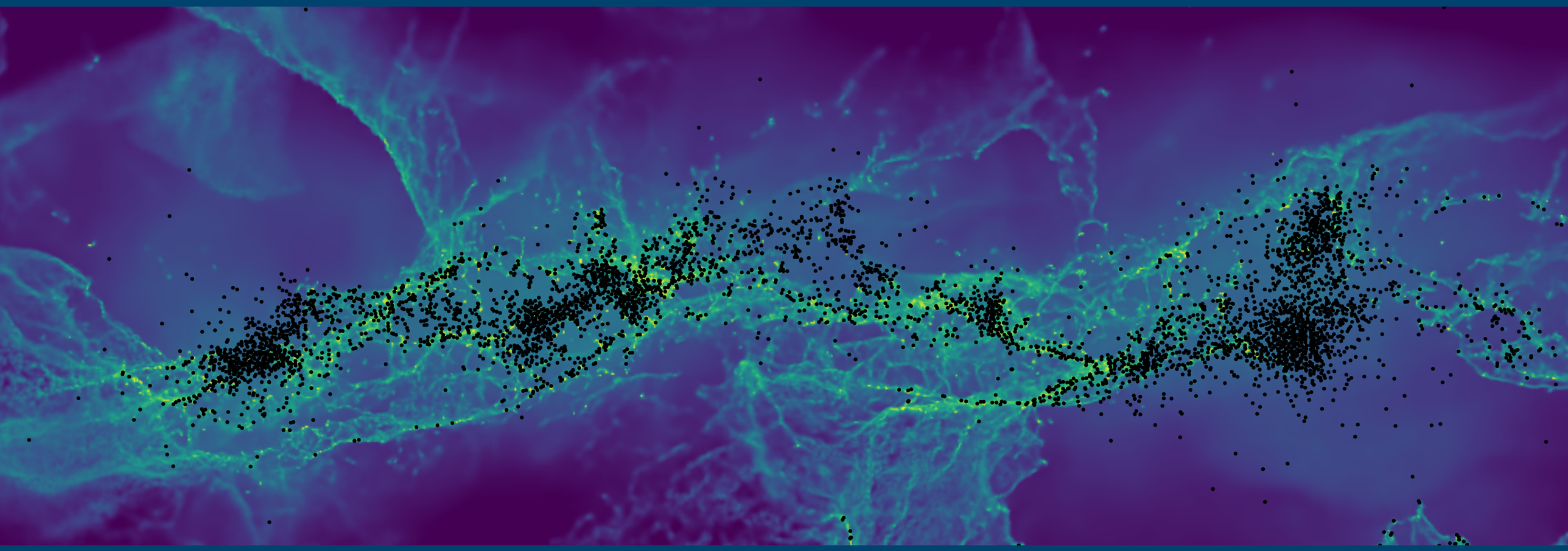
Massive star feedback in different galactic environments

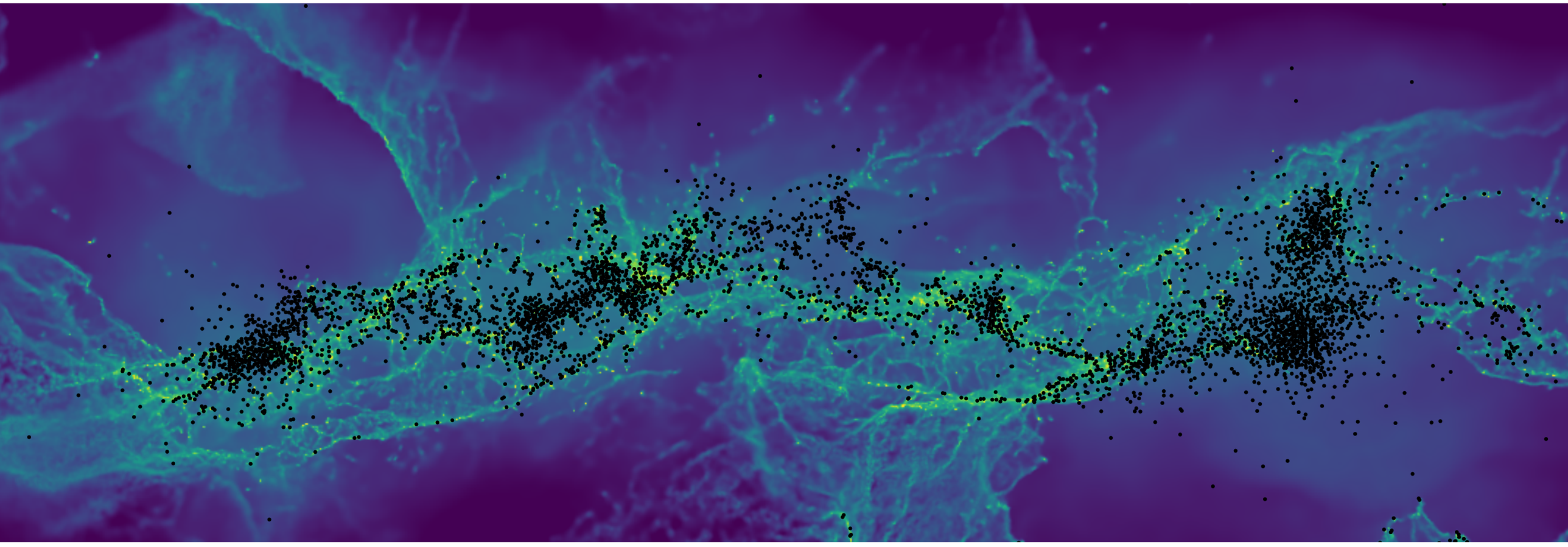


Ahmad Ali

UNIVERSITY OF COLOGNE

Star formation across environments, NAM 2025, Durham UK

Massive star feedback



photoionization

radiation pressure

stellar winds

supernovae

ISM heating/turbulence

star formation rate/efficiency

star cluster properties

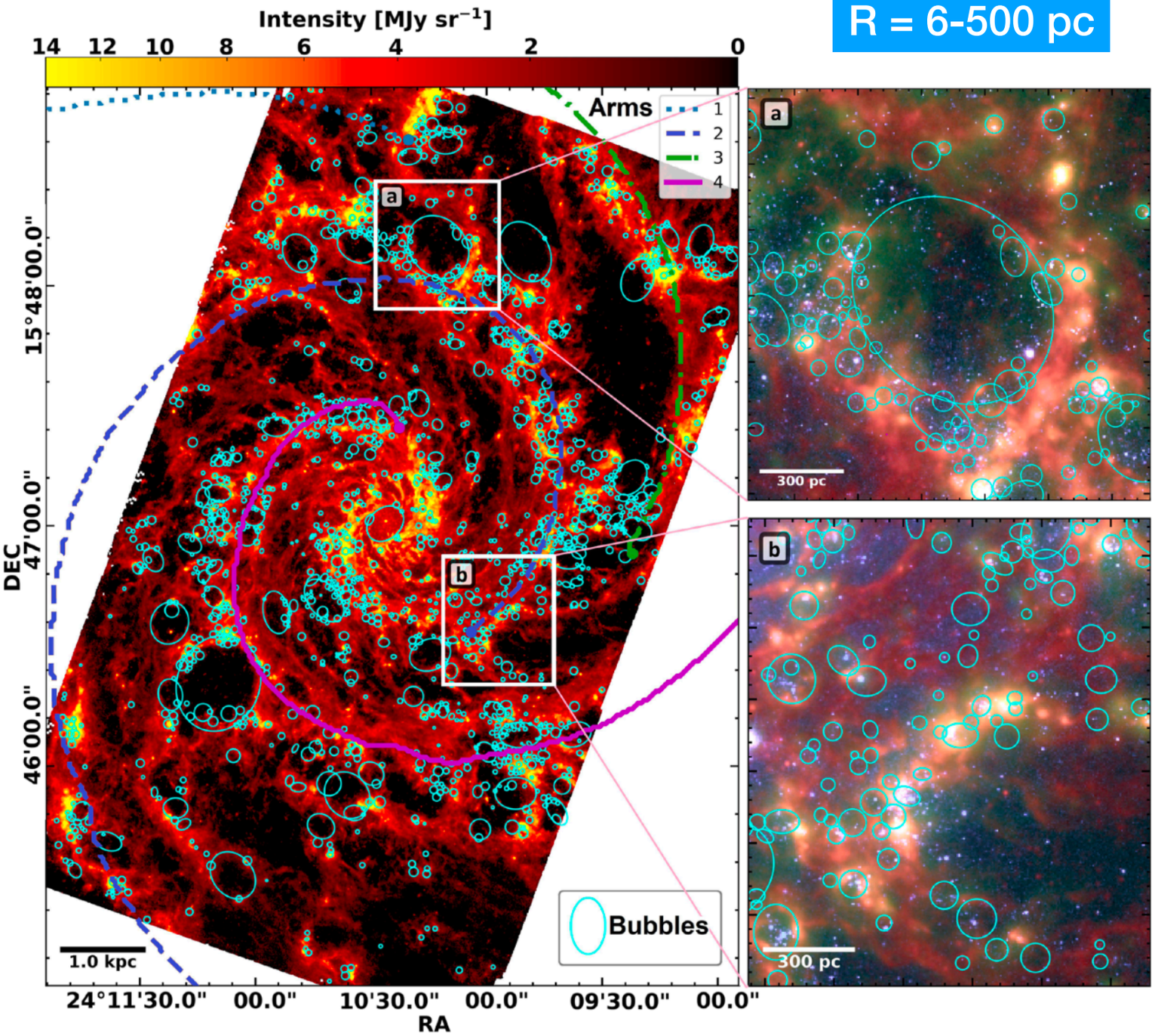
cloud dispersal

momentum/energy escape

Bubbles are everywhere

NGC 628 (Watkins+ 2025)

1694 bubbles
R = 6-500 pc



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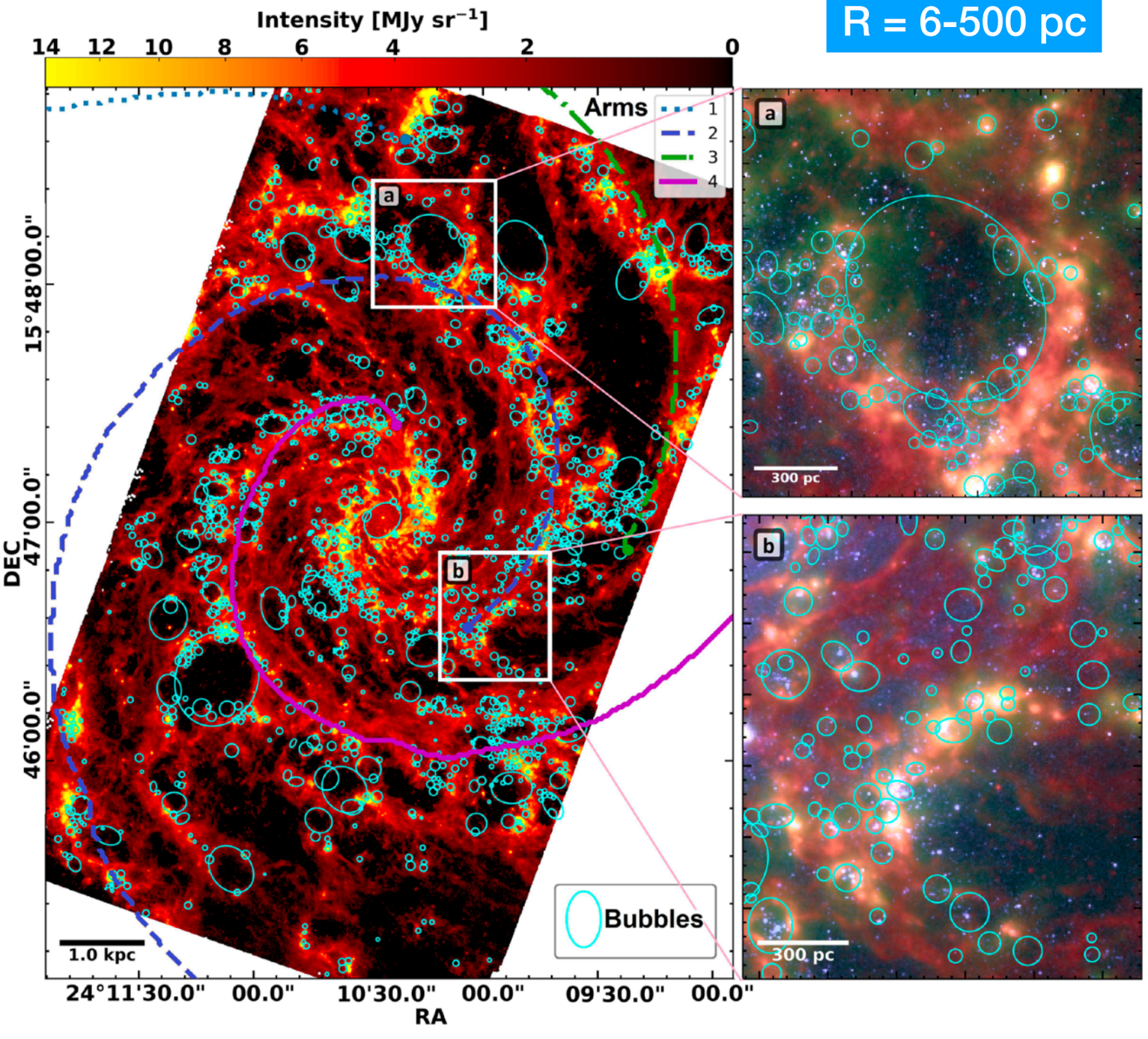

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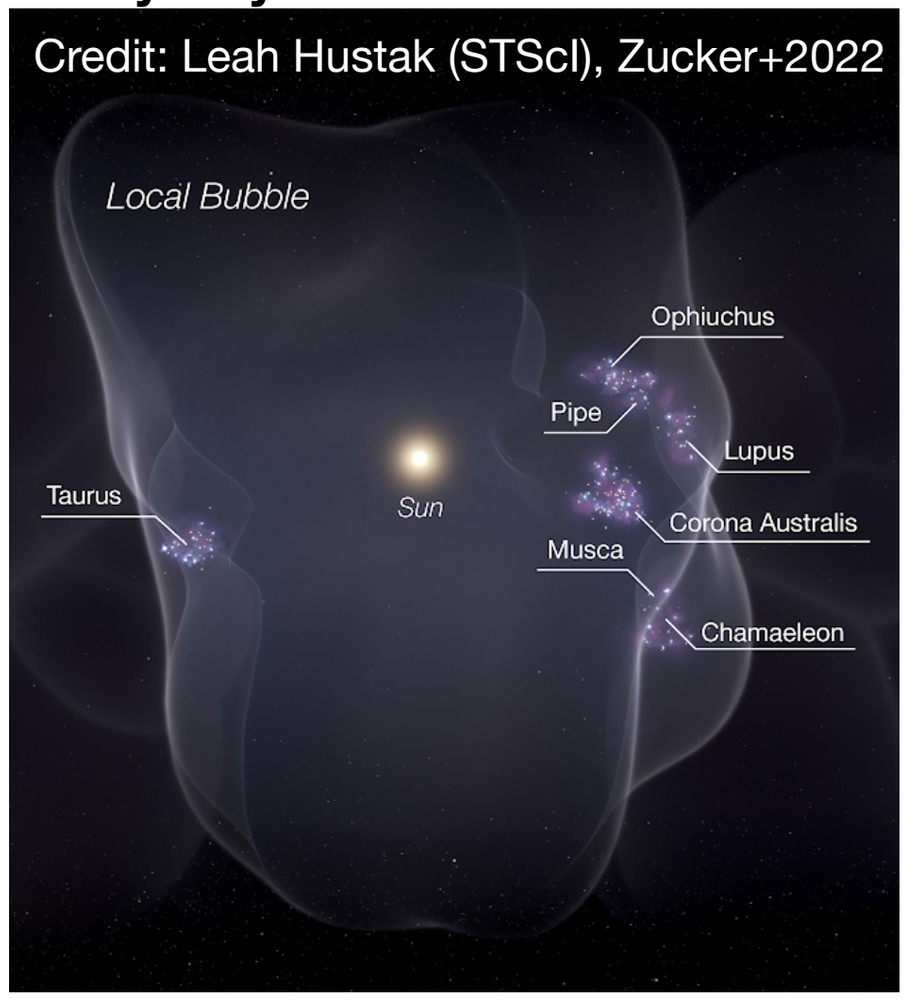
Milky Way Local Bubble



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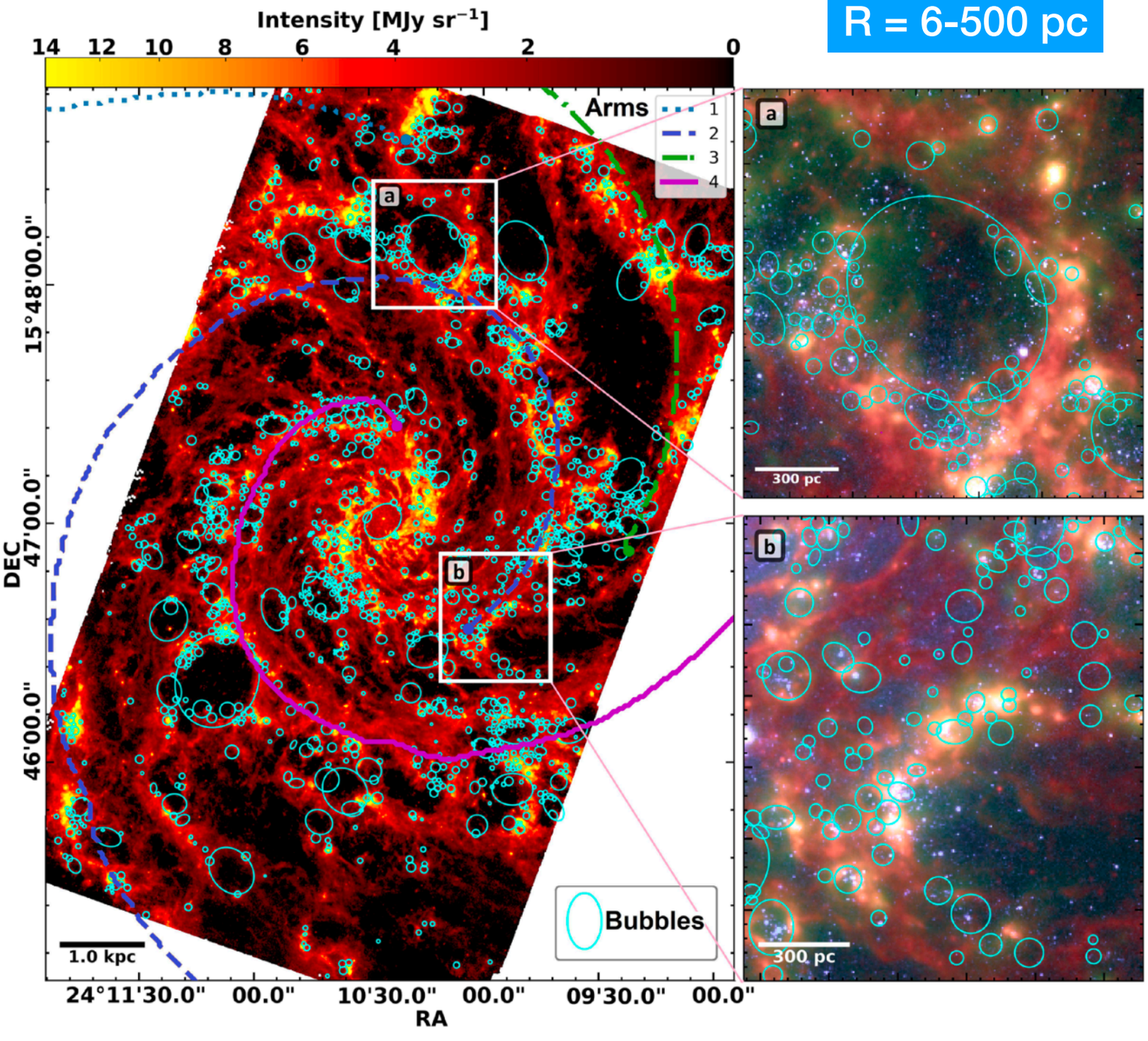

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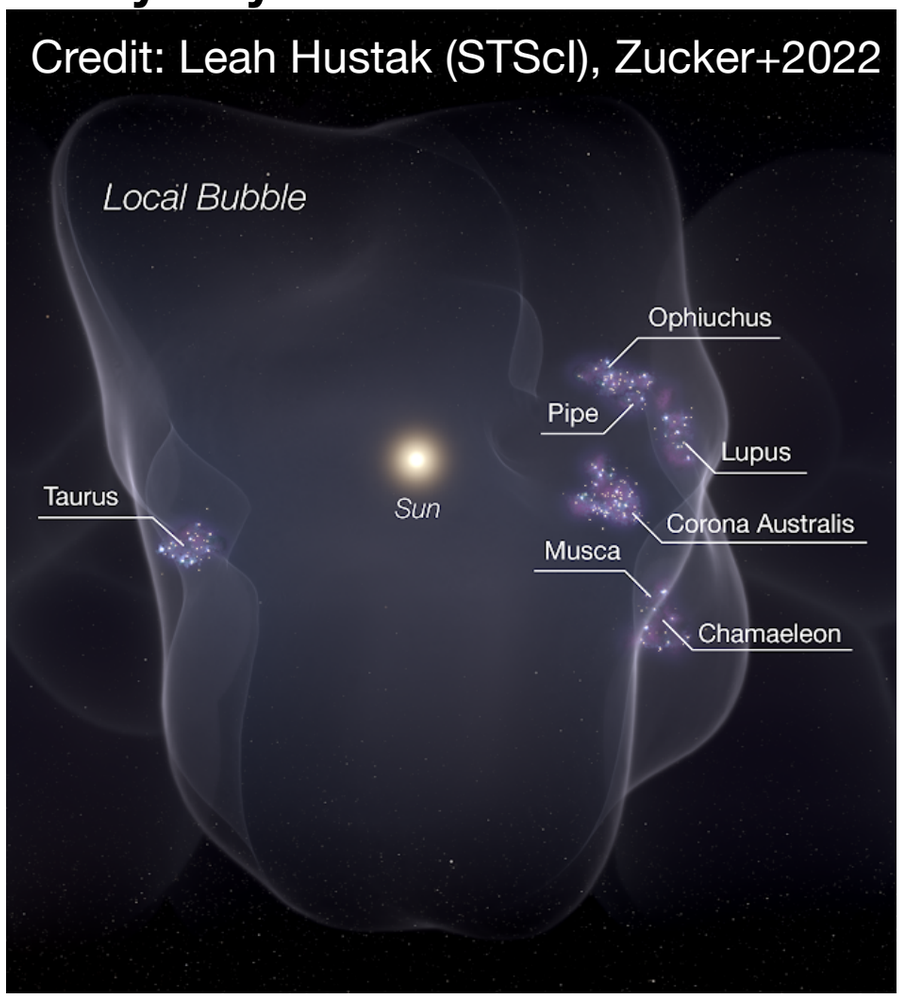
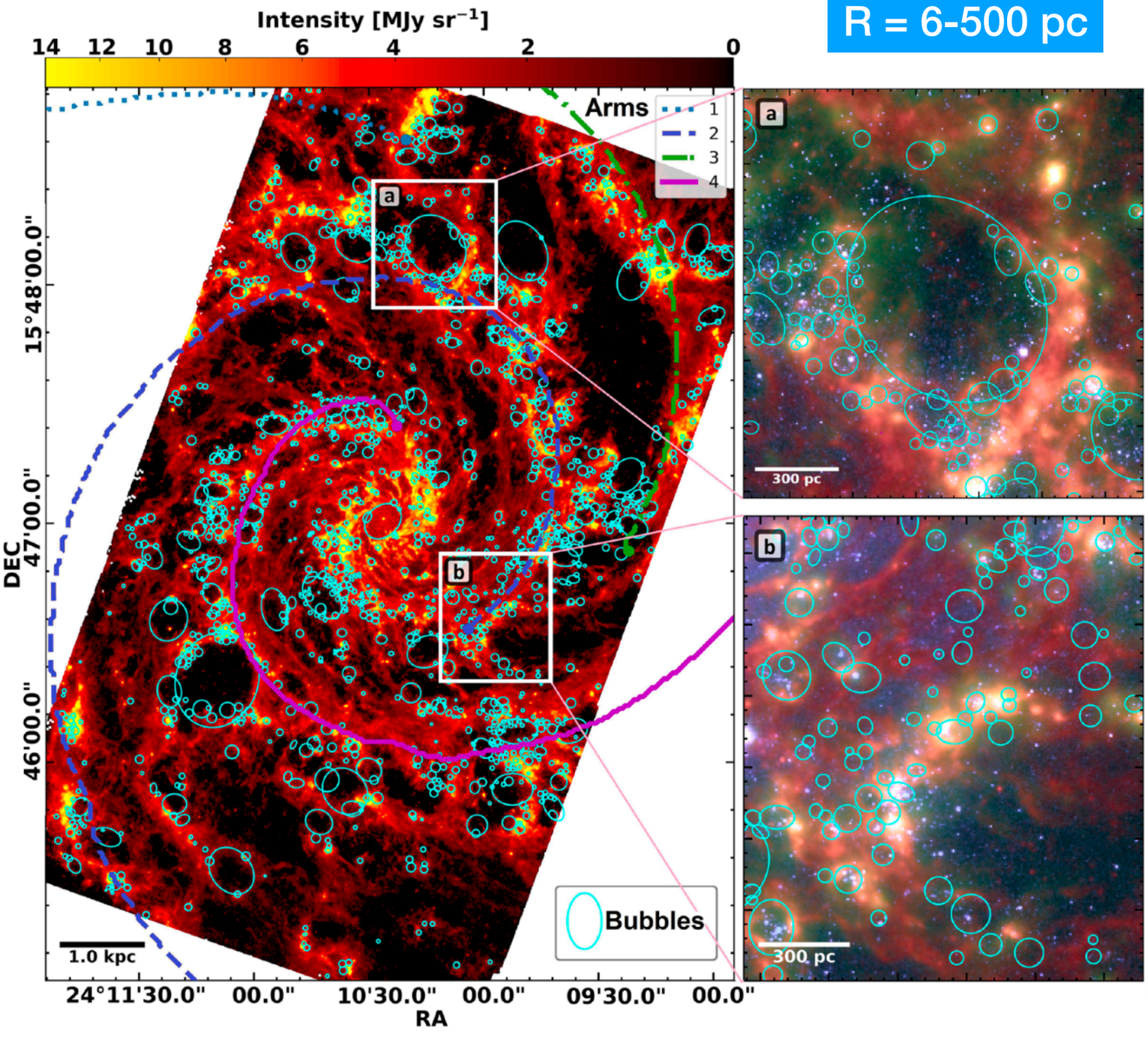


Feedback vs. galaxy dynamics?
Need to understand feedback

Bubbles are everywhere

NGC 628 (Watkins+ 2025)



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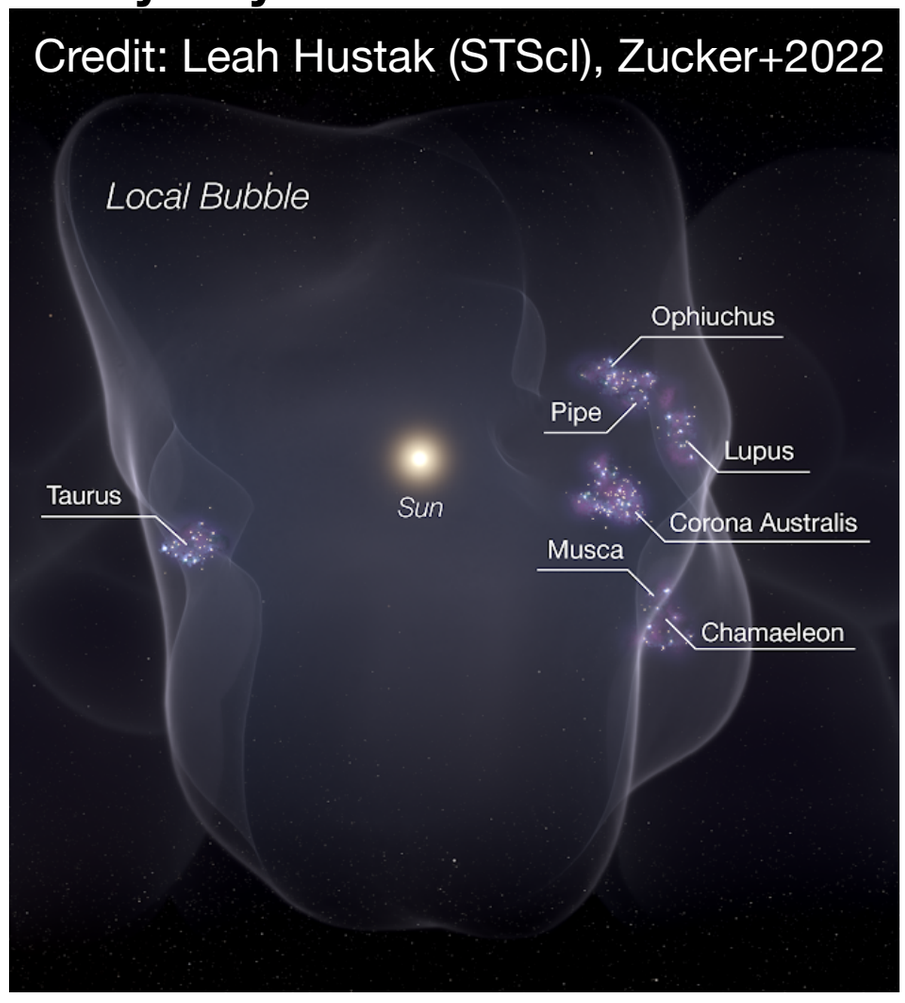
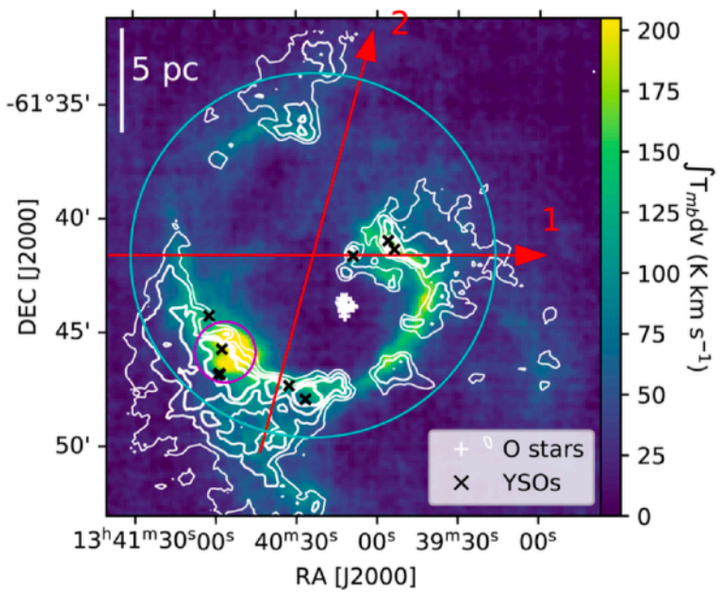


Feedback vs. galaxy dynamics?
Need to understand feedback

Which feedback processes are responsible?

