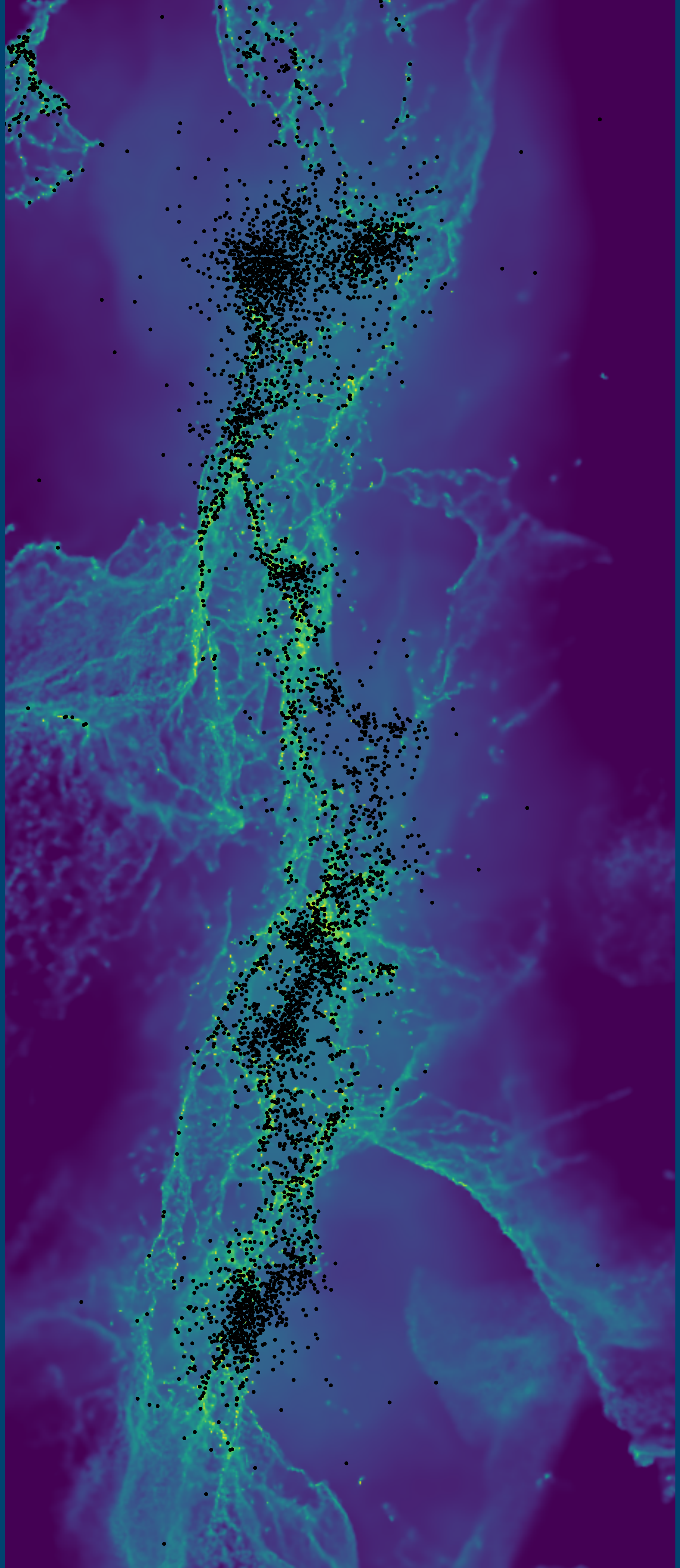
TOSCA - Siena, Italy - Oct 2024

Star formation and feedback in different environments

Ahmad Ali

UNIVERSITY OF COLOGNE



Collaborators:
C. Dobbs, T. Bending, T. Harries (Exeter),
A. Buckner (Cardiff),
A. Pettitt (Sacramento State),
A. McLeod (Durham),
L. Qiao, T. Haworth (QMUL)

University of Exeter   ICYBOB.co.uk   erc   DiRAC

Massive star feedback

photoionization

radiation pressure

stellar winds

supernovae

ISM heating

ISM turbulence

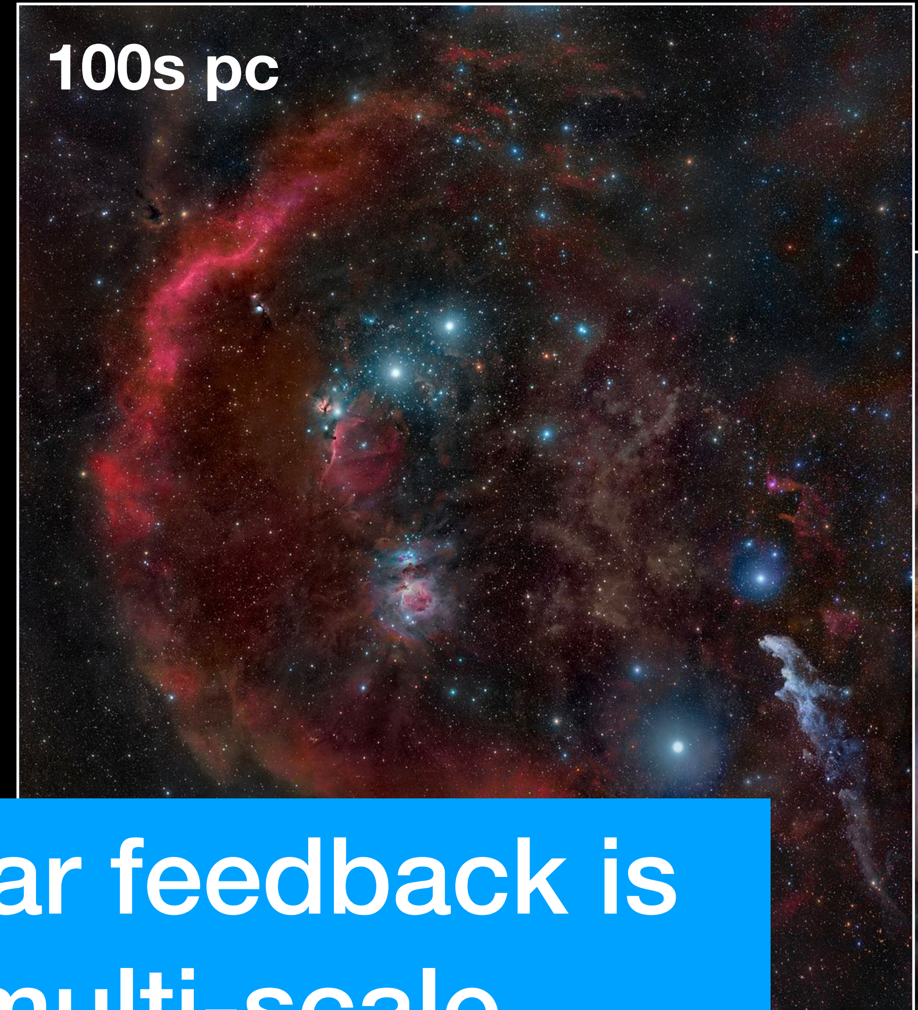
star formation rate/efficiency

momentum/energy escape

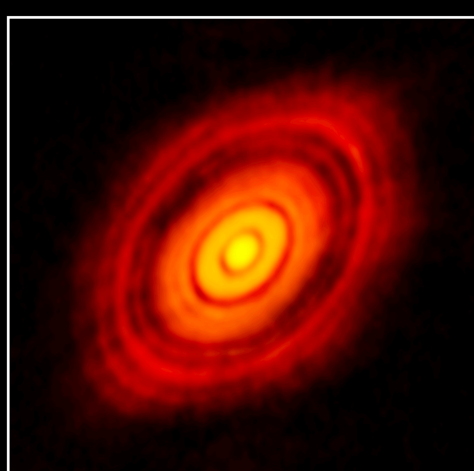
stellar feedback is multi-scale

with environmental dependences

kpc



pc



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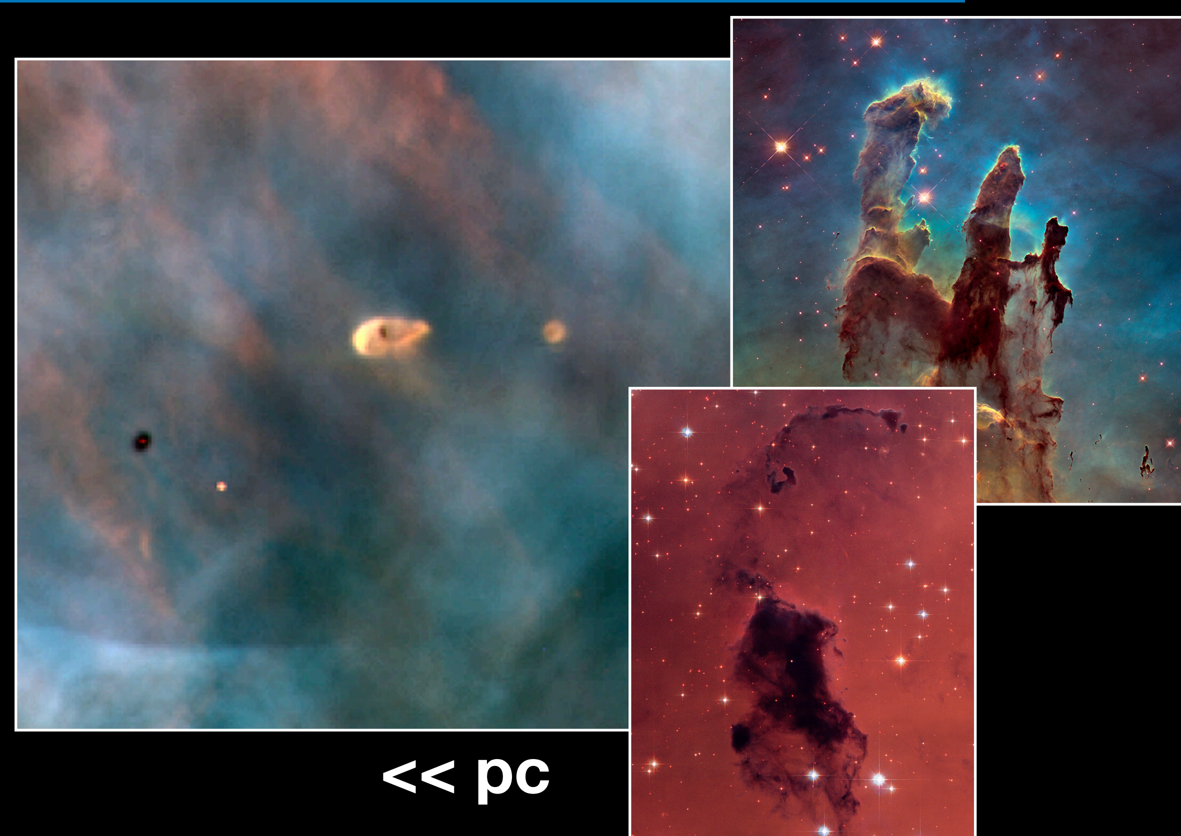
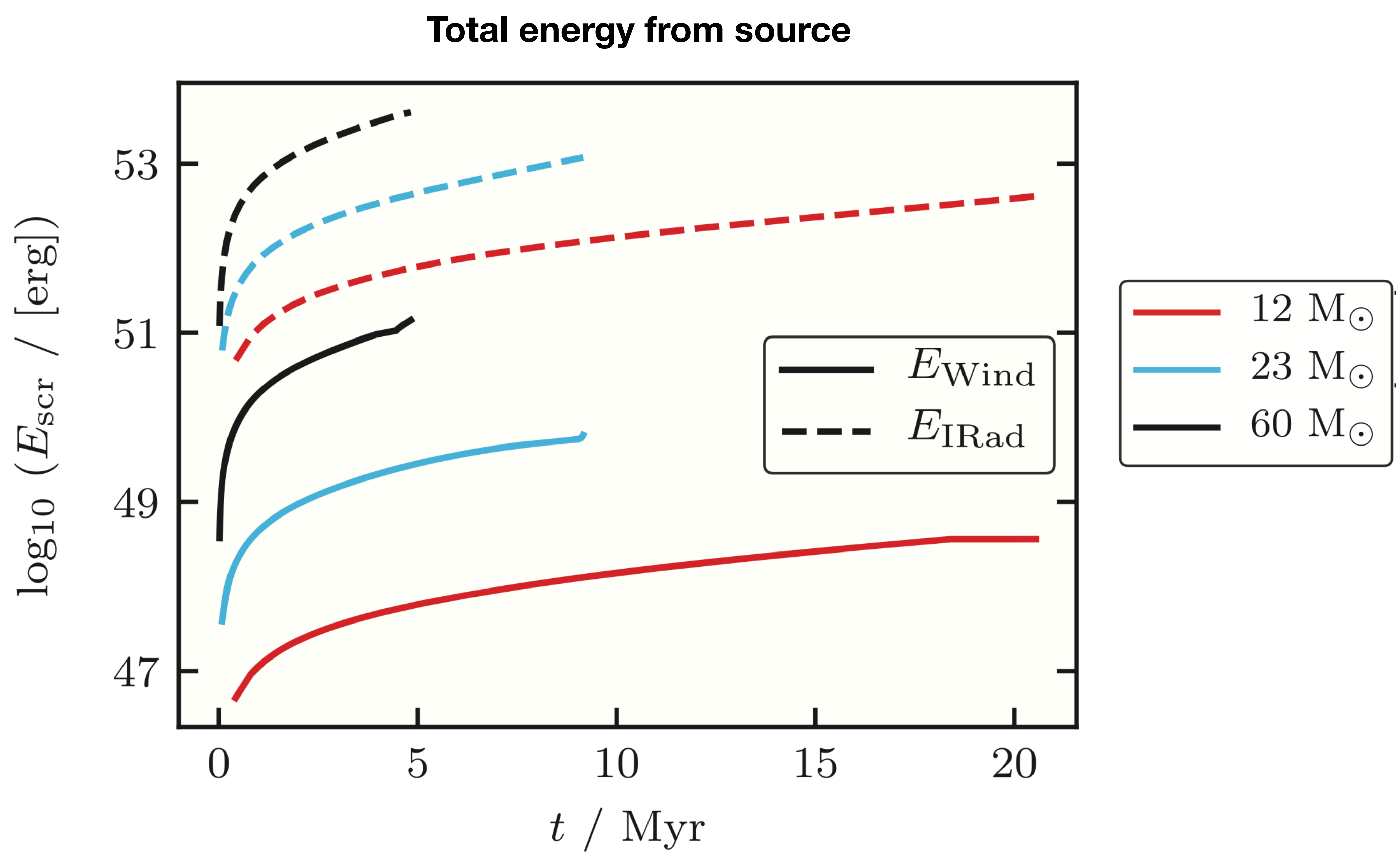


<< pc

Radiation vs. wind energy



Haid+ 2018

H II regions

- Ionized gas - cools through metal lines
- Dust - attenuates ionizing photons
- Radiation is multifrequency -> momentum/energy transfer (= RP/heating)
- -> **expansion of H II regions**

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want RHD models with detailed RT

TORUS Harries+ 2019

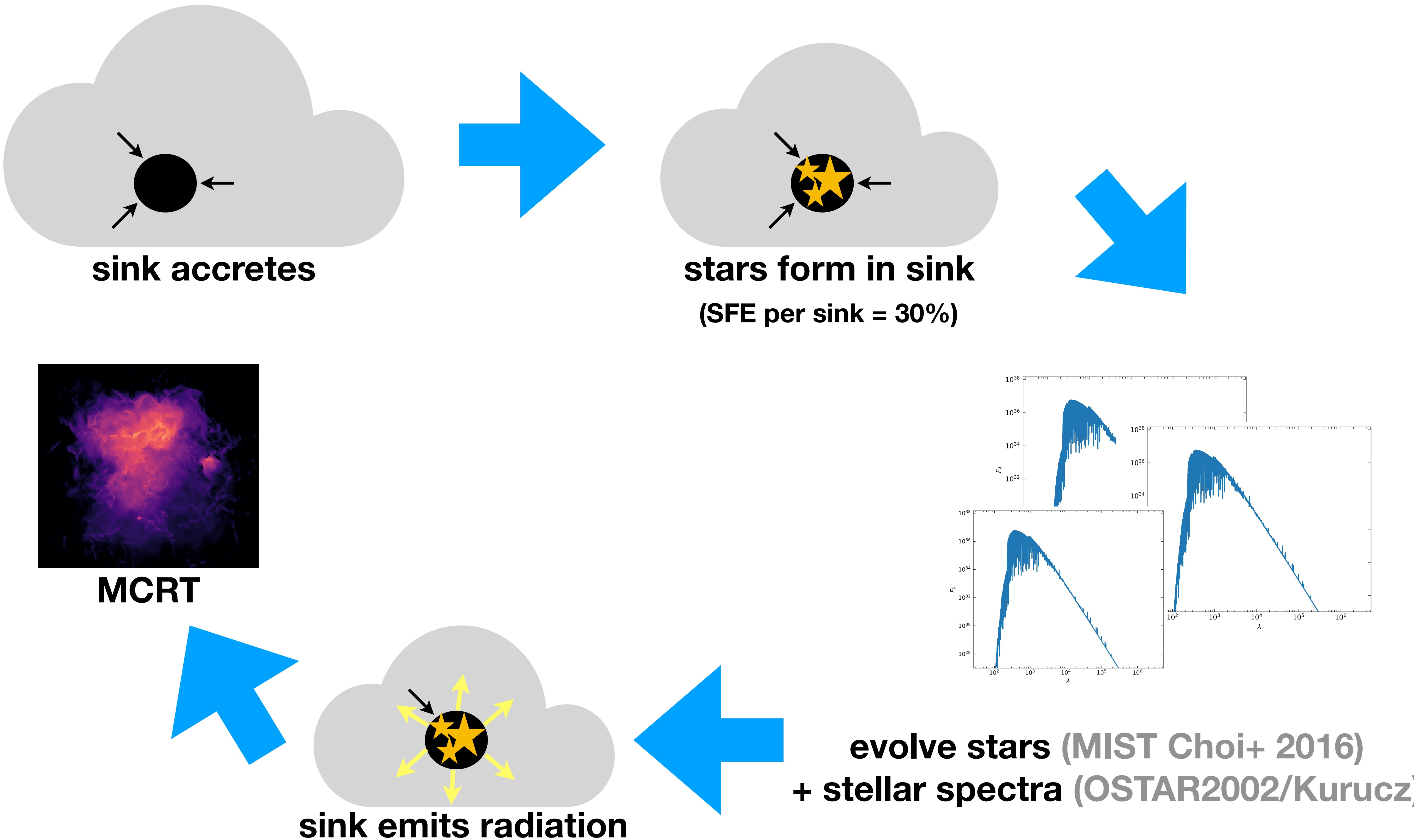
Monte Carlo RT

- stellar + diffuse radiation
- dust microphysics (scattering + absorption/remission)
- multifrequency (10^2 - 10^7 Å in 10^3 bins)
- **photoionization** (H, He, C, N, O, Ne, S)
- **radiation pressure** (gas & dust; dynamically coupled)
- heating/cooling (gas + dust + gas-dust coupling)

Hydrodynamics

- 3D fixed grid (256^3)
- self-gravity
- cluster-sink particles

Sinks to stars to feedback



Cloud conditions

- turbulent sphere **$M = 10^5\,M_\odot$** / R = 12 pc / surface density = 240 $M_\odot$ pc^{-2} / α_{vir} = 2 / resolution 0.17 pc

Parameters

- **$Z/Z_\odot$ = 2, 1, 0.5, 0.1** → MW centre ~ 2, MW disc ~ 1, LMC ~ 0.5, SMC ~ 0.2
- dust/gas = 0.01 $Z/Z_\odot$

For $Z = Z_\odot$

- one model without RP
- one model without dust

Ali 2021, MNRAS, 501, 4136

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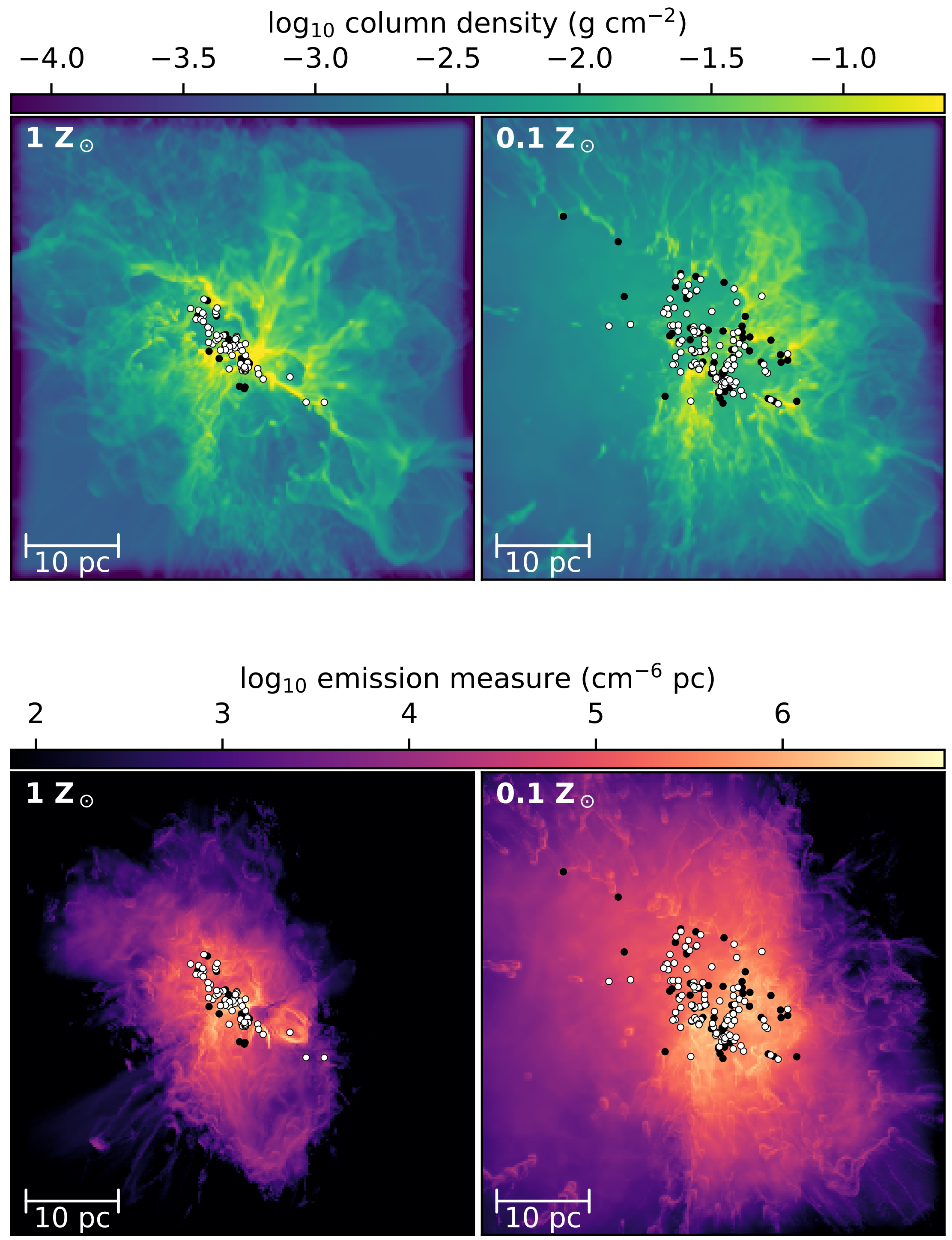
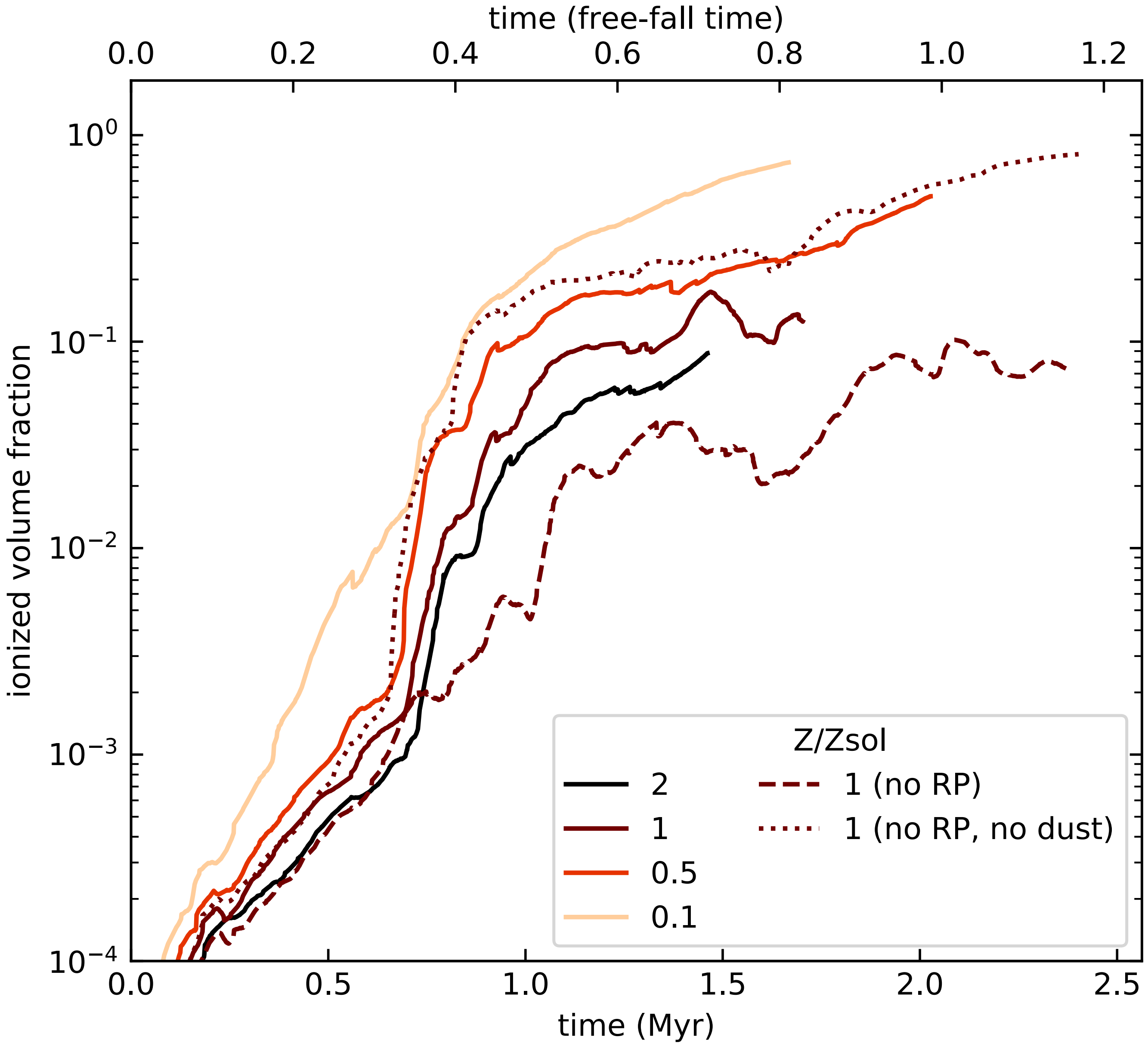
Ali 2021, MNRAS, 501, 4136



H II region volume

Ali 2021, MNRAS, 501, 4136

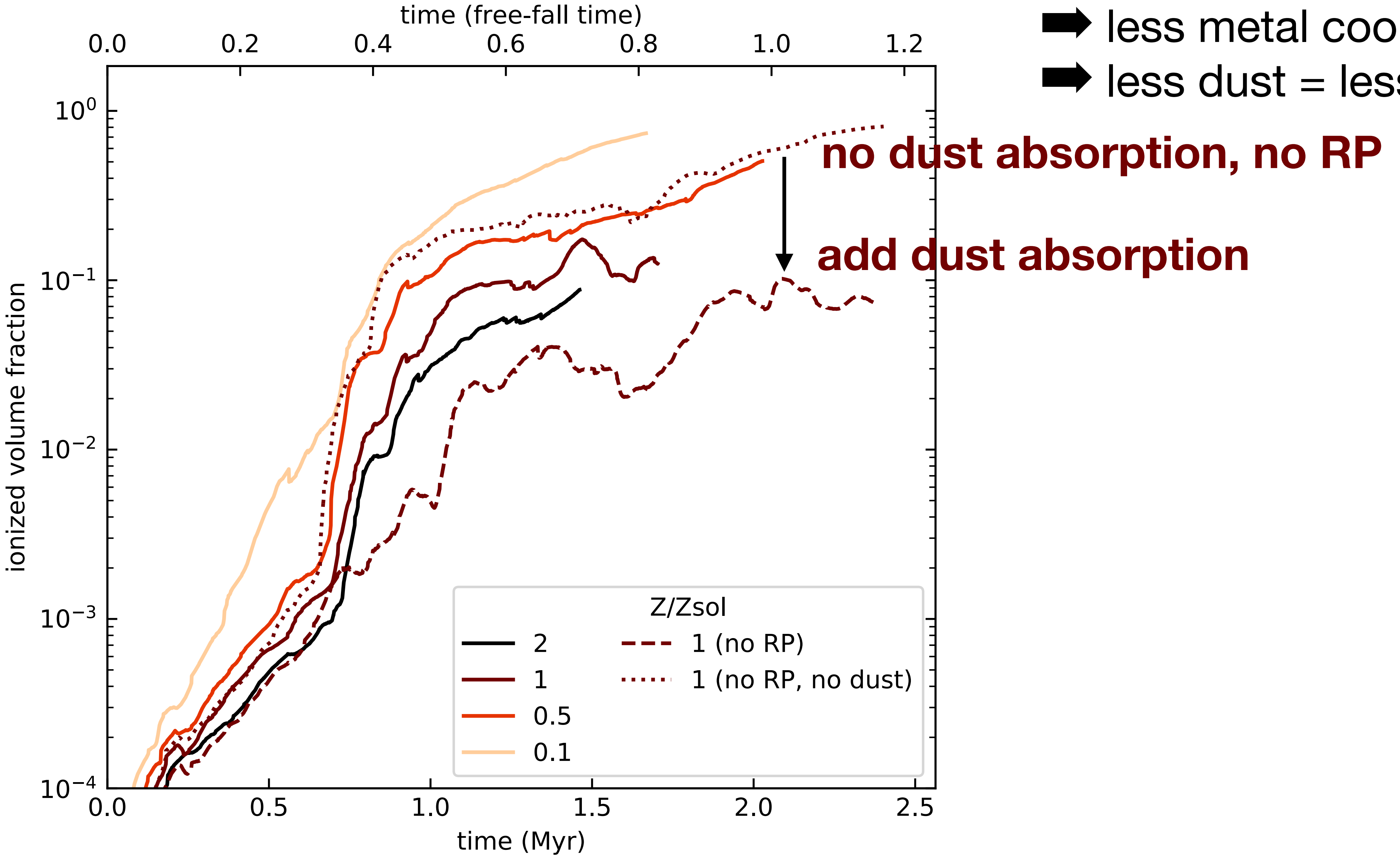


lower Z = larger

- ➡ less metal cooling = hotter
- ➡ less dust = less dilution of UV

H II region volume

Ali 2021, MNRAS, 501, 4136



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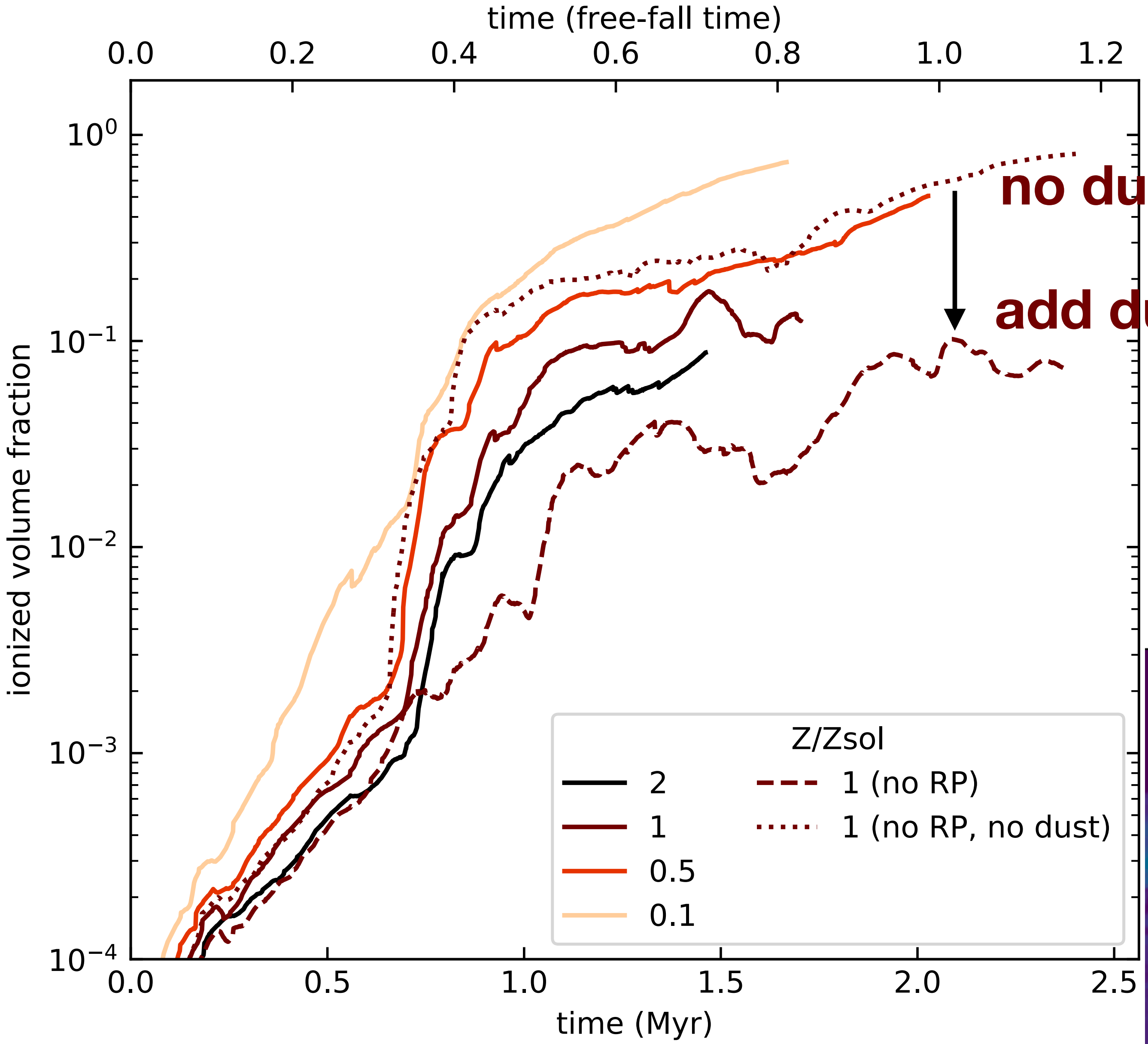

