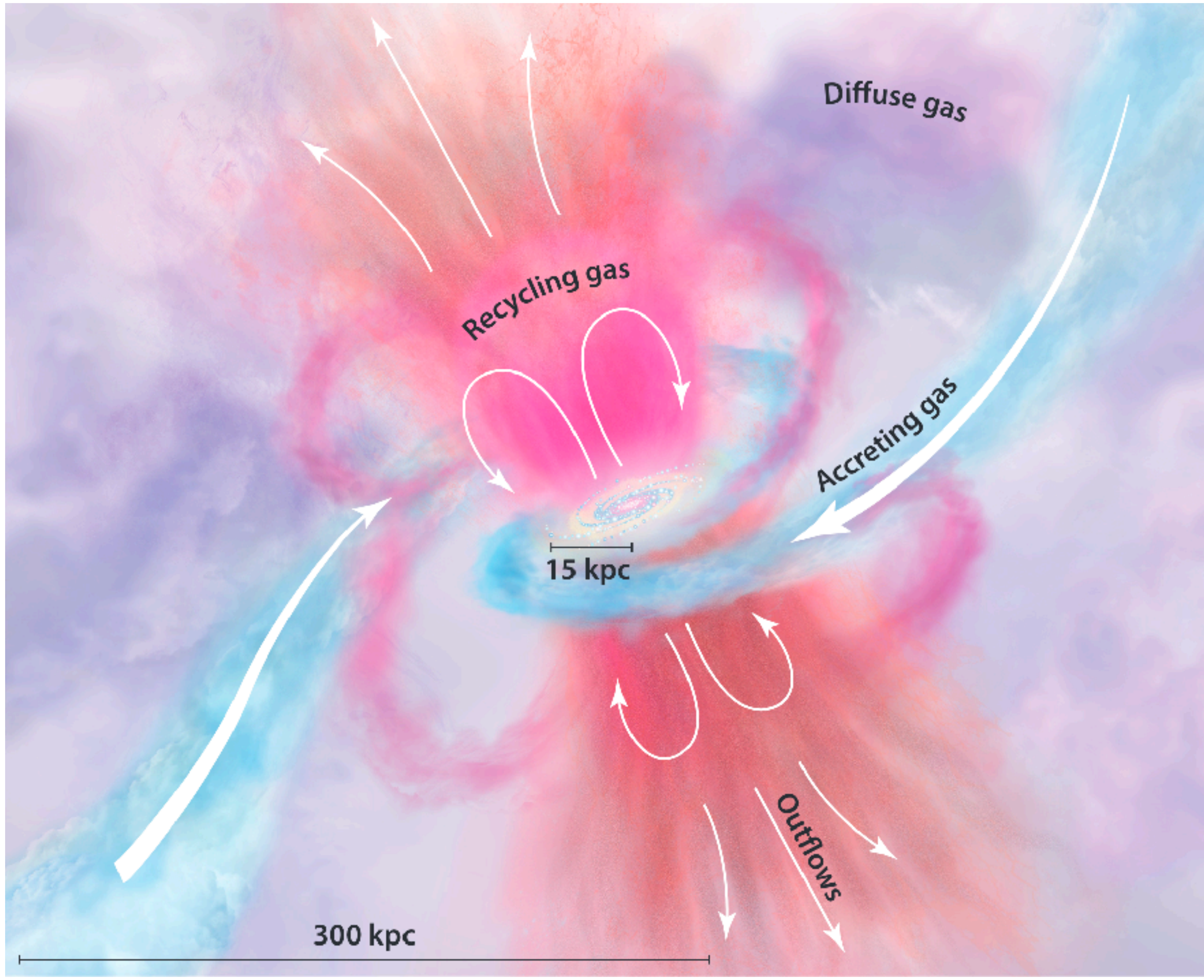
Circumgalactic medium and multiphase gas

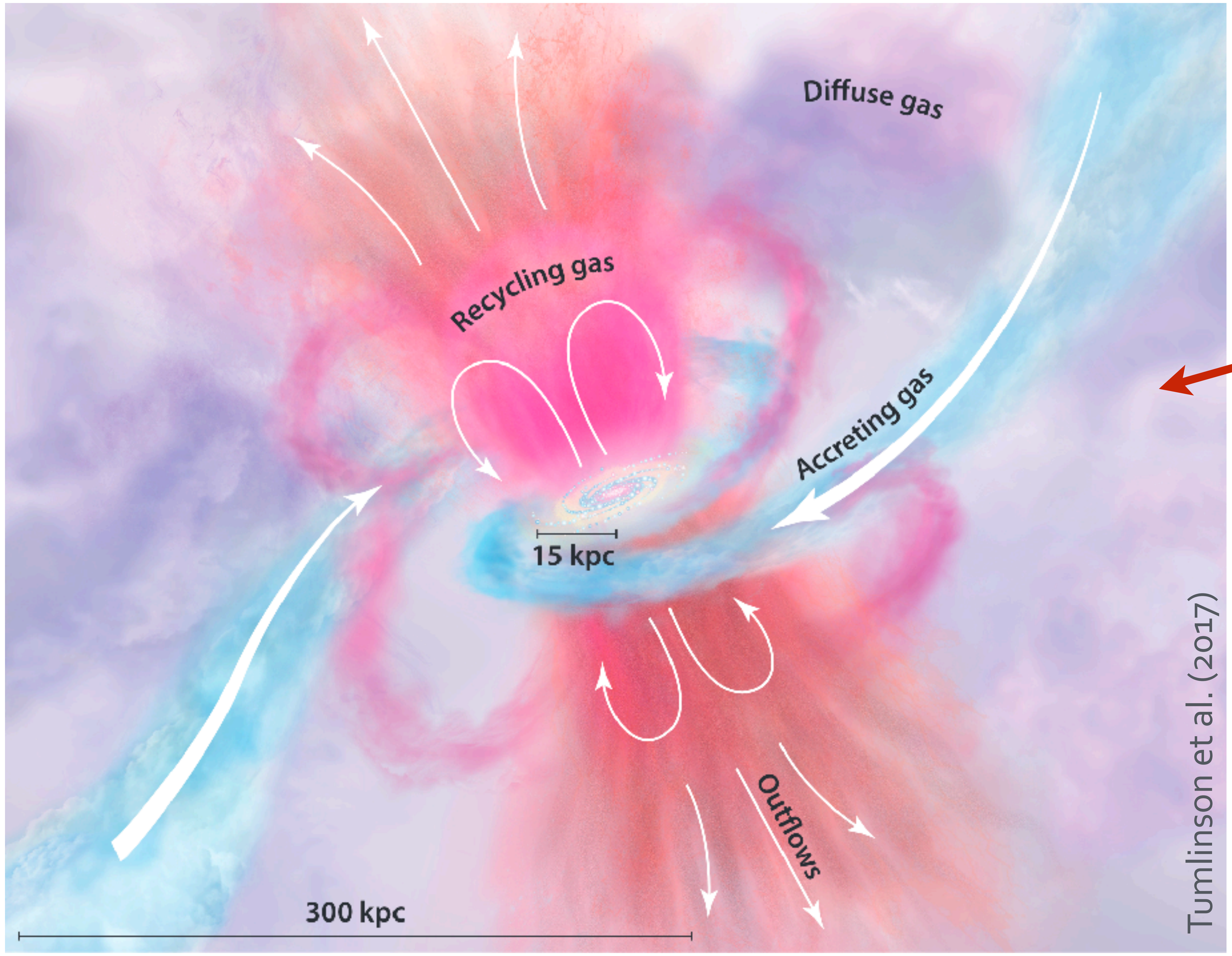
Max Gronke
MPA → ARI/ZAH Heidelberg University

The *multiphase* CGM and galactic ecosystem



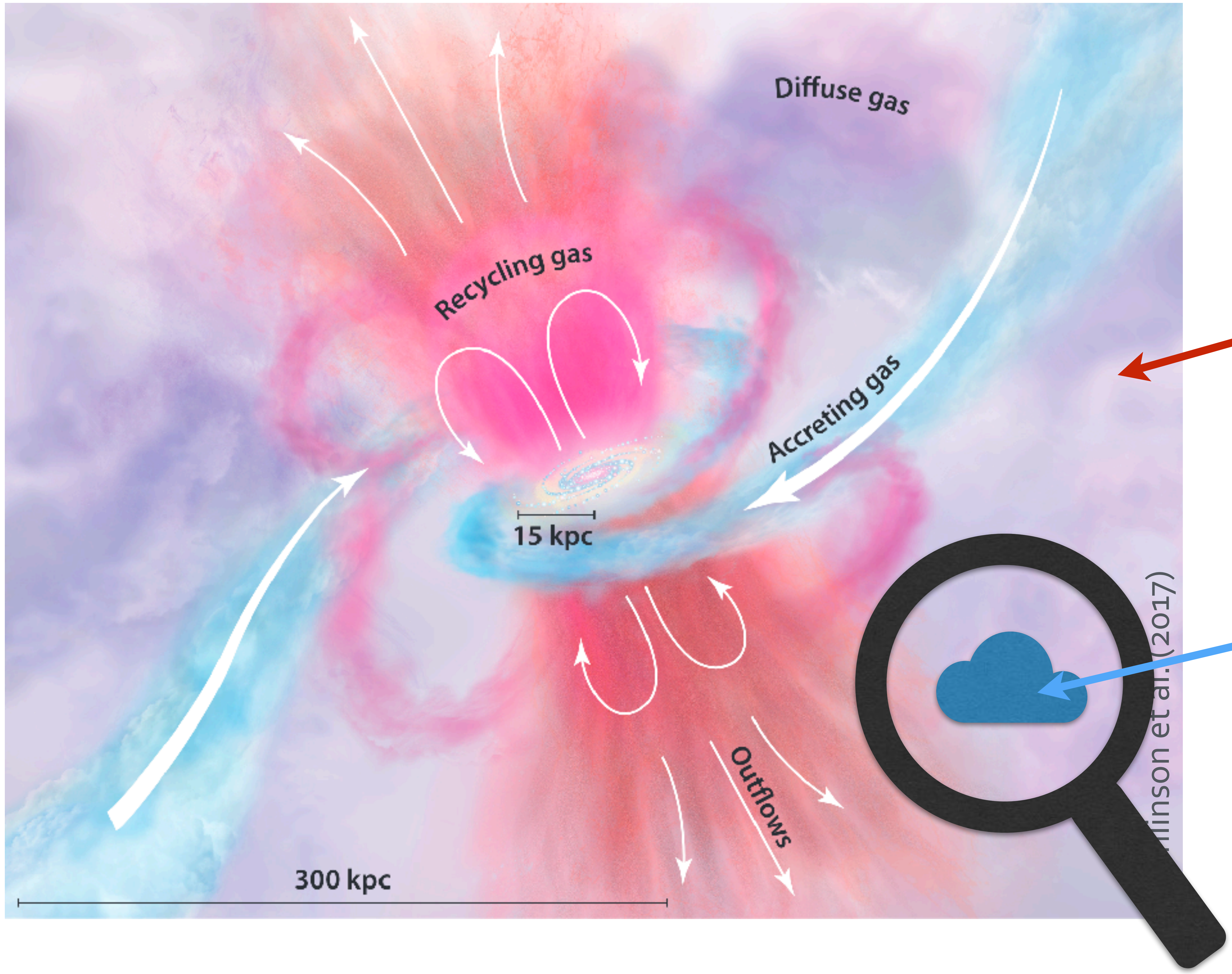
Tumlinson et al. (2017)

The *multiphase* CGM and galactic ecosystem



hot $T \sim T_{\rm vir} \sim 10^6\,{\rm K}$
gas halo

The *multiphase* CGM and galactic ecosystem



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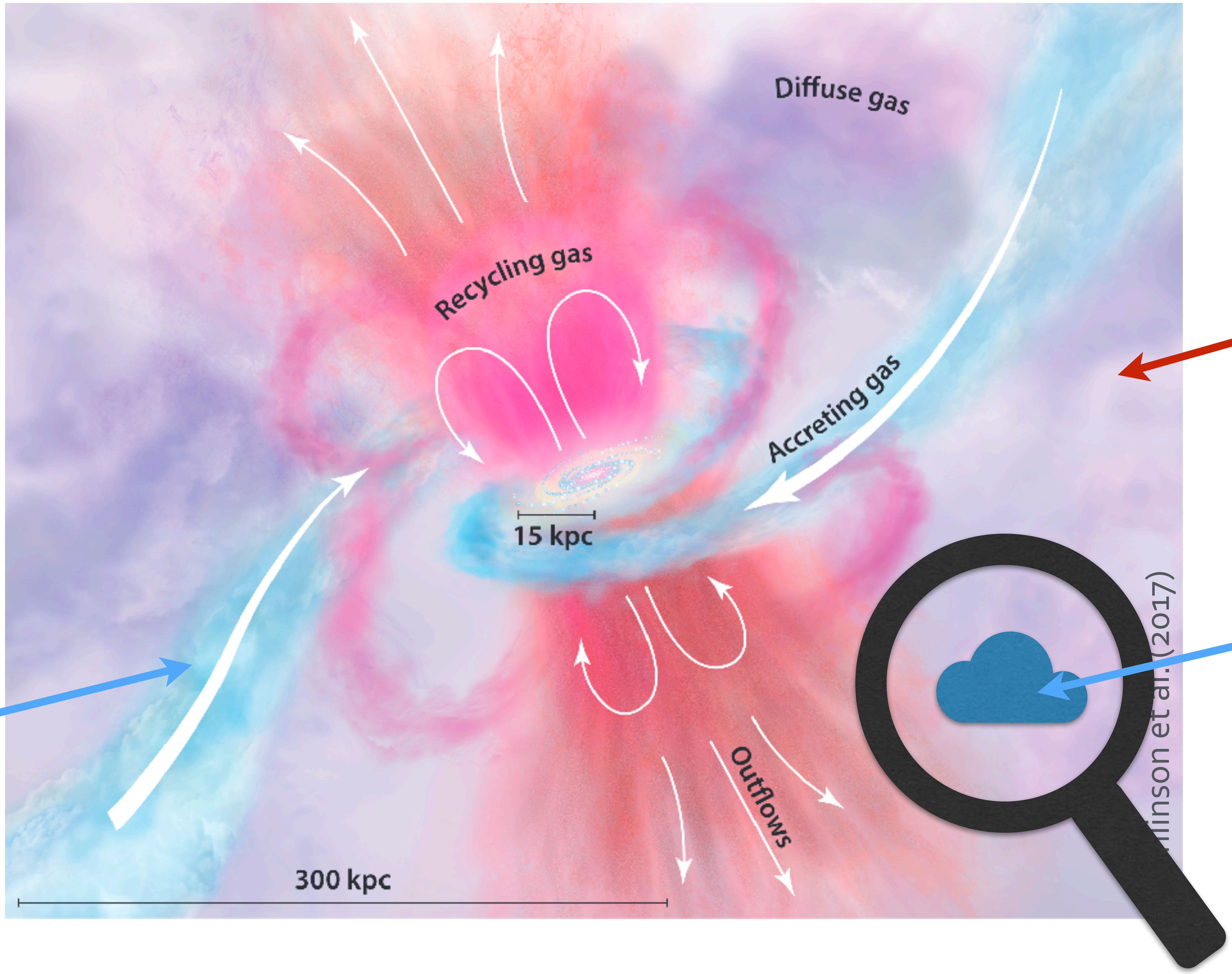

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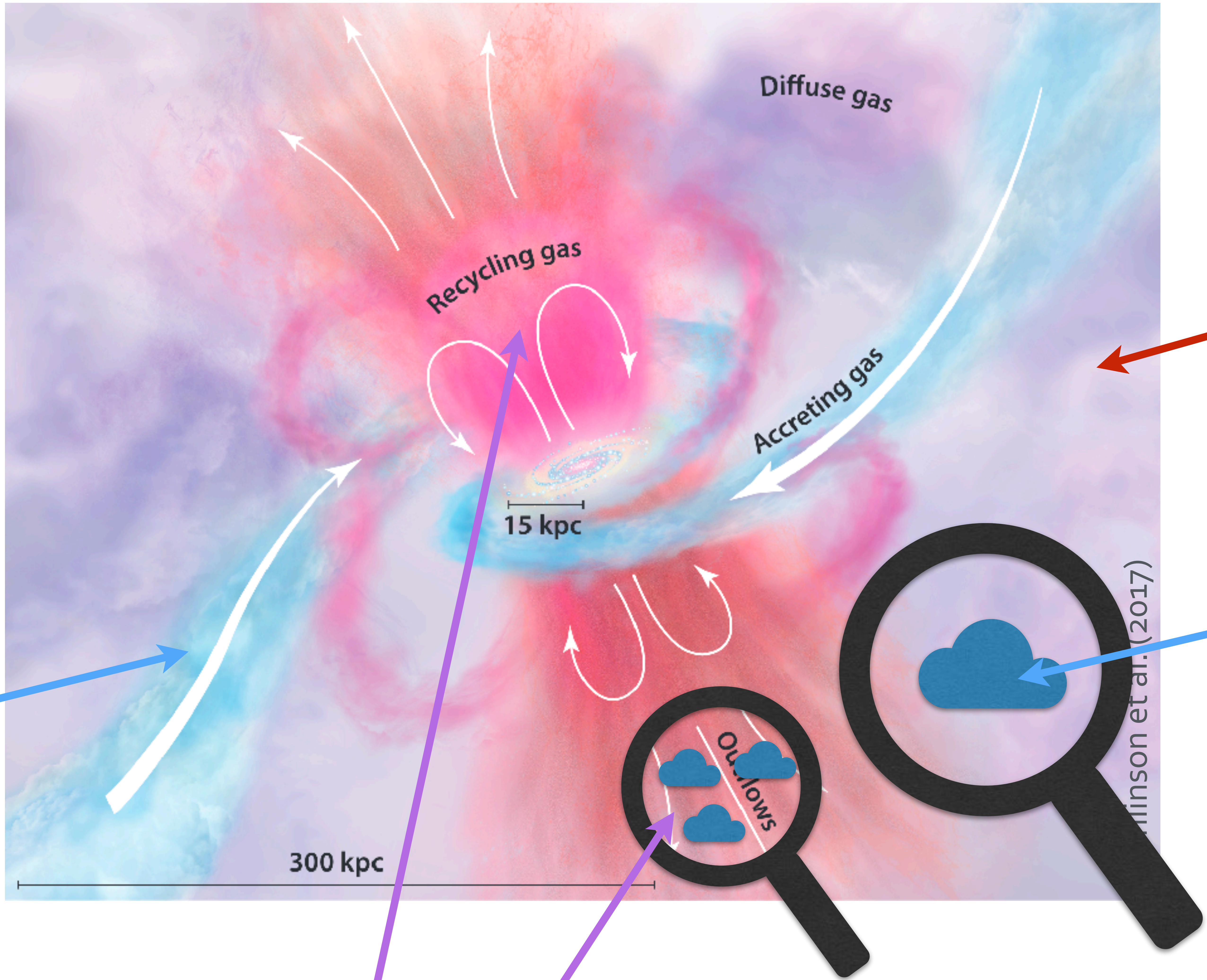

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multiphase ($\sim 10^{6-8}\,{\rm K}$ vs. $10^{1-4}\,{\rm K}$) galactic winds and fountain flows

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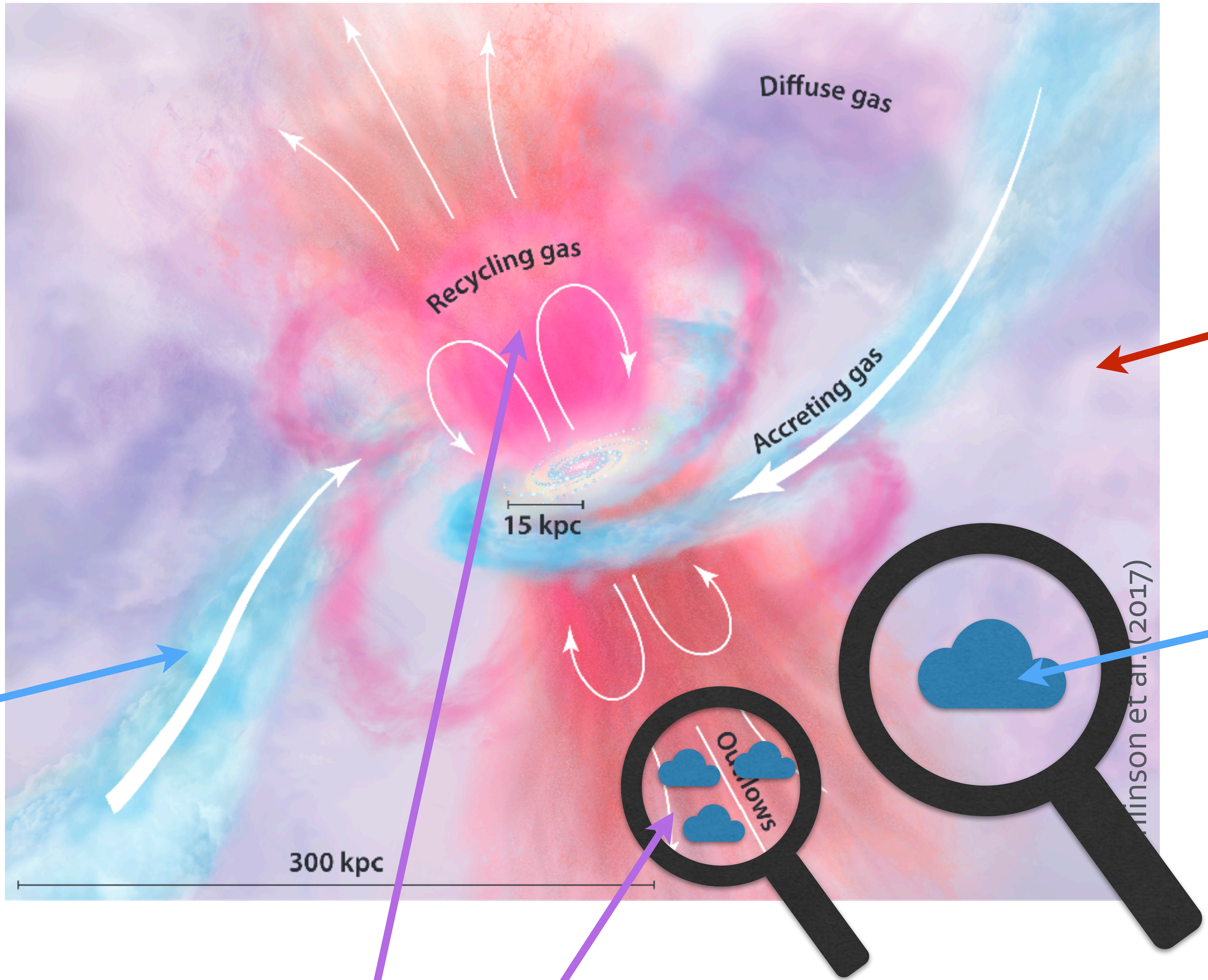

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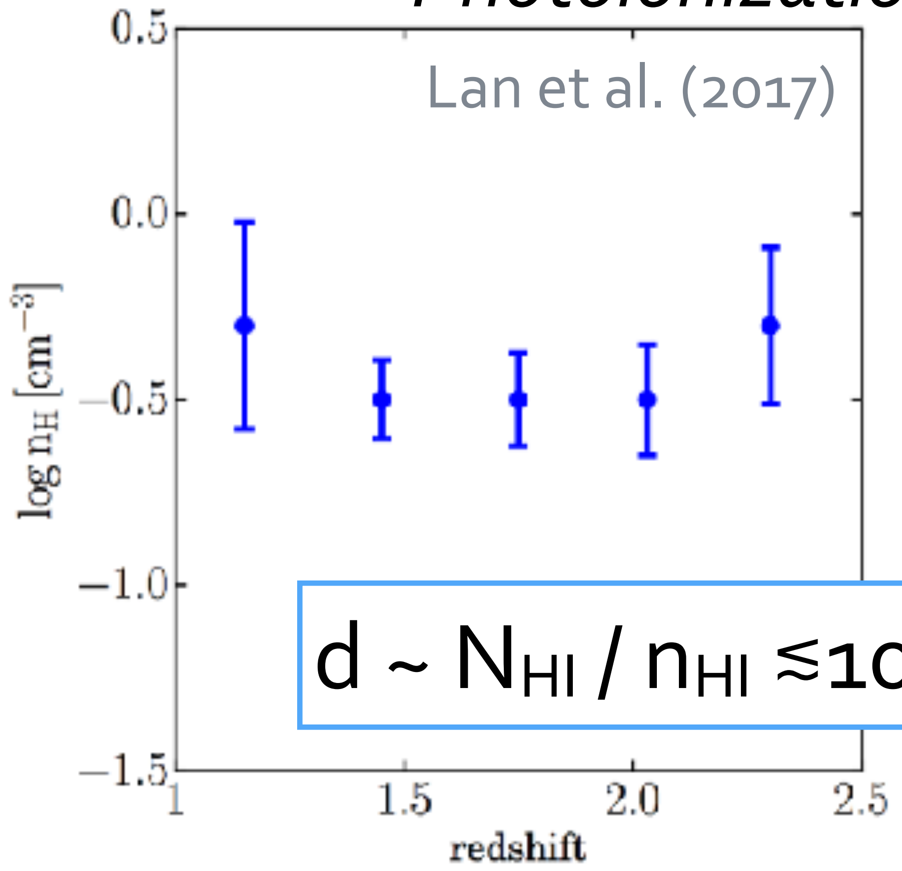
Multiphase gas dynamics crucial to model galactic ecosystems!