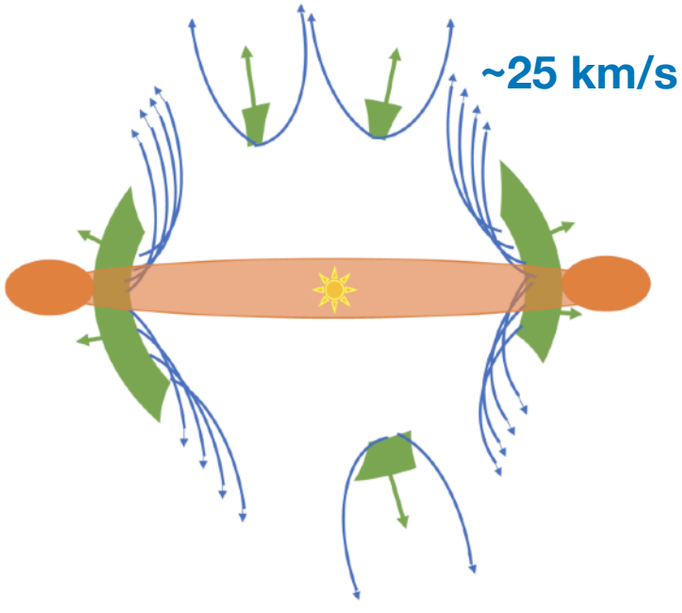
Feedback in action

RCW 79 (Bonne+ 2023)



colour: [C II] 158 um
contours: ^{12}CO(3-2)

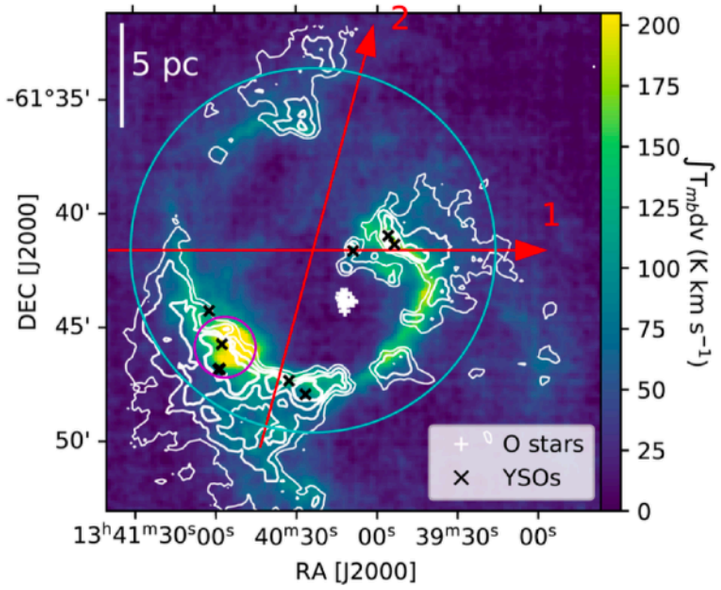
expanding shell + ablation



~25 km/s neutral gas

Feedback in action

RCW 79 (Bonne+ 2023)



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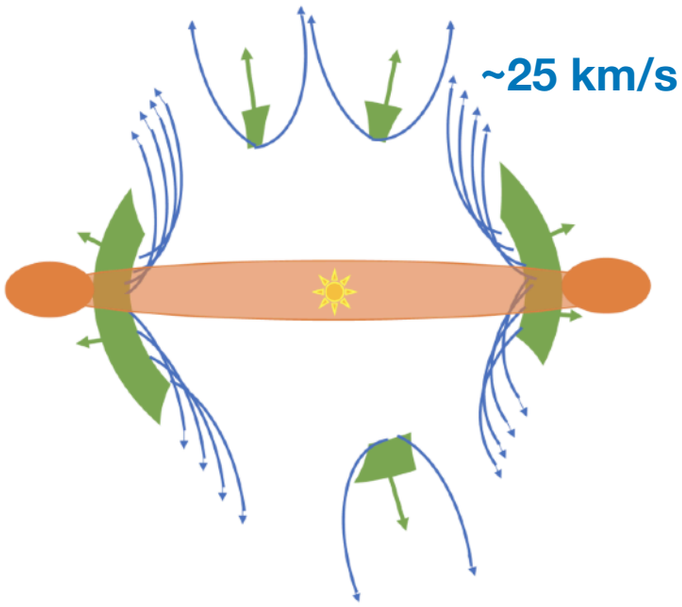

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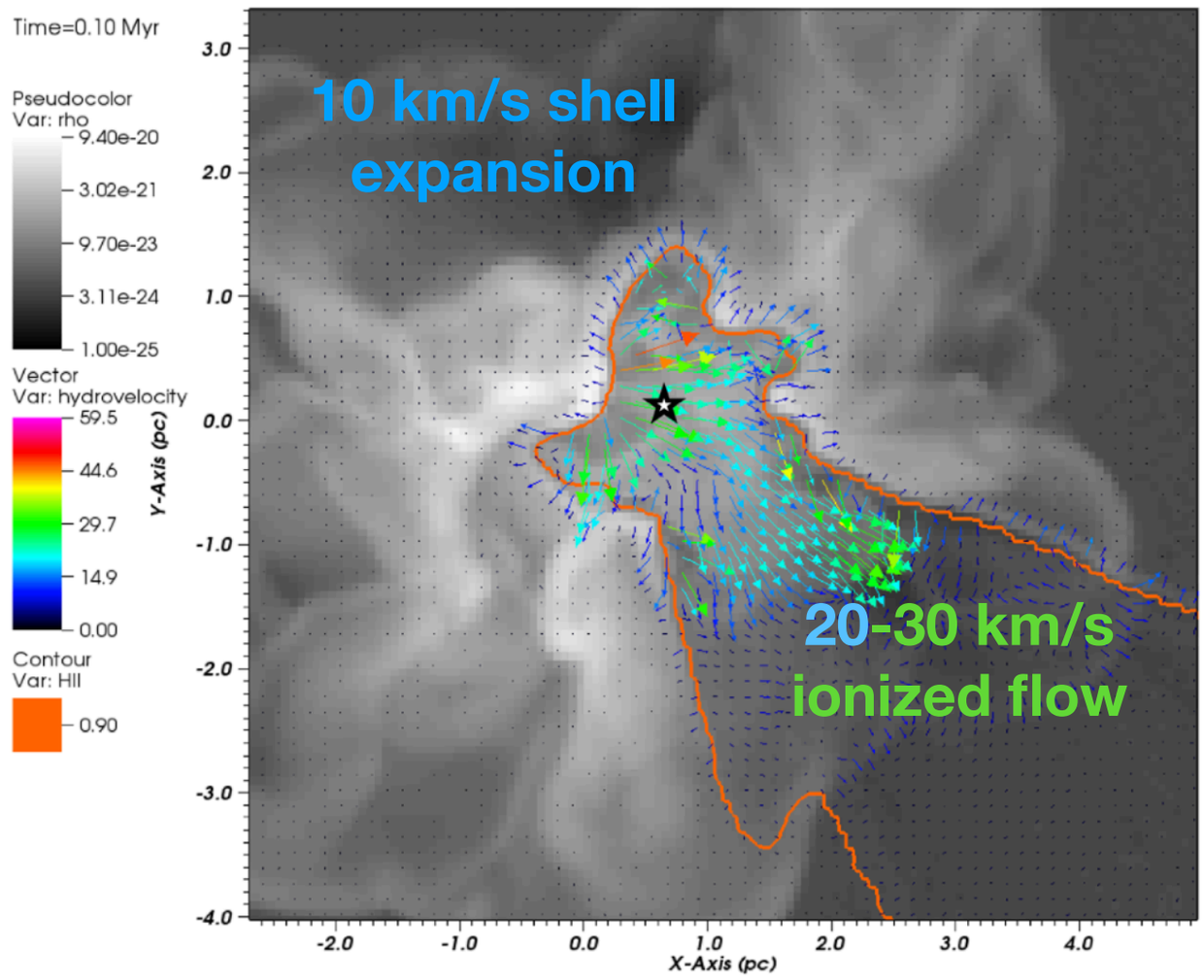
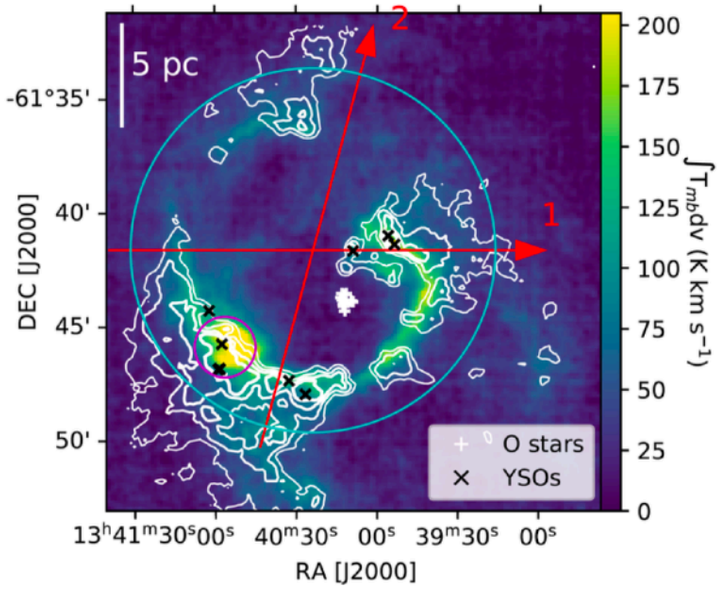
Simulations (radiation only) (Ali+ 2018)

See also Kim+ 2018



Feedback in action

RCW 79 (Bonne+ 2023)



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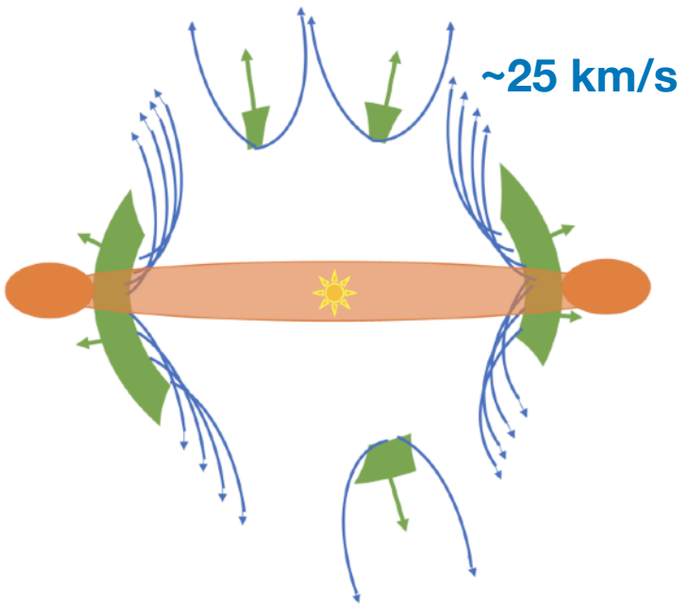

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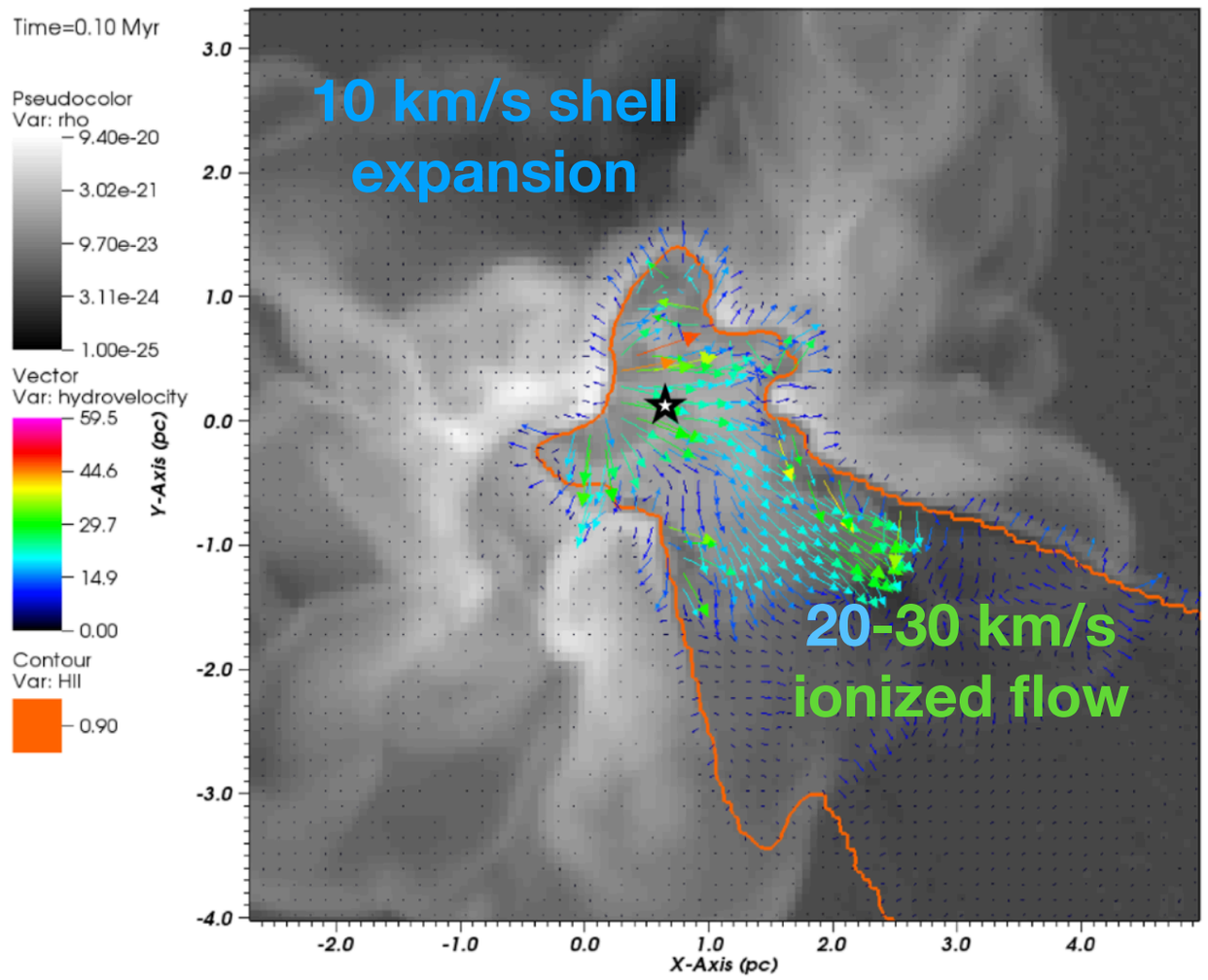
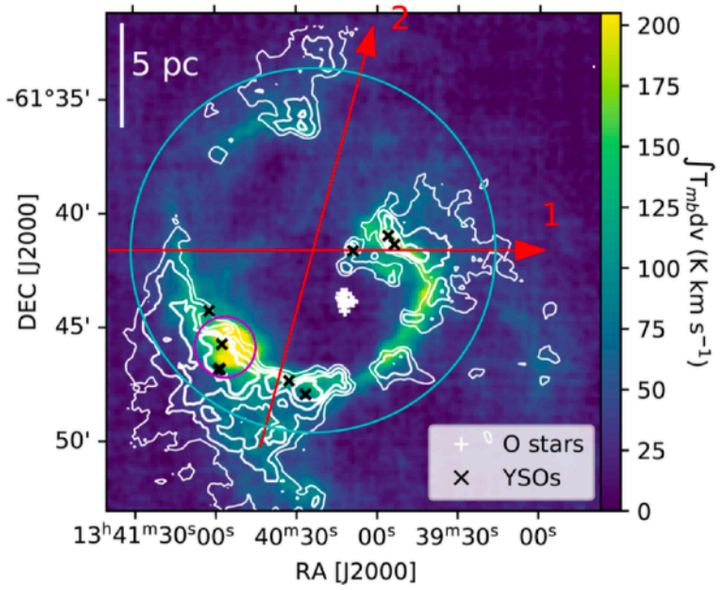


high-velocity dispersal: is ionization enough?

Feedback in action

RCW 79 (Bonne+ 2023)



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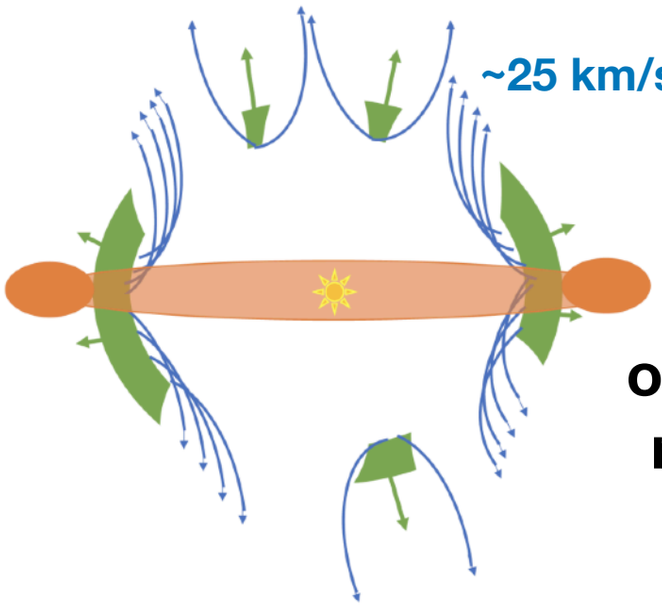
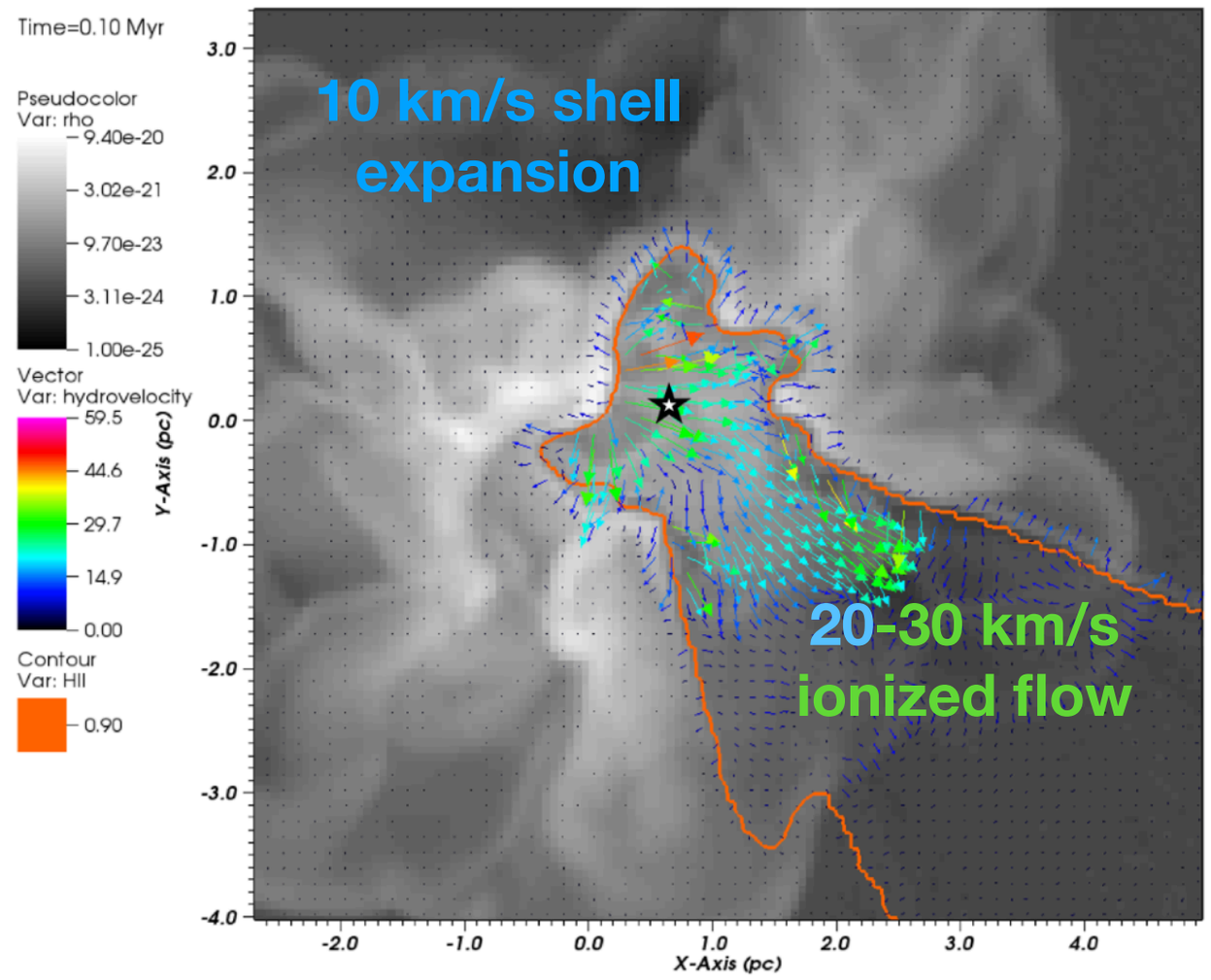


~25 km/s neutral gas

or are stellar winds/ radiation pressure important?

Simulations (radiation only) (Ali+ 2018)

See also Kim+ 2018



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Feedback in action

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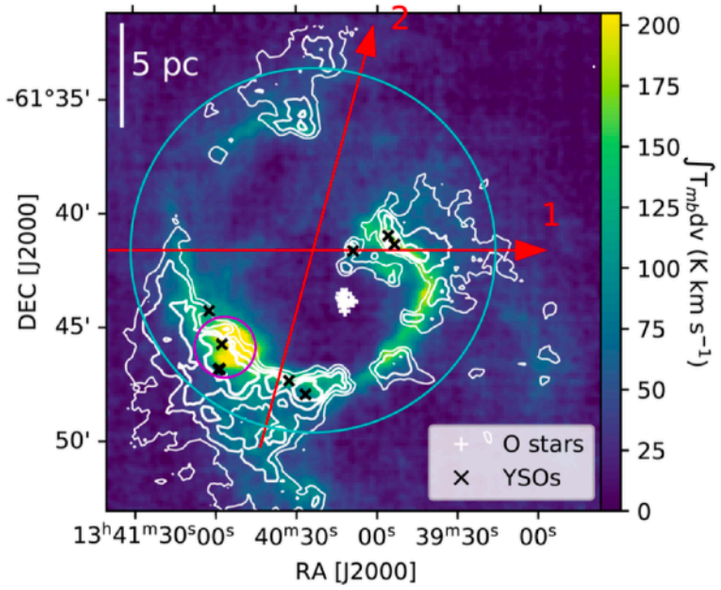

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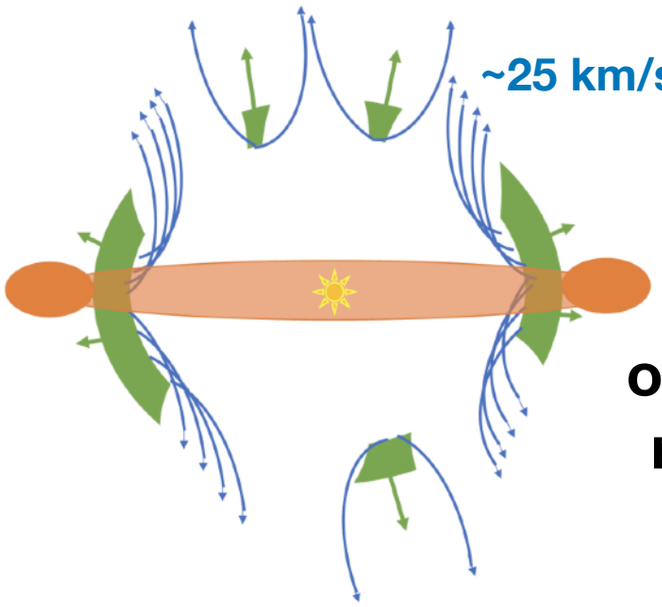

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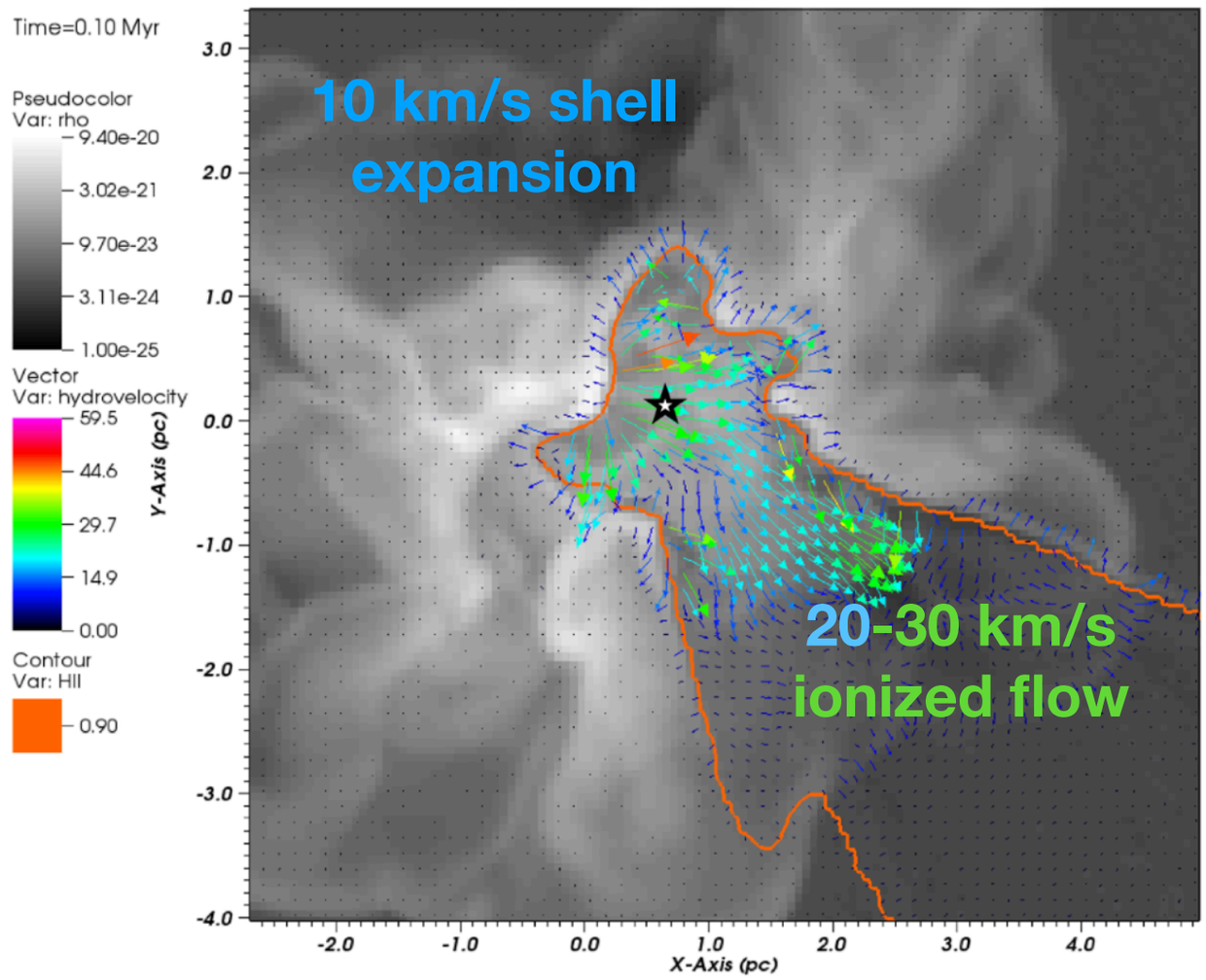


high-velocity dispersal: is ionization enough?

Relative impacts of different feedback mechanisms?

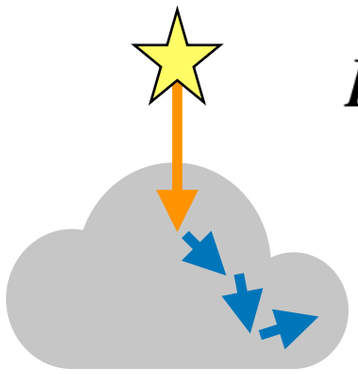
Feedback pressures

Infer dynamics from pressure terms

- H II thermal pressure (~10^4 K gas)

$$P_{\mathrm{H\,II}} = (n_{\mathrm{e}} + n_{\mathrm{H}} + n_{\mathrm{He}})kT_{\mathrm{e}} \approx 2n_{\mathrm{e}}kT_{\mathrm{e}}$$

- Radiation pressure
  - direct
  - dust-processed

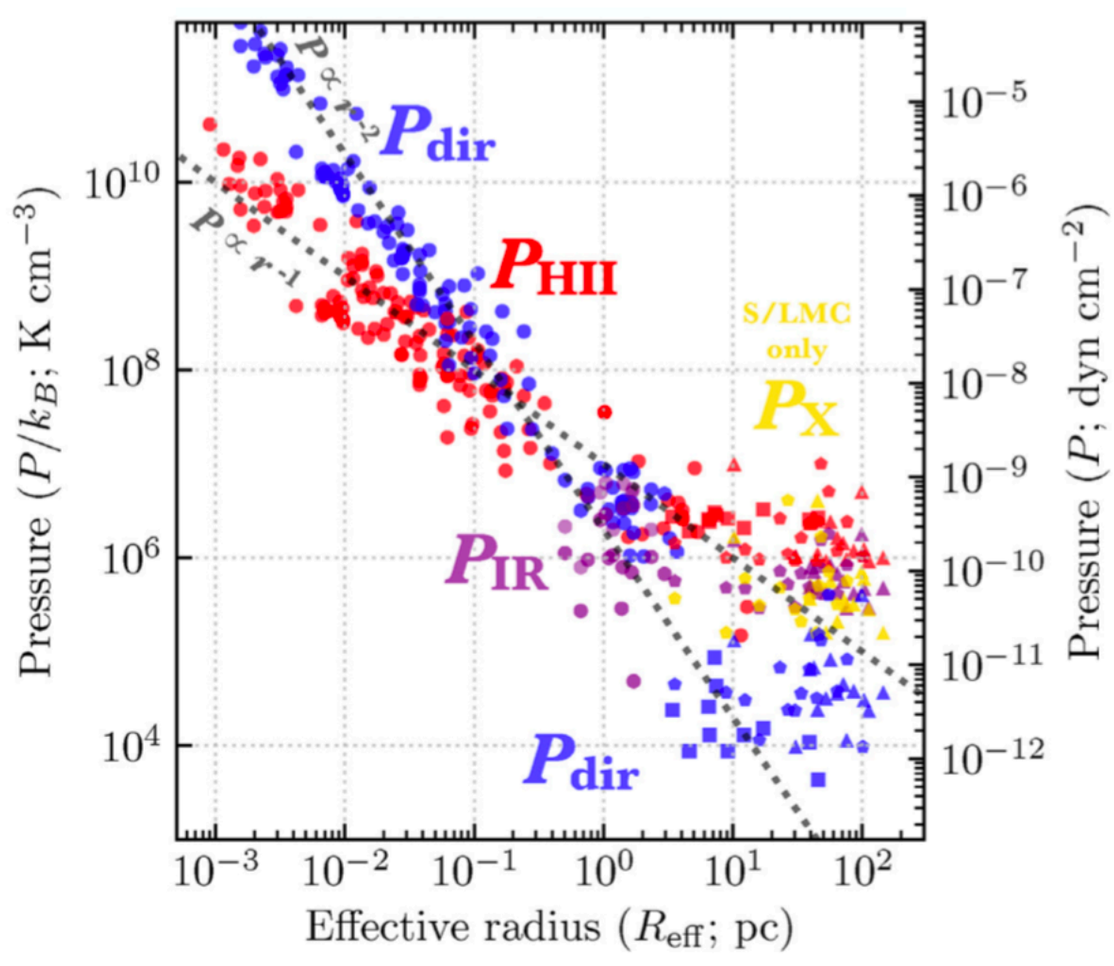


$$P_{\mathrm{dir}} = \frac{3L_{\mathrm{bol}}}{4\pi r^2 c}$$

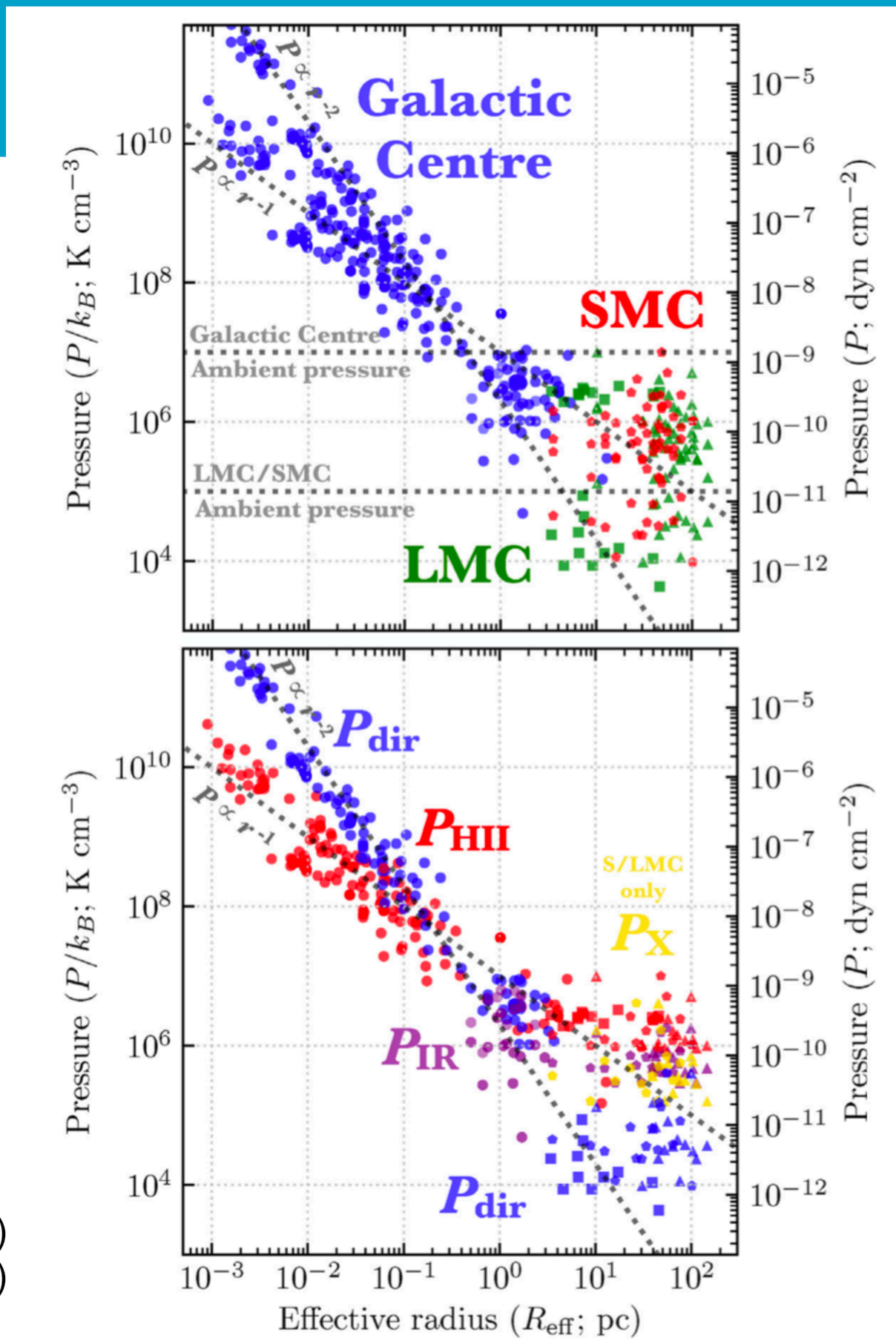
- Stellar wind pressure (>10^6 K gas)

Pressure vs. size

MW: **Barnes+ (2020)**
LMC/SMC: Lopez+ (2011,2014), McLeod+ (2019)



Pressure vs. size



MW: **Barnes+ (2020)**
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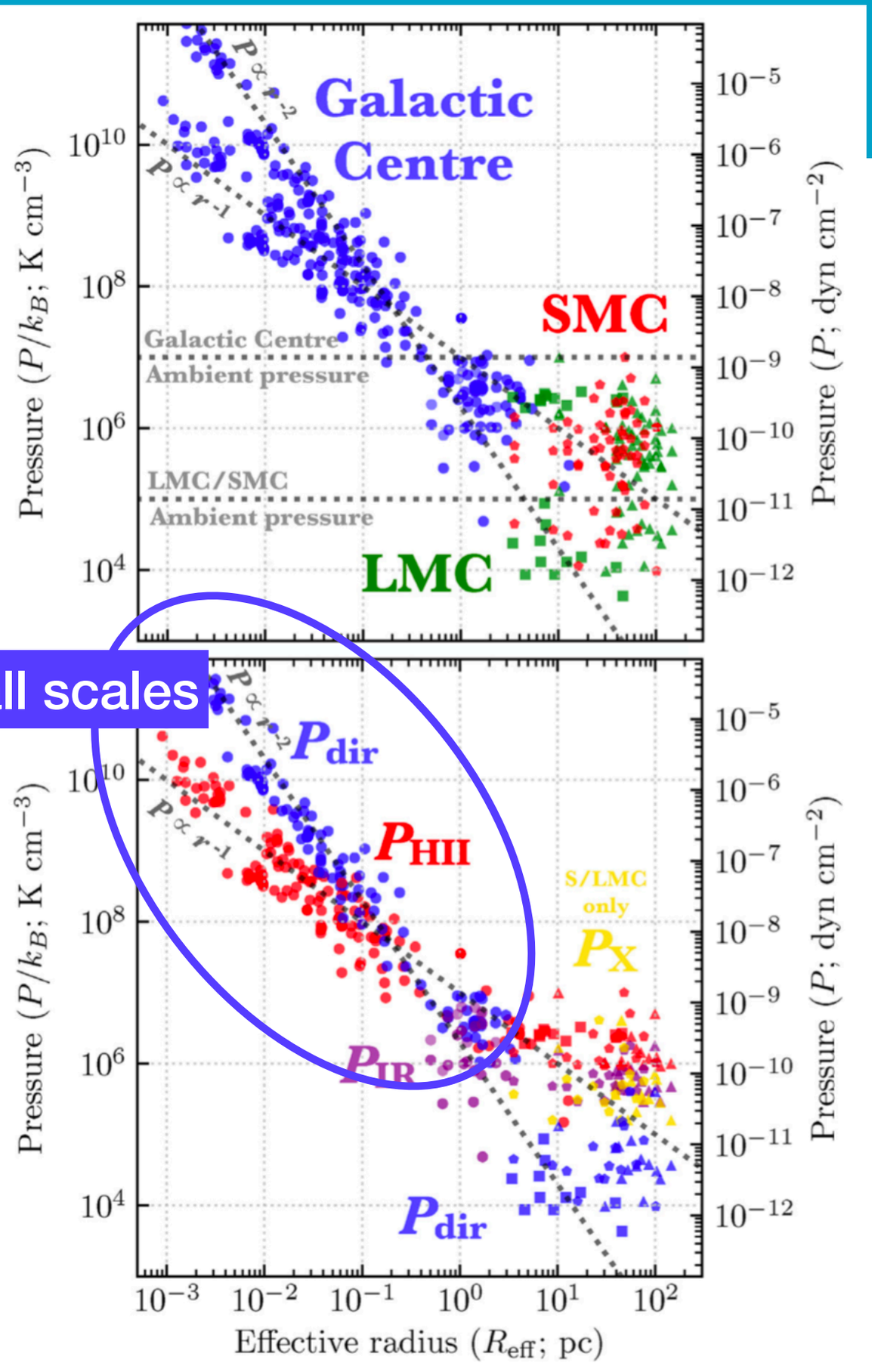
Pressure vs. size

Pdir dominates in Galactic Centre / small scales



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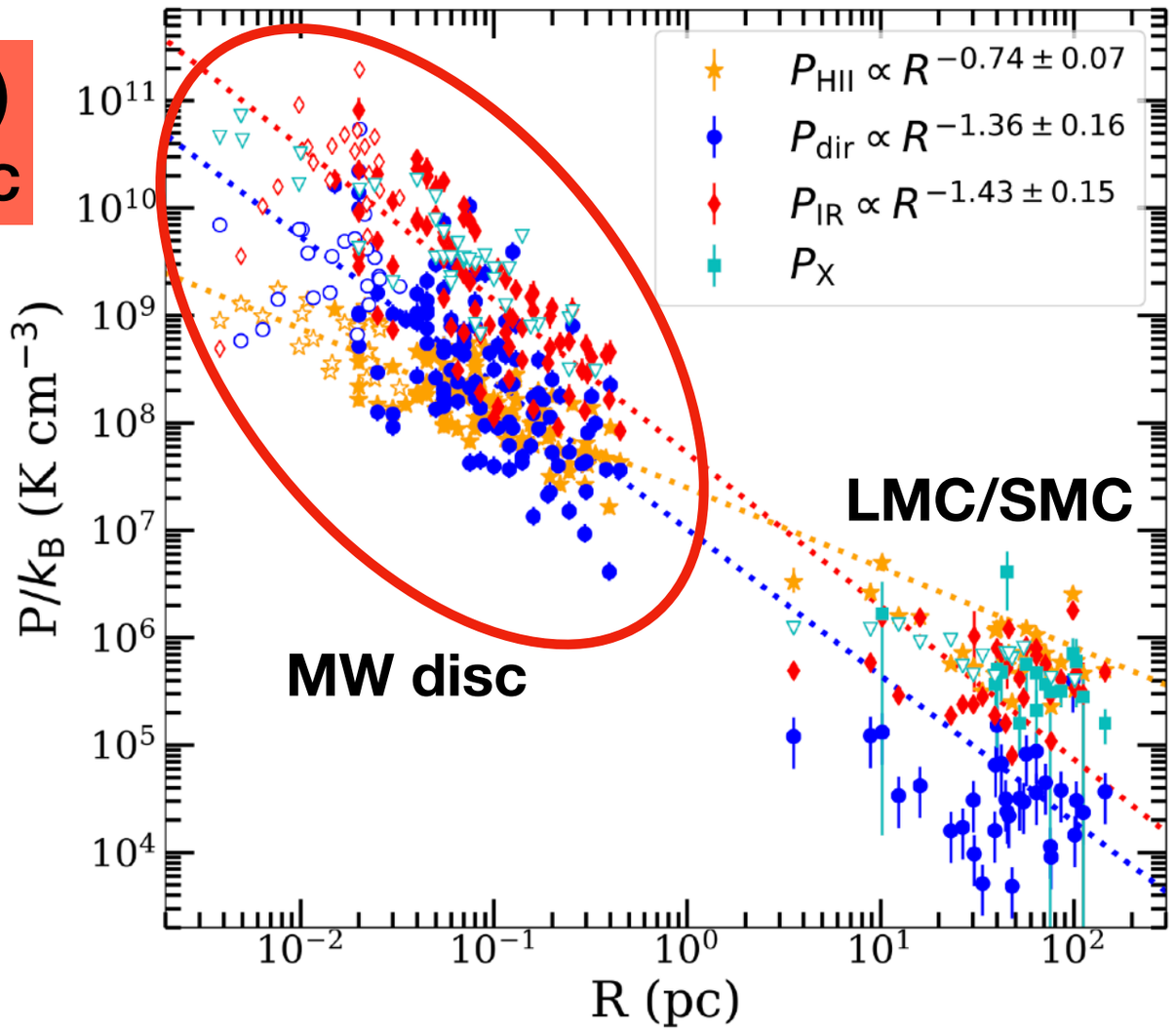
Milky Way disc

P_{IR} (re-processed RP) dominates in MW disc

Olivier+ (2021)



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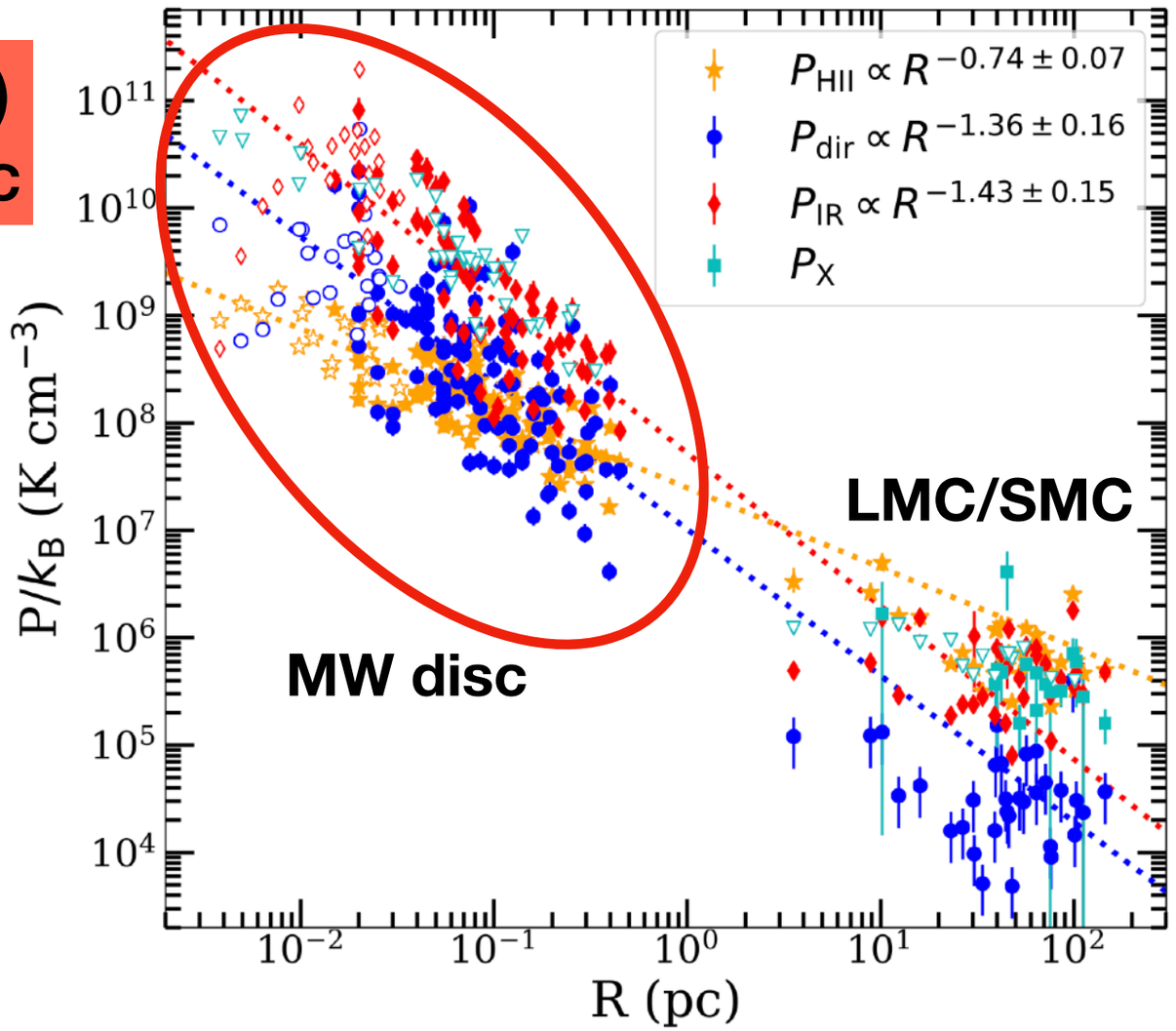
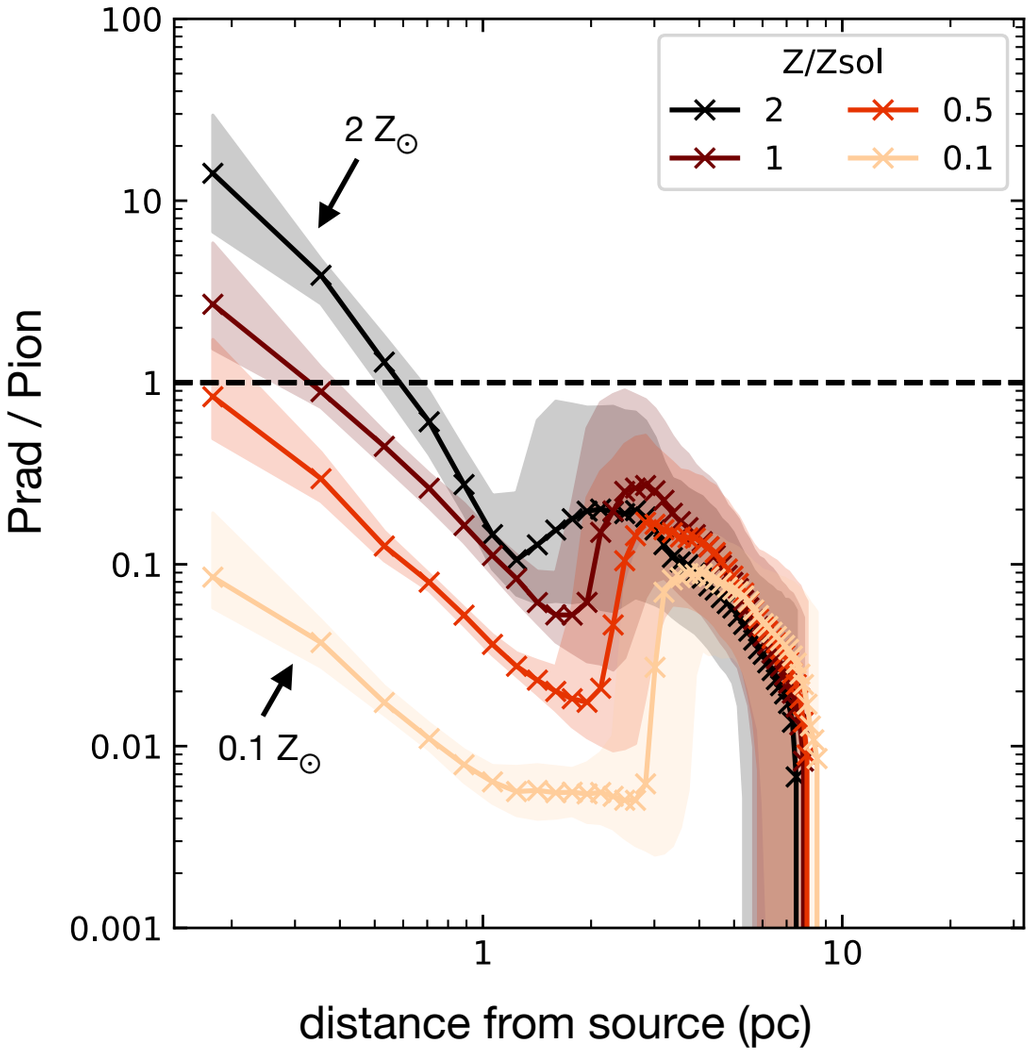
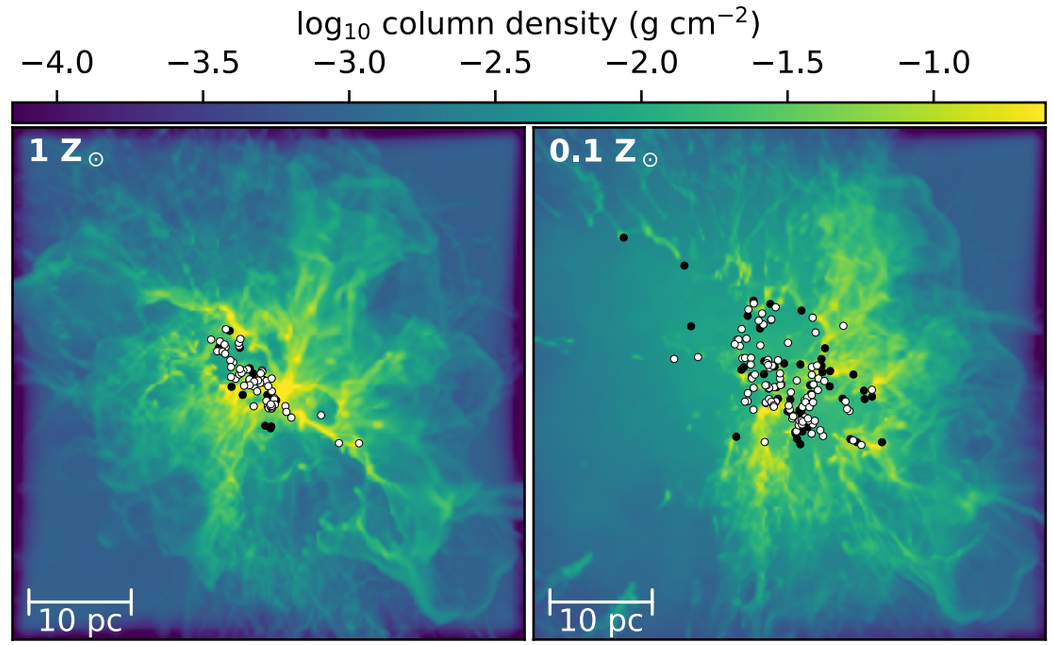


size scale or environment?

Simulations



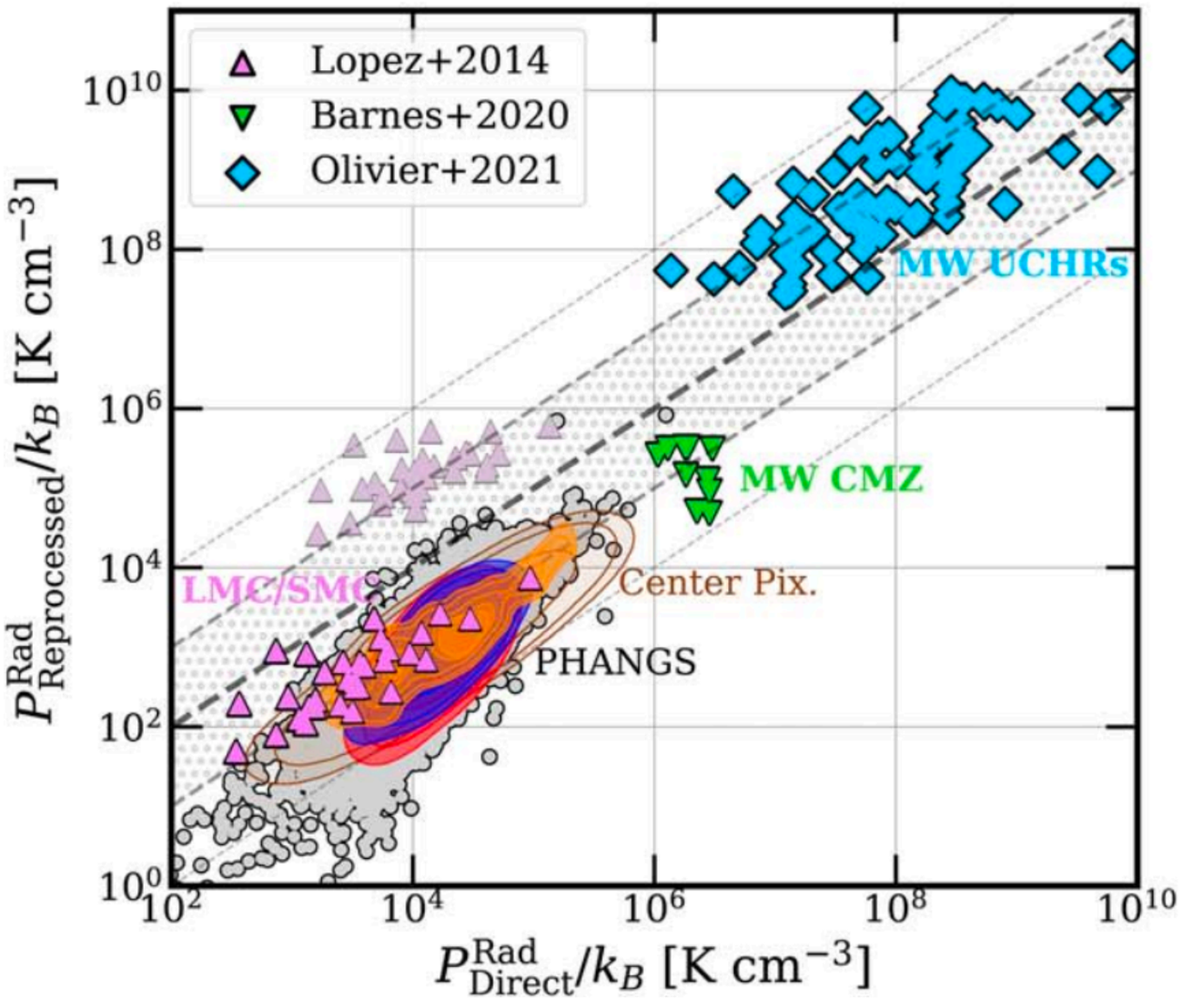


Ali 2021

=> size scale AND environment

Statistics!

Pathak+ 2025 (gray points)
19 nearby galaxies (~18,000 HII regions)



See also: McLeod+ 2019,2021; Della Bruna+ 2022; Rowland+ 2024

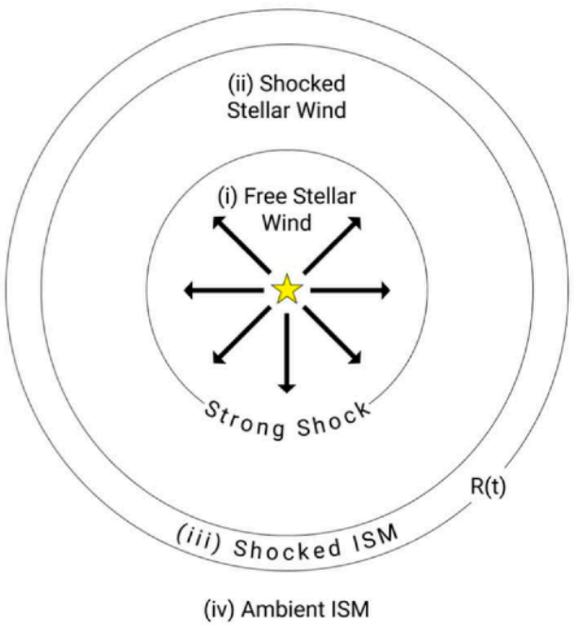
Dynamics

- RP > photoionization on small scales (< pc)
- Photoionization > RP on large scales (> pc)
- But environment also matters
- (stellar winds ???)

Stellar wind models

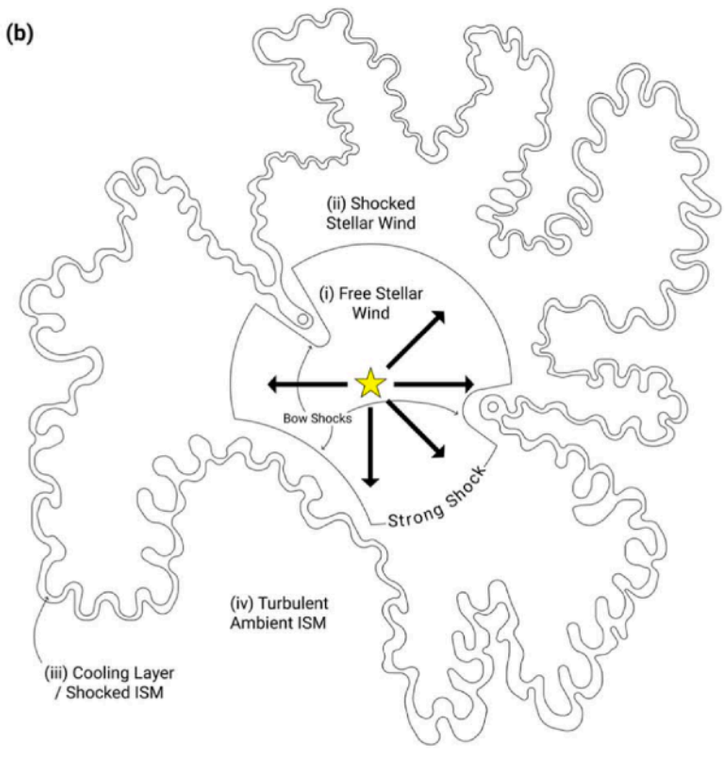
Weaver+ (1977)

adiabatic,
uniform density

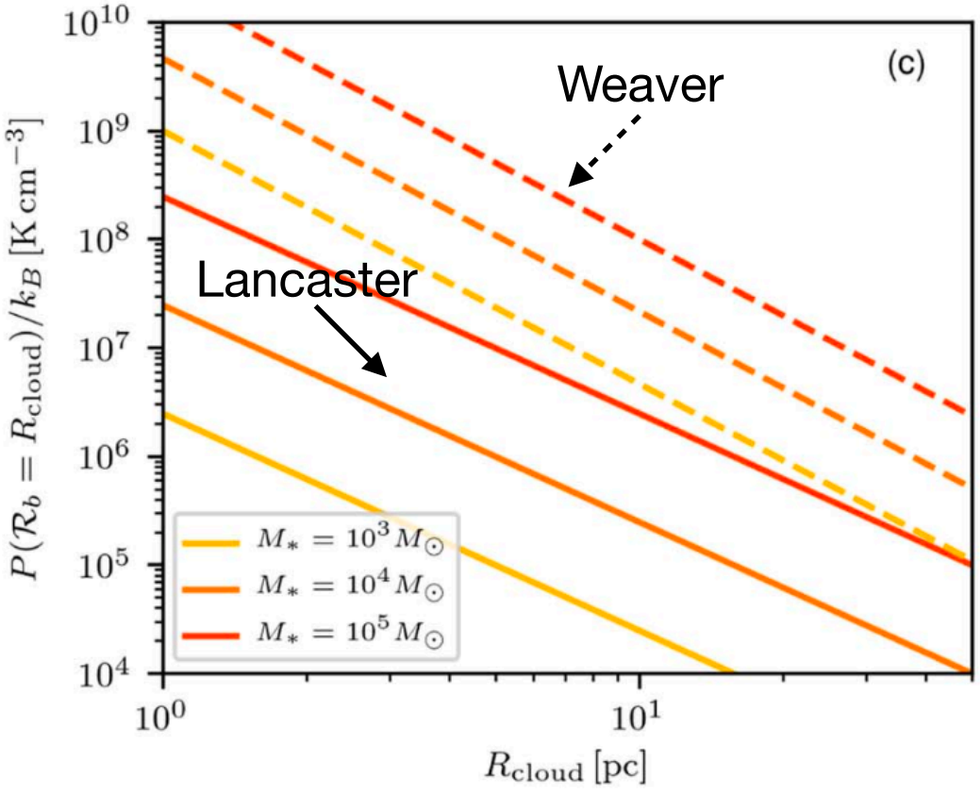


Lancaster+ 2021

Turbulent mixing at interface
+ cooling



thermal pressure at bubble radius



See also: Geen+ 2021,2023; Lancaster+ submitted

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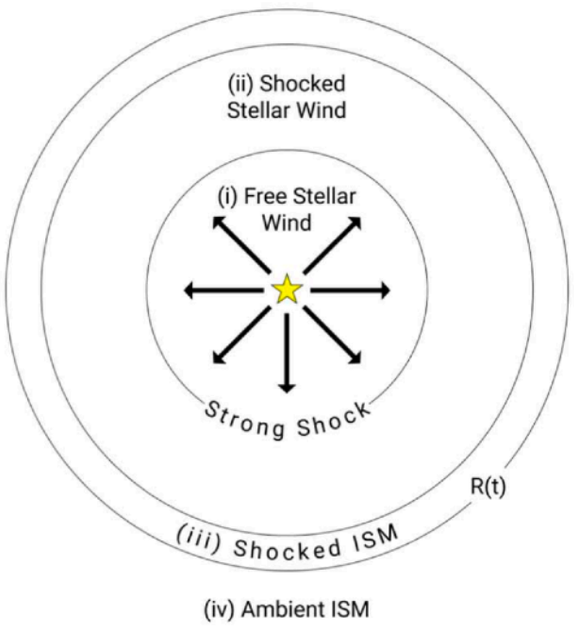

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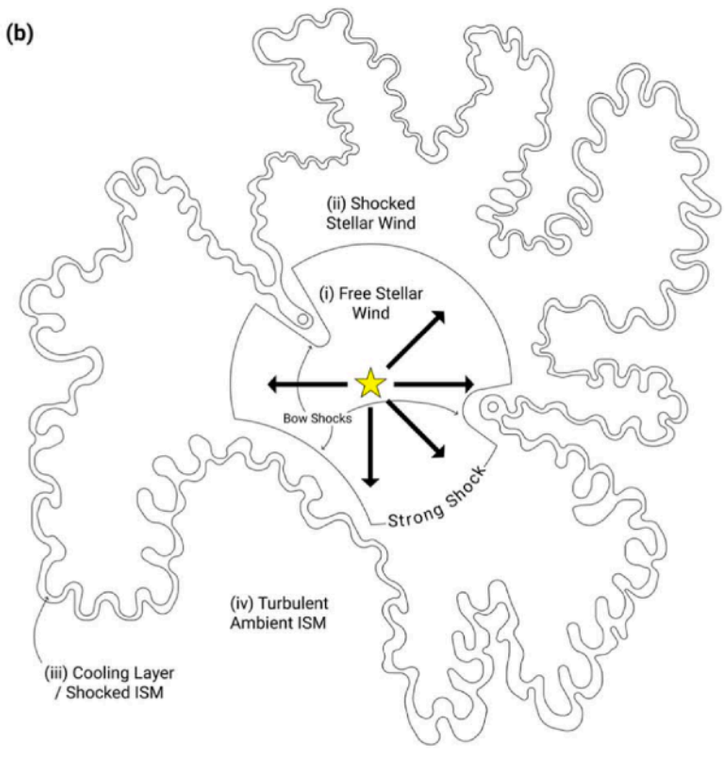

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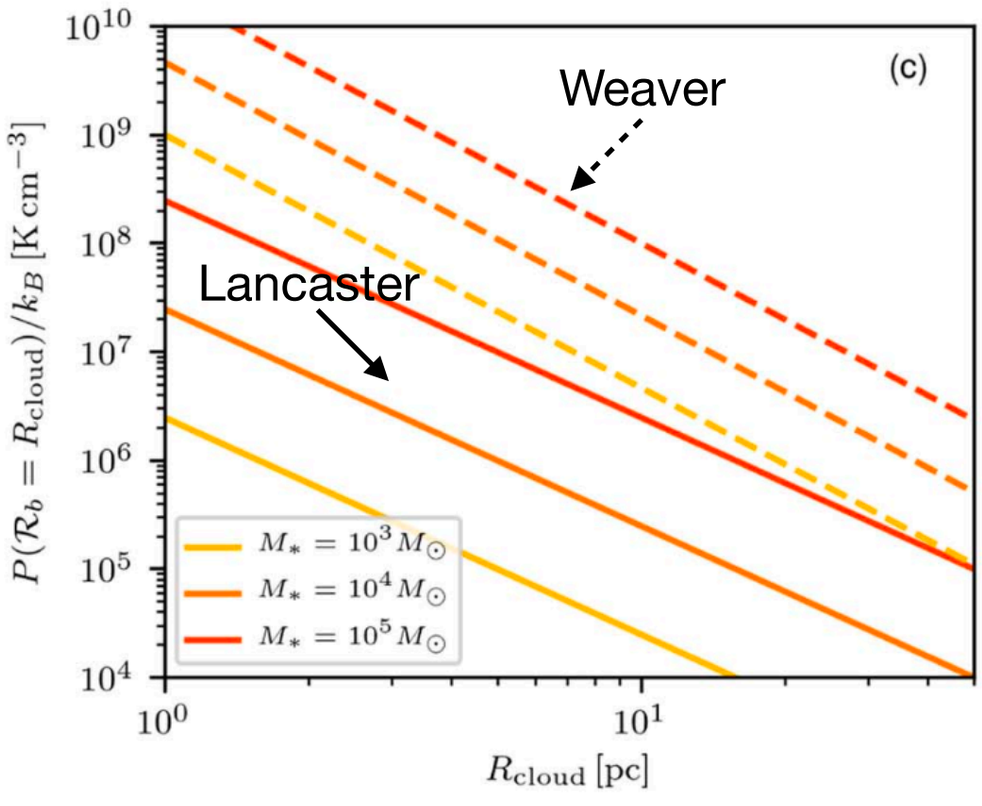
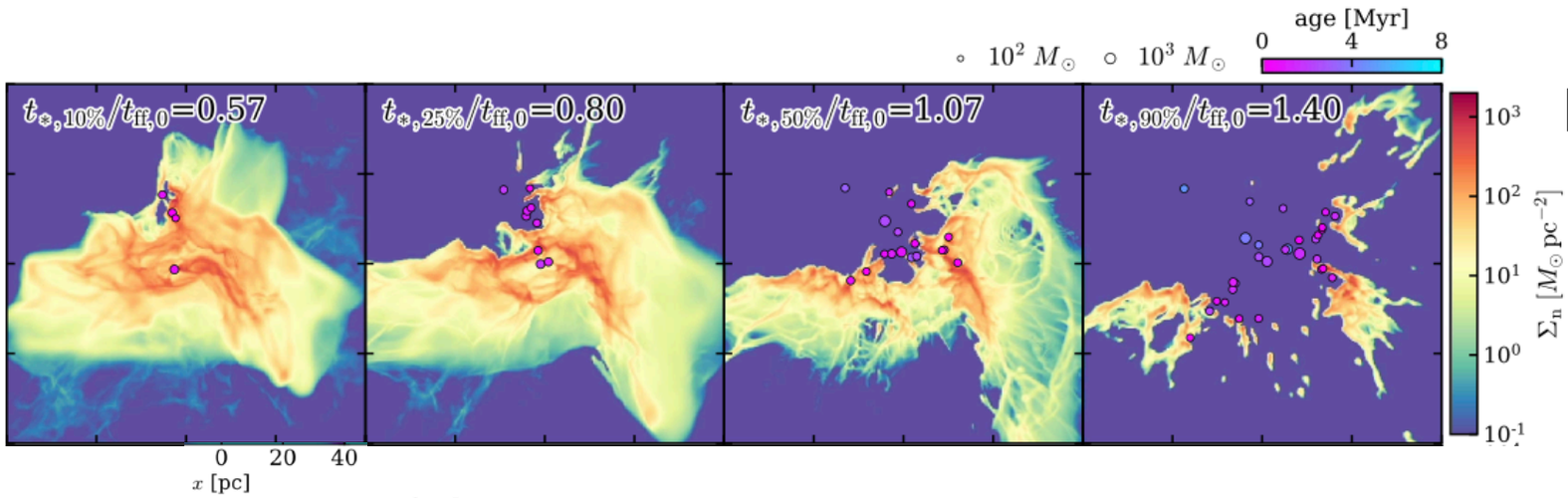


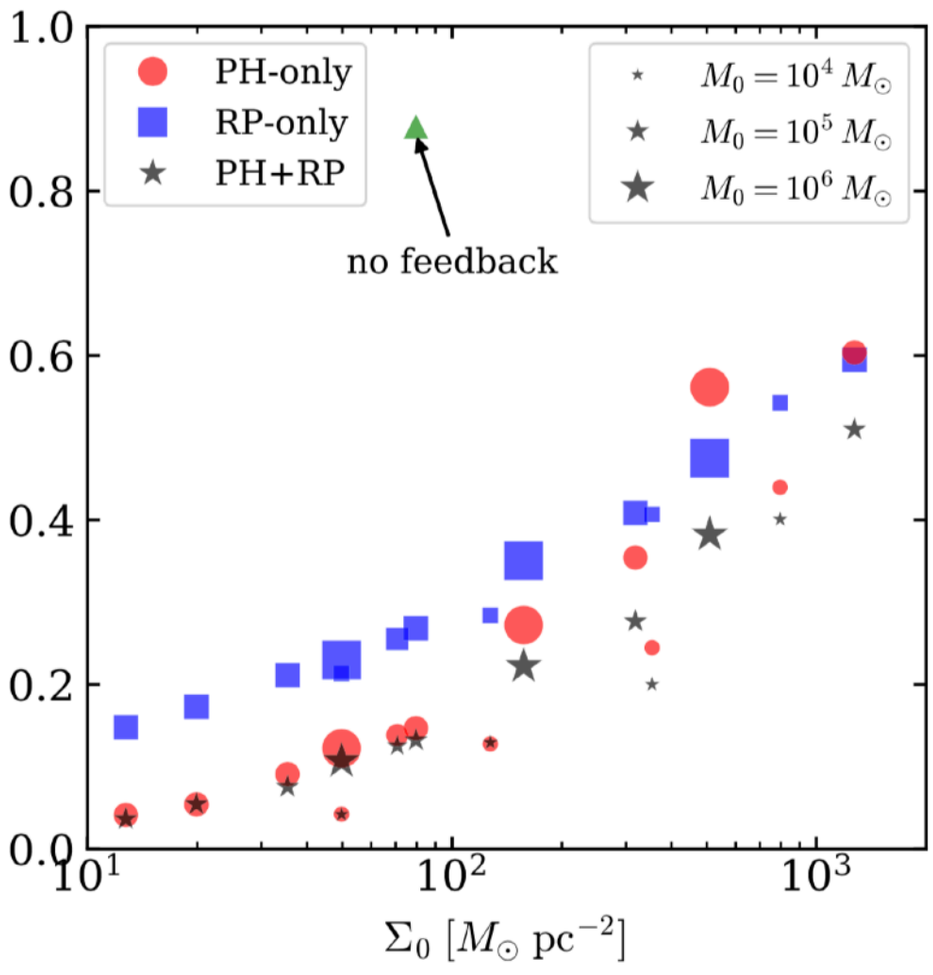
How does feedback alter star formation?

See also: Geen+ 2021,2023; Lancaster+ submitted

Star formation efficiency: ionization vs. RP



Kim+ 2018



$$\mathrm{SFE} = \frac{\sum M_*}{M_{\rm cloud}}$$

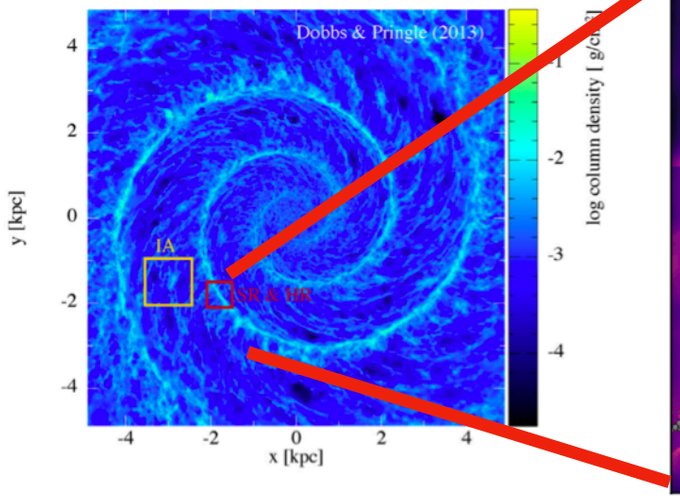
surface density

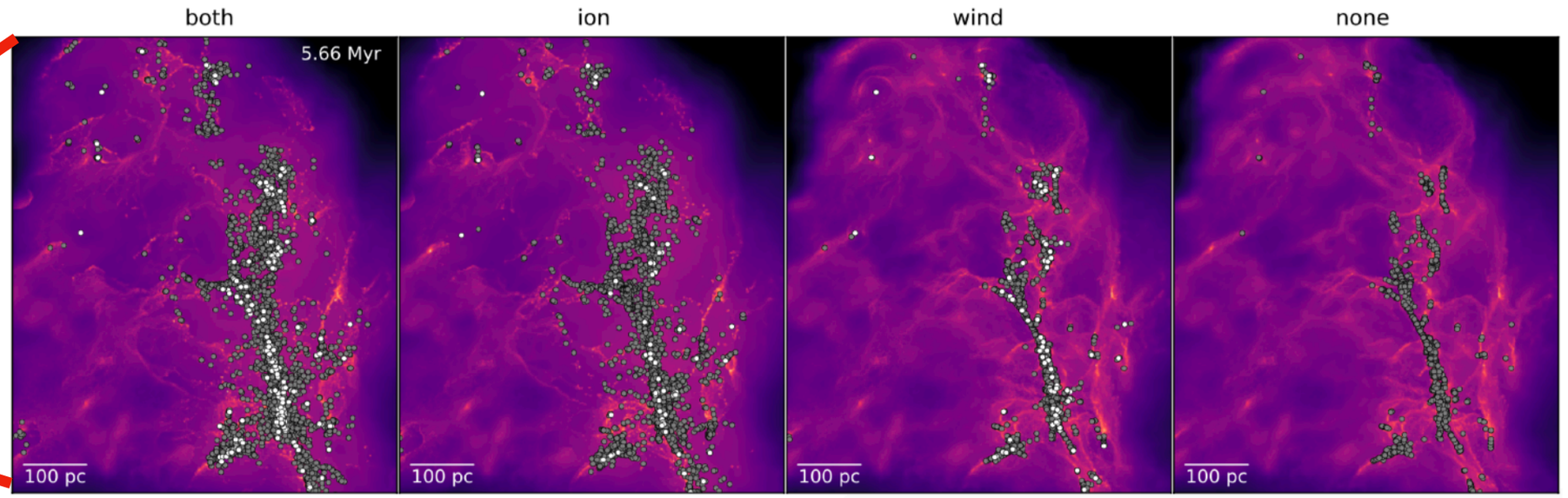
- feedback lowers SFE
- photoionization > RP
  (at low surface density)

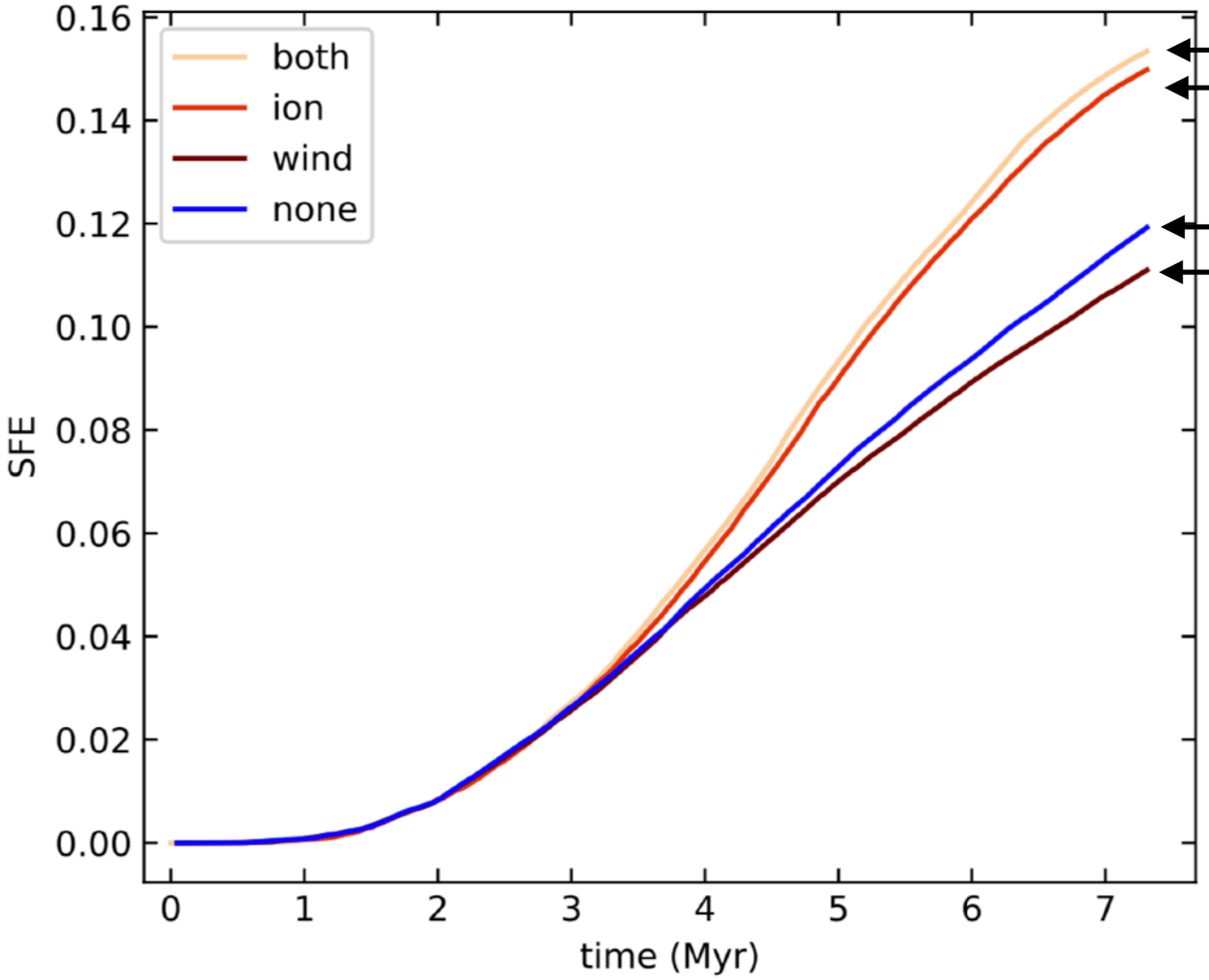
See also: Howard+ 2017; Decataldo+ 2020; Geen+2020; Fukushima+ 2020,2022; Guszejnov+ 2022; Menon+ 2022,2024

Photoionization vs. winds

Ali+ 2022







wind
non-wind

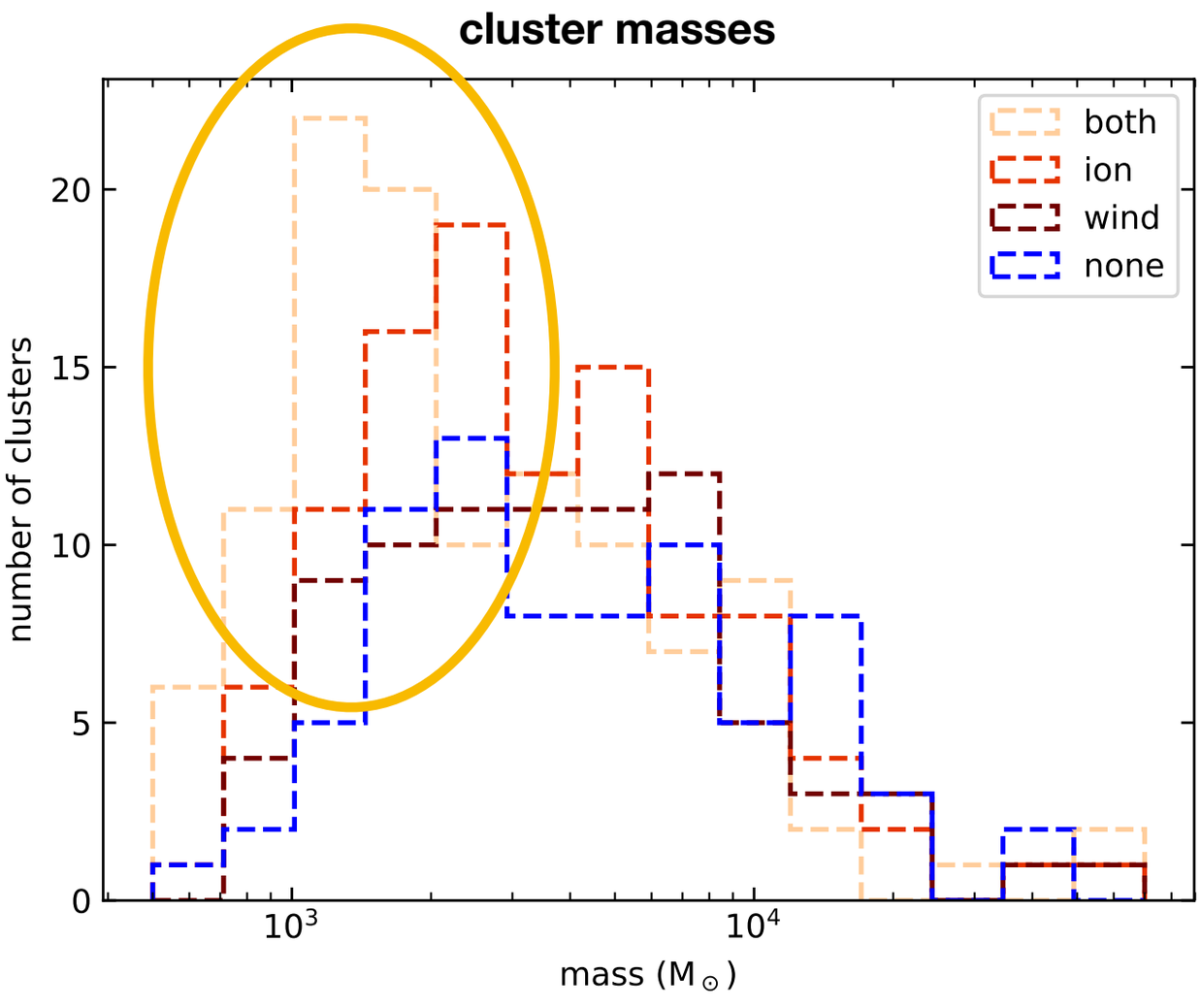
non-wind
wind

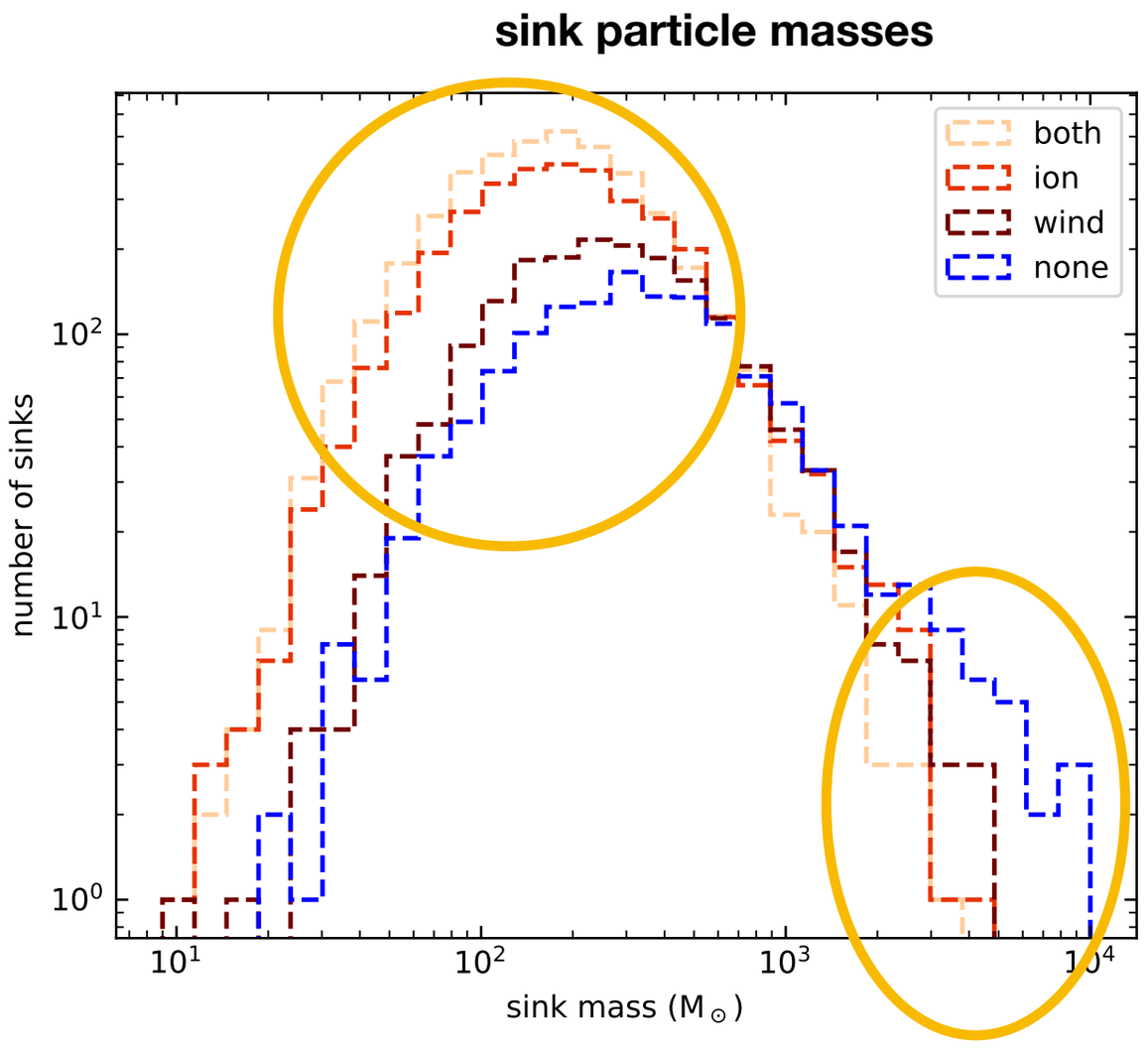
- feedback slightly increases SFE
- winds are negligible

See also: Dale+ 2014; Ngoumou+ 2015; Haid+ 2018; Geen+ 2020,2021,2023; Lancaster+ submitted

Photoionization vs. winds

DBSCAN (Ester+ 1996) clustering algorithm applied to sink particles



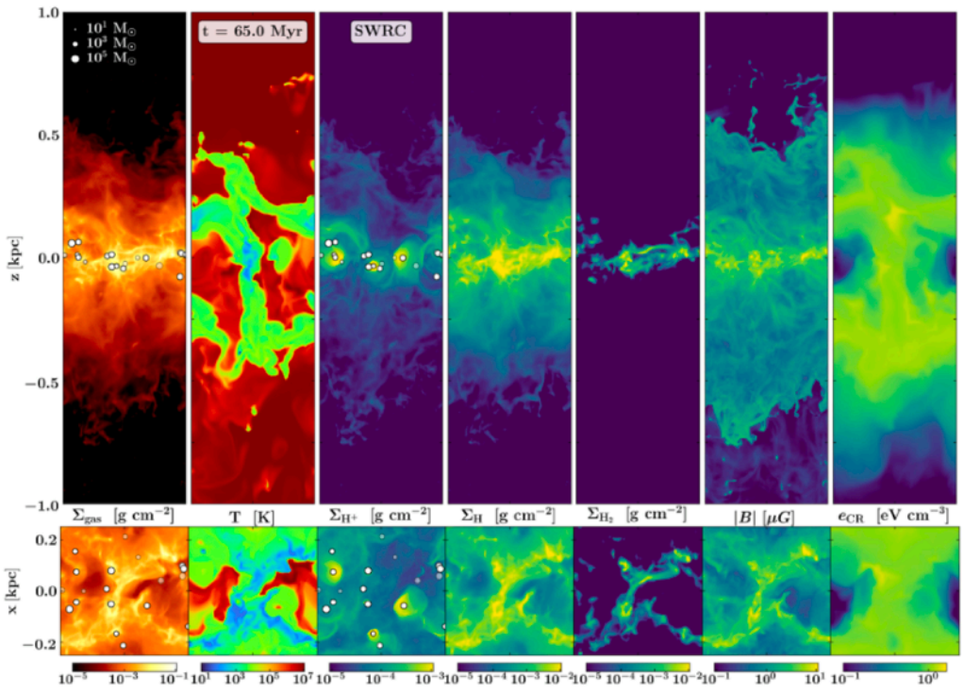


adding winds

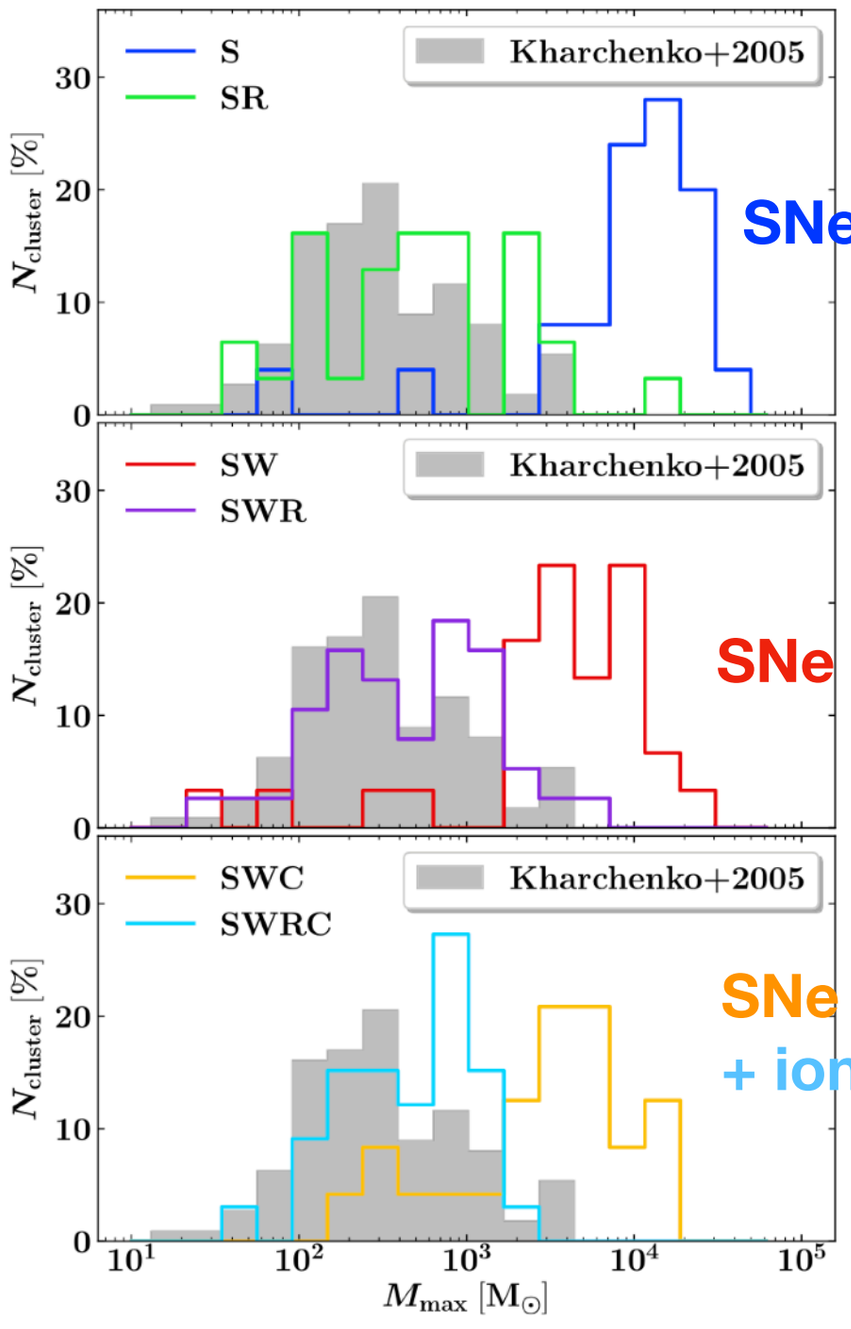
produces more low-mass clusters

Cluster mass functions

Rathjen+ 2021



SILCC simulations:
multi-physics, multi-phase ISM



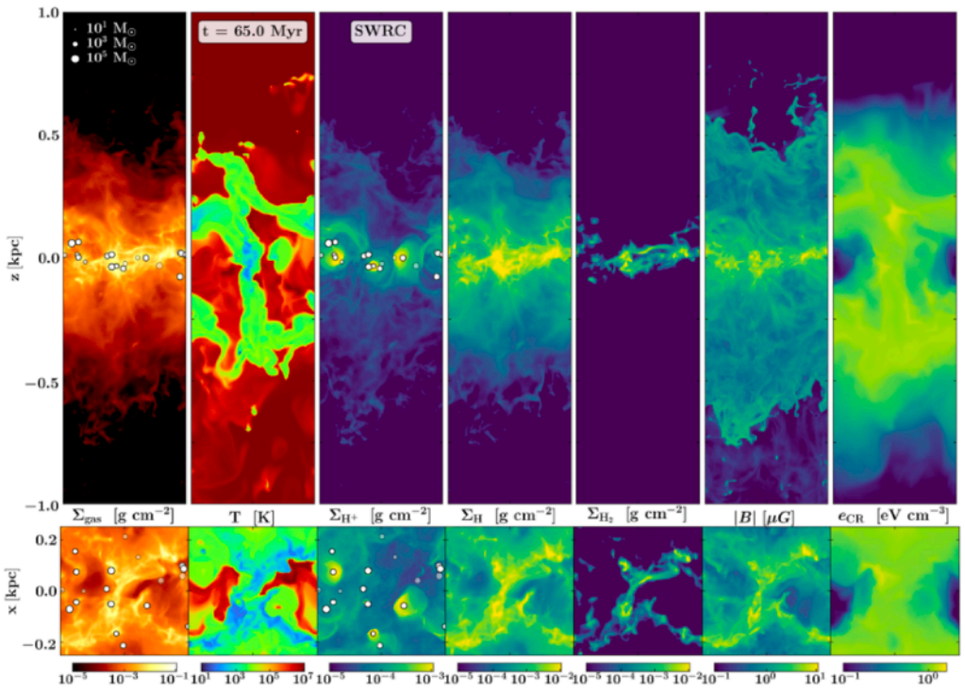
SNe + ionization

SNe + winds + ionization

SNe + winds + cosmic rays + ionization

Cluster mass functions

Rathjen+ 2021



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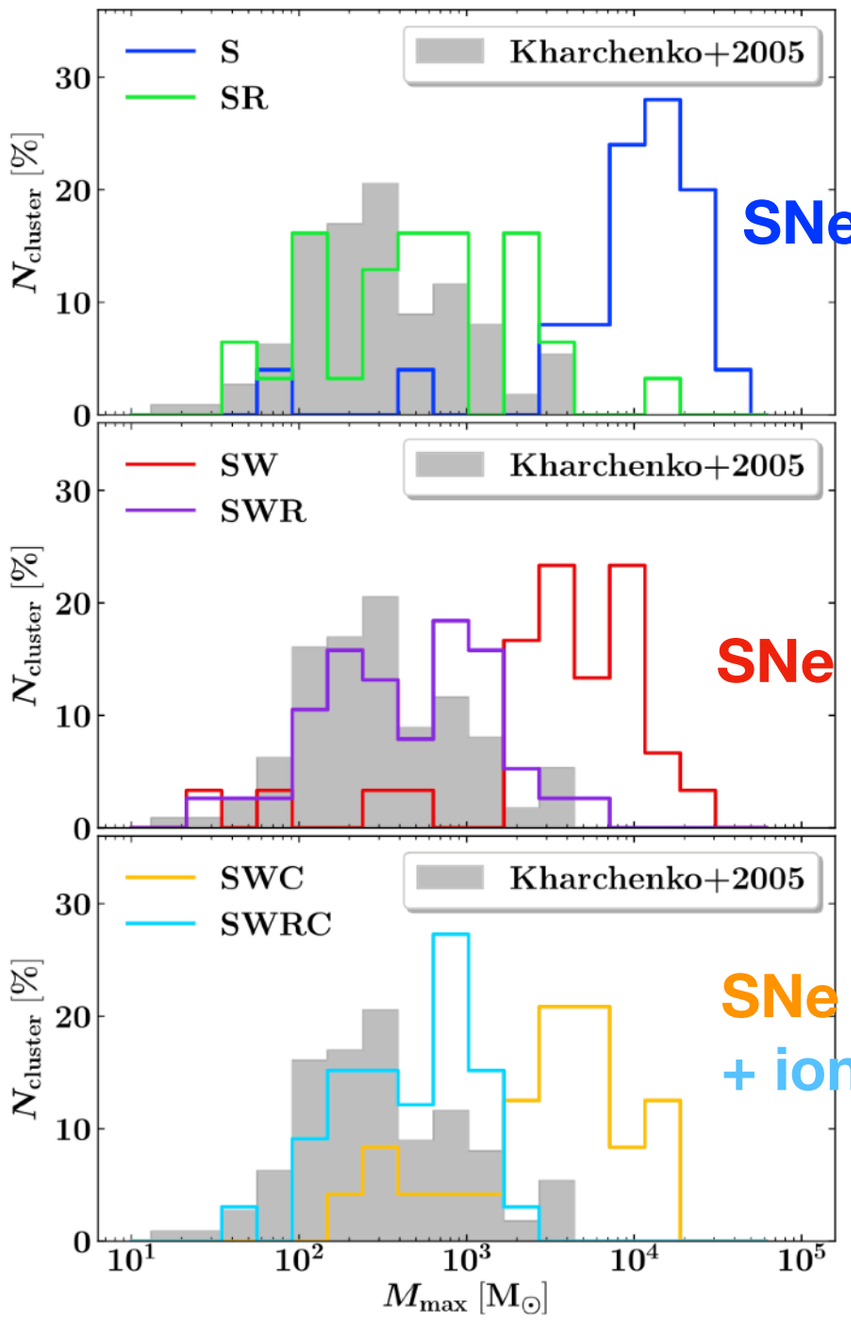


SNe + ionization

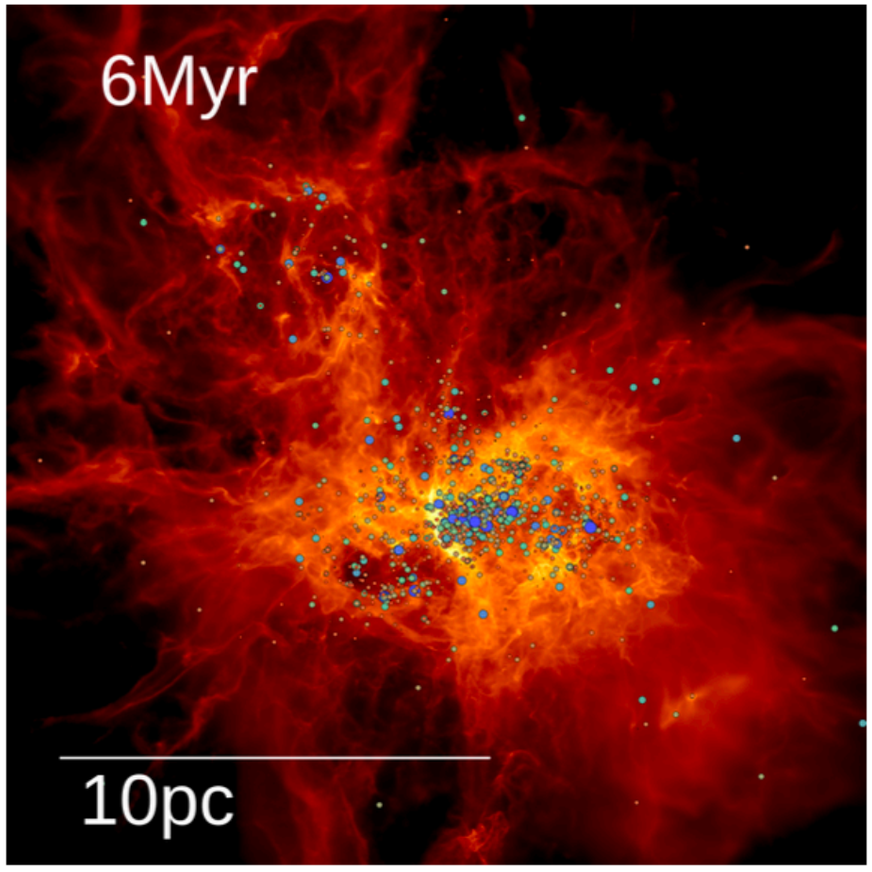
SNe + winds + ionization

SNe + winds + cosmic rays + ionization

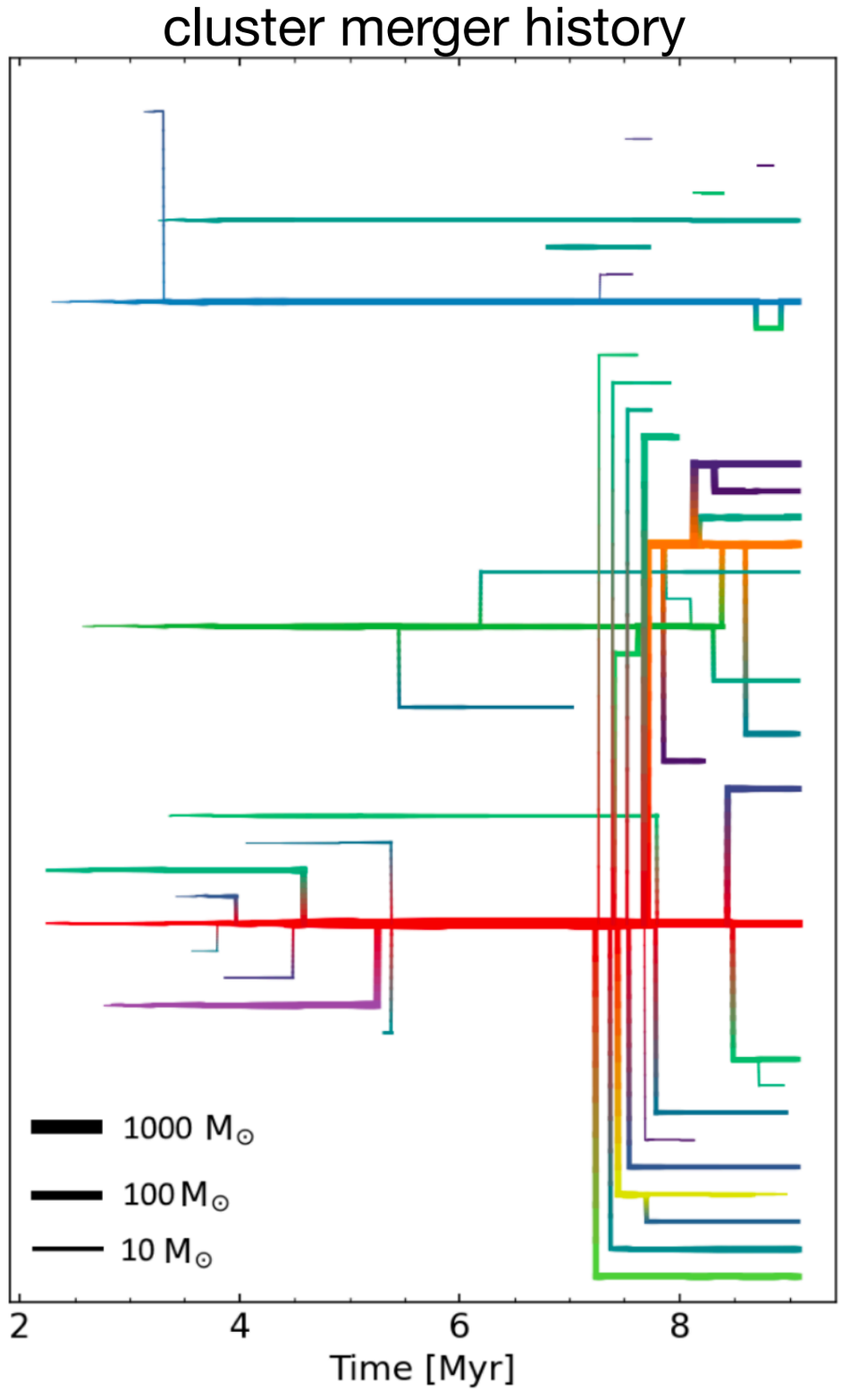
radiation is key!

Cluster assembly

- Massive clusters tend to form through mergers of small clusters

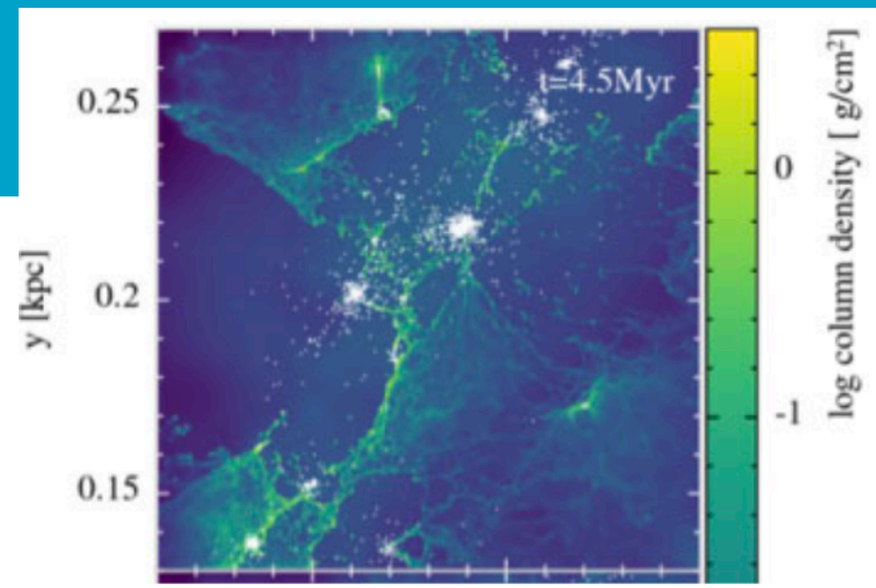


Guszejnov+ 2022

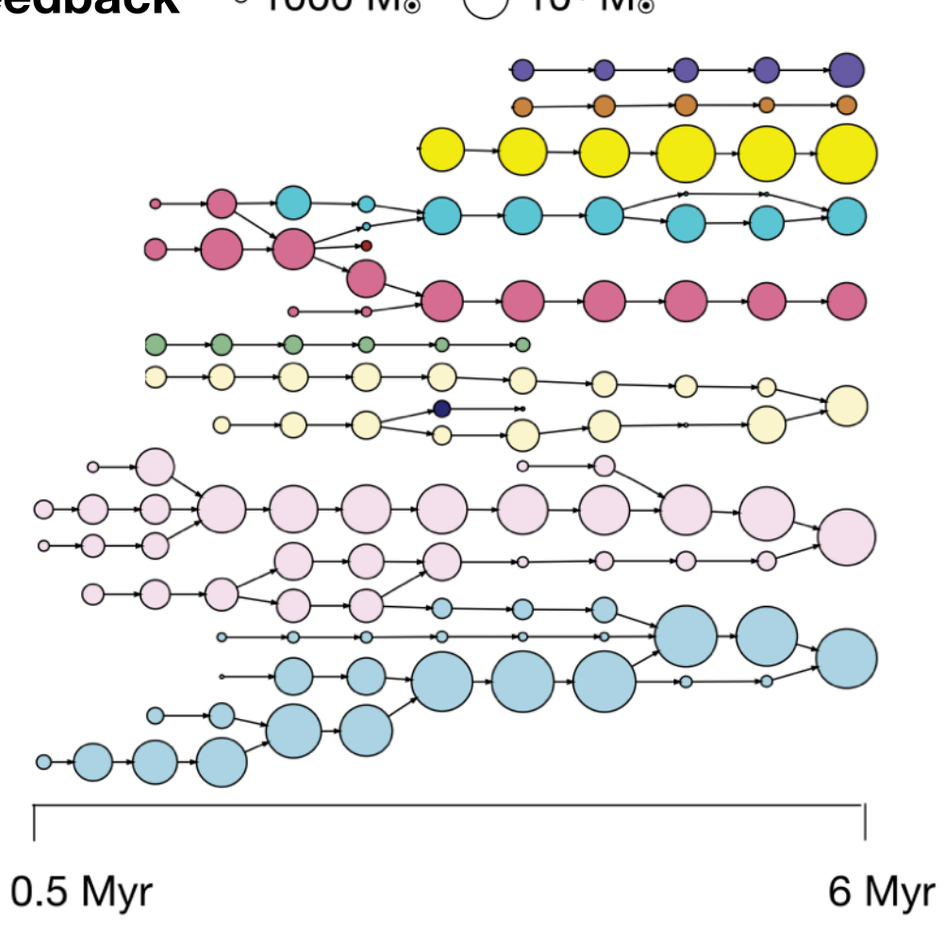


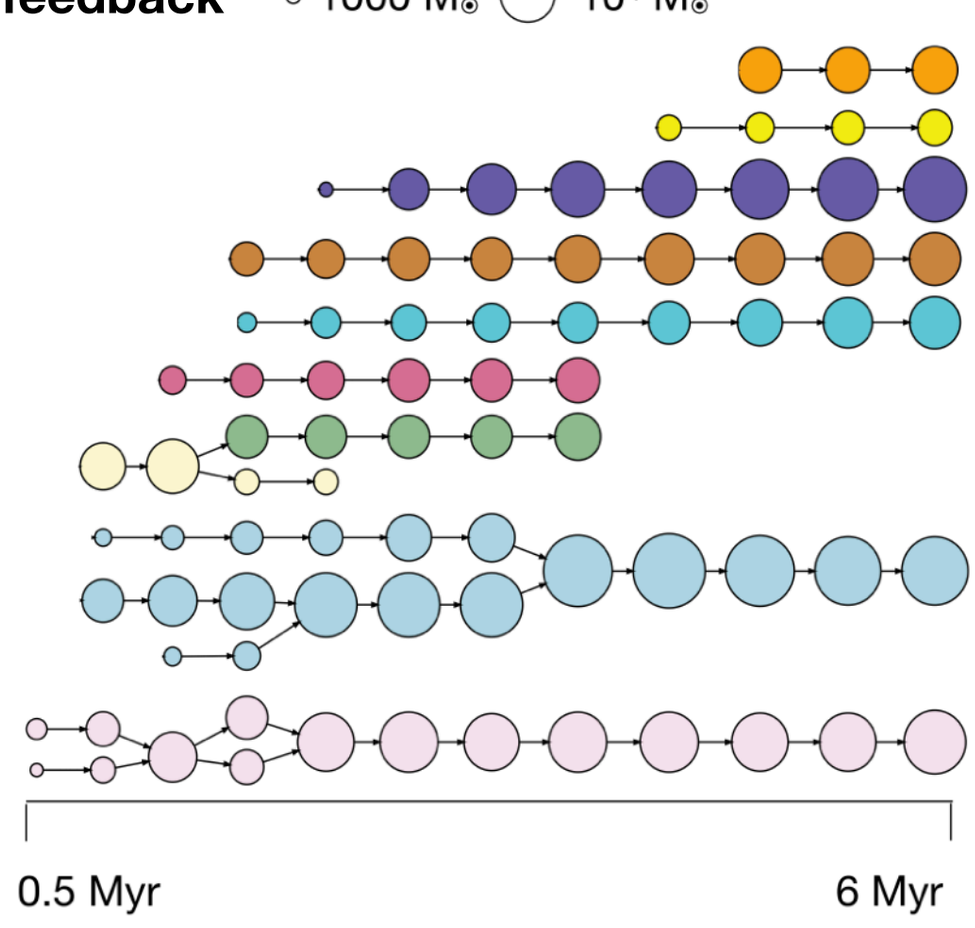
Cluster assembly

- Massive clusters tend to form through mergers of small clusters
- + more mergers with feedback

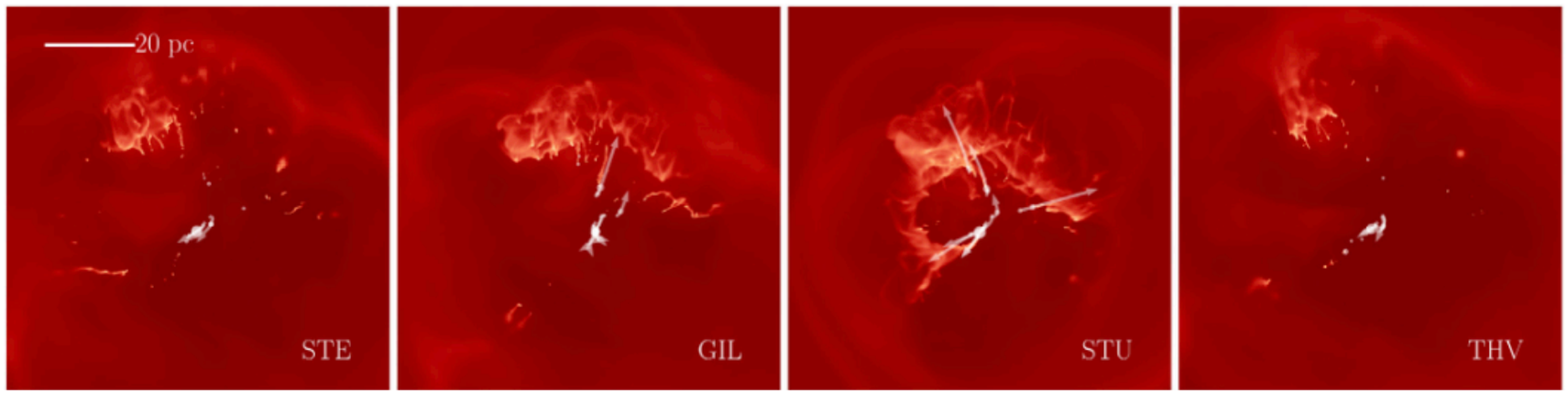


Dobbs+ 2022





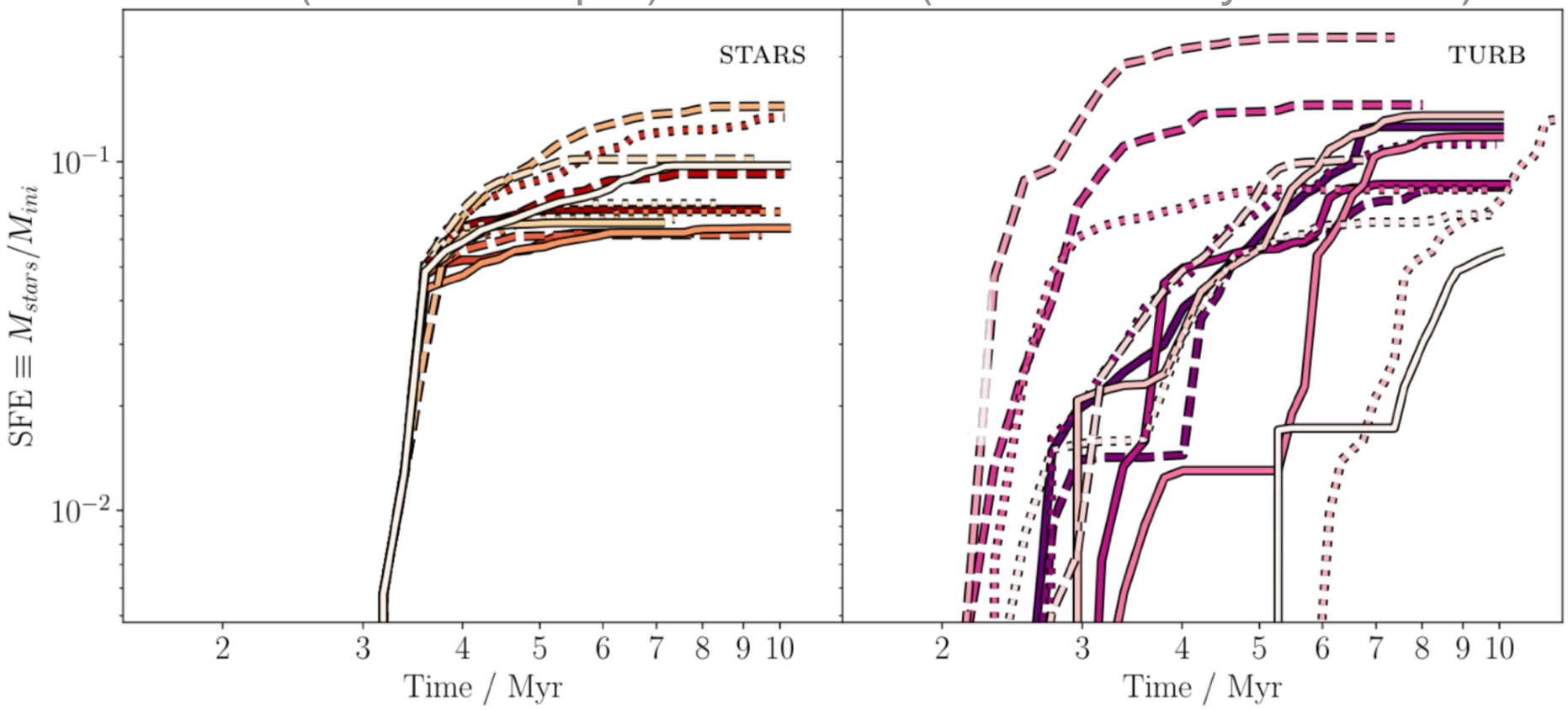
Uncertainties....



Geen+ 2018
clouds with ionization

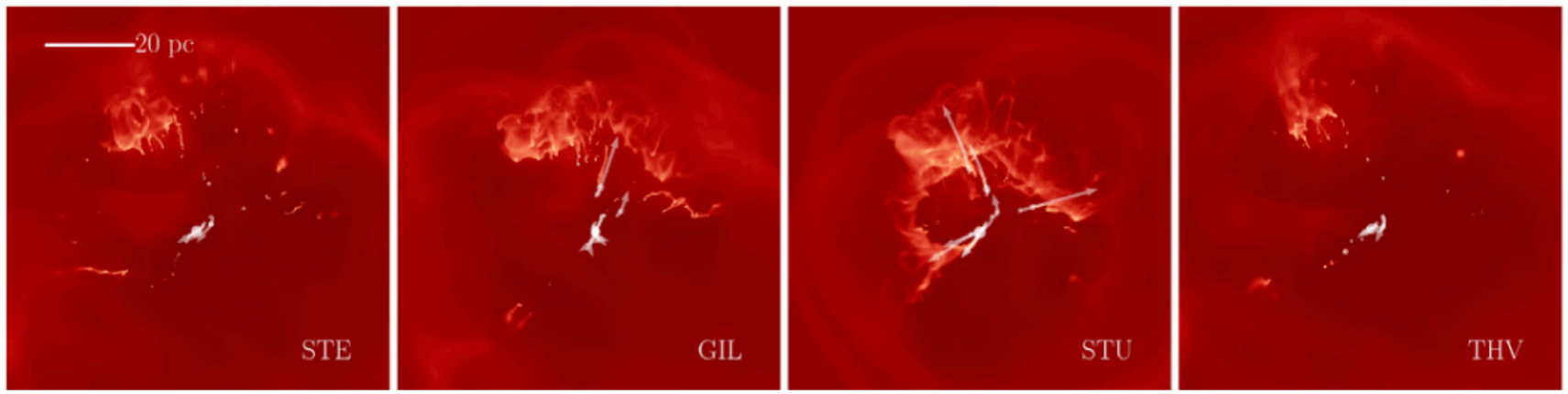
star sampling realisations
(feedback input)

turbulence realisations
(cloud velocity/structure)



See also: Jaffa+ 2022

Uncertainties....



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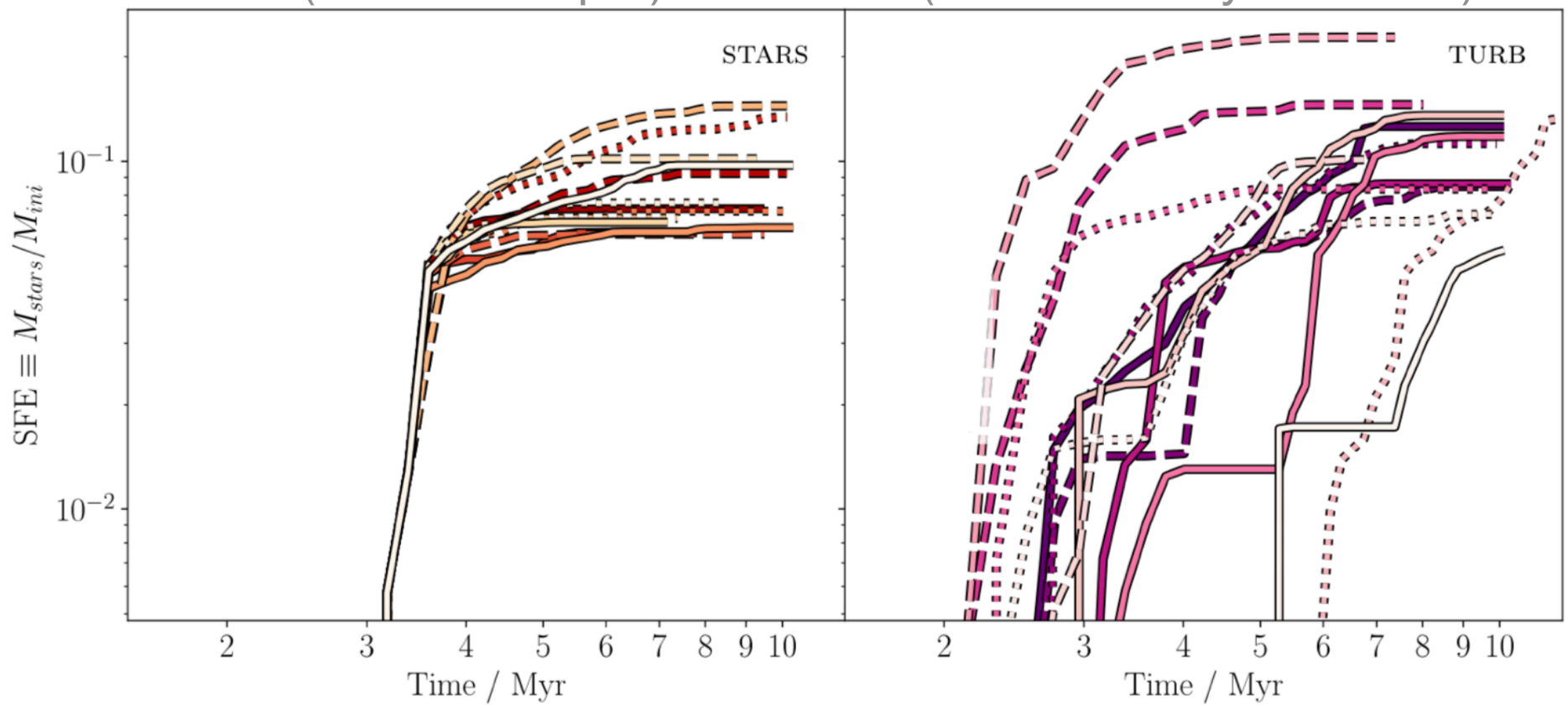


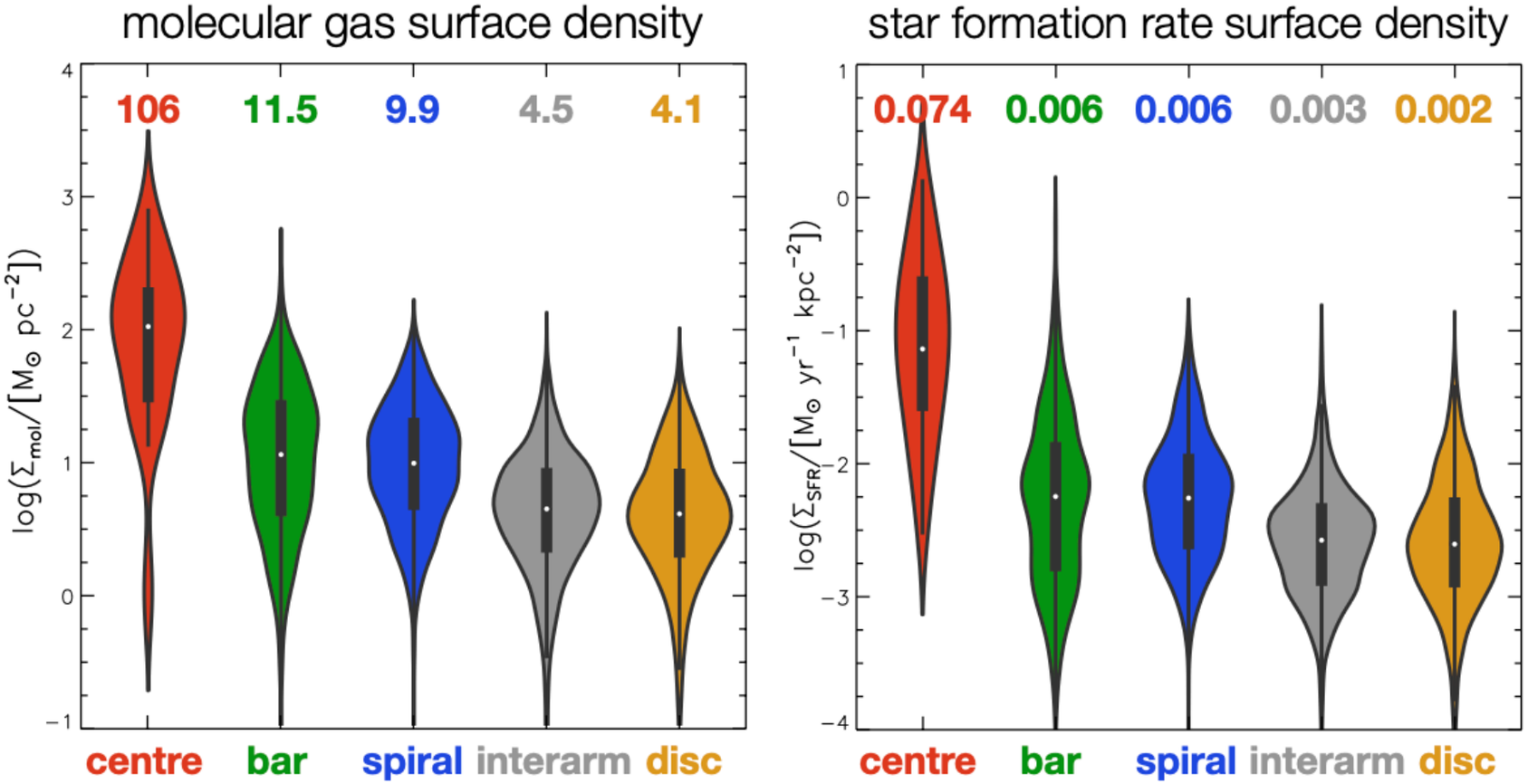
numerics / initial conditions matter!

See also: Jaffa+ 2022

Galactic environments

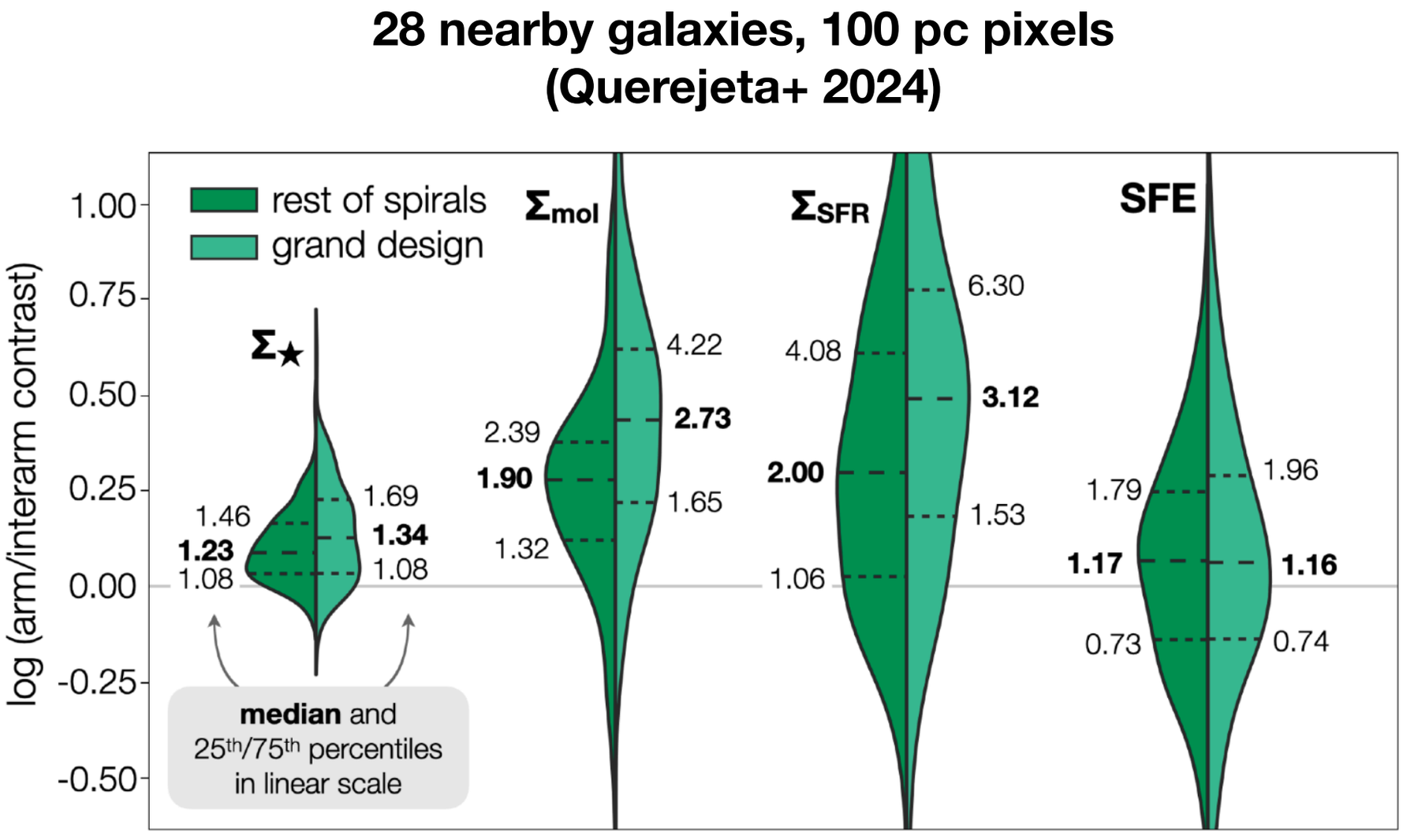
- Most MW massive clusters are near the Centre or Bar (e.g. Arches, Quintuplet, W43)

74 nearby galaxies, 100 pc pixels (Querejeta+ 2021)



(but also different external pressures, tidal forces, B-fields, etc...)

Arm vs. inter-arm

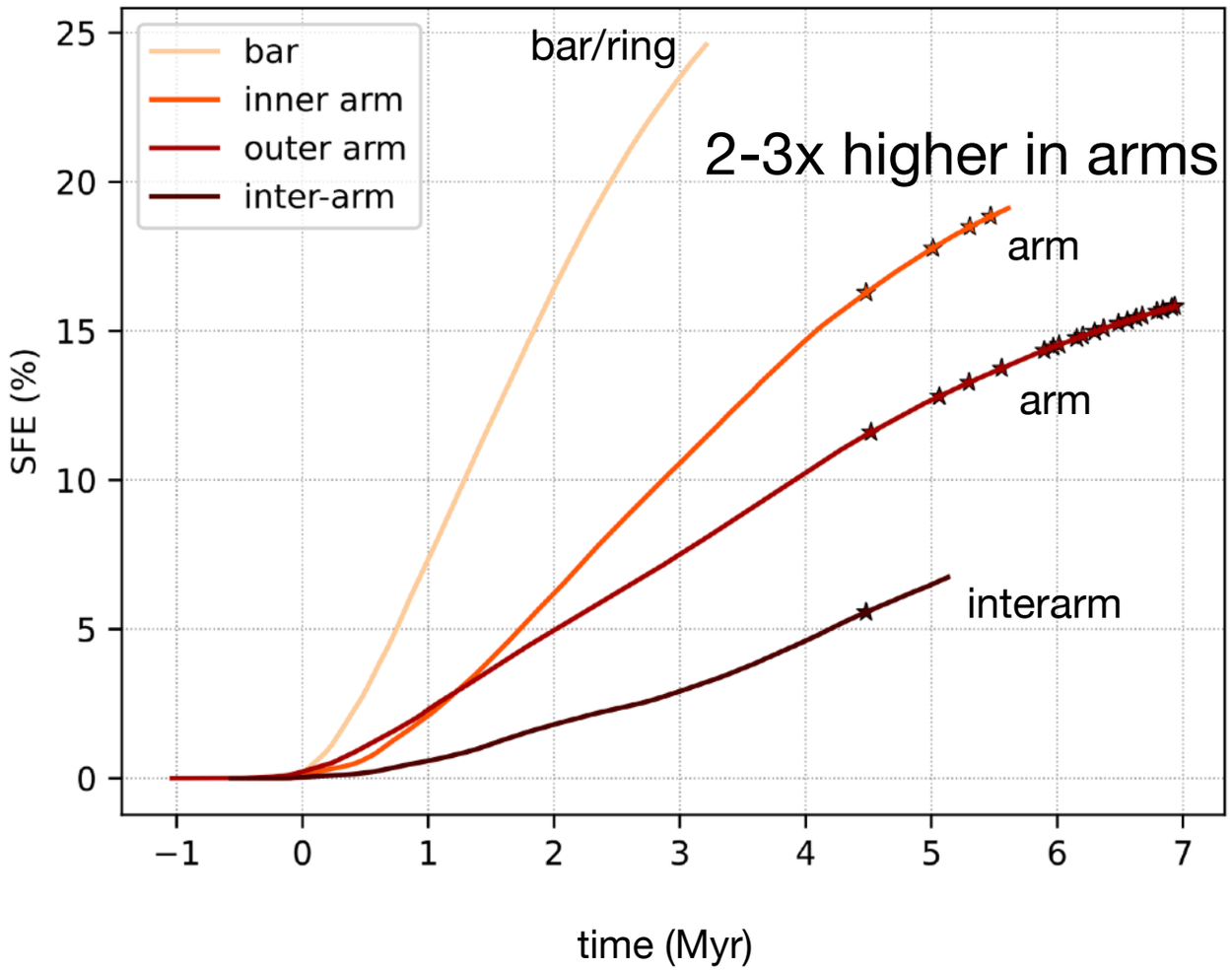


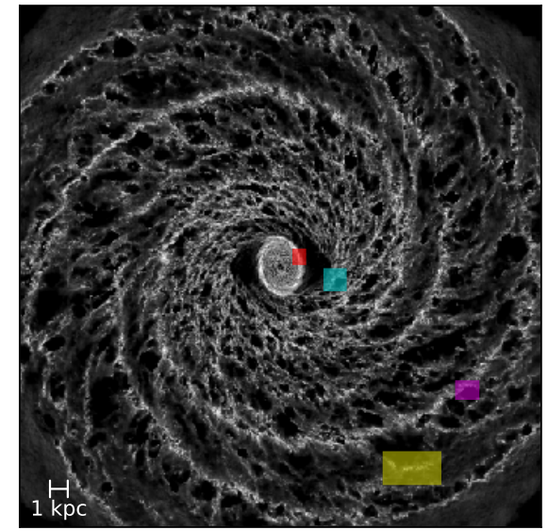
SFE in arms only
16% higher

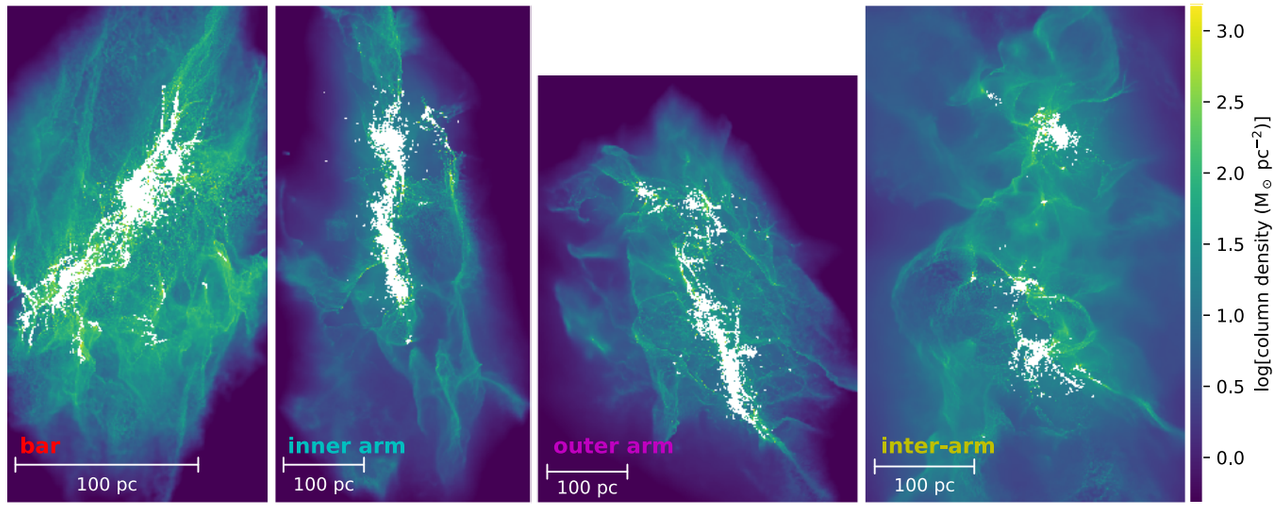
SFE = 1/depletion time = $\Sigma_{SFR}/\Sigma_{mol}$

Arm vs. interarm (simulations)

zoom-in simulations, sub-pc resolution (Ali+ 2023)







See also: Bending+ 2020,2022; Dobbs+ 2022a,b

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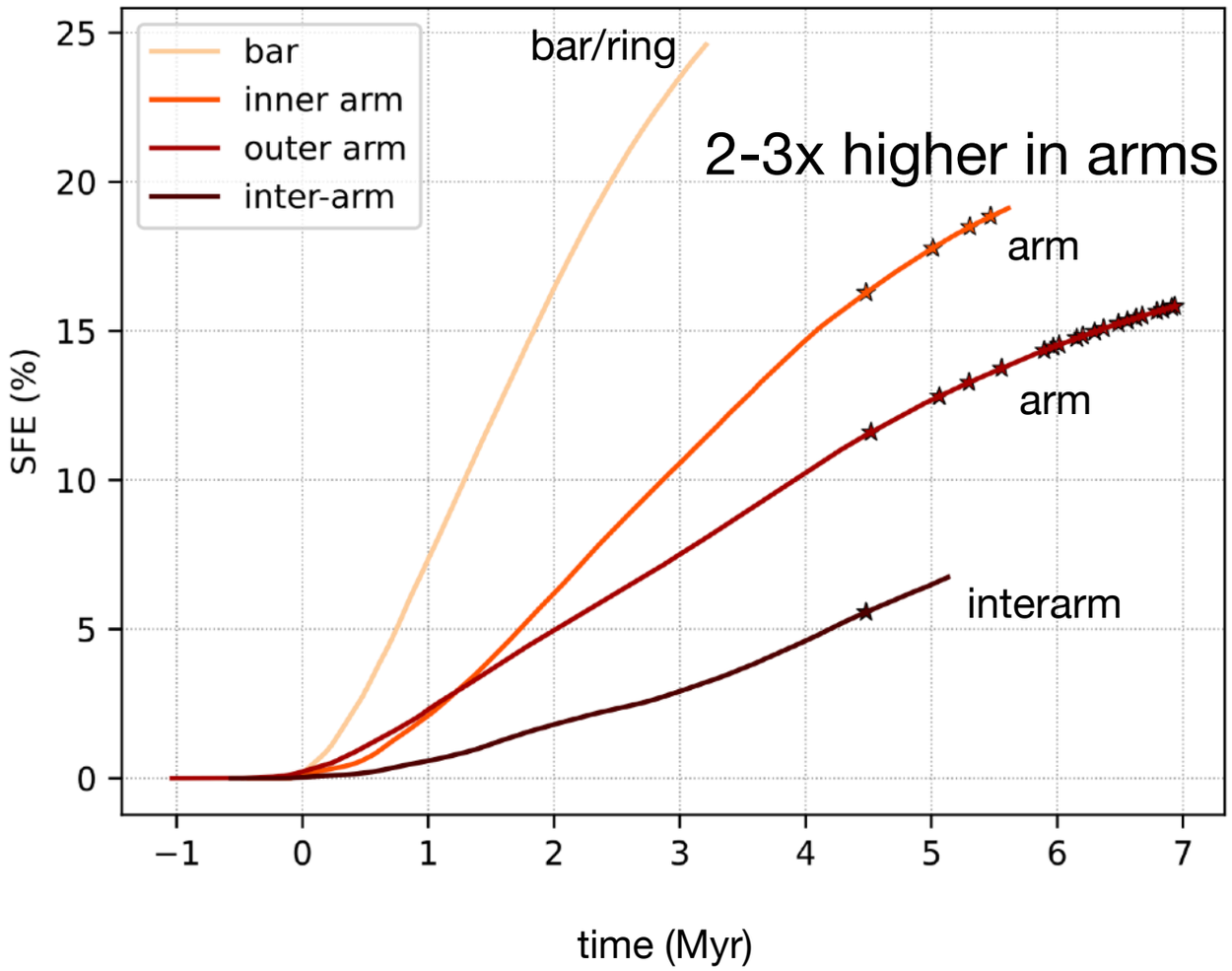
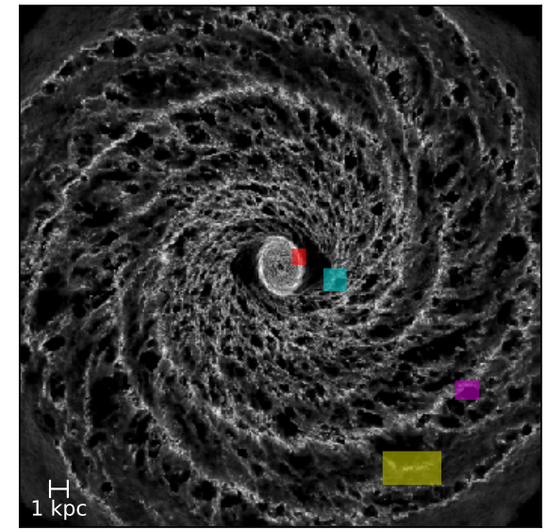
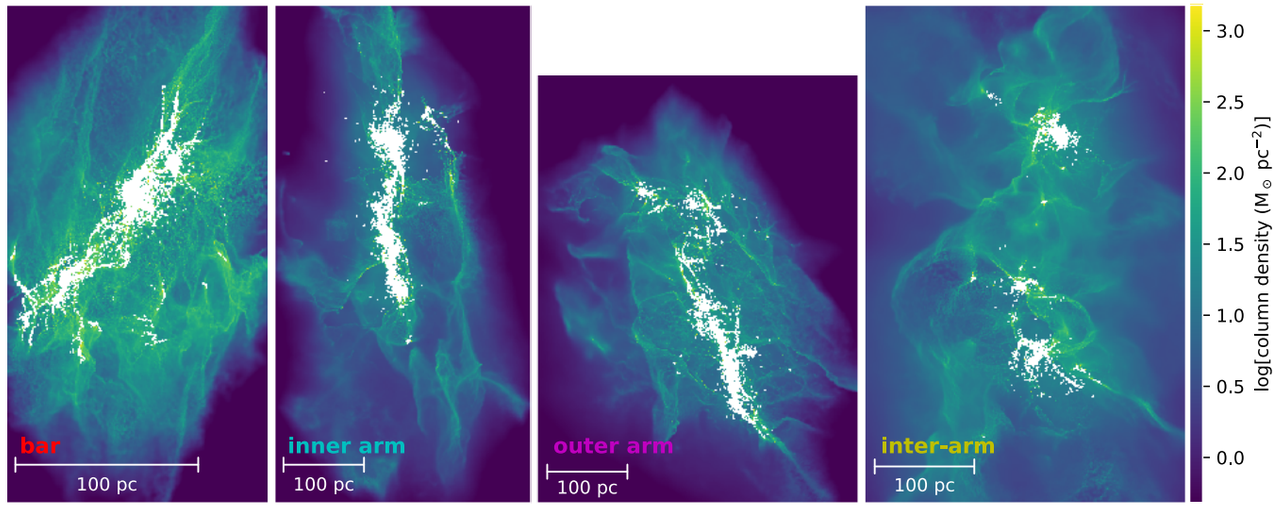






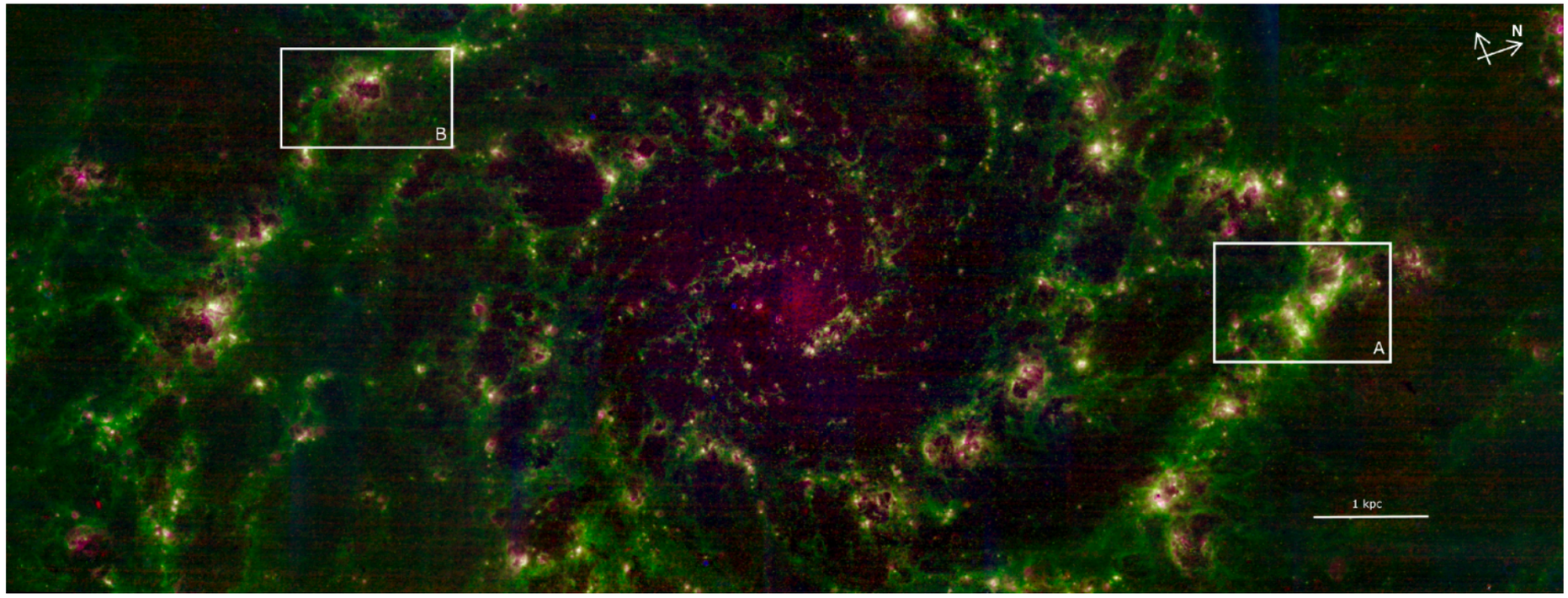
more work needed!

See also: Bending+ 2020,2022; Dobbs+ 2022a,b

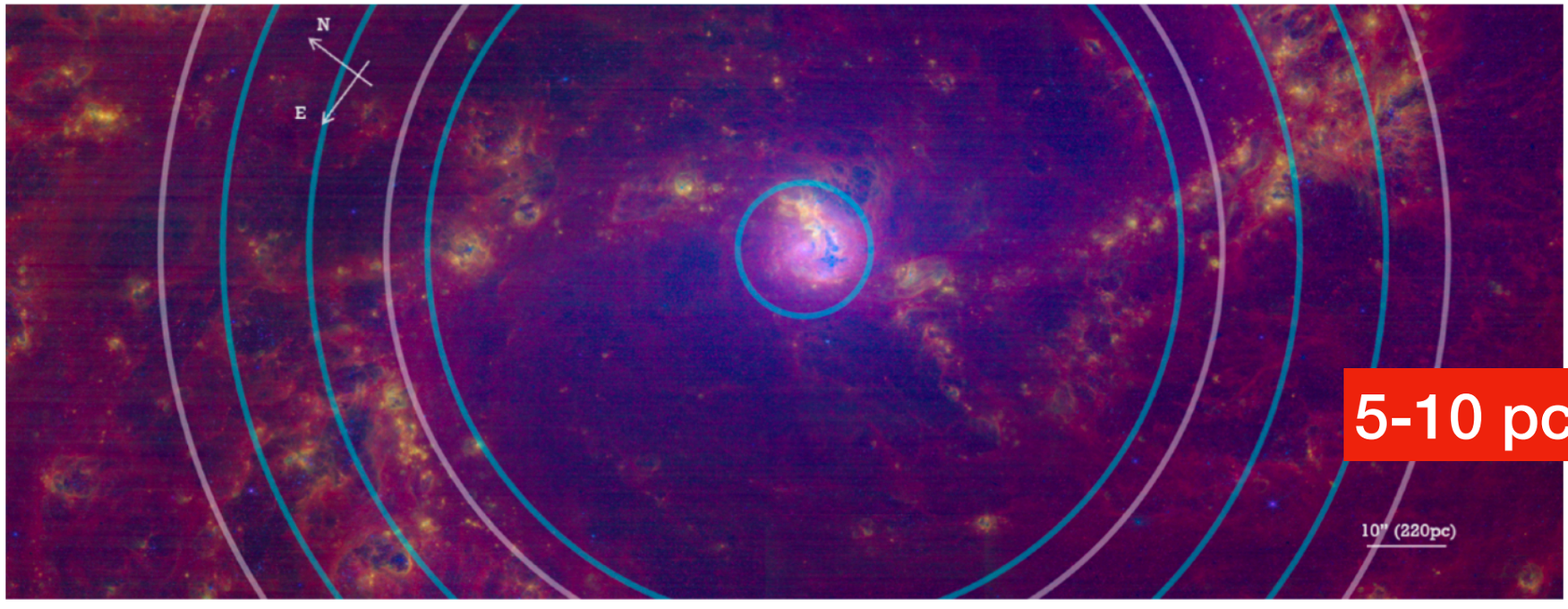
JWST FEAST survey

PI: A. Adamo

NGC 628 (Pedrini+AA 2024)



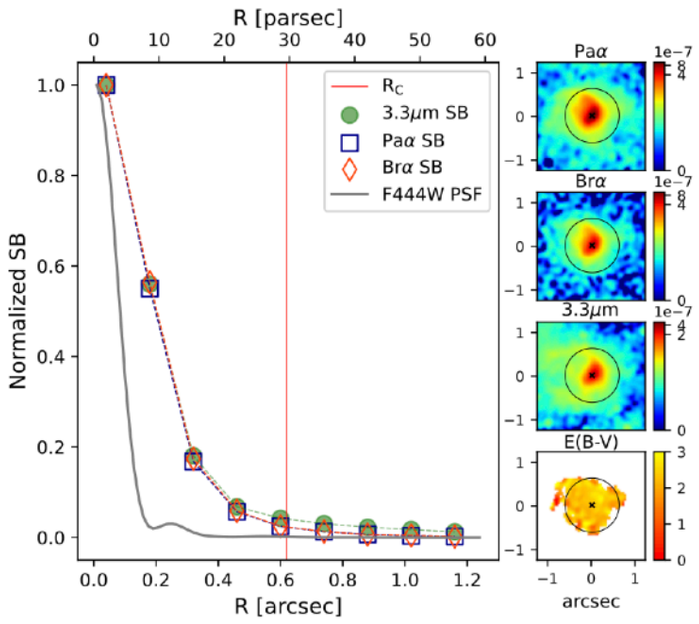
M83 (Knutas+AA submitted, arXiv:2505.08874)

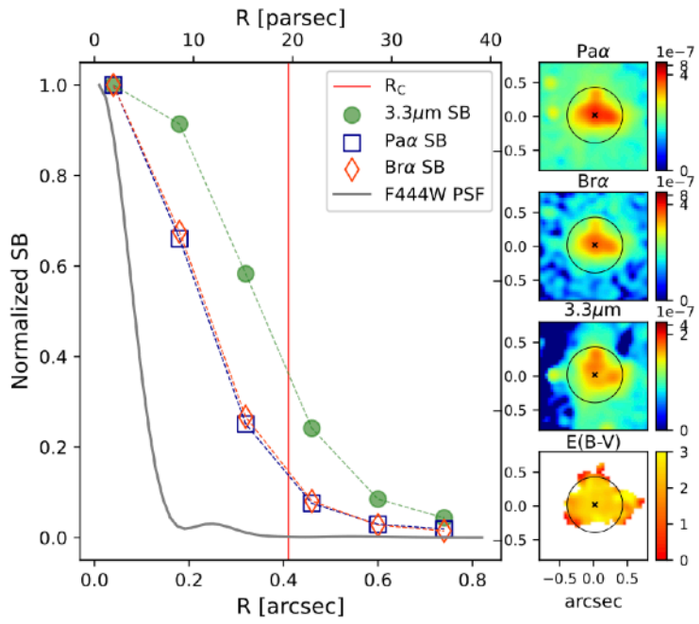


5-10 pc resolution

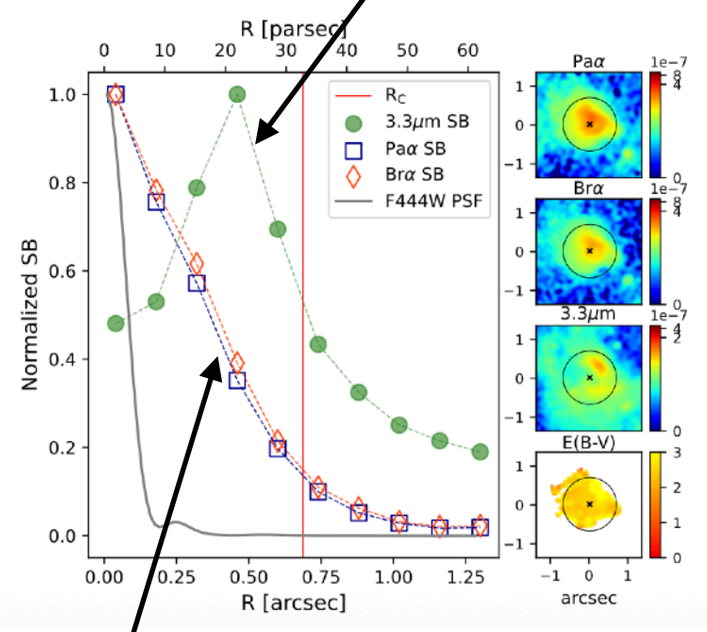
FEAST: emerging clusters

NGC 628 (Pedrini+AA 2024)





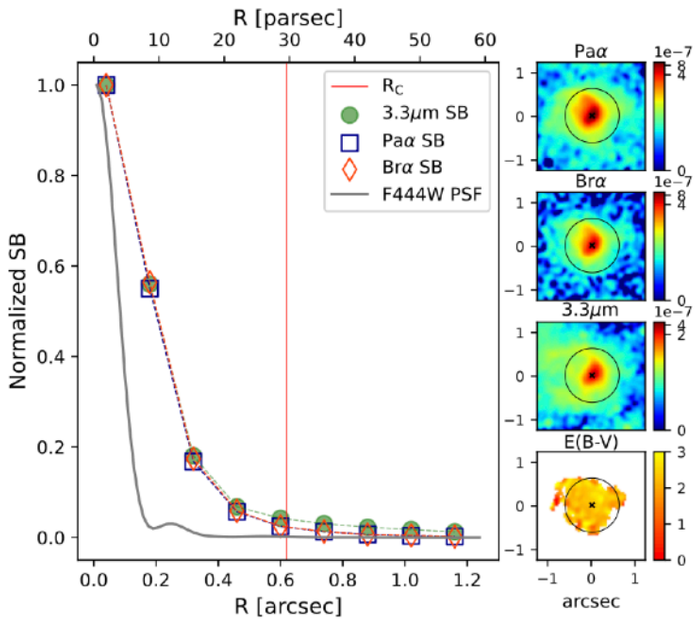
3.3 um PAH (PDR)

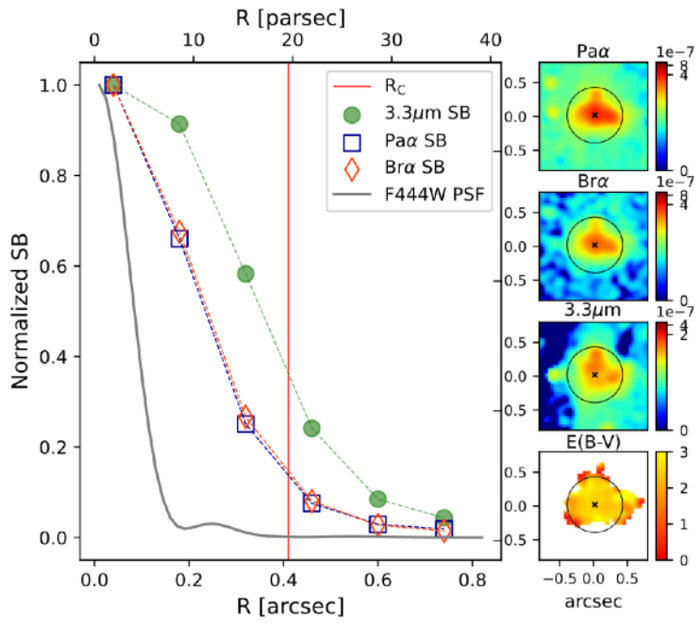


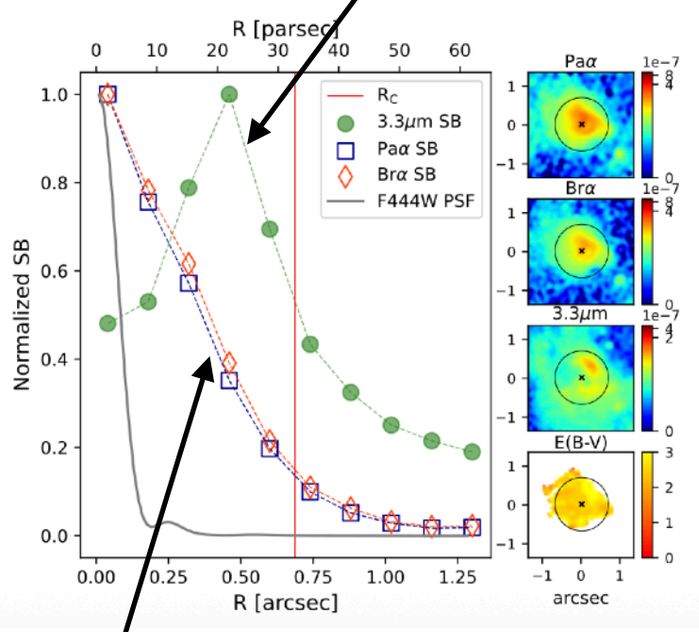
Pa-alpha (H II region)

FEAST: emerging clusters

NGC 628 (Pedrini+AA 2024)



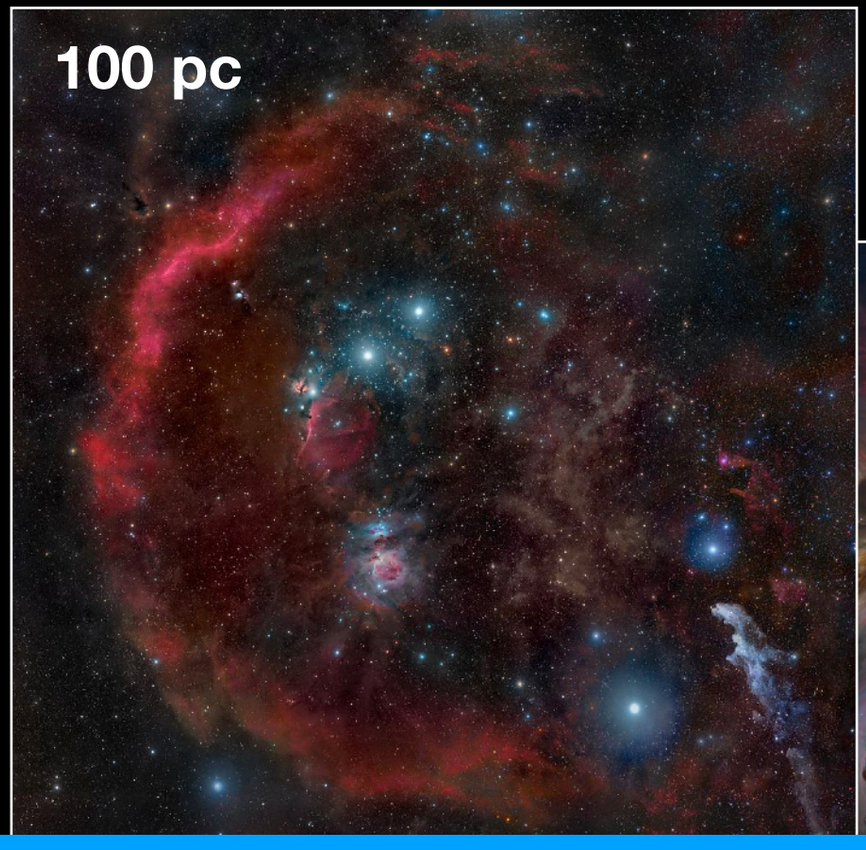




evolutionary sequence showing dispersal

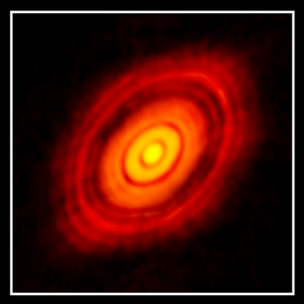
=> obtain timescales over galactic environments

> kpc

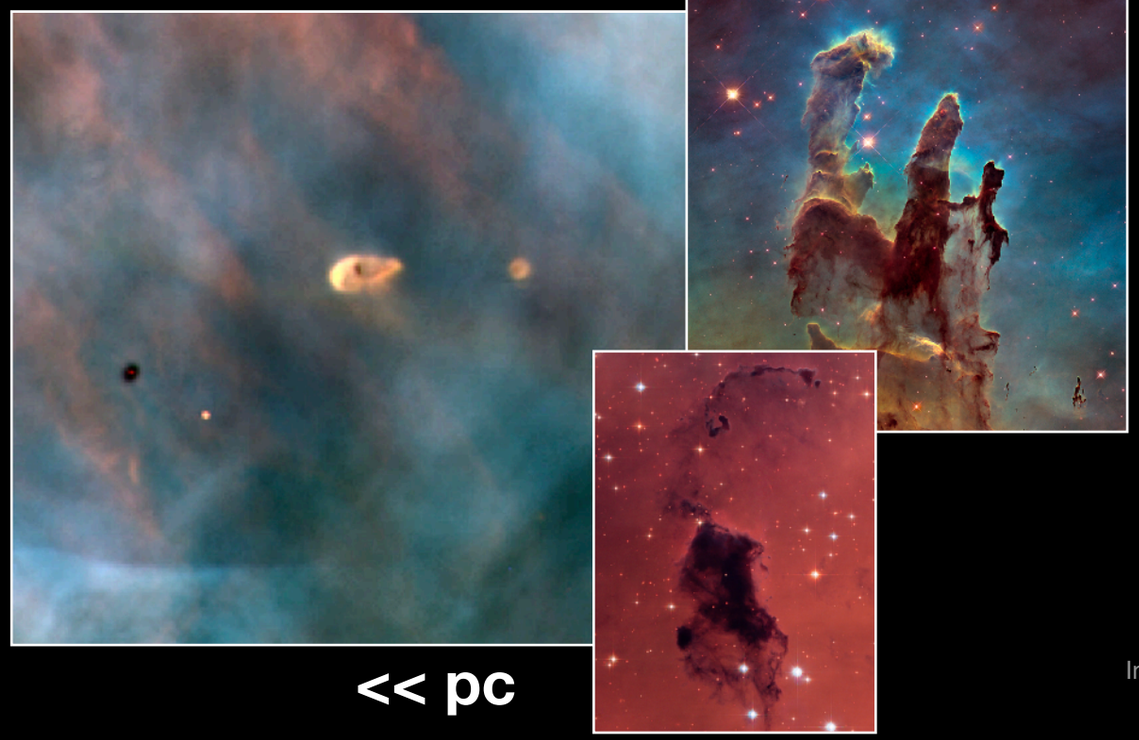


pc

stellar feedback is multi-scale



au



<< pc

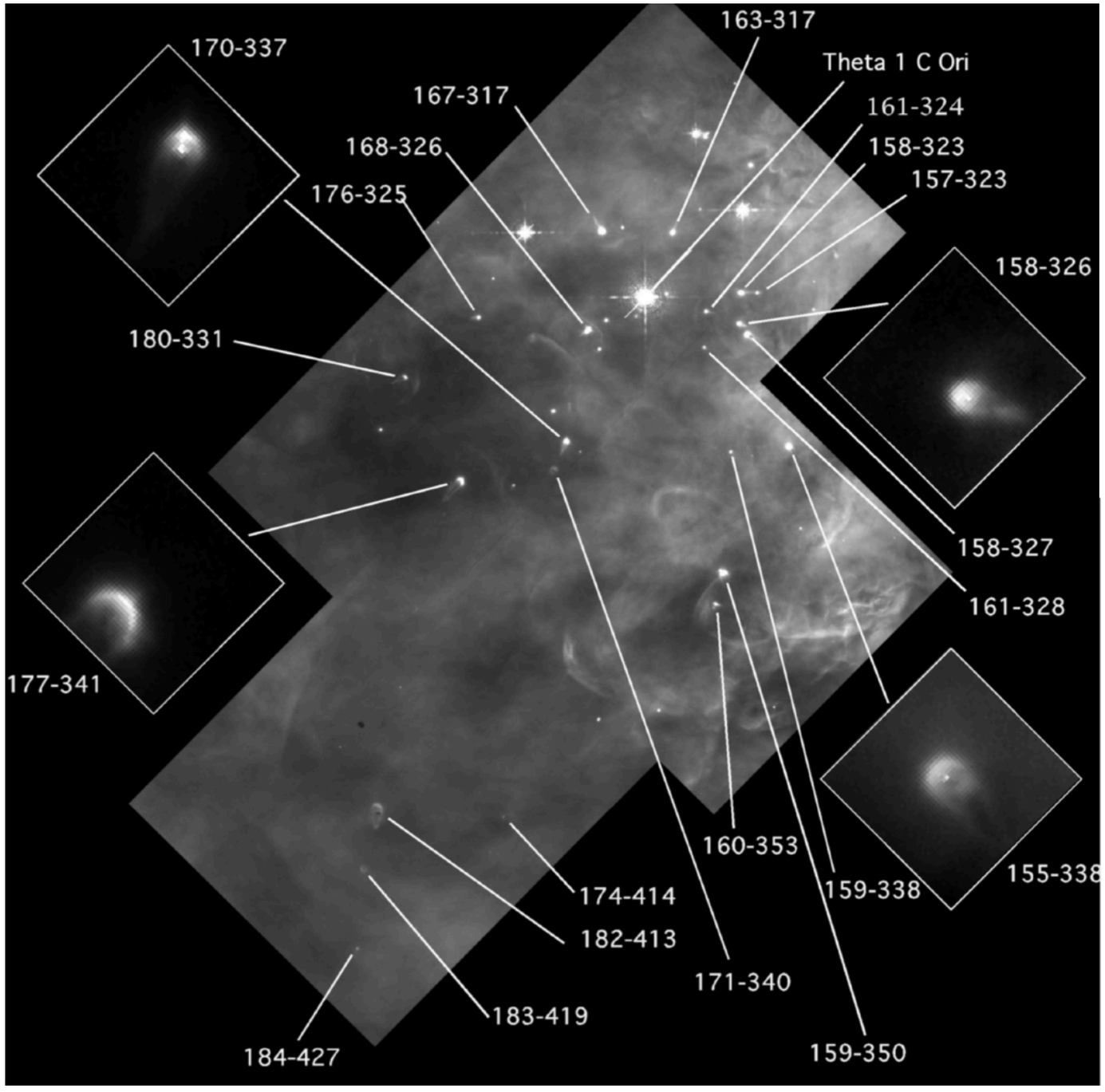
environmental dependences?

roles of "2nd order" feedback?

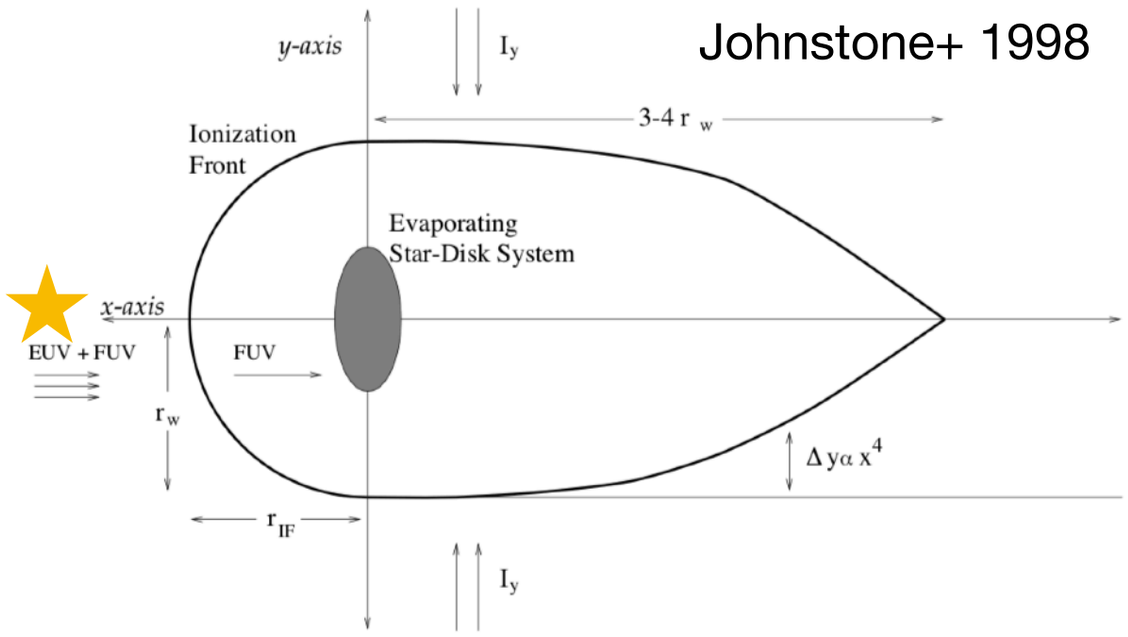
- stellar winds
- radiation pressure
  - direct vs. re-processed

Image credits: NASA, ESA, CSA, STScI, J. Lee (STScI), T. Williams (Oxford), PHANGS; R. Bernal Andreo; HST Orion Treasury Project Team, M. Robberto (STScI, ESA); Hubble Heritage Team (STScI/AURA); O'Dell/Rice University; ESO/NAOJ/NRAO)

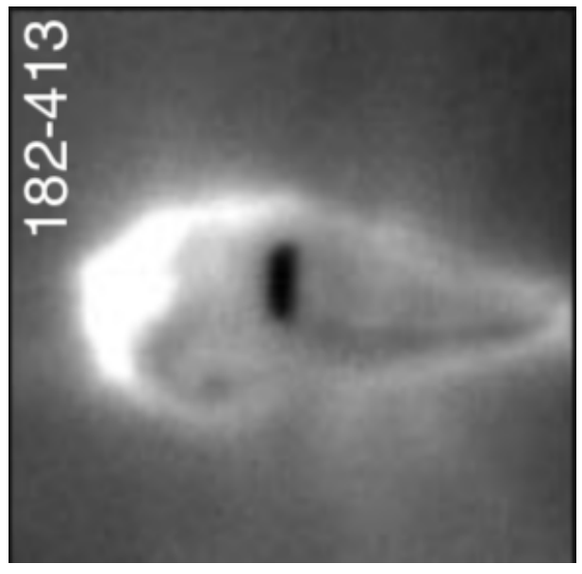
Proplyds



ONC (O'Dell 1998)

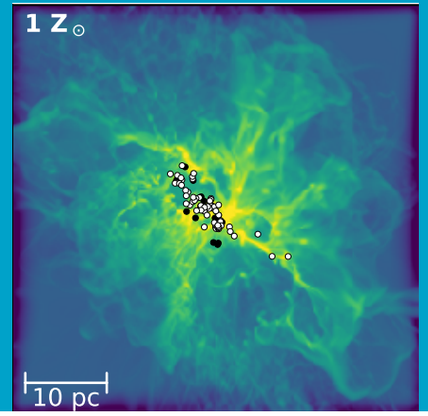


Johnstone+ 1998

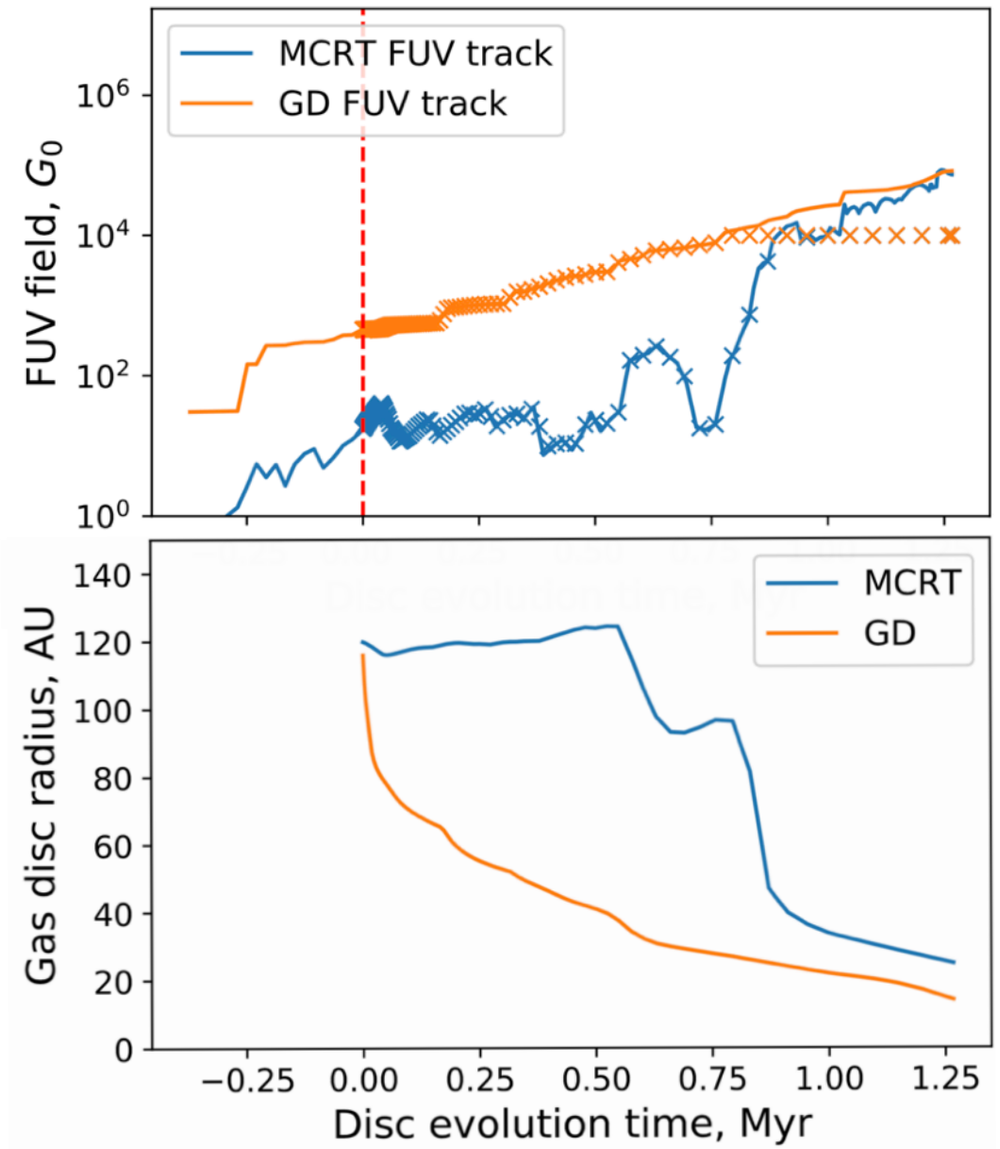


Bally+ 2000

Disc photoevaporation



- using Ali (2021) 10^5 $M_\odot$, $Z_\odot$ model
- Feed flux into disc models
  - viscous gas + grain growth/radial drift (Sellek+ 2020)
  - + external photoevaporation (FRIED grid Haworth+ 2018)
- Each disc
  - $1/r^2$ geometric dilution
  - MCRT absorption



Qiao,... Ali, 2022, MNRAS, 512, 3788

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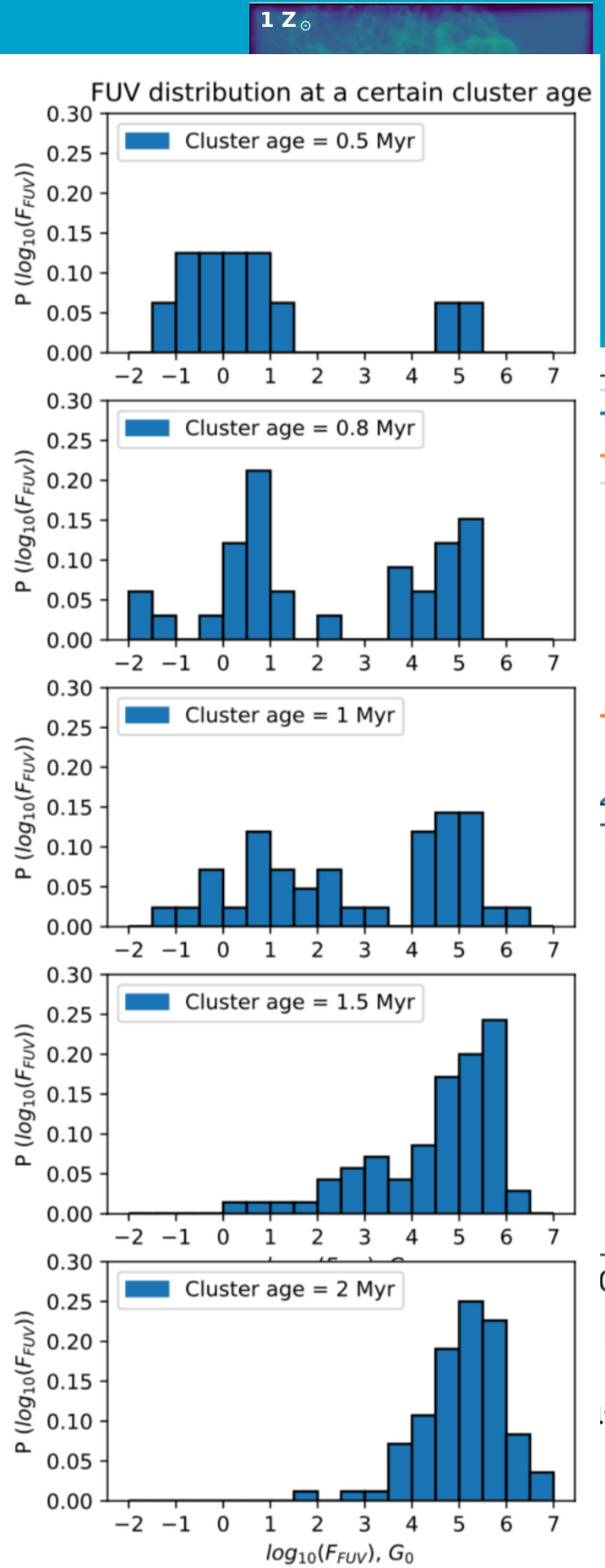

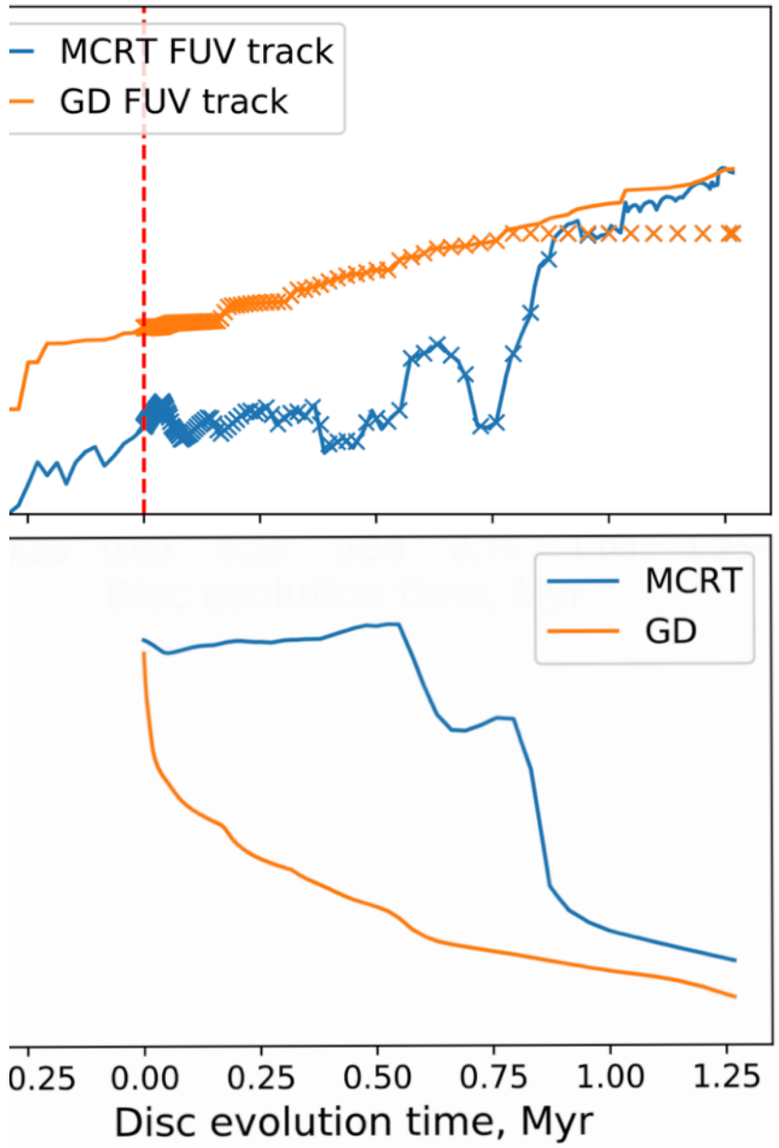

.o,... Ali, 2022, MNRAS, 512, 3788