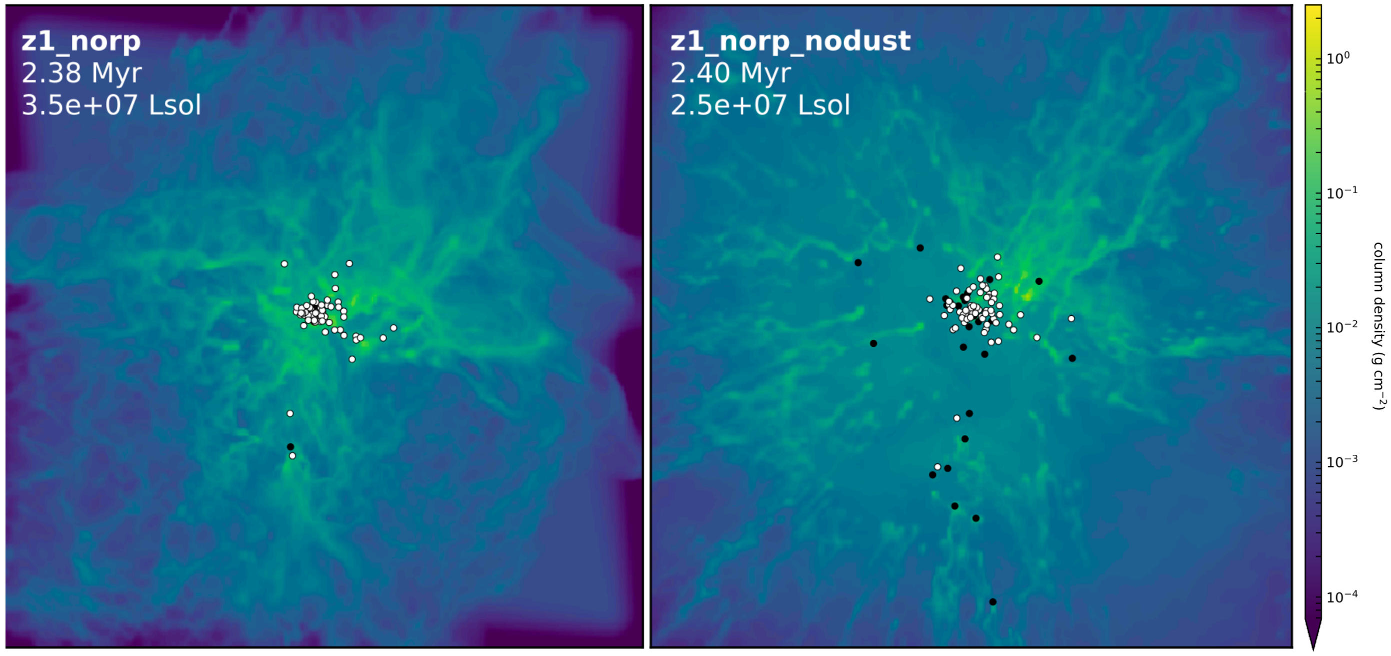

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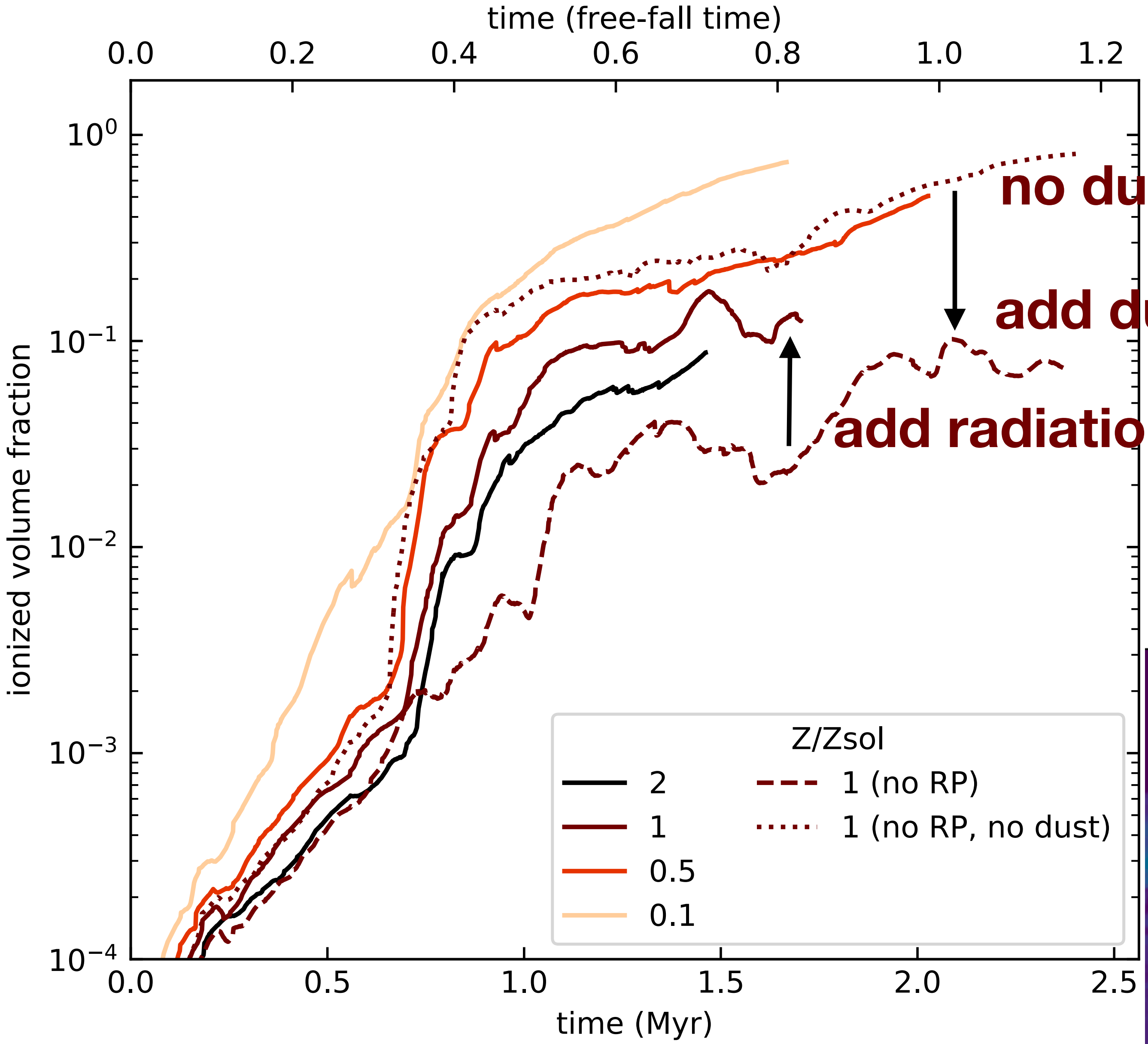

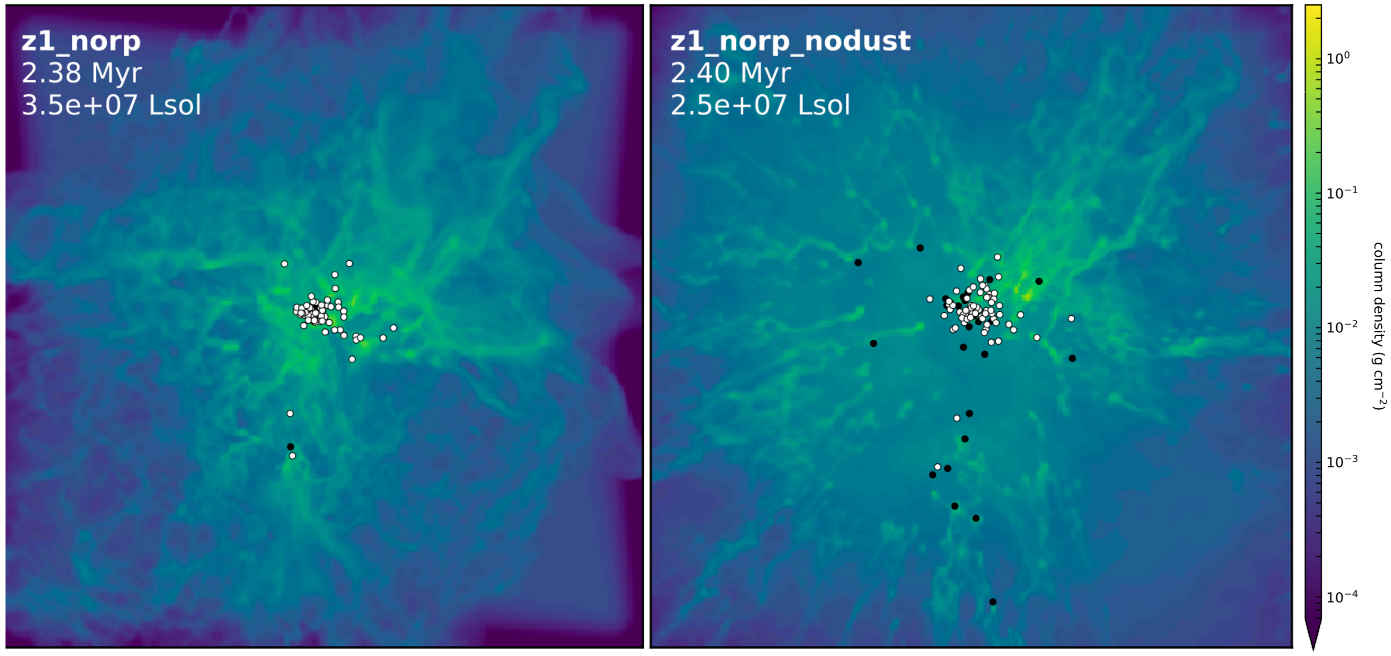

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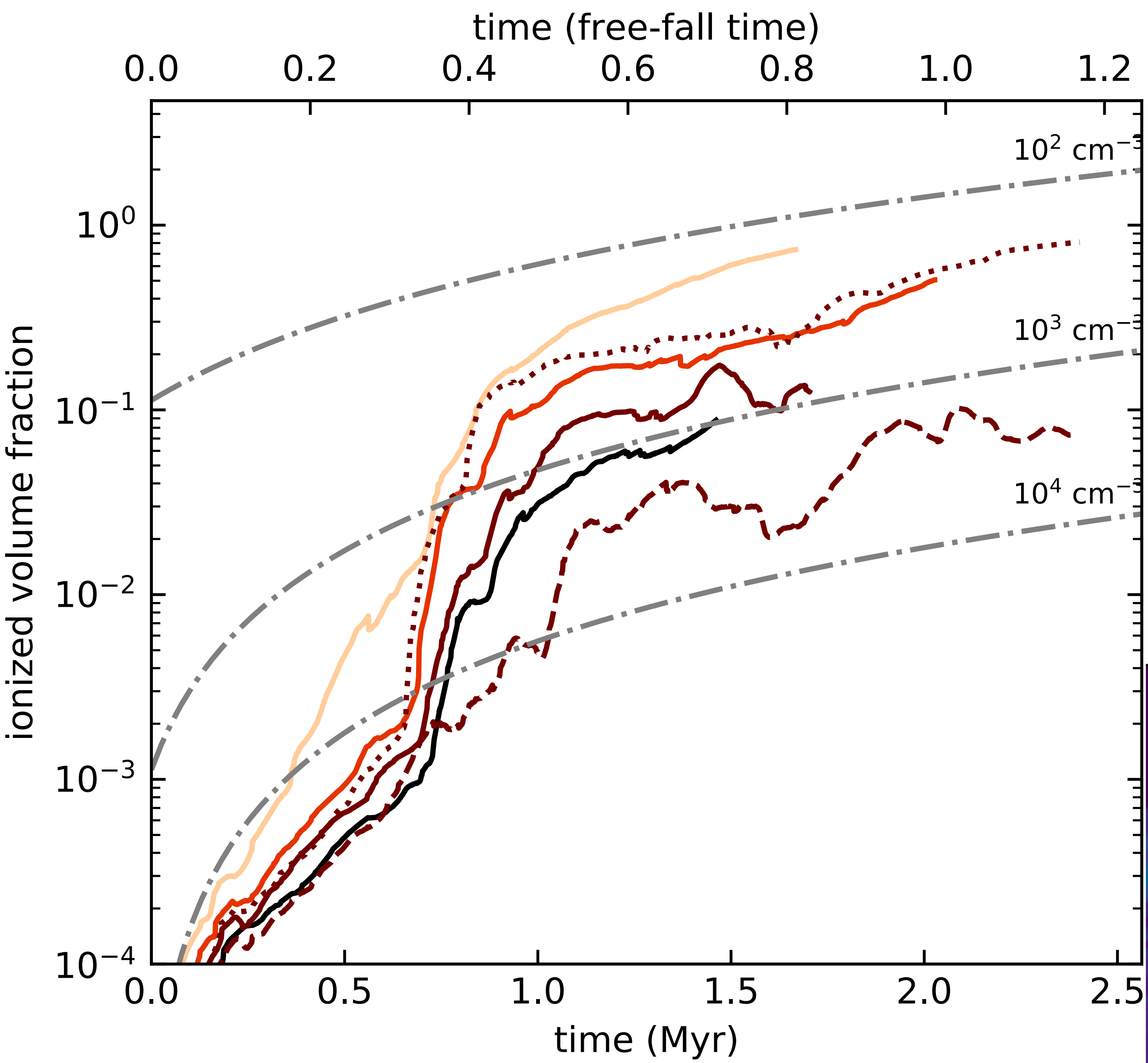

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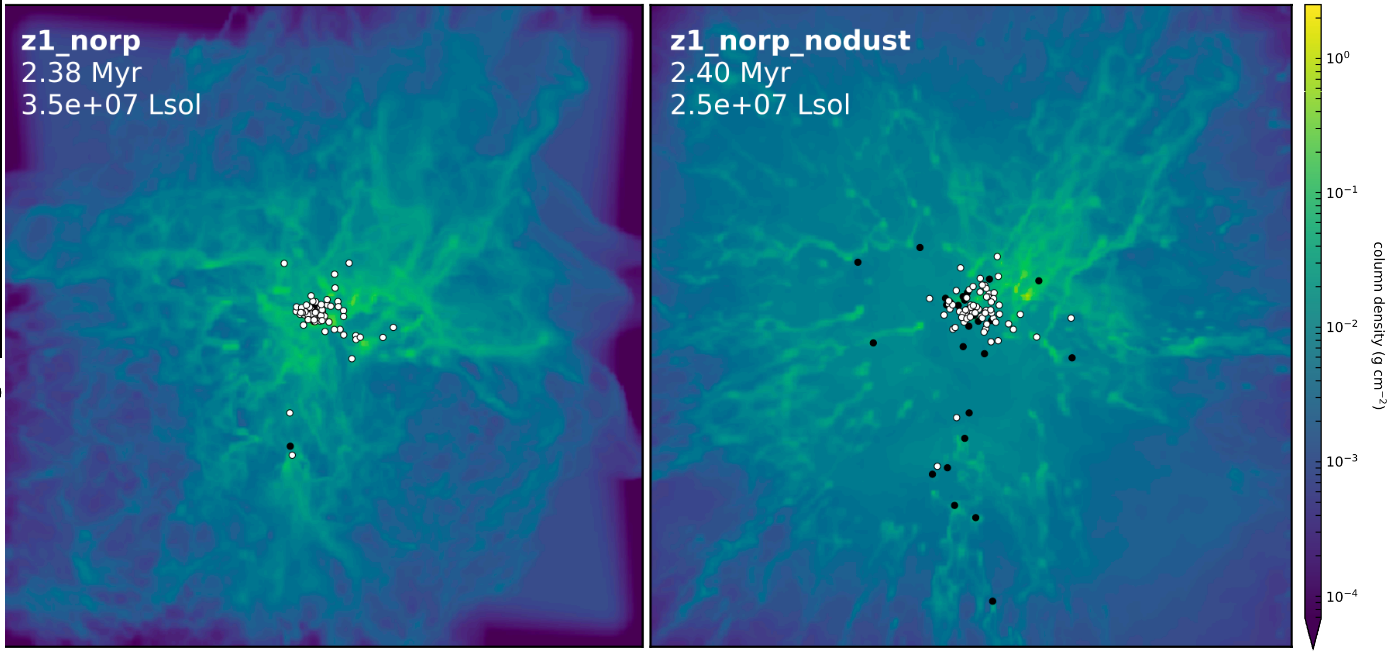
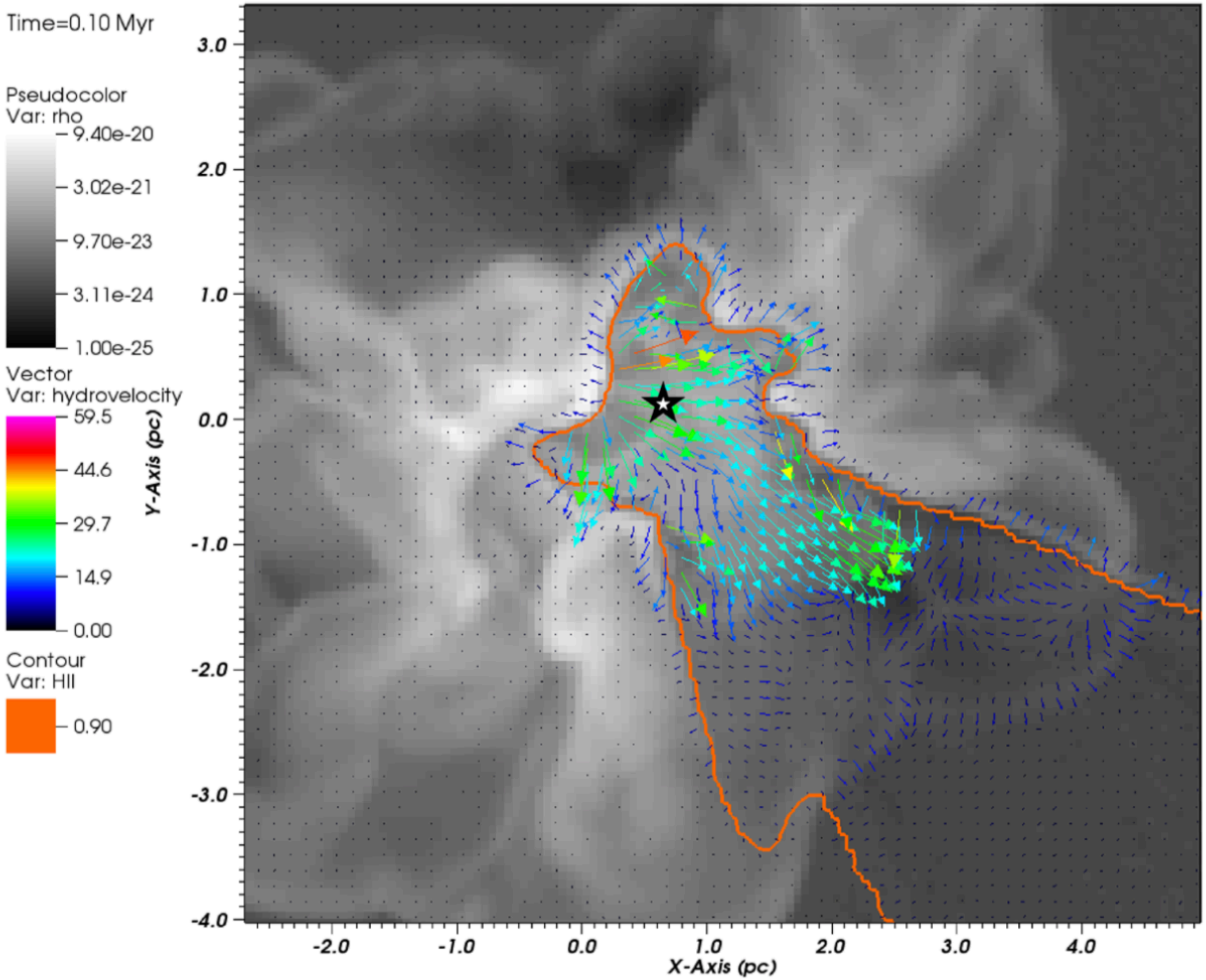
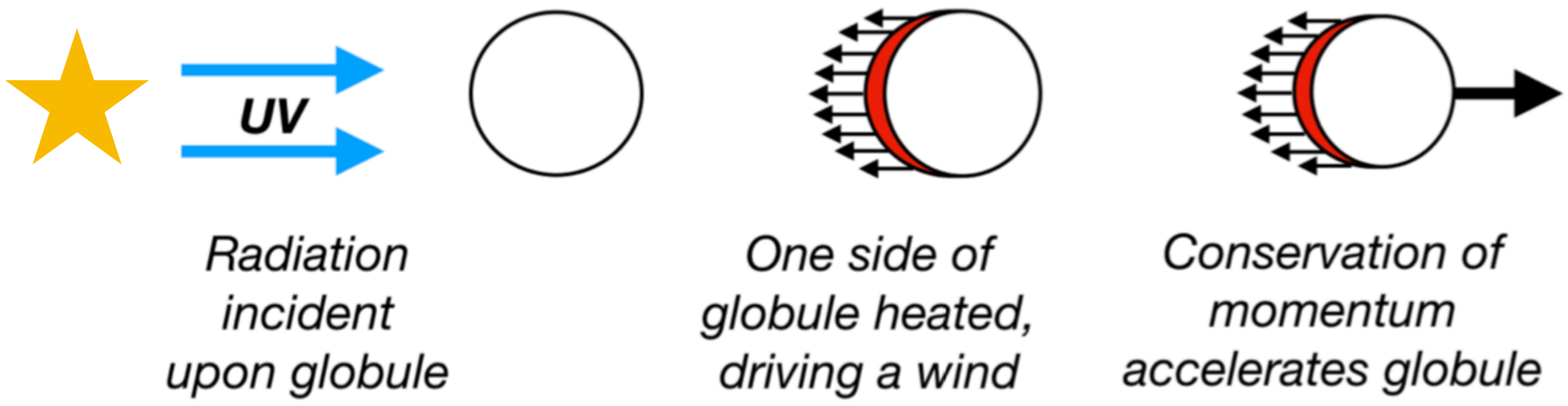


Expanding H II region

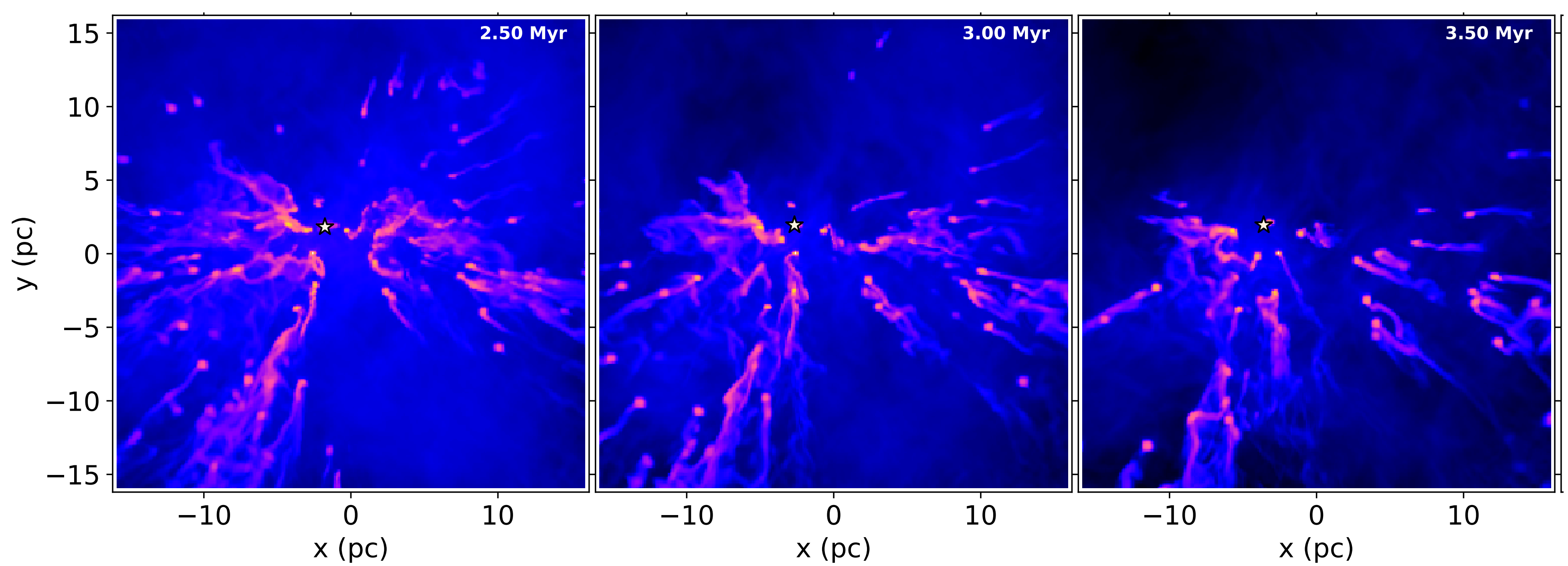


Ali+ 2018, MNRAS 477, 5422

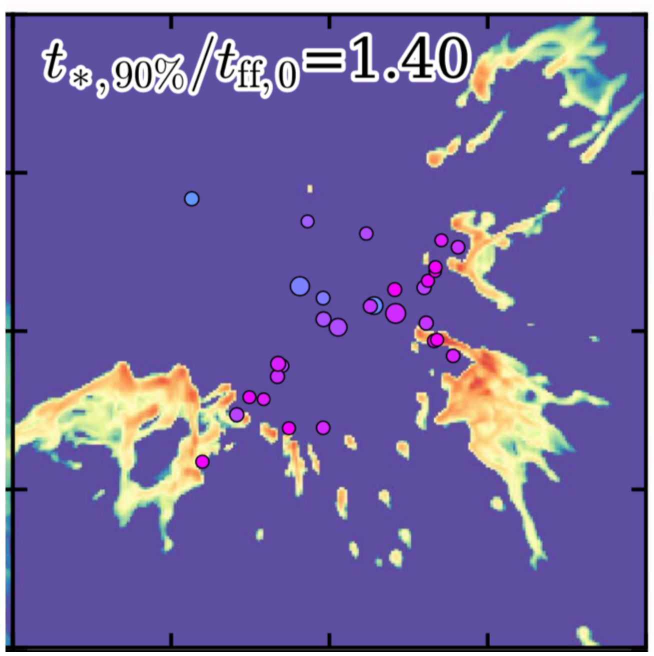
Rocket effect



Reiter+ 2020

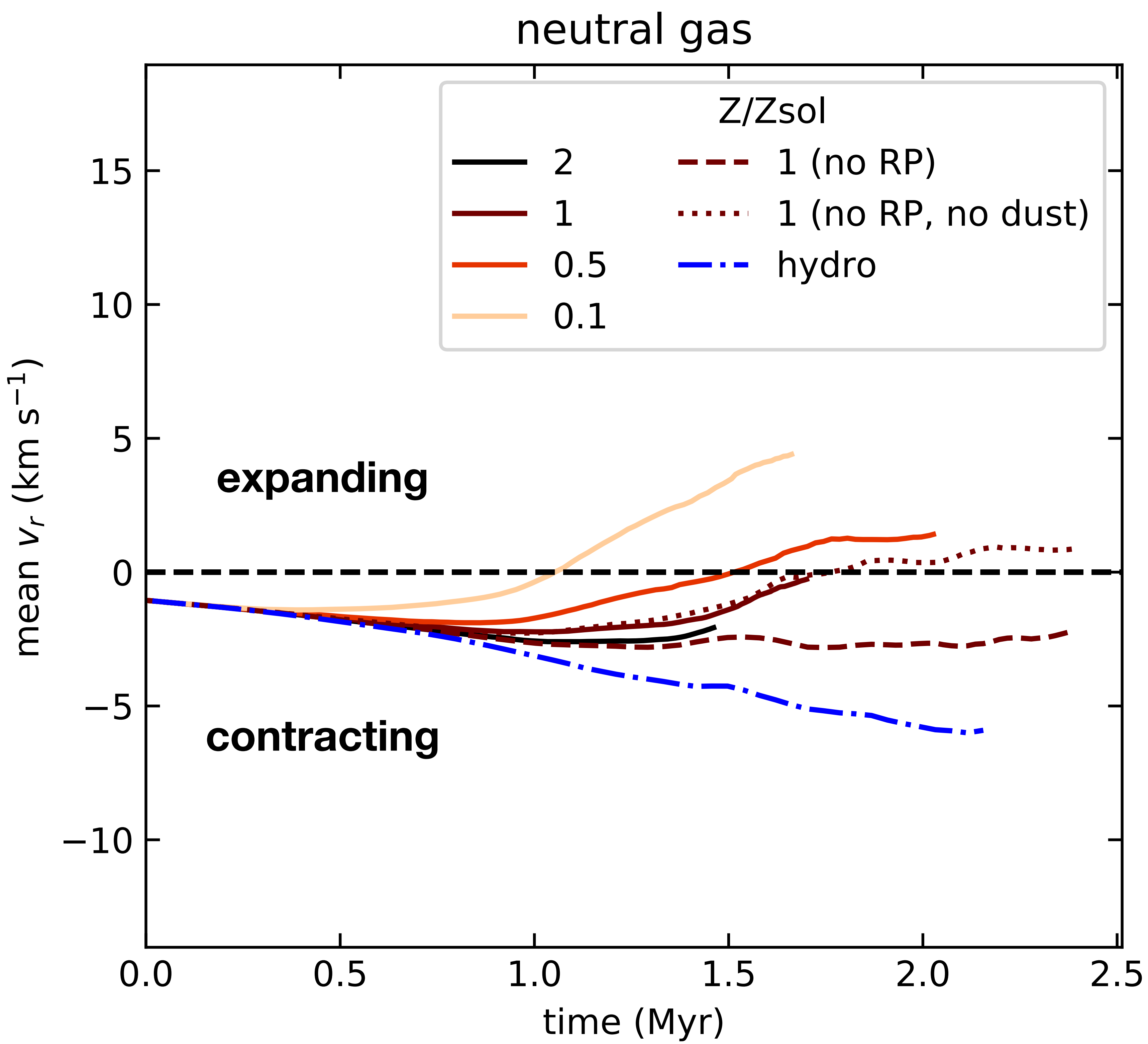


Ali & Harries 2019

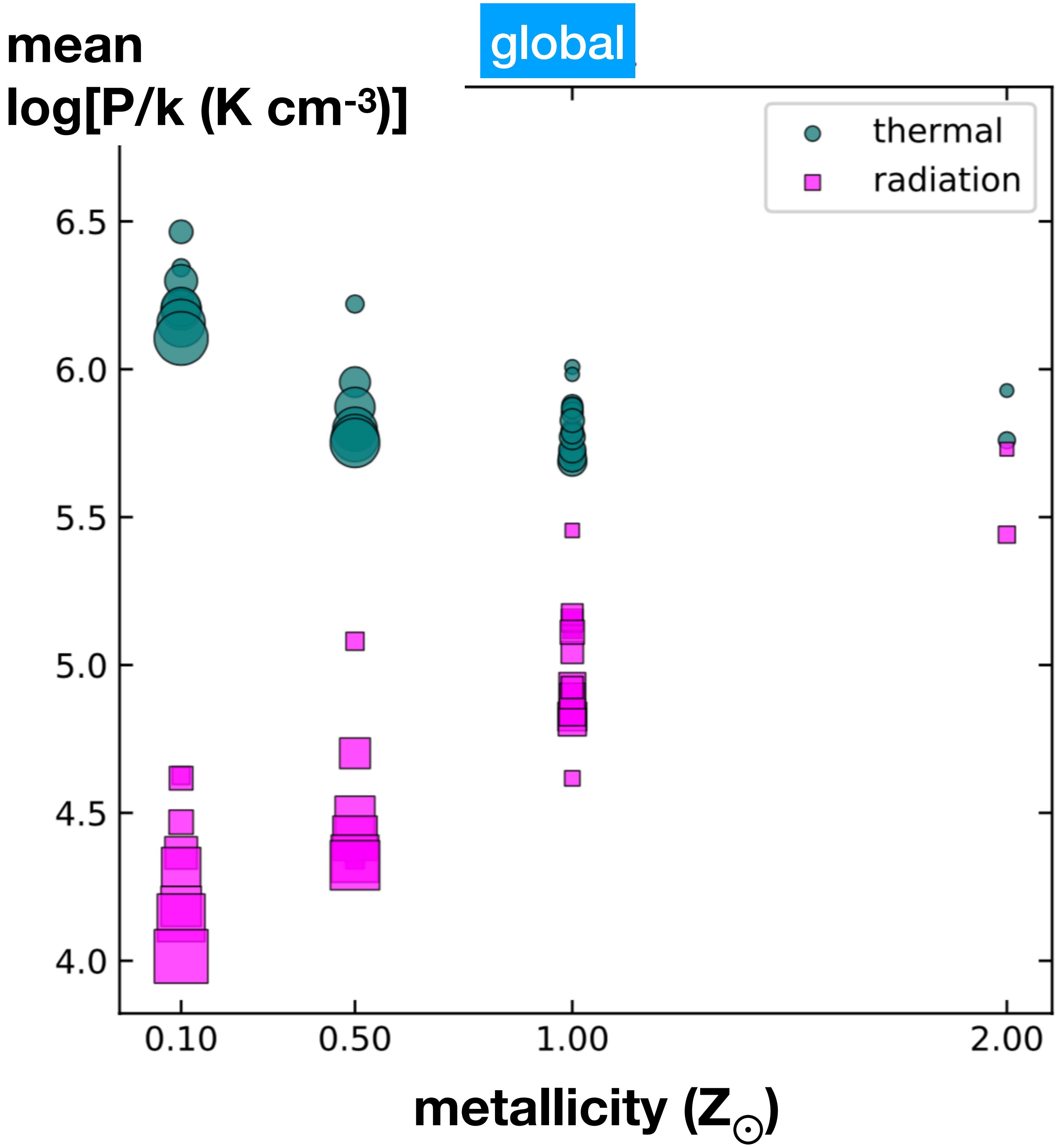


Kim+ 2018

Radial velocity



Radiation pressure vs thermal pressure



McLeod, Ali, et al. 2021

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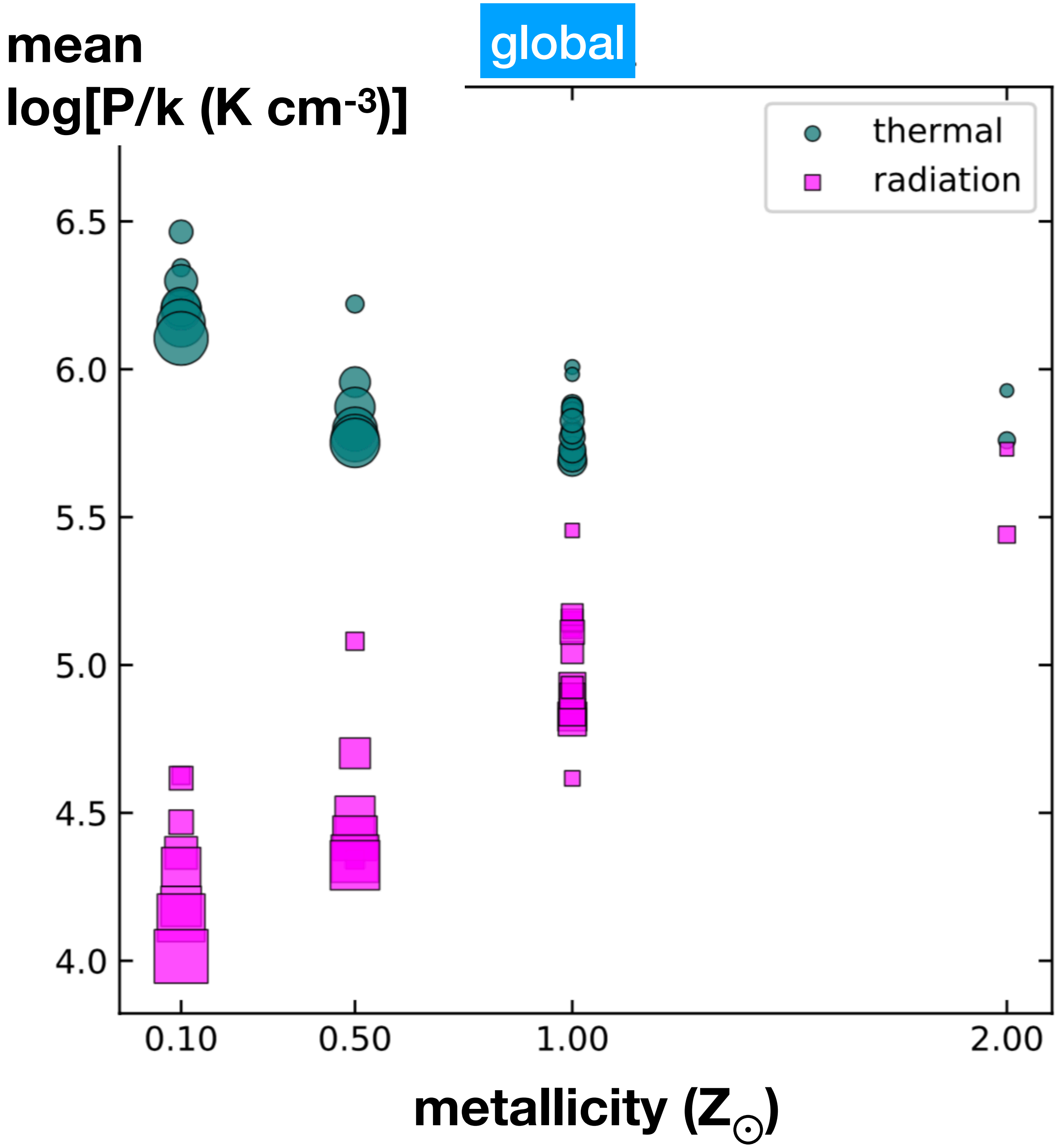
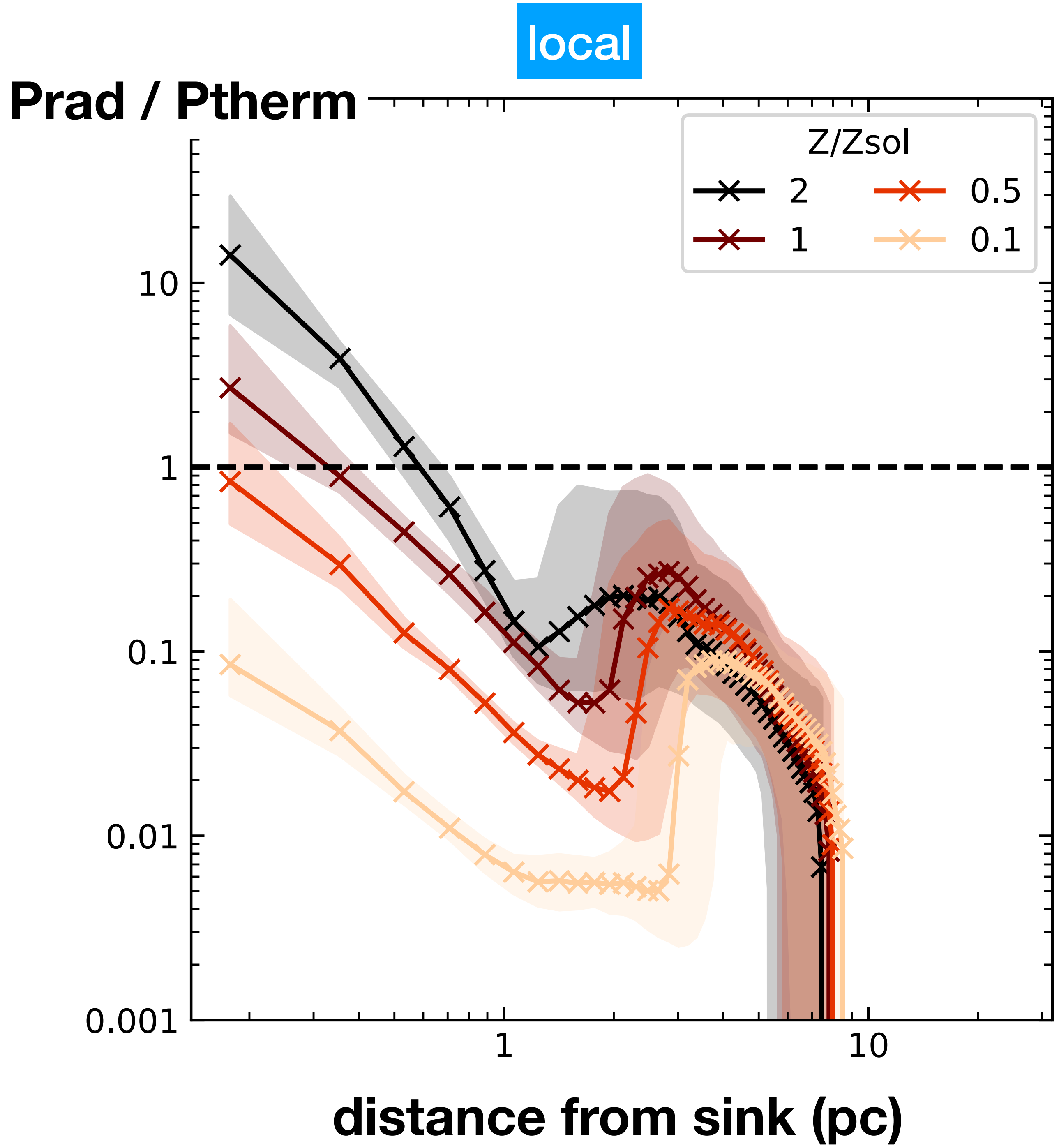
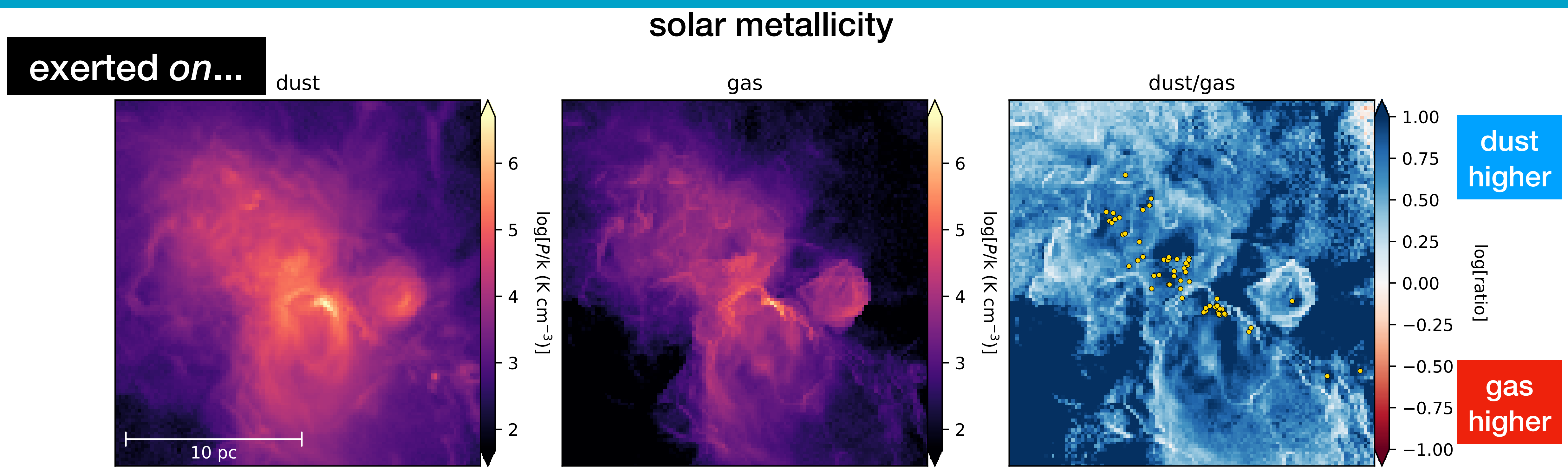




McLeod, Ali, et al. 2021

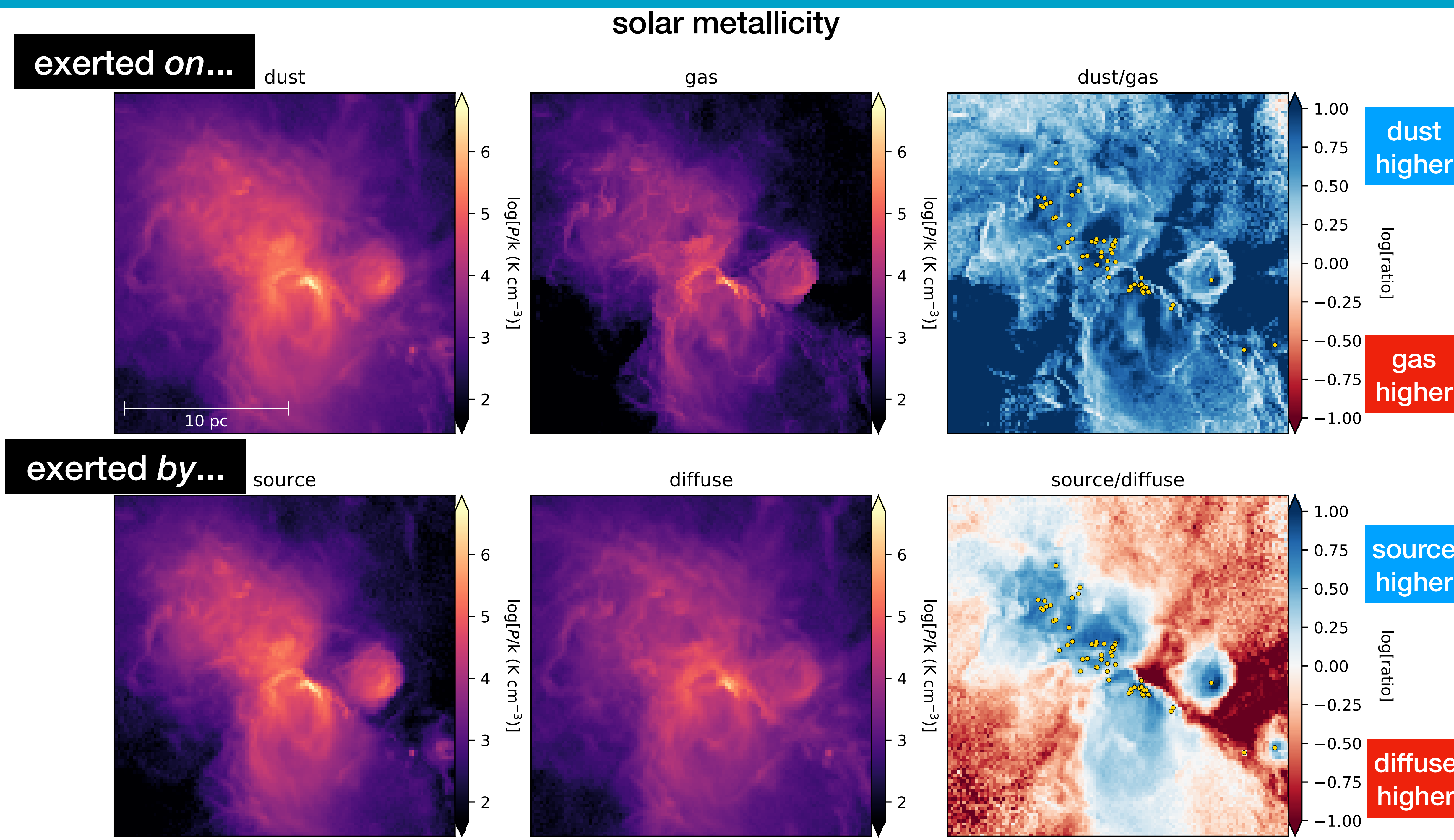
Ali 2021

Radiation pressure



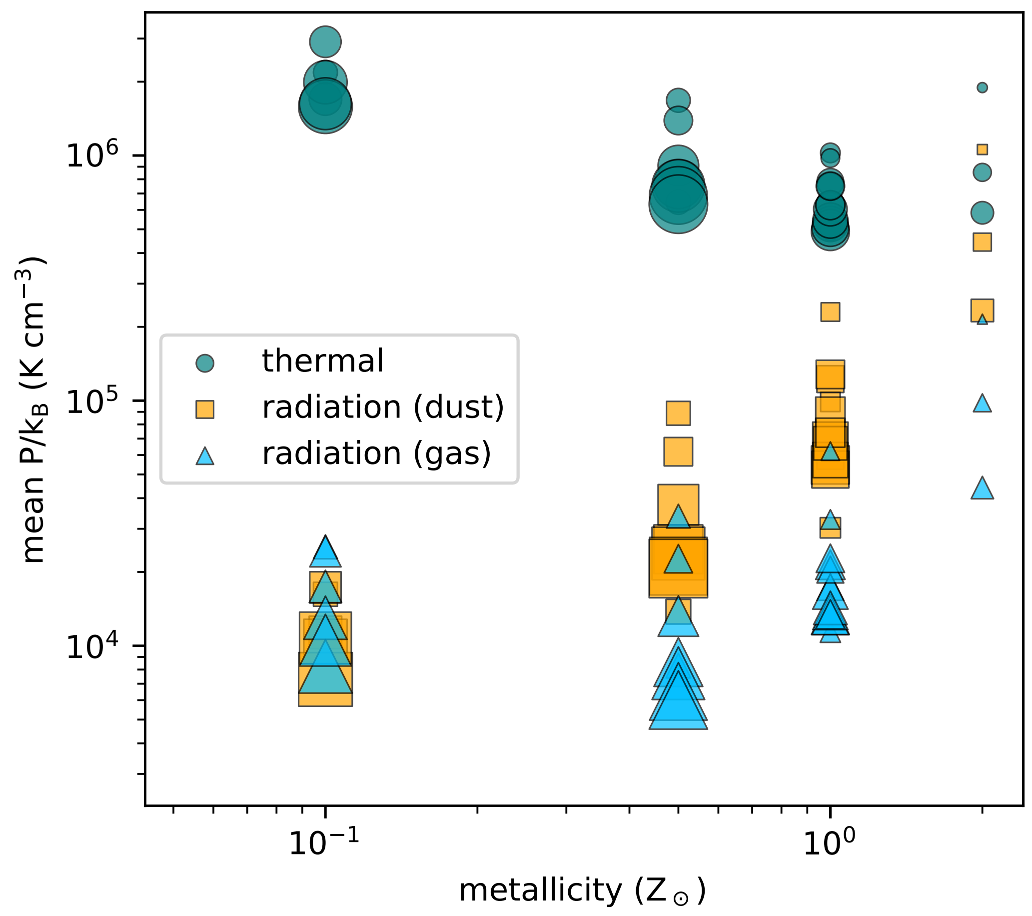
Ali+ in prep

Radiation pressure



Ali+ in prep

Dust vs. gas / source vs. diffuse



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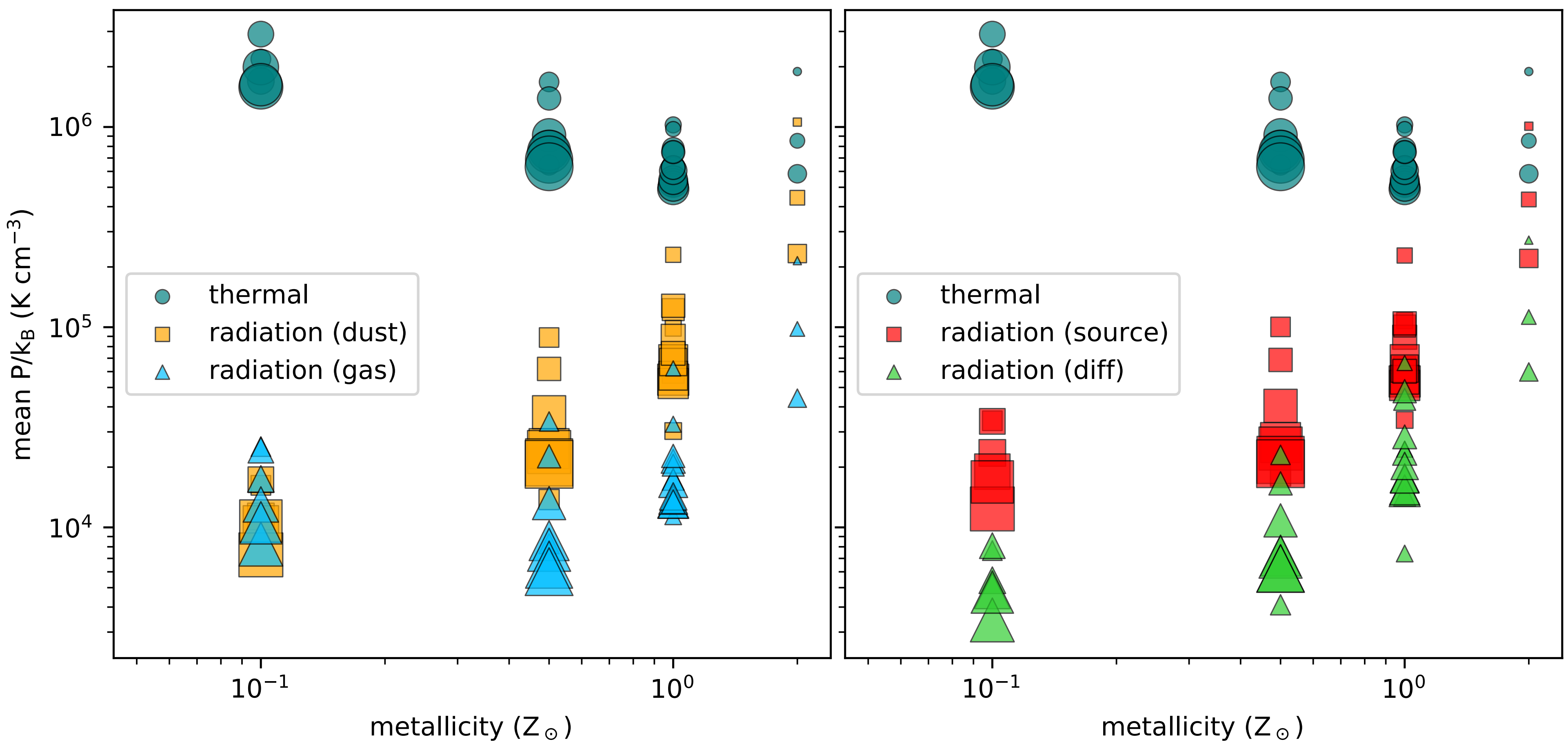


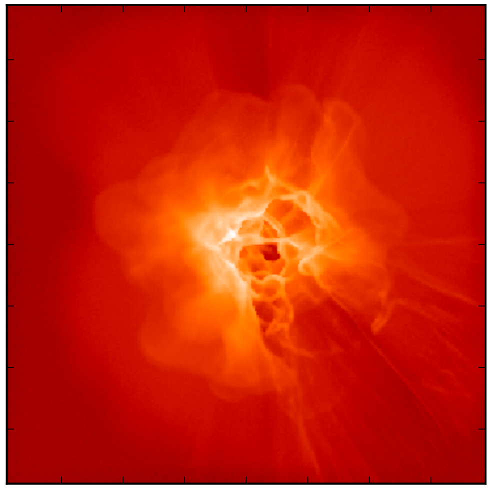
Ali+ in prep

Synthetic observations

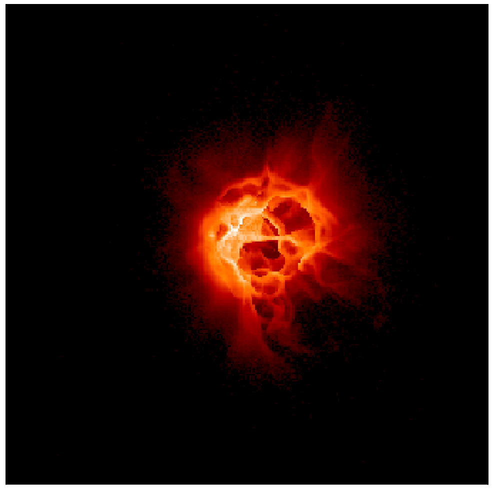
IR/sub-mm dust continuum:

T_{dust}, SFR, P_{IR}

450 micron



24 micron



(PAH emission coming soon...)

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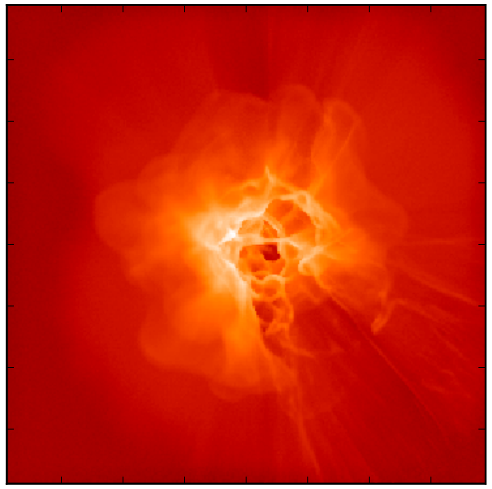

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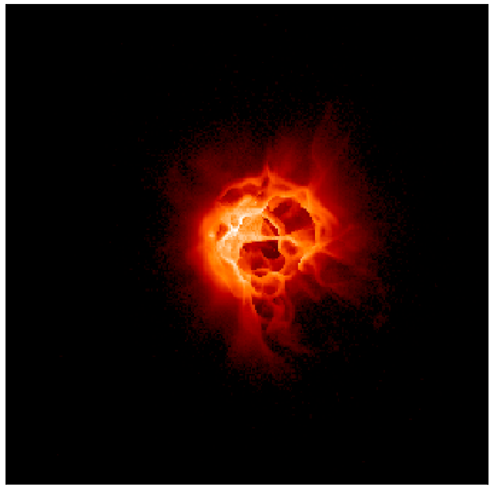

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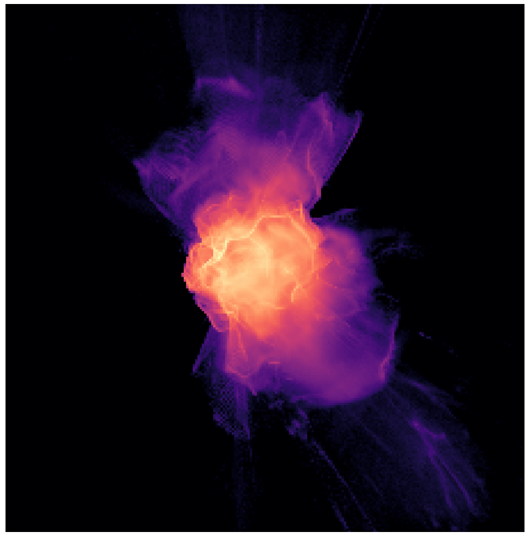
Radio free-free continuum:

$n_e \sim P_{therm}$

1.5 GHz



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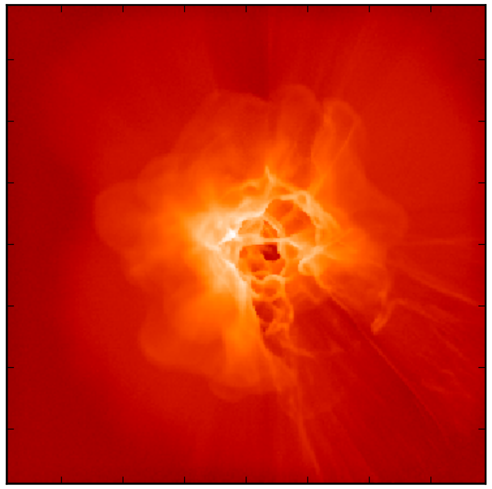

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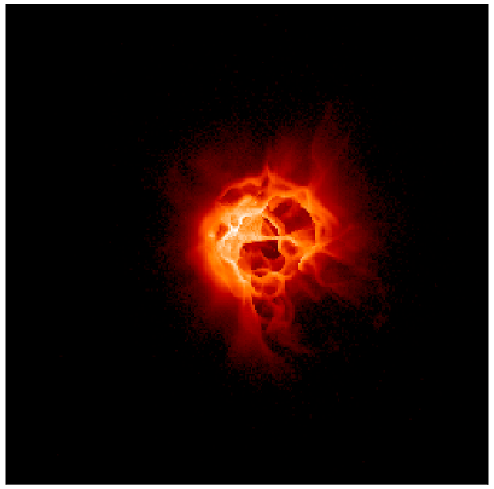

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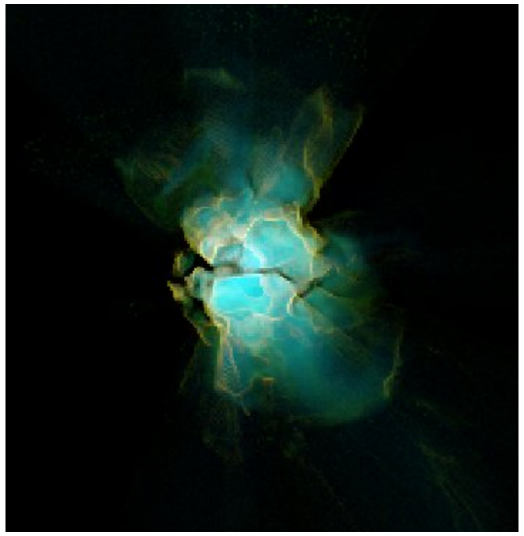
Optical recombination/forbidden lines:

SFR; n_e, T_e ~ P_{therm}; L(Hα) ~ L_{bol} ~ P_{dir}



[S II]
Hα
[O III]

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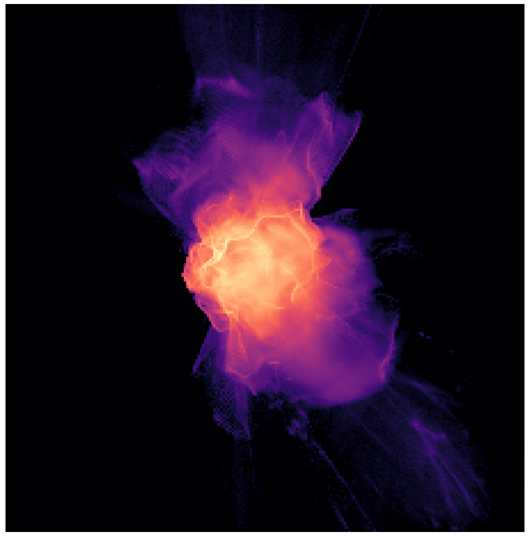

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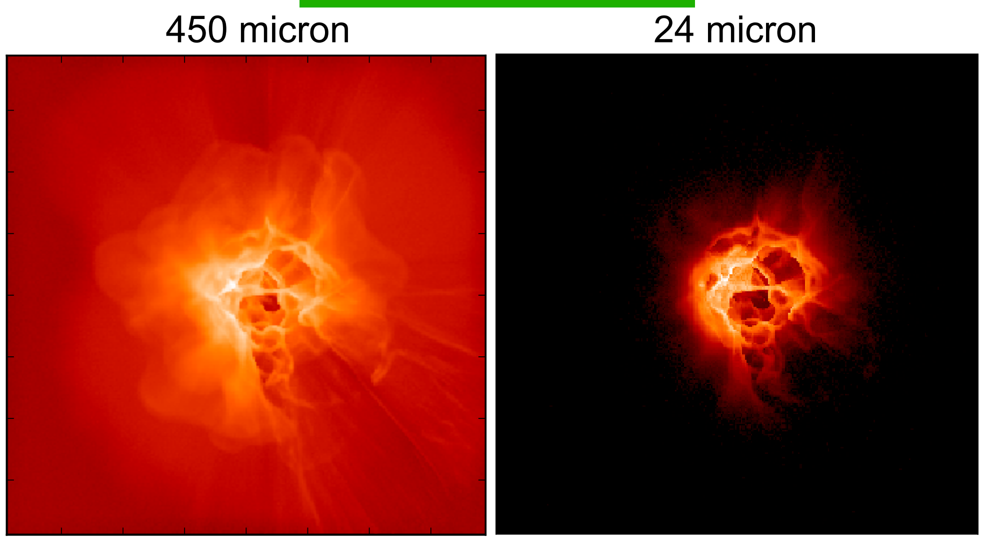

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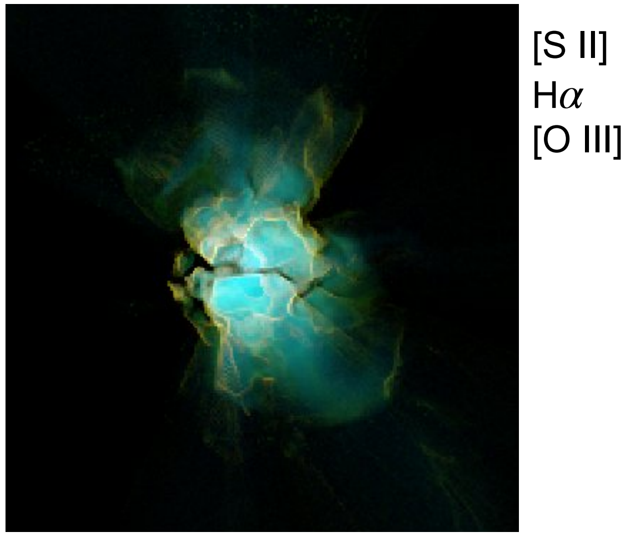

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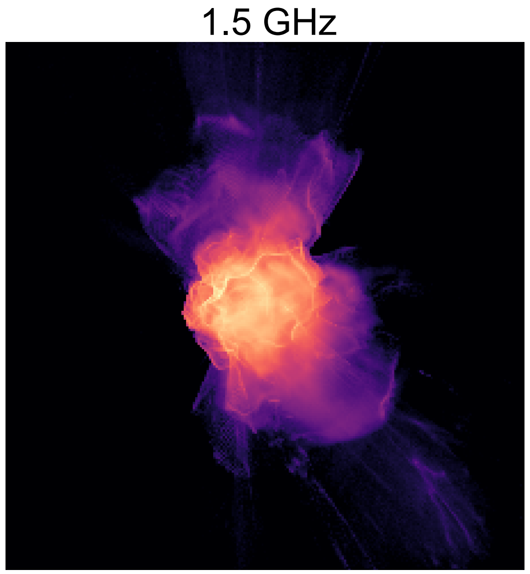
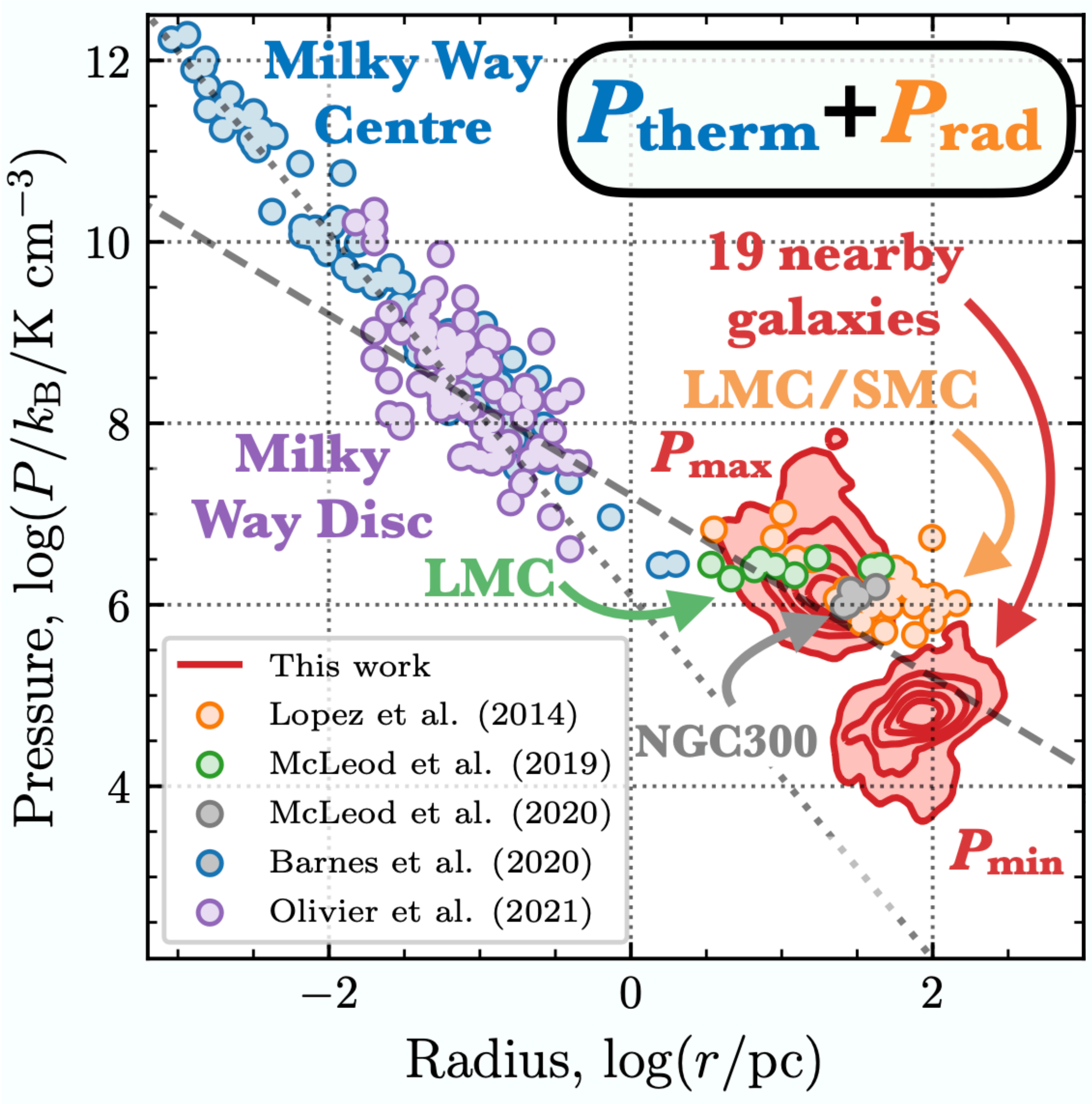


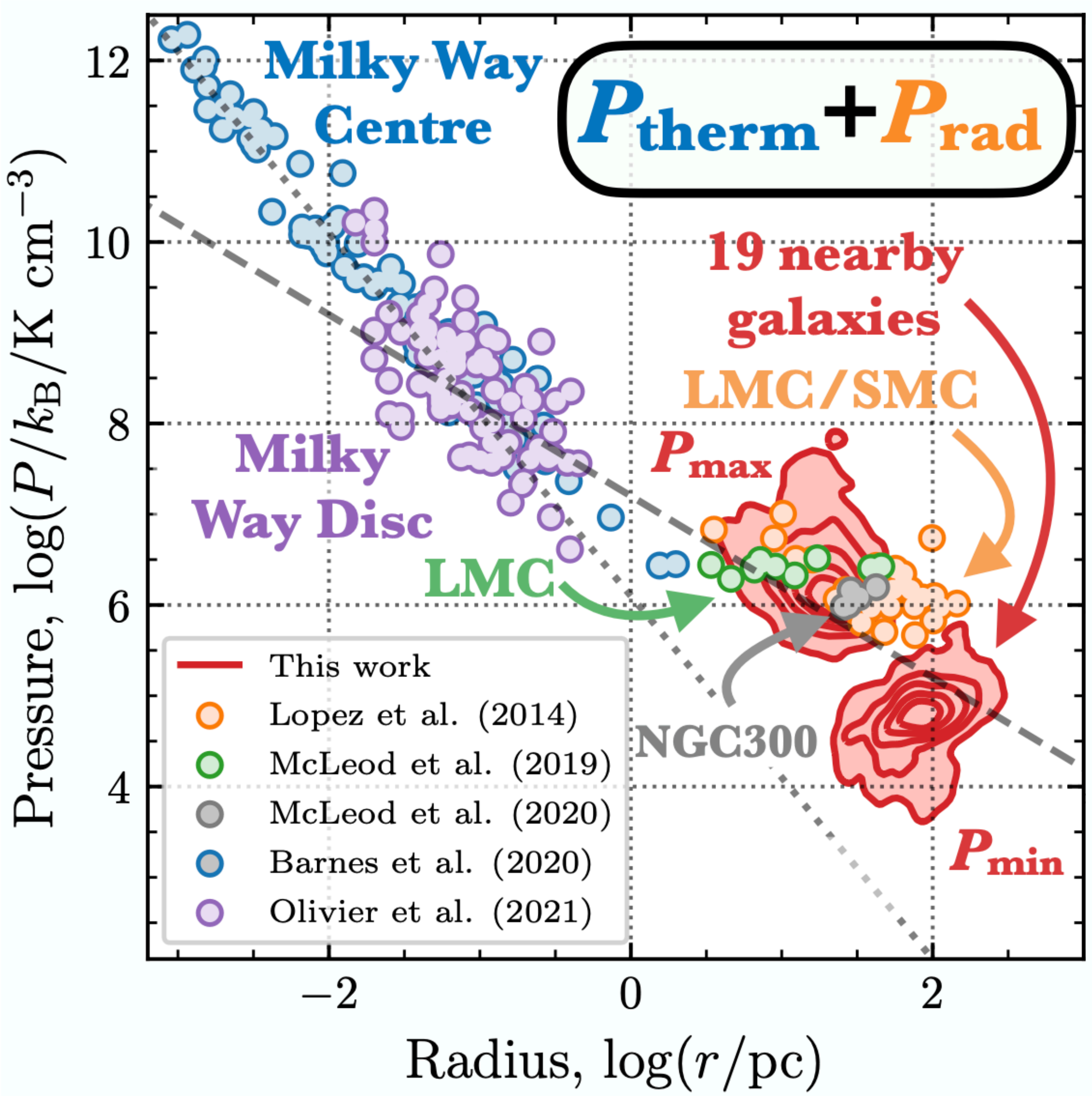
Compare with observations....

Observational pressures



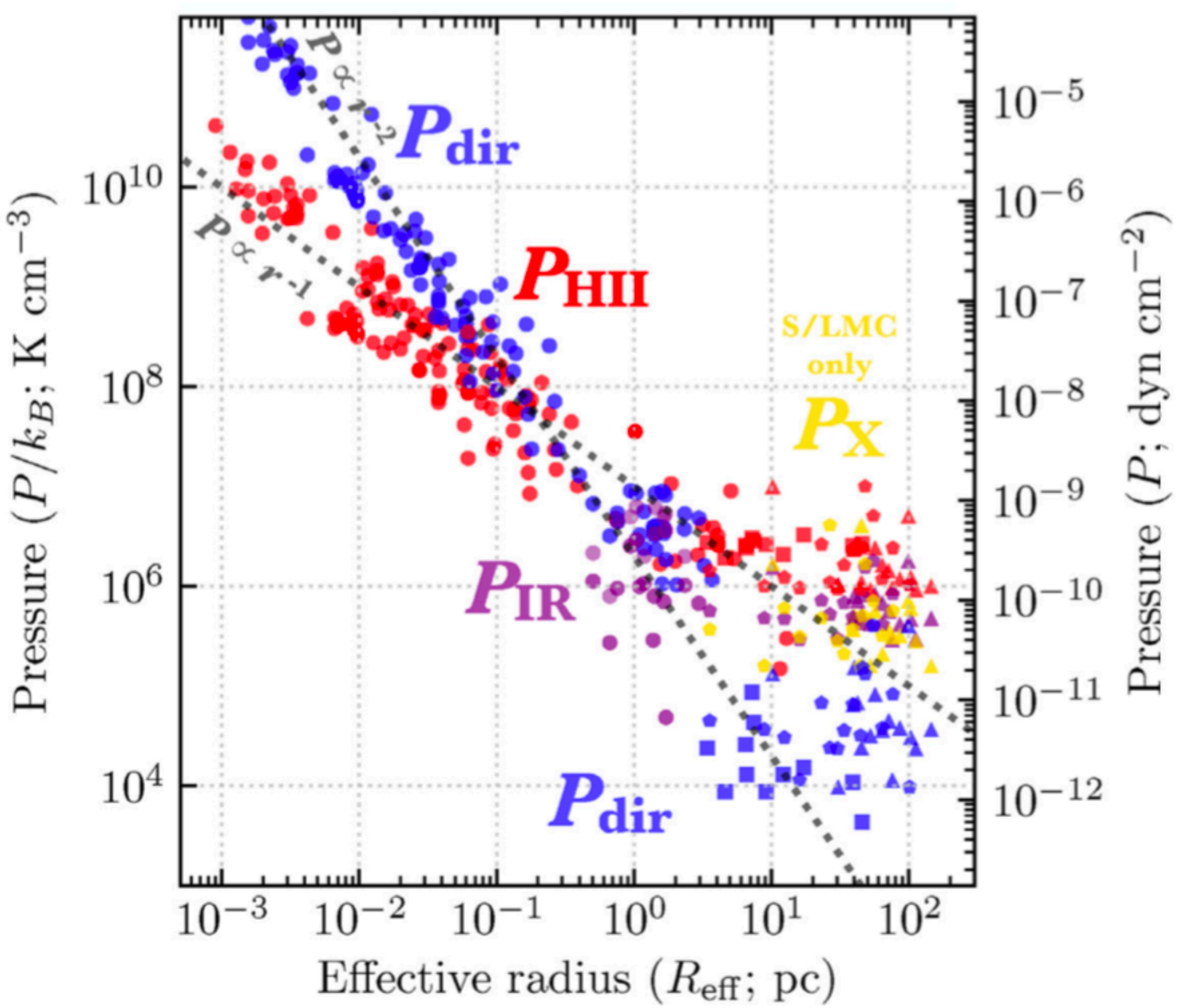
Barnes+2021

Observational pressures



Barnes+2021

only MW + LMC + SMC



Barnes+2020
and data from Lopez+2011,2014, McLeod+2019

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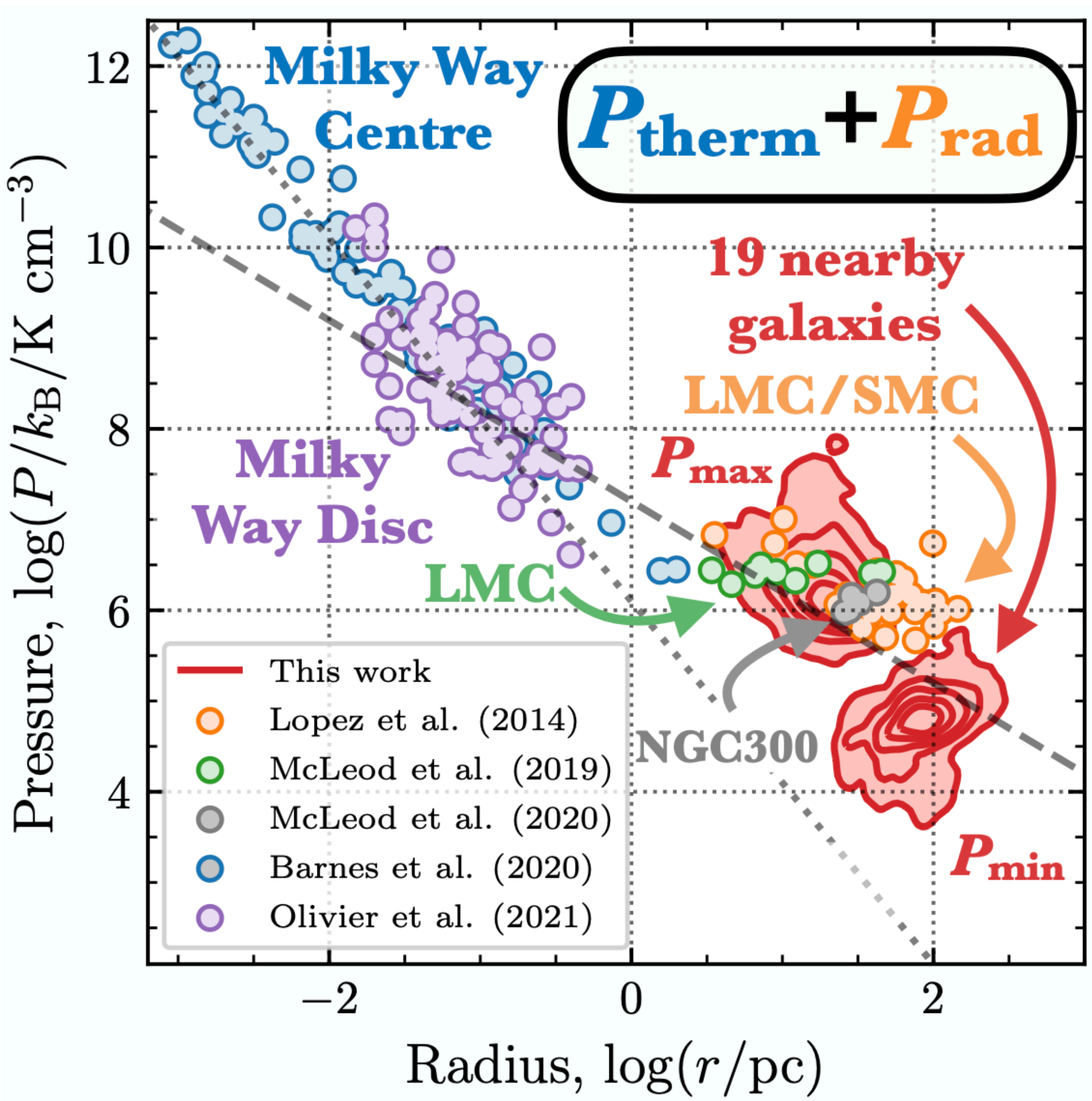

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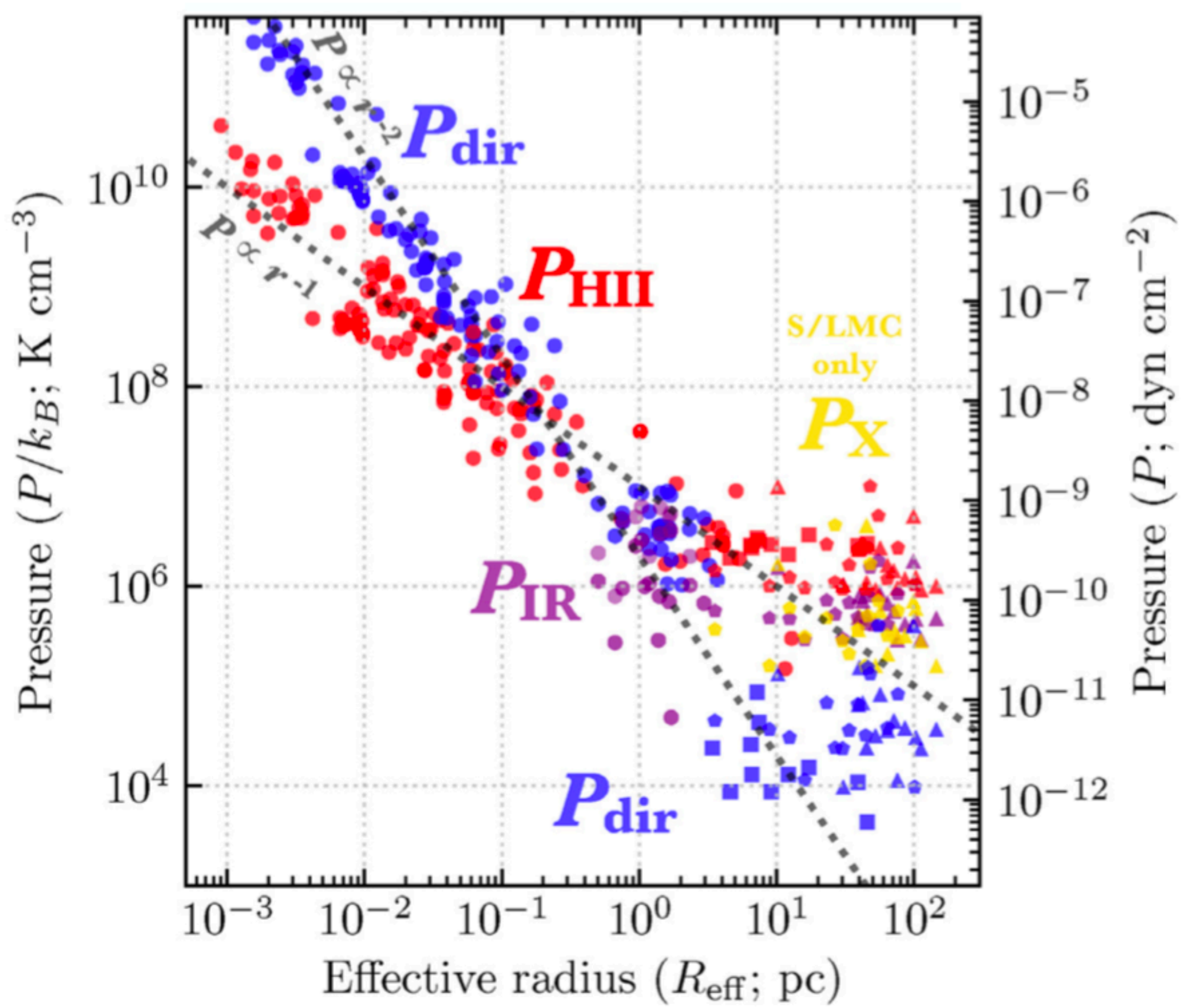

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-> determine which processes drive evolution of star forming regions

Initial conditions

- Isolated spherical clouds are not realistic

We need...

- no more isolated spheres
- galactic potentials
- shear, tidal forces

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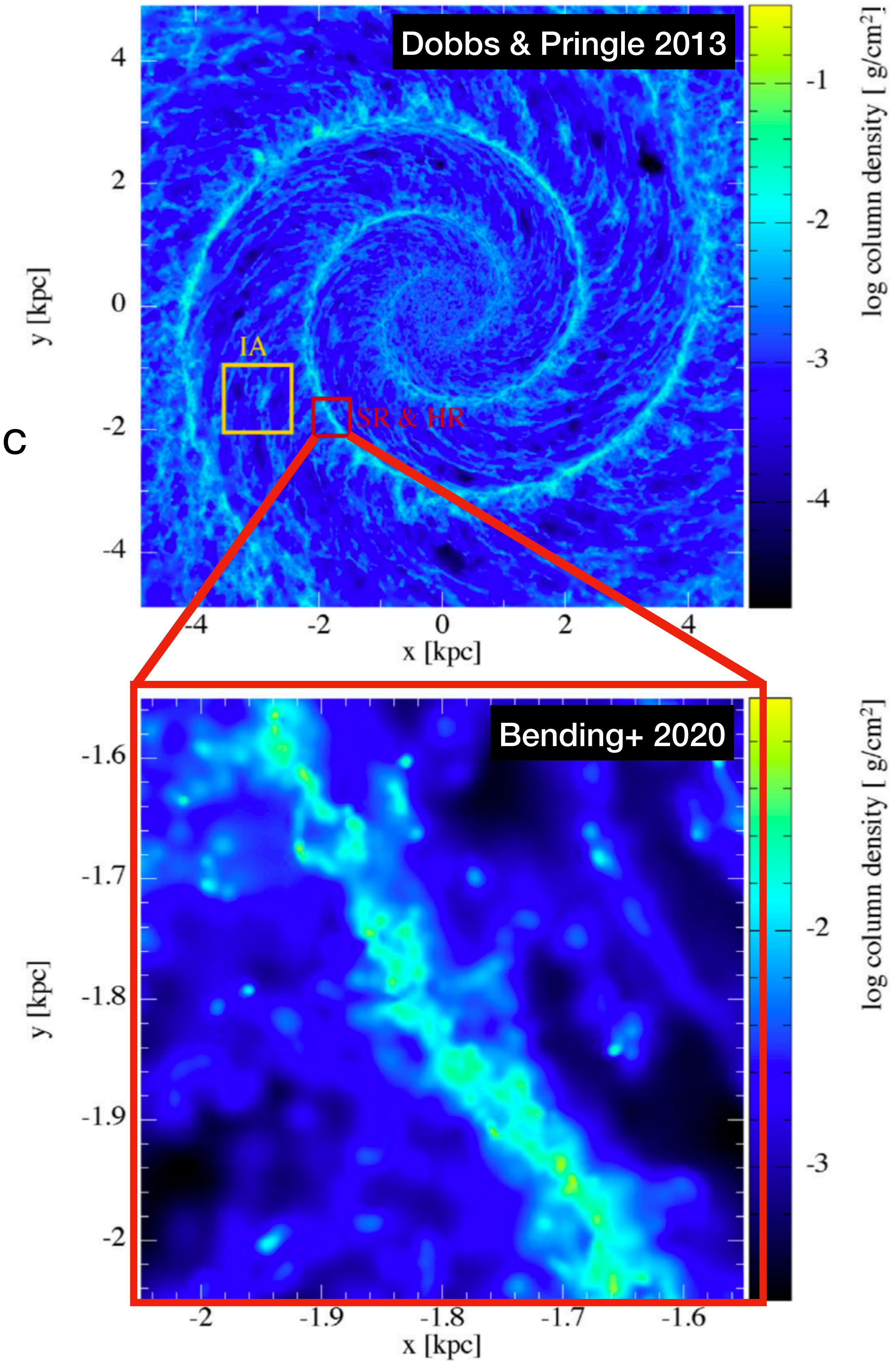

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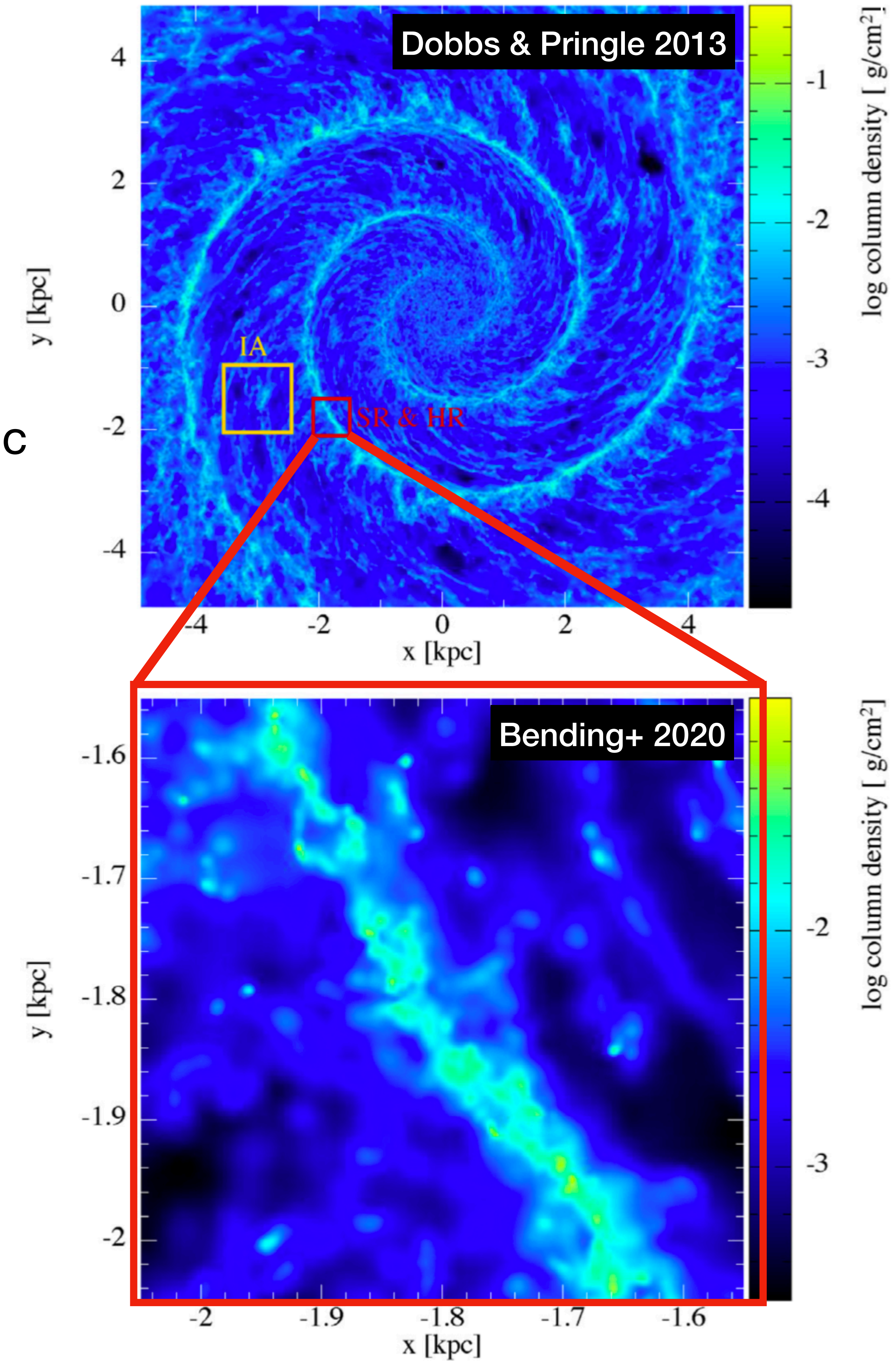
use a sample of ICs in galactic context



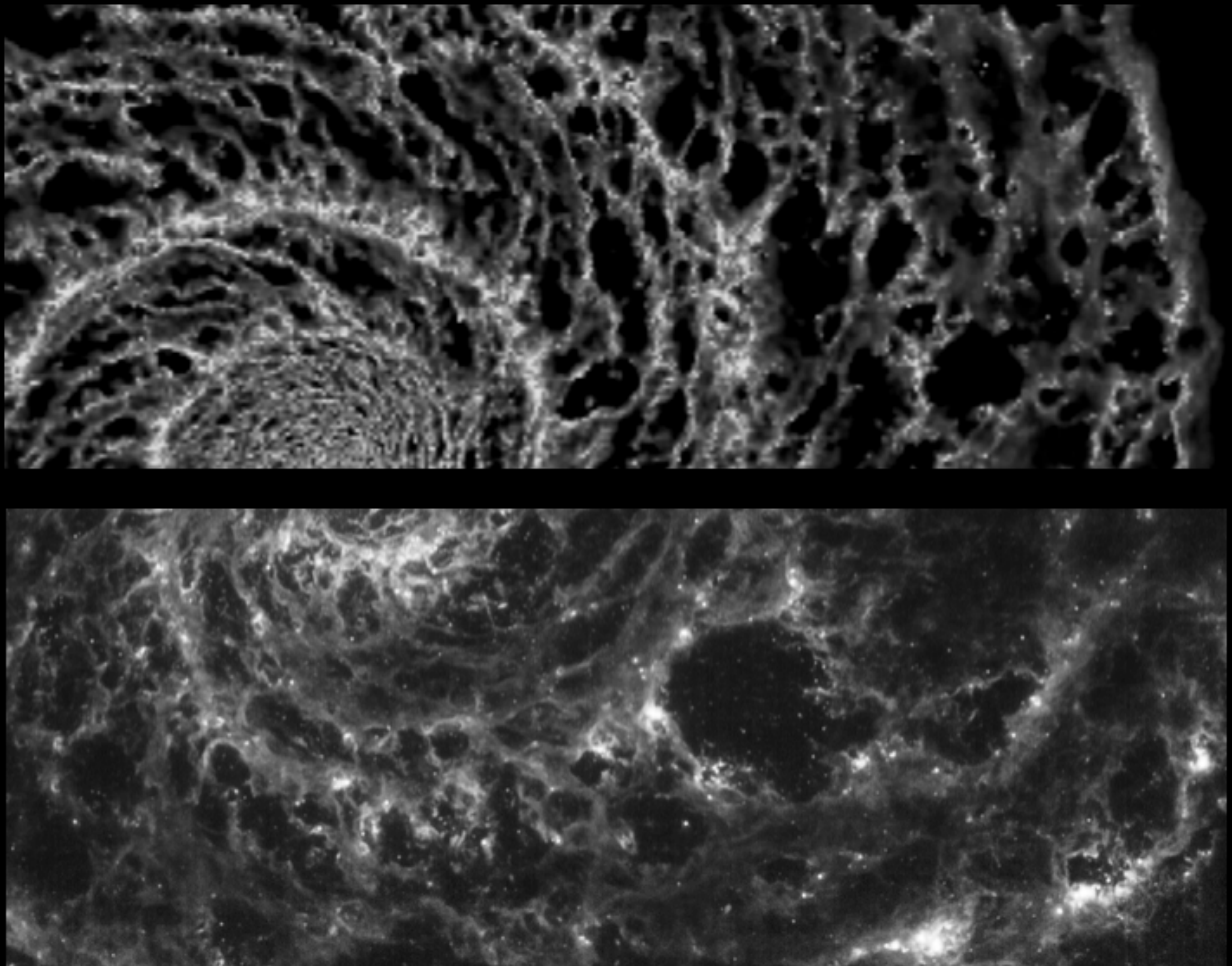
Smoothed particle hydrodynamics

SPHNG (Bate+)

- self-gravity
- cluster-sink particles
- **galactic potentials** (disc, bulge, halo, arms, bar)
- ISM heating/cooling (H_2/CO chemistry, Glover+ 2007)

Feedback

- **photoionization** (ray-tracing)
- **SNe**



Alex Pettitt, ESA/NASA/PHANGS-JWST

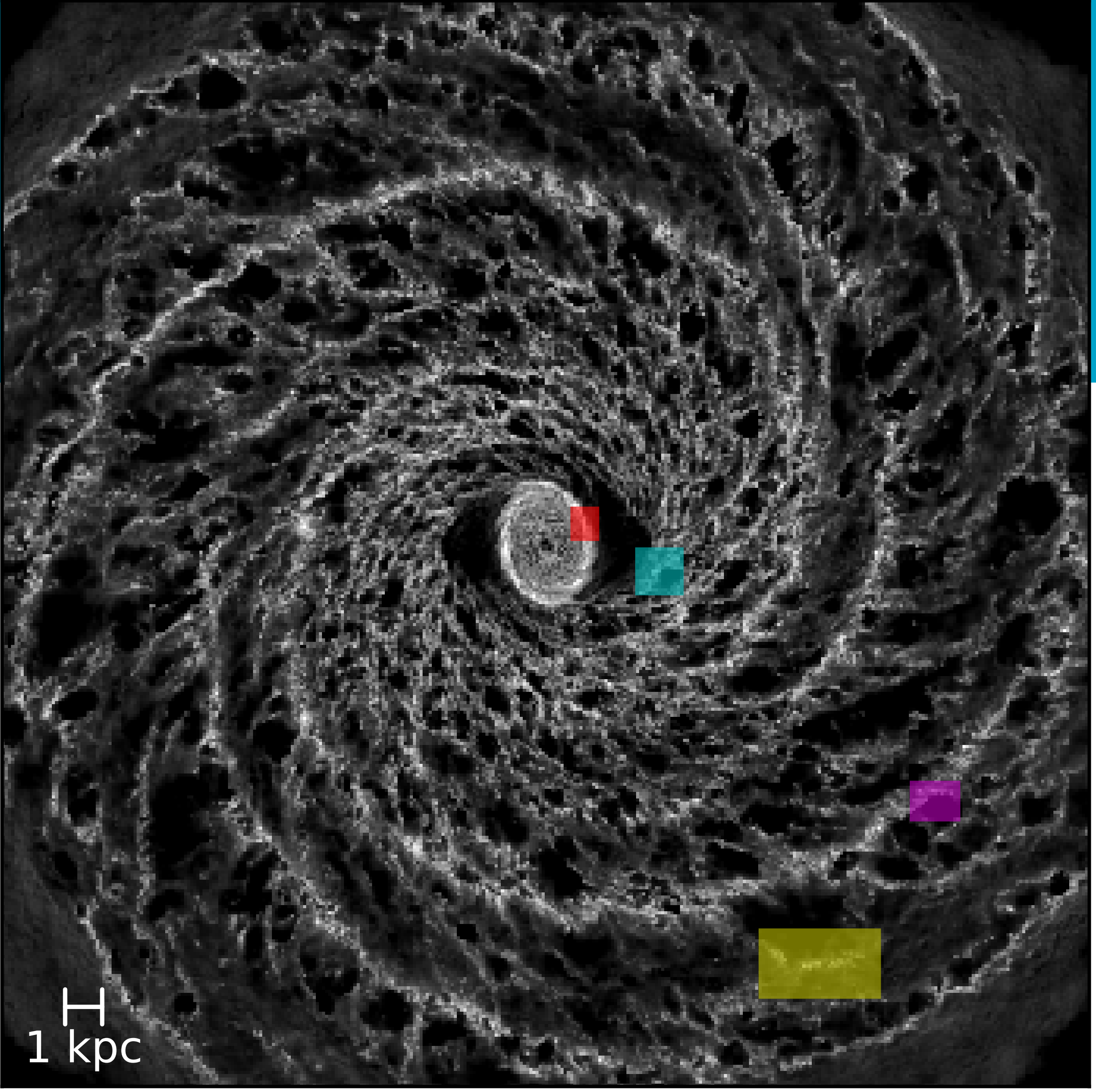
MW-like barred spiral

- Compare bar / arms / inter-arm

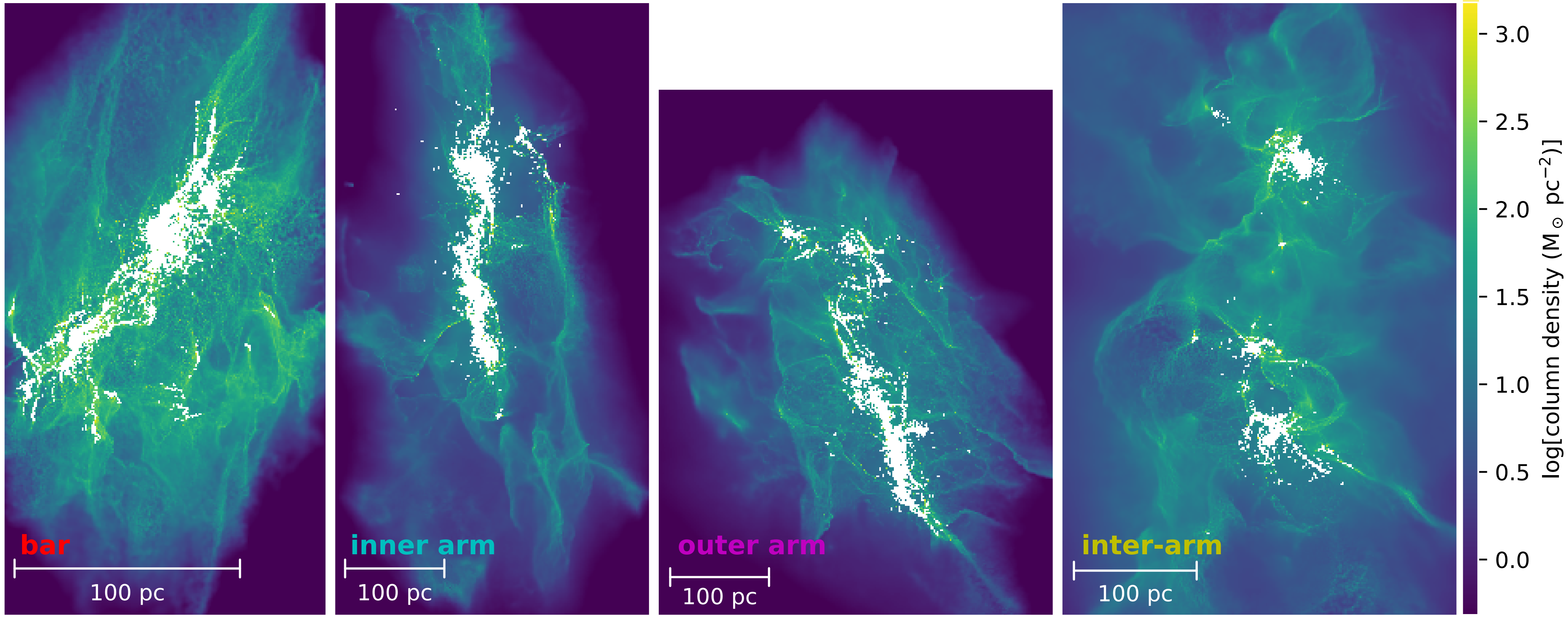
regions of

10^6 M$_\odot$

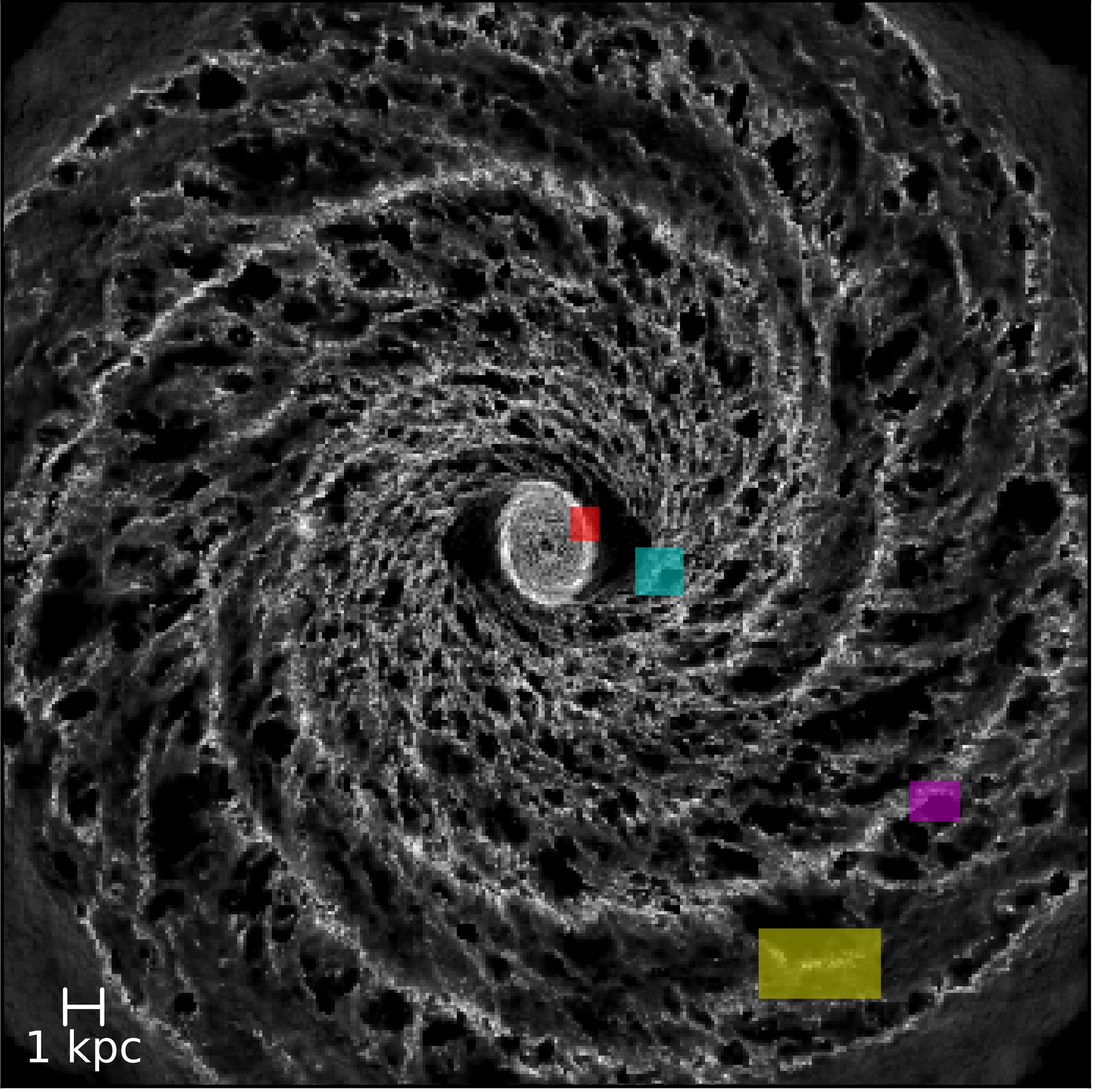
100-300 pc



Pettitt+ 2020

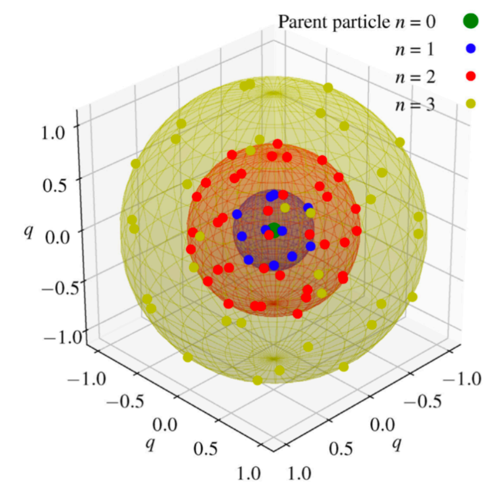


Ali+ 2023, MNRAS, 524, 555



Galaxy: 600 $M_\odot$/particle
SNe

Zoom-ins (particle splitting):
0.4 $M_\odot$/particle
0.1 pc cluster-sinks
Photoionization + SNe



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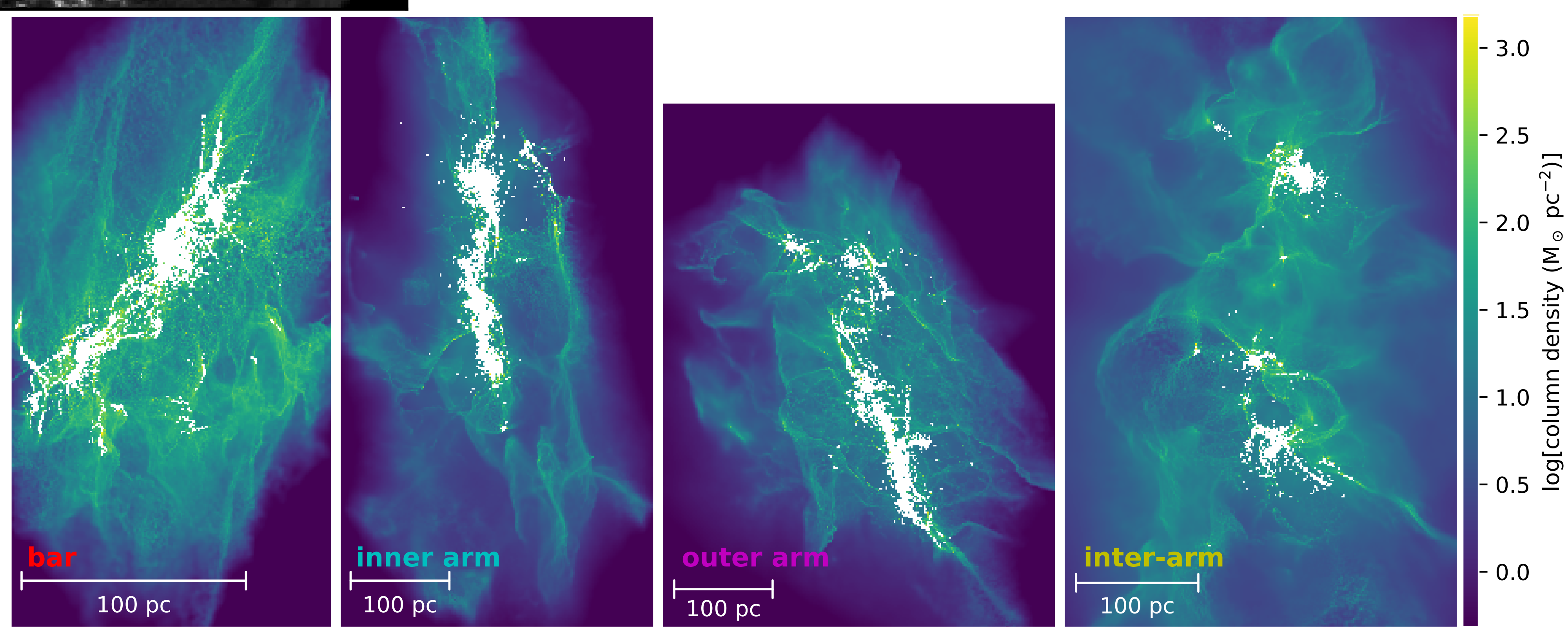
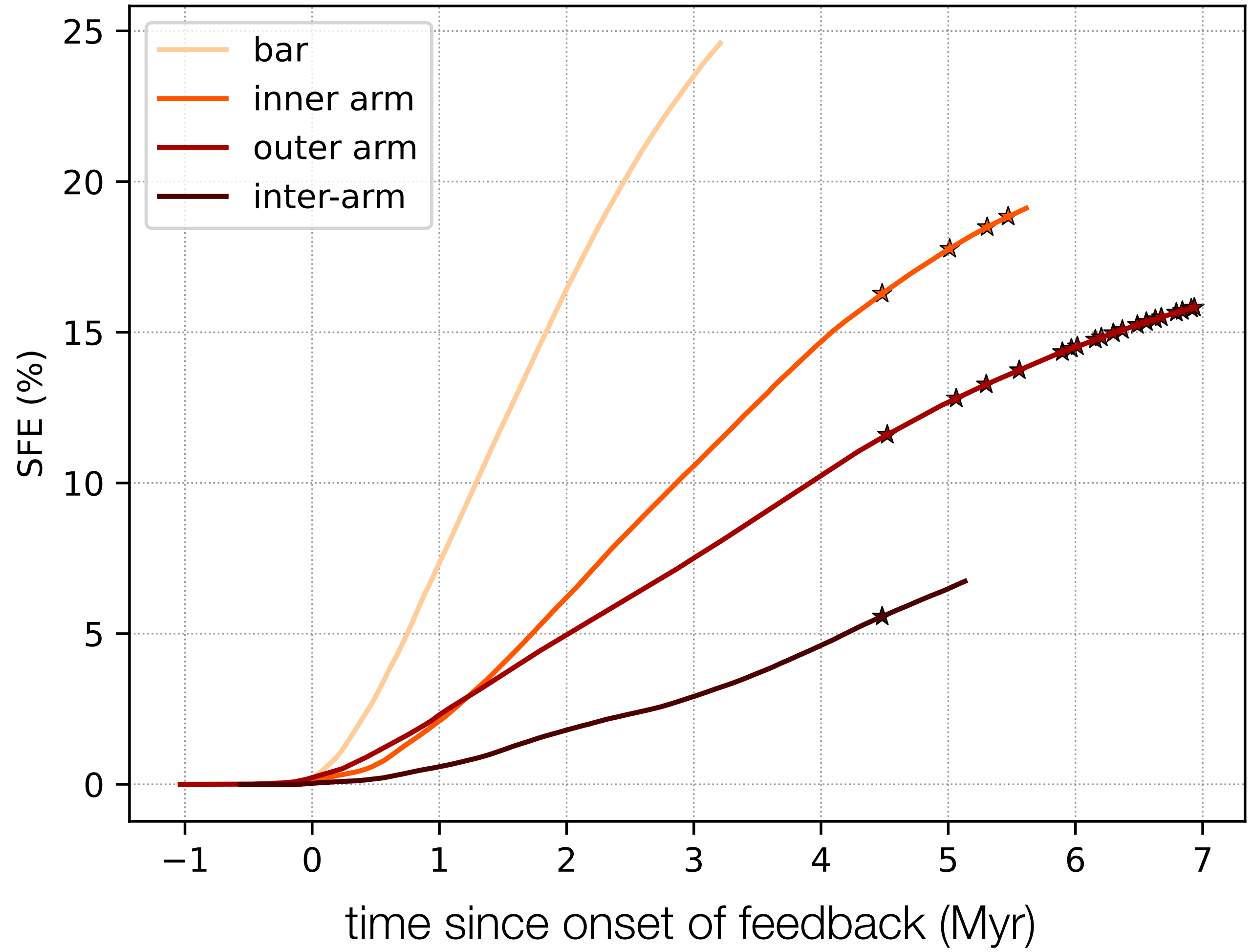


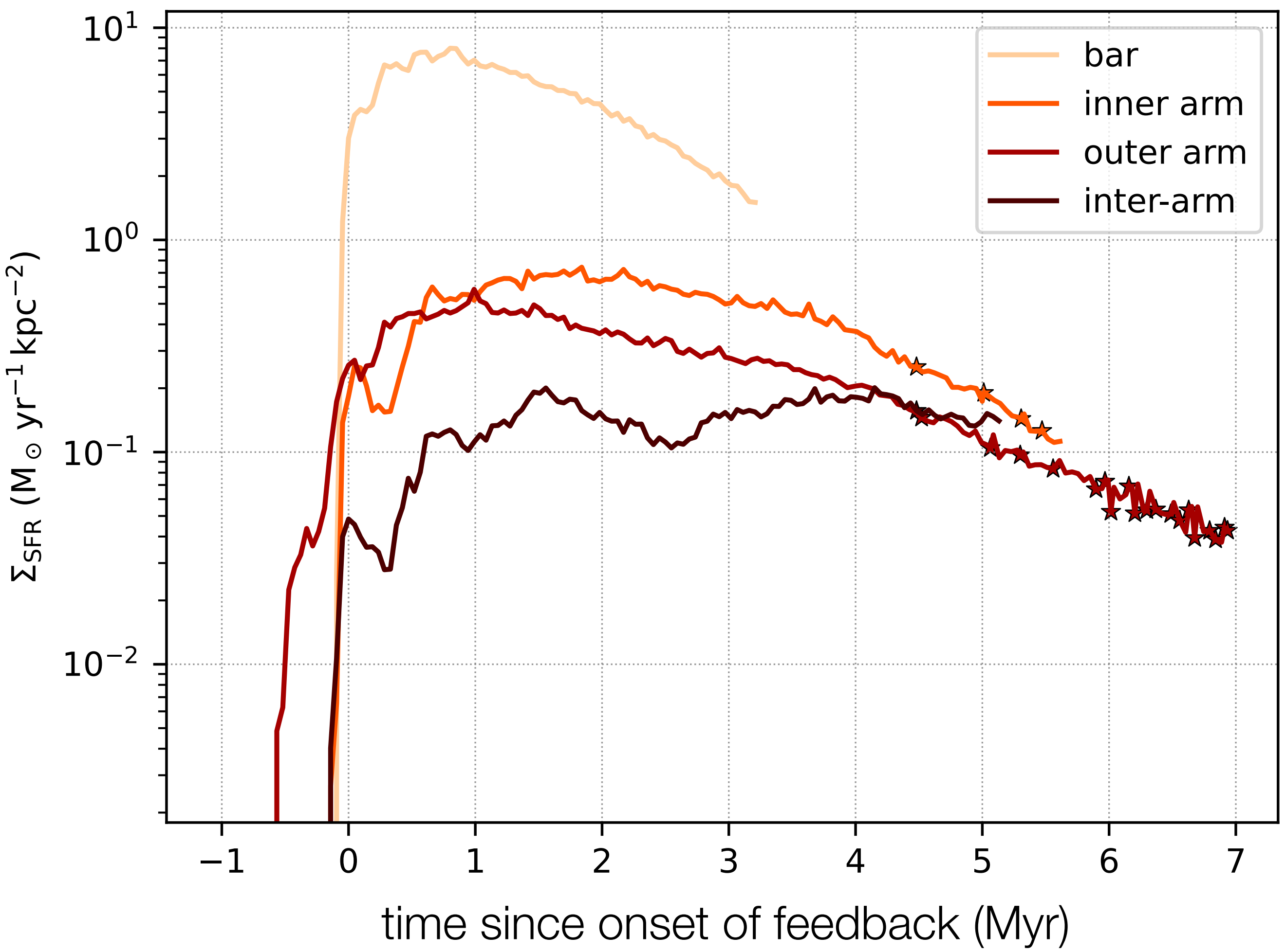
Ali+ 2023, MNRAS, 524, 555

SFE, SFR

$$\mathrm{SFE} = \frac{M_*}{M_{\mathrm{tot}}}$$

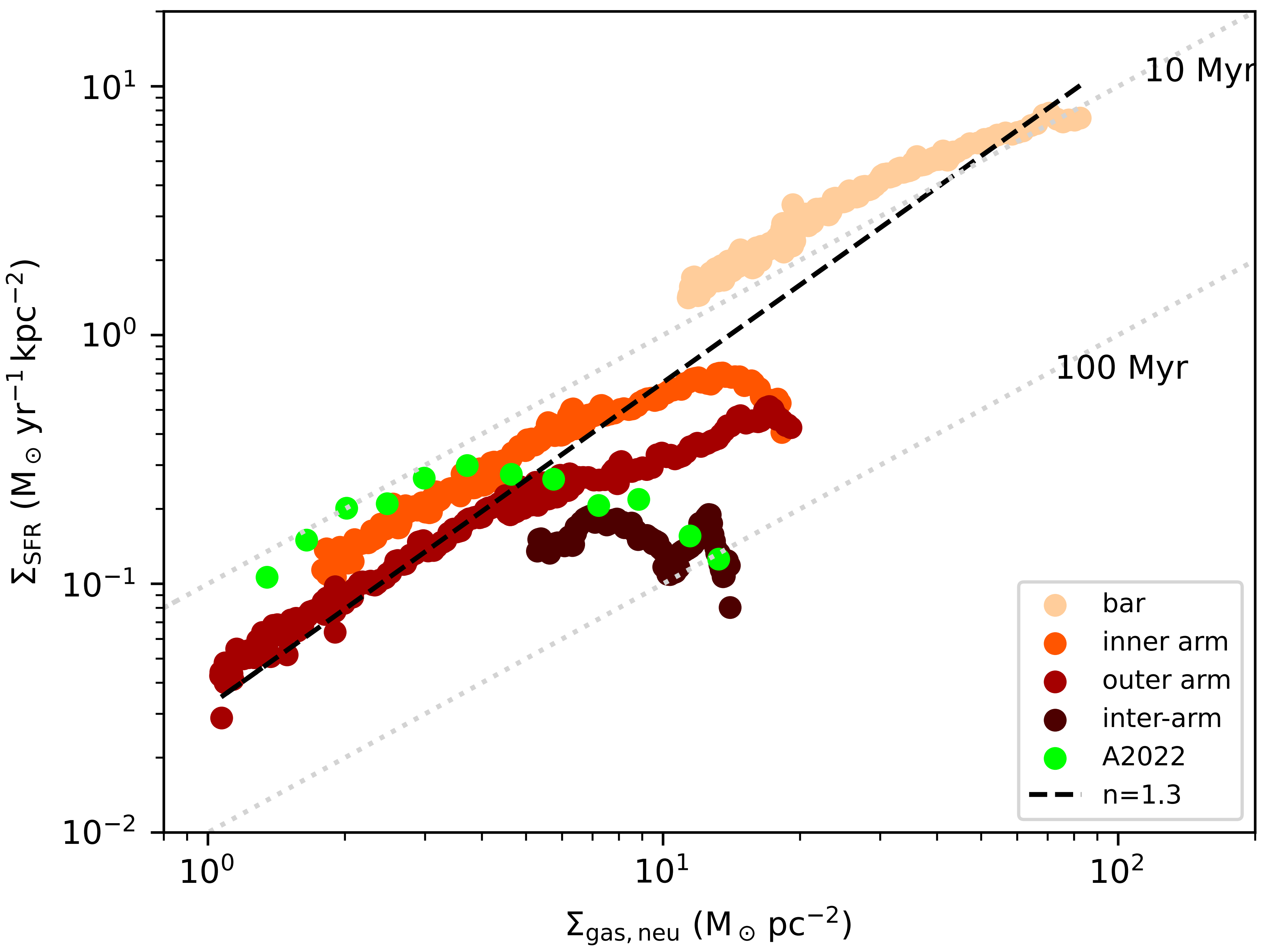


$$\Sigma_{\mathrm{SFR}} = \frac{\Delta M_*}{XY\Delta t}$$



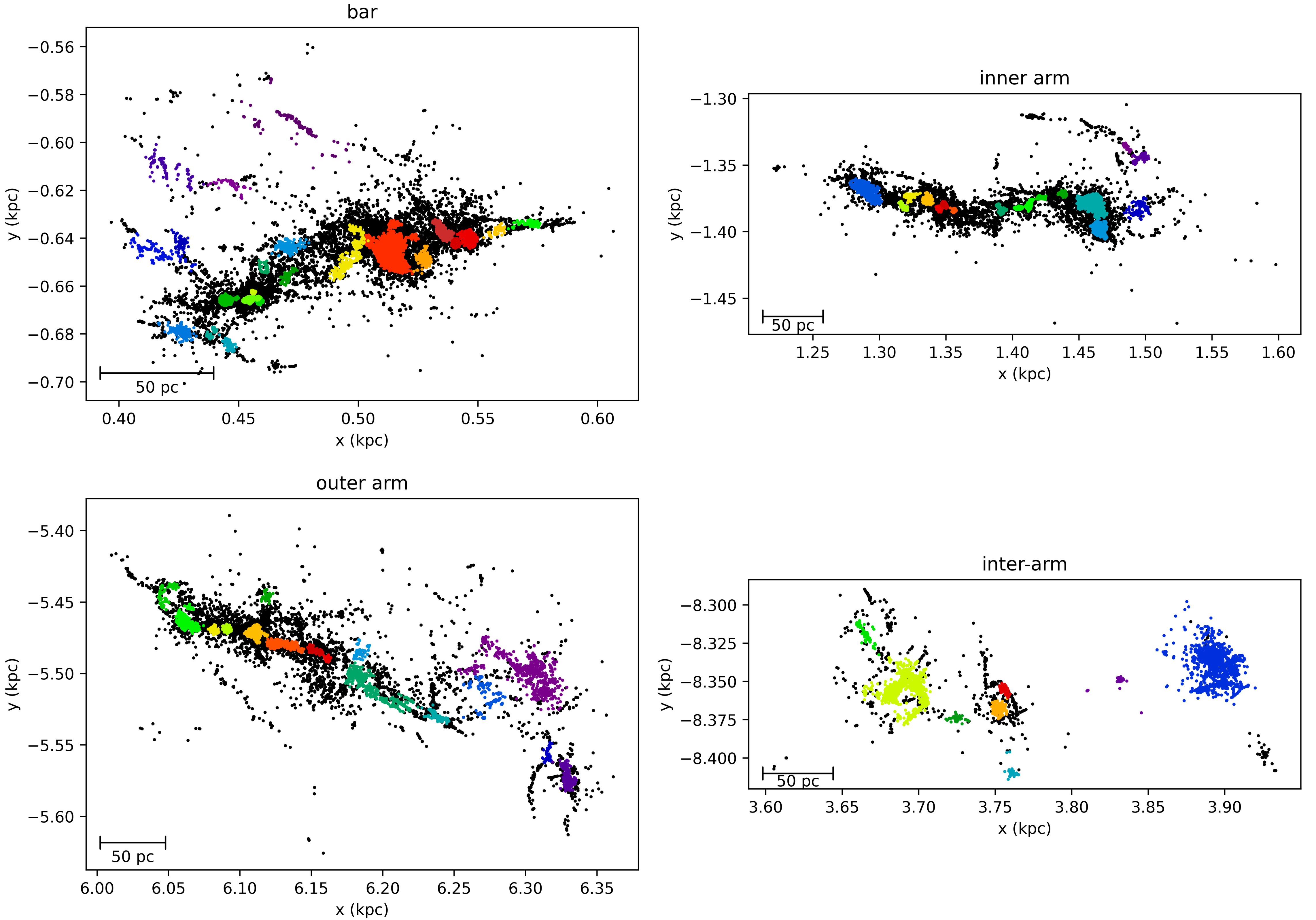
Ali+ 2023

Kennicutt-Schmidt relation

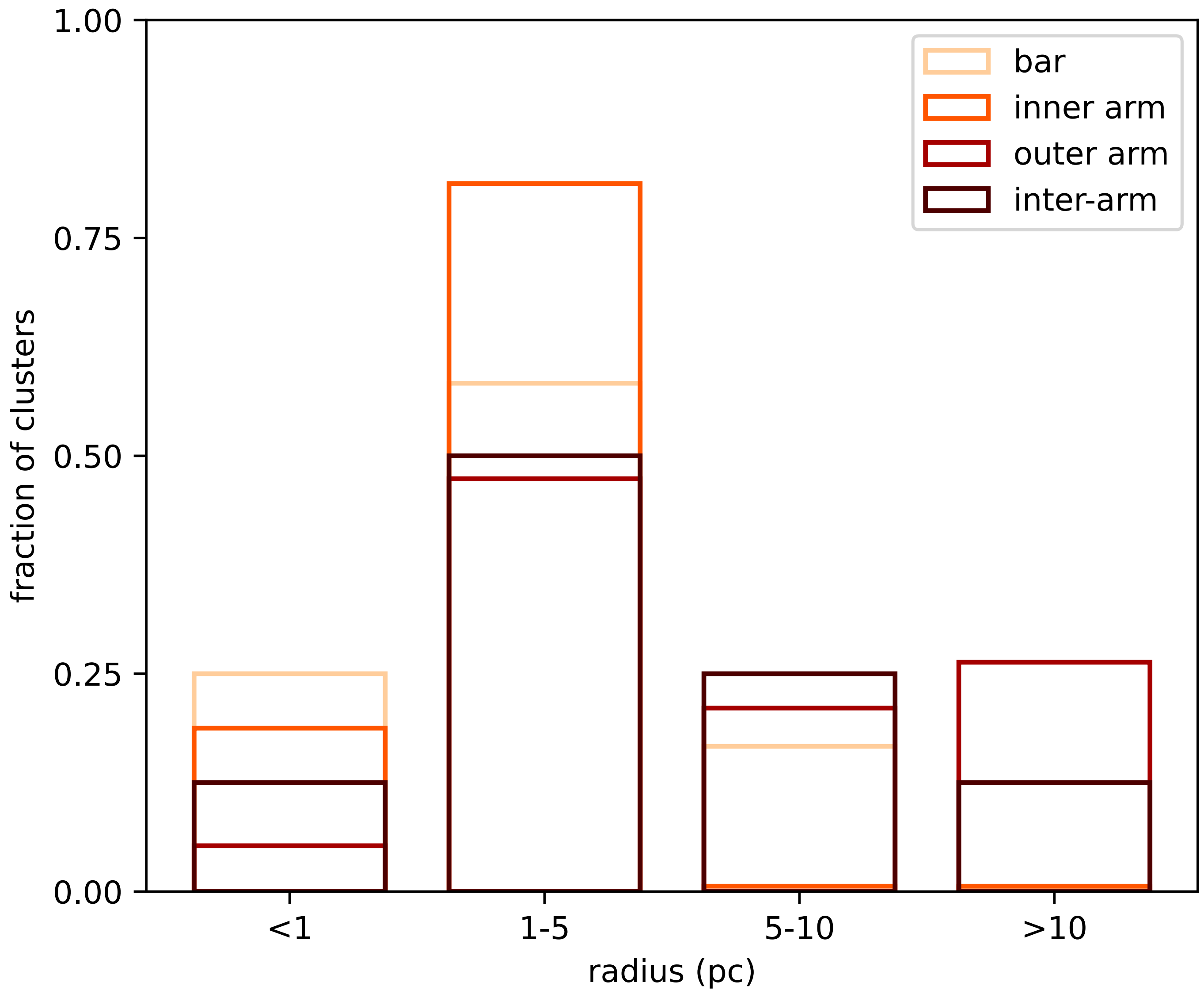


- power law consistent with K-S law
- bar is higher up the law
- **inter-arm** 2-3x less efficient than arms

Clusters with HDBSCAN (Campello+ 2013)

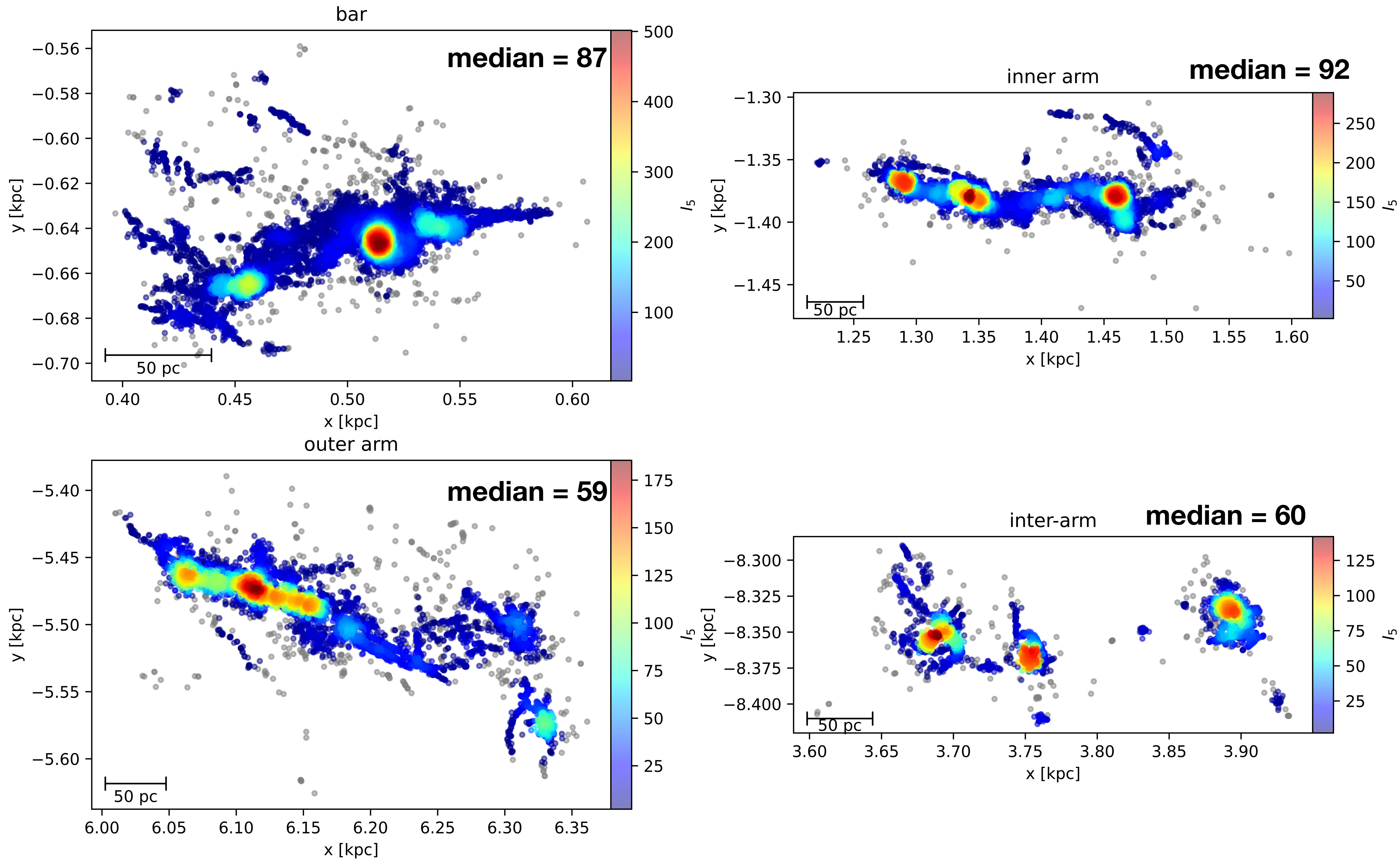


Cluster sizes

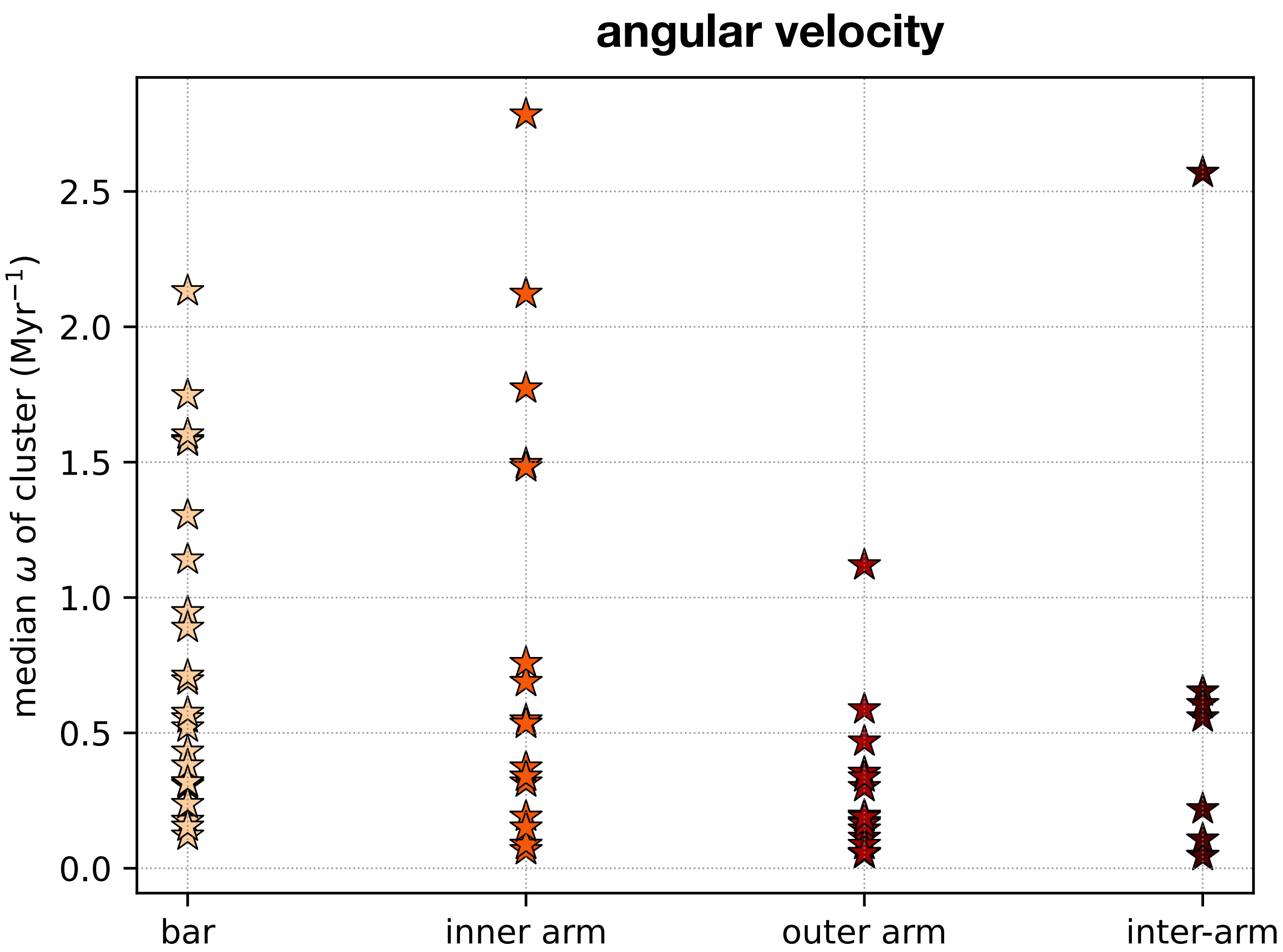


- bar / inner arm prefer smaller clusters
- outer arm / inter-arm create larger clusters

Degree of clustering with INDICATE (Buckner+ 2019)

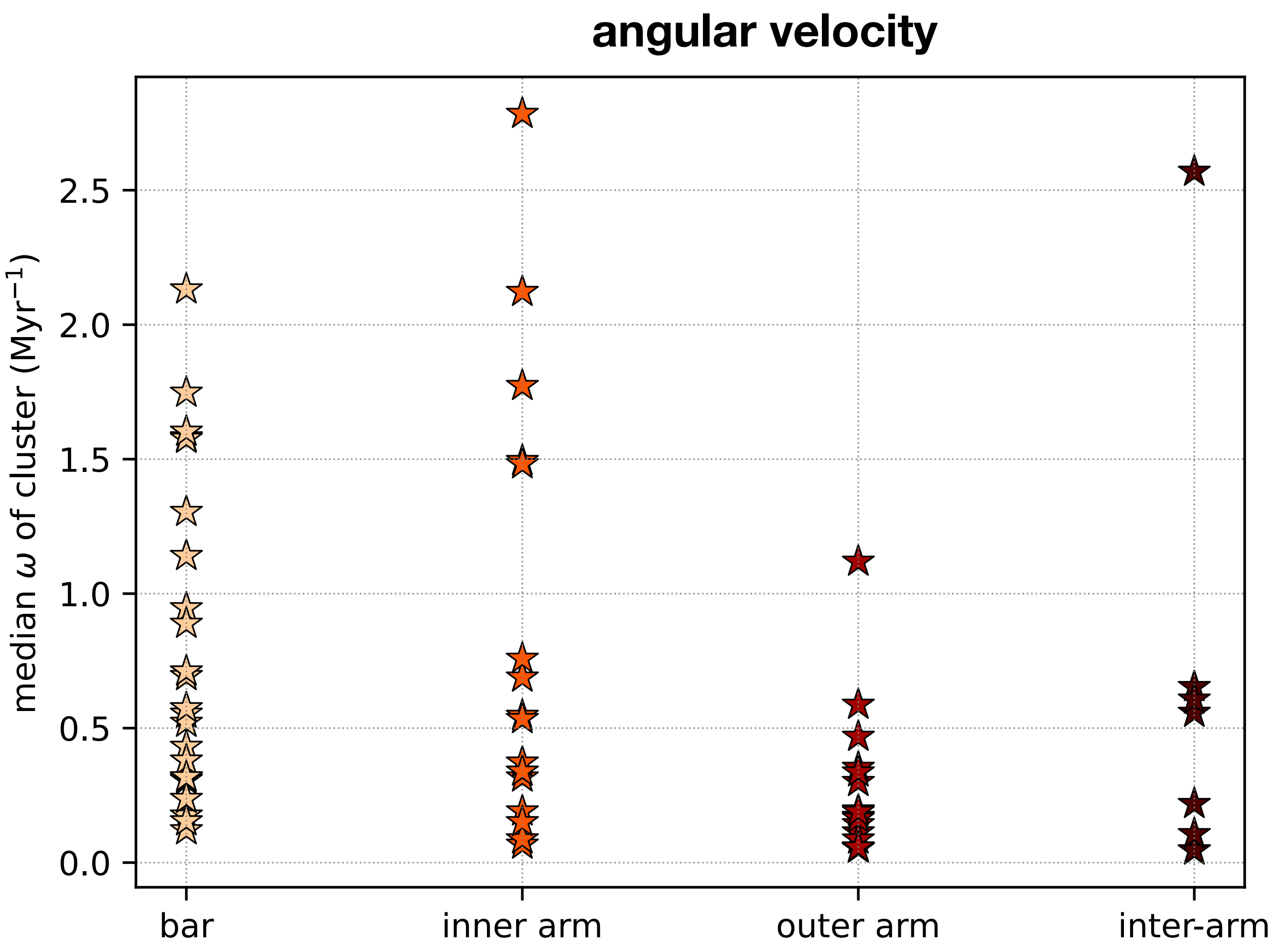


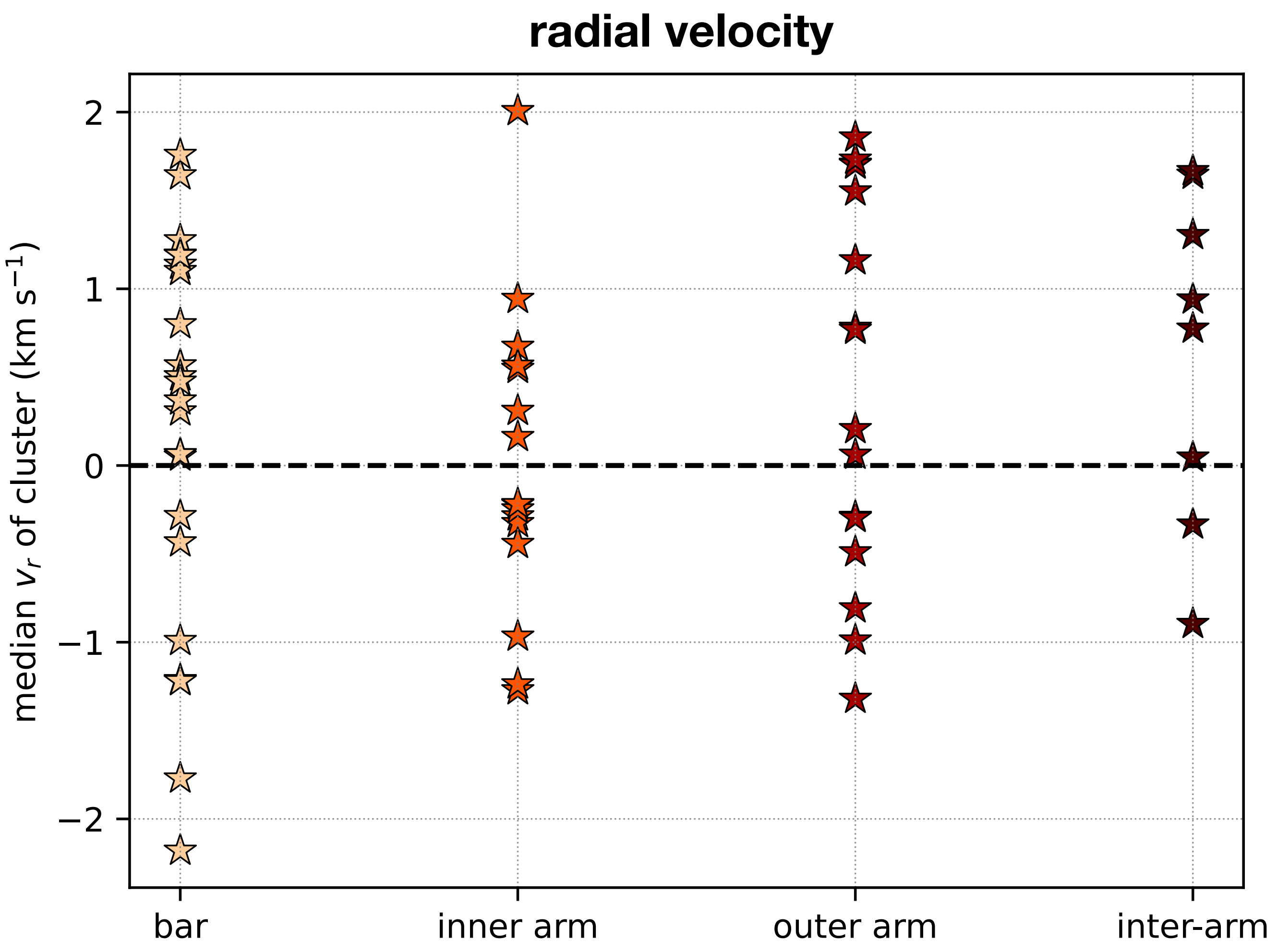
Cluster rotation/expansion



bar / inner arm rotate faster (on average)

Cluster rotation/expansion





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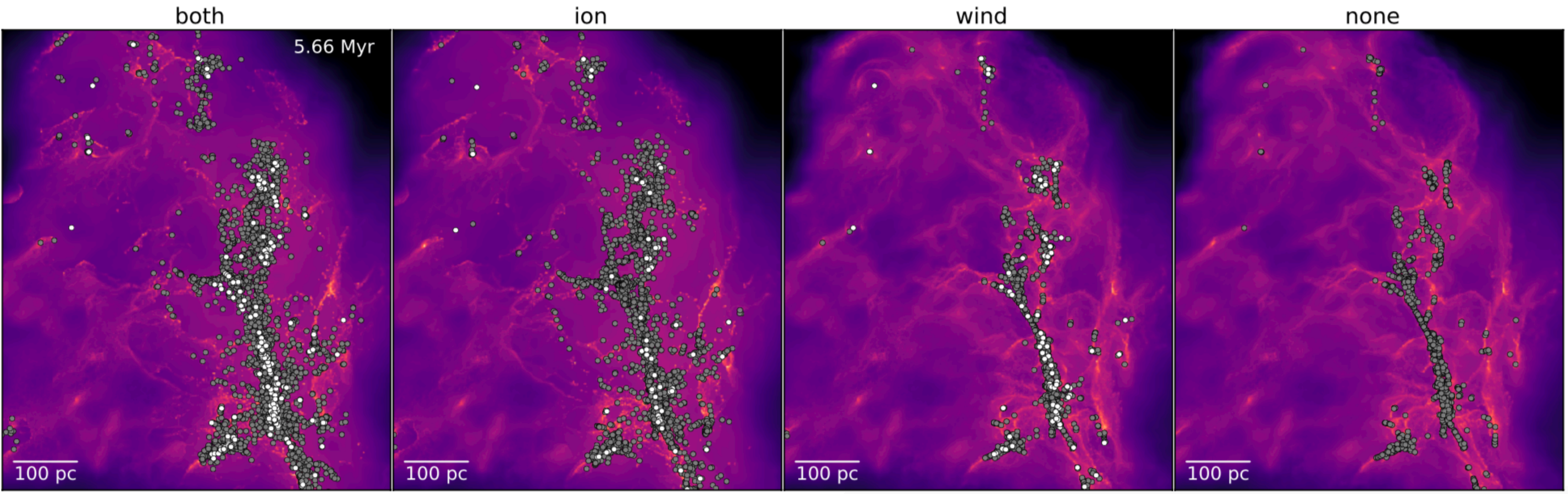
Ionization + stellar winds

Ali, Bending, Dobbs, 2022, MNRAS, 510, 5592



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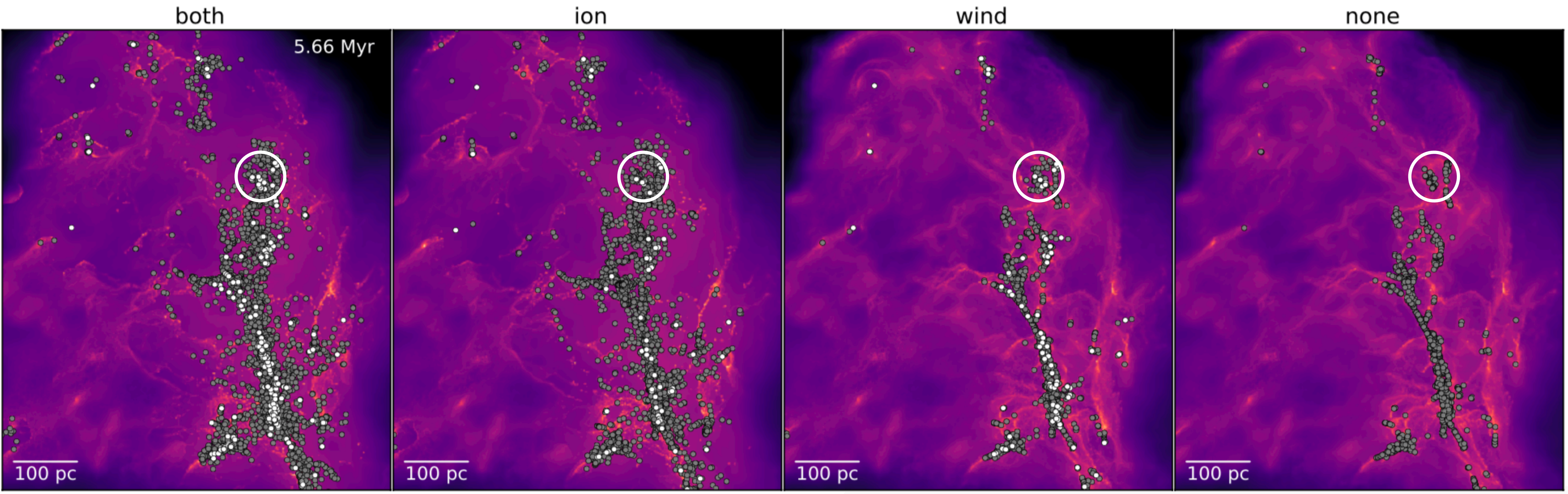

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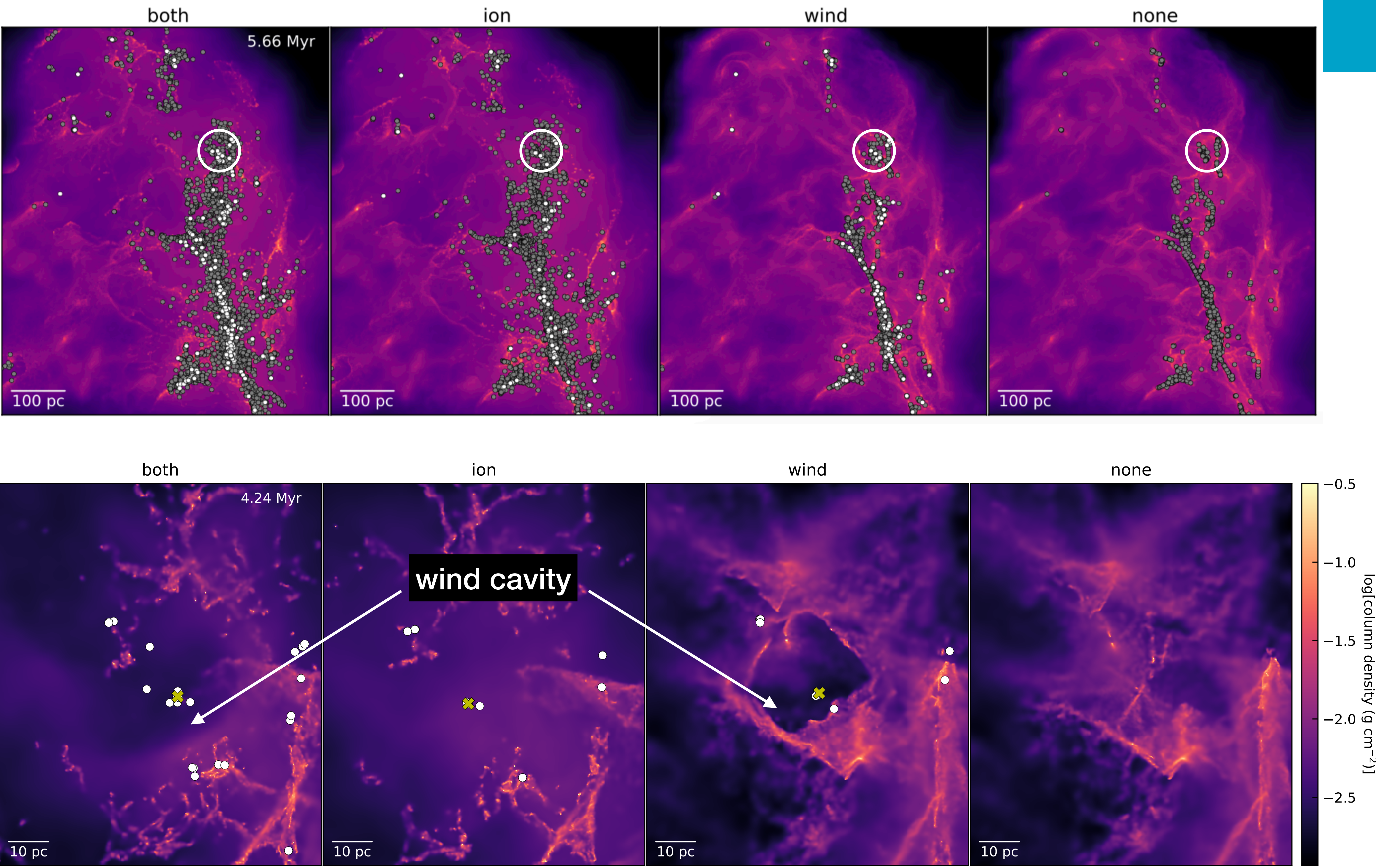
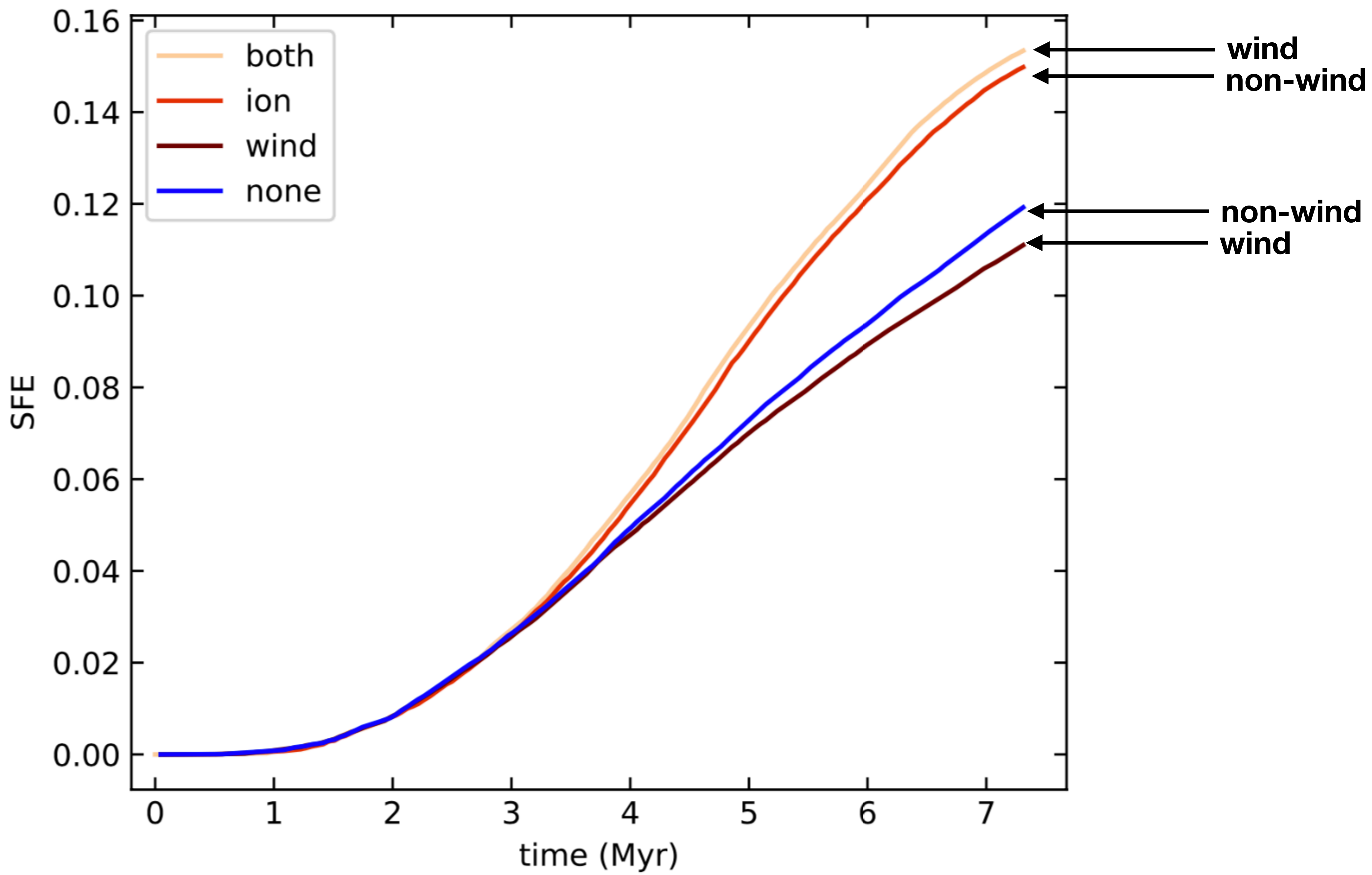
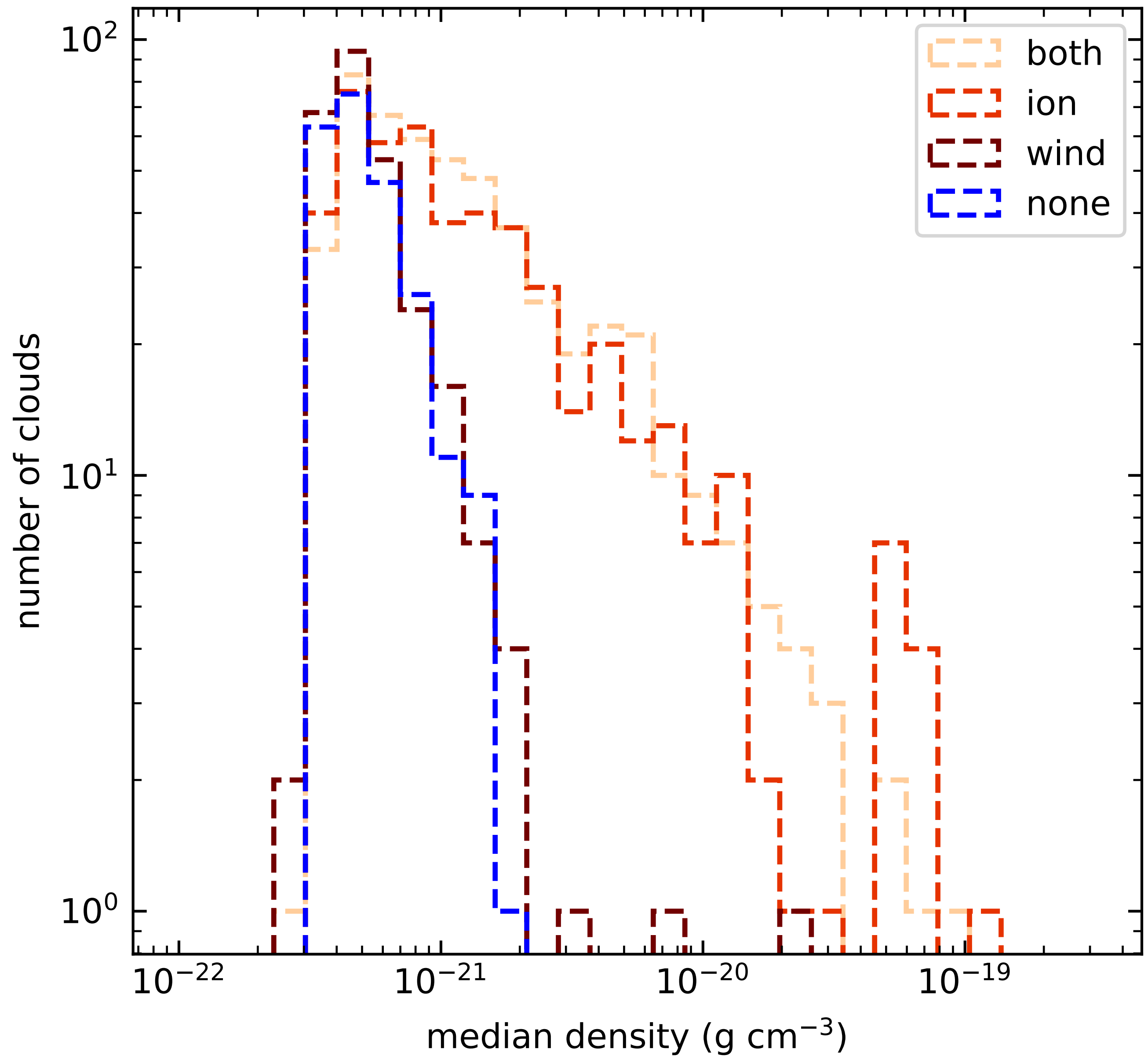


Star formation efficiency



Cloud/core properties



ionization

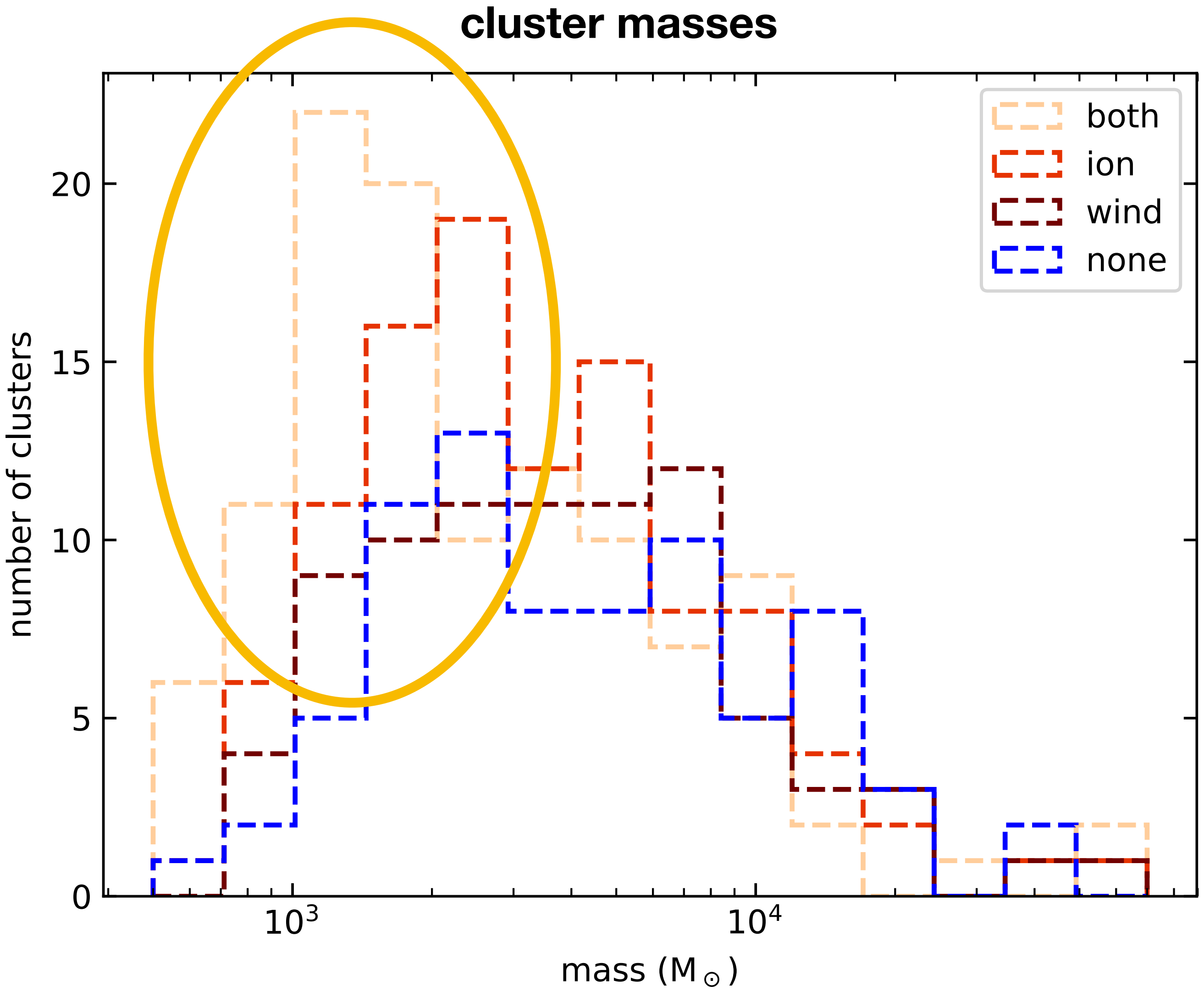
- 2x more clouds
- denser clouds

adding winds

+10% more clouds

Cluster properties

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

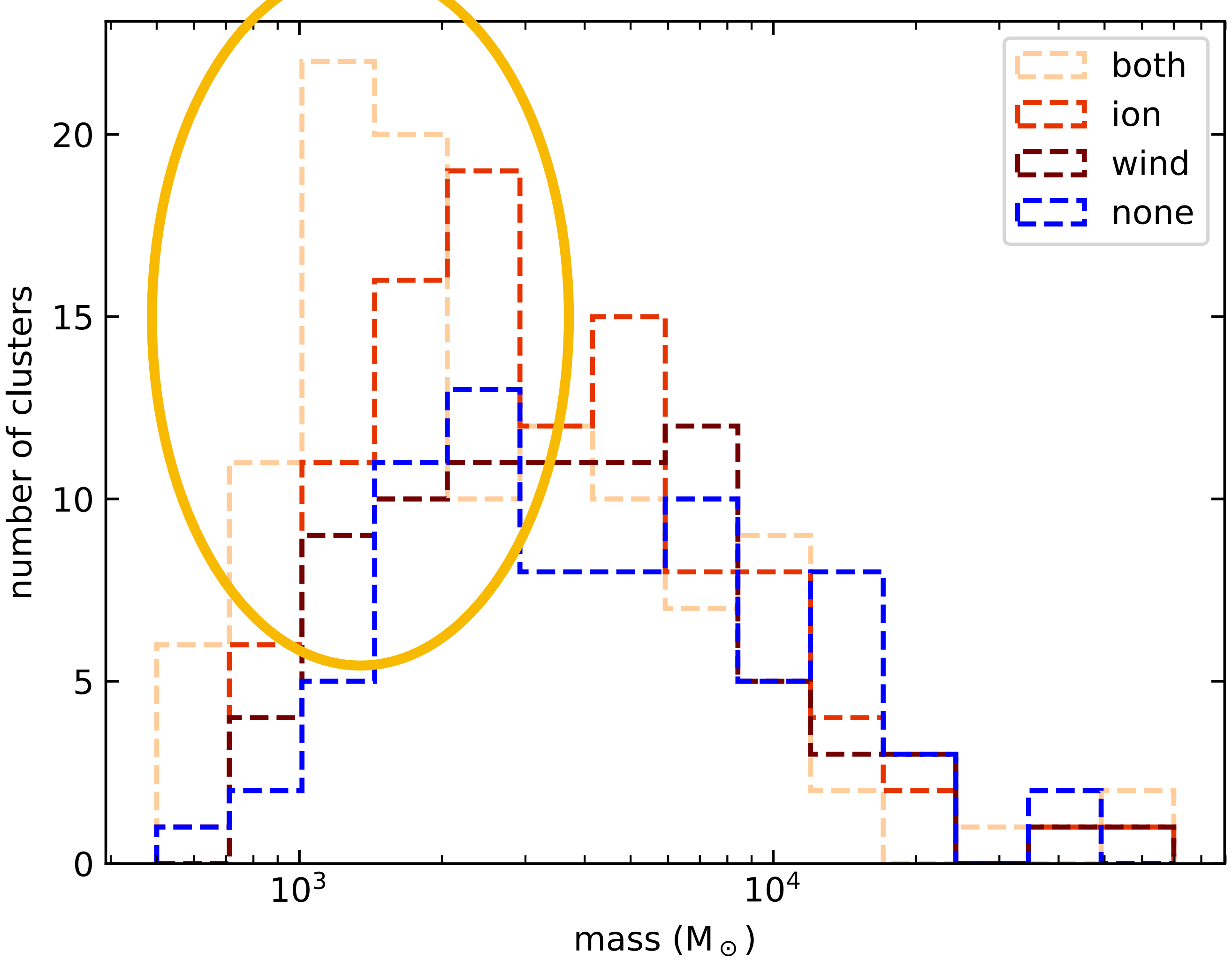


adding winds
produces more low-mass clusters

Cluster properties

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

cluster masses



adding winds
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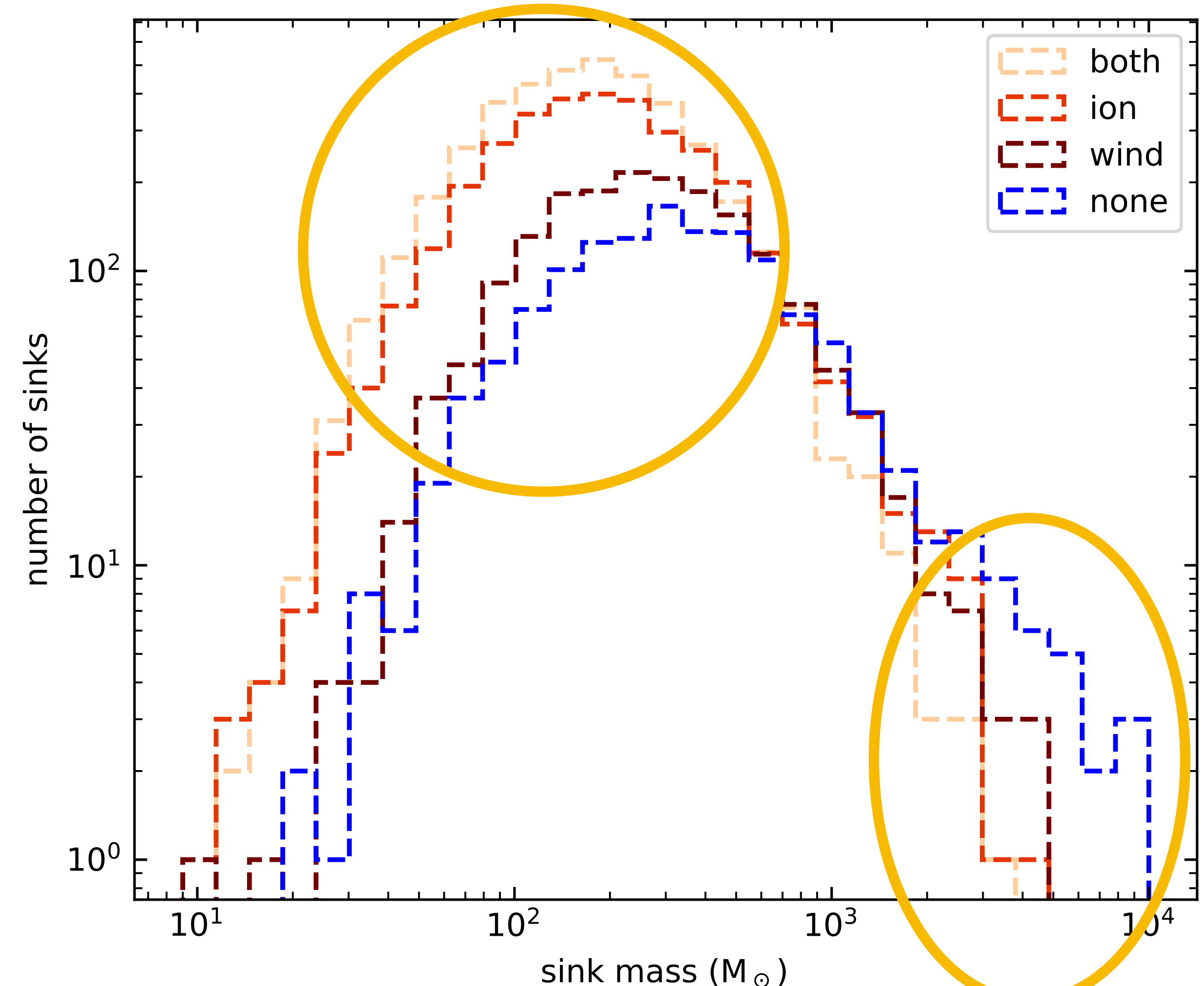
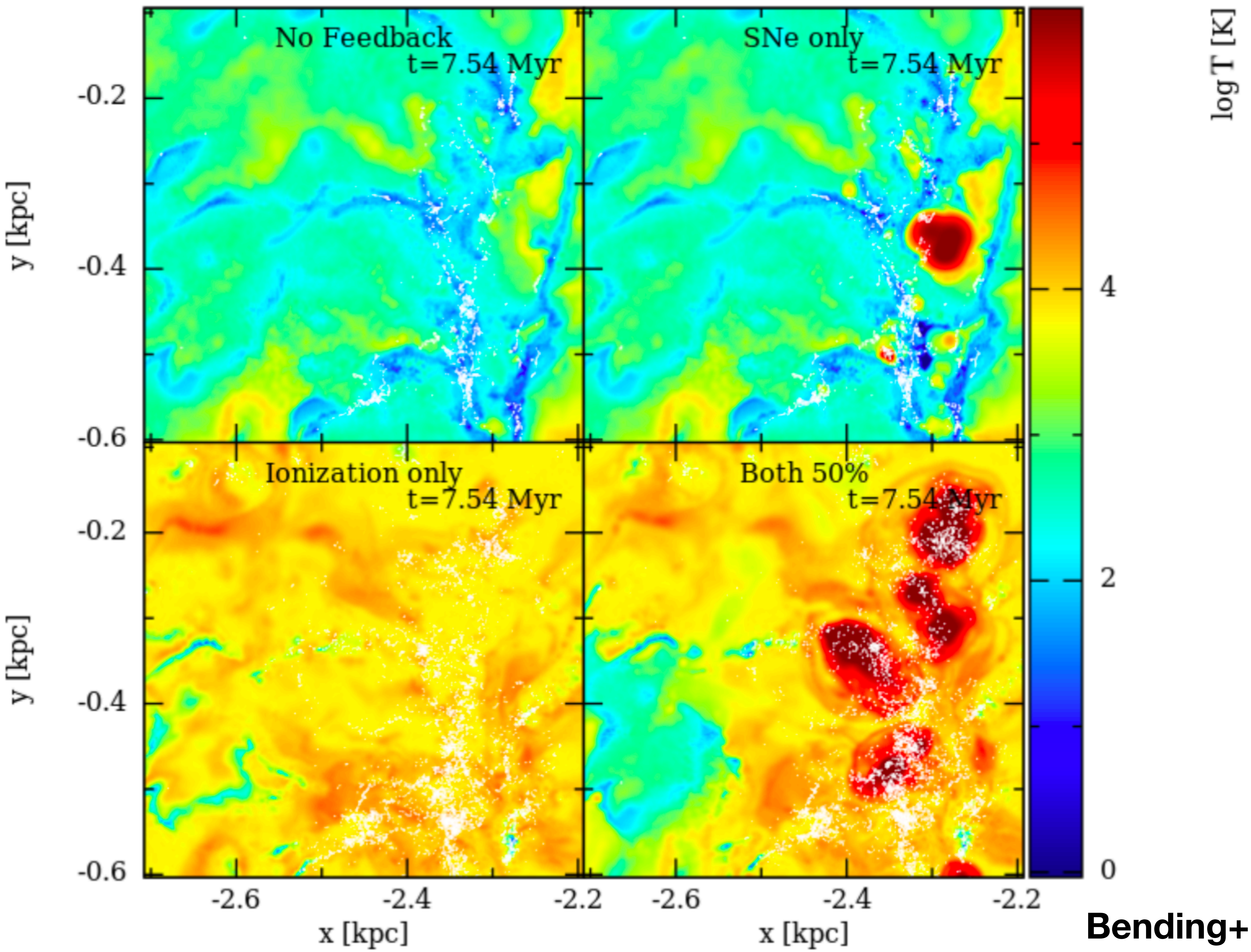
sink masses

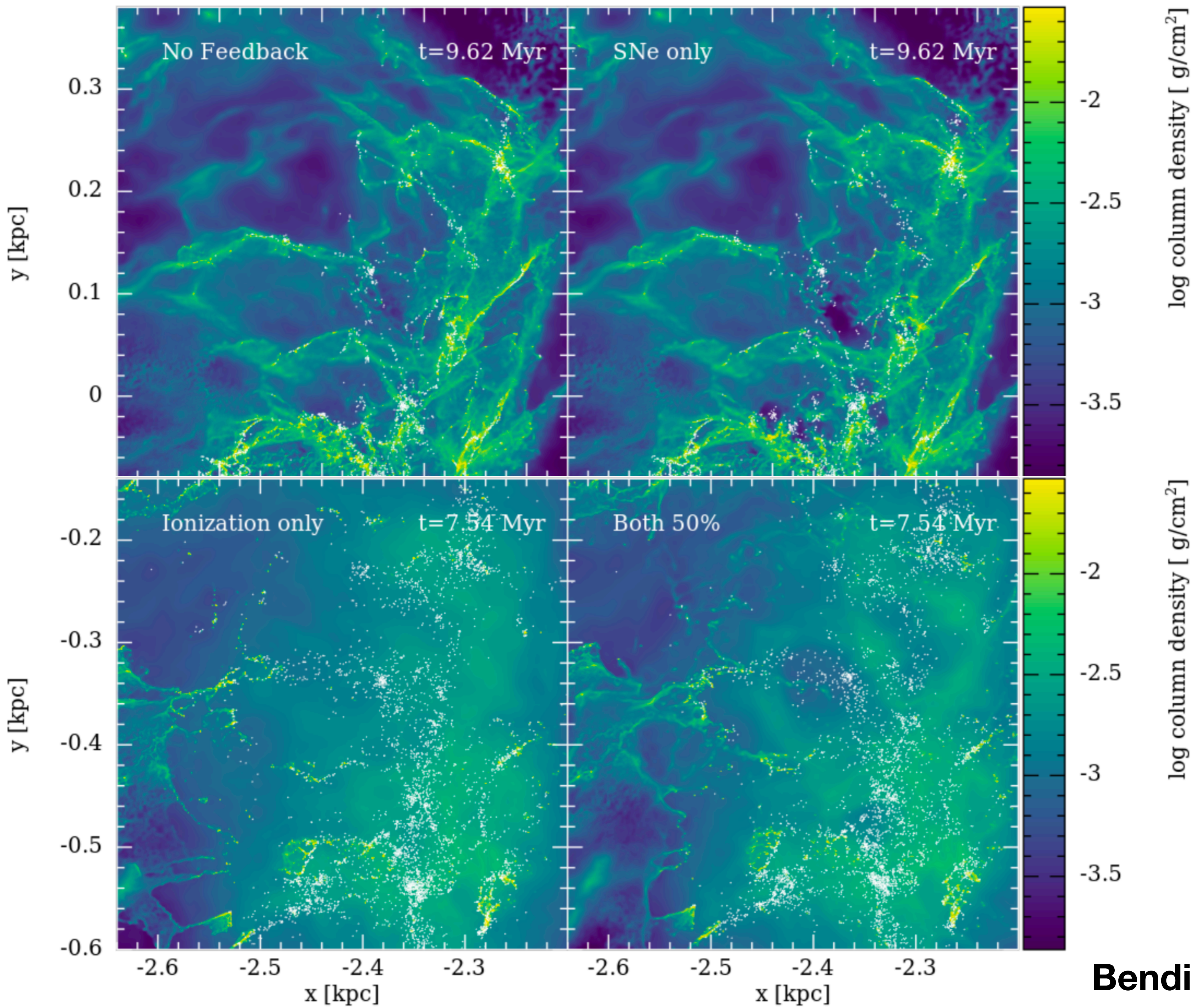


Ionization + SNe



Bending+ 2022

Ionization + SNe



Bending+ 2022

Summary

- Photoionization dominates over RP/stellar winds
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  - hotter HII region
  - weaker RP
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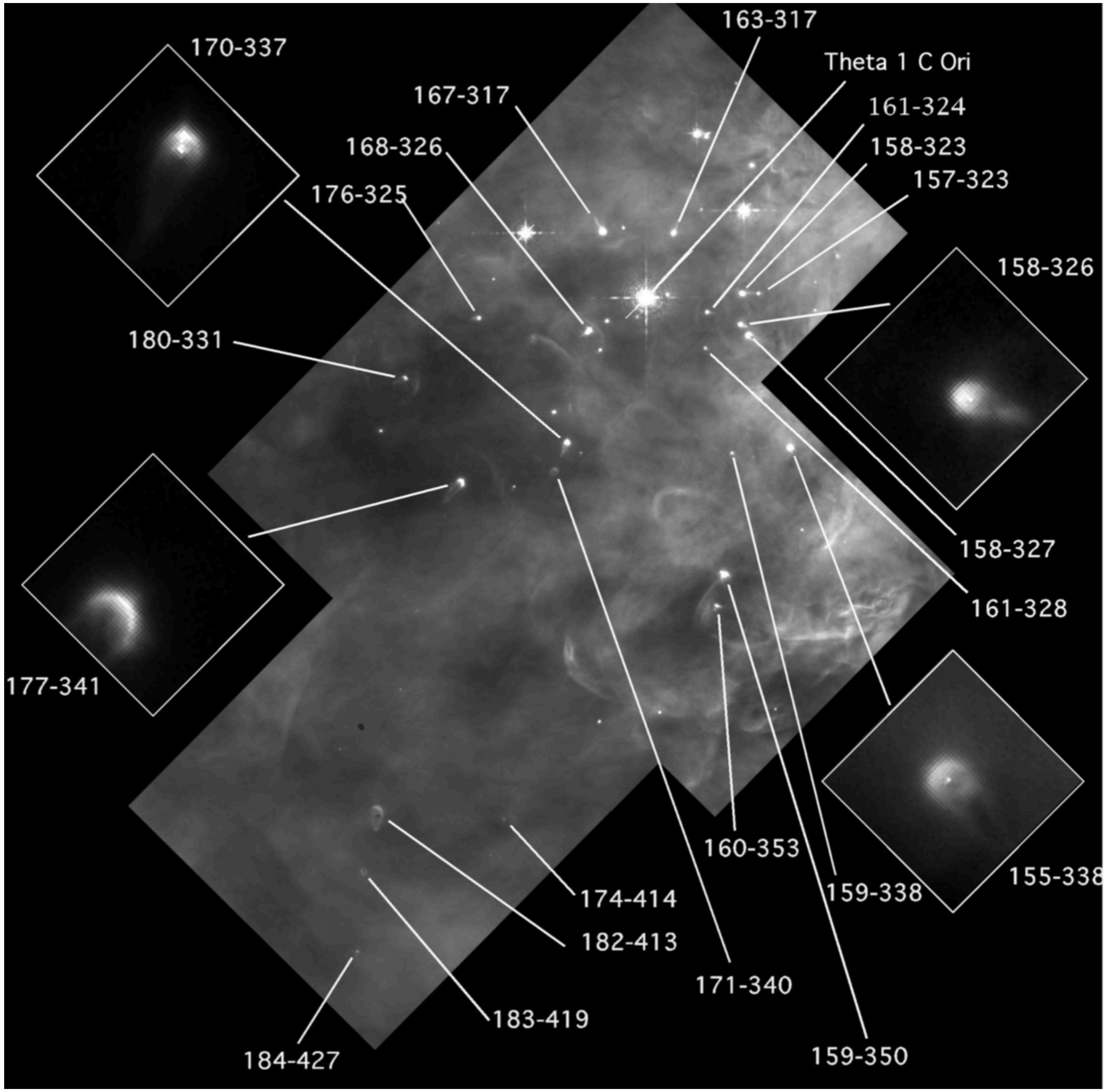
Thank you!

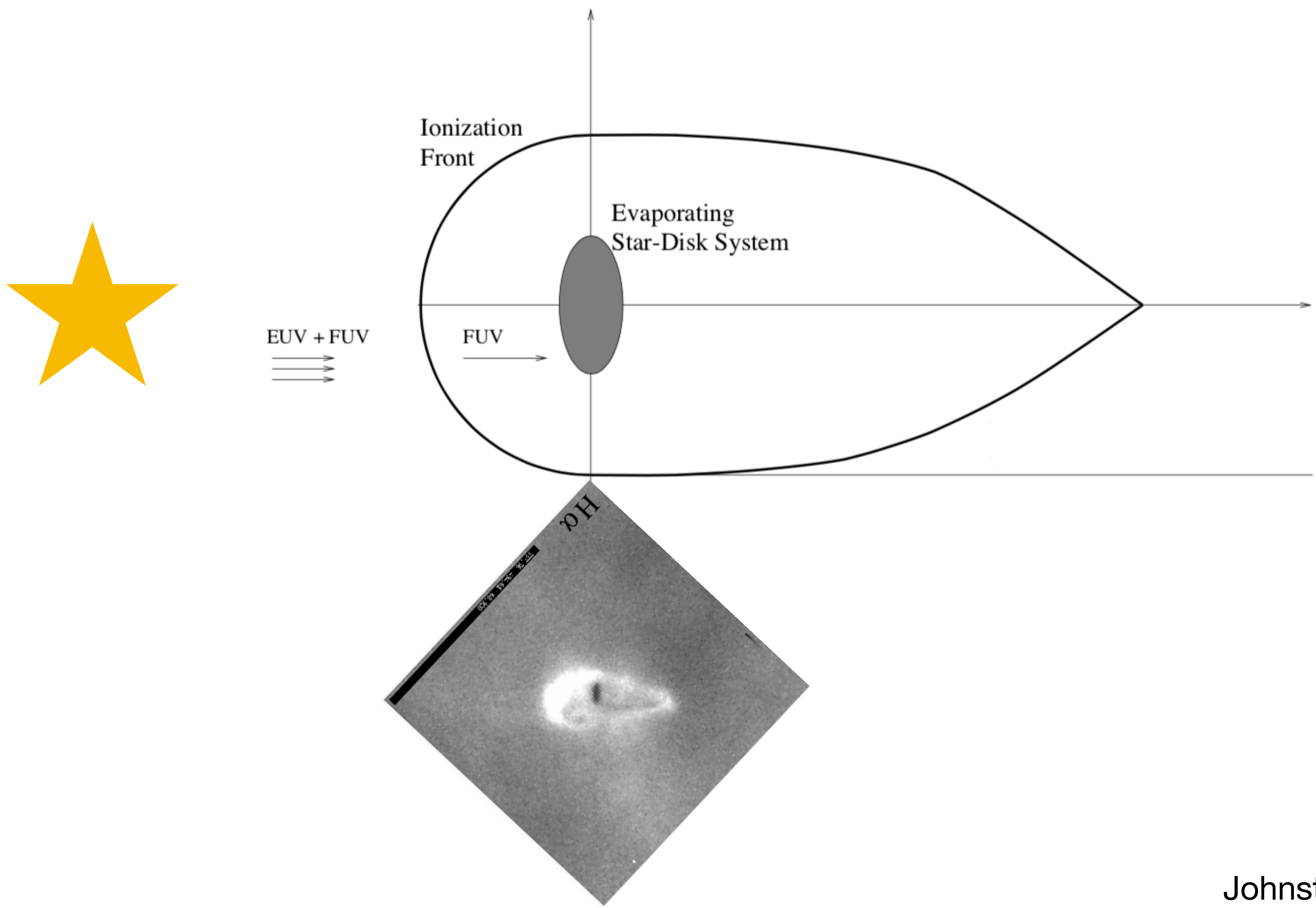
Proplyds



ONC (O'Dell 1998)

ONC (Bally+ 2000)

Proplyds



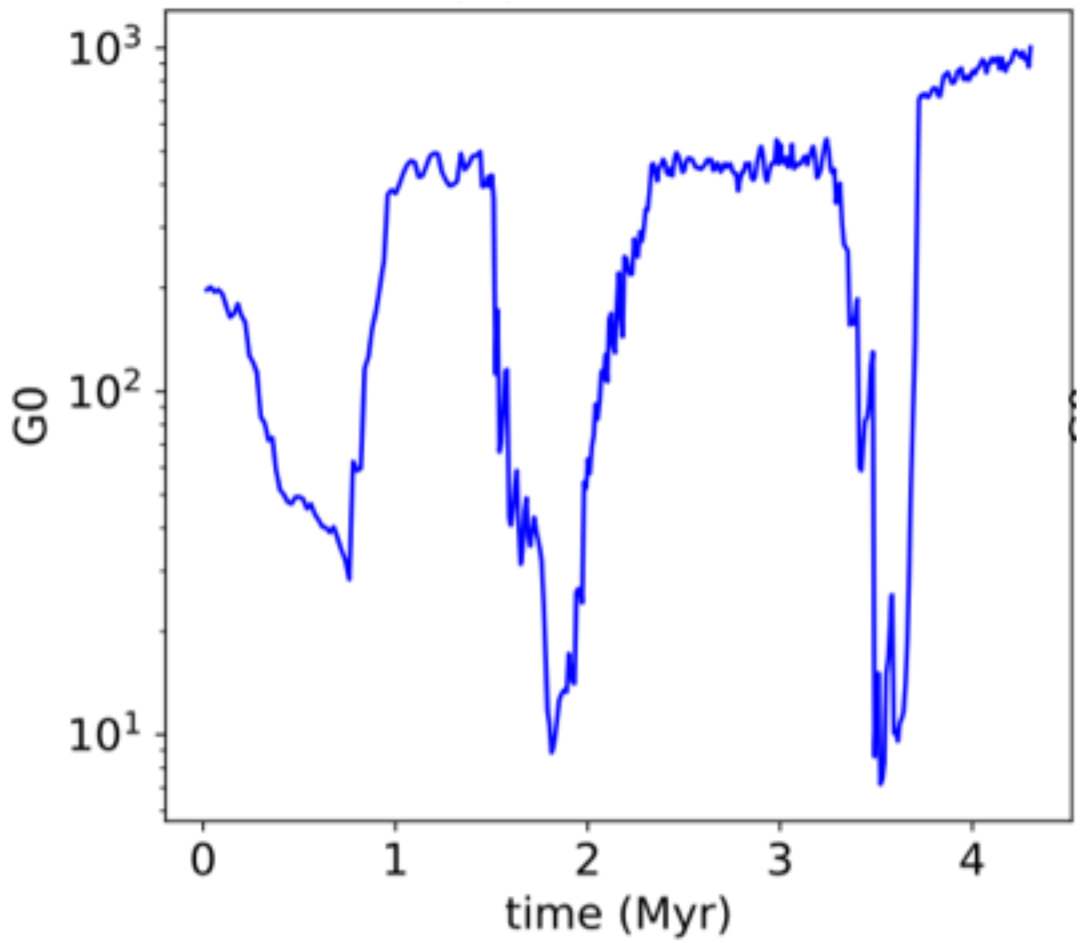
Johnstone+ 1998

Back to MCRT... FUV fluxes

- Calculate FUV flux (G0) on each sink
  - $1/r^2$ geometric dilution
  - MCRT absorption

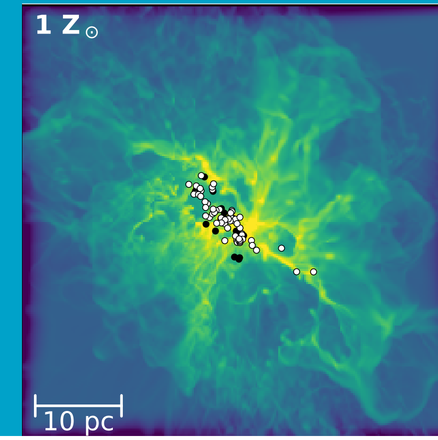
- **Time-varying, space-varying flux**

$$G_0 = \frac{1}{H}\int_{5\,\mathrm{eV}}^{13.6\,\mathrm{eV}} 4\pi J_\nu \,\mathrm{d}\nu$$

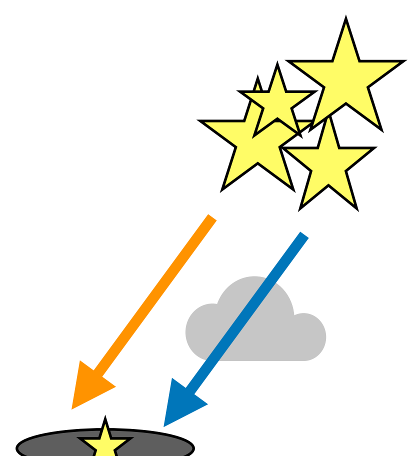


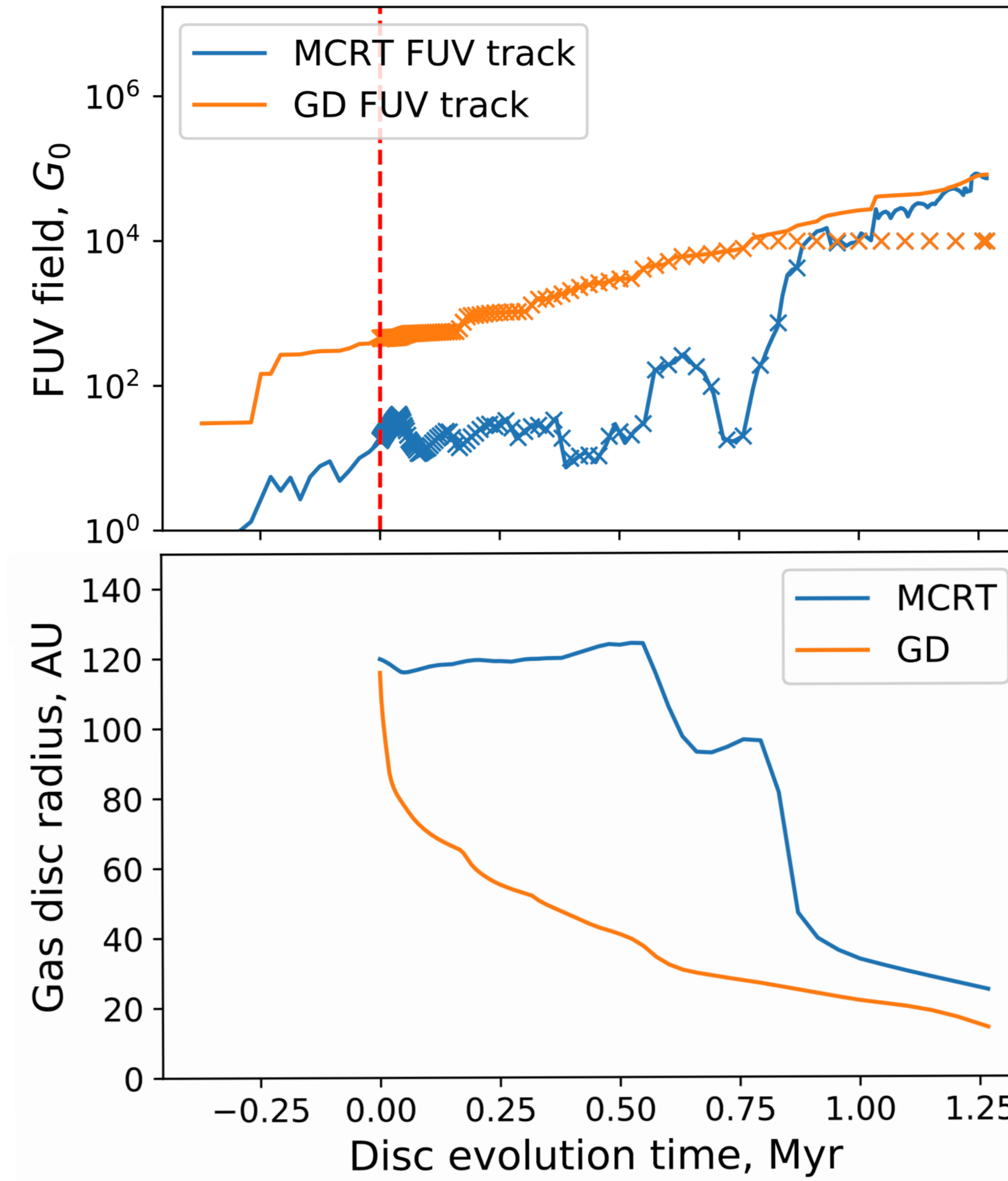
Ali & Harries 2019, MNRAS, 487, 4890

Disc photoevaporation



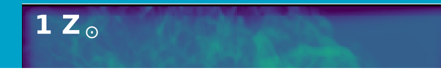
- using Ali (2021) 10^5 $M_\odot$, $Z_\odot$ model
- Feed flux into disc models
  - viscous gas + grain growth/radial drift (Sellek+ 2020)
  - + external photoevaporation (FRIED grid Haworth+ 2018)
- Each disc
  - $1/r^2$ geometric dilution
  - MCRT absorption





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

Disc photoevapor



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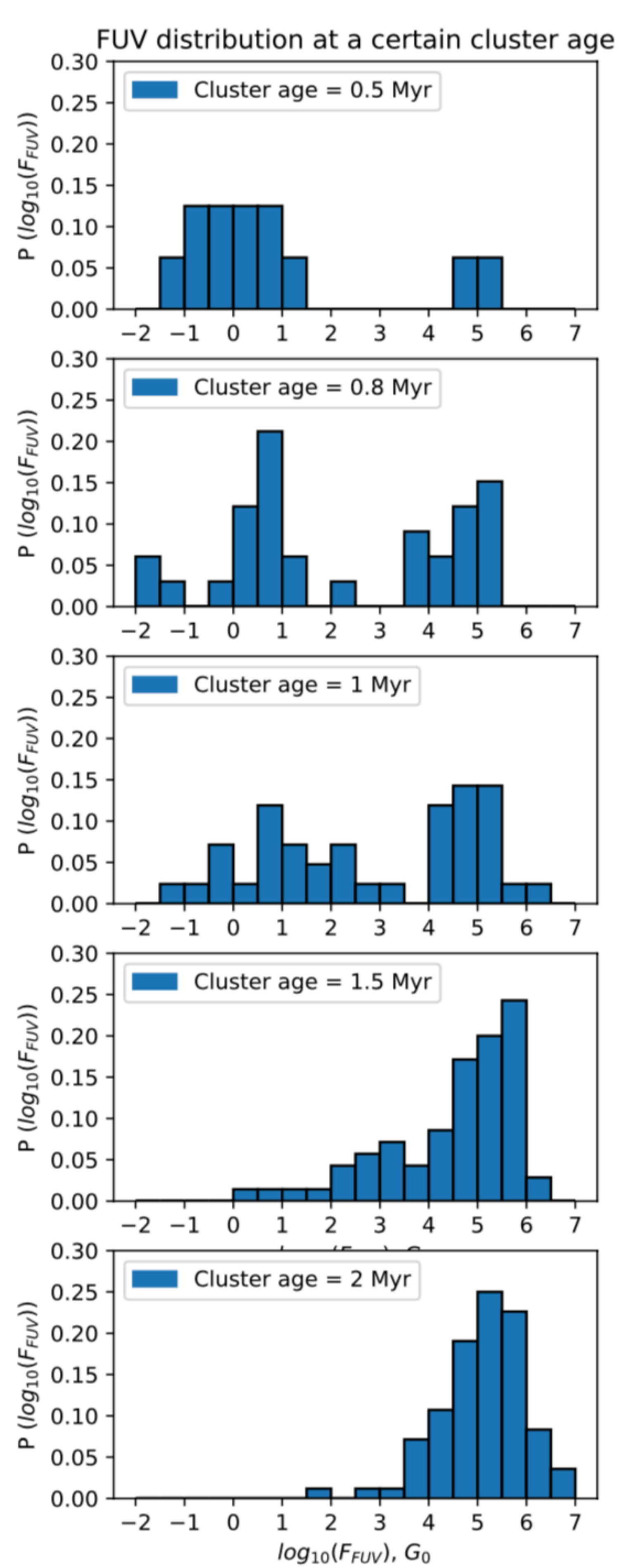
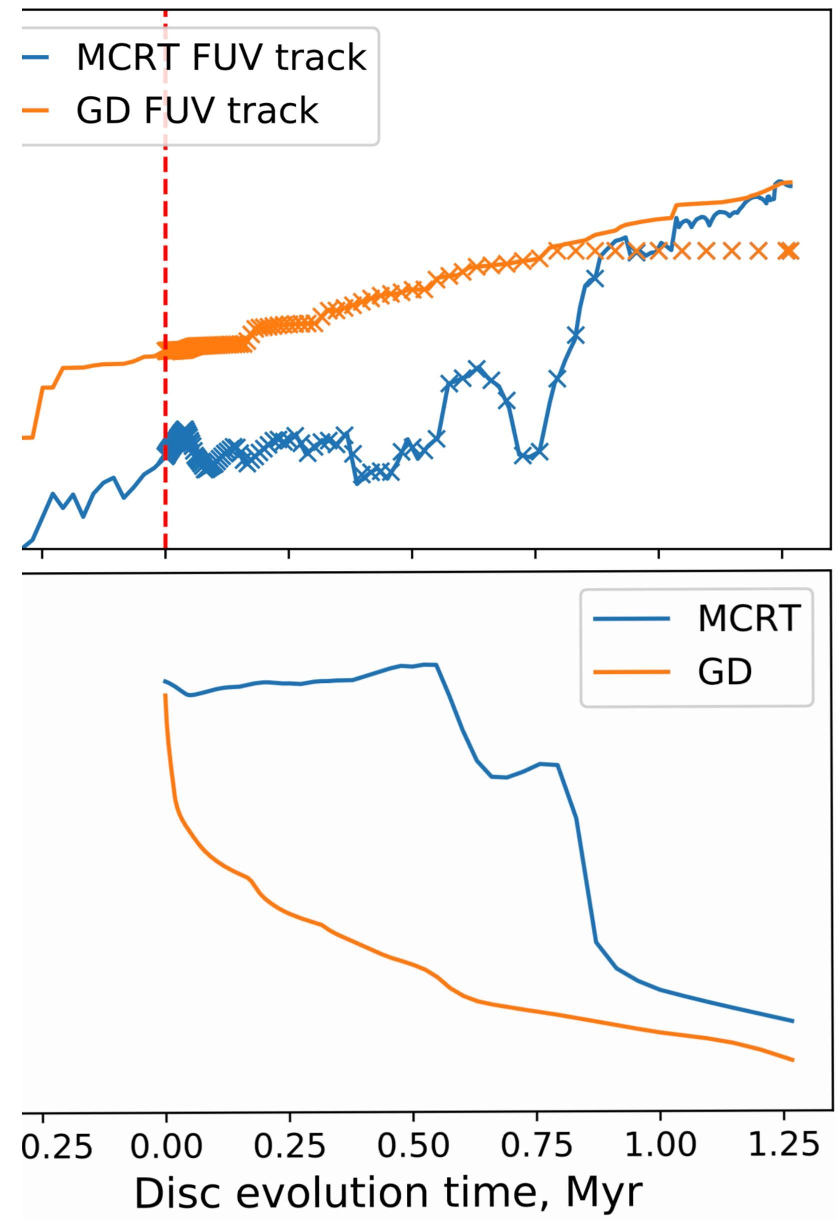
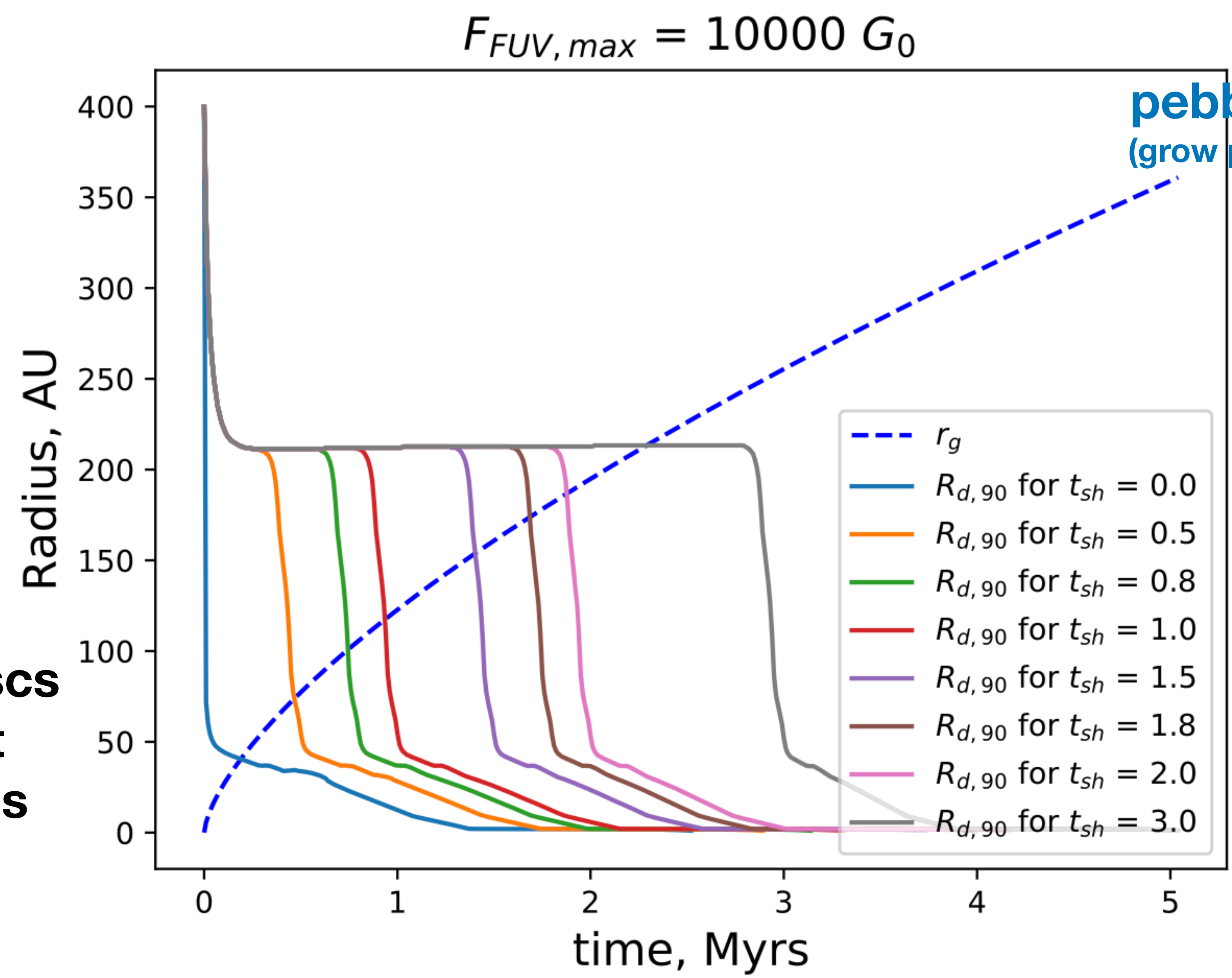




o,... Ali, 2022, MNRAS, 512, 3788

Shielding and pebble production



pebble production front
(grow pebbles large enough to start drifting inwards)

evaporating discs with different shielding times

Qiao+ 2023

longer shielding = larger pebble reservoir for planet formation

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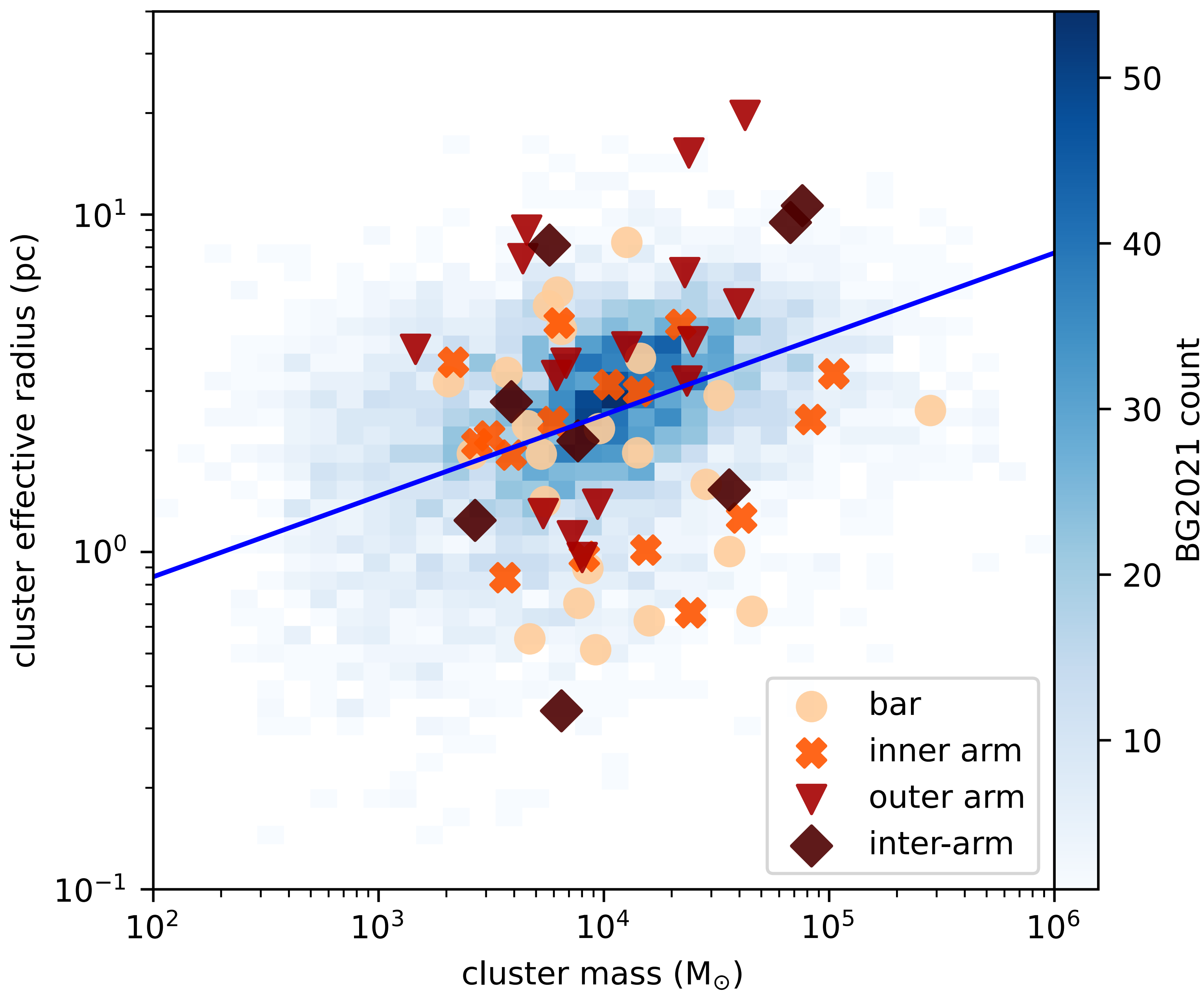
Thank you!

Extra slides

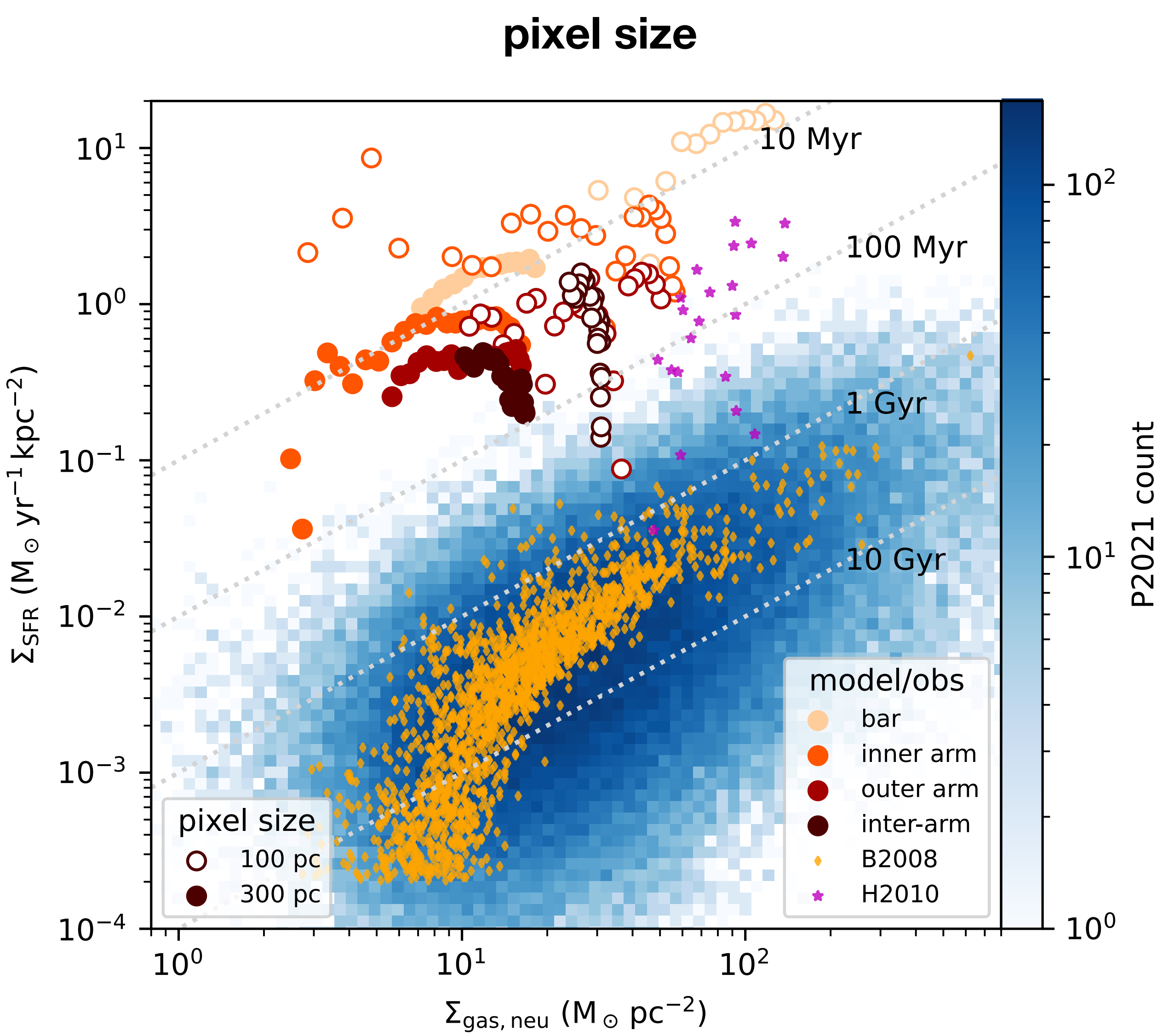
Cluster mass/size



observations from Brown & Gnedin (2021)

- highest mass cluster in bar followed by **inner arm**

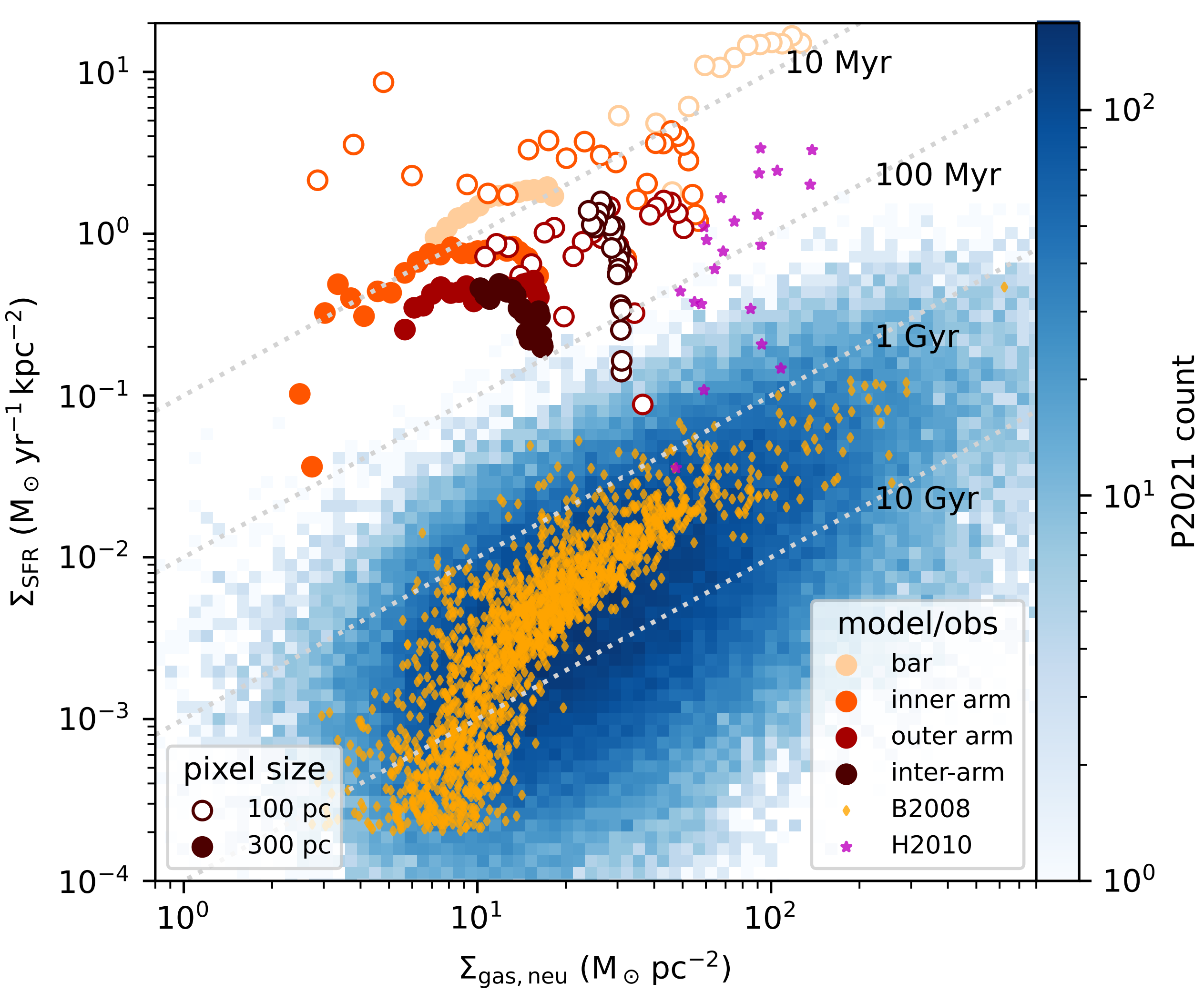
Kennicutt-Schmidt relation



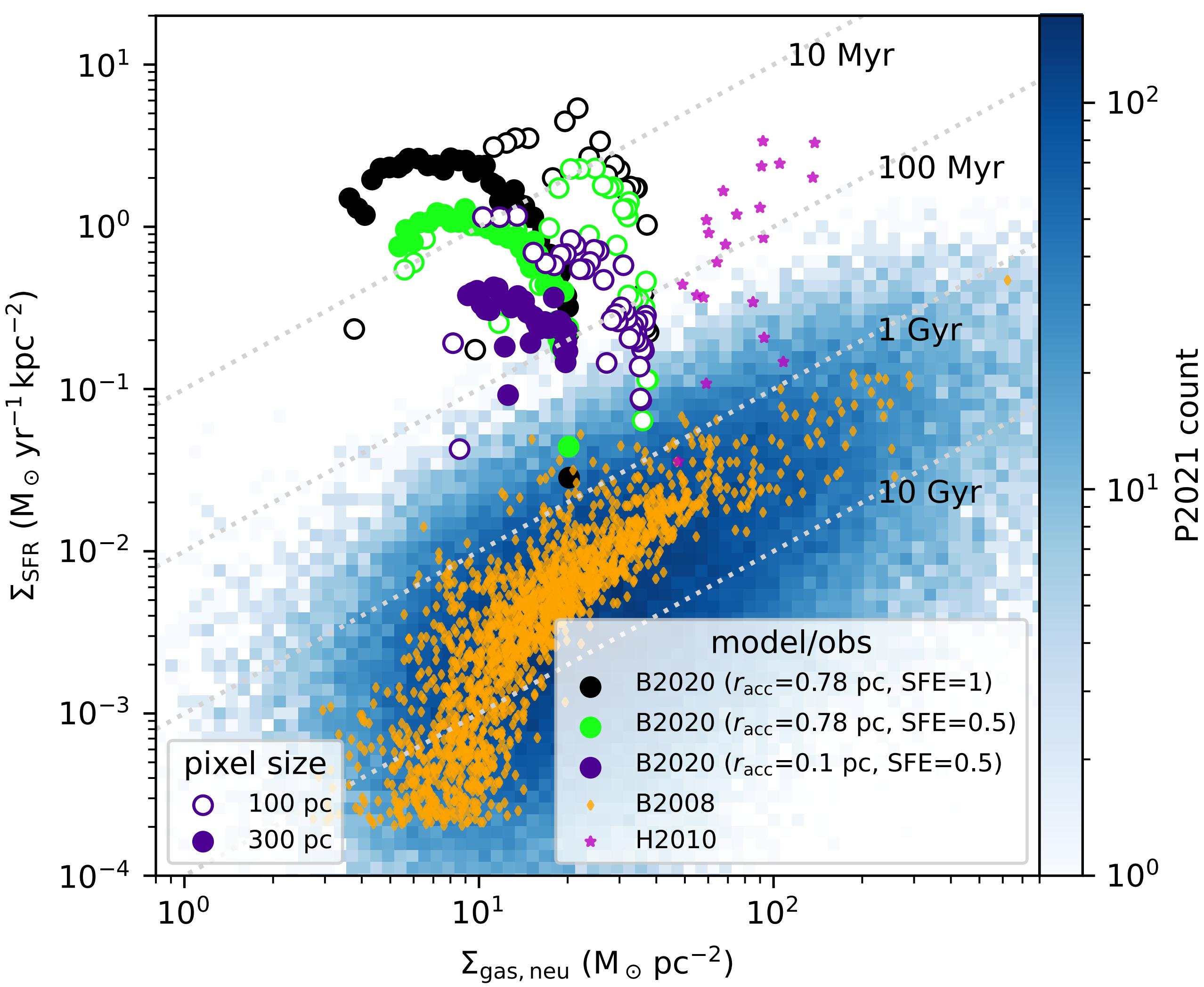
observations from
Bigiel+ 2008
Heiderman+ 2010
Pessa+ 2021

Kennicutt-Schmidt relation

pixel size



accretion radius, sink SFE



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