The *multiscale* CGM

Photoionization modelling



$d \sim N_{HI} / n_{HI} \lesssim 100pc$

also:
Rauch et al. (1999)
Rigby et al. (2002)
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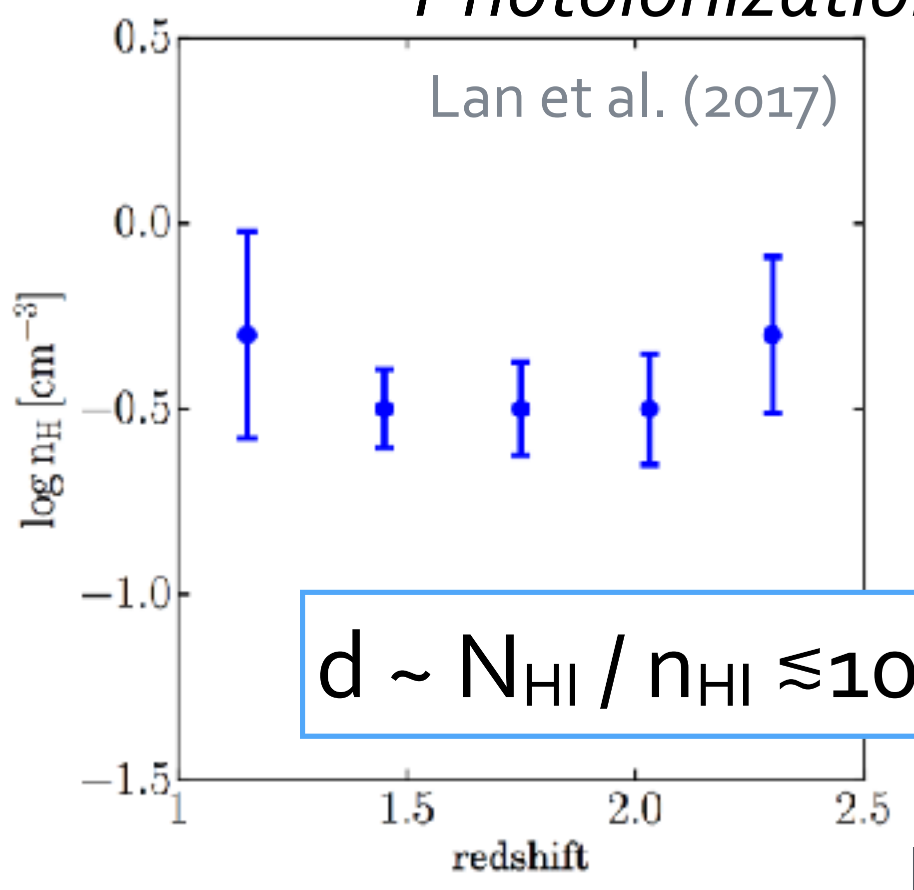

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Morrison et al. (2024) with Matthew Pieri

From silicon alone we find that gas clumping on scales of at most 36 parsecs is required assuming temperatures of at least $10^{3.5}$ K. However, when we include C IV, C II, Si IV, Si III, C II, Si II, and O I we find that a clumping scale of 0.009 parsecs is favoured (with a 1σ upper limit of 0.38 parsecs) and super-solar metallicities are required.

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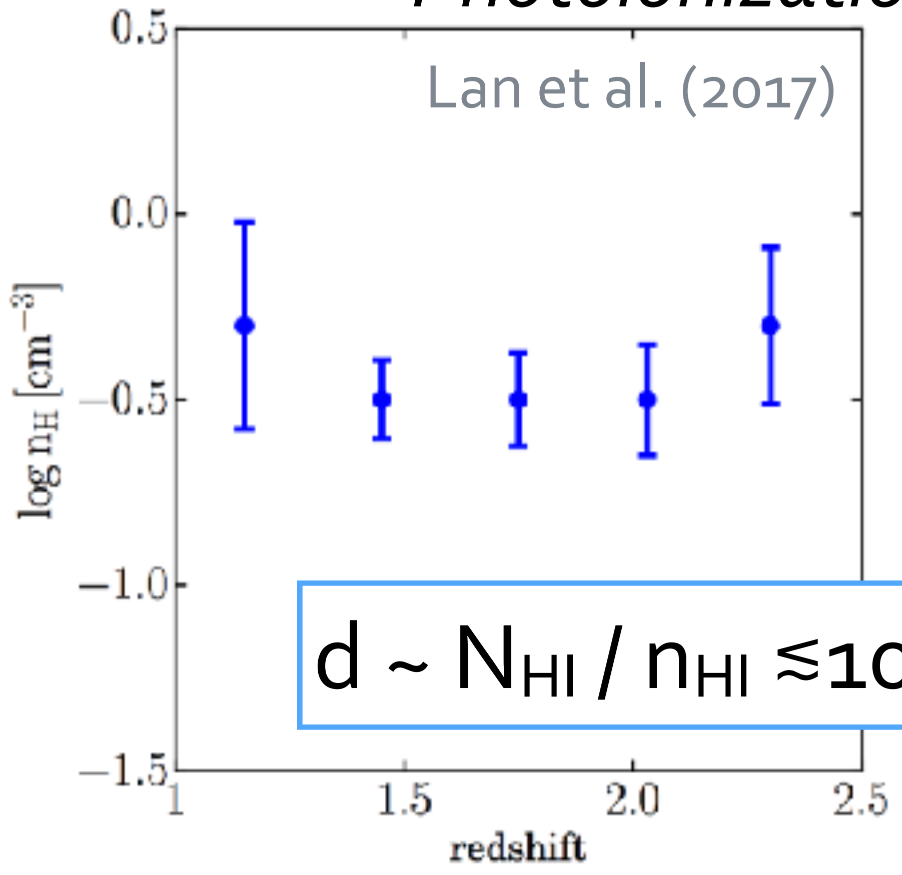

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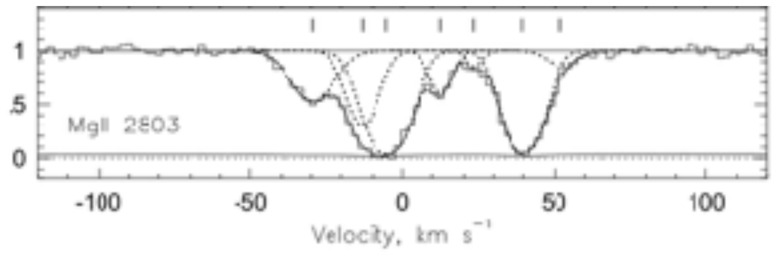

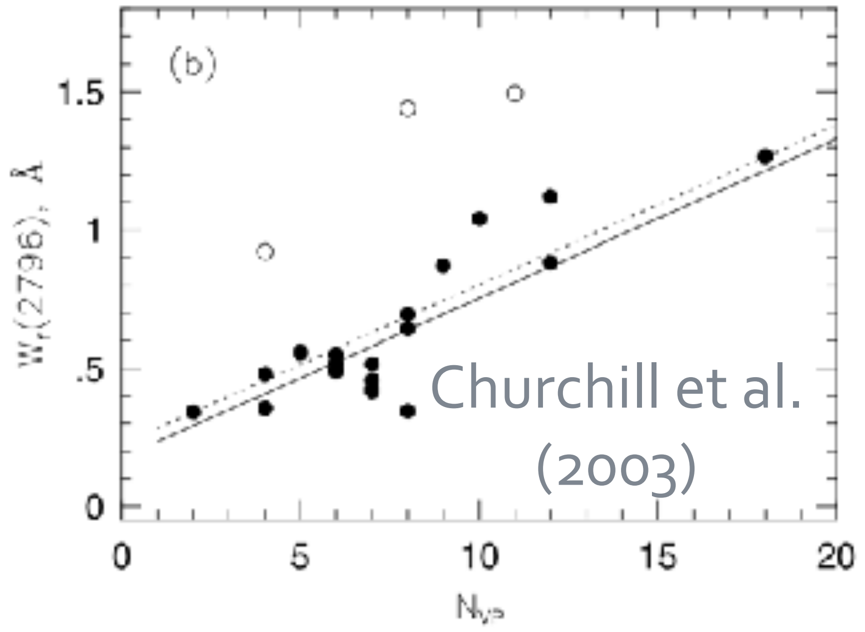

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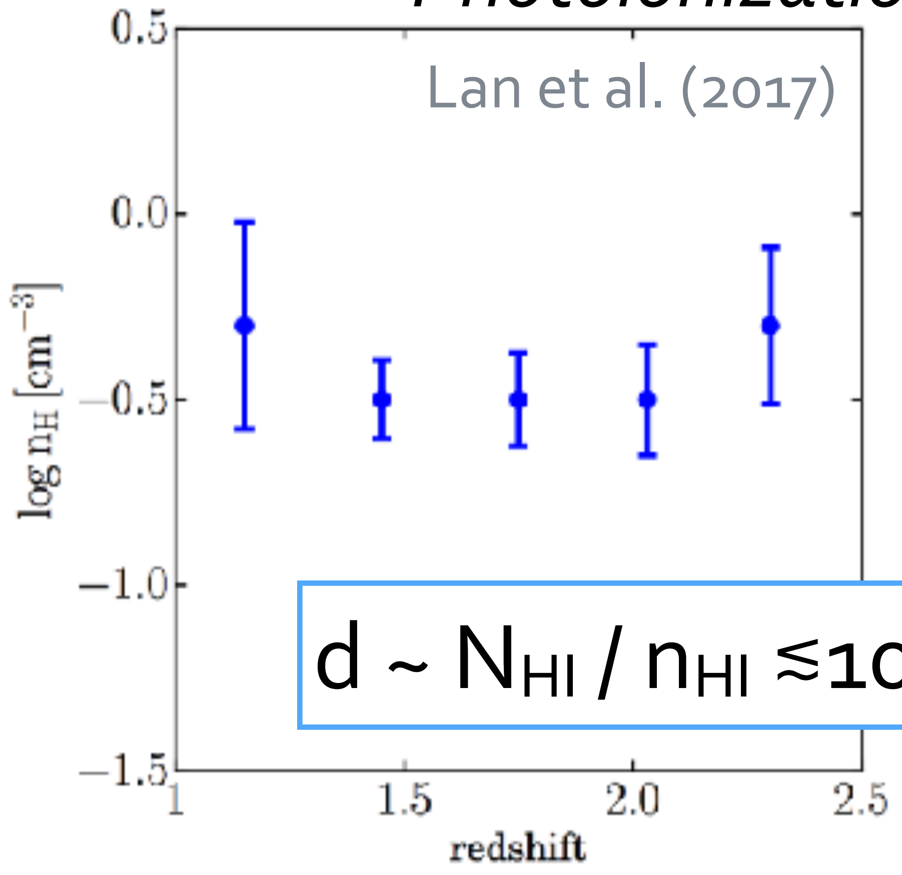

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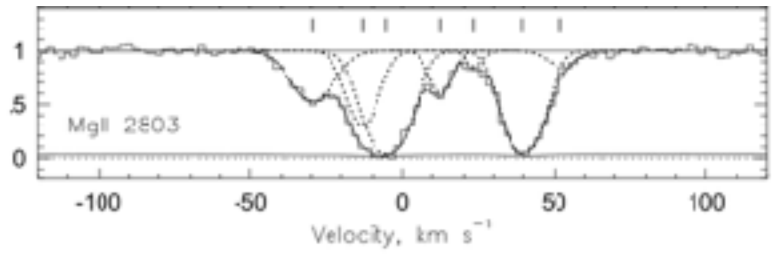

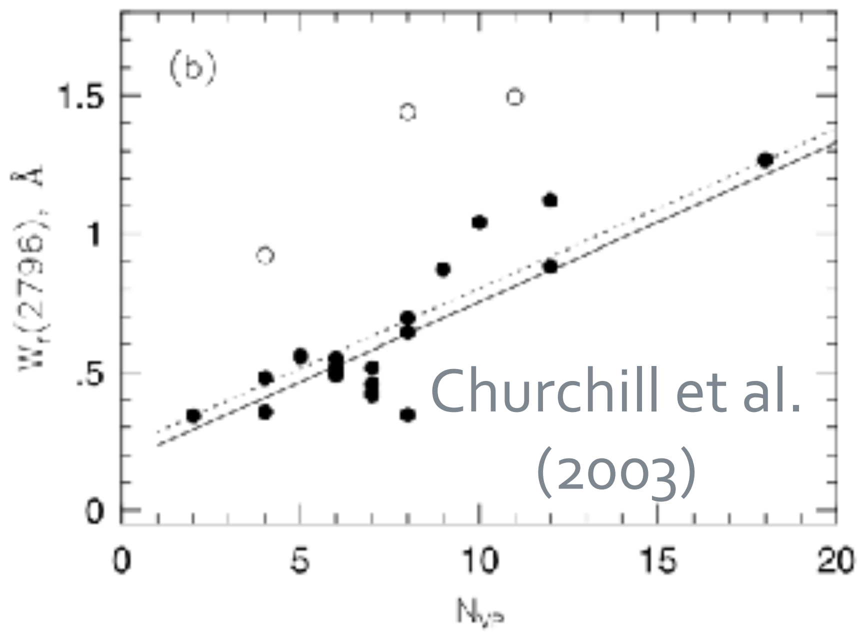

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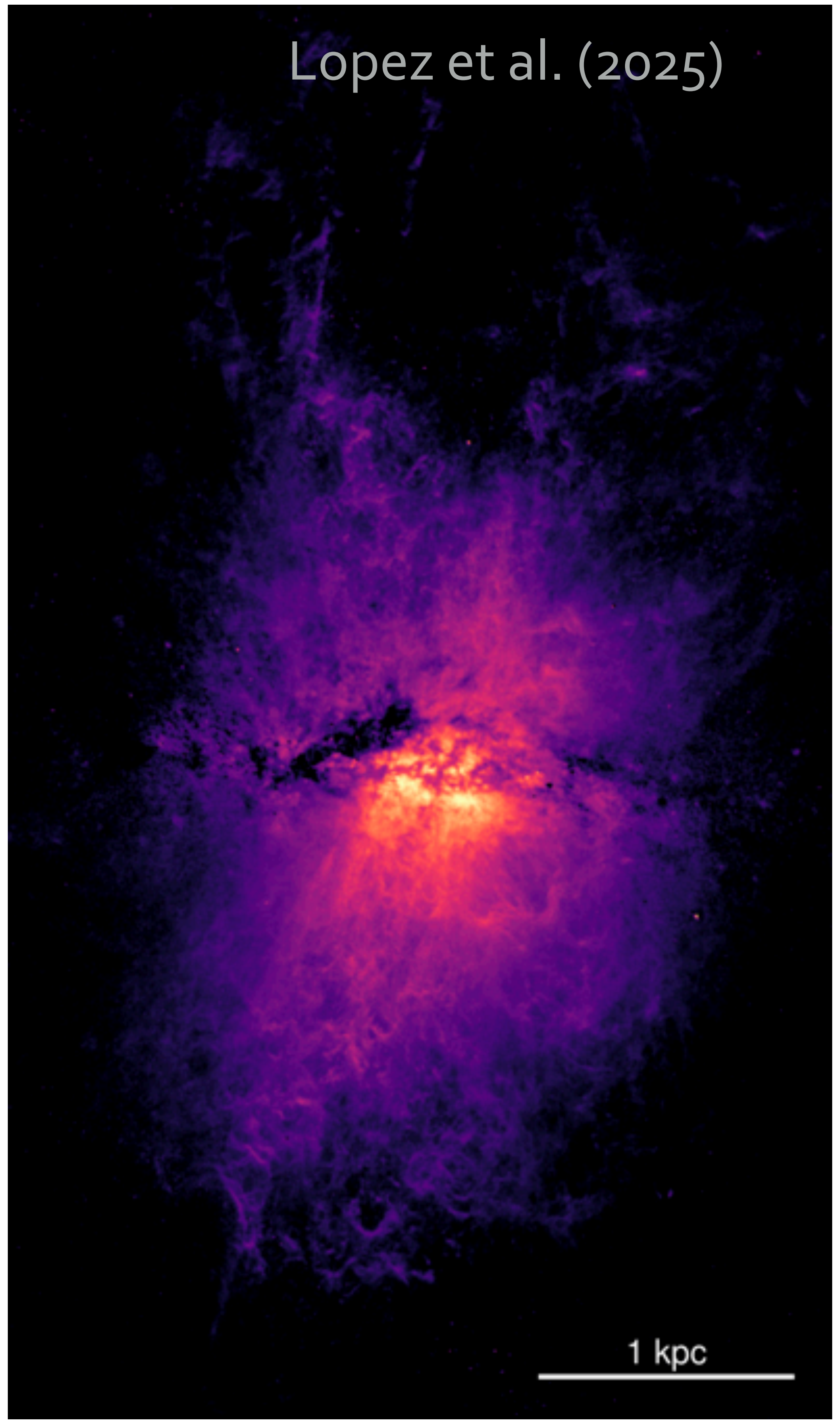
Direct imaging of nearby winds



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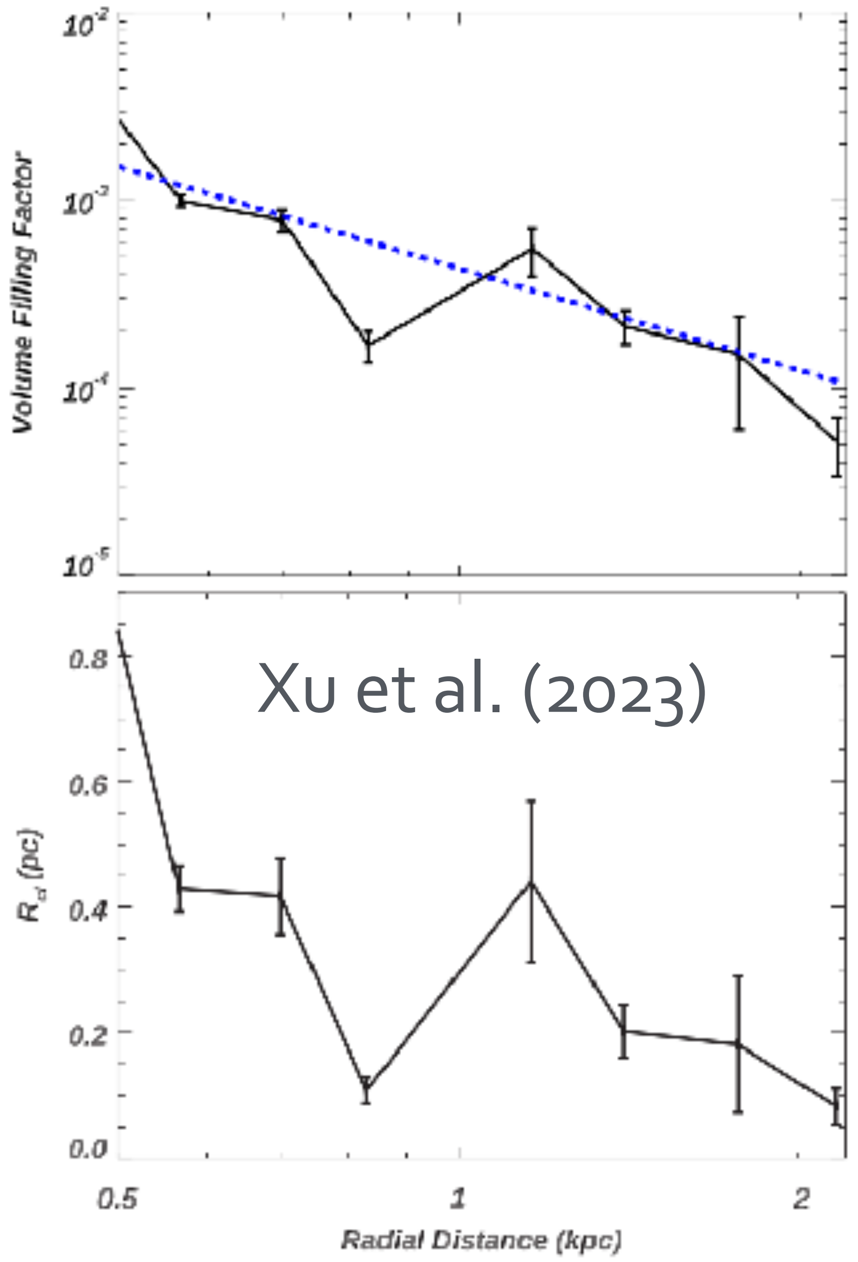

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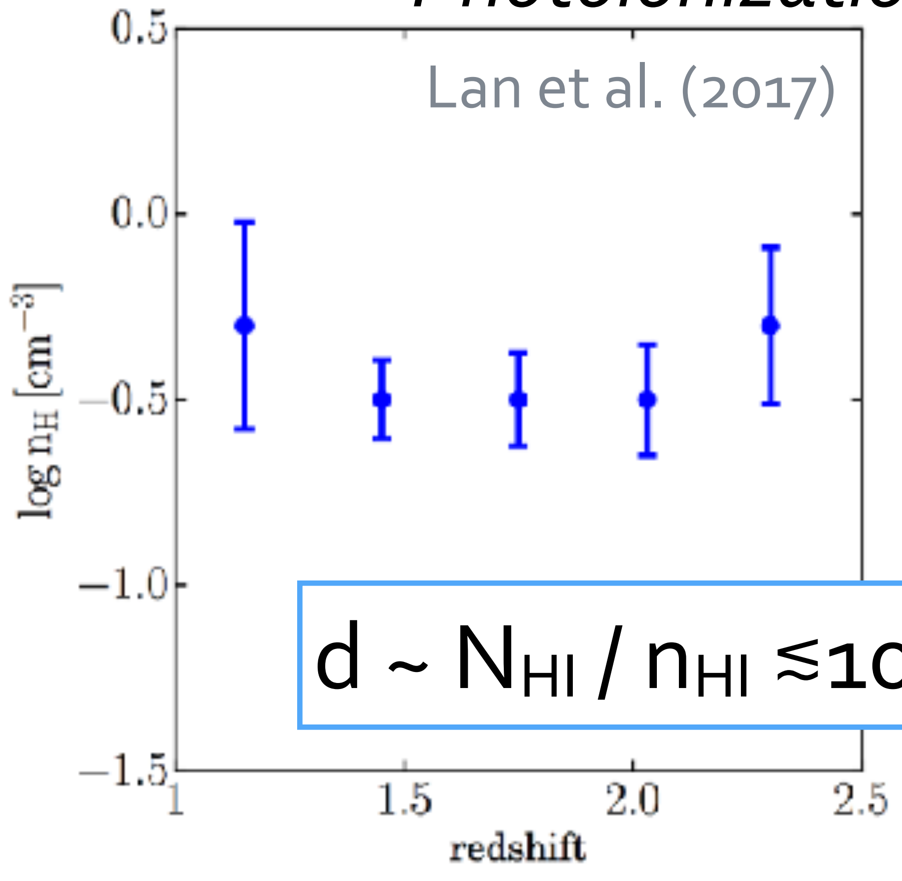

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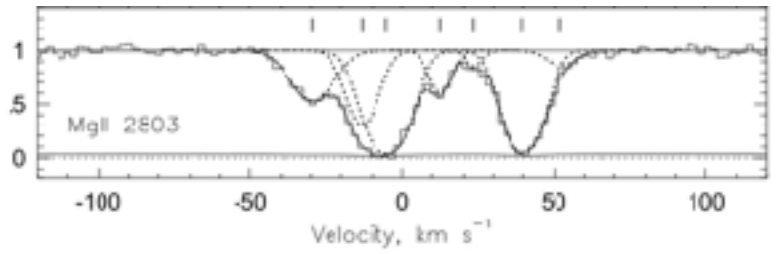

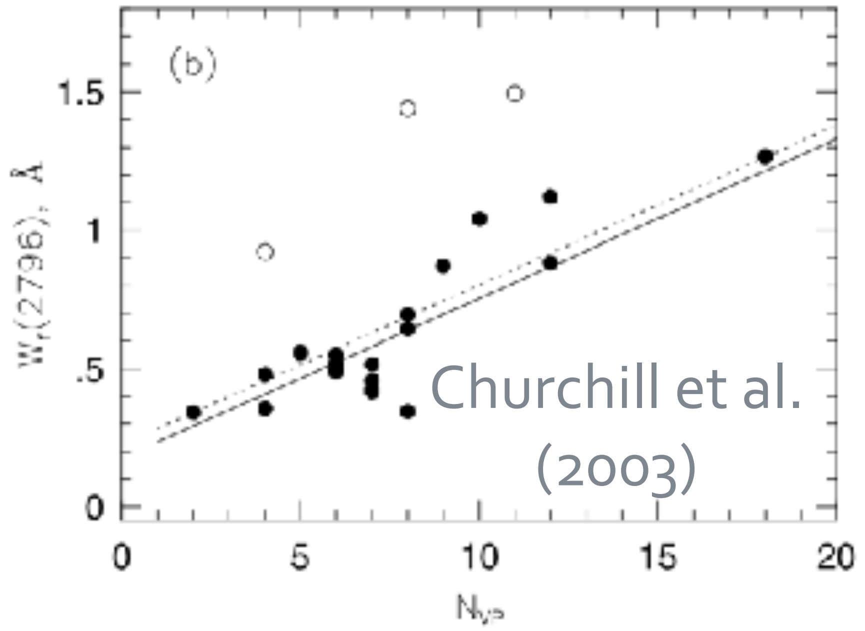

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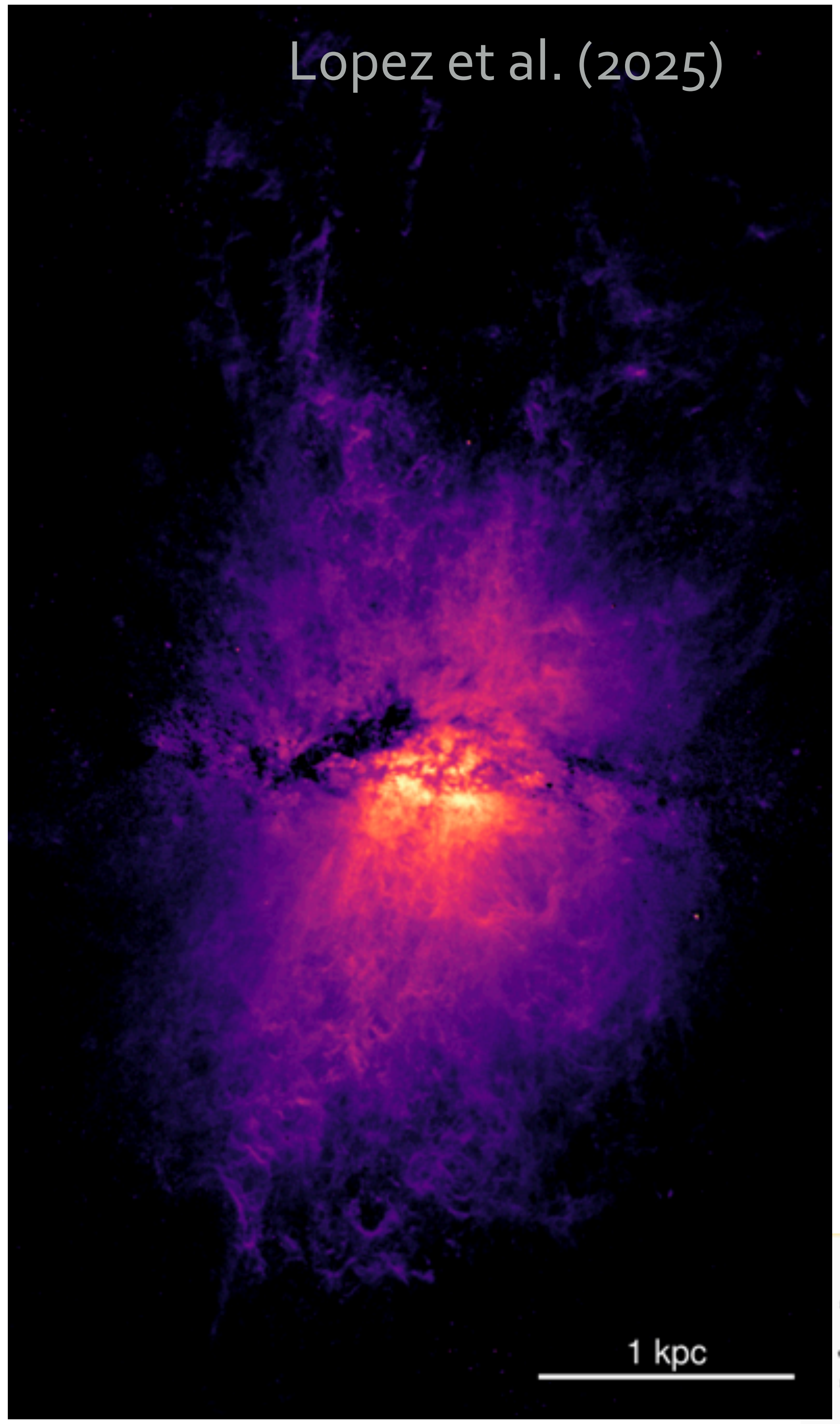

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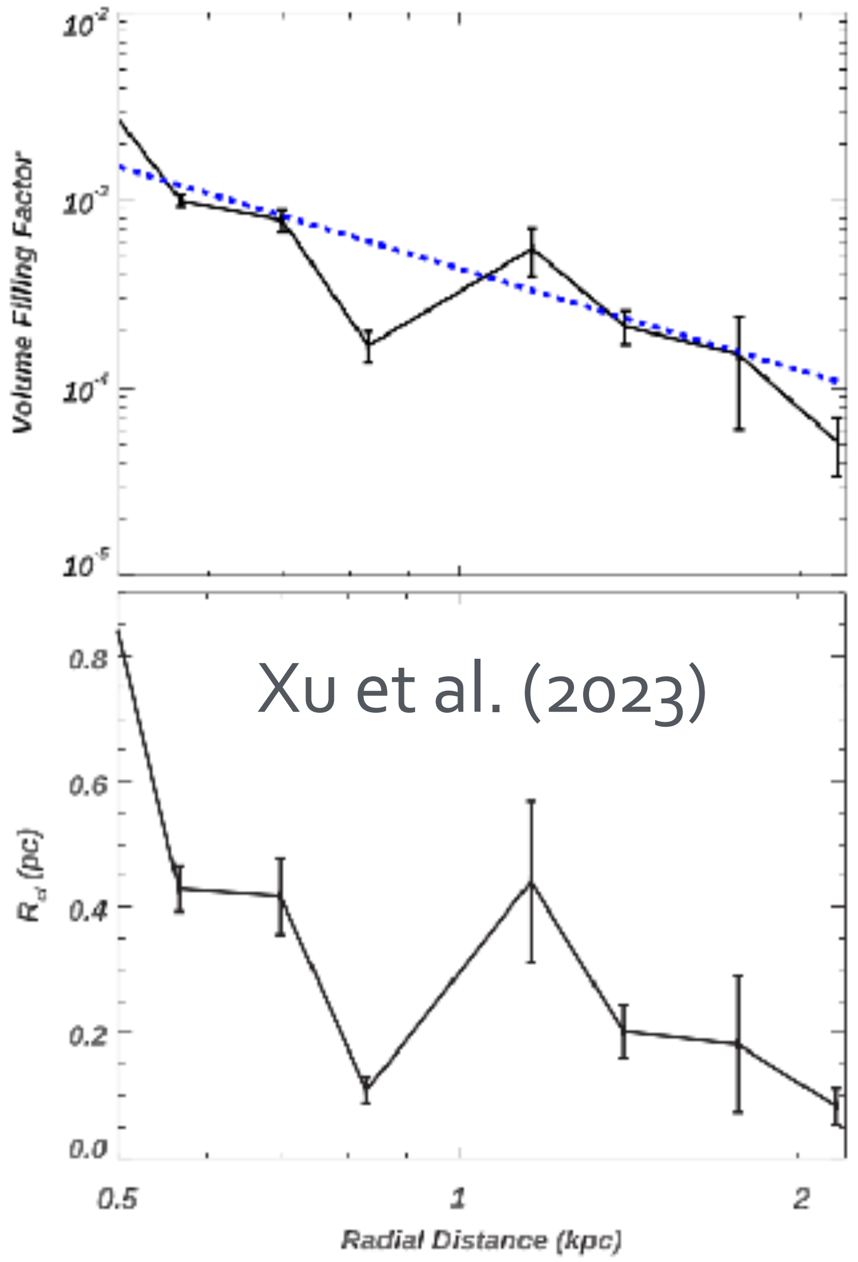
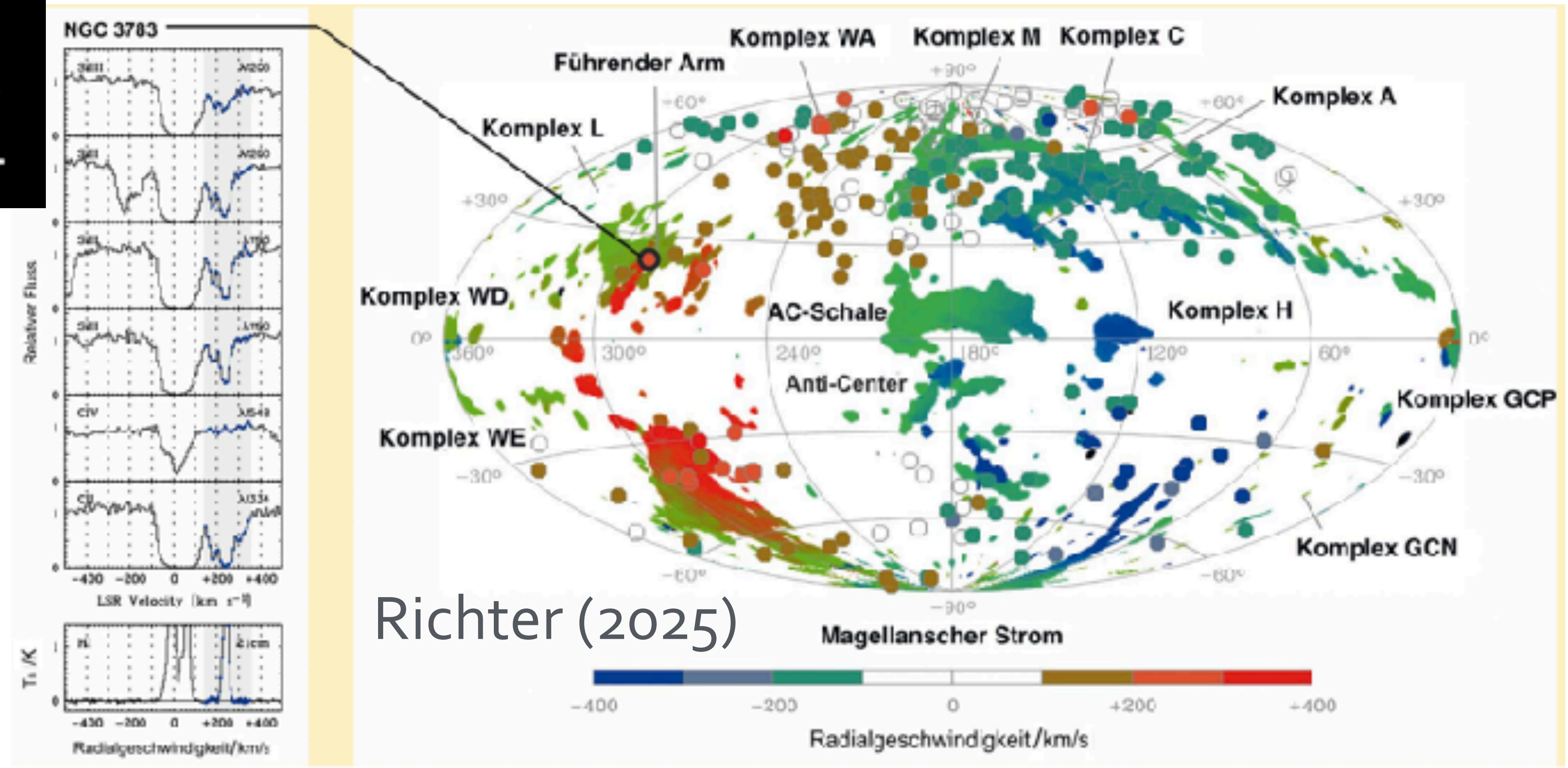
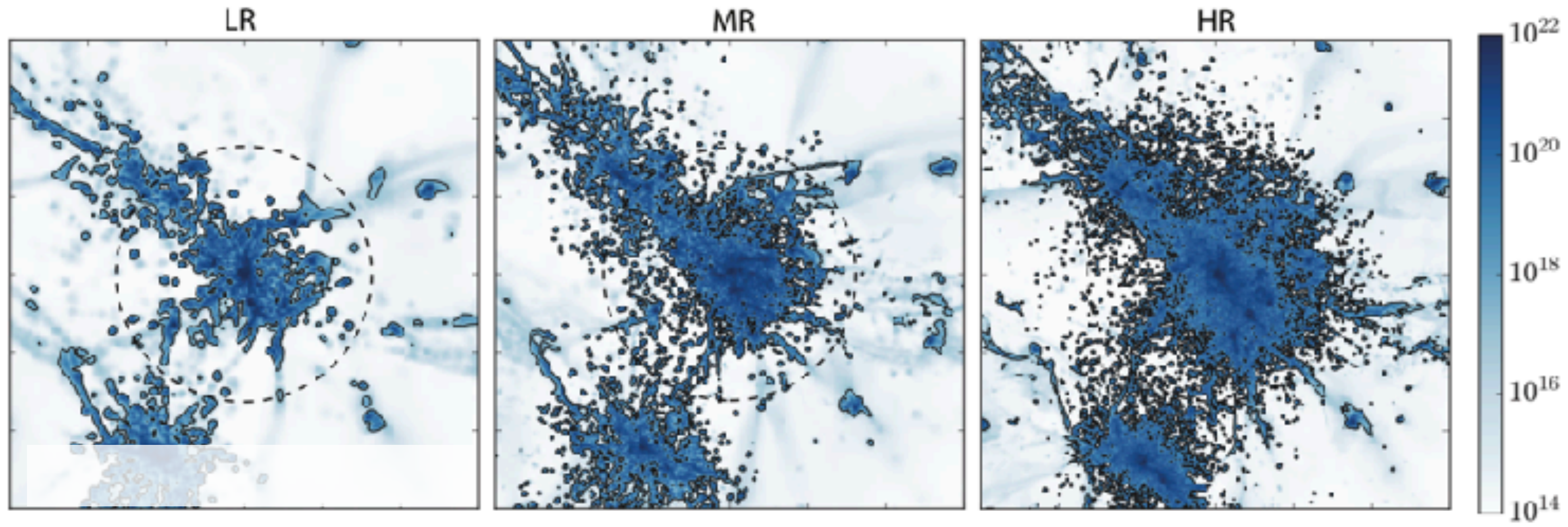
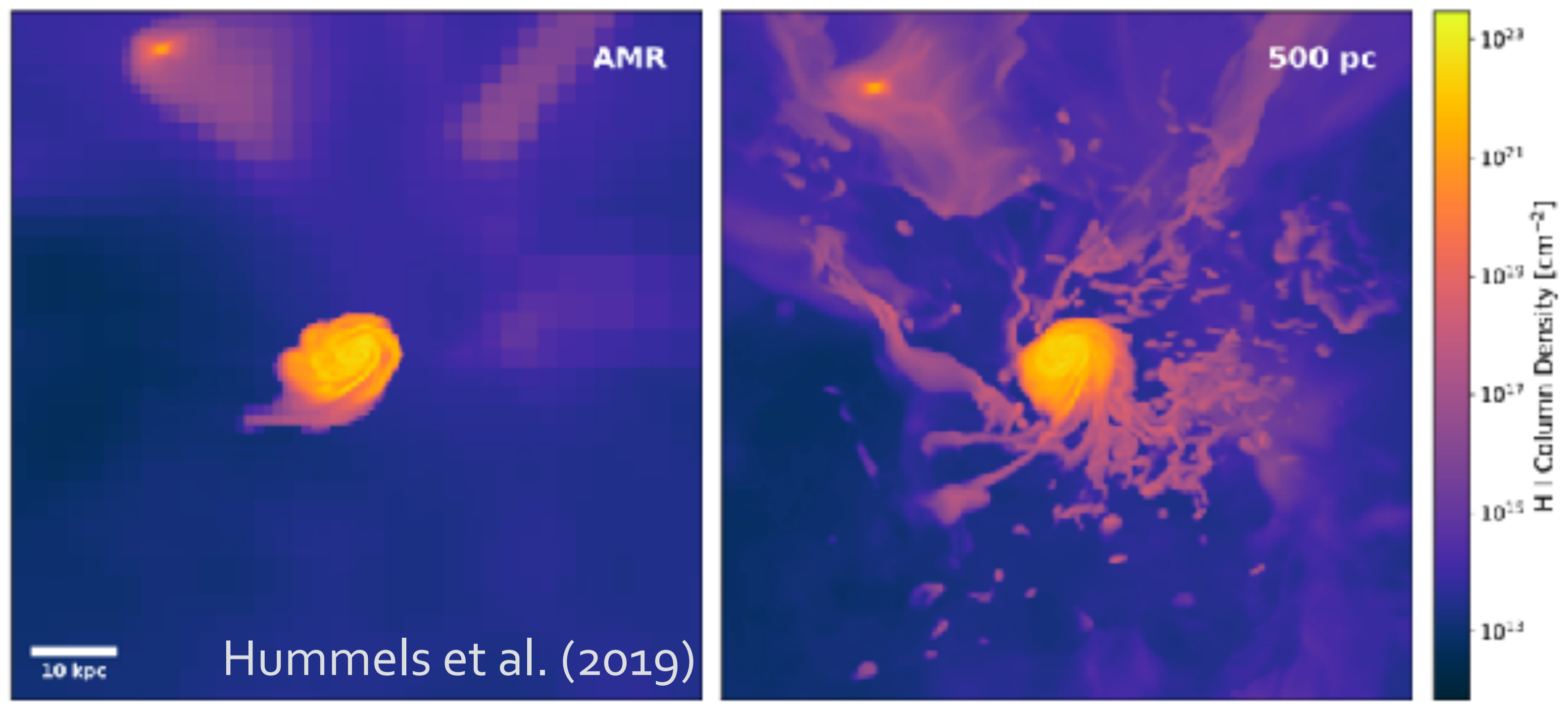


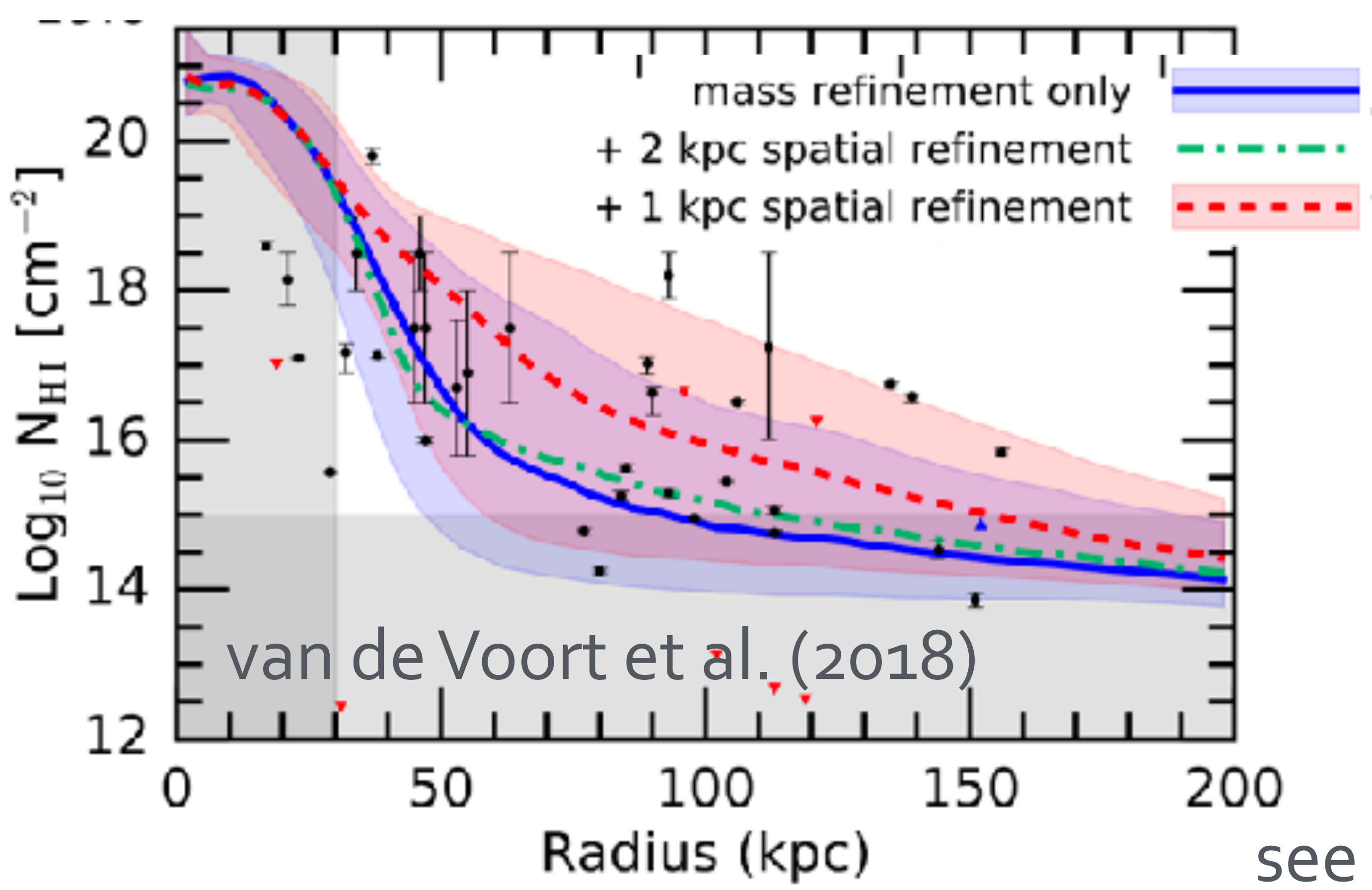
Milky Way observations



Challenge for large scale simulations







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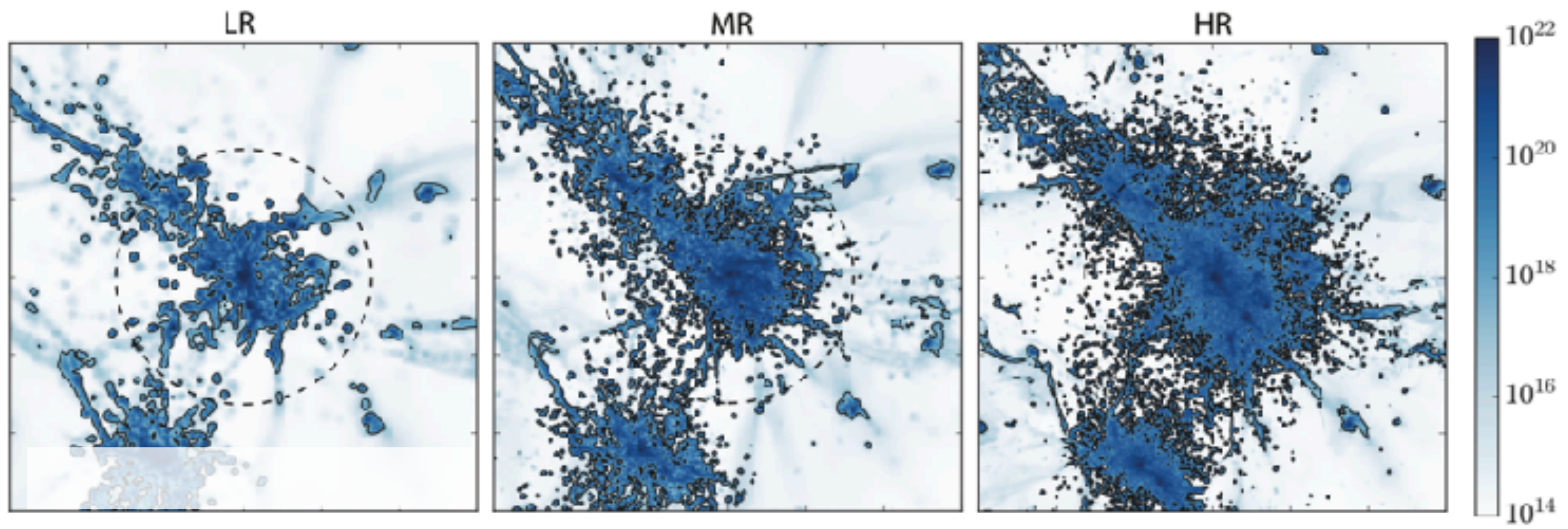

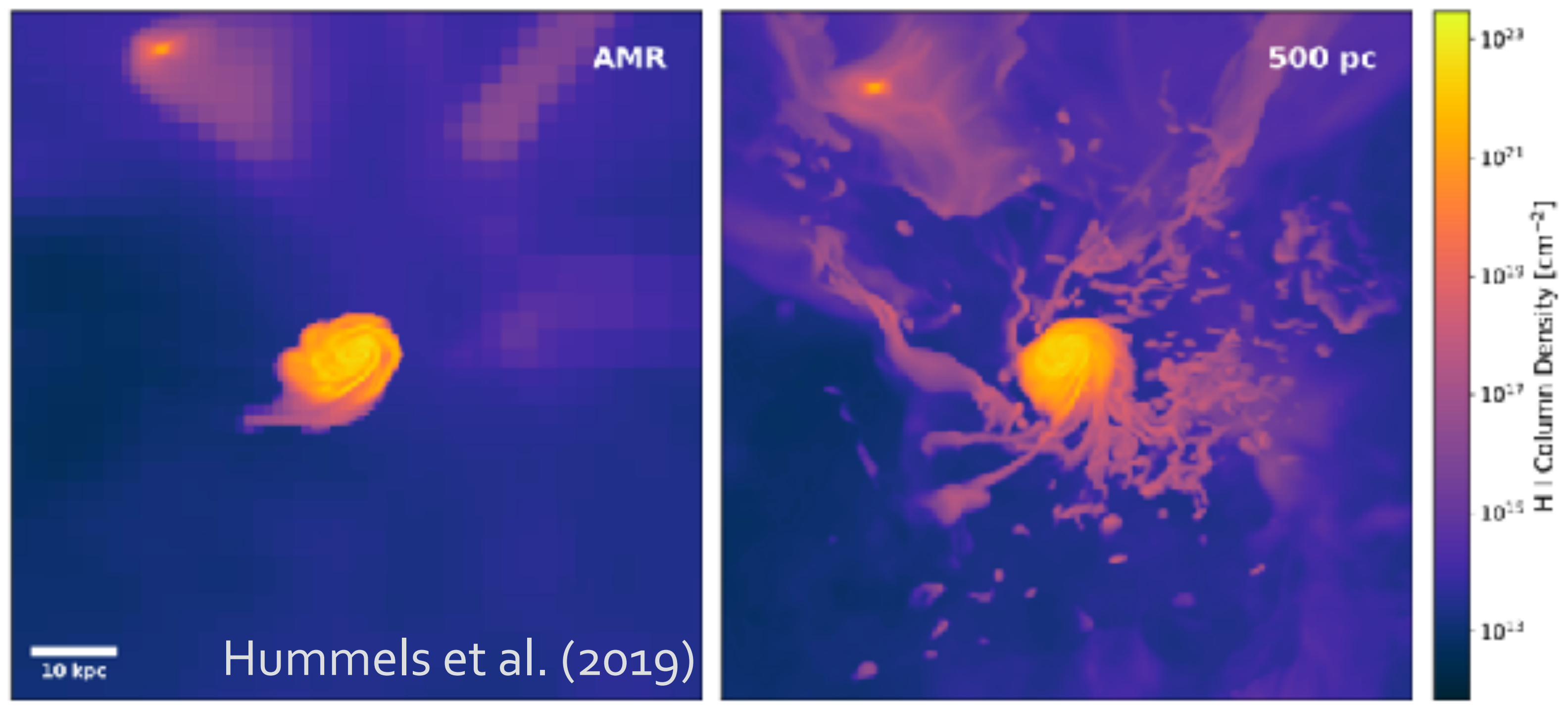

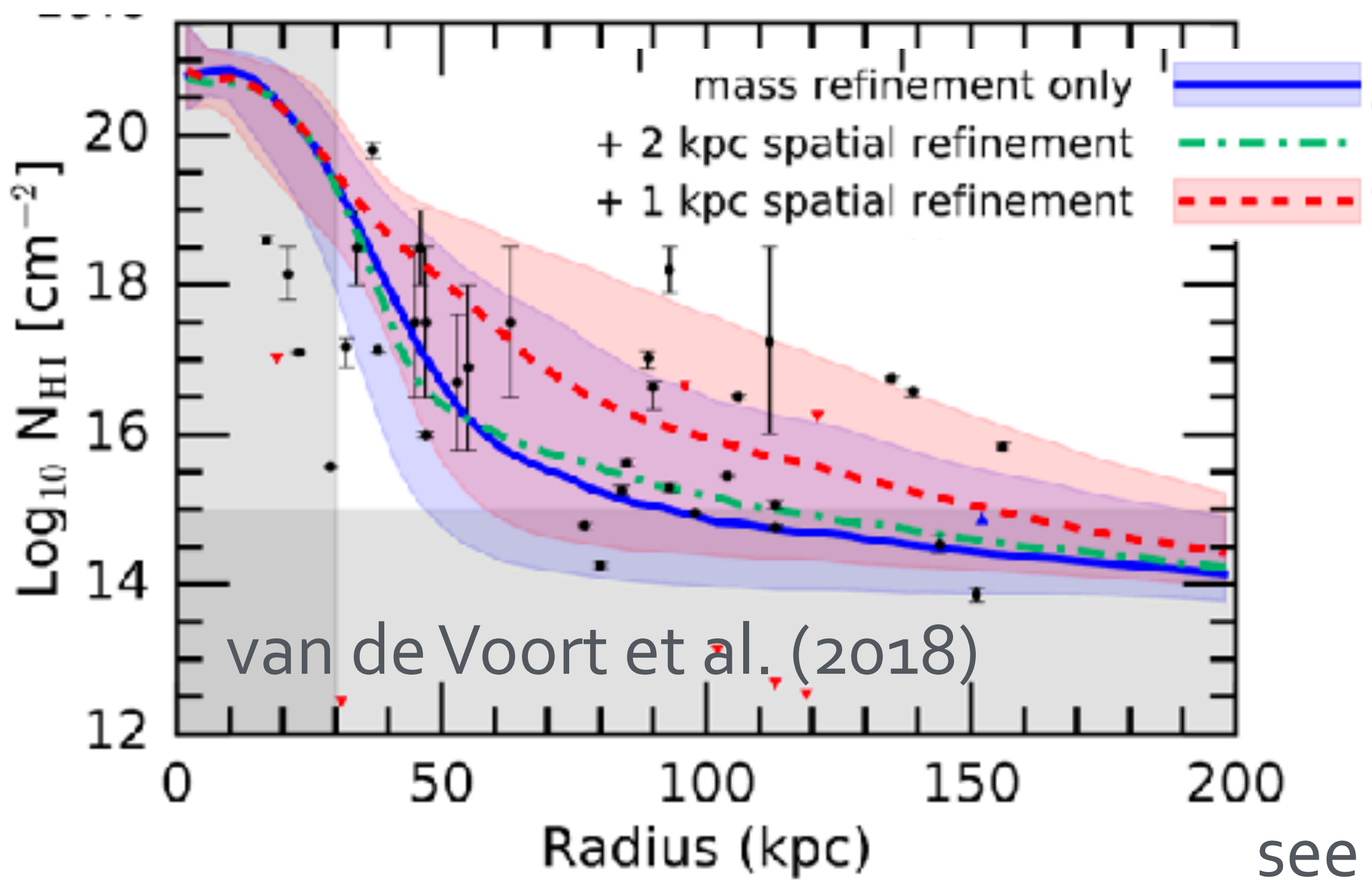

Affecting:

- CGM observables (QSO absorption lines, Lyα halos, …)
- wind / fountain flow observables (how are the phases coupled?)
- impact of winds energetically and content (dust, PAHs, …)
- fuel for future star-formation
- impact on cosmological environment (LyC escape, …)
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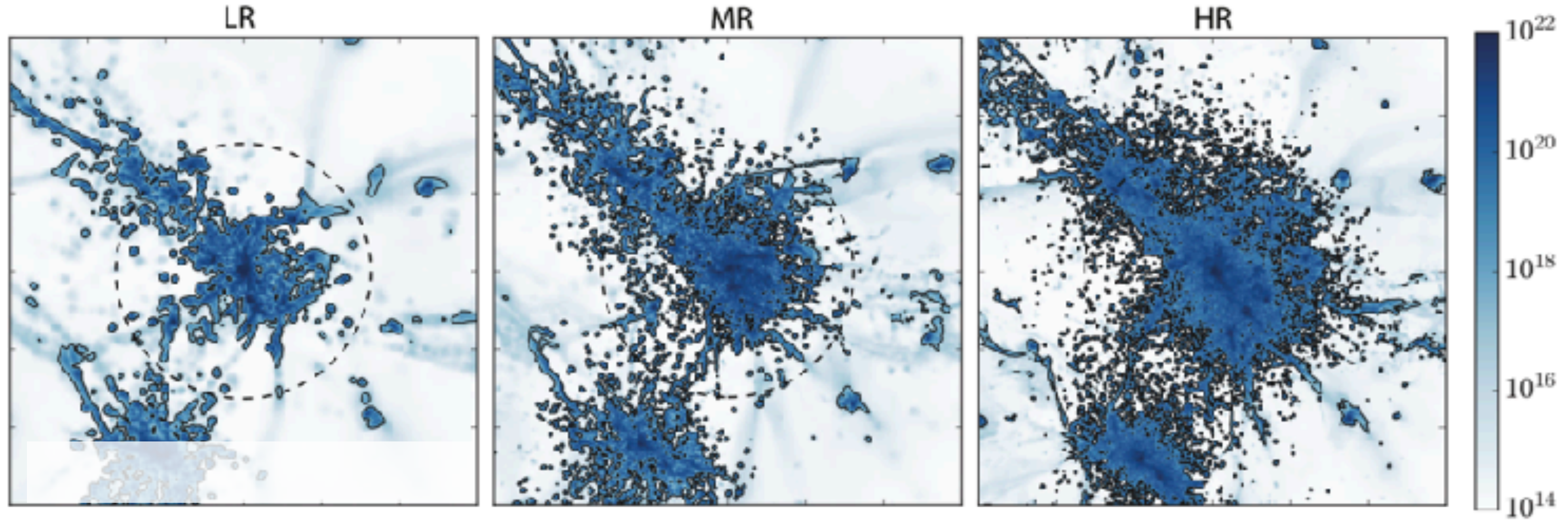

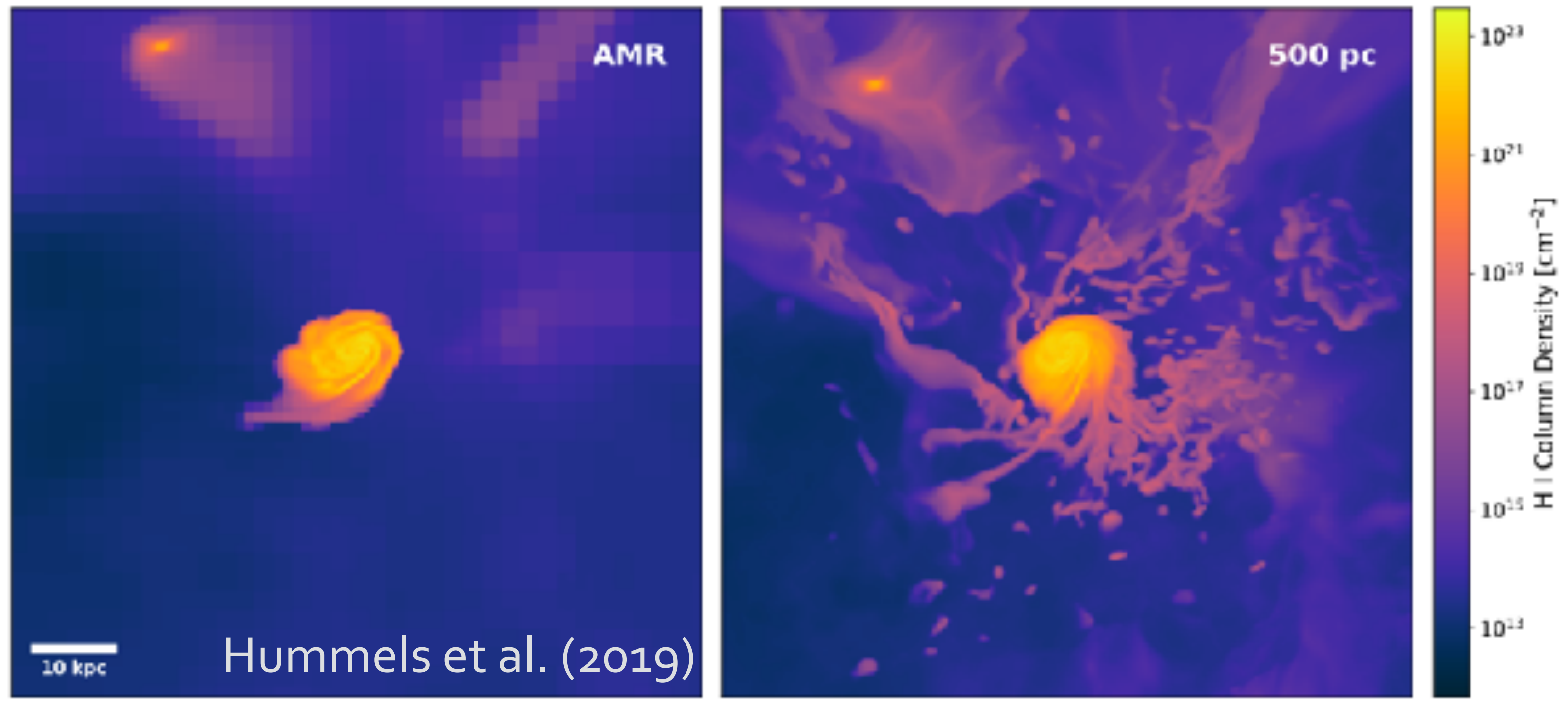

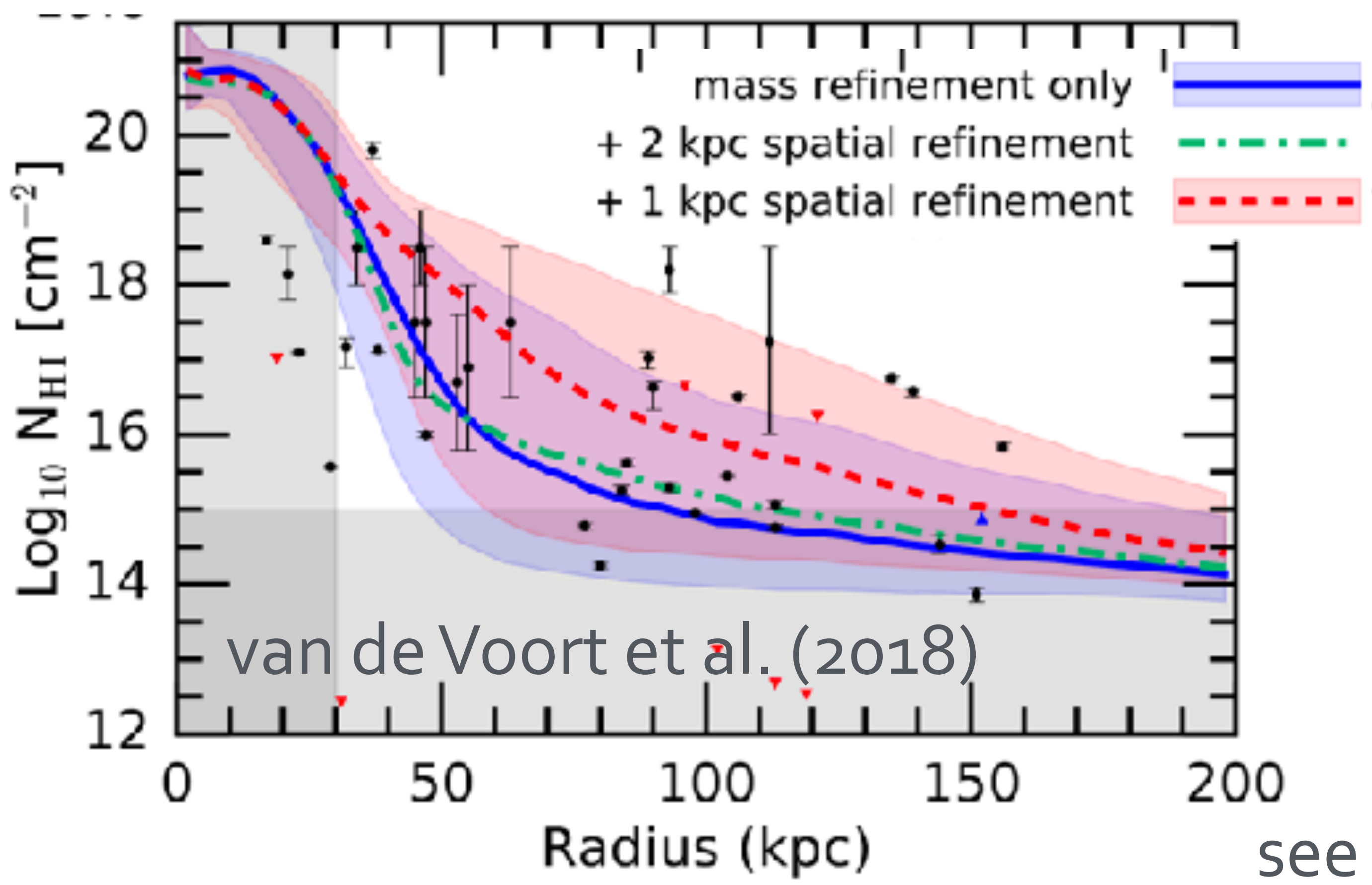

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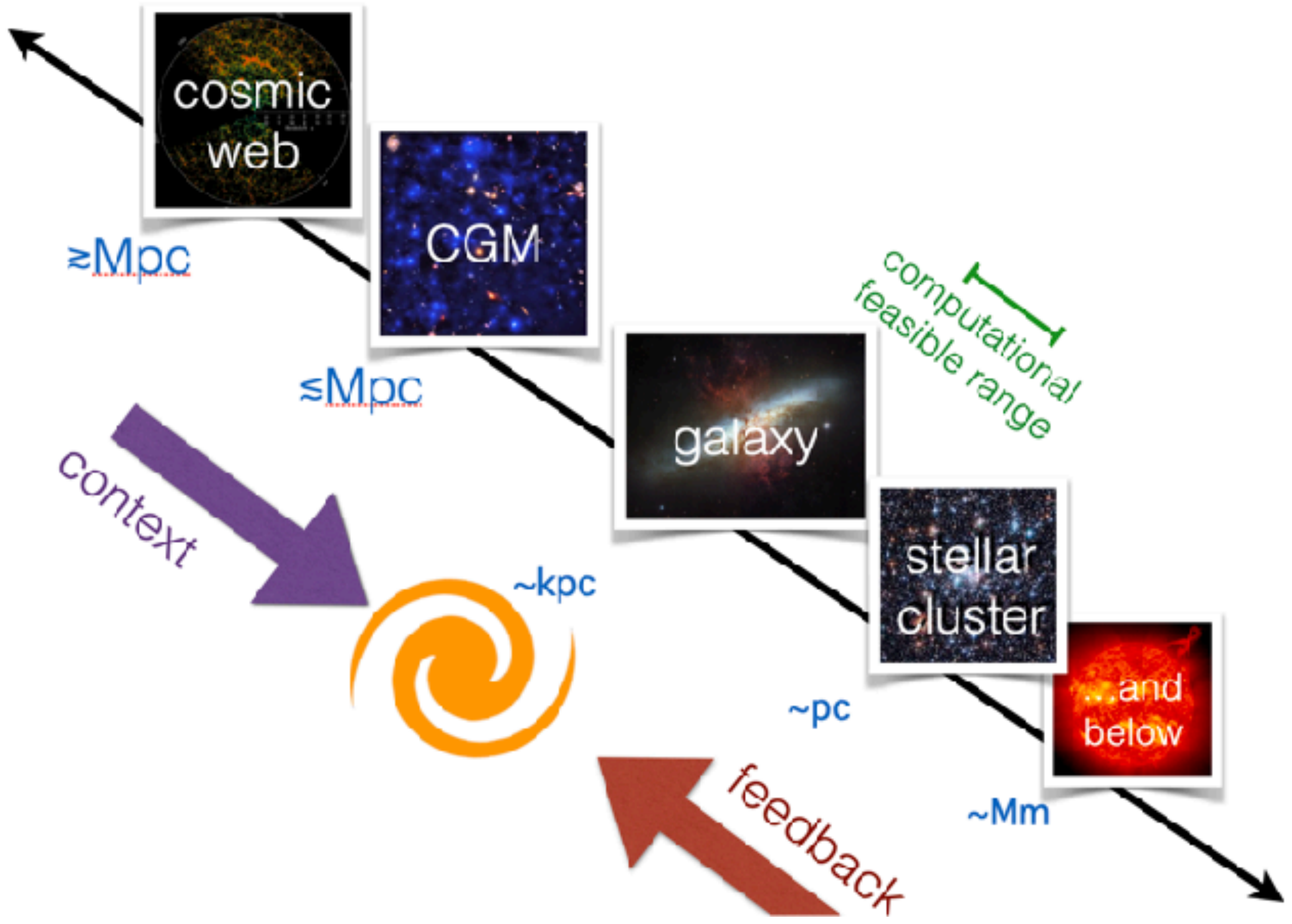
Topics

- The role of feedback in self-regulating star formation and ISM properties in galaxies
- Physical properties of gaseous halos and imprints of feedback on them
- Circulation of metals and gas in and out of galaxies
- Observational evidence for feedback
- Theoretical challenges in modelling feedback
- Galaxies: stellar feedback
- Active galactic nuclei feedback
- Feedback via supernovae, cosmic rays and radiation
- Impact of cosmological environment on feedback processes

see also, Peeples et al. (2018), Suaresh et al. (2018), Nelson et al. (2020), …

Go subgrid?



Solutions in computational astrophysics:

(1) adaptive techniques (SPH, AMR, …)
(2) subgrid models (feedback, star-formation, …)

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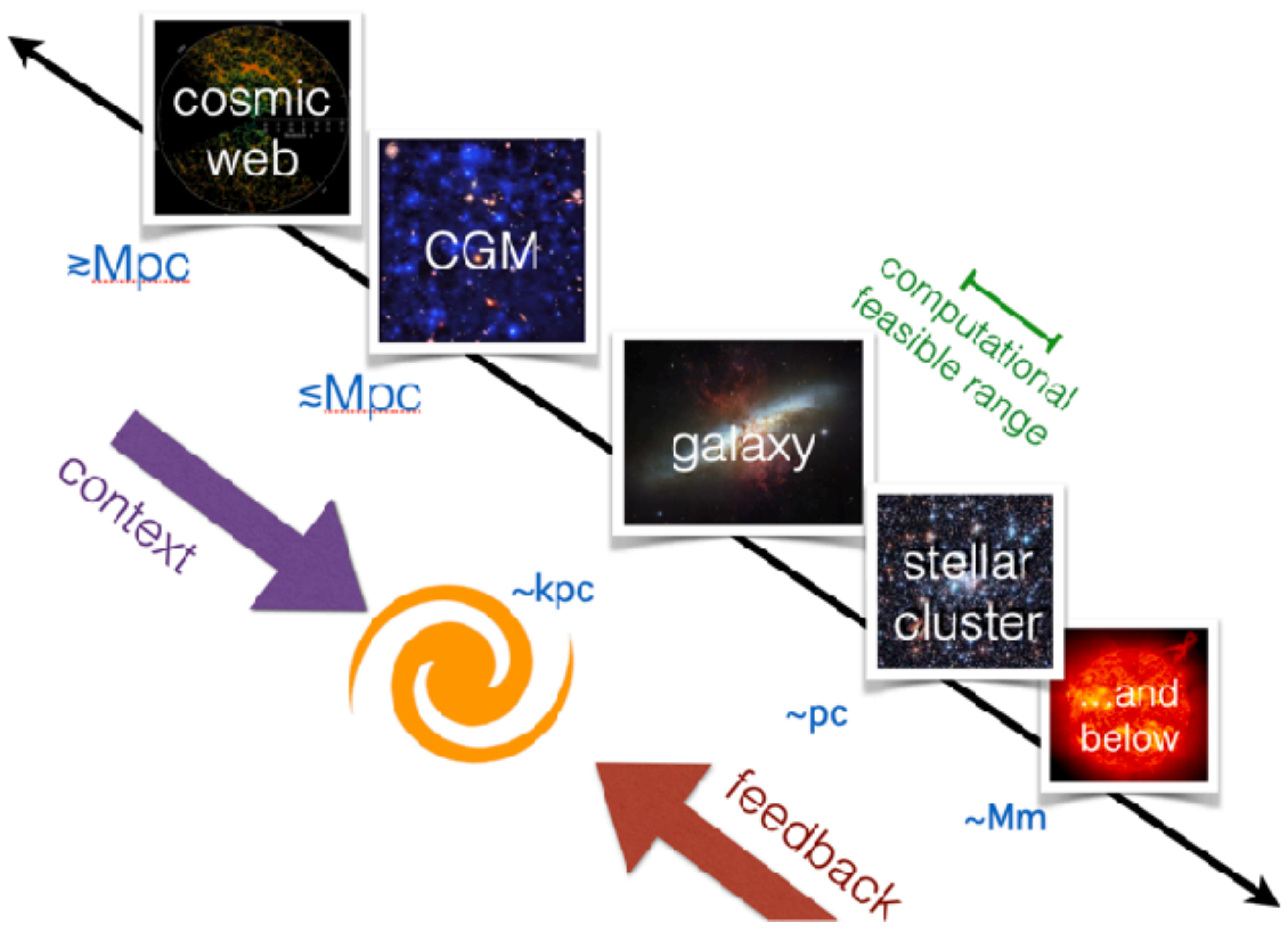

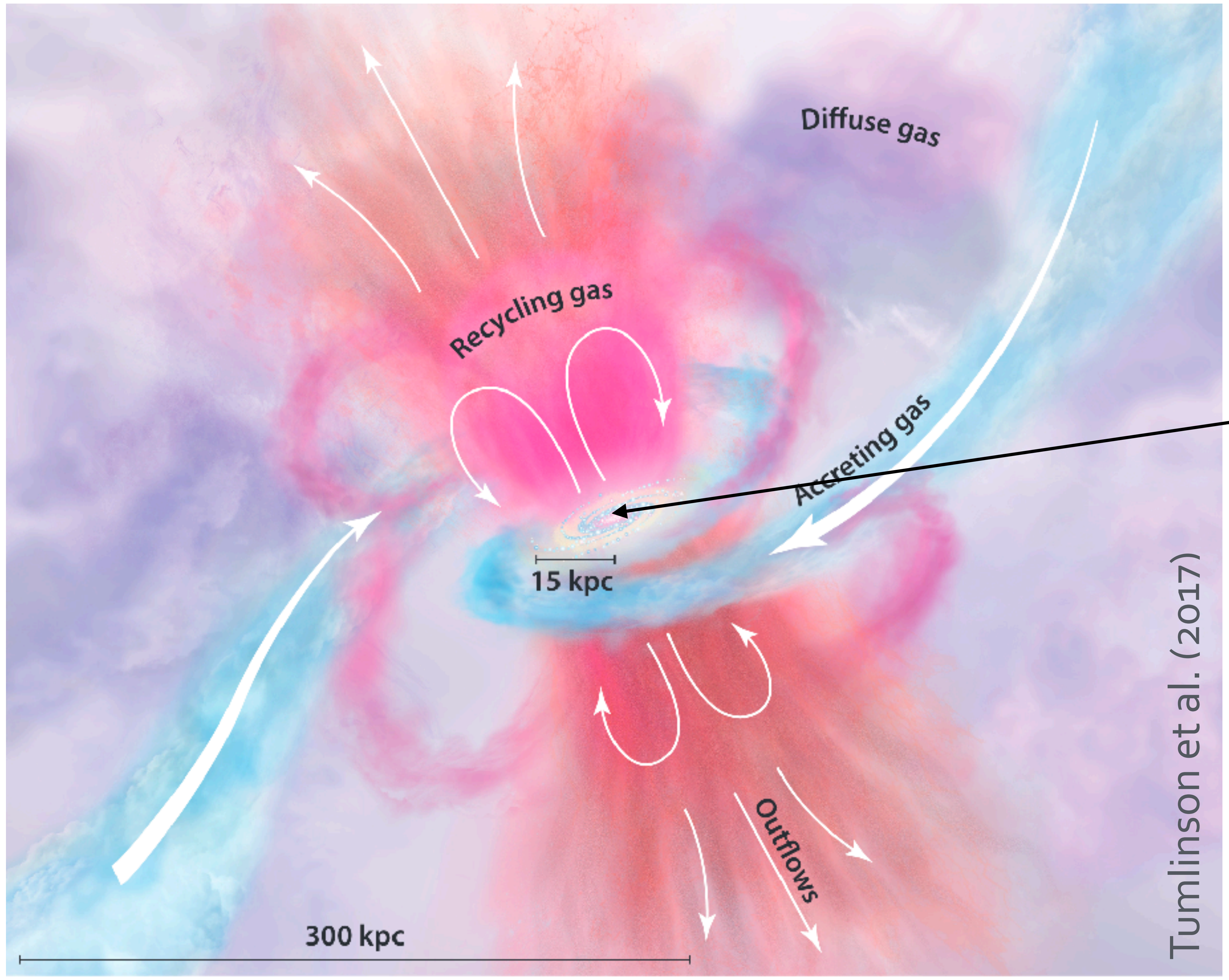

Tumlinson et al. (2017)

Add feedback & star-formation: fudge here

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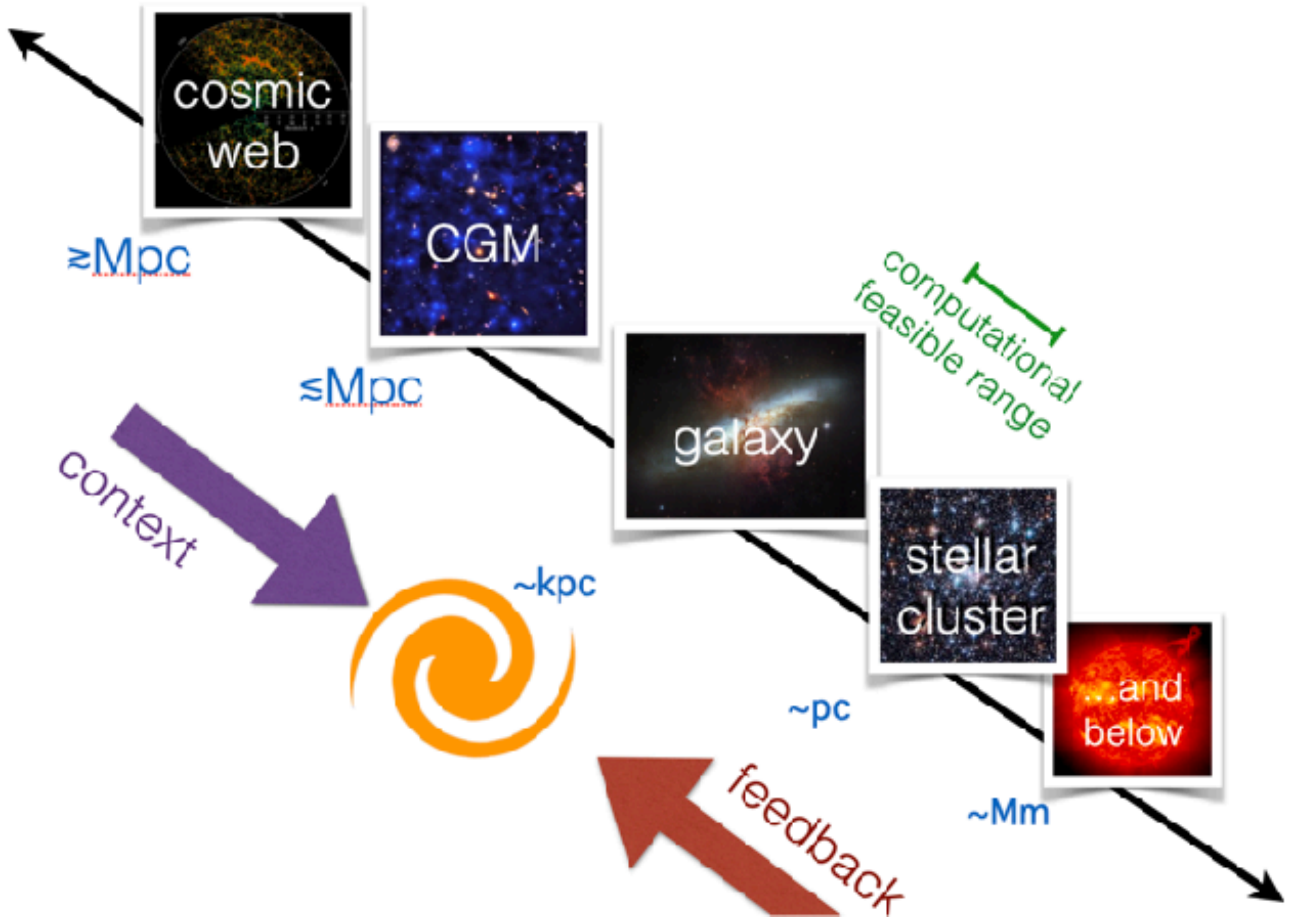

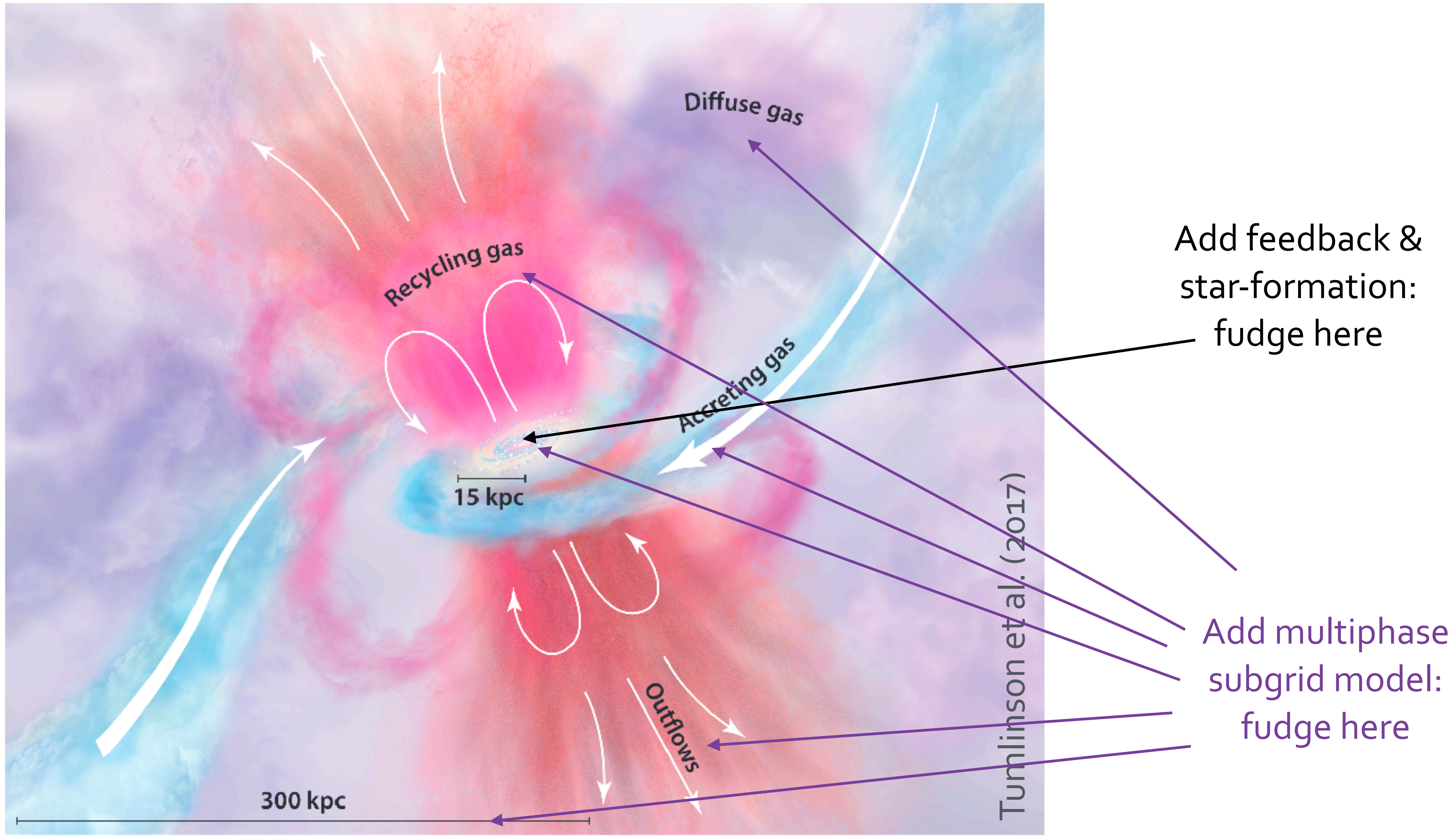

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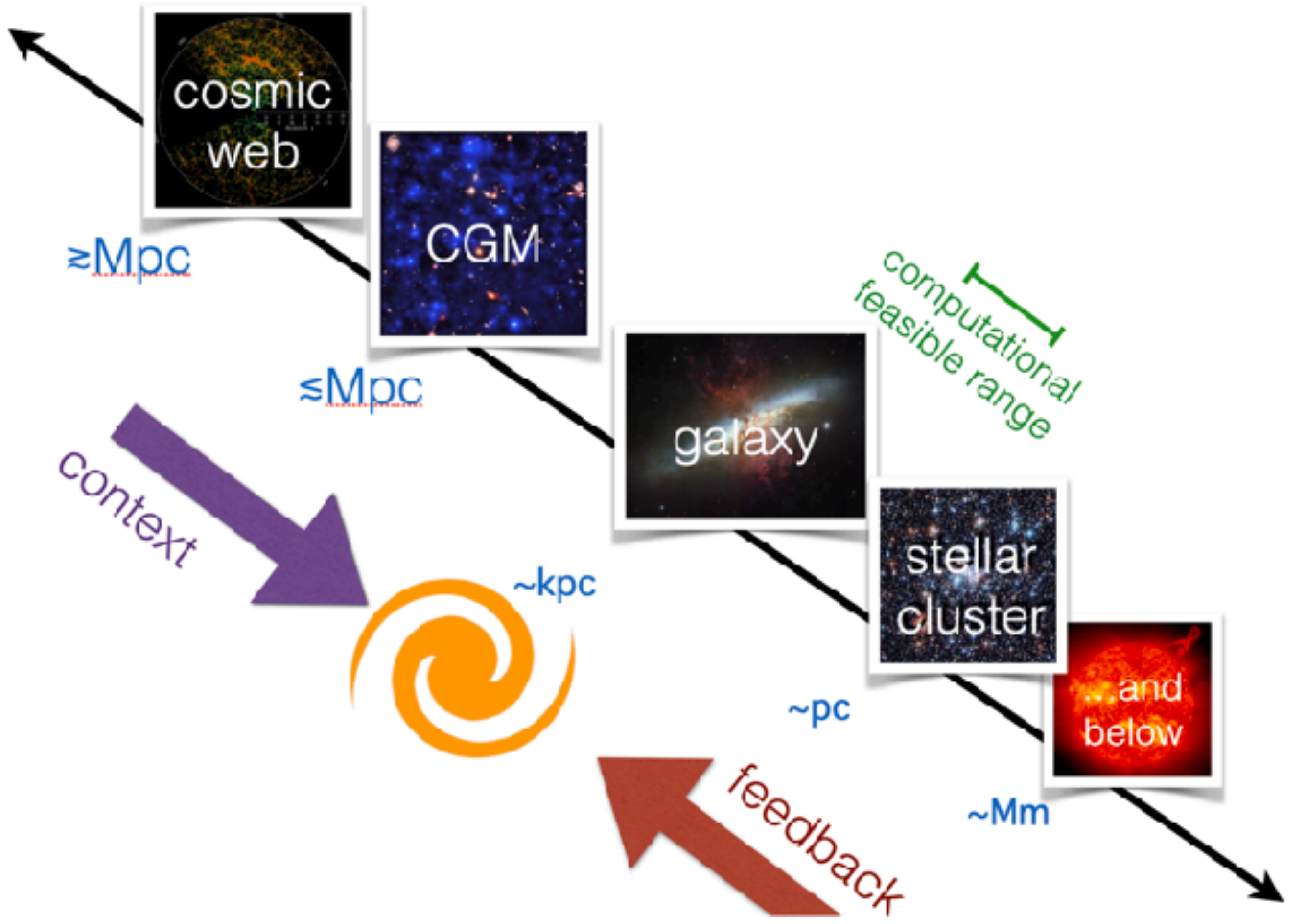

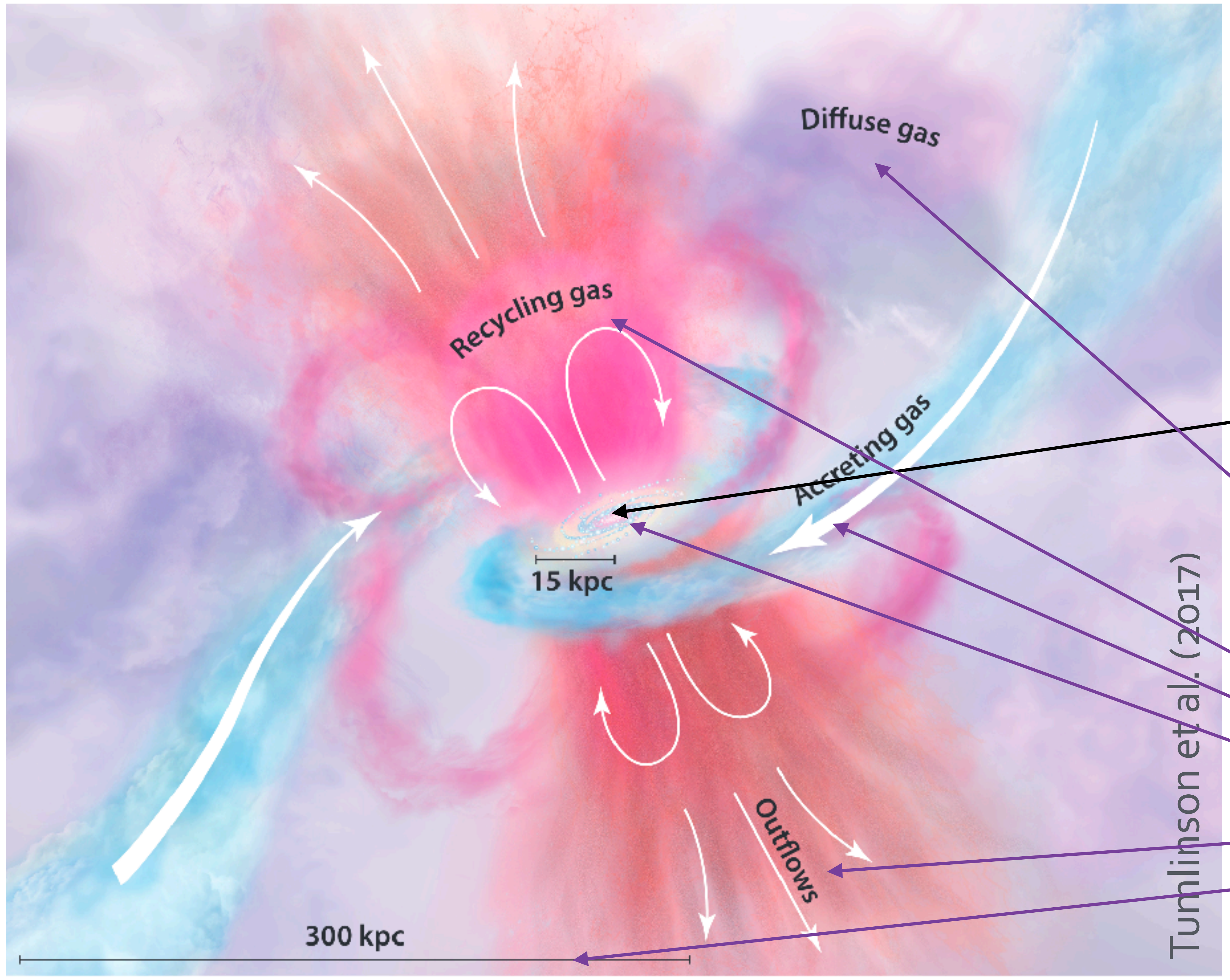

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Add multiphase subgrid model: fudge here

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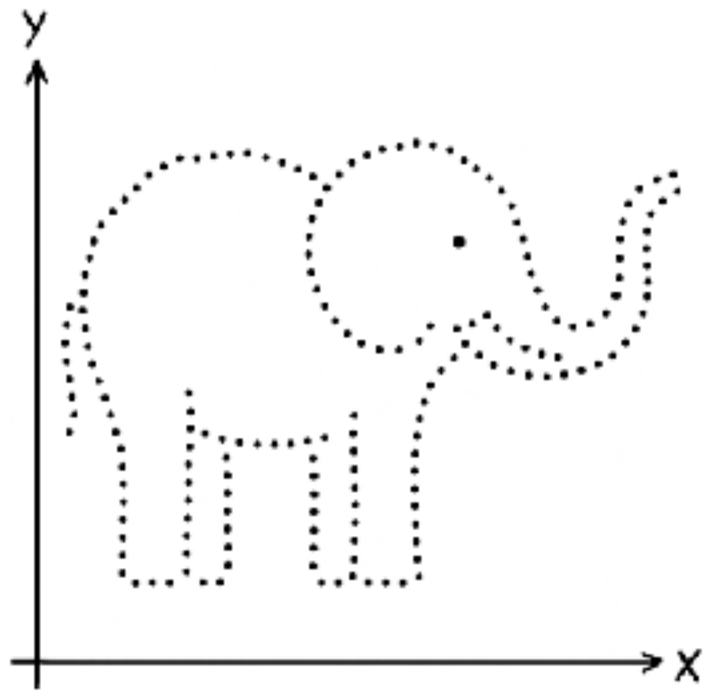
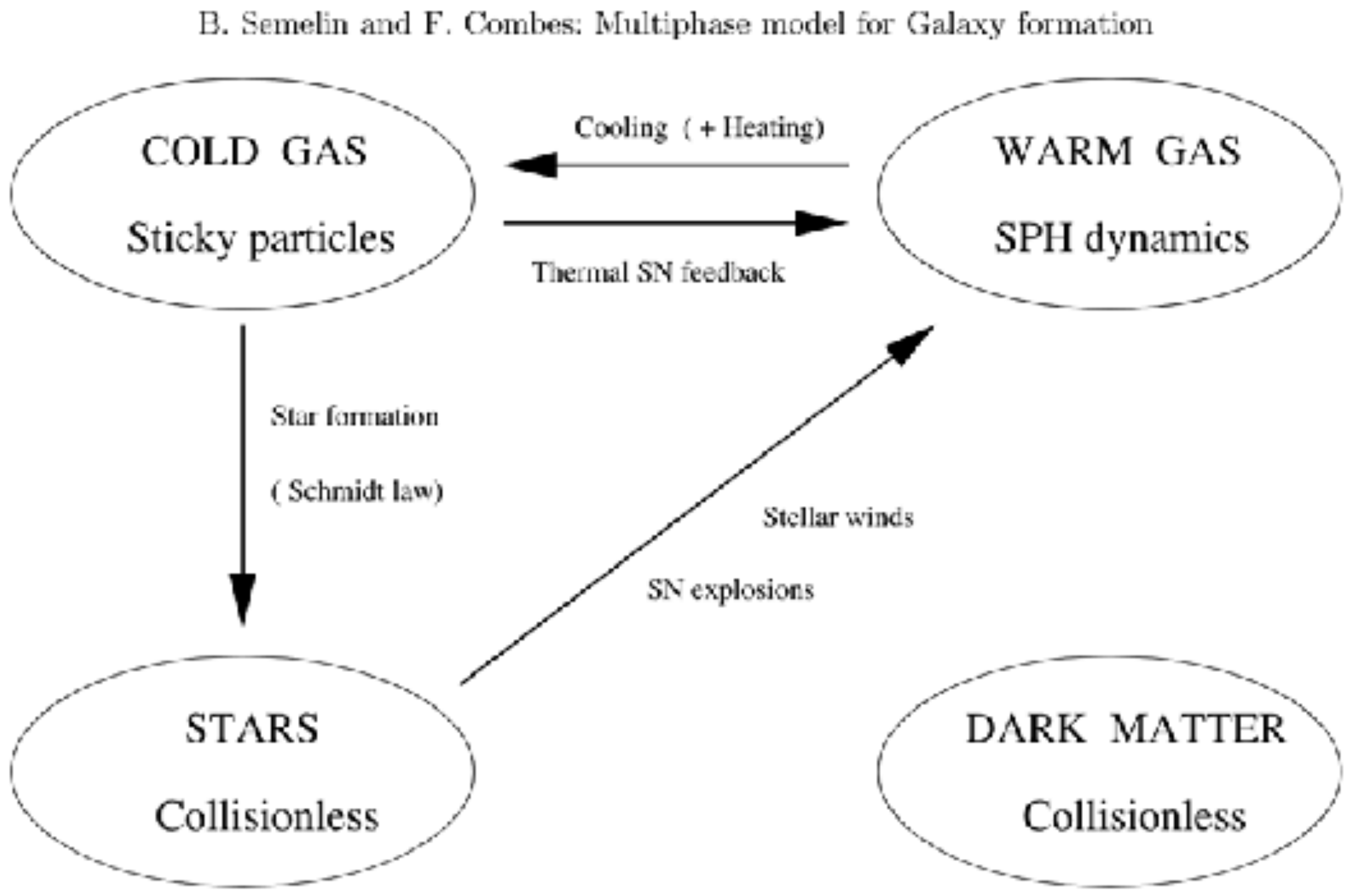
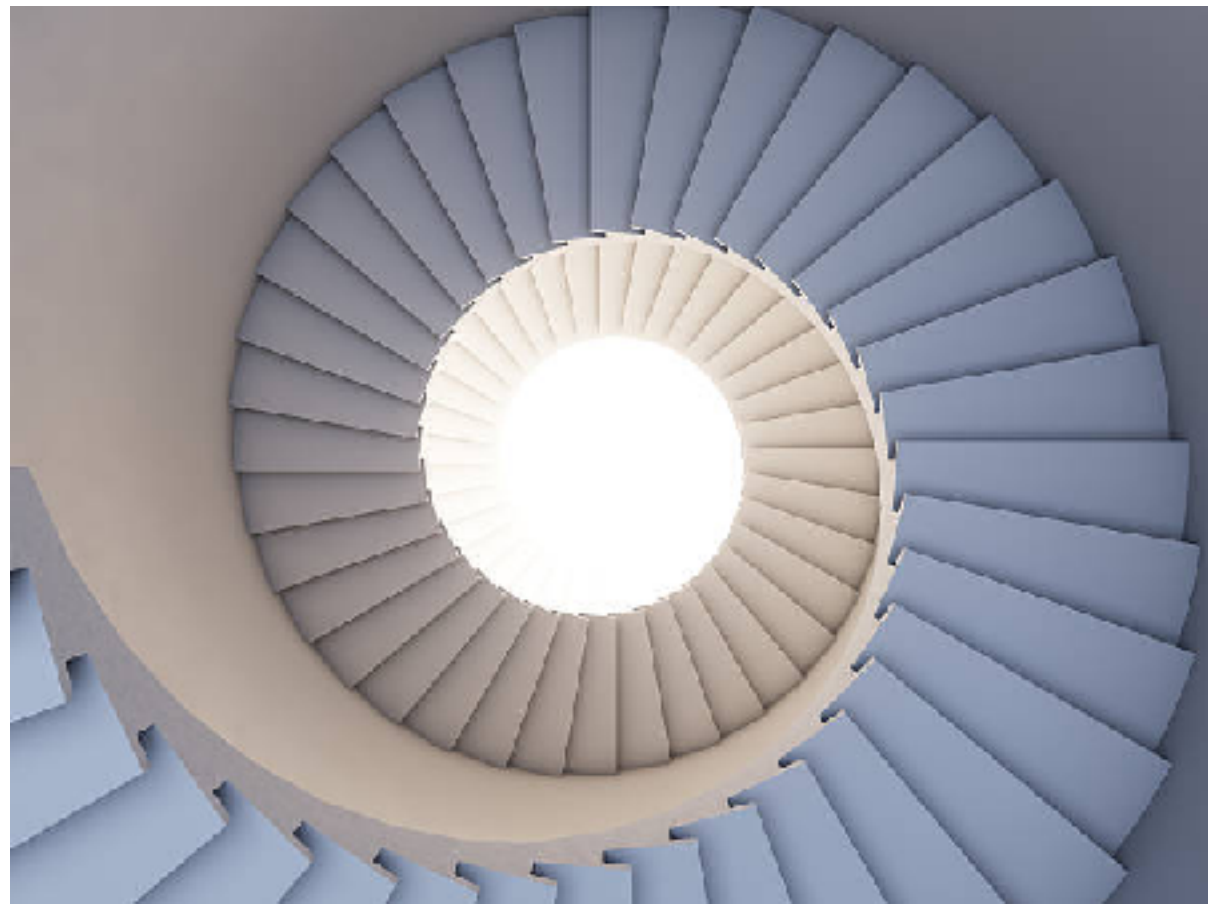


With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.
- John von Neumann

Not your grandma's subgrid model!

Previous work: Semelin & Combes (2002), Berczik et al. (2003), Harfst et al. (2004), Scannapieco et al. (2006), Huang et al. (2020), Weinberger & Hernquist (2022), Smith et al. (2024), Butsky et al. (2024), Das et al. (2025) ...





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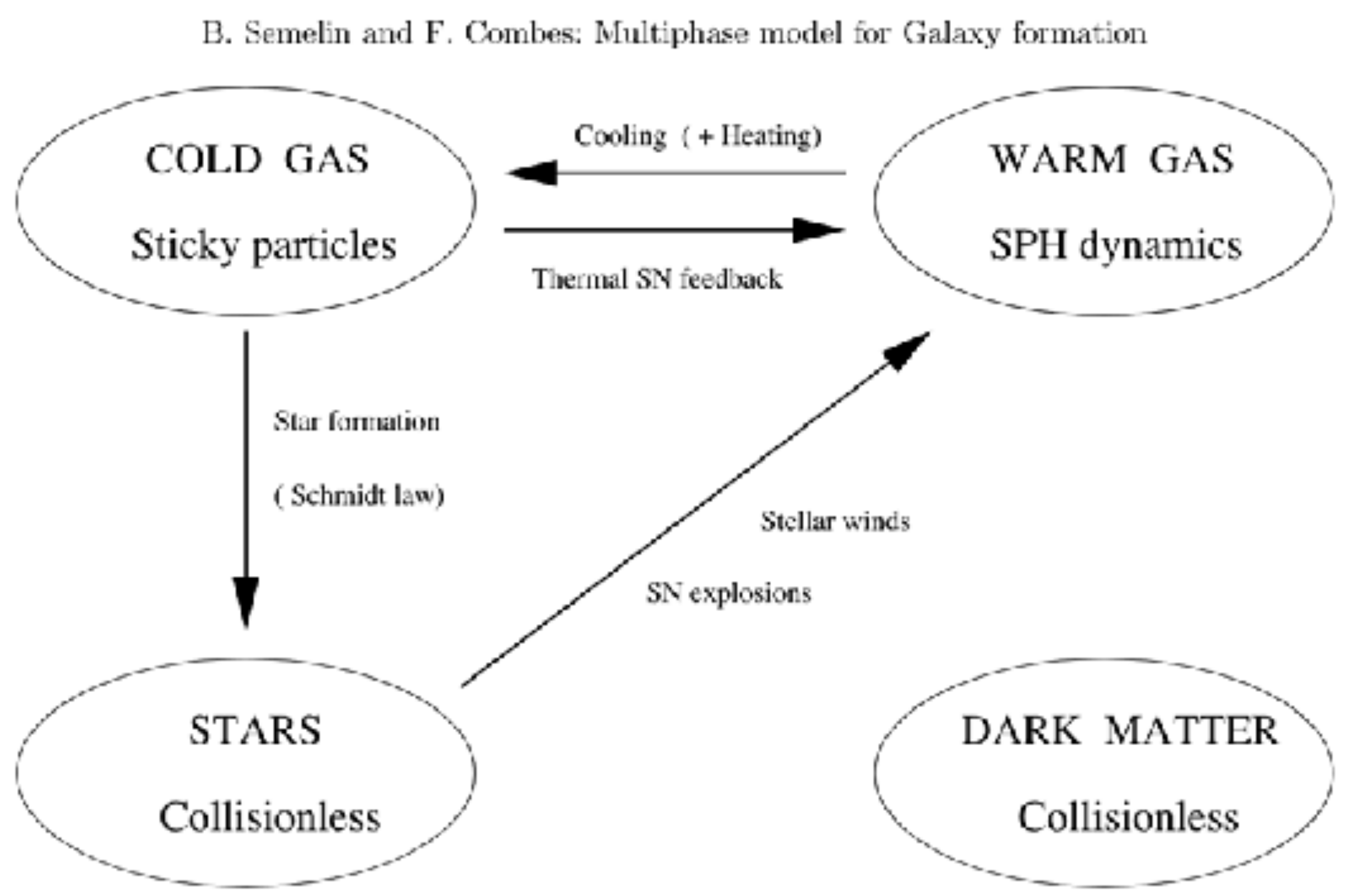

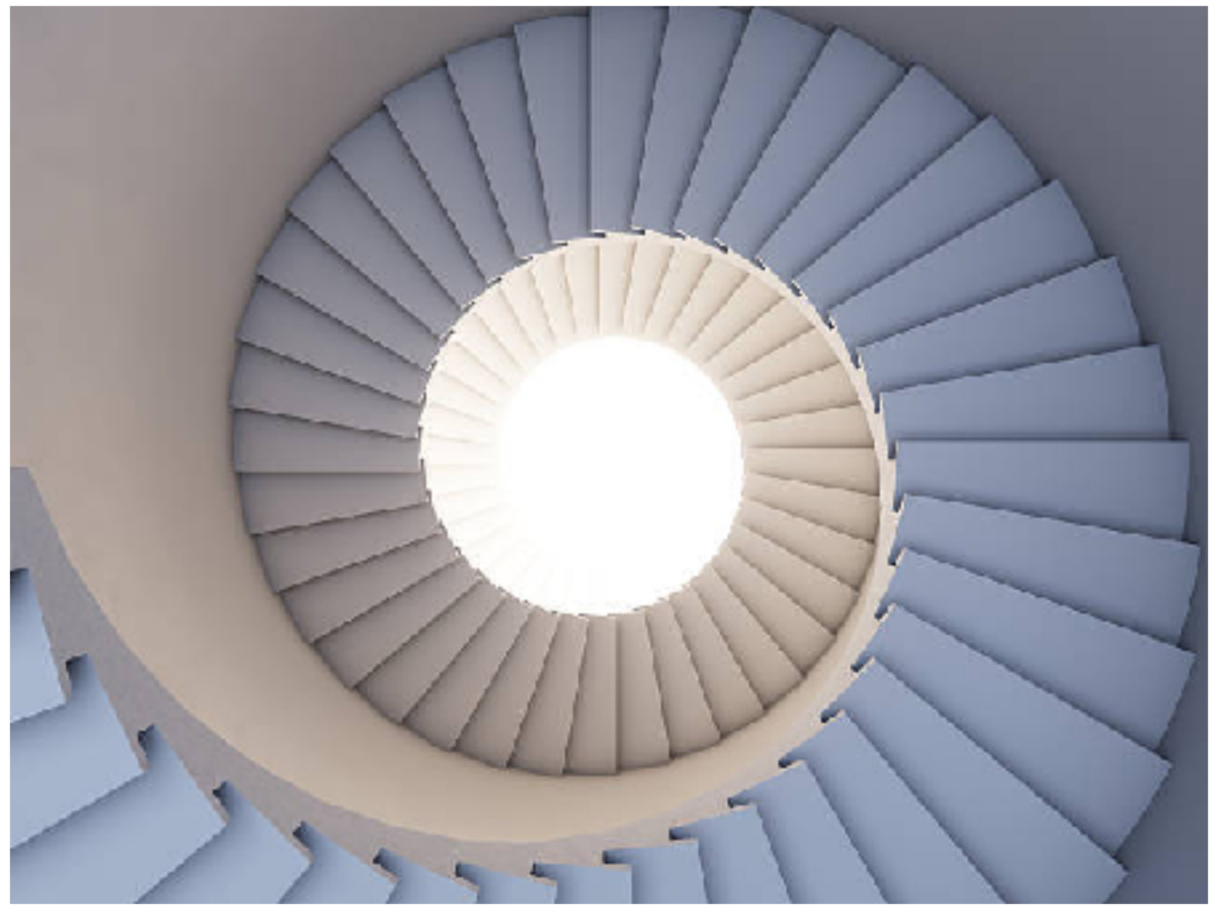

Towards a *multiphase subgrid model:*

1. Multi-fluid code
2. Sound multiphase theory → crucial for *predictable power*
3. Subgrid implementation & testing

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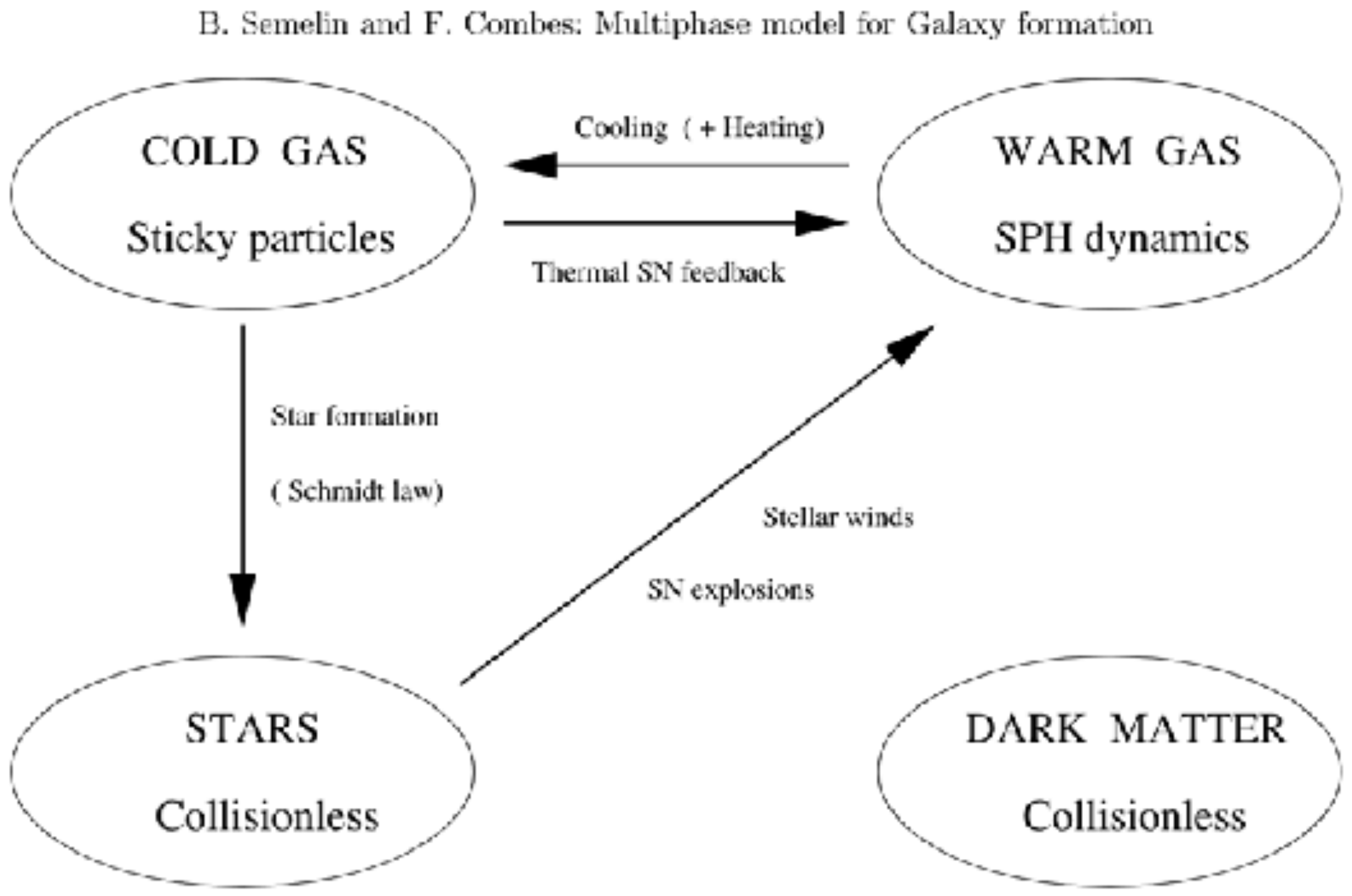

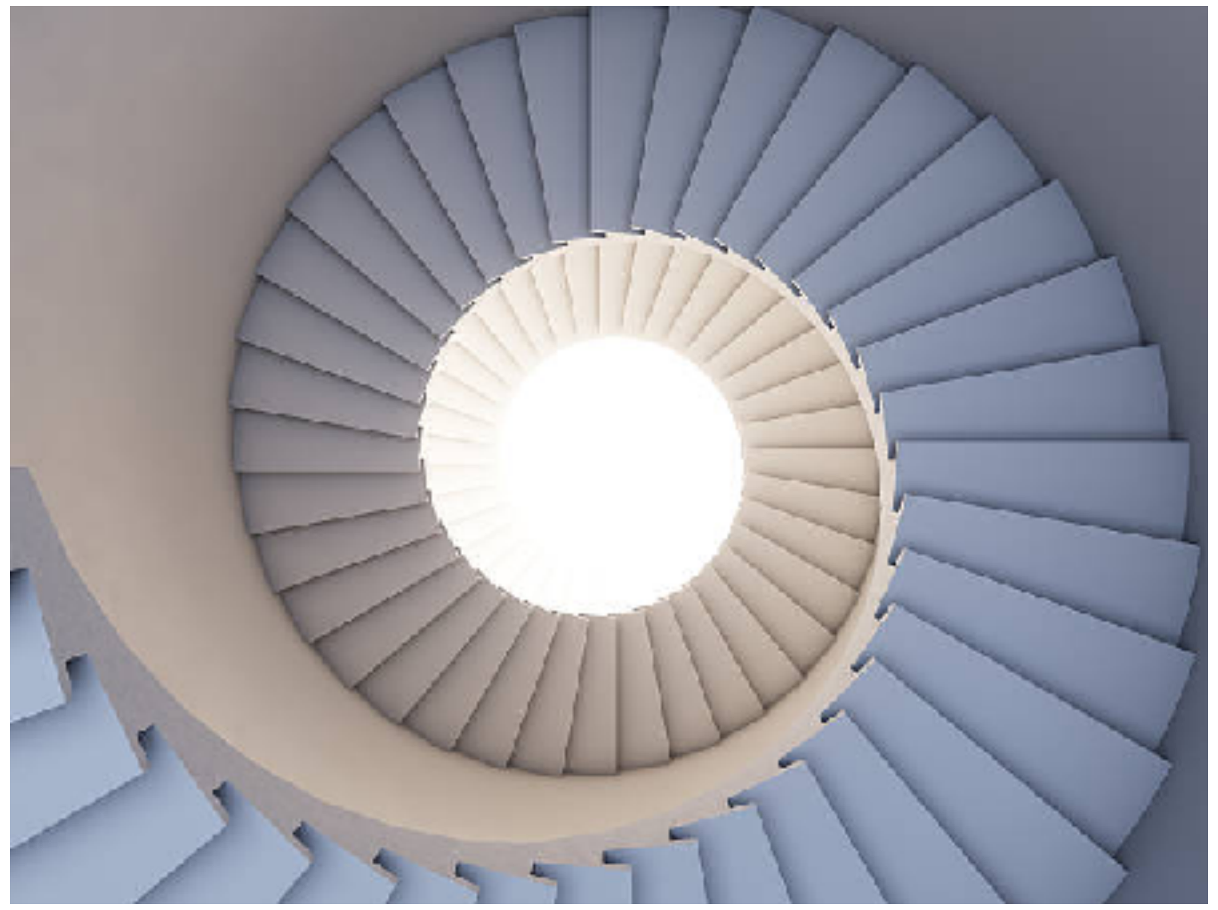

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Our take:

(see Rainer's talk (?) and posters)

This talk.

(see Hitesh's talk tomorrow)

The two sides of mixing

Cold gas can mix with hot gas (turbulence, shear, ...) *and become hot ("destroyed").*

or mixed gas cools ("survives").

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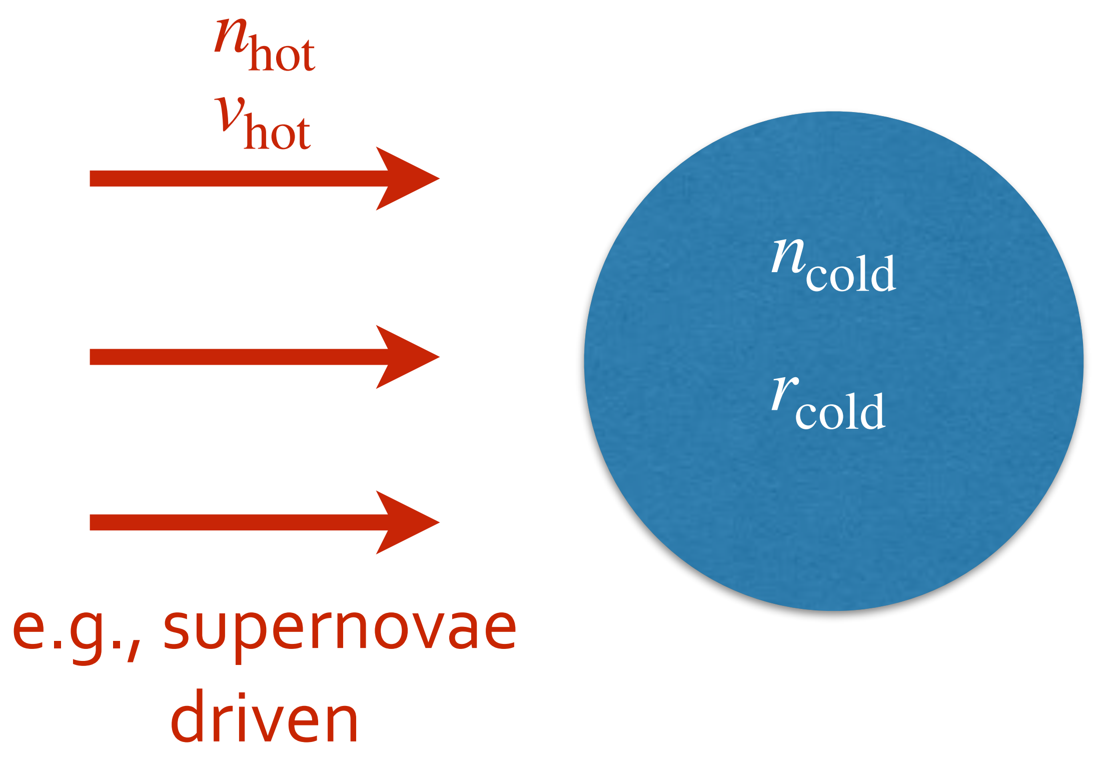
"Cloud crushing" (as requested by Christoph)



$$t_{\rm destroy} \sim \sqrt{\frac{n_{\rm cold}}{n_{\rm hot}}}\frac{r_{\rm cold}}{v_{\rm hot}}$$

$$t_{\rm drag} \sim \sqrt{\frac{n_{\rm cold}}{n_{\rm hot}}} t_{\rm destroy}$$

$$t_{\rm cool} \sim \frac{nkT}{n^2\Lambda(T)}$$

Nittman et al. (1982), Klein et al. (1994), Schneider & Robertson (2015), Scannapieco & Bruggen (2015), Marinacci et al. (2010), Armillota et al. (2016, 2017), Li et al. (2020), Sparre et al. (2020), Kanjilal et al. (2020), Abruzzo et al. (2023), …

https://bit.ly/cloud-crushing
(courtesy of W. Banda-Barragán)

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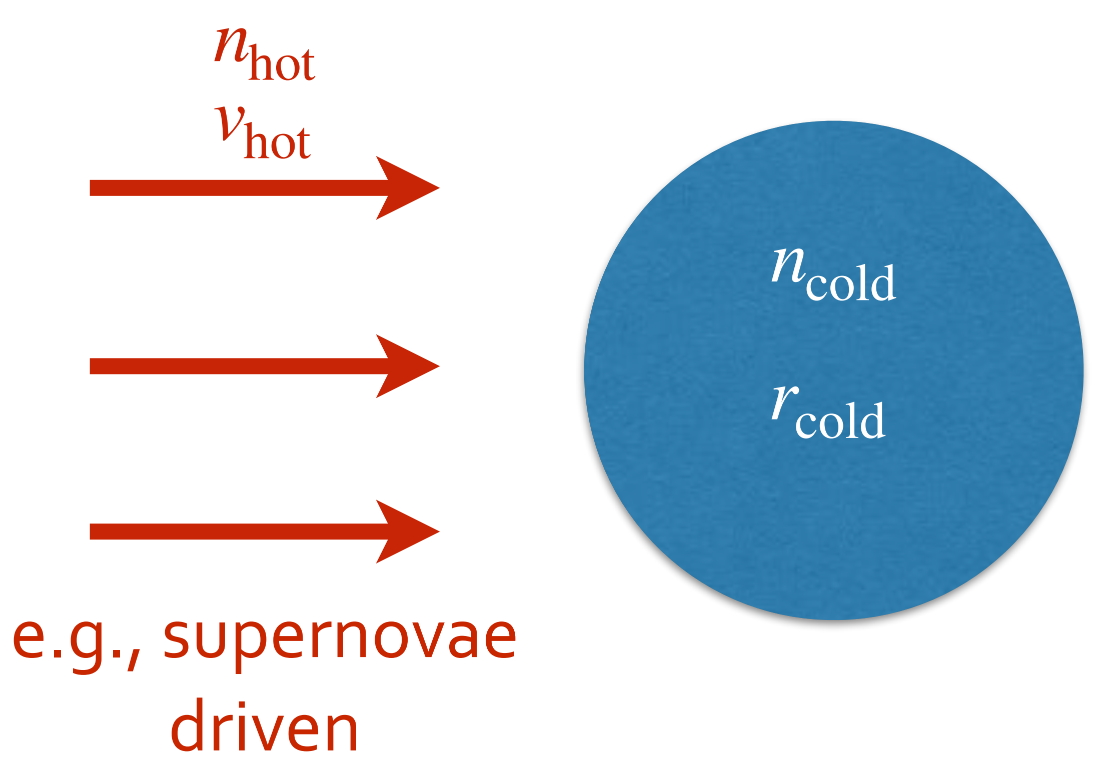

$$t_{destroy} \sim \sqrt{\frac{n_{cold}}{n_{hot}}} \frac{r_{cold}}{v_{hot}}$$

$$t_{drag} \sim \sqrt{\frac{n_{cold}}{n_{hot}}} t_{destroy}$$

$$t_{cool} \sim \frac{nkT}{n^2 \Lambda(T)}$$

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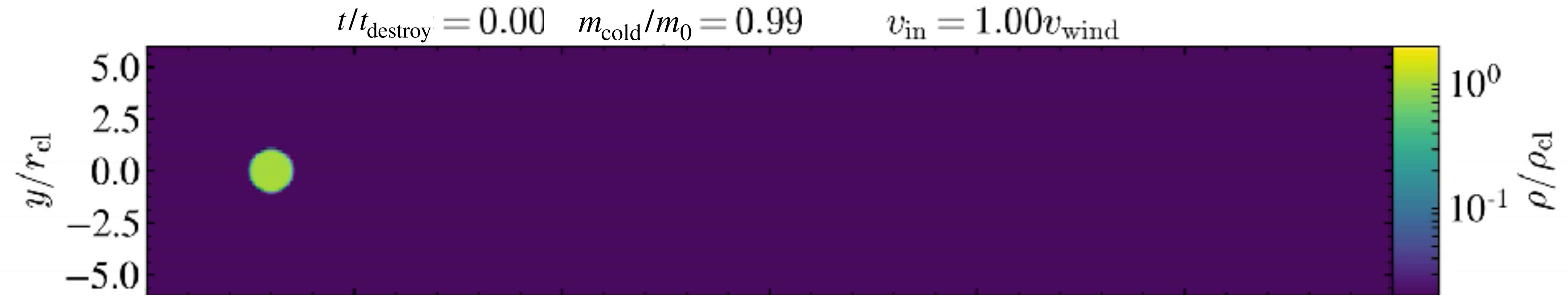
https://bit.ly/cloud-crushing
(courtesy of W. Banda-Barragán)

MG & Oh (2018,2020)

$t_{cool,mix}/t_{destroy} \sim 8$



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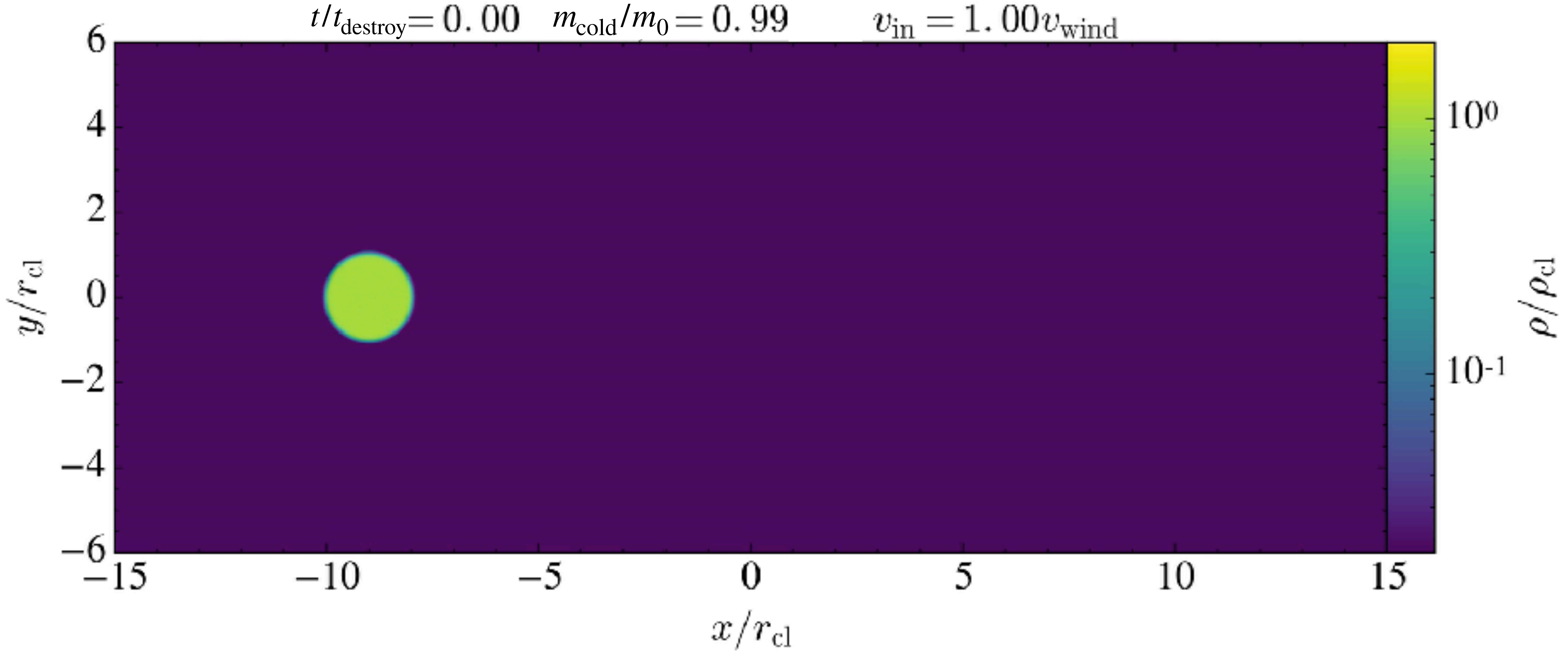
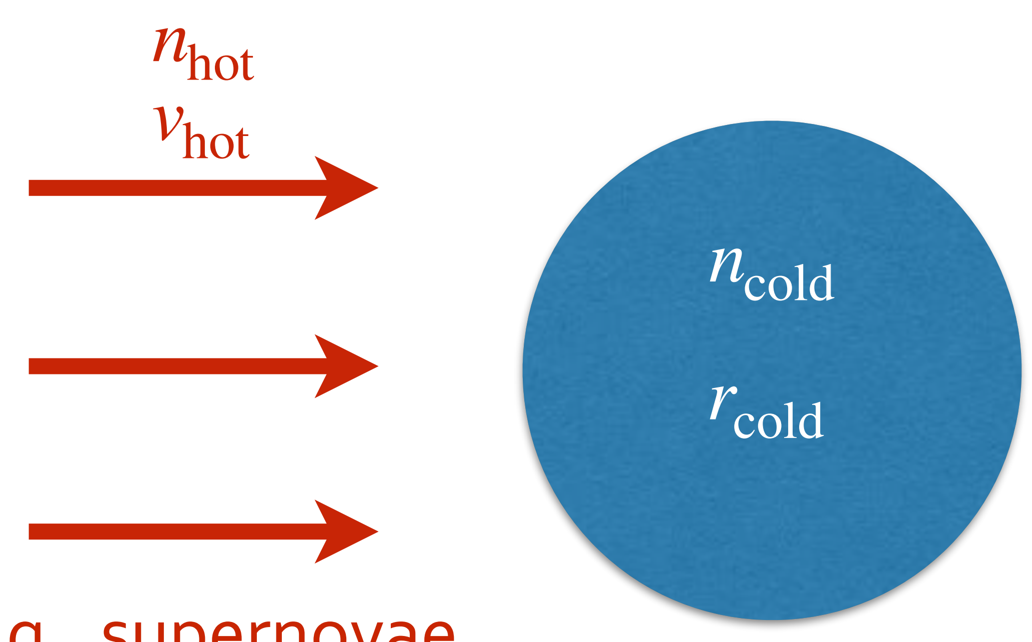


The two sides of mixing

Cold gas can mix with hot gas (turbulence, shear, …) *and become hot ("destroyed").*

or mixed gas cools ("survives").

"Cloud crushing" (as requested by Christoph)



e.g., supernovae driven

$$t_{destroy} \sim \sqrt{\frac{n_{cold}}{n_{hot}}}\frac{r_{cold}}{v_{hot}}$$

$$t_{drag} \sim \sqrt{\frac{n_{cold}}{n_{hot}}} t_{destroy}$$

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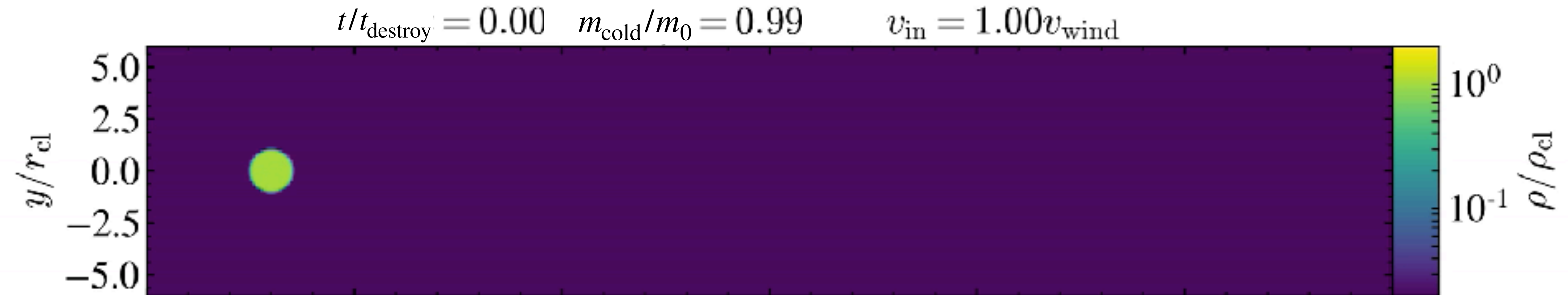

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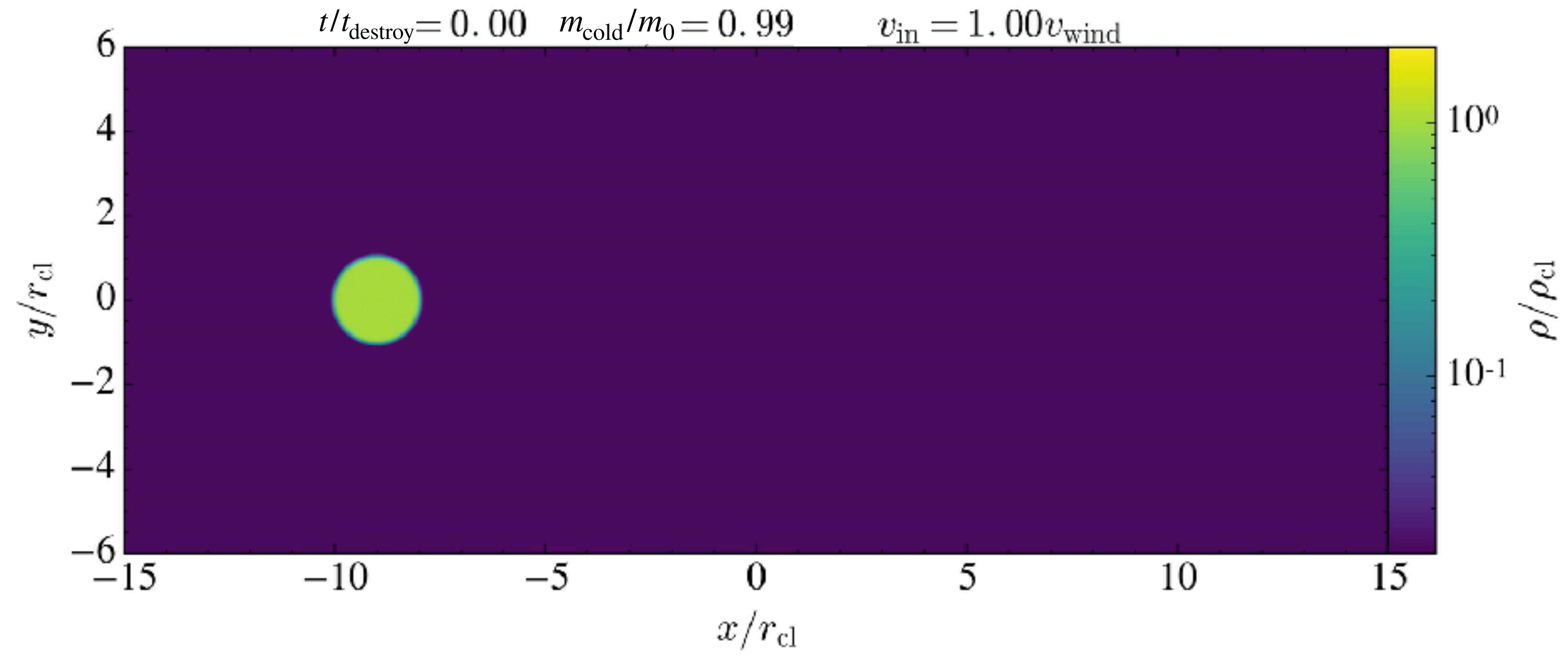

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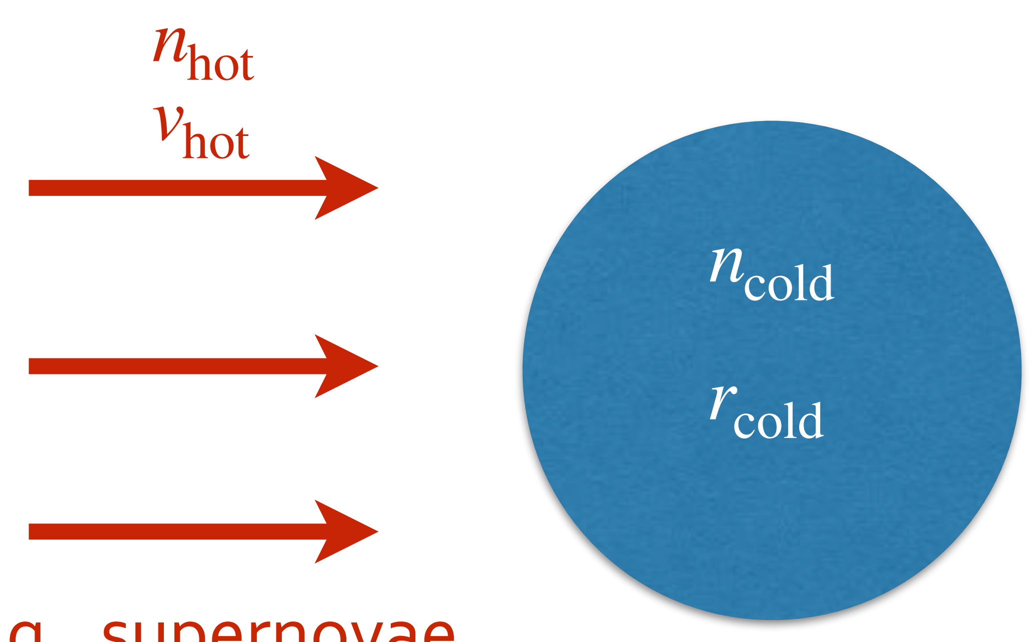

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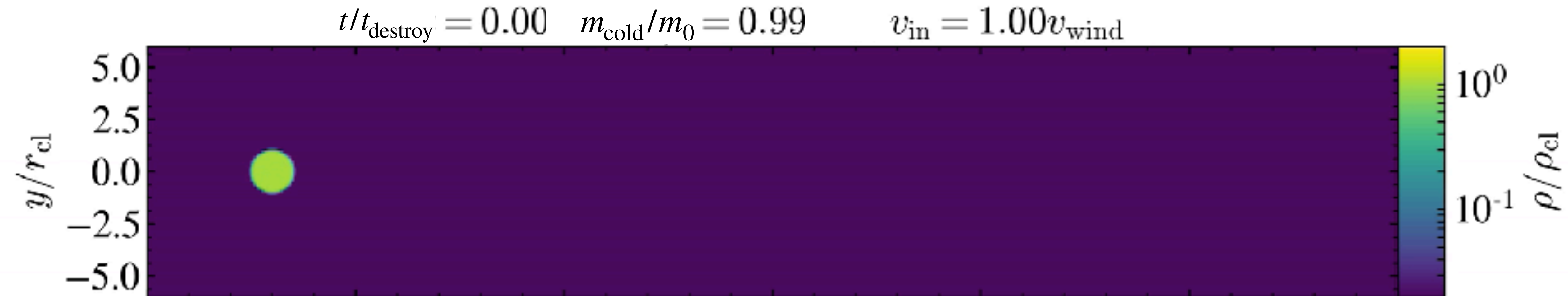

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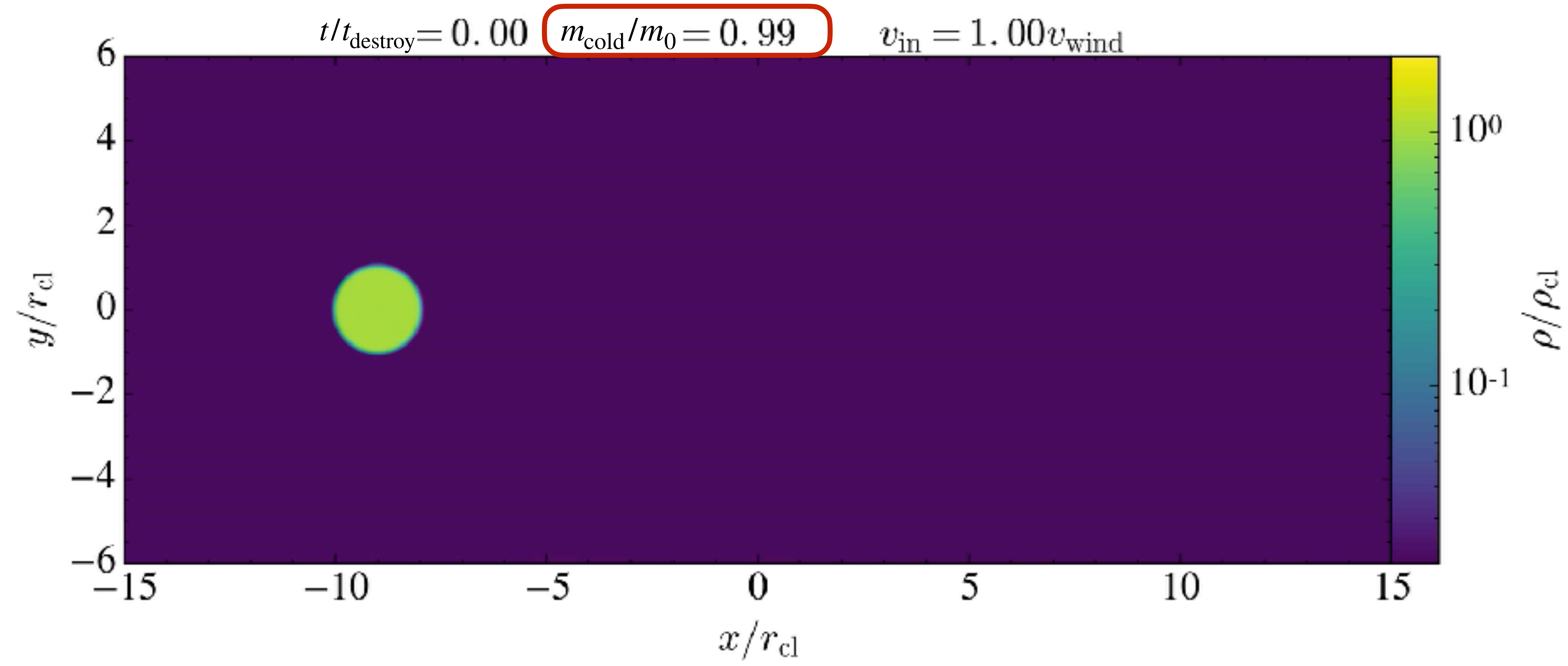
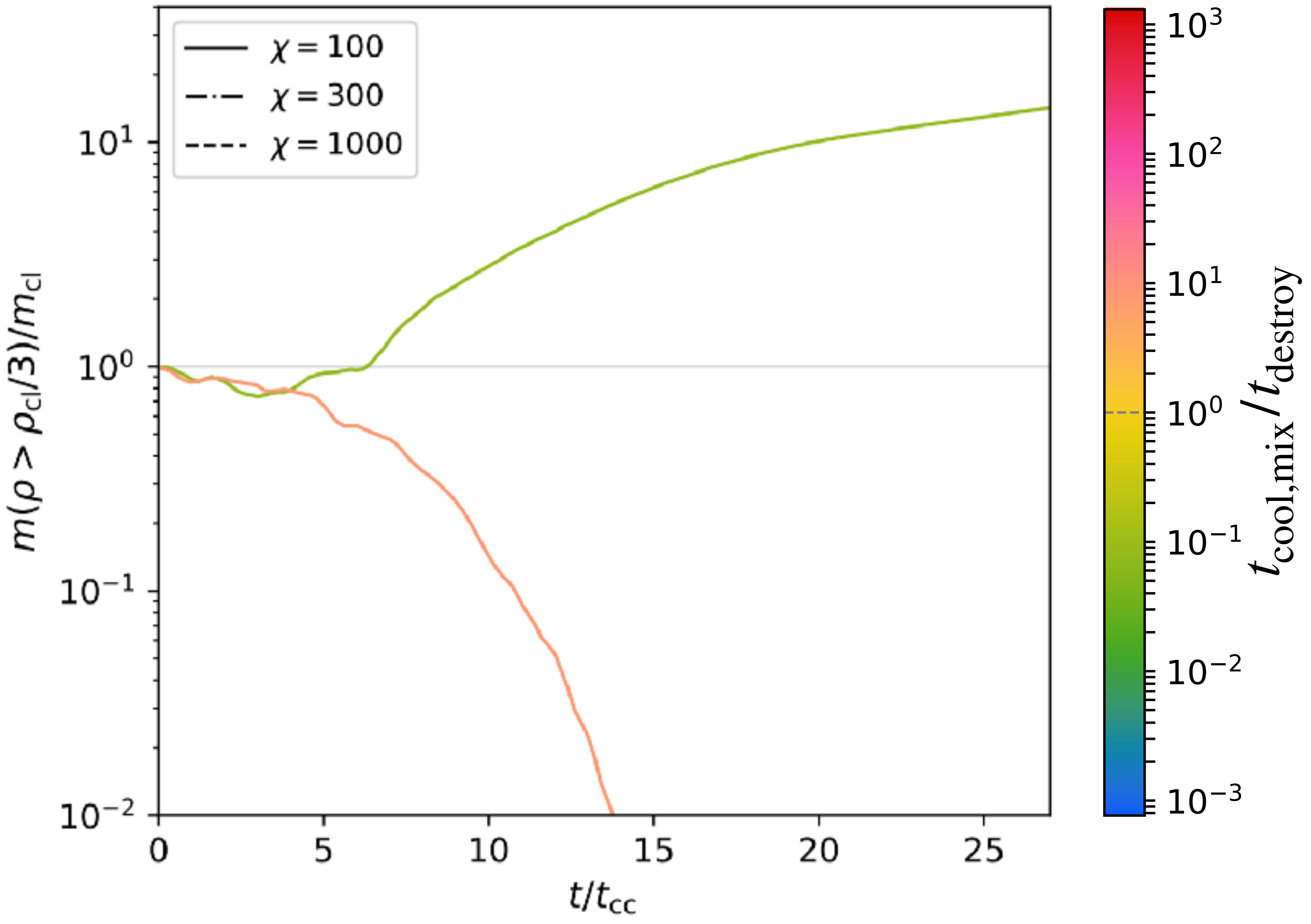
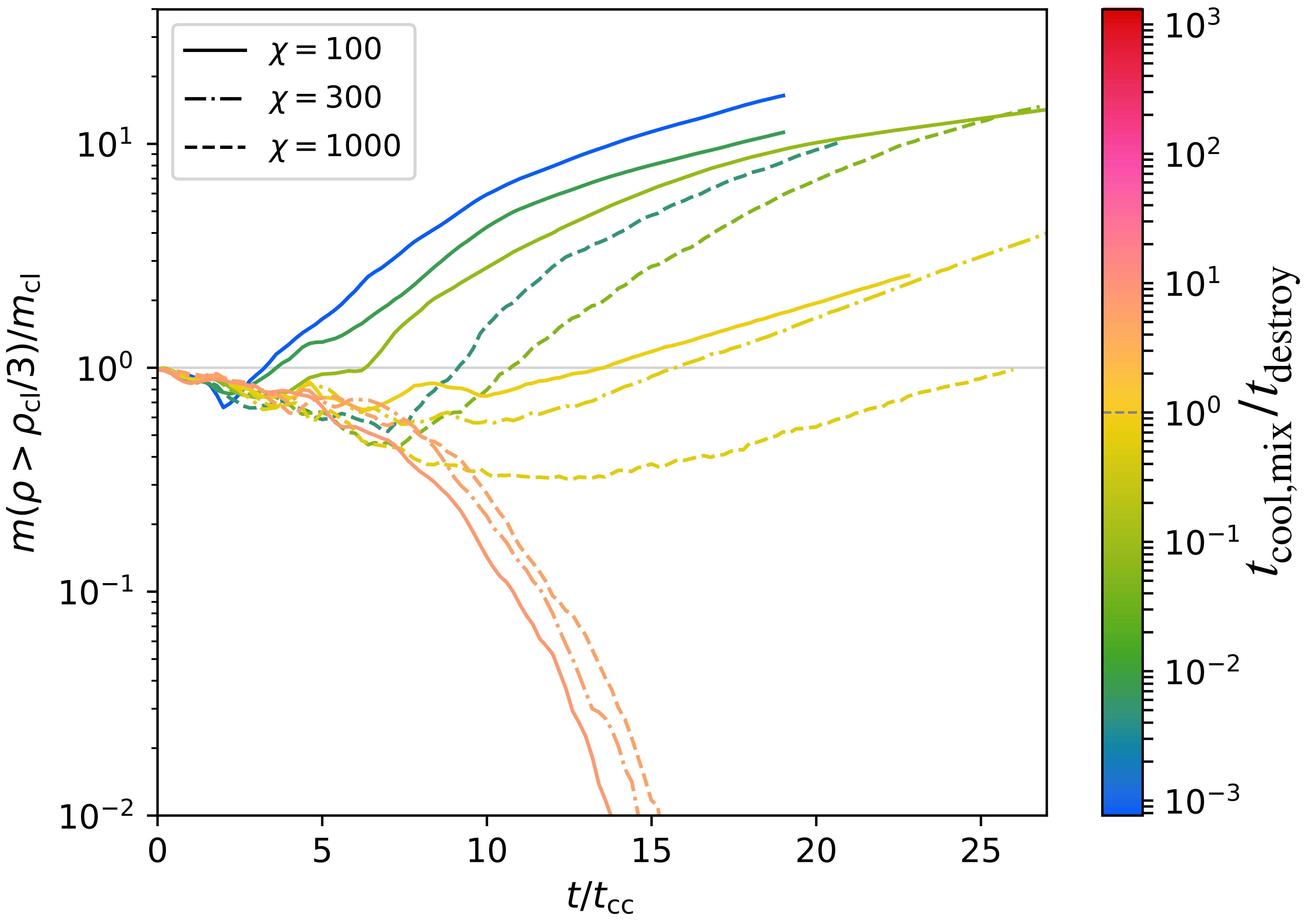


Mixing versus cooling



Mixing versus cooling

- Survival criterion $t_{\rm cool,mix} < t_{\rm destroy}$



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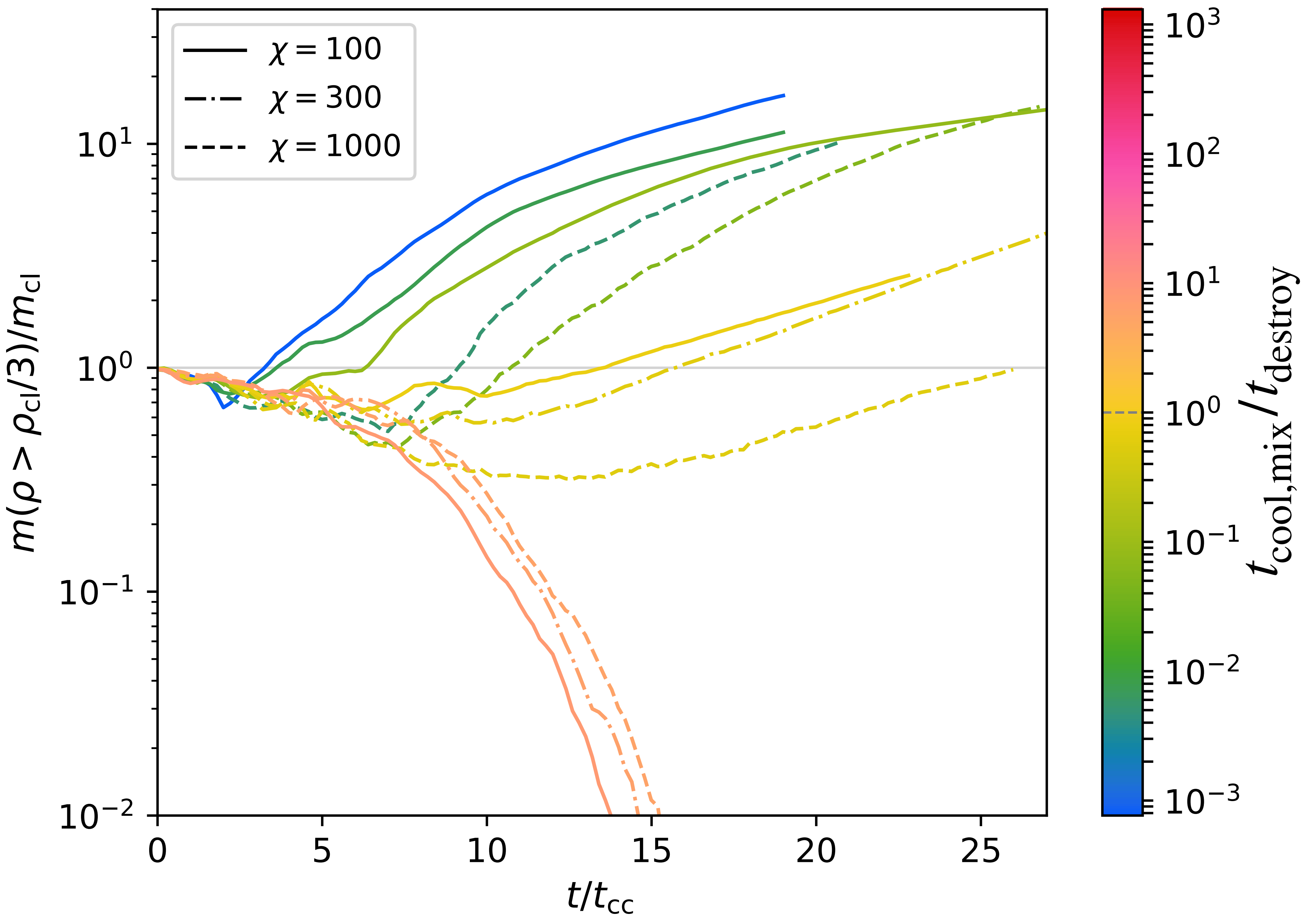

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$\updownarrow$

$$r_{\rm cold} > r_{\rm crit} \equiv \frac{v_{\rm hot} t_{\rm cool,mix}}{\chi^{1/2}}$$

$$\approx 2\,{\rm pc} \frac{T_{\rm cold,4} \mathscr{M}}{P_3 \Lambda_{\rm mix,-21.4}} \frac{\chi}{100}$$

$T_{\rm cold,4} \equiv T_{\rm cold}/(10^4\,{\rm K})$

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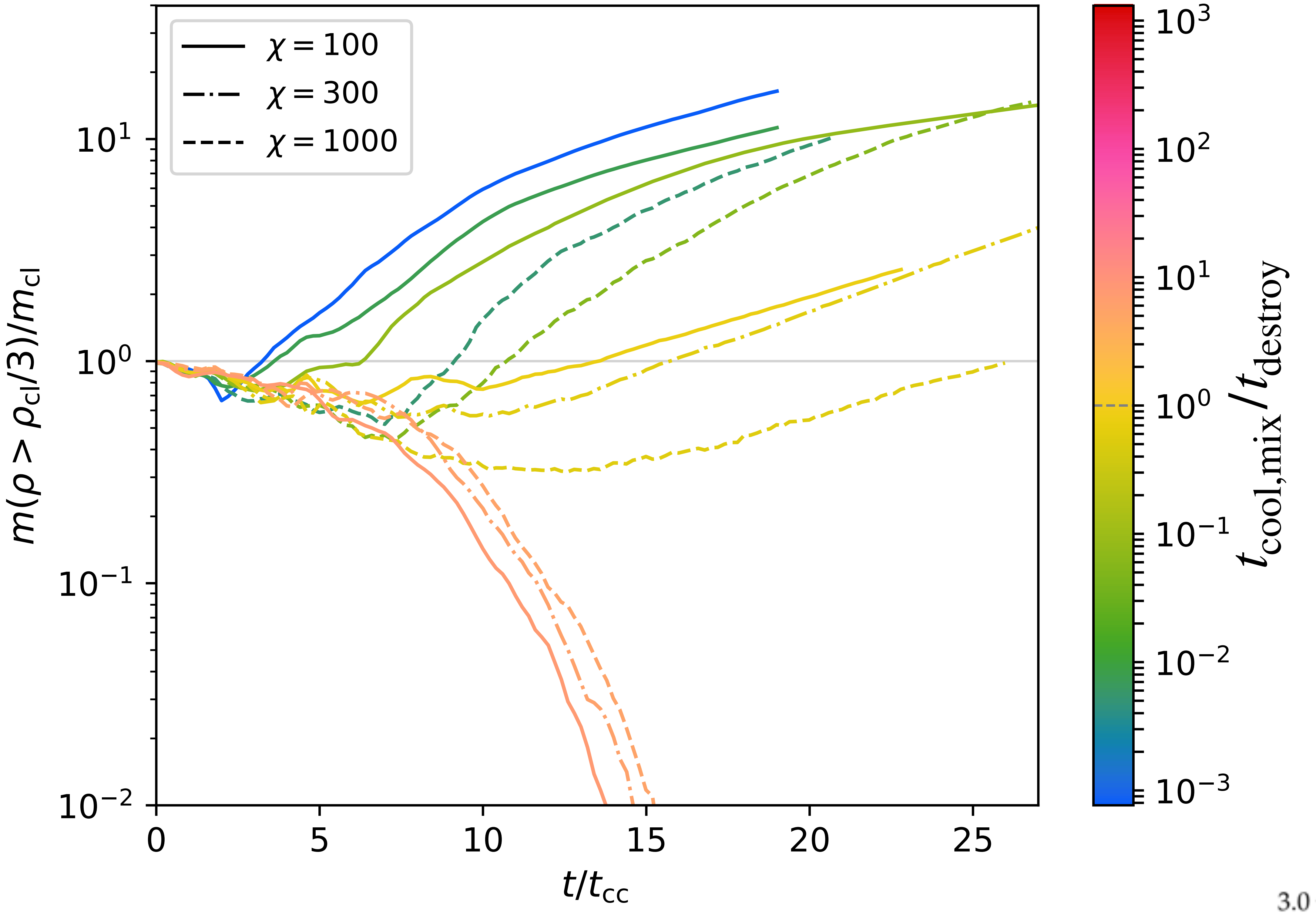

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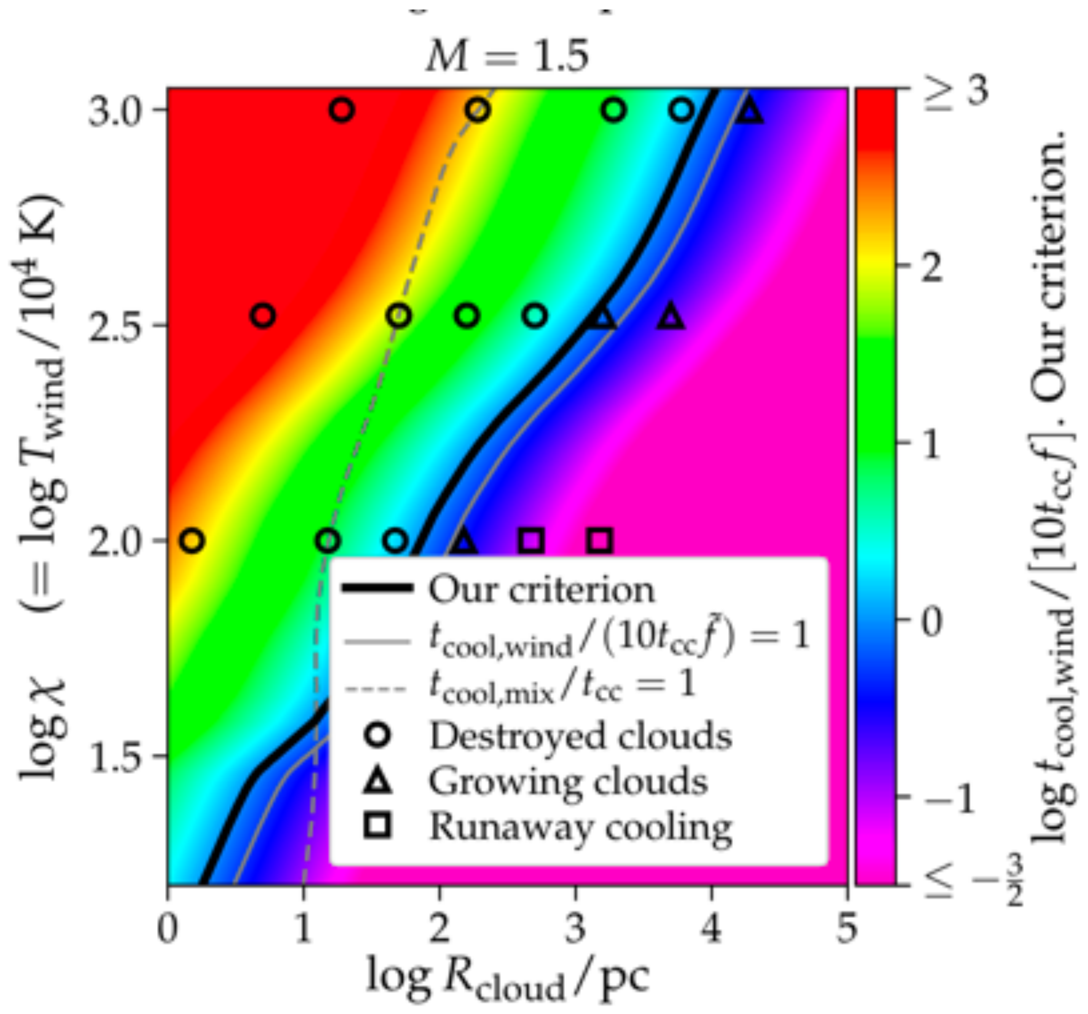
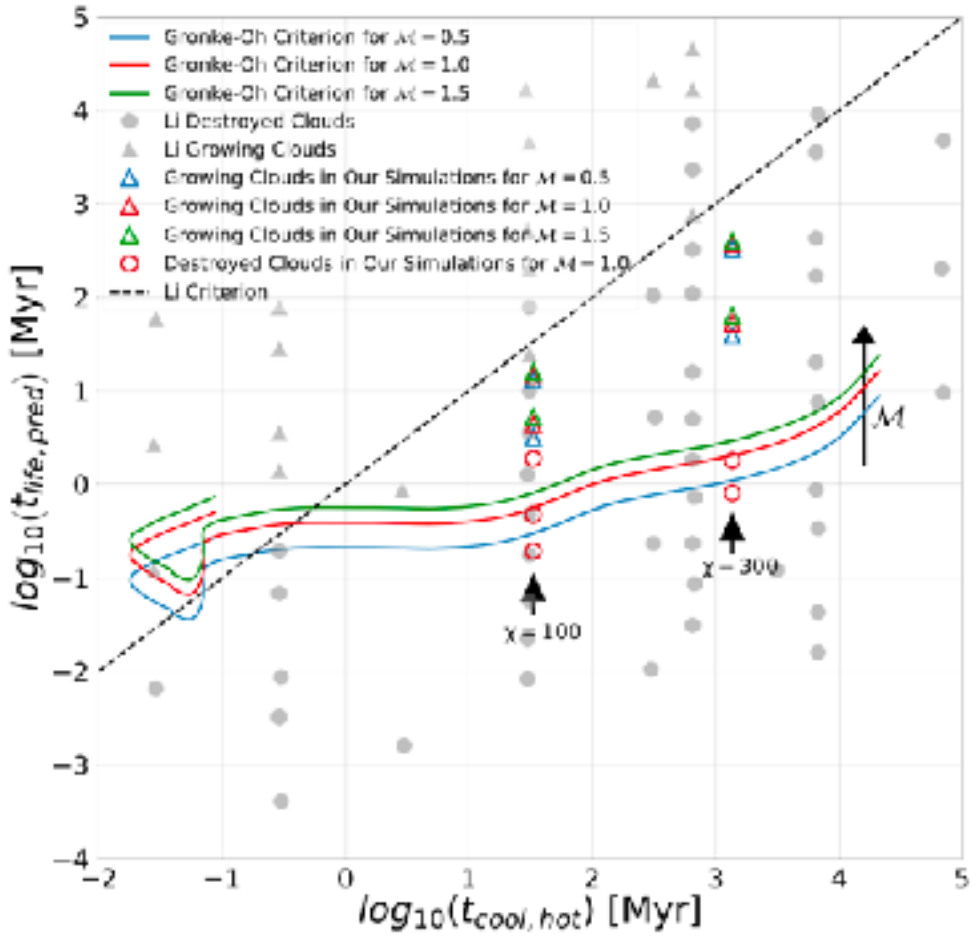
But see Li+20, Sparre+20, Kanjilal+20, Farber+21, Abruzzo+22, … for alternative survival criteria

Sparre+20





Kanjilal+20

…but what about…?

- Magnetic fields

  e.g., Dursi & Pfrommer (2008), McCourt et al. (2015), Hidalgo-Pineda et al. (2023)

- Colder gas (dust & PAHs)

  e.g., Girichidis et al. (2021), Farber & MG (2021), Chen & Oh (2024)

- “Shielding” by multiple clouds

  e.g., Aliza’s et al. (2012, 2014), Forbes & Lin (2019), Seidl et al. (2025)

- An expanding wind?

- A turbulent wind?

- A complex cloud morphology?

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Alankar Dutta


Ritali Ghosh


Fernando Hidalgo-Pineda

Towards a realistic ISM

Cold clouds are not spherical!

How does r_{crit} relate to a (scale free) ISM morphology?

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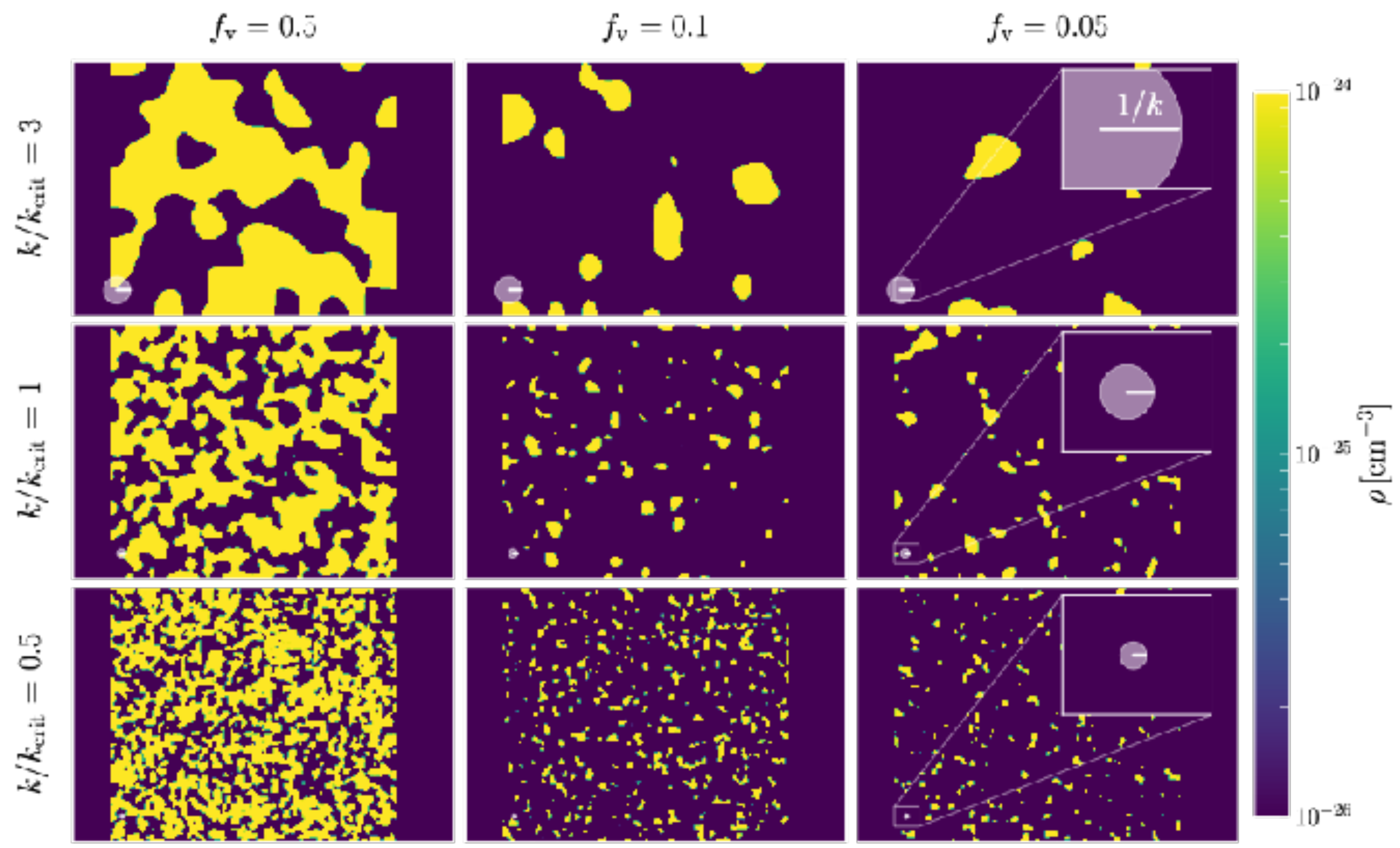

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→*AthenaPK*

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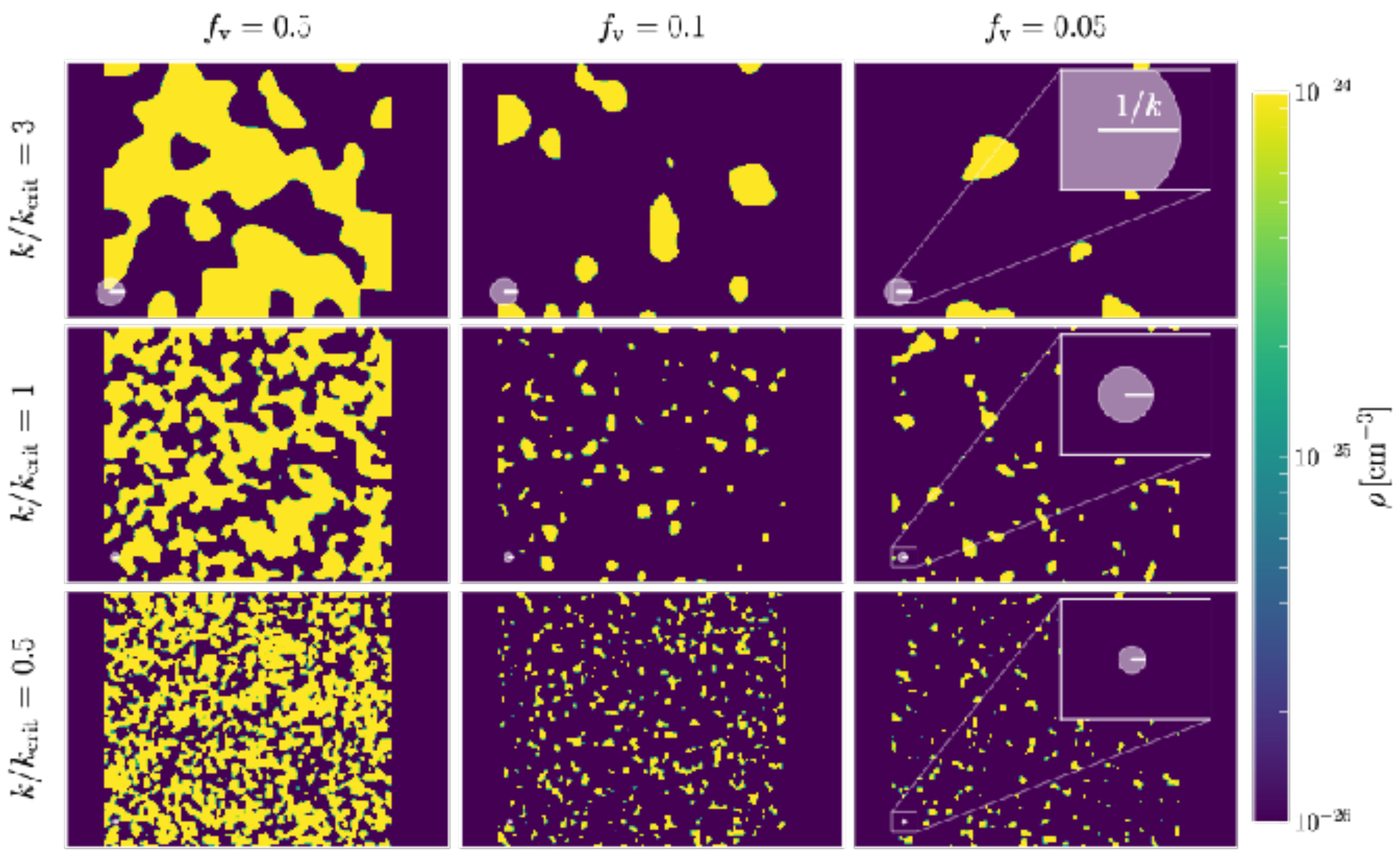

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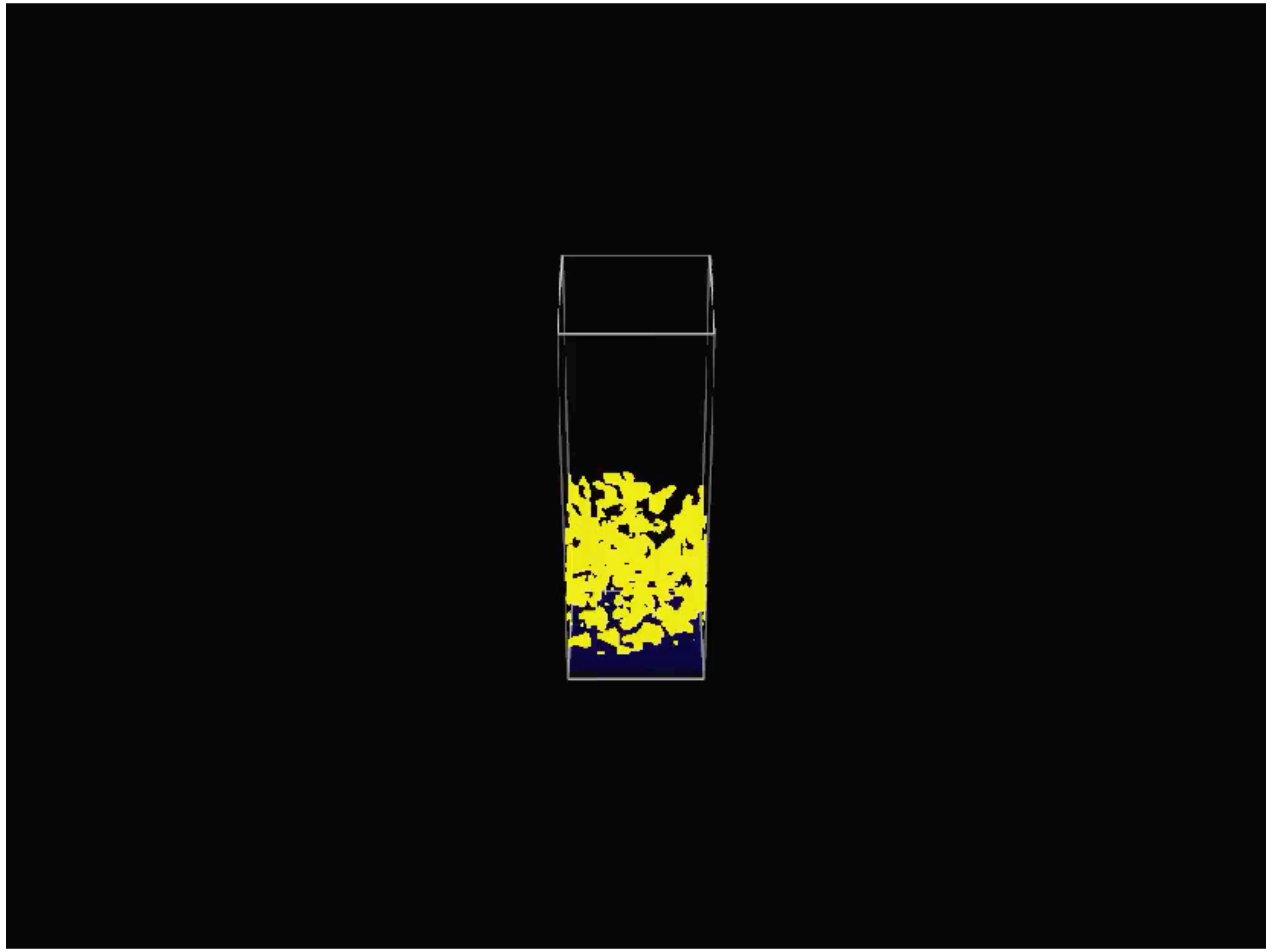

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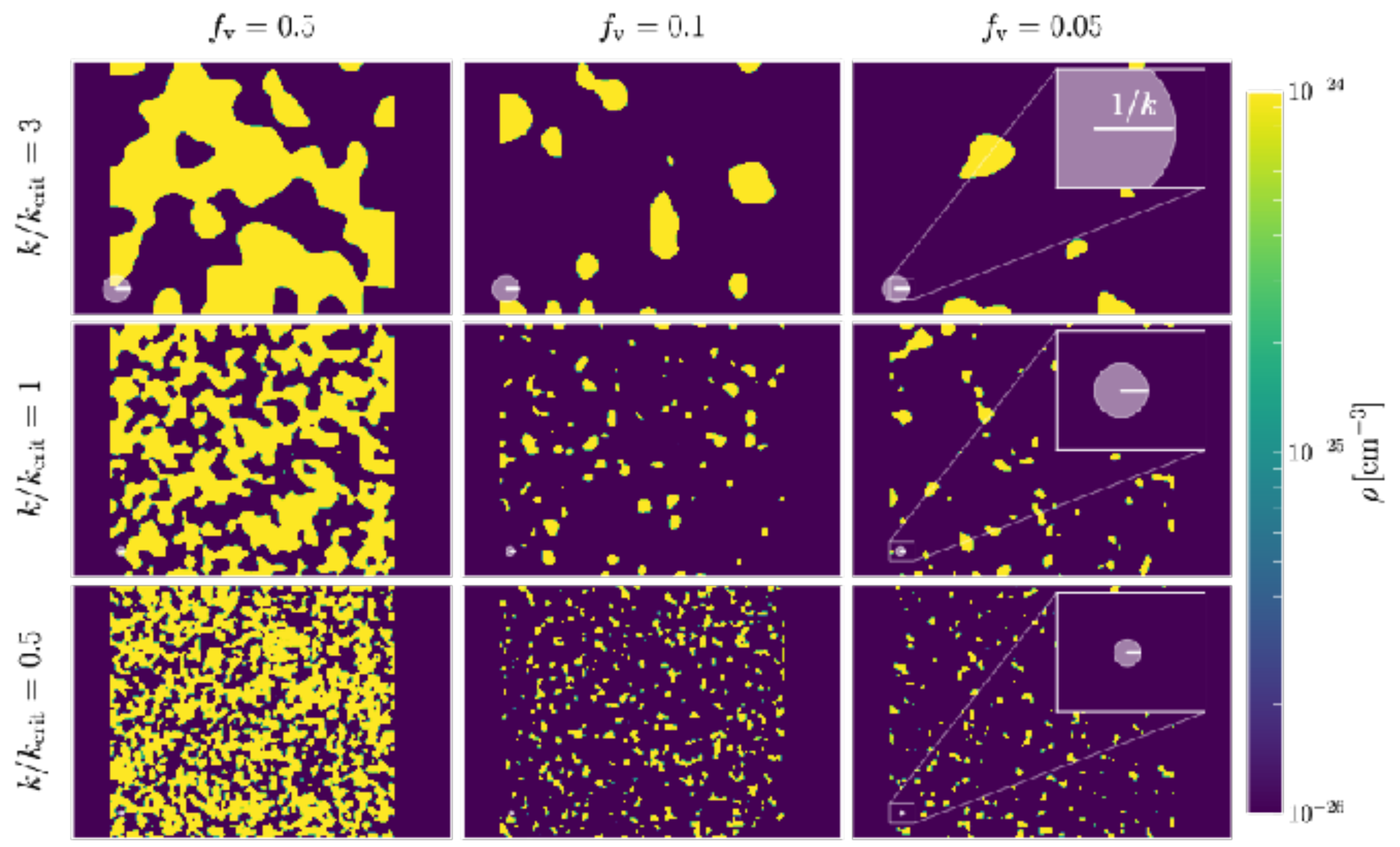
How does $r_{\rm crit}$ relate to a (scale free) ISM morphology?

How is the ISM morphology imprinted in the winds?

In what way are the phases kinematically coupled?



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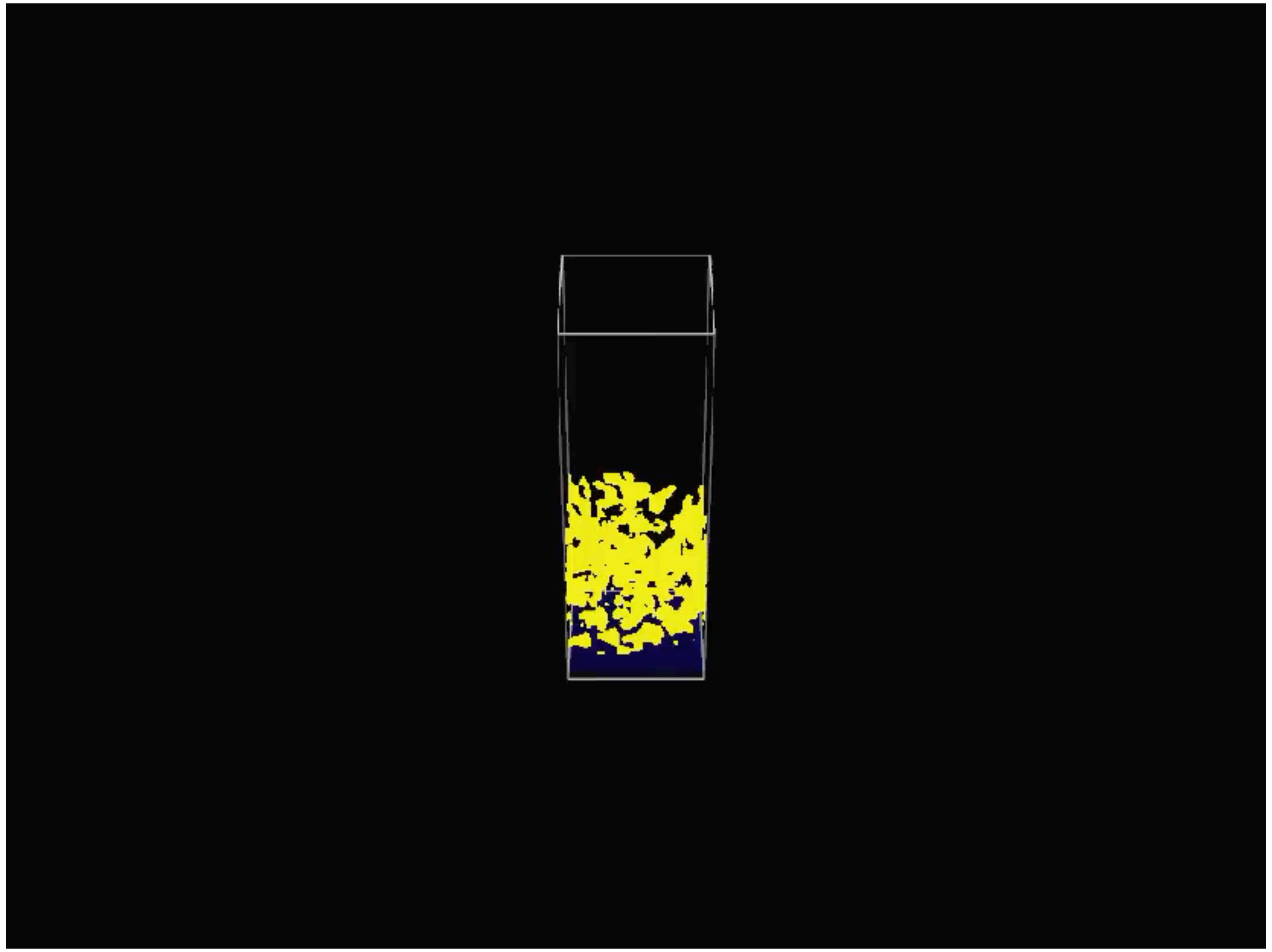


Visit his poster!

A cold cloud in an expanding (CC85 like) wind

Alankar Dutta

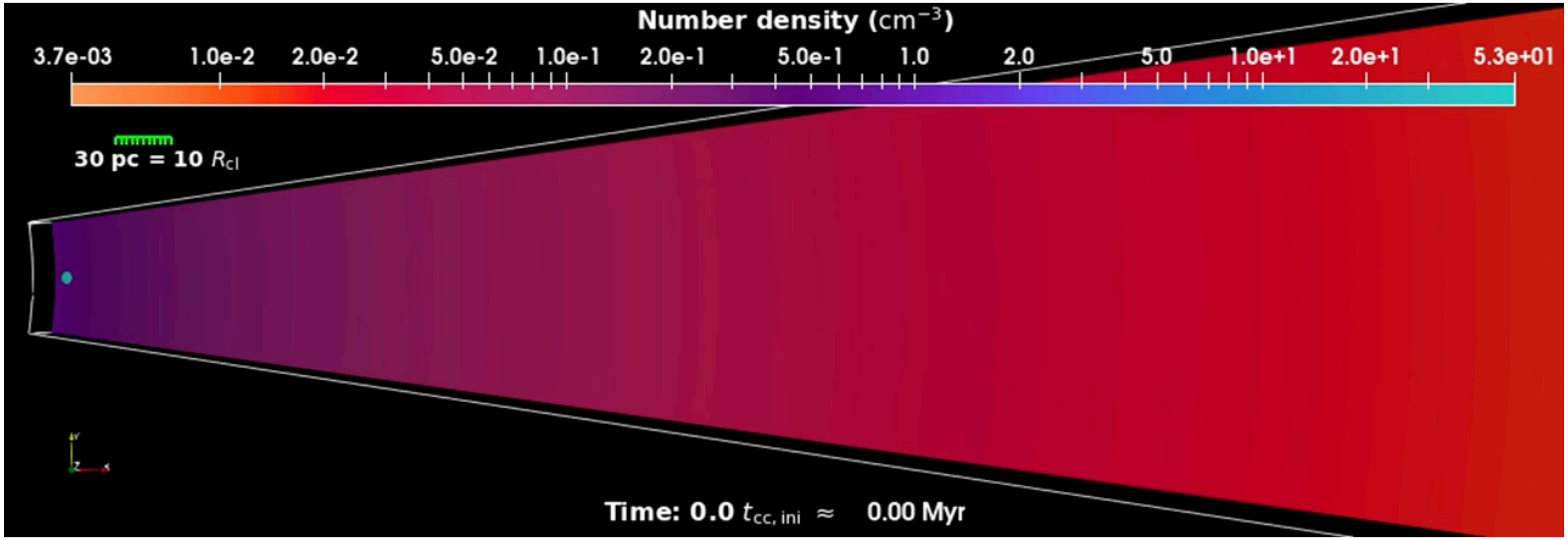
Galactic winds are not uniform!

Can a cold cloud survive in a CC85 wind?

Mass transfer between the phases $\dot{m}_{\mathrm{hot}\to\mathrm{cold}} \sim A_{\mathrm{cl}}\rho_{\mathrm{hot}}v_{\mathrm{mix}}$

A_{cl}: cloud's surface area

v_{mix}: mixing & cooling physