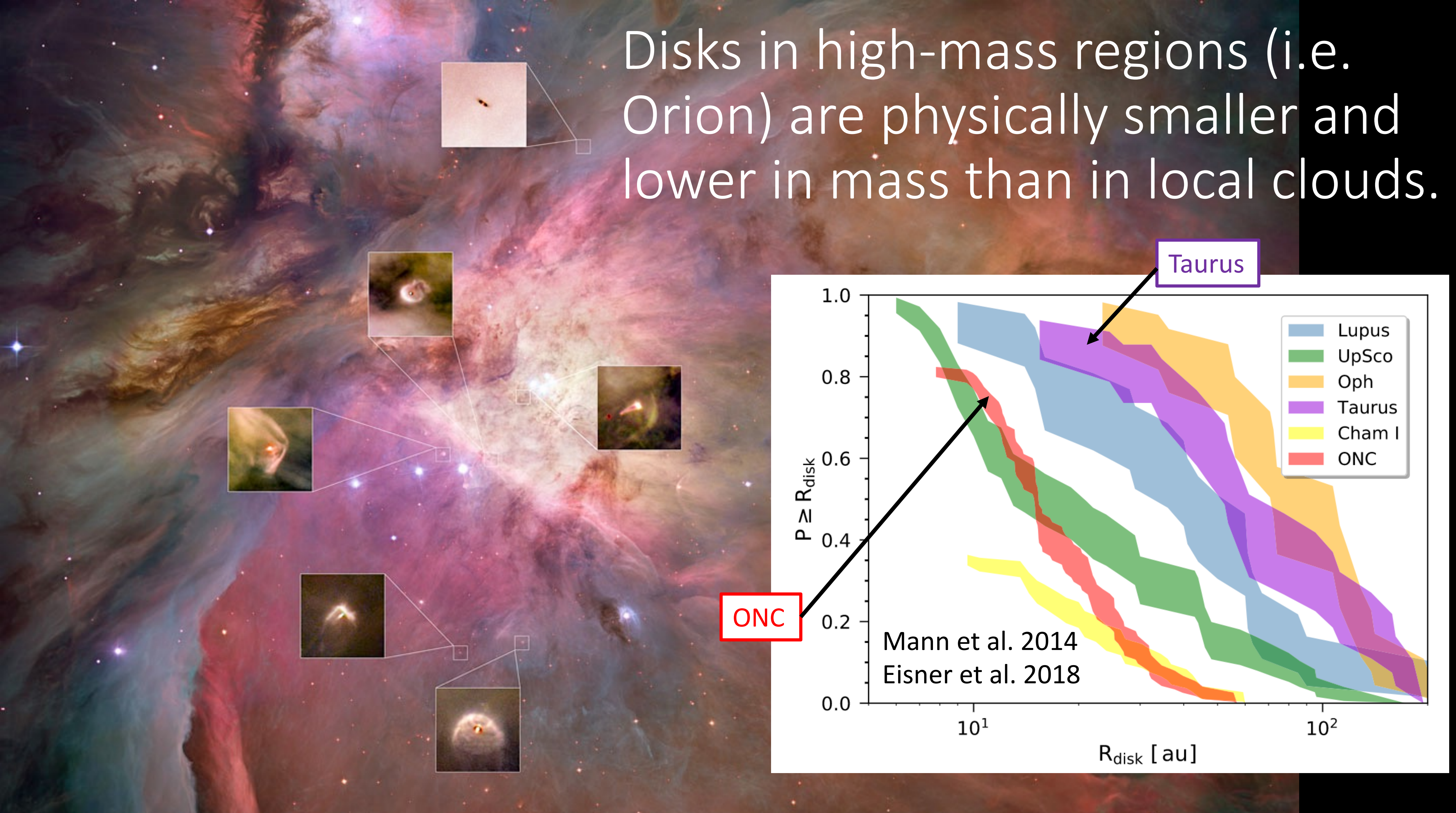
Reiter et al. 2020

→ see also: Qiao et al. 2023

Yesterday, we talked a lot about disks that look a bit like this. UV radiation from neighbors can change the picture a lot.



Disks in high-mass regions (i.e. Orion) are physically smaller and lower in mass than in local clouds.



NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA), the Hubble Space Telescope Orion Treasury Project Team and L. Ricci (ESO)

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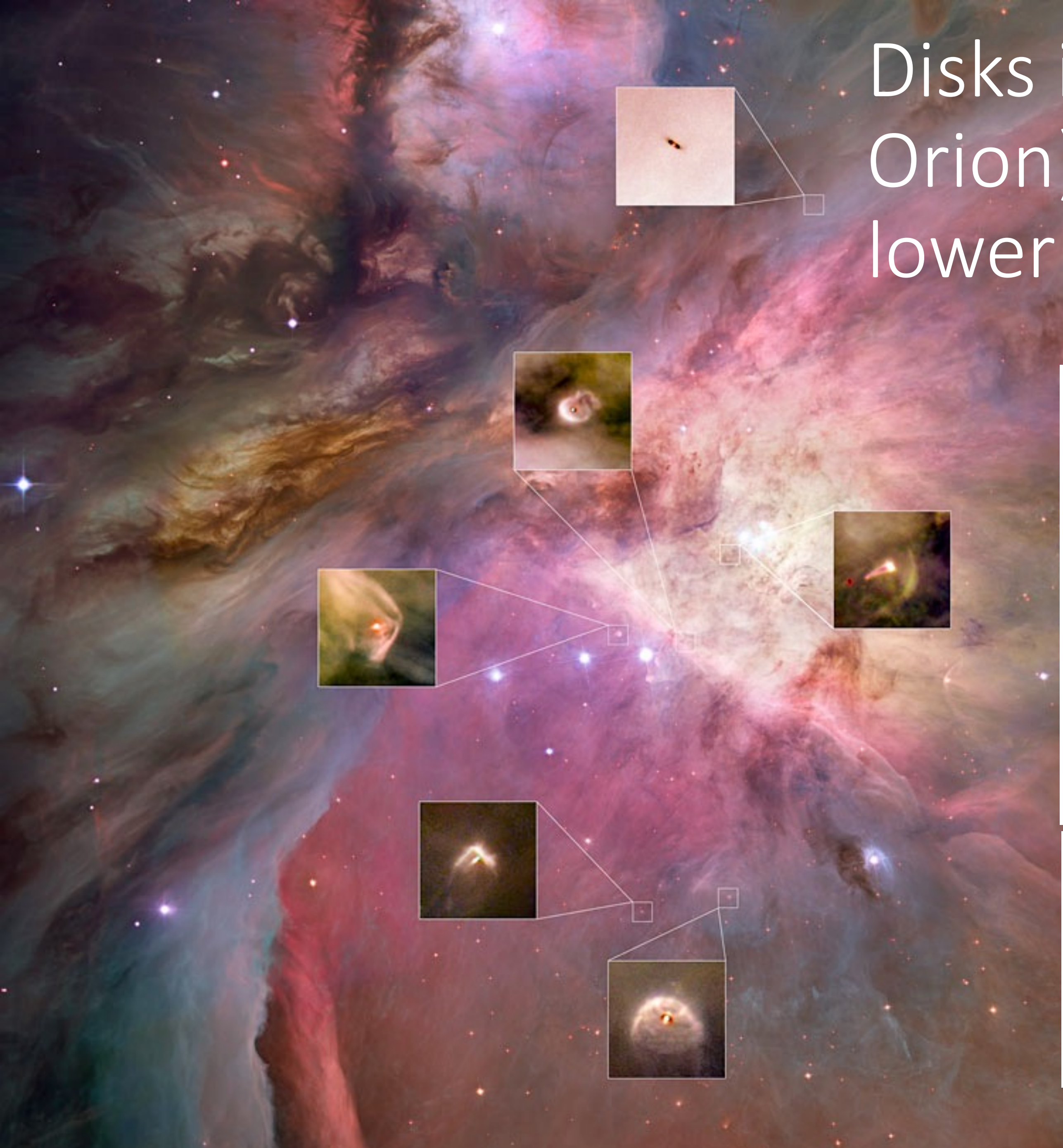
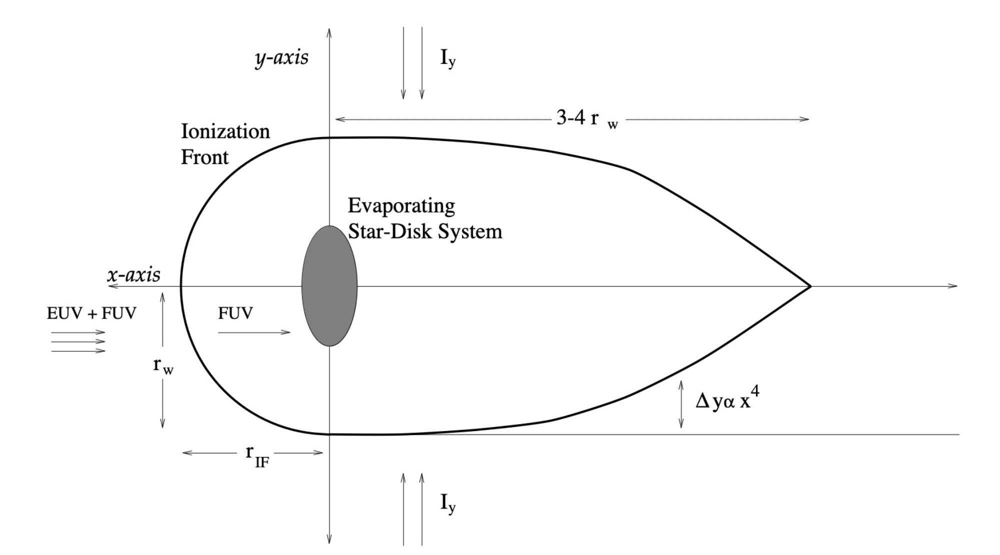
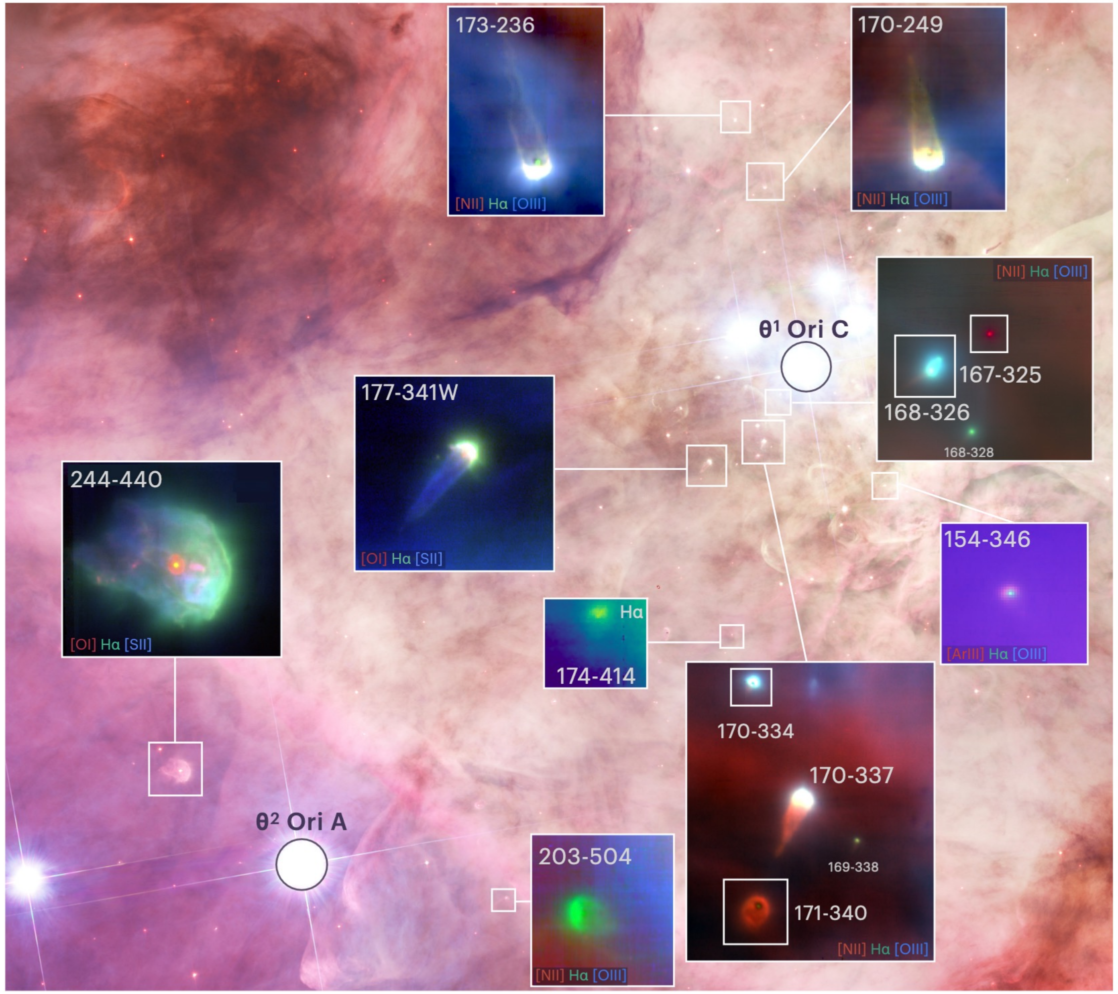


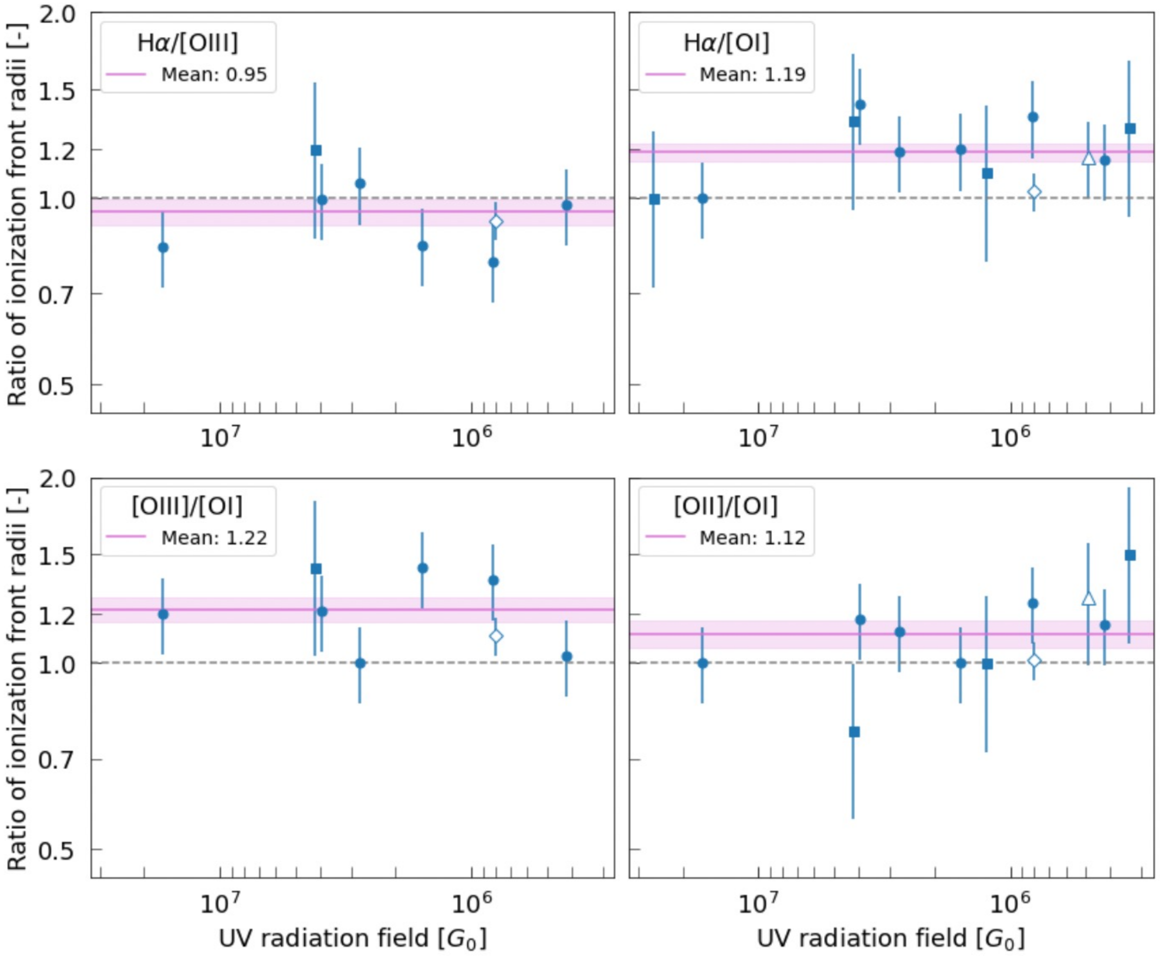


Johnstone et al. 1998; Ballering et al. 2023; Boyden & Eisner 2020, 2023; Concha-Ramirez et al. 2019, 2020, 2021; Haworth et al. 2018, 2023; Nicholson et al. 2019; Qiao et al. 2022, 2023; Winter et al. 2018; …

NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA), the Hubble Space Telescope Orion Treasury Project Team and L. Ricci (ESO)

External UV irradiation may change the mass, lifetime, and chemistry of planet-forming disks – eg, Orion proplyds.





Kirwan et al. 2023; Aru et al. 2024

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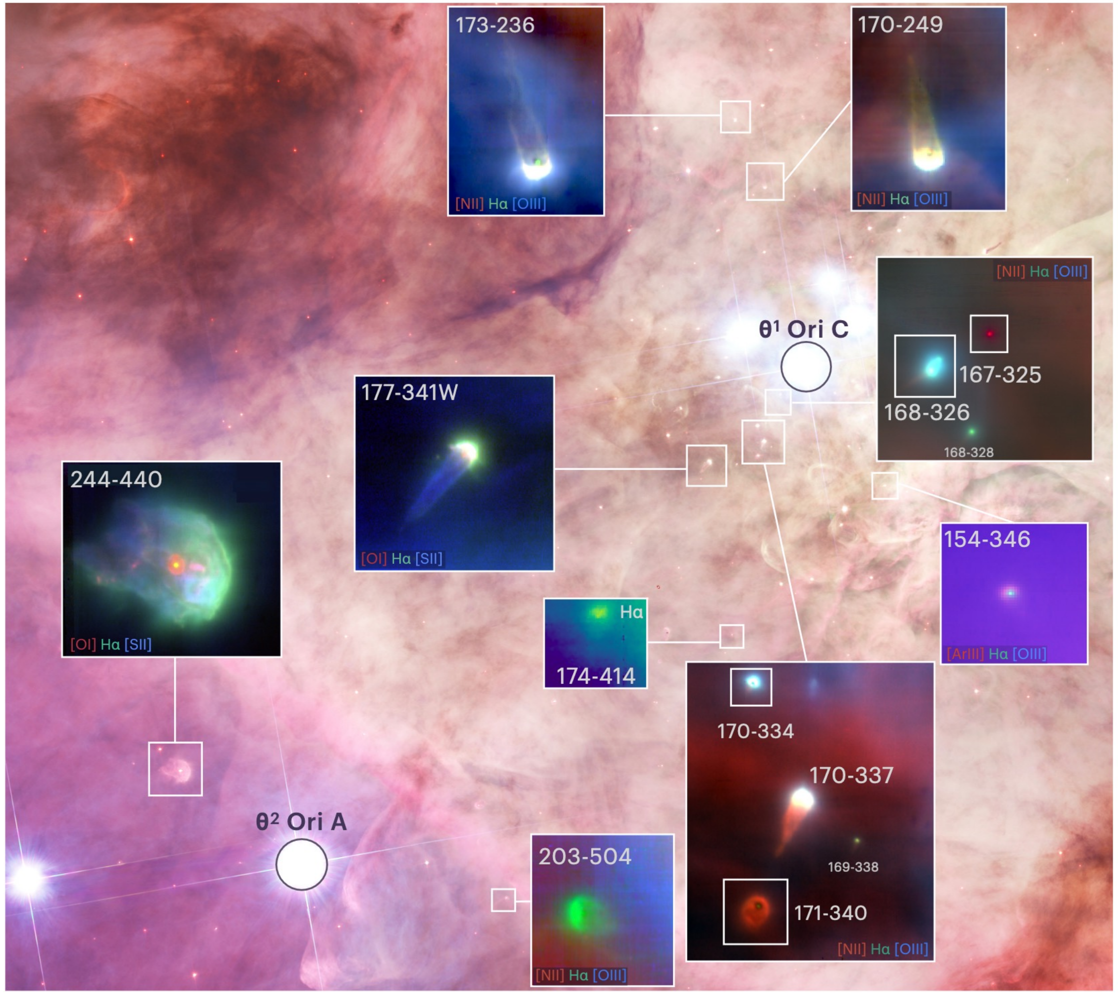

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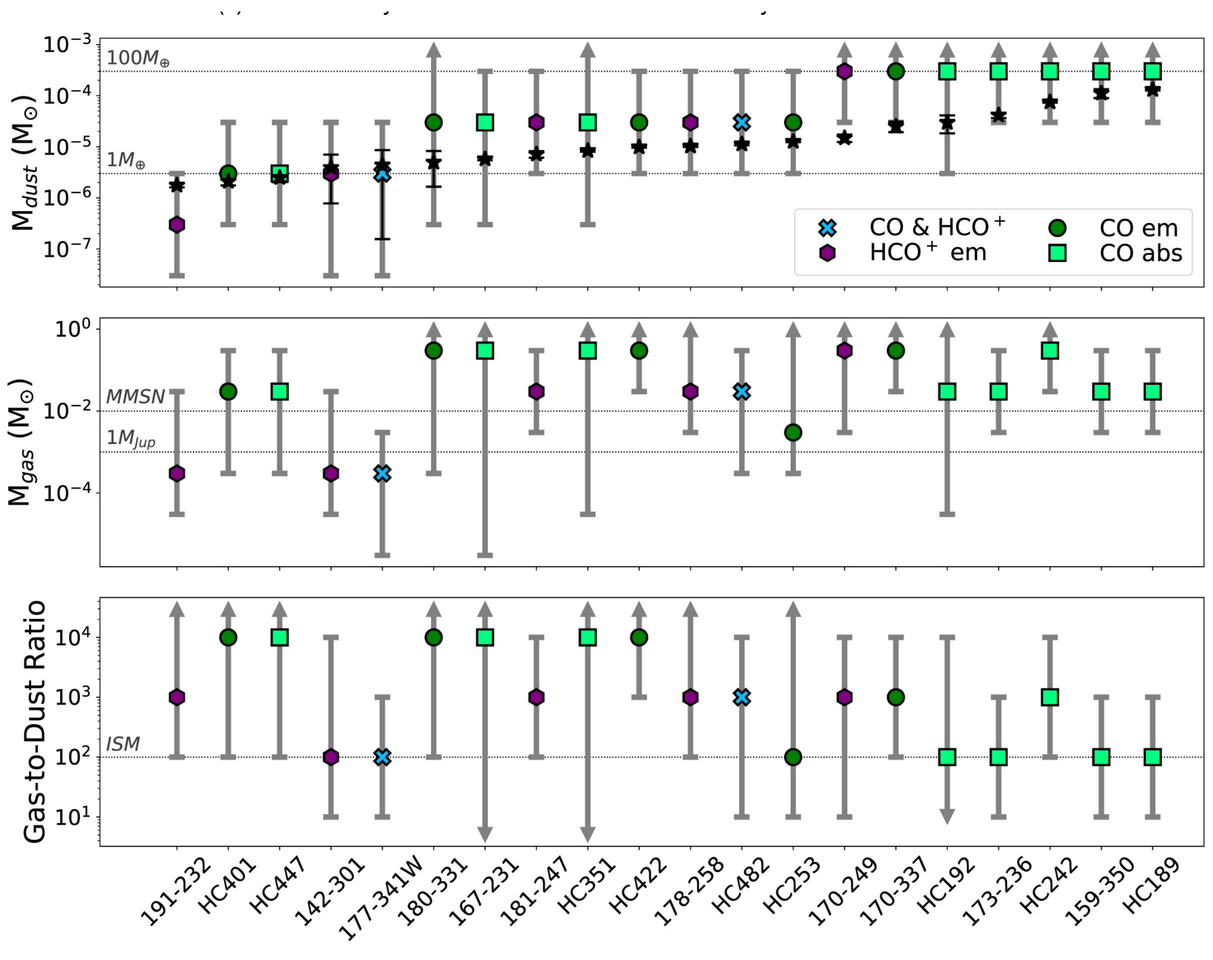
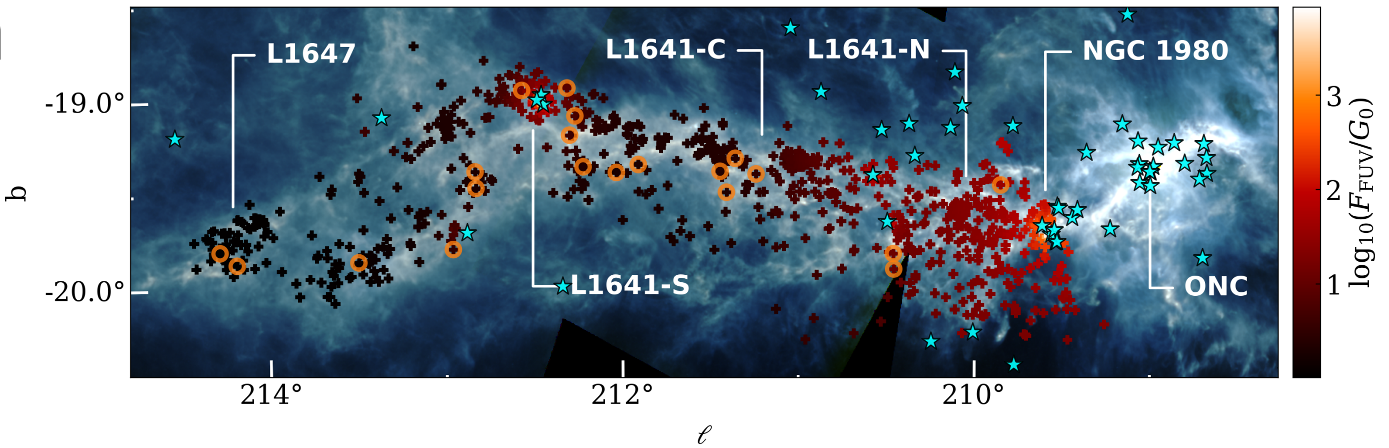
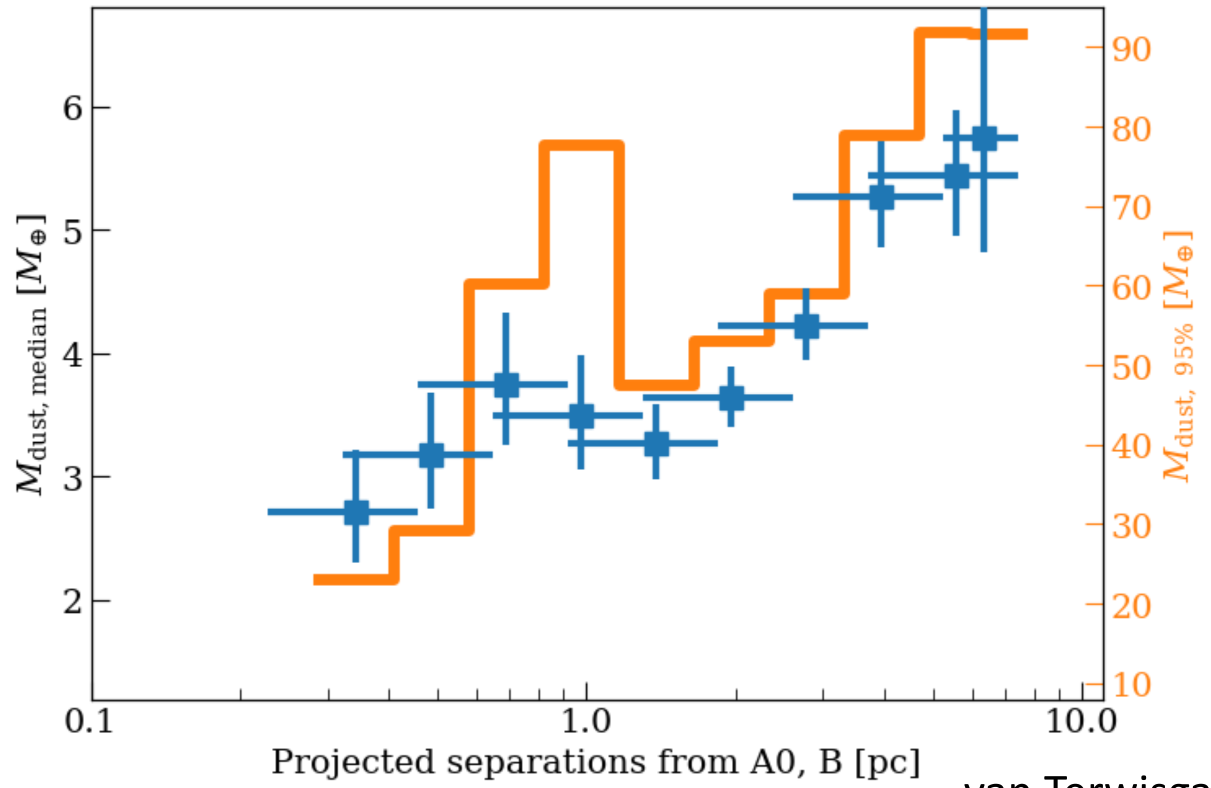
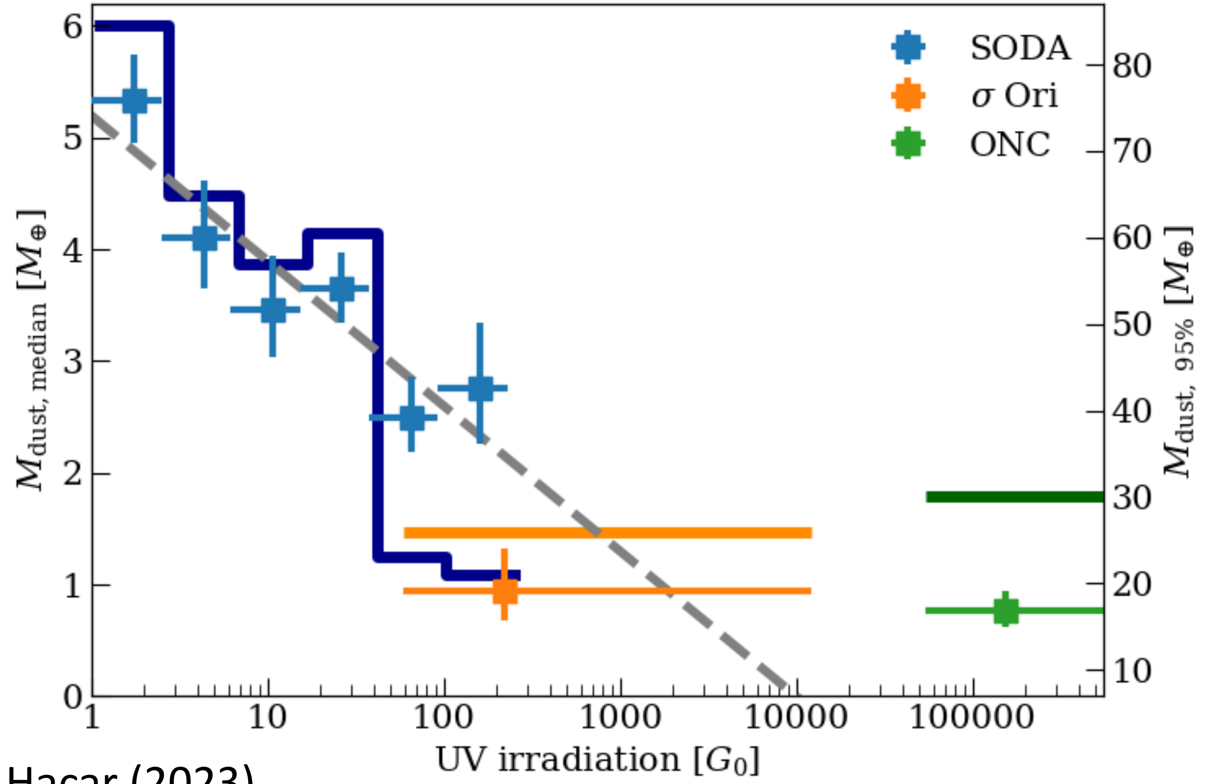


Boyden & Eisner 2023

External photoevaporation reduces disk sizes, masses, and lifetimes but for what fraction of stars?



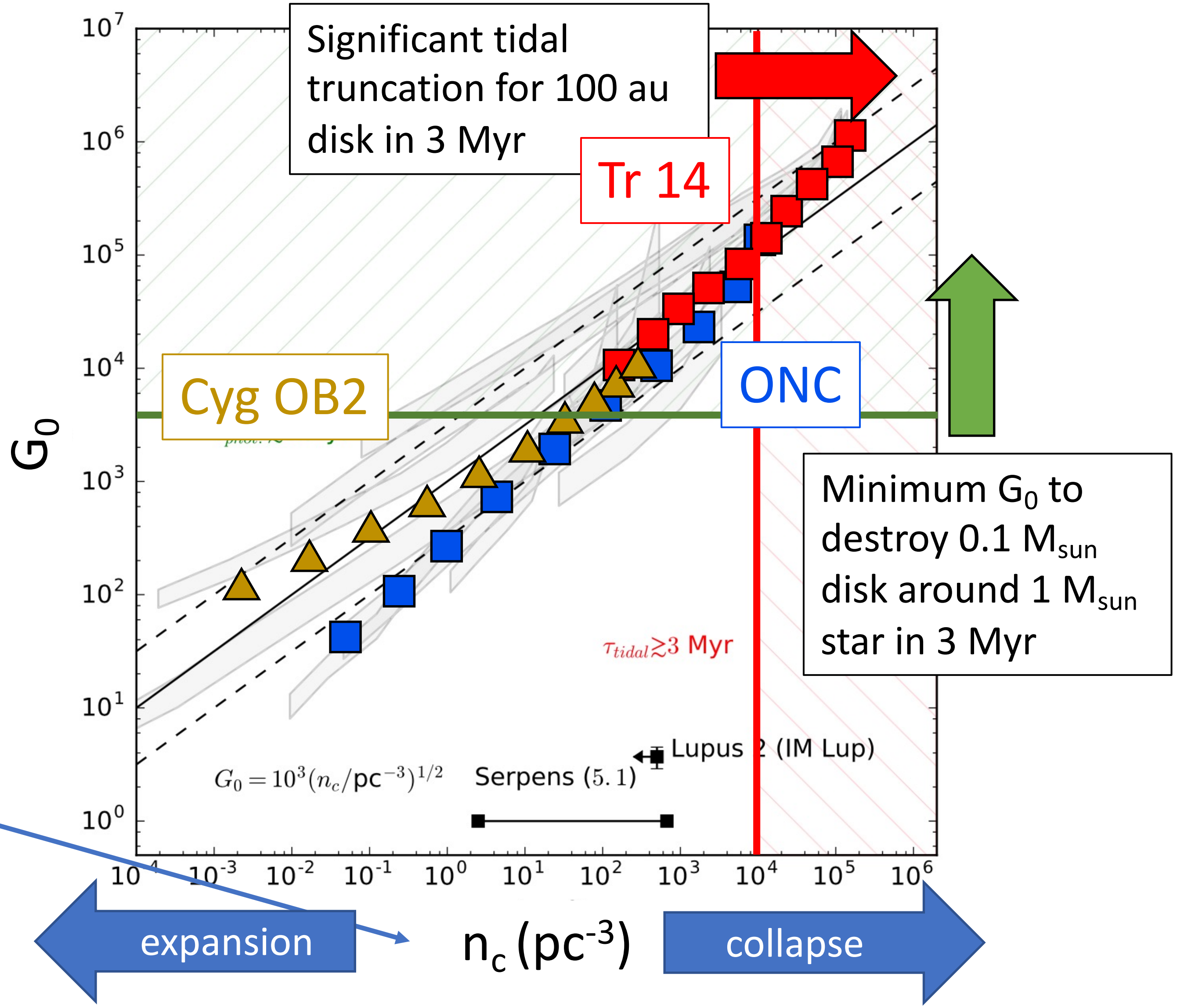




van Terwisga & Hacar (2023)

Dynamical evolution of star-forming regions can change a lot the impact of feedback on relevant timescales.

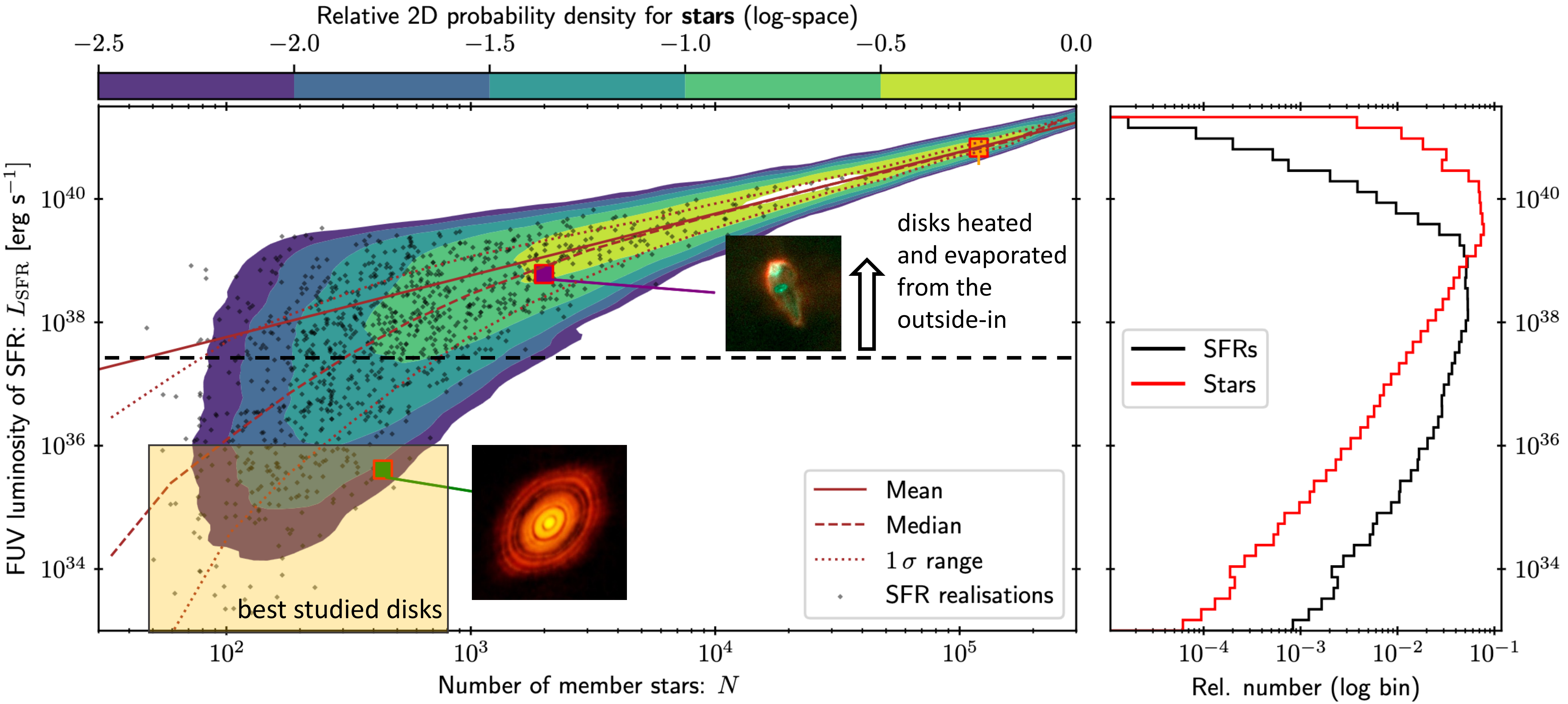
→ posters:
P07 Josefa Großschedl
P18 Núria Miret-Roig
P26 Cameren Swiggum
→ talk: João Alves



Dynamical evolution means density changes with time

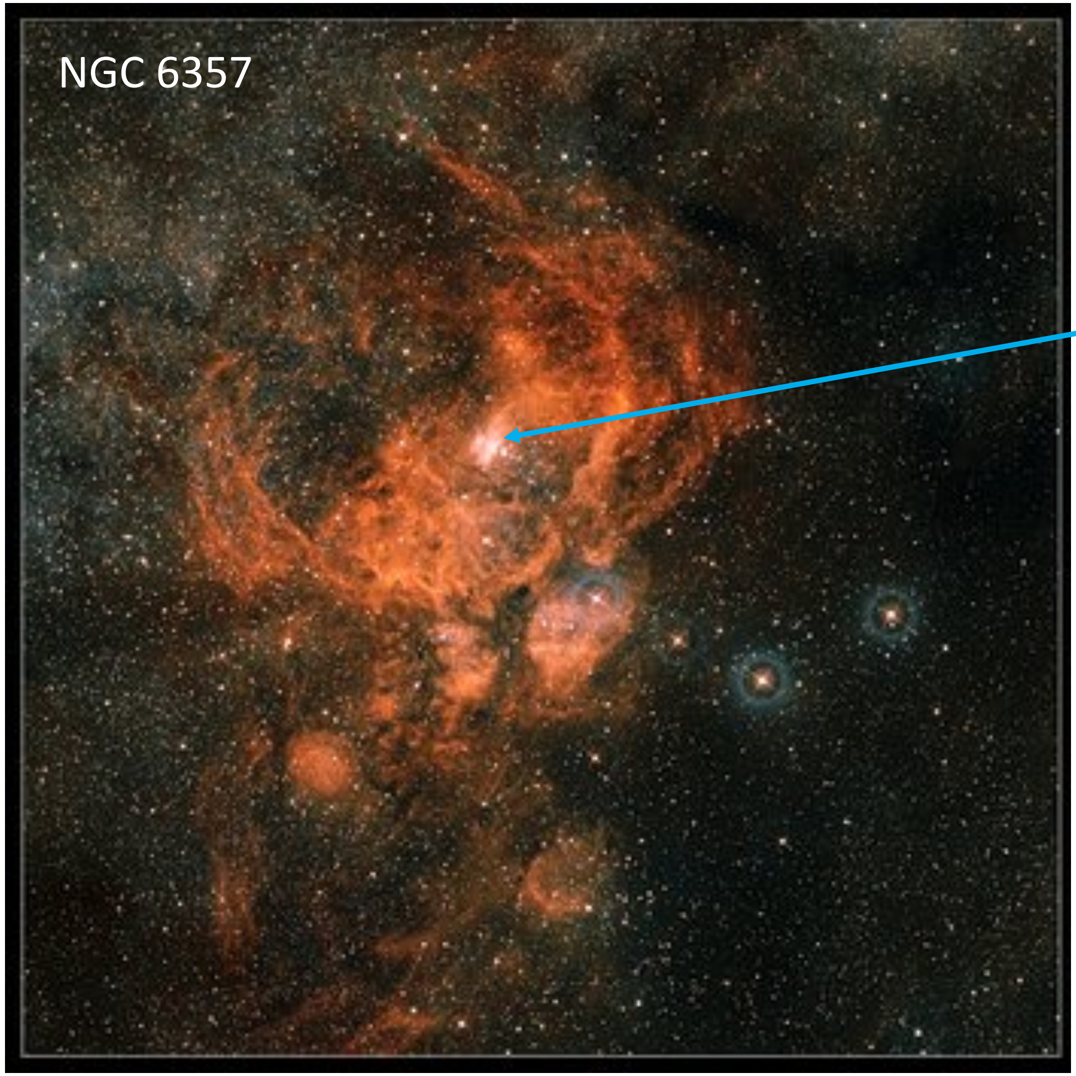
Winter et al. 2018

Most disks will be affected by external UV radiation but most studies target local isolated disks.

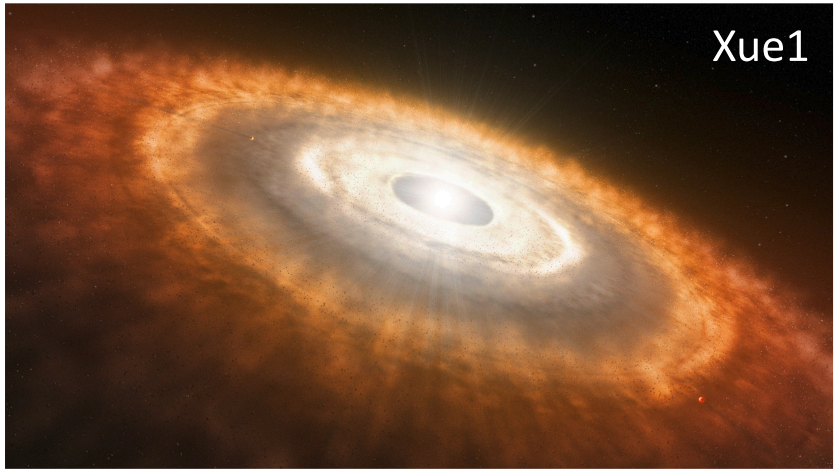


Winter & Haworth 2022

Disk lifetimes appear shorter in high-mass regions… but terrestrial planet-forming conditions resemble local clouds.



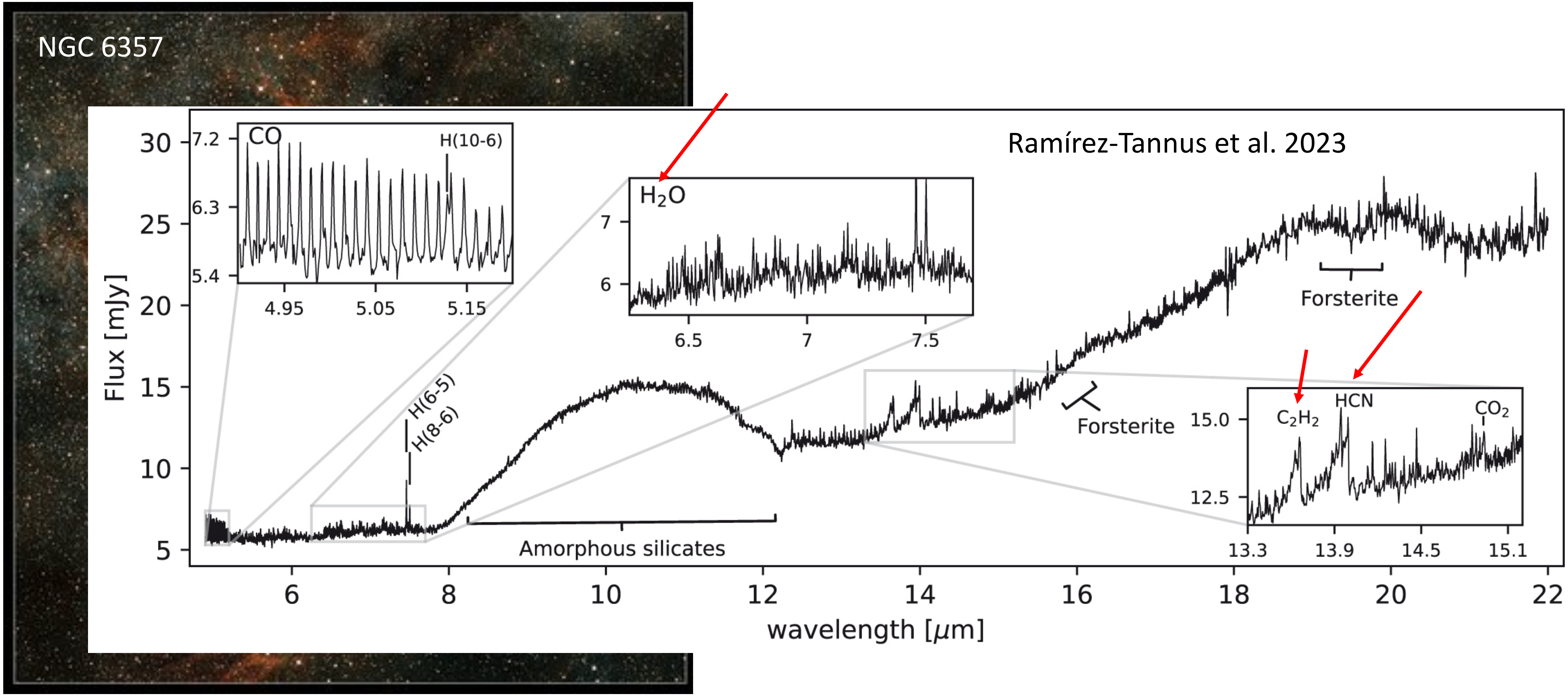
ESO/VVV Survey/Digitized Sky Survey 2/D. Minniti. Acknowledgement: Ignacio Toledo



1/15 disks in NGC 6357 observed with MIRI

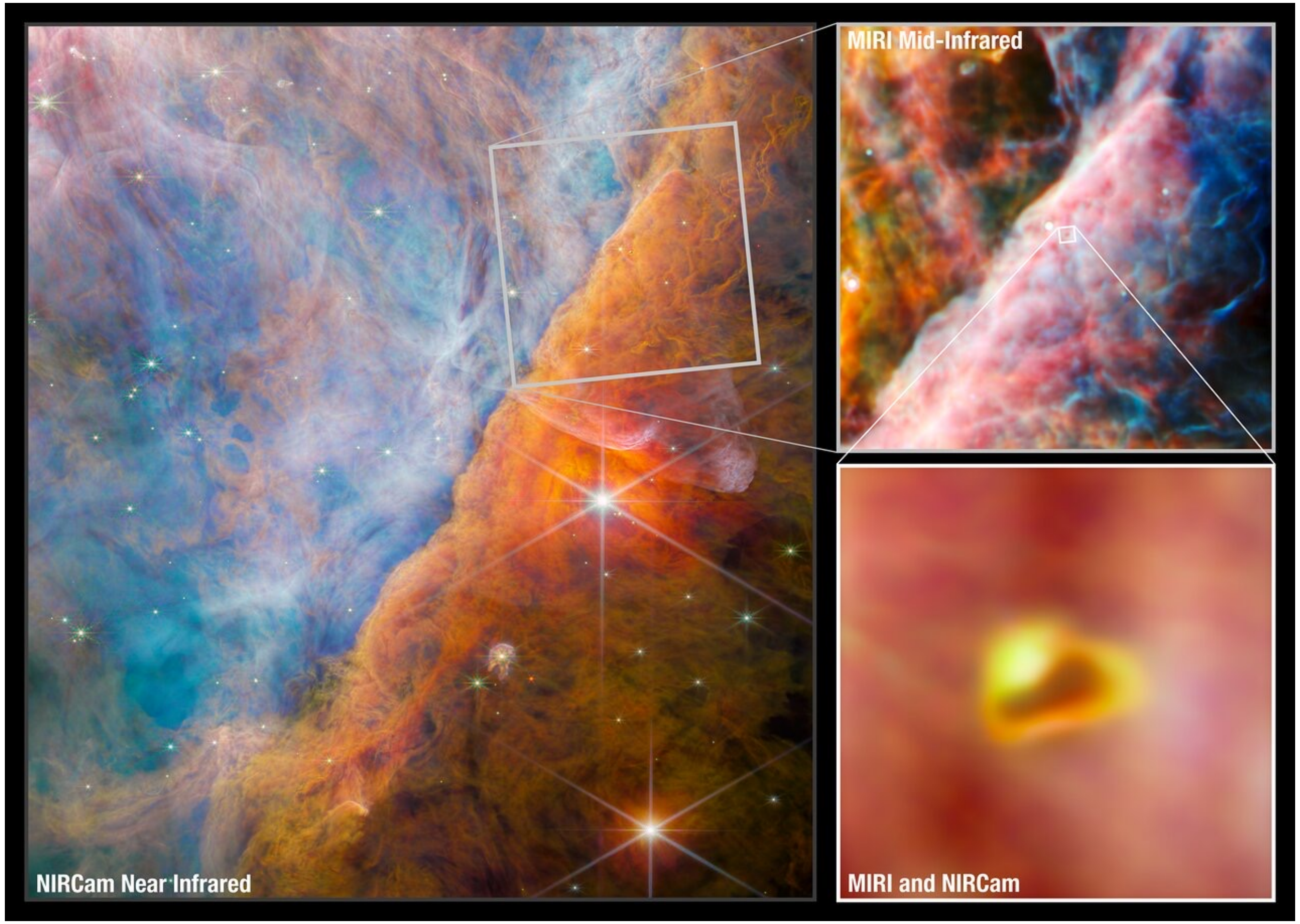
Ramírez-Tannus et al. 2023

Xue1 has all the elements to make Earth-like planets that are seen in nearby planet-forming disks.



ESO/VVV Survey/Digitized Sky Survey 2/D. Minniti. Acknowledgement: Ignacio Toledo

Externally irradiated disks in Orion show evidence for UV-enabled organic chemistry but few other organic molecules.



Berné et al. 2023

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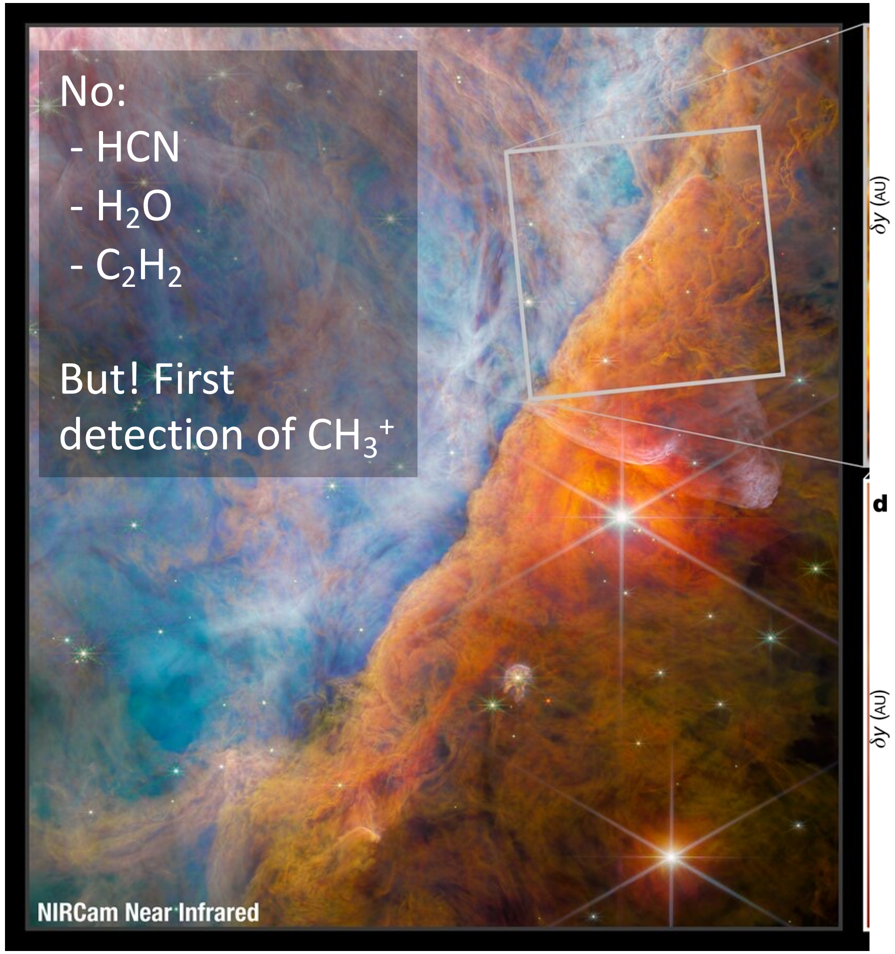
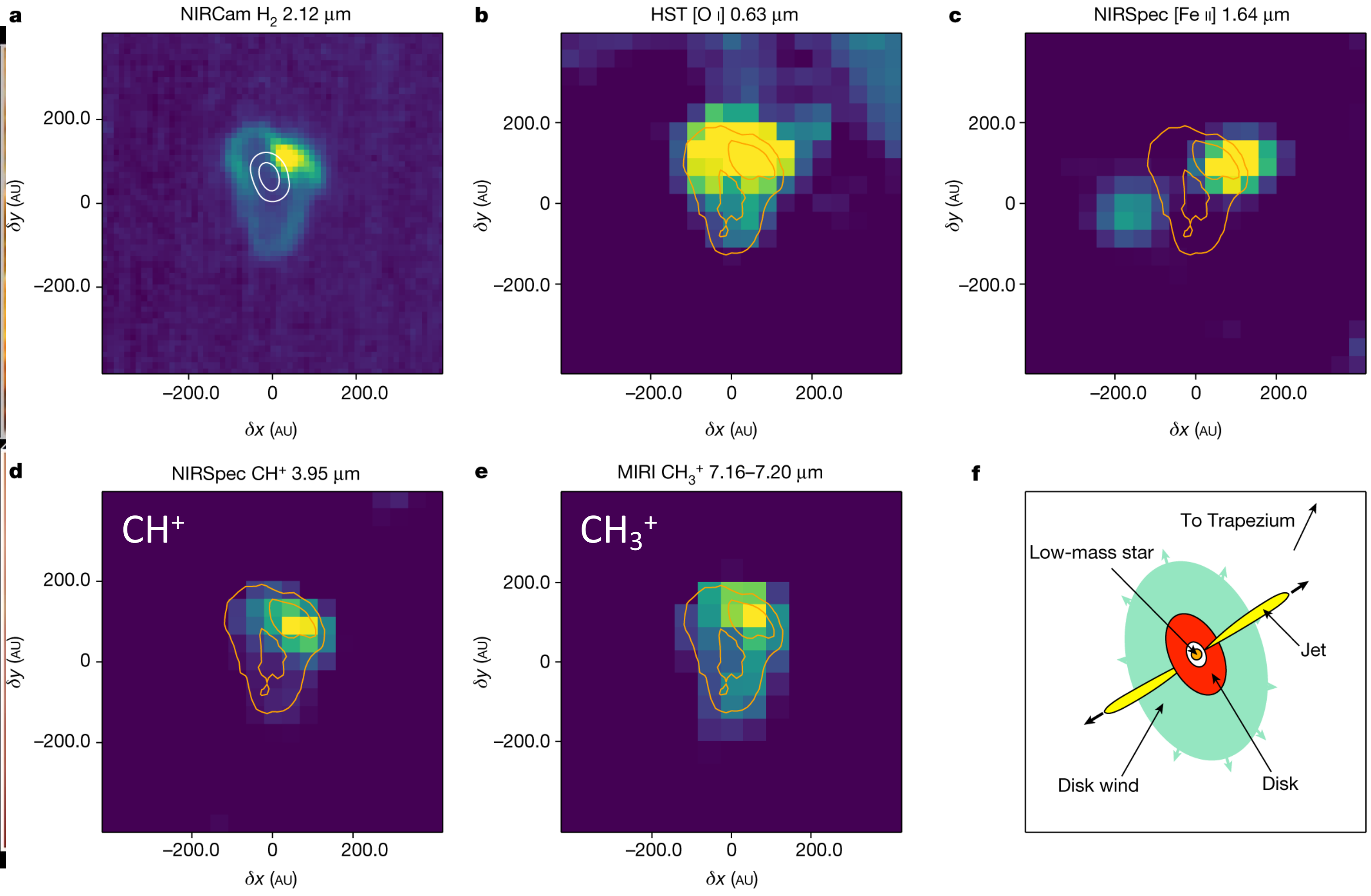
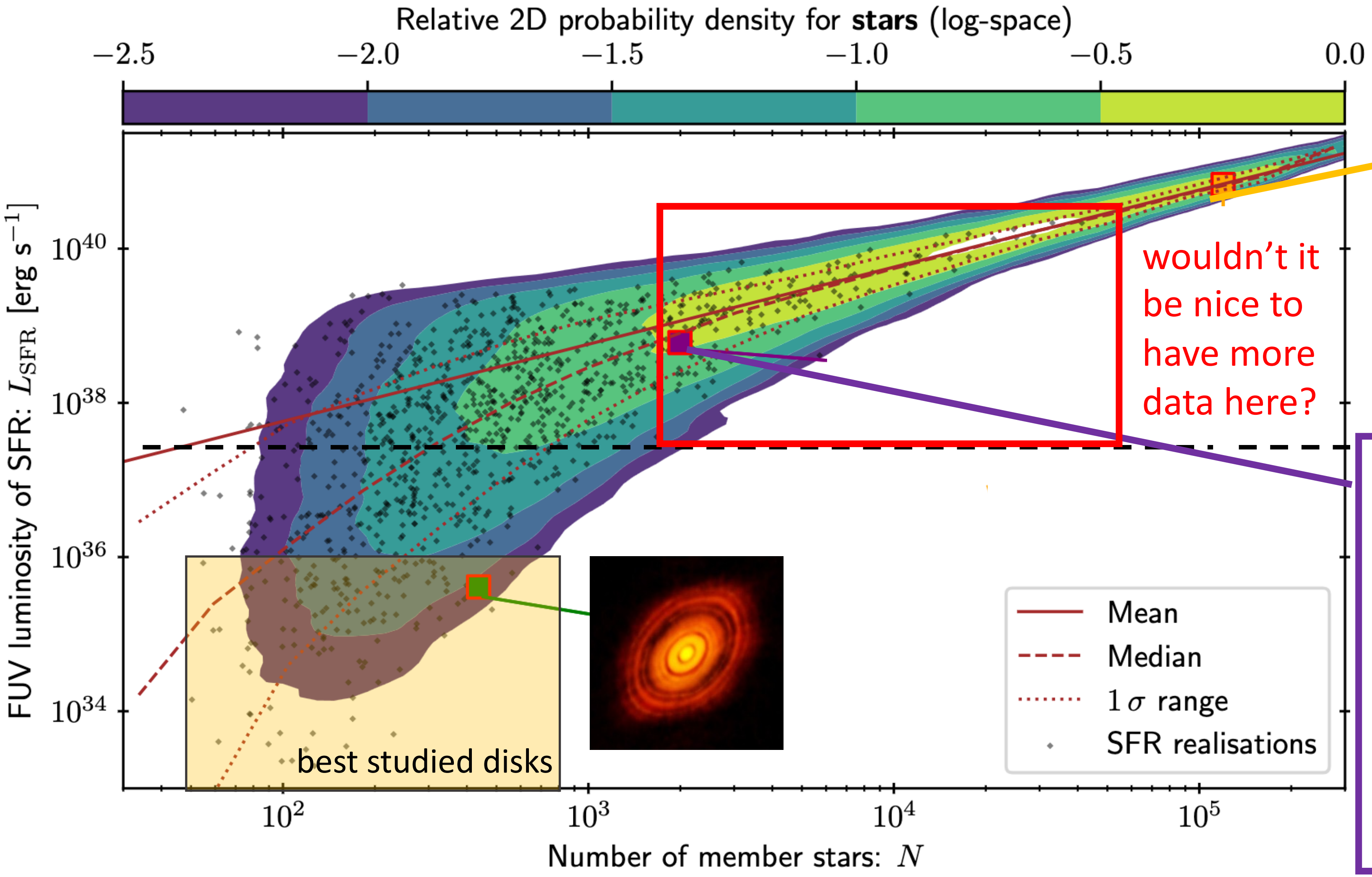


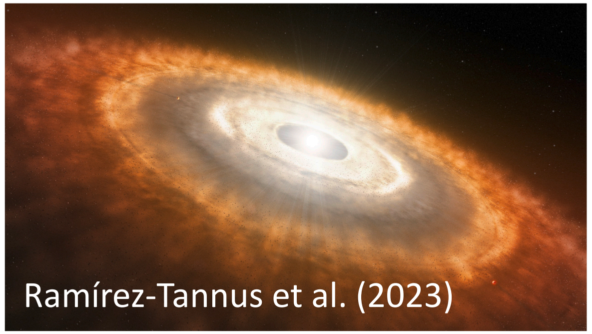


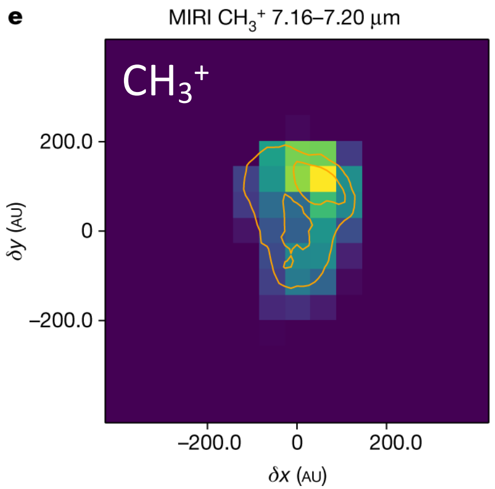
Berné et al. 2023

A few detailed examples do not constrain how much external UV radiation shapes planet-forming disks – statistical surveys needed.



Xue1 looks "normal" compared to local disks





Disk in Orion look "weird" compared to local disks

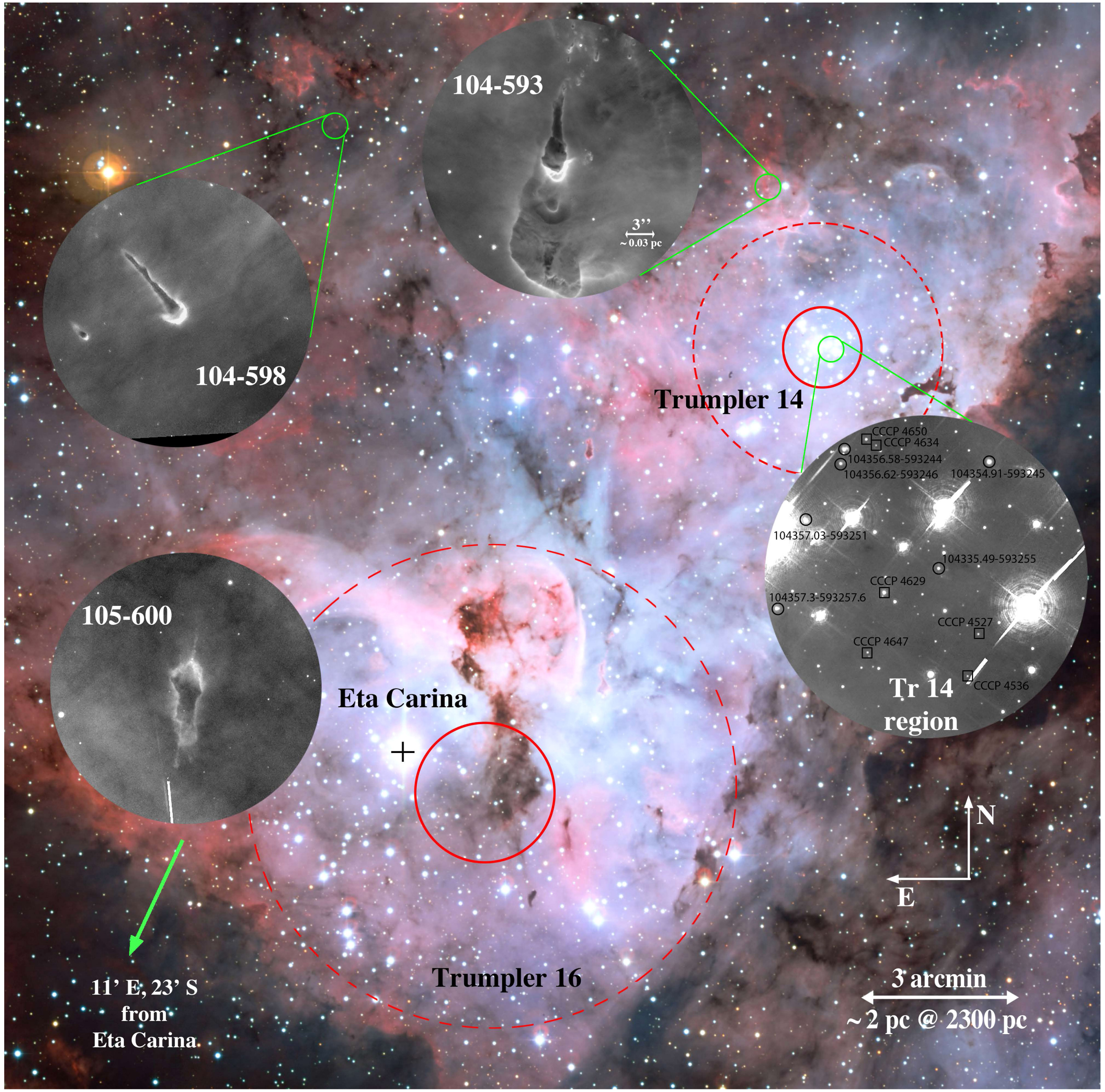
Berné et al. 2023

Winter & Haworth 2022

Few disk detections in regions with D >2 kpc… for now.

→No mm continuum detected from proplyd candidates in Tr14

→Two disk detections in evaporating gaseous globules – evidence of the importance of shielding?



Smith et al. 2003; Smith et al. 2010**; Mesa-Delgado et al. 2016**; Reiter et al. 2020; Cortes-Rangel et al. 2020; 2023

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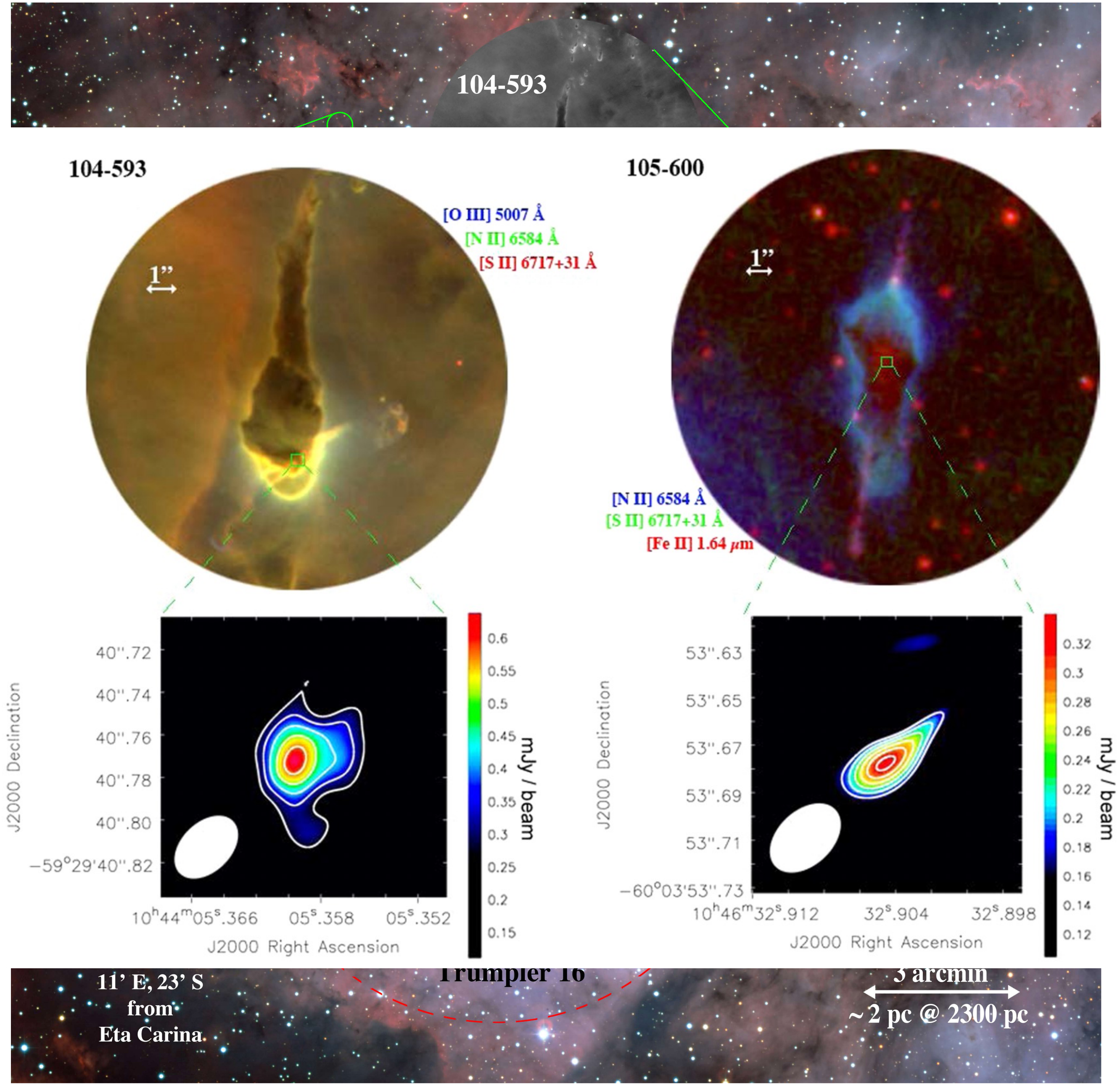

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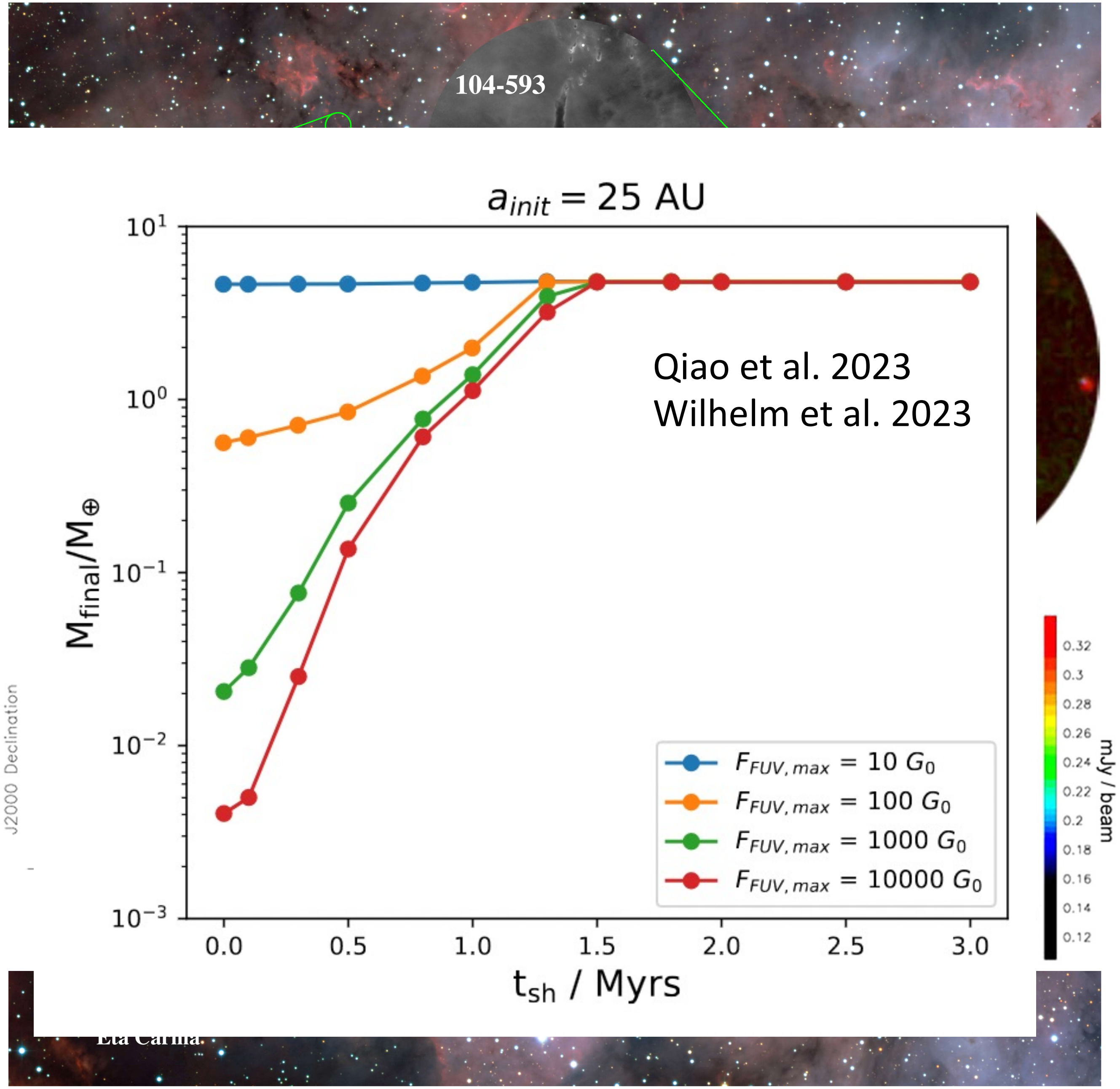
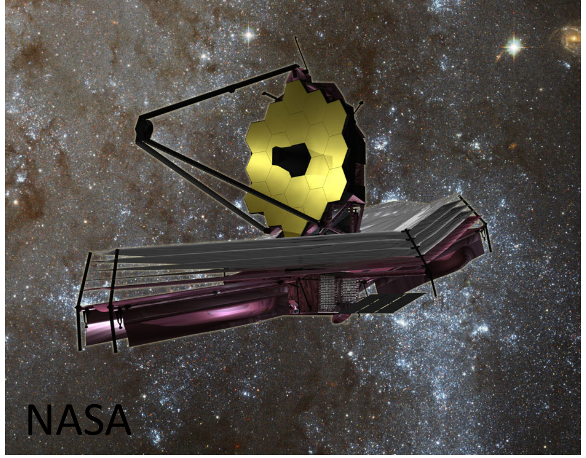
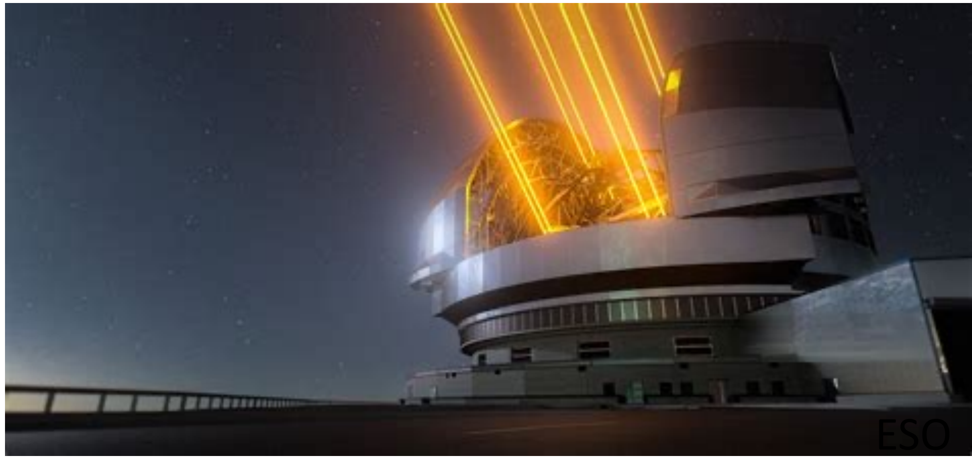


Smith et al. 2003; Smith et al. 2010**; Mesa-Delgado et al. 2016**; Reiter et al. 2020; Cortes-Rangel et al. 2020; 2023

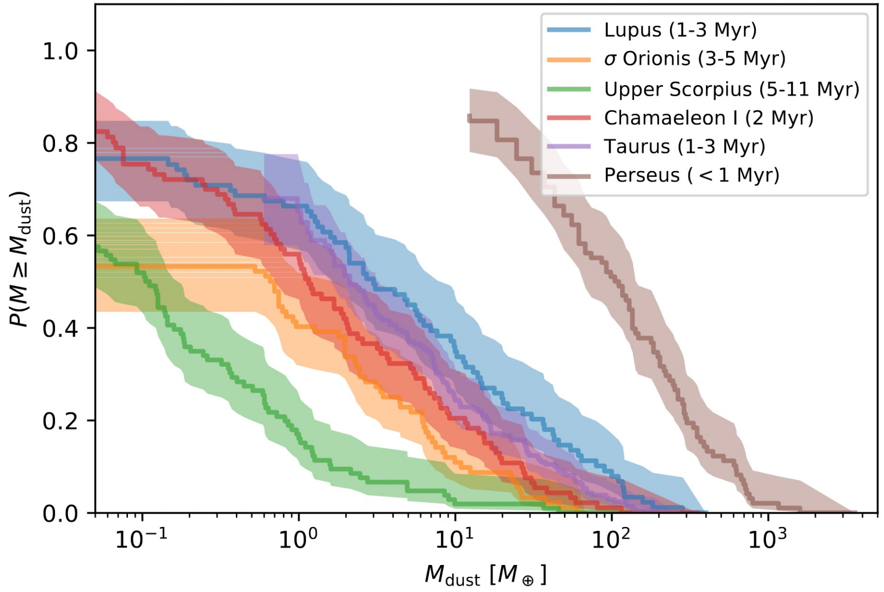
Looking ahead to future EPoS meetings…

- **JWST** – imaging, spectroscopy, proper motions…?
- **ALMA** – esp with wide band upgrades
- **ELTs** – need 30m class telescopes to resolve photoevaporative flows in sources at >2 kpc
- **Simulations** – resolution and additional physics (magnetic fields)
- **Models** – 3D models of external photoevaporation of planet-forming disks





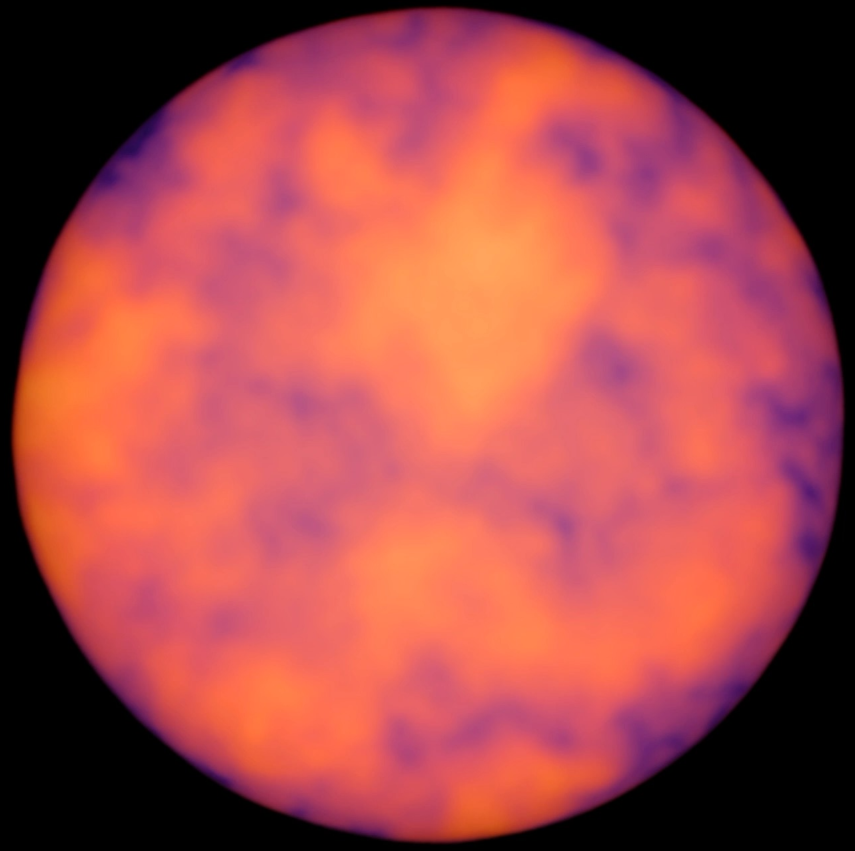
Looking ahead to future EPoS meetings…



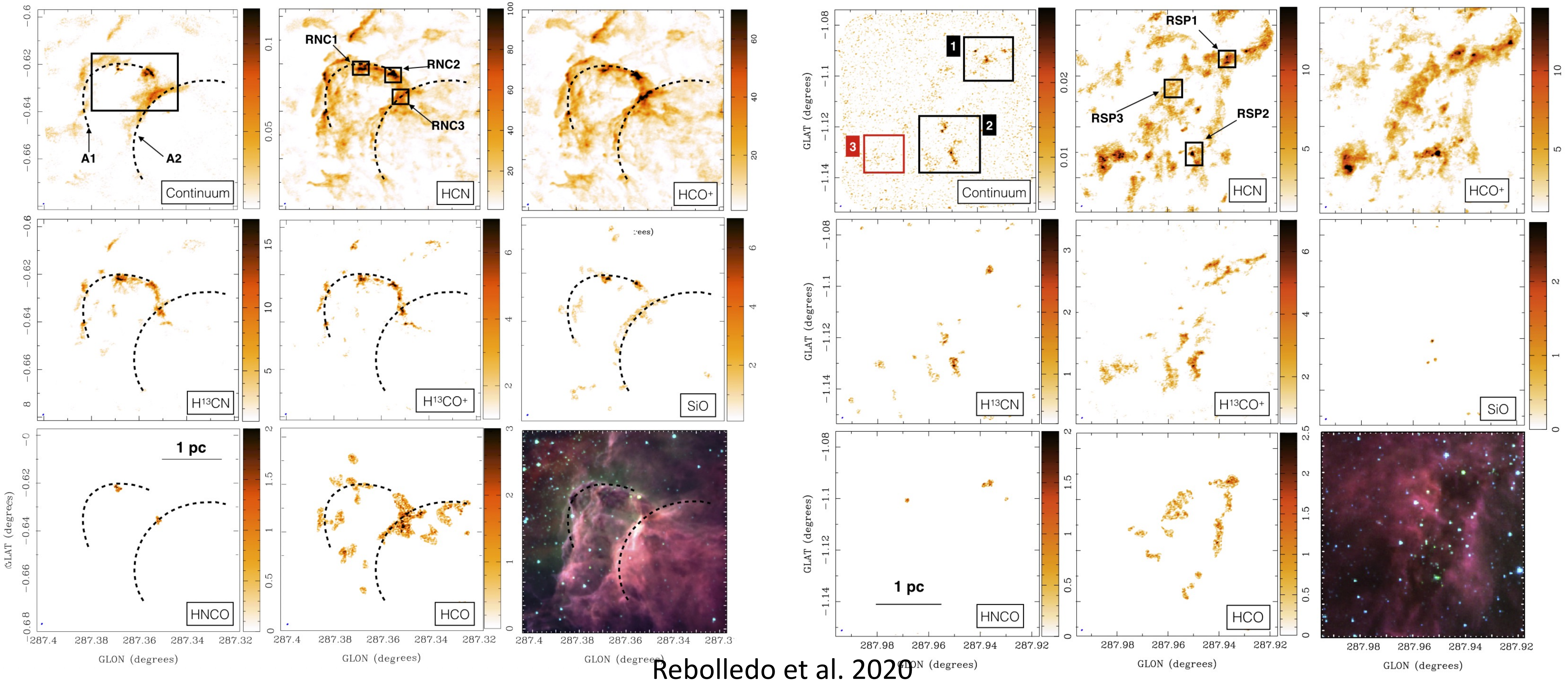
Miotello et al. 2023

Multi-wavelength surveys
of Galactic HMSFRs

PHANGS



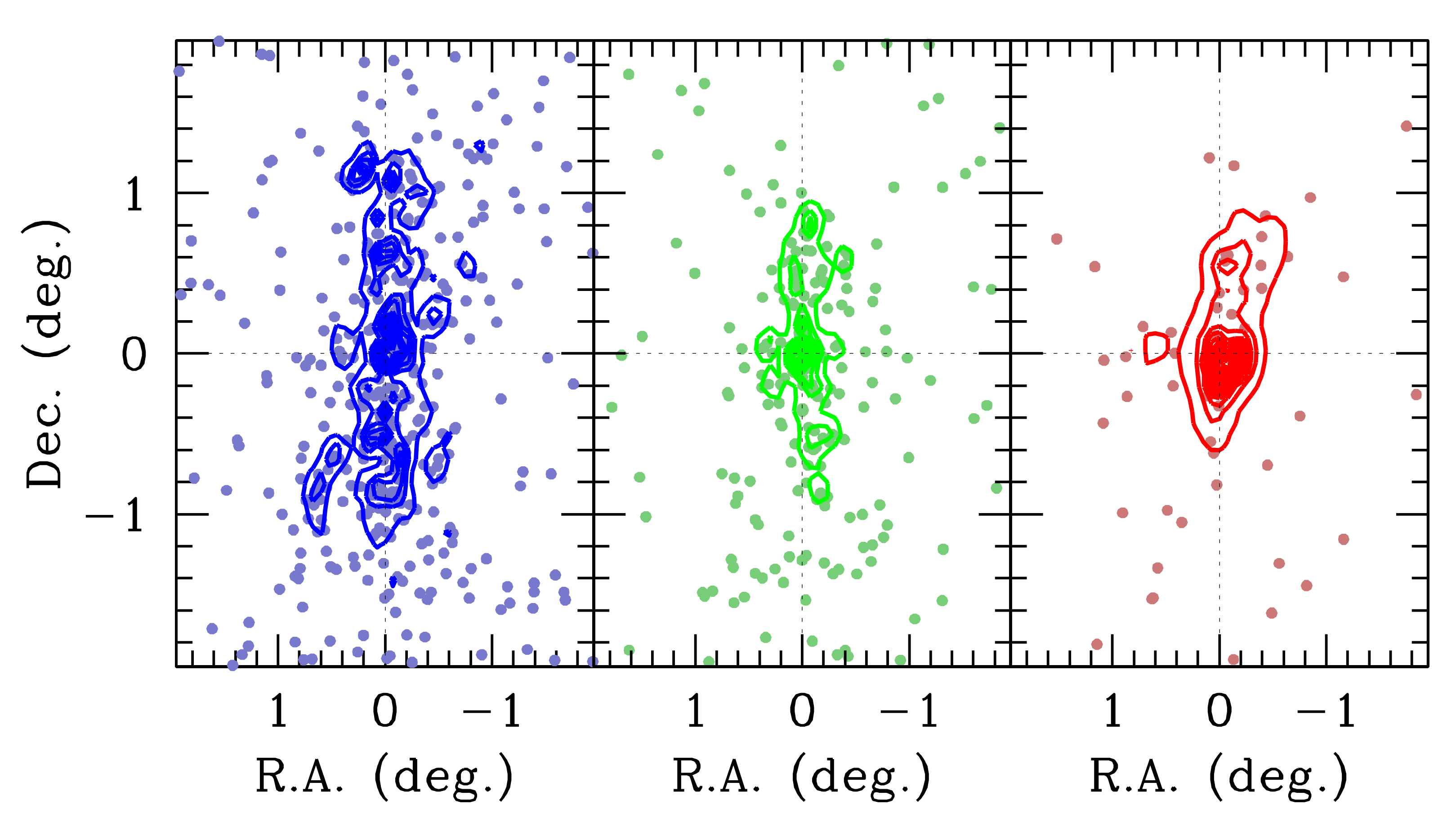
Comparing dust and gas properties in two regions with an order of magnitude difference in the incident UV radiation.

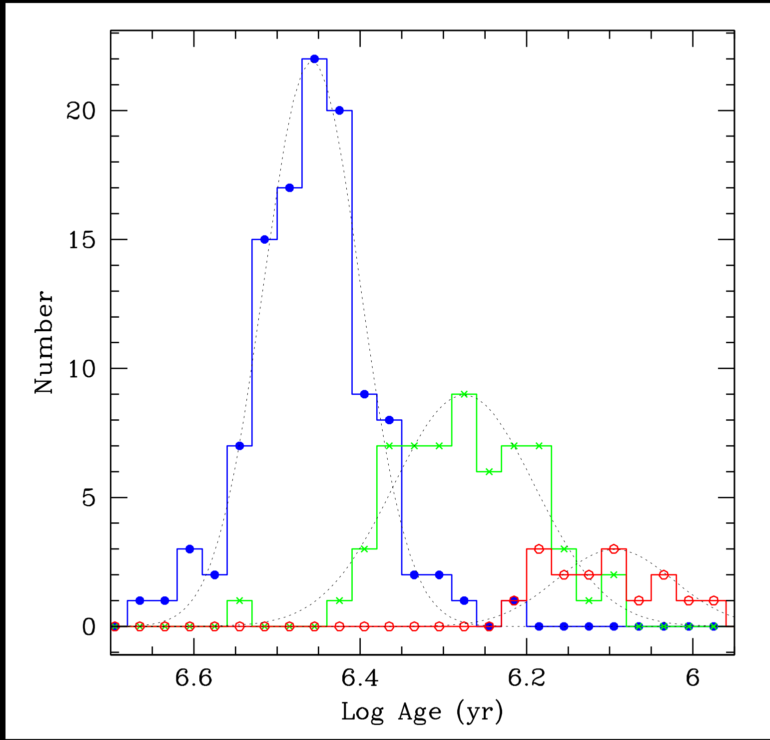


Rebolledo et al. 2020

Orion as a case study:

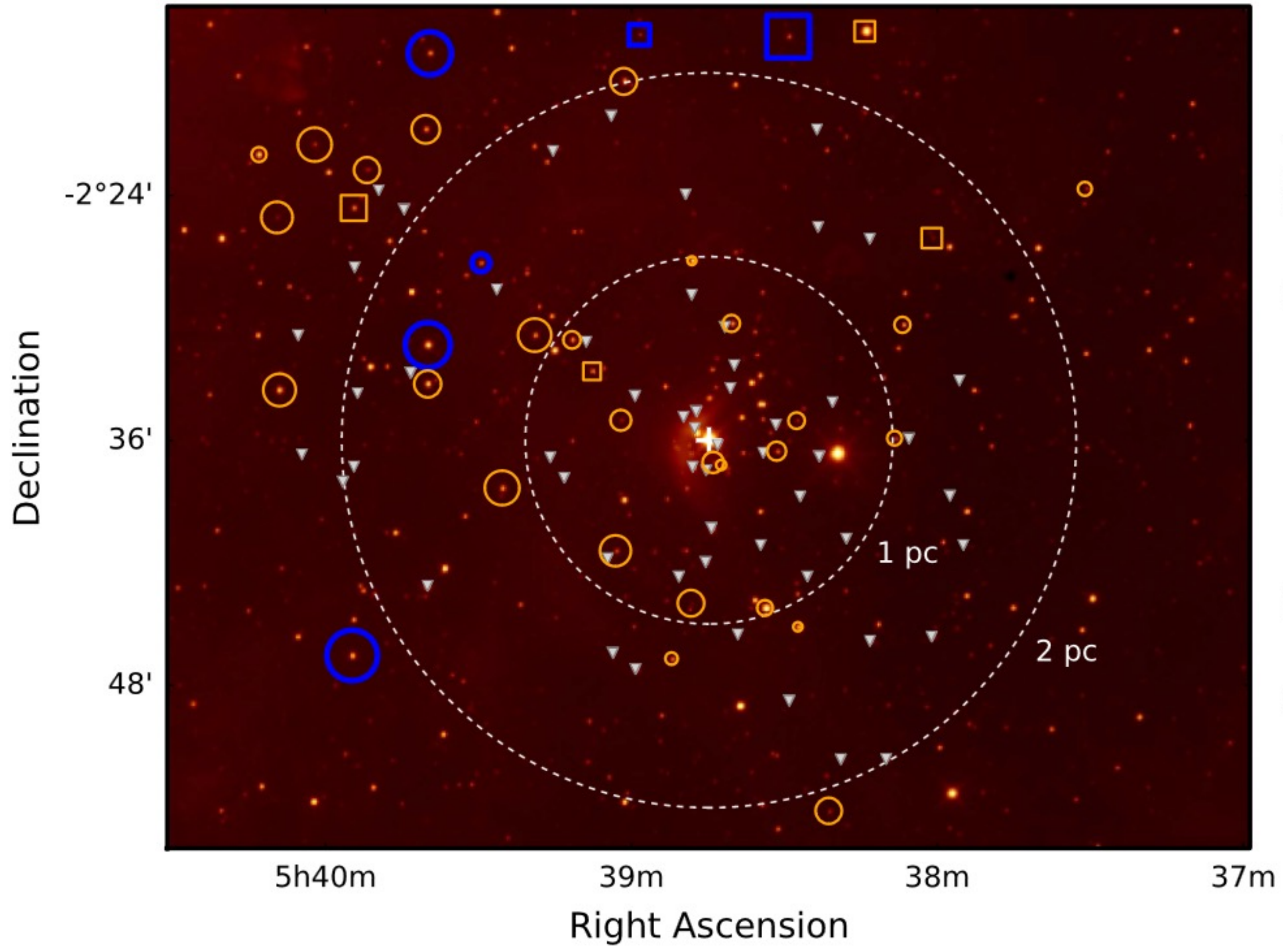
three pre-main-sequences tracing three populations of different ages?

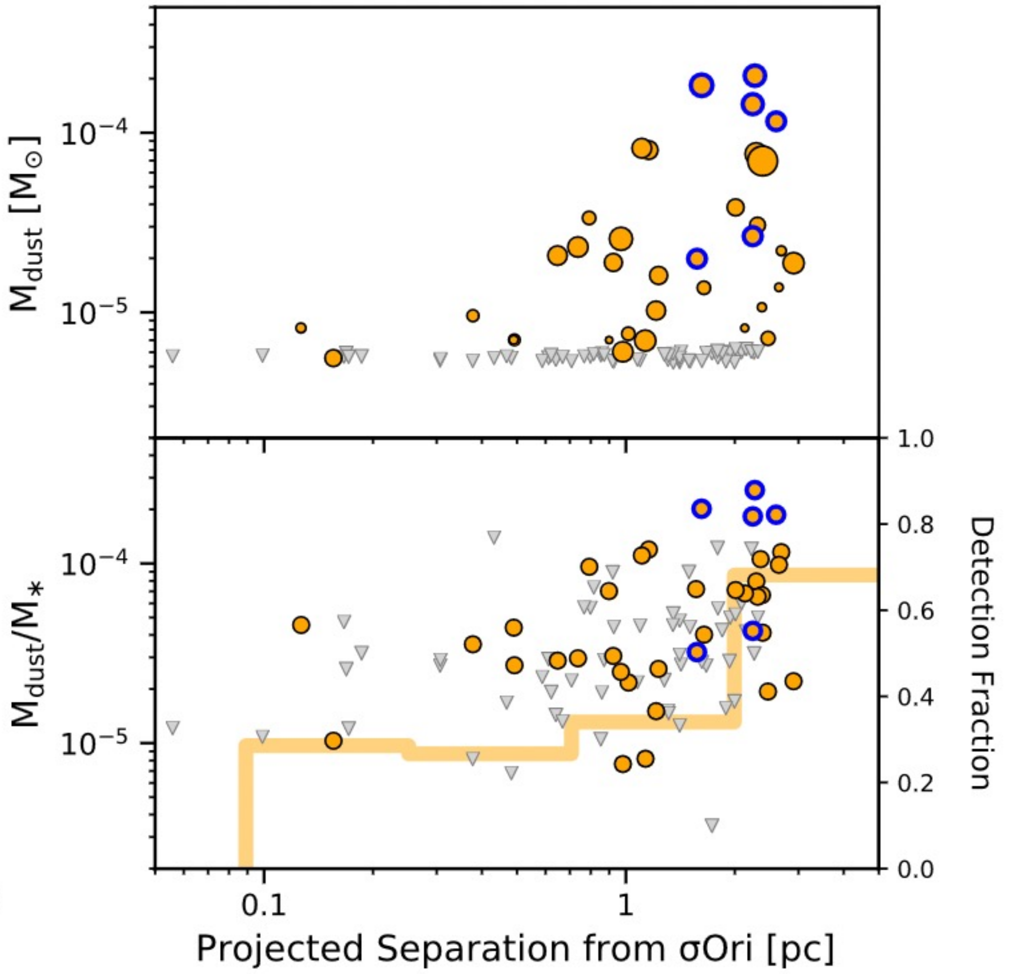




Beccari et al. (2017)

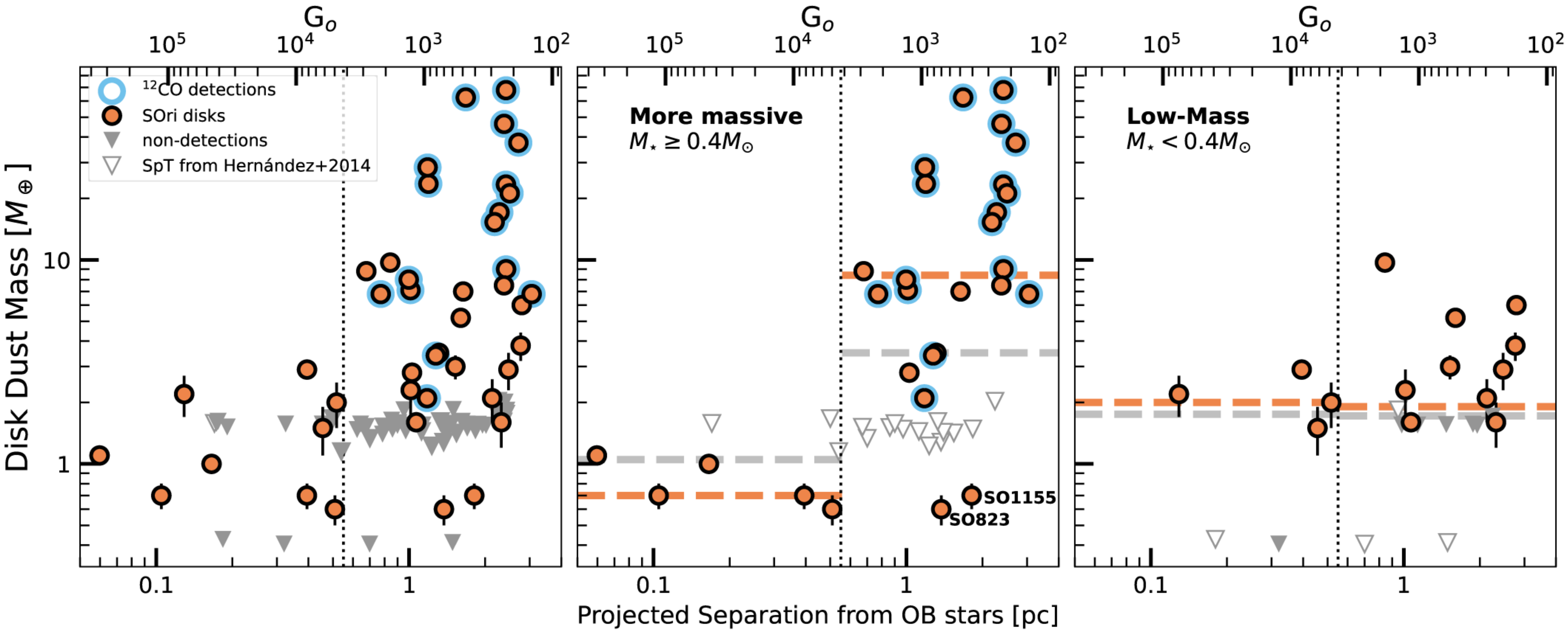
The mass and size of protoplanetary disks in high-mass regions are smaller than in nearby quiescent regions.





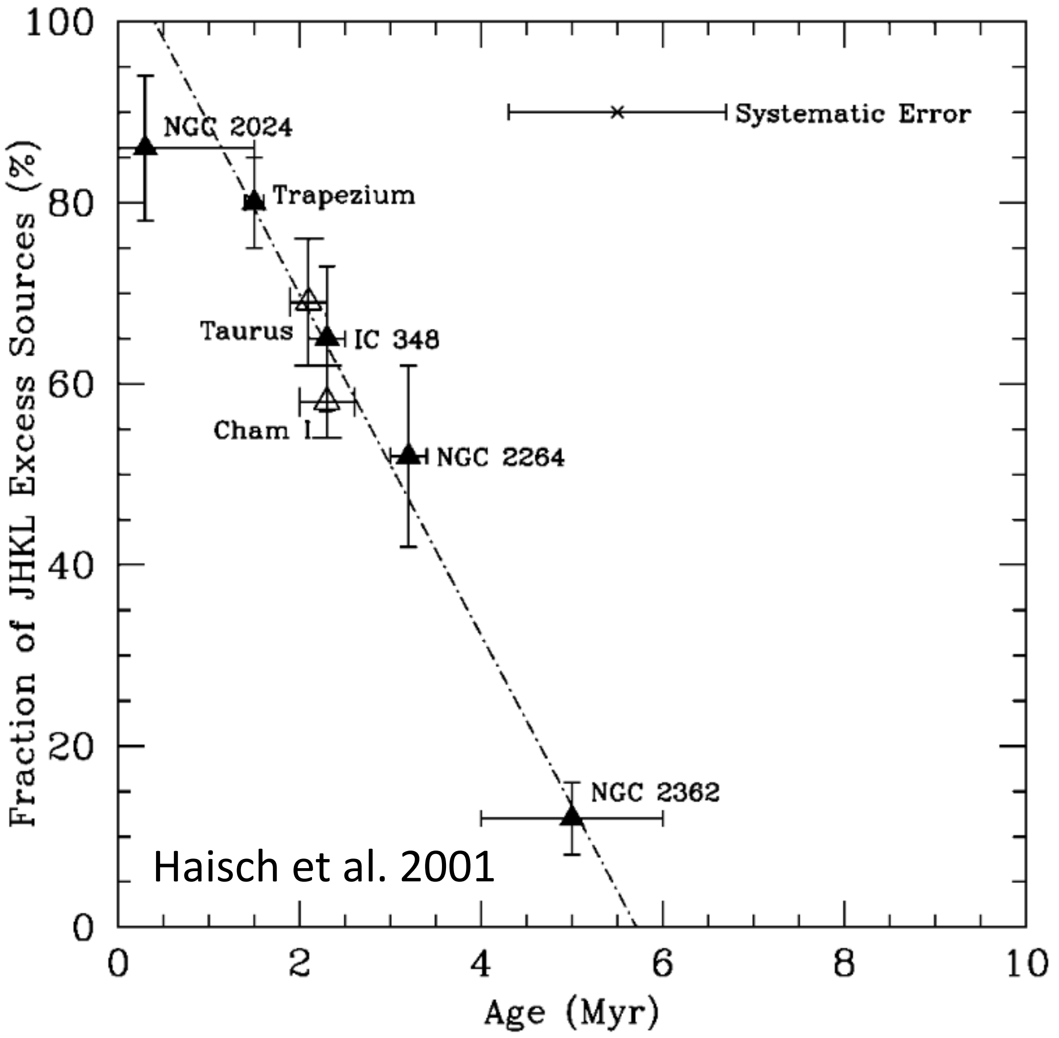
Ansdell et al. (2017)

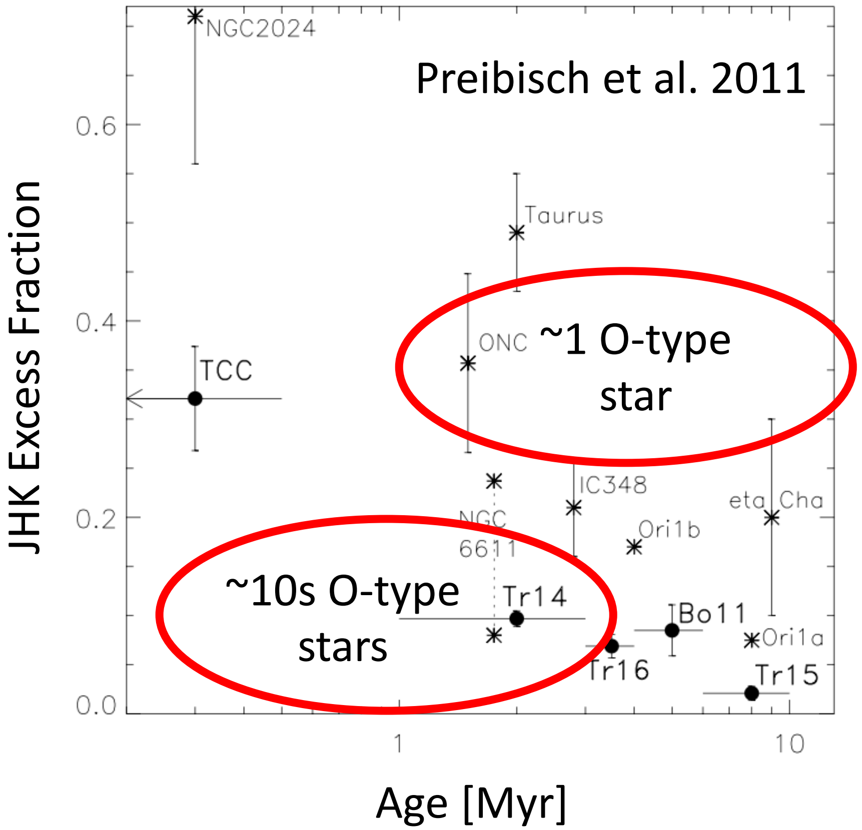
Mass dependence of external photoevaporation is not behaving as expected.



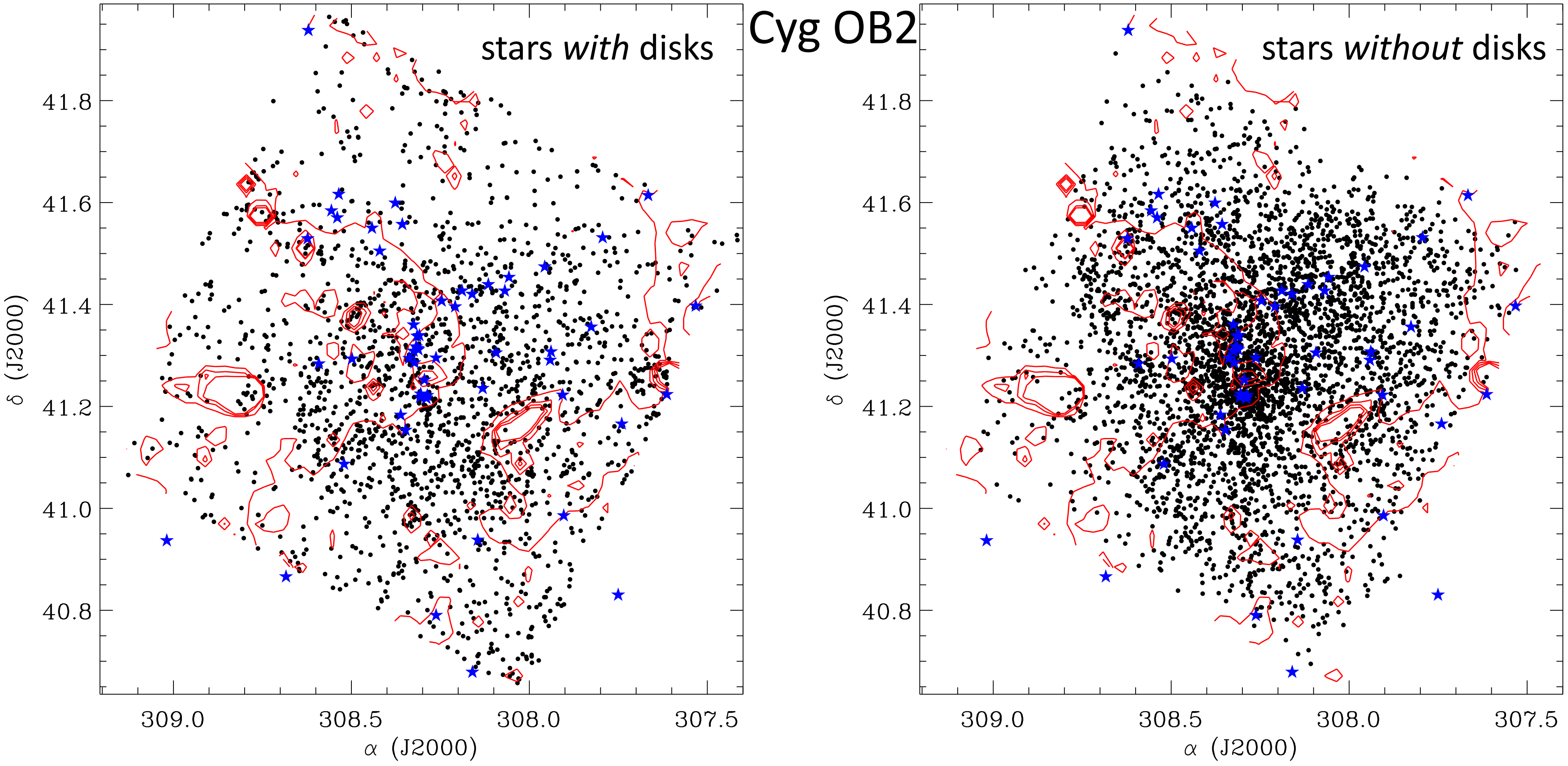
Maucó et al. 2024

Disk lifetimes may be shorter overall in the presence of high-mass stars.





External photoevaporation leaves fewer intact disks near high-mass stars (provided there is not too much dynamical mixing).



Guarcello et al. (2016)

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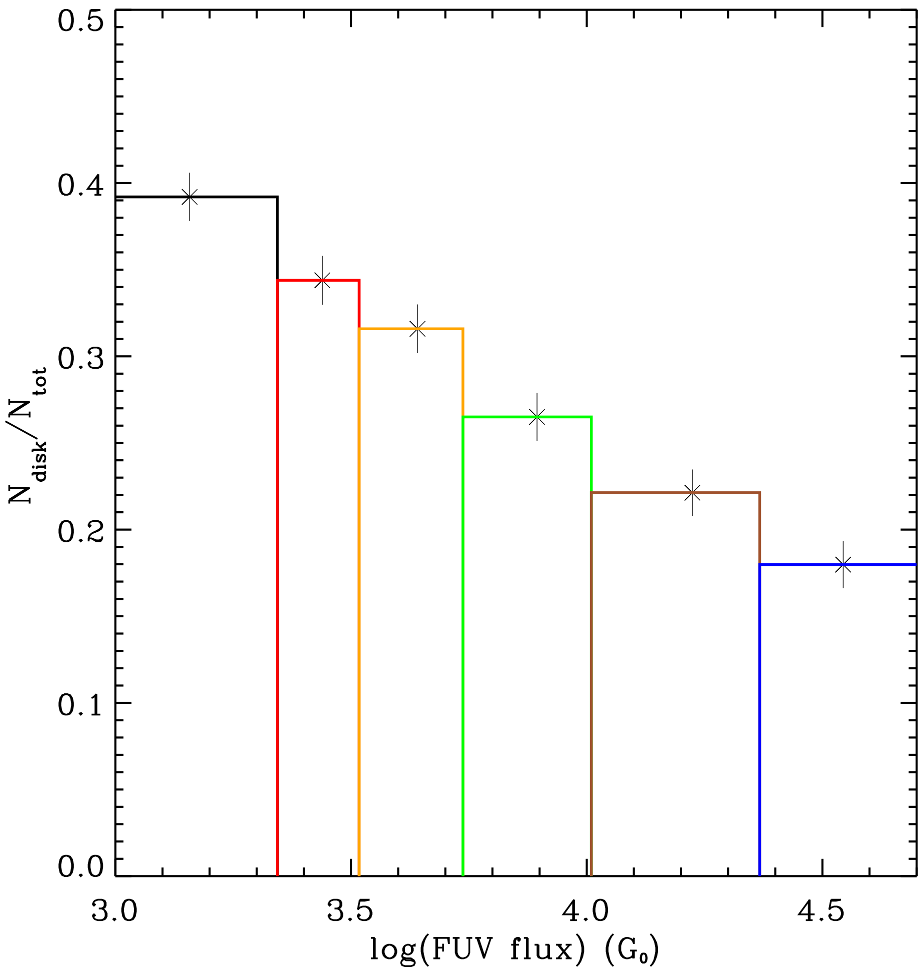
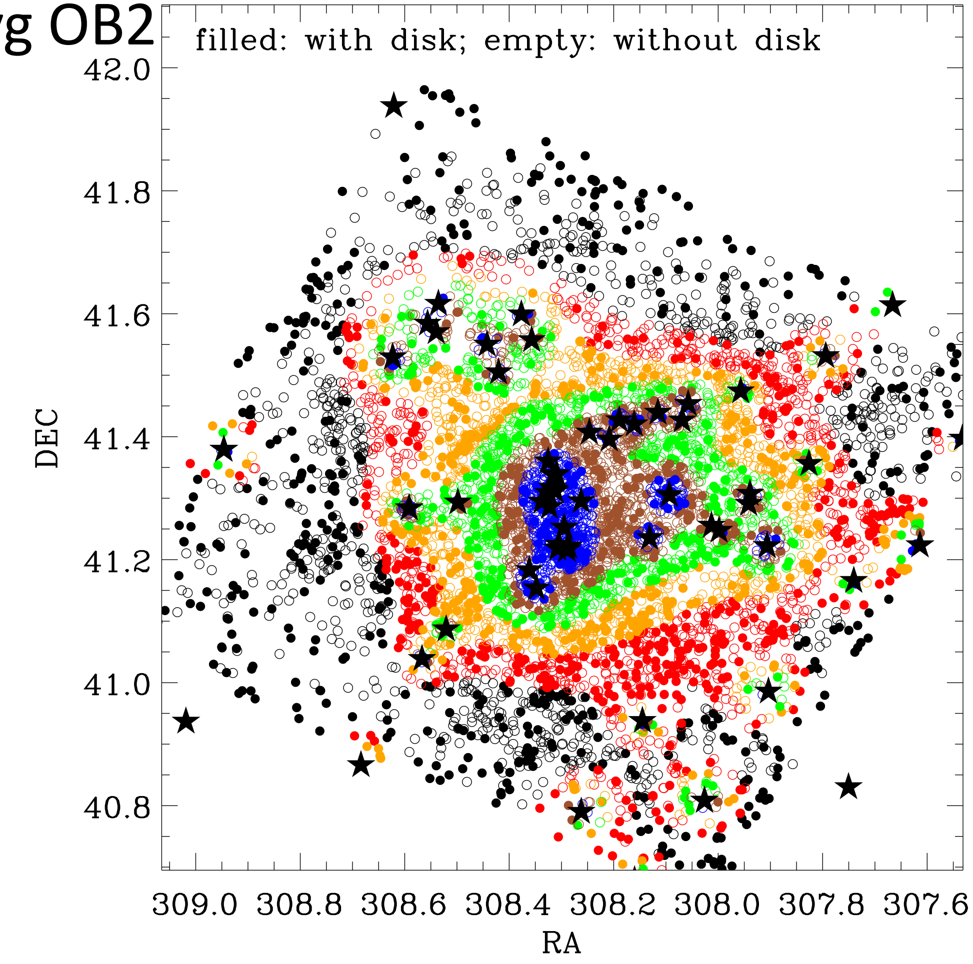
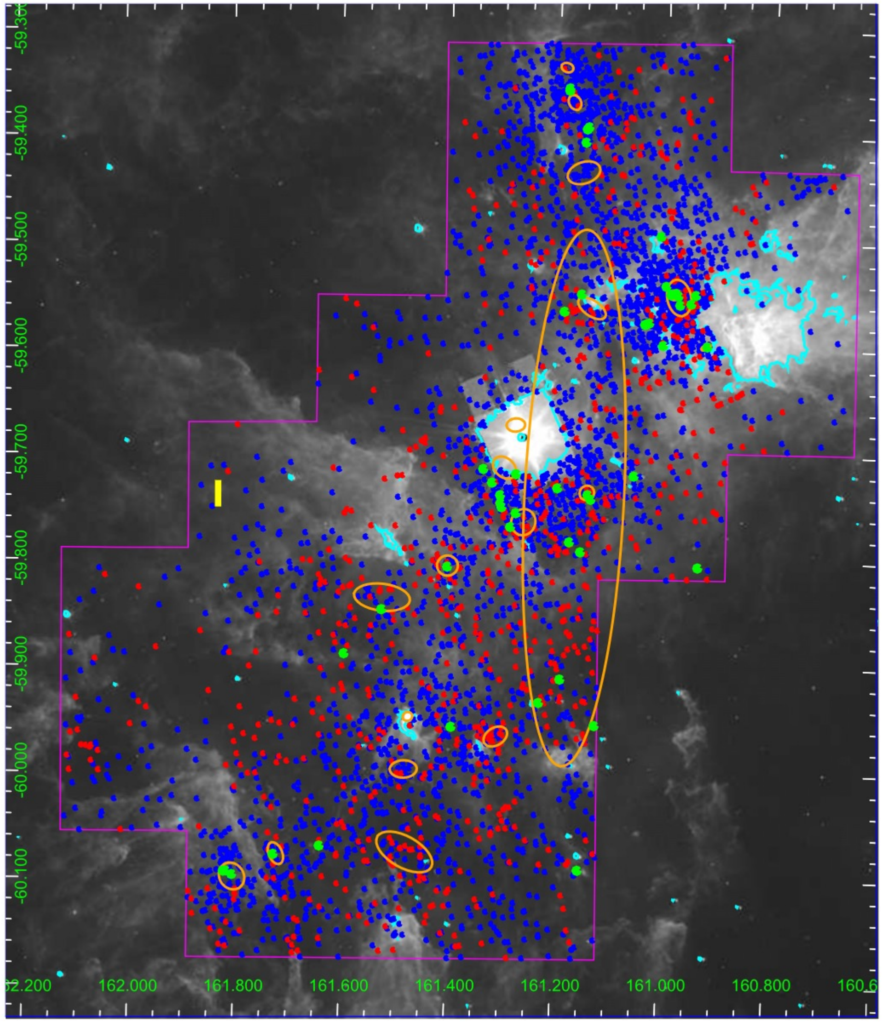


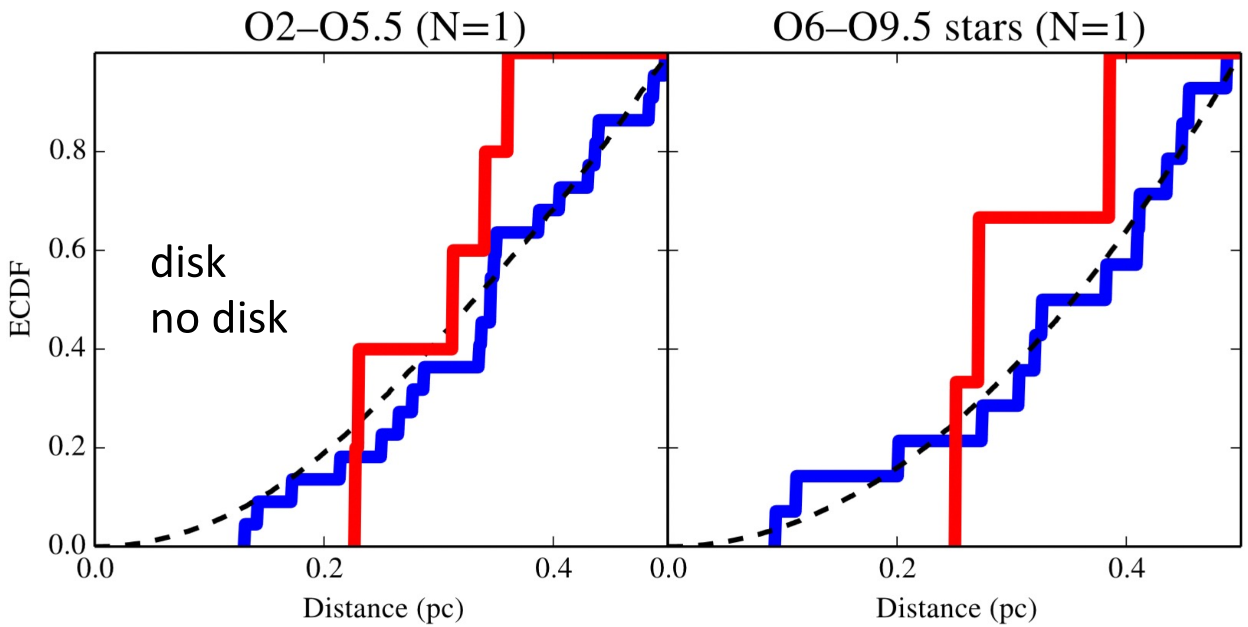
Cyg OB2



Guarcello et al. (2016)

… but not all studies agree that more high-mass stars lead to shorter disk lifetimes.

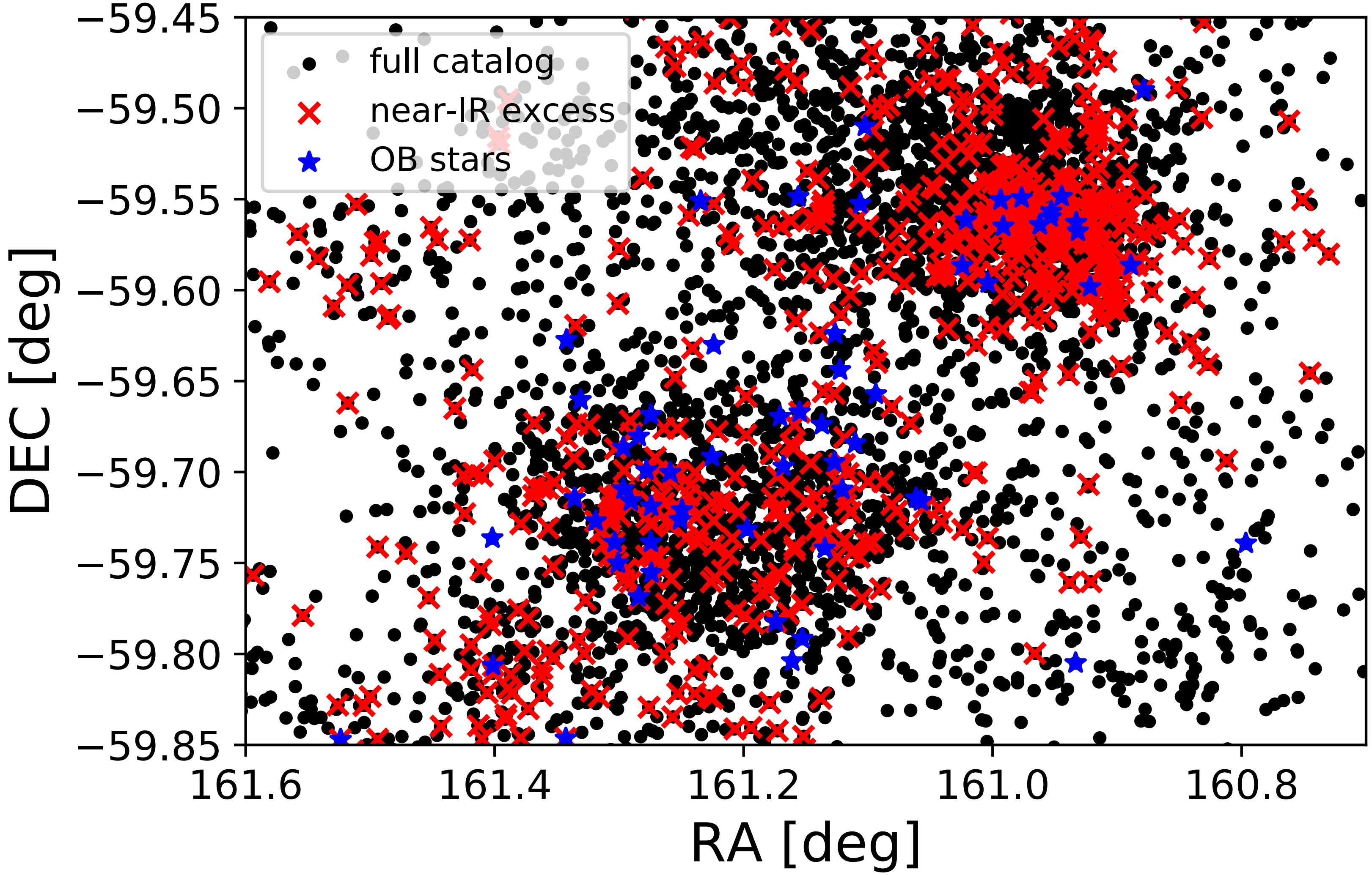




Carina Nebula; Richert et al. (2015)

→ must separate effects of external photoevaporation from stellar mass dependent disk lifetimes!

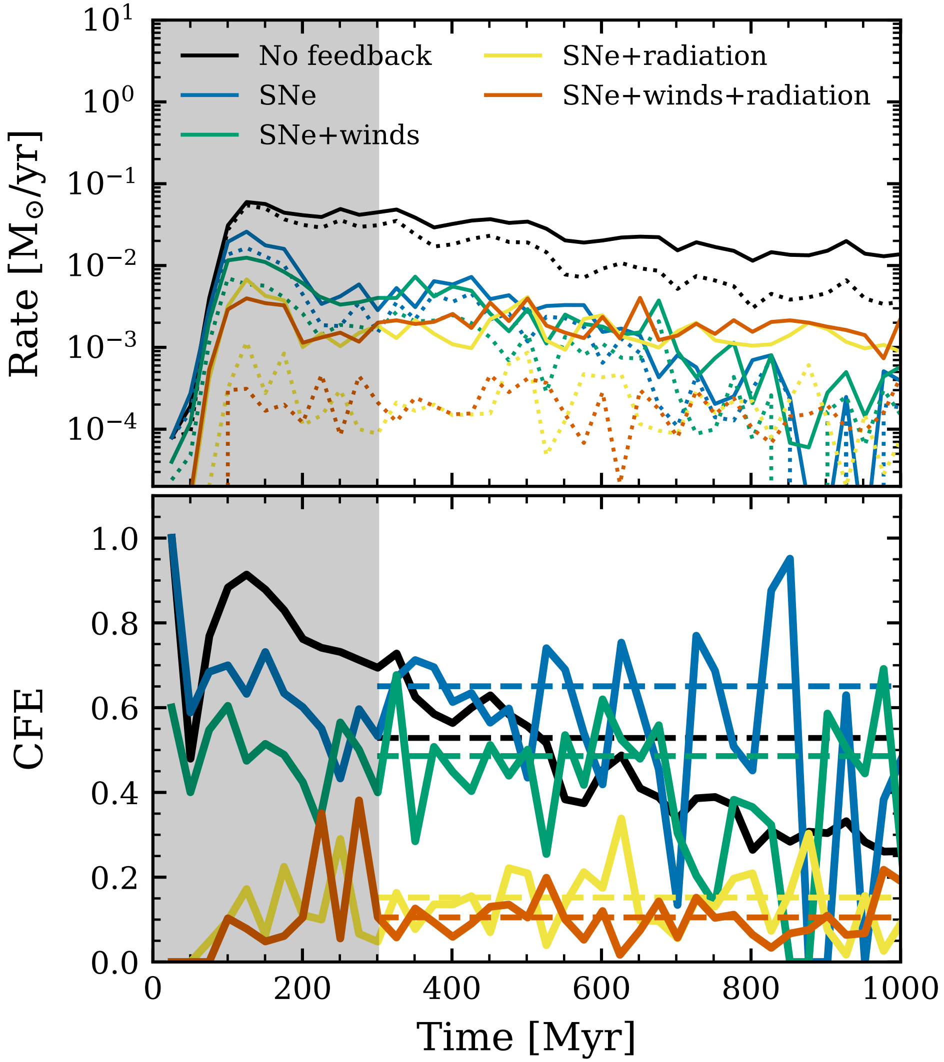
Ongoing dynamical evolution will mix stars with/without disks; unclear what structure to expect for multiple HM stars.



*also note that images provide a 2D projection of a 3D distribution

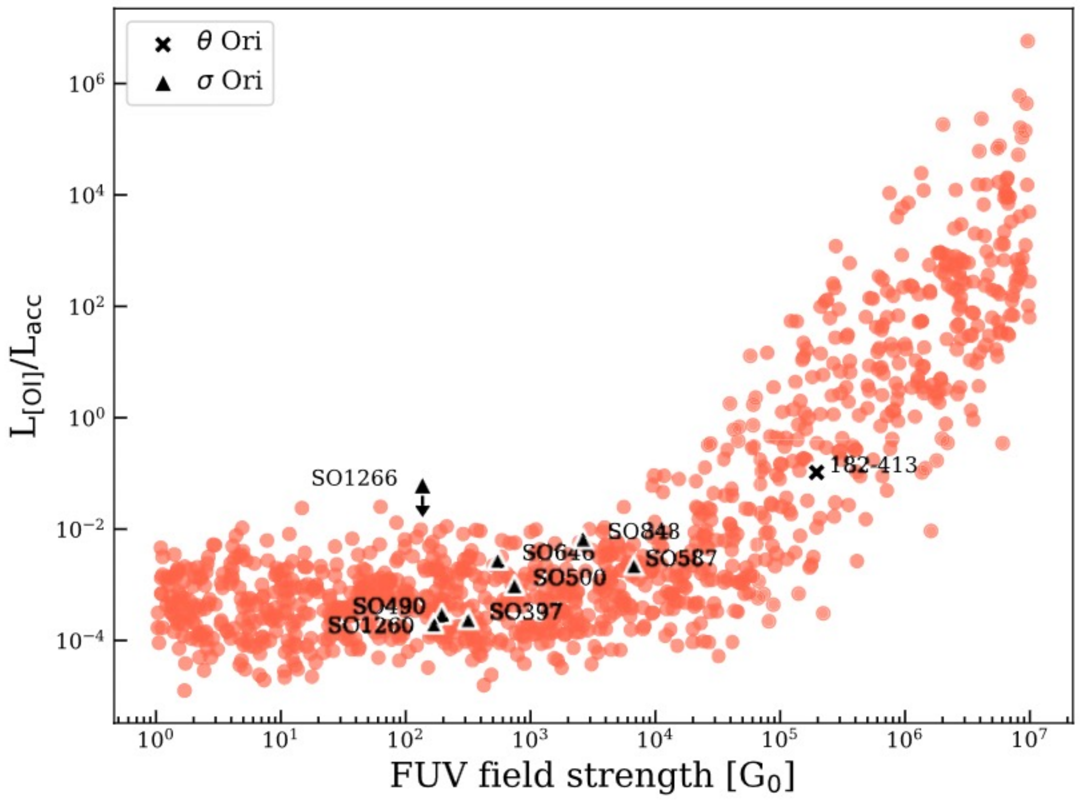
Reiter & Parker (2019) using near-IR data from Preibisch et al. (2011)

Fraction of stars forming in clusters

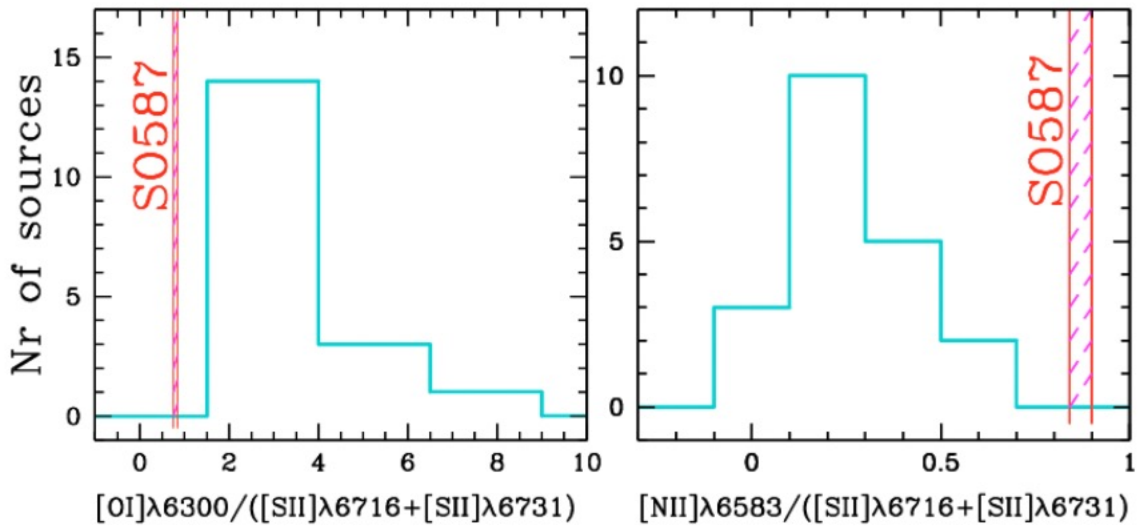


Andersson, E. P., et al.: A&A 681, A28 (2024)

3. Where do we go from here with other tracers of external photoevaporation?

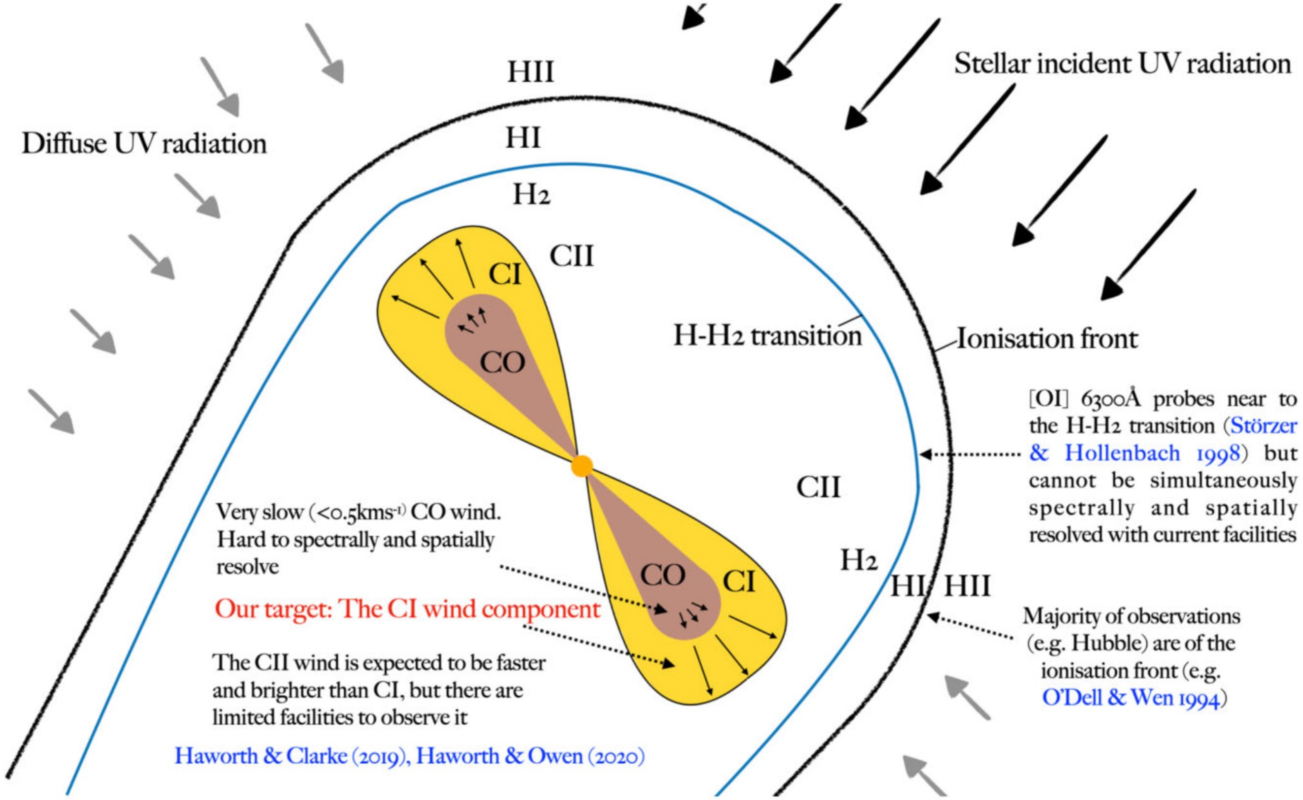


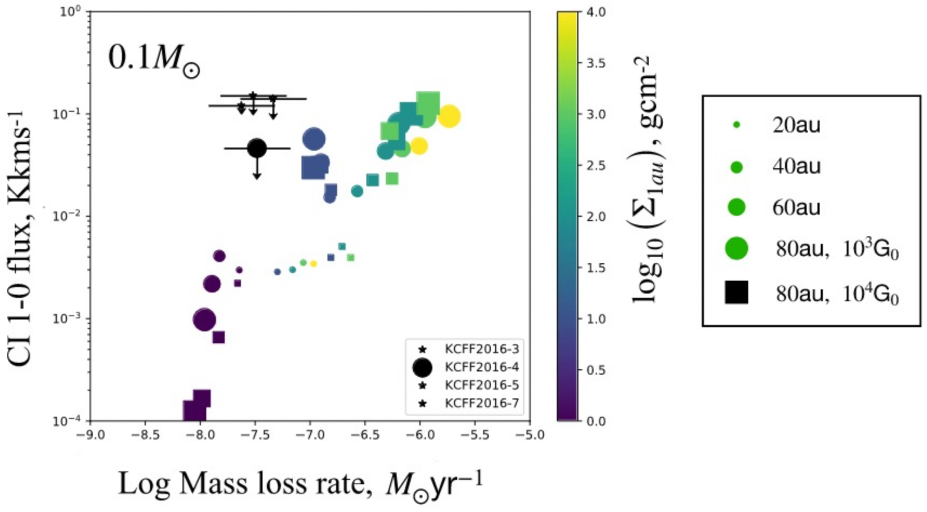
Ballabio et al. (2023)



Rigliaco et al. (2009)

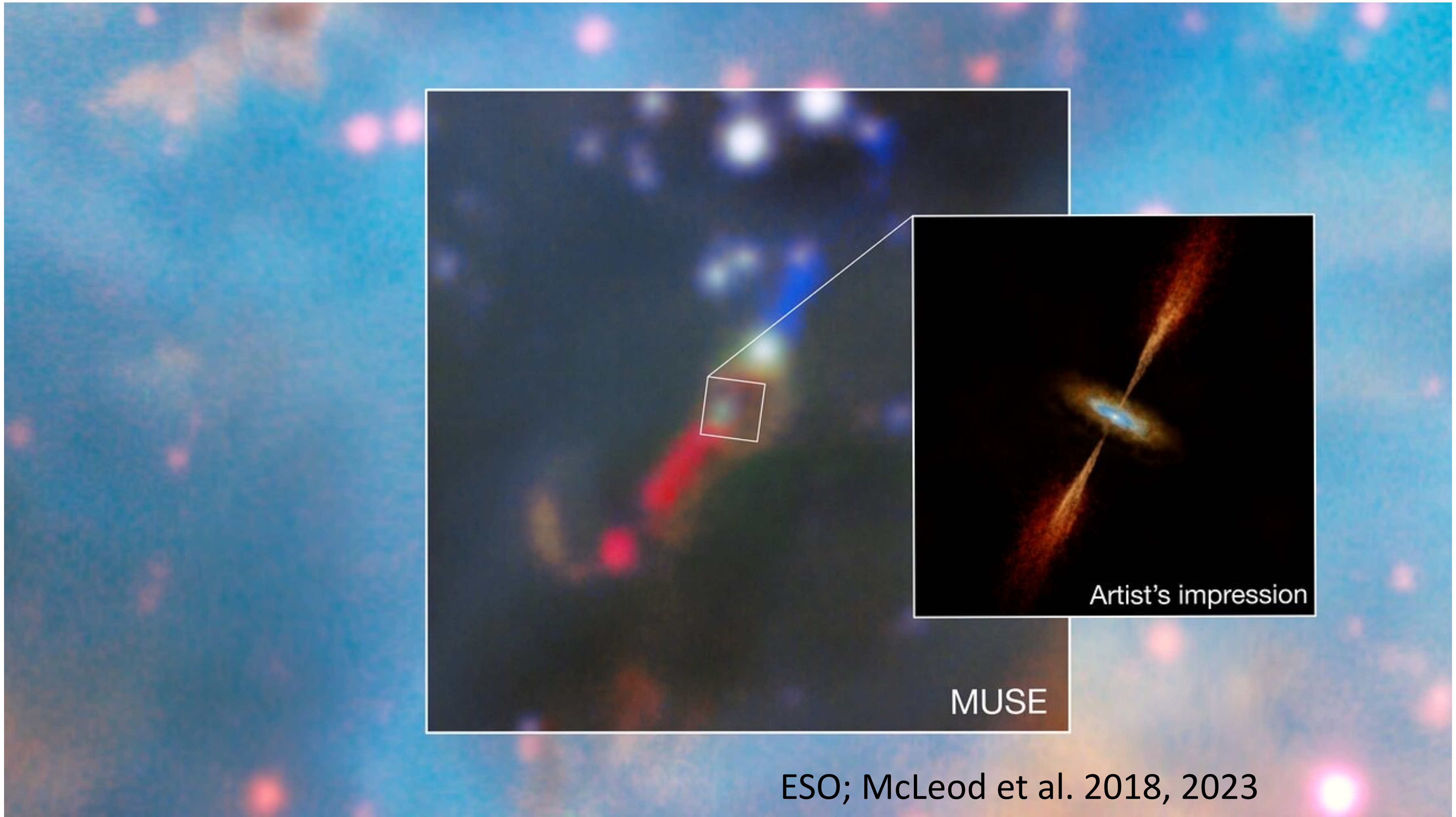
CI may be an excellent tracer of the photoevaporative flow for more modest UV fields… if detected.





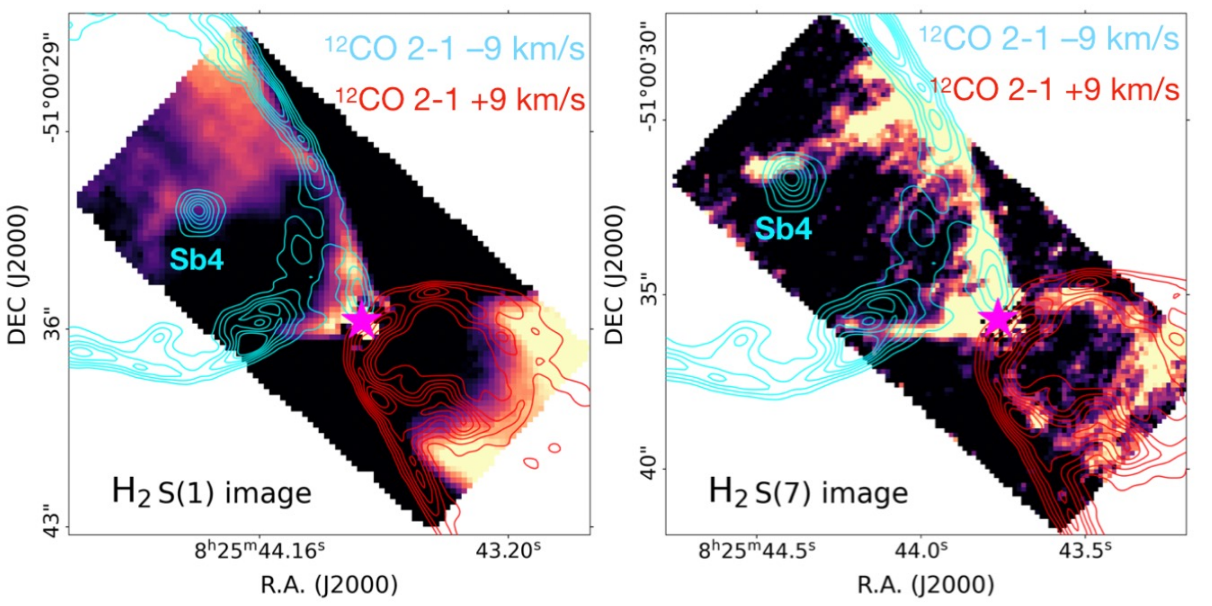
Haworth et al. (2022)

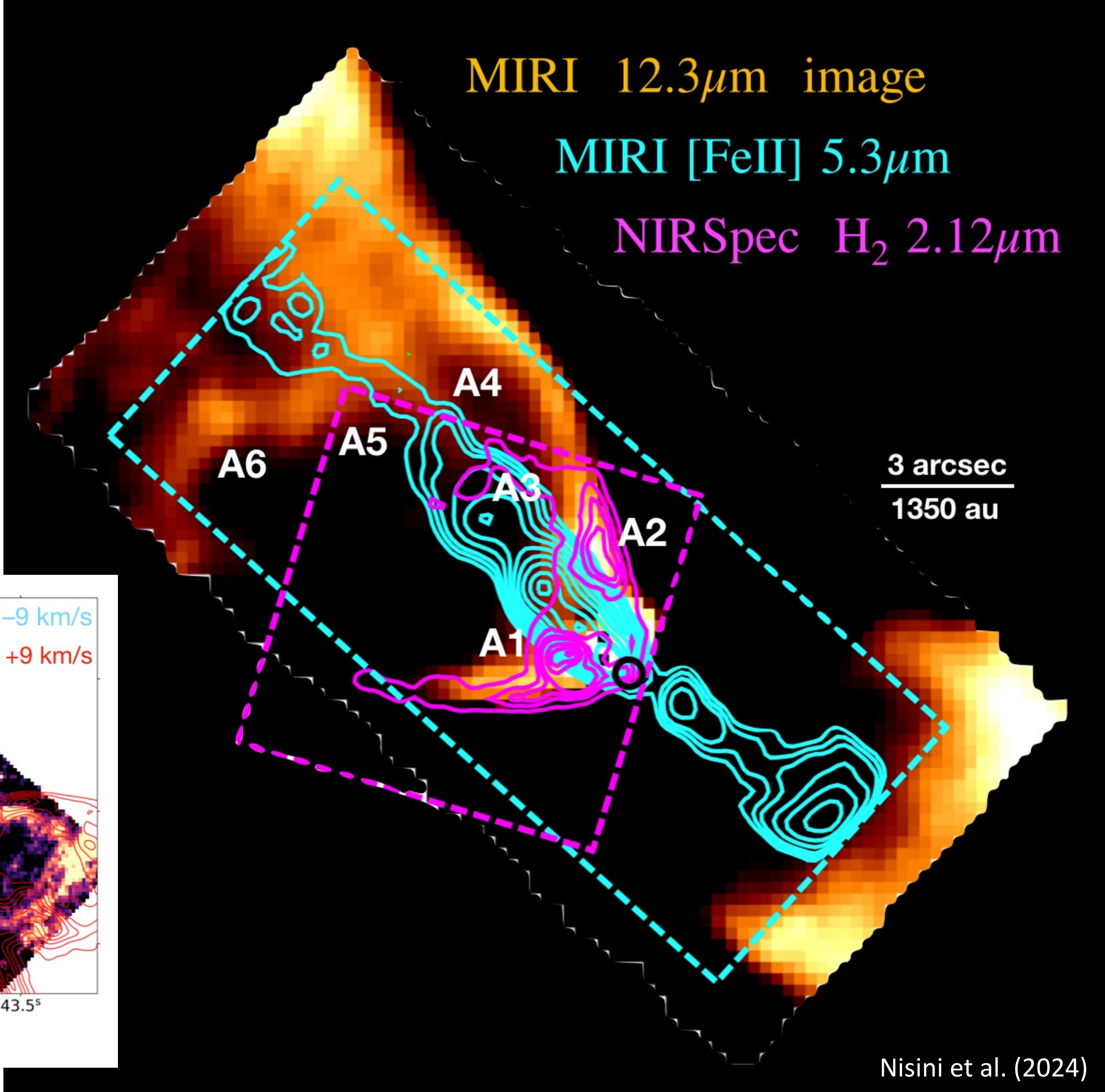
Few jets and outflows seen at low metallicity (but see Anna McLeod’s talk). … for now.



ESO; McLeod et al. 2018, 2023

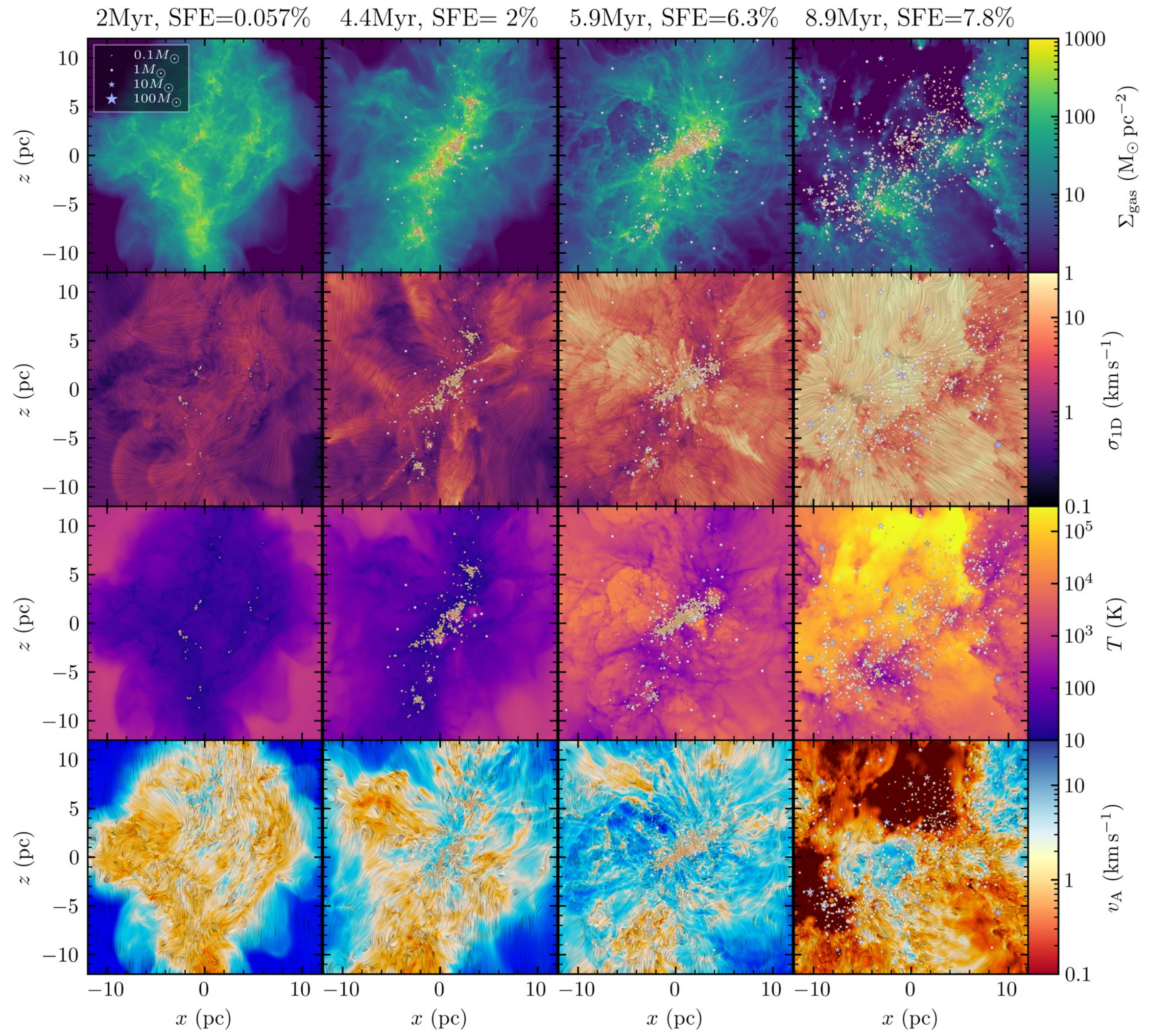
Project-J: resolving multiple outflows from multiple stars in HH 46/47.

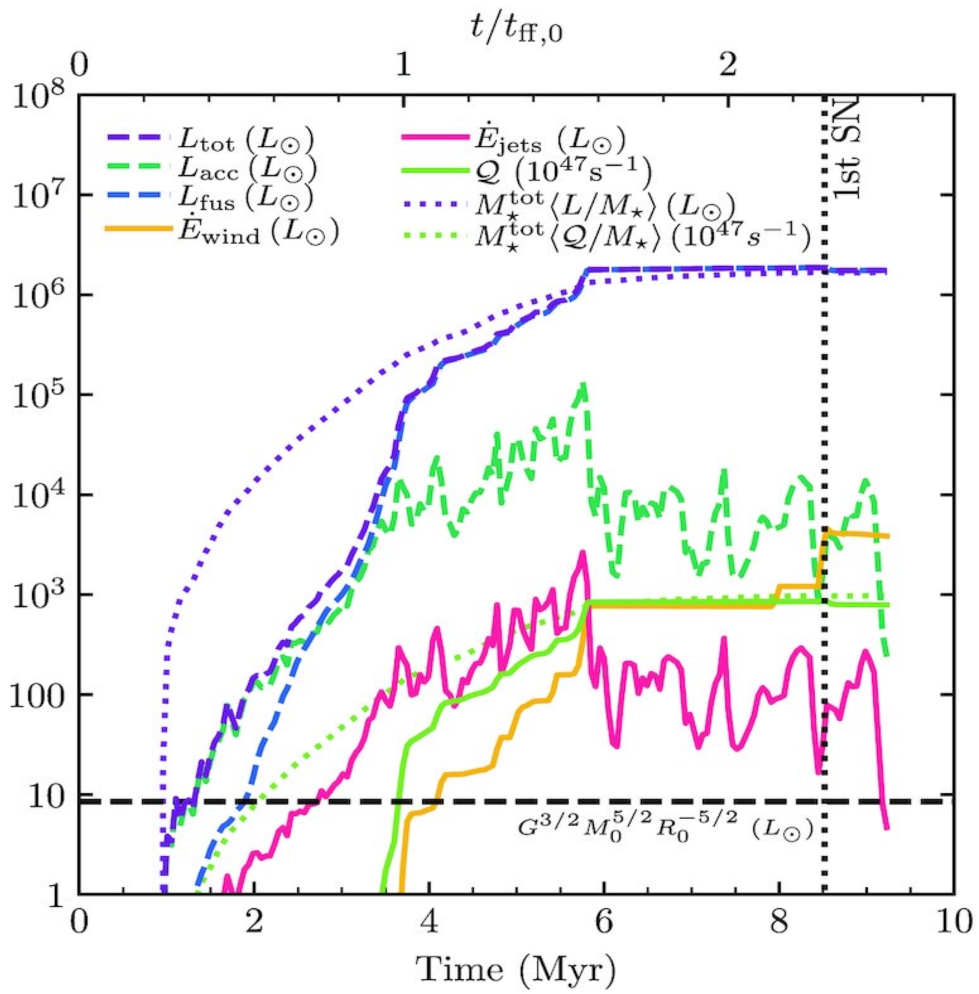




Nisini et al. (2024)

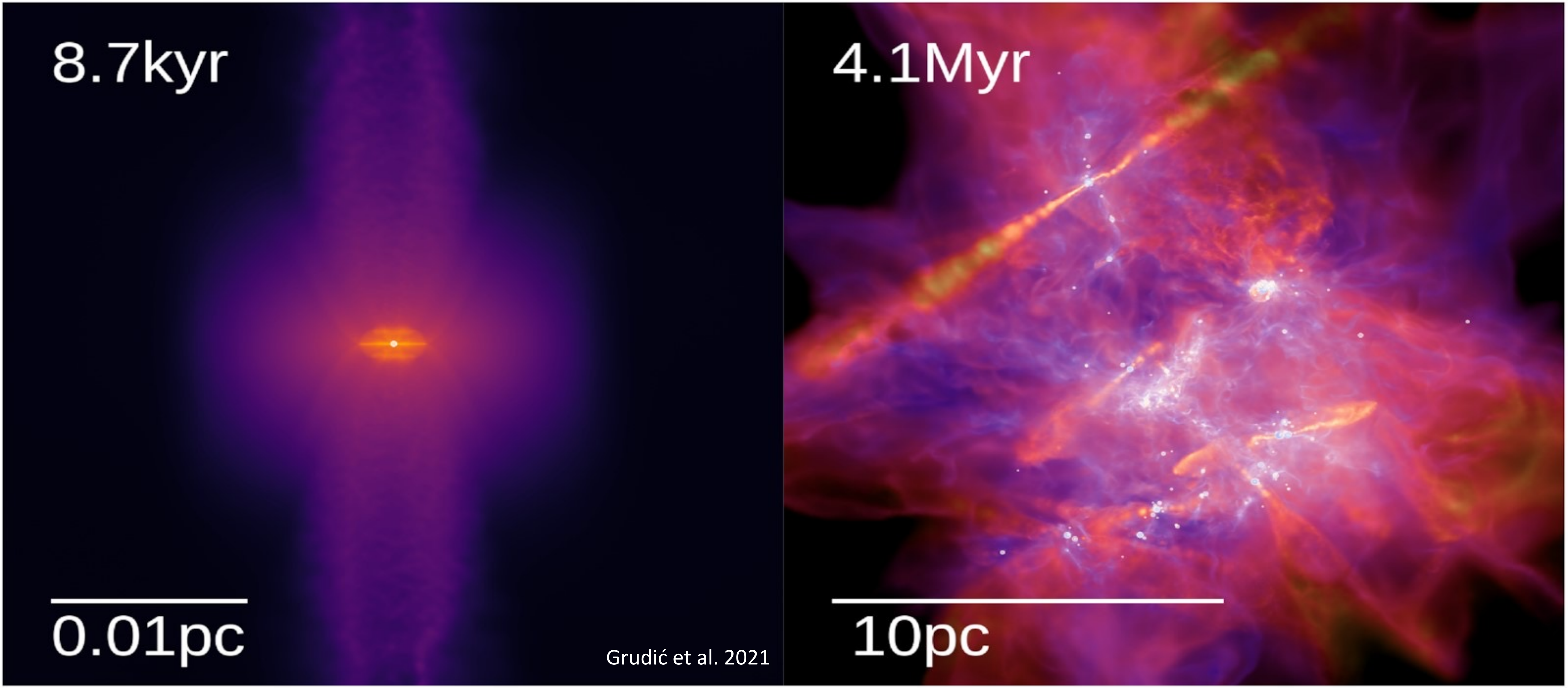
High resolution simulations that include all relevant forms of feedback: outflows, radiation, winds, SNe.





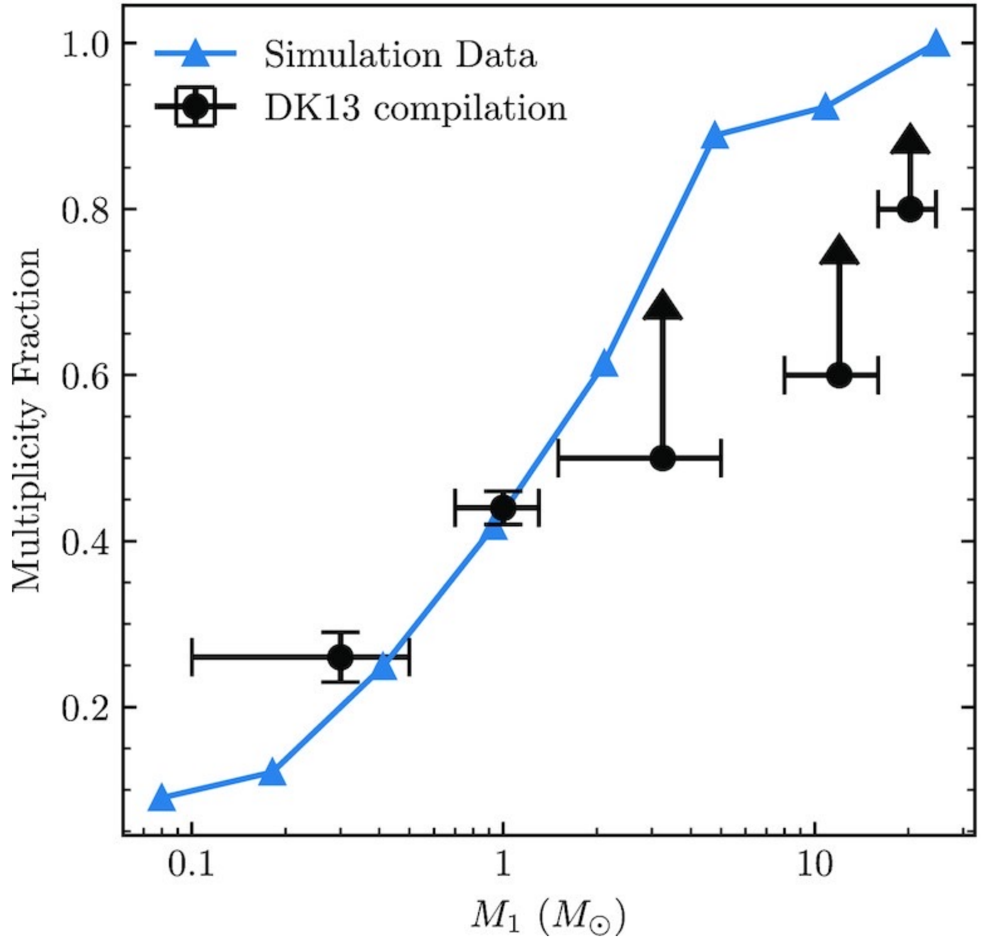
Grudíc et al. 2022

Outflows in STARFORGE



Grudić et al. 2021

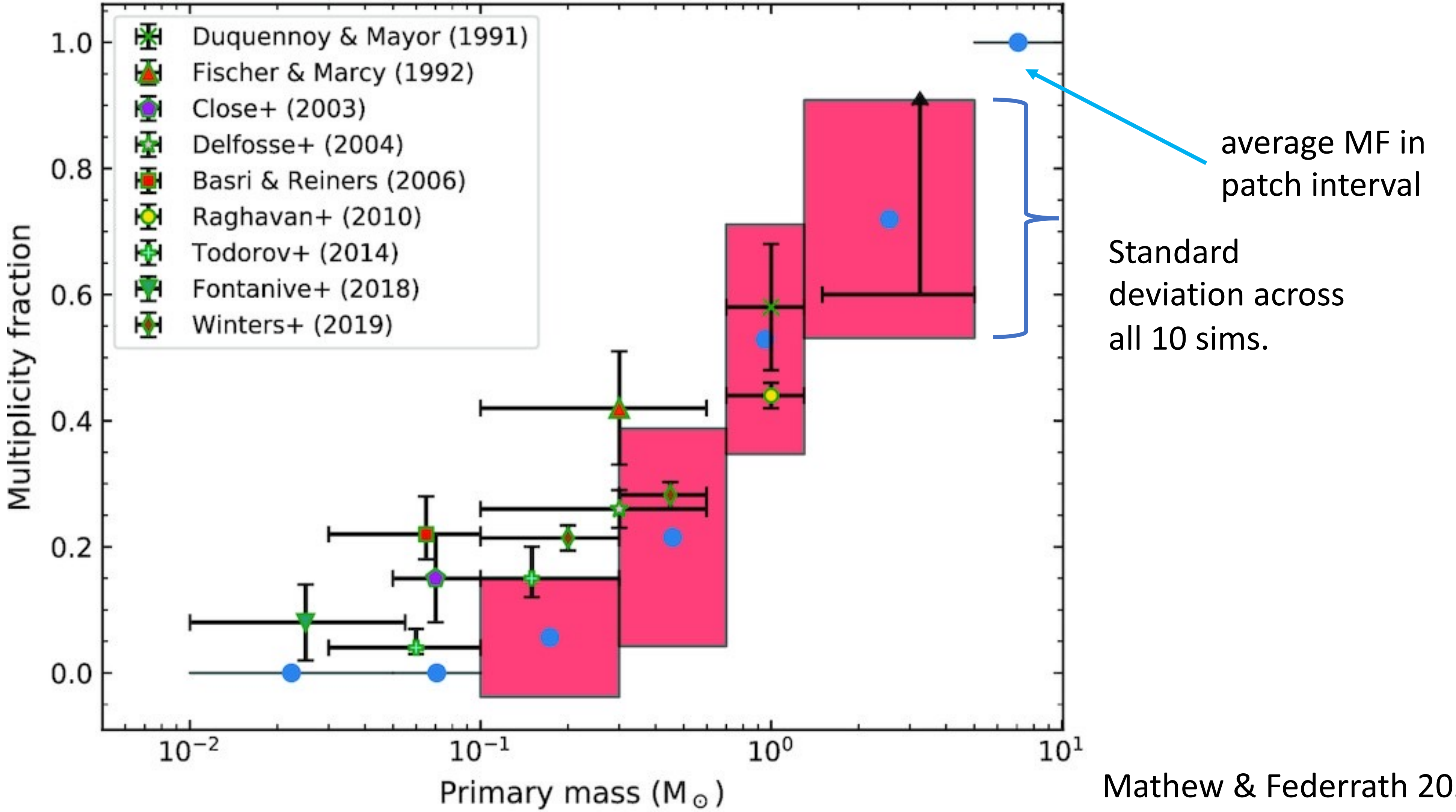
Multiplicity in STARFORGE under-predicts multiples probably because disk fragmentation not included.



→ posters: P16 Shanghuo Li

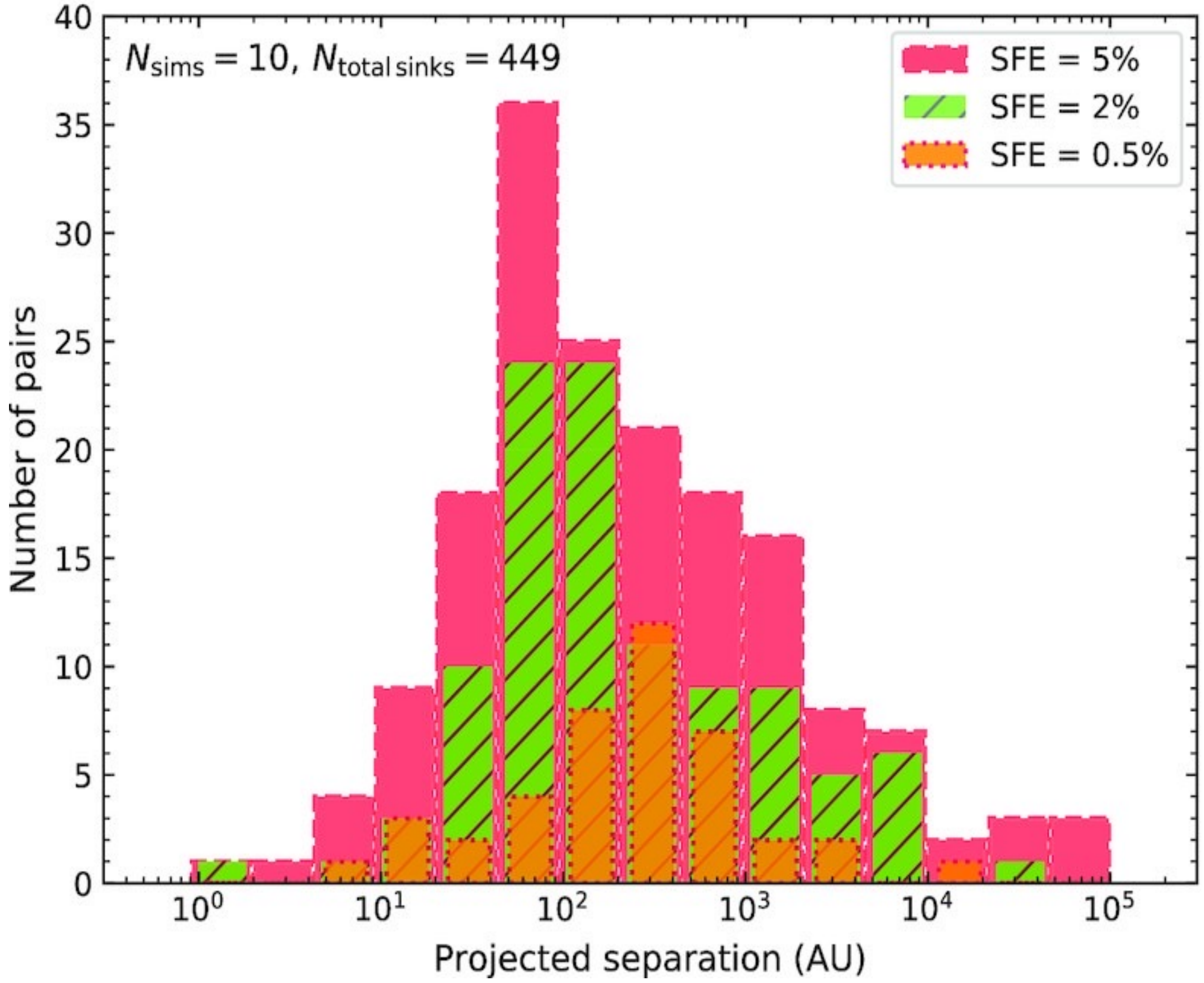
Grudić et al. 2022

Broad agreement in 3D MHD simulations that include gravity, turbulence, magnetic fields, stellar radiative heating, and outflows.



Mathew & Federrath 2021

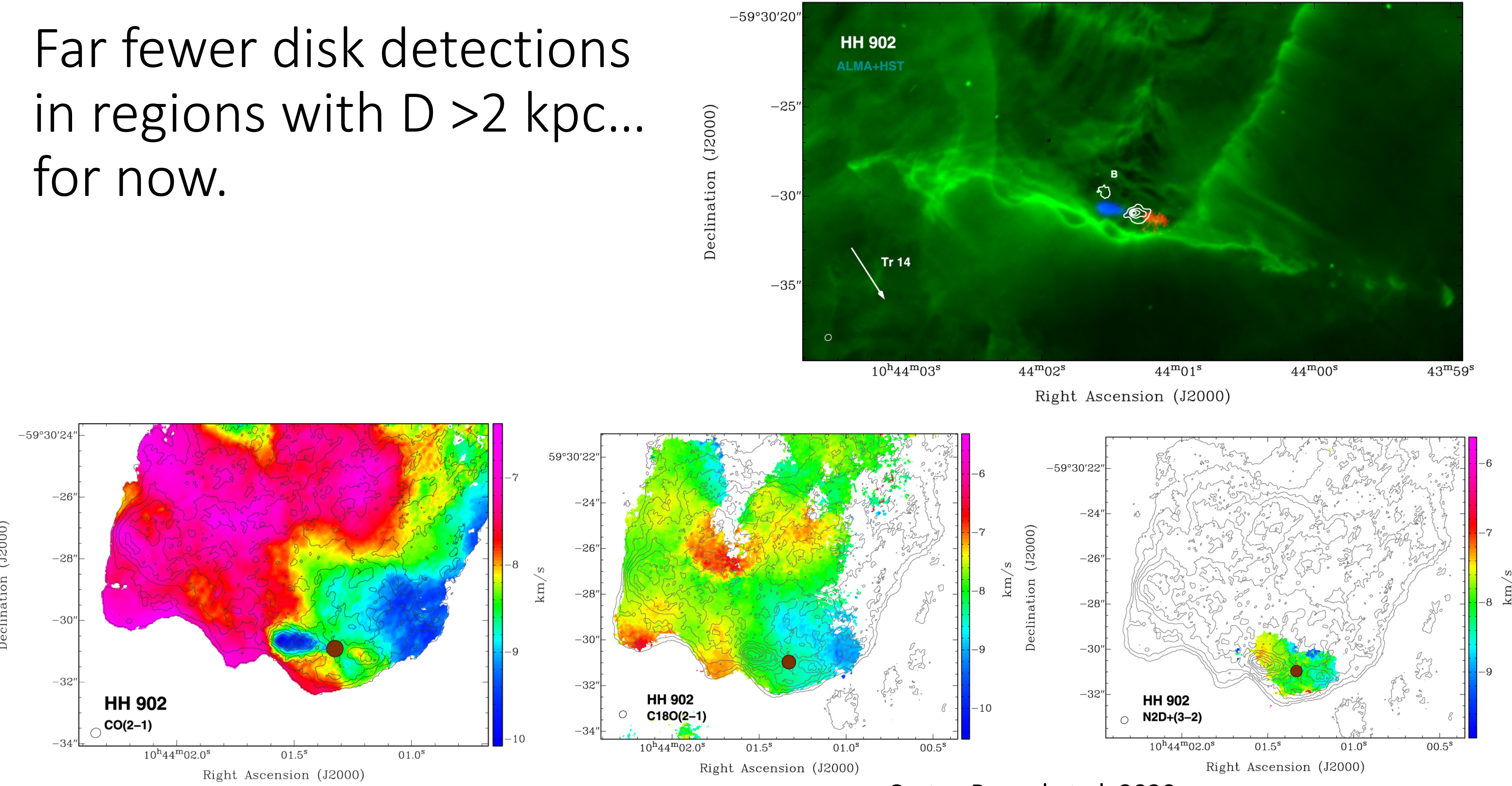
Projected separation-from-primary distribution in 10 simulations including outflow feedback.



Mathew & Federrath 2021

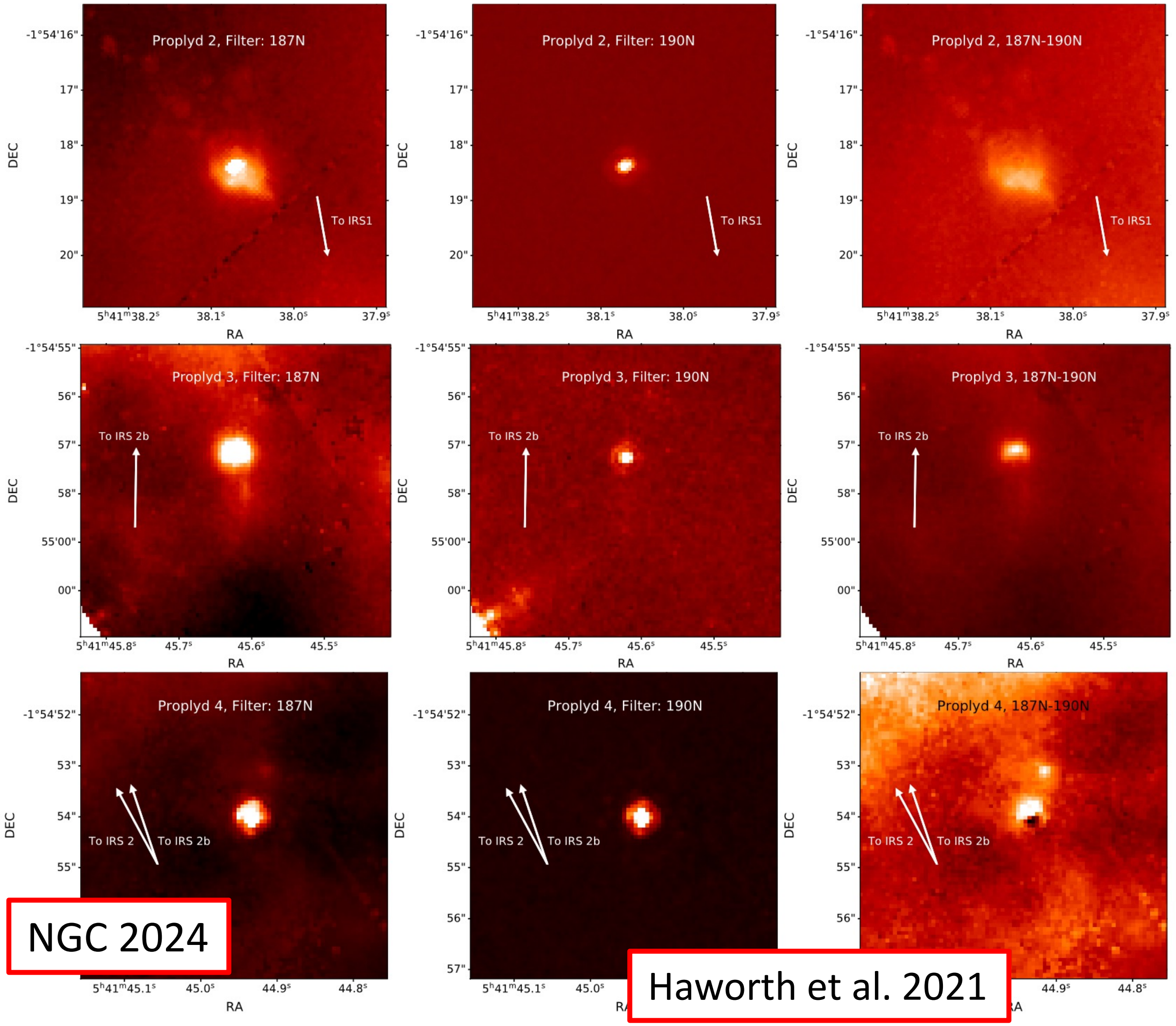
The inner Orion Nebula seen with JWST
PDRs4All
Towards Trapezium cluster
Young star with disk inside its cocoon
Cocoon
Disk
Orbit of Neptune
Young star inside globule
Orion Bar
θ² Orionis A
Filaments
Credits : NASA / ESA / CSA / PDRs4All team S. Fuenmayor

Far fewer disk detections in regions with D >2 kpc… for now.



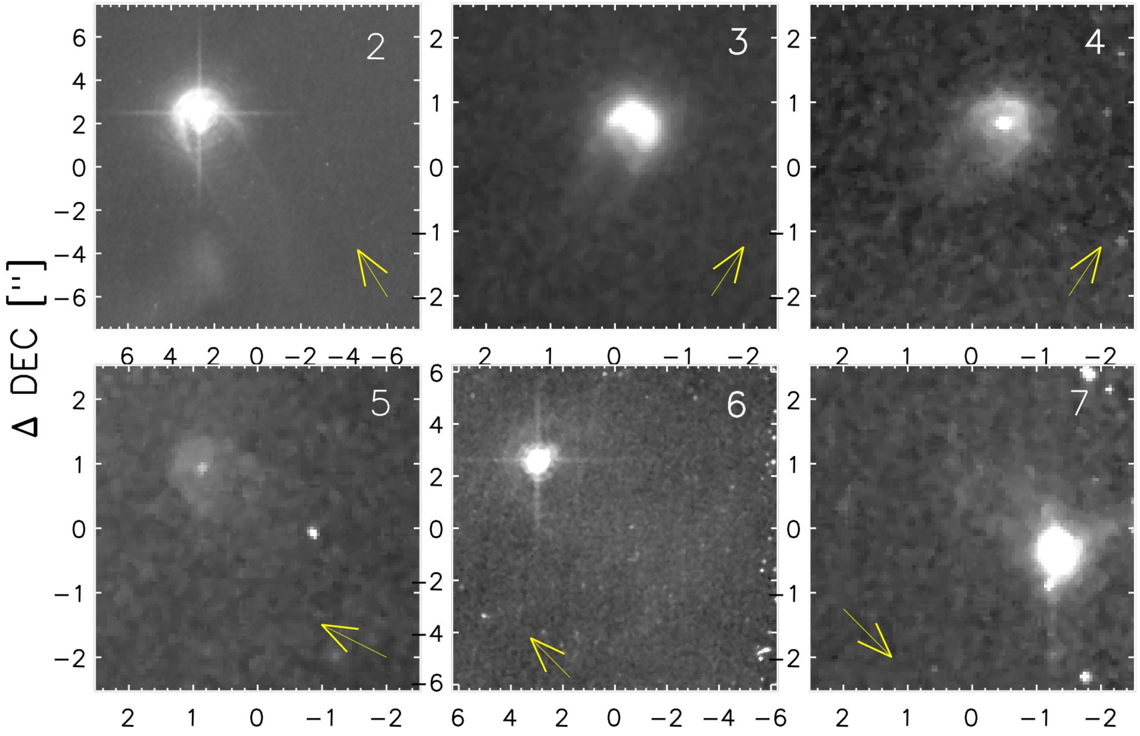
Cortes-Rangel et al. 2020

Proplyds most often been observed in hydrogen recombination lines like Hα and Pa-α that trace the i-front



NGC 2024

Haworth et al. 2021

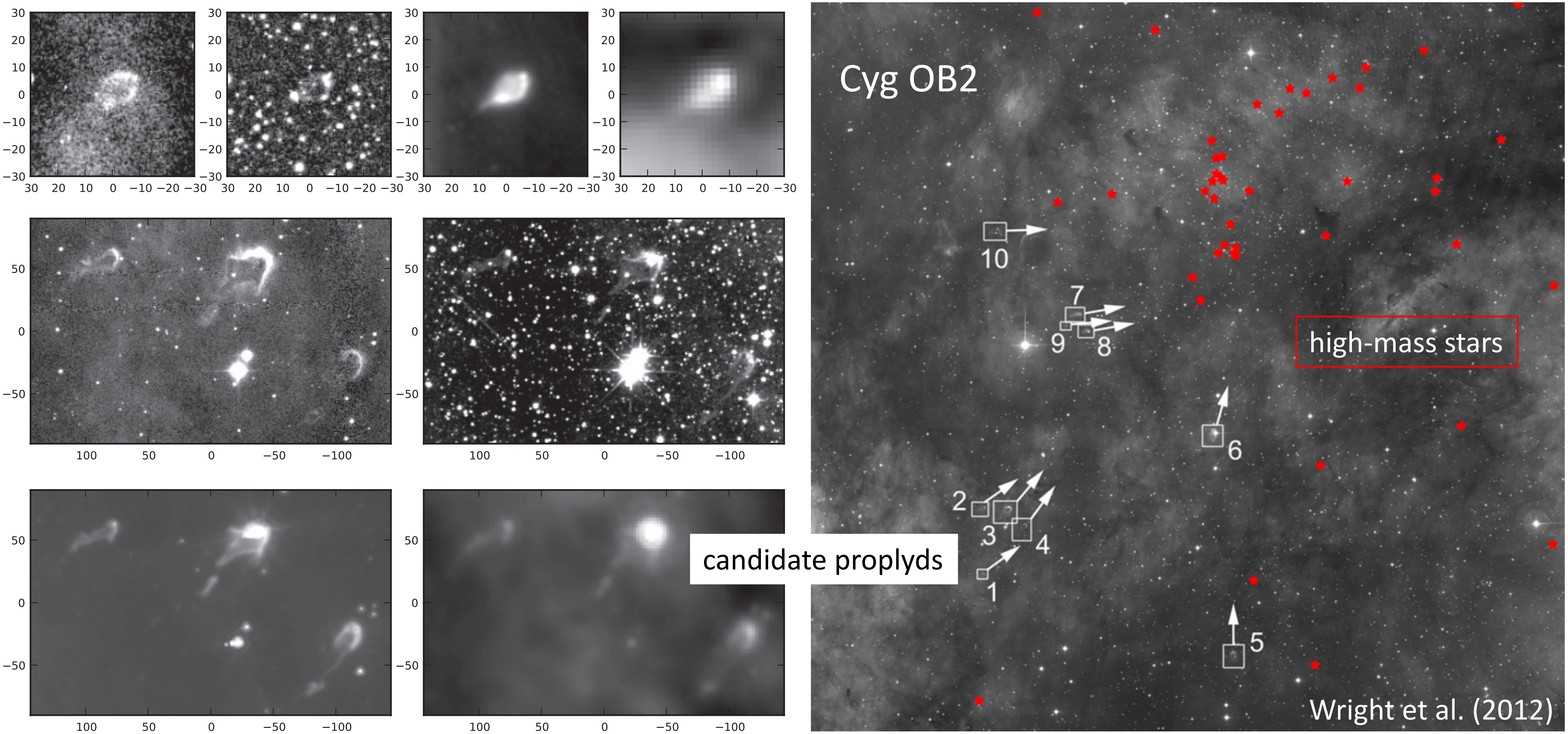


Kim et al. (2016)

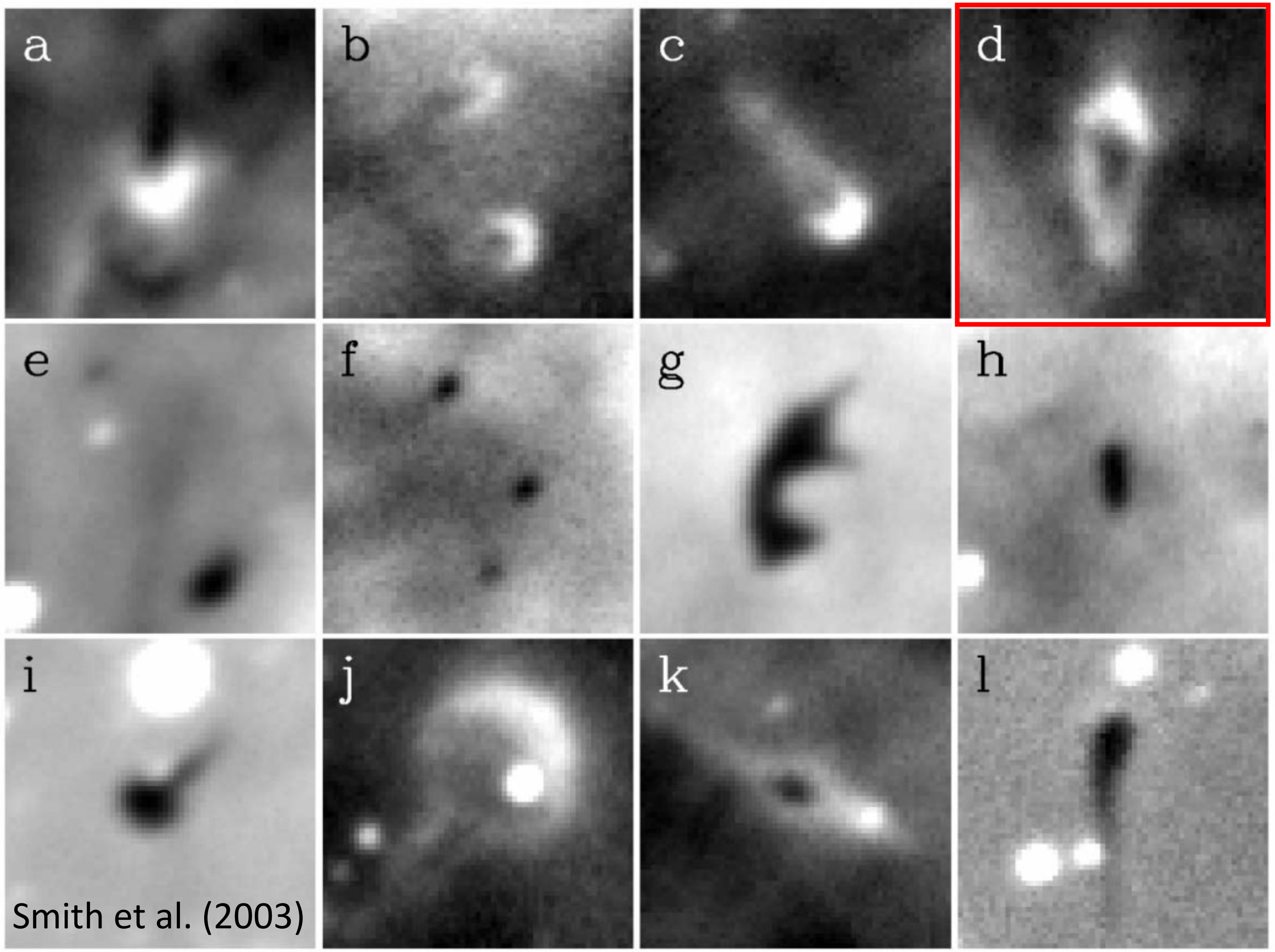
NGC 1977

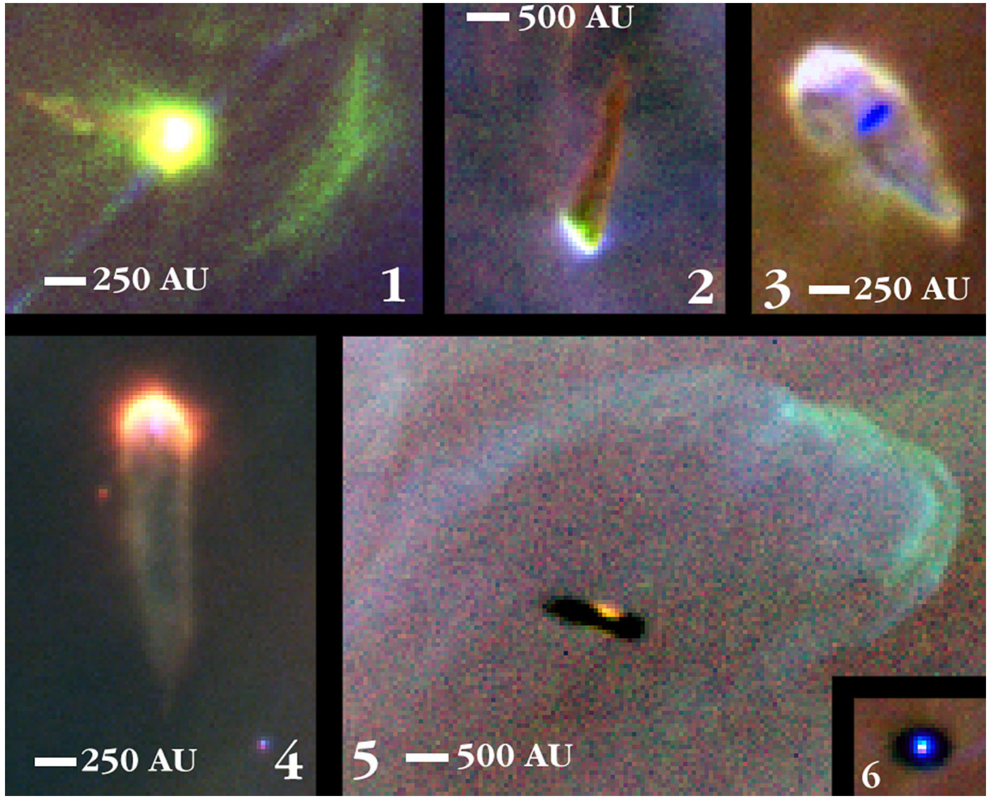
→ Incident UV ~10-30x lower than ONC

Based on Hα morphology, many bright-rimmed blobs are flagged as proplyd candidates despite their size and mass.



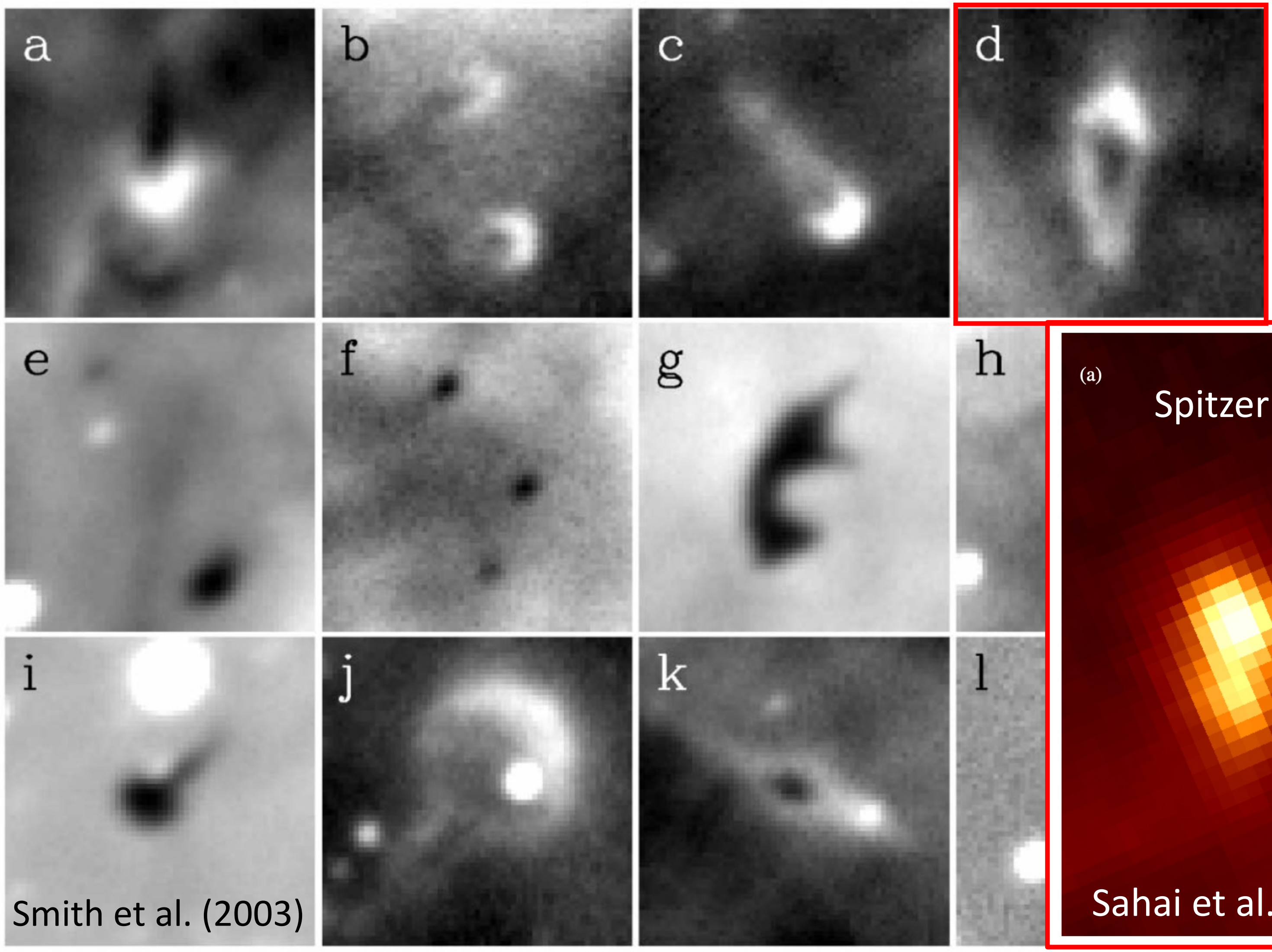
A word about resolving things: proplyds are not *that* much larger than the disks themselves.



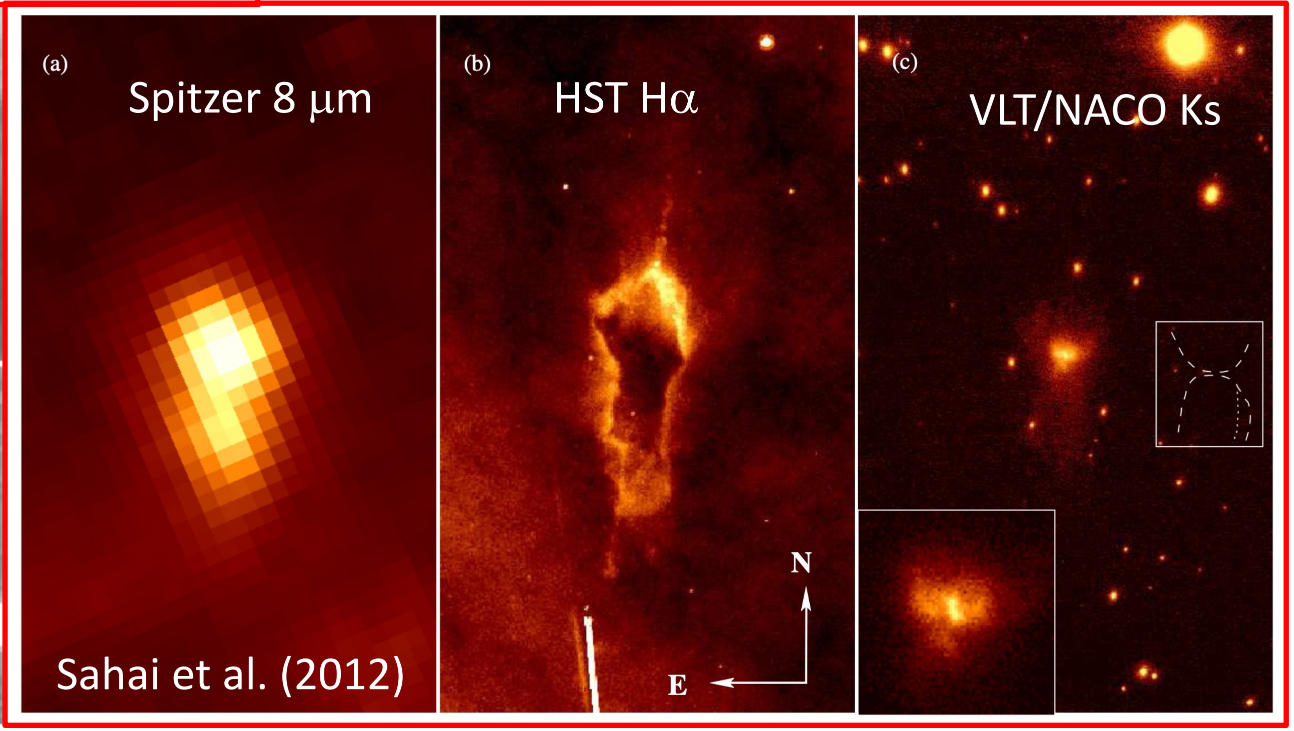


ESA/Hubble

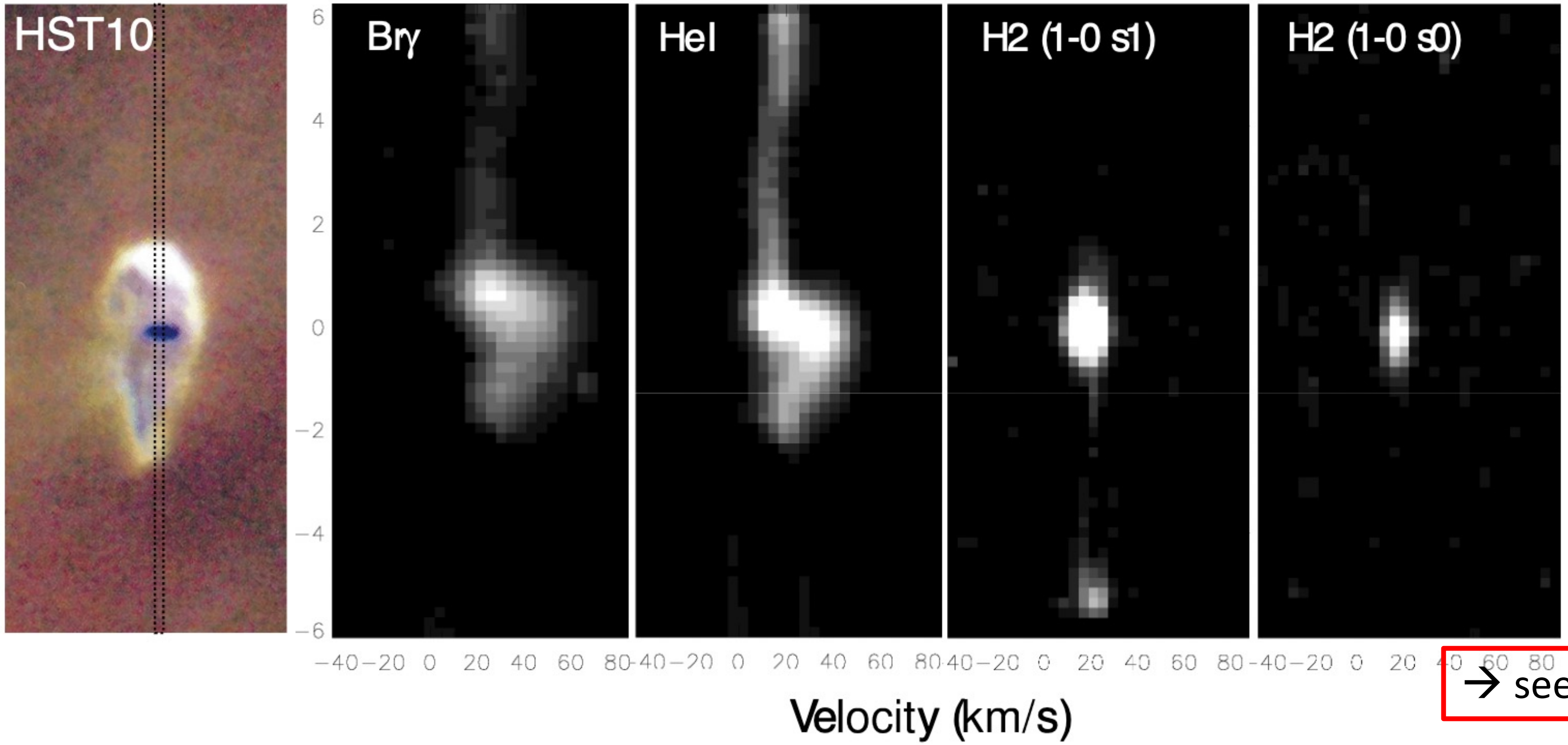
Most candidate proplyds identified in regions with d ≥ 1 kpc are likely evaporating gaseous gloubles.



→ Molecular mass ≈ 0.35 Msun



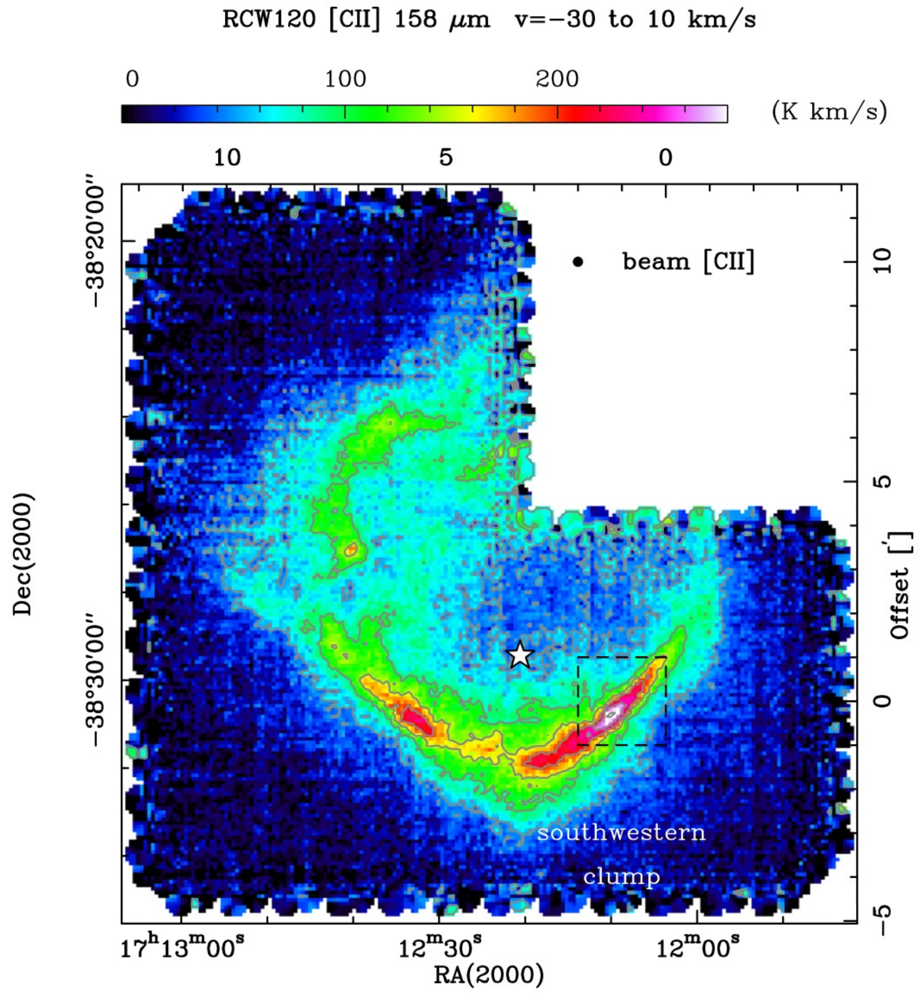
New near-IR IFUs like ERIS provide spatial and spectral resolution to measure kinematics as well as excitation.

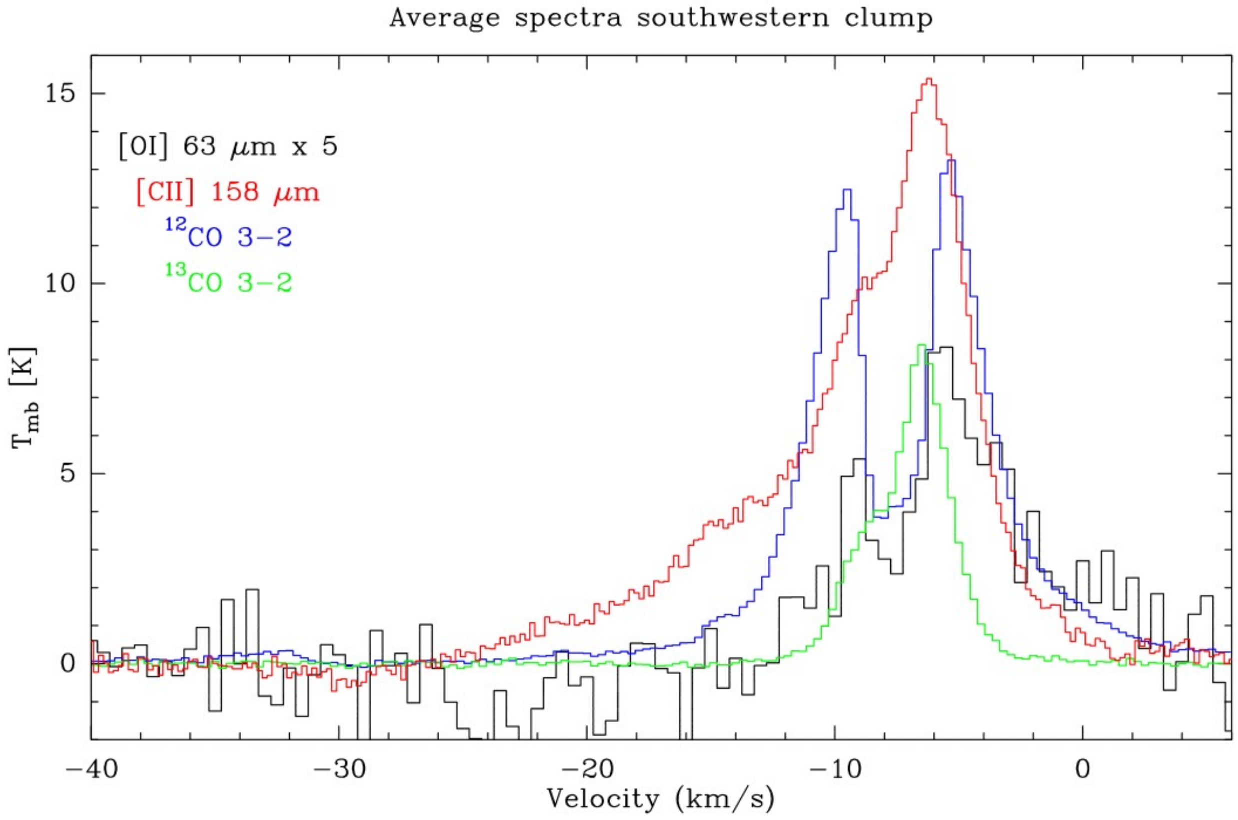


→ see Winter & Haworth (2022)

Shuping et al. (2003)

FEEDBACK: SOFIA legacy survey shows that winds are important early, radiation alone cannot explain kinematics.





e.g., Schneider et al. 2020; Luisi et al. 2021; Tiwari et al. 2021; Beuther et al. 2022; Bonne et al. 2022; Kabanovic et al. 2022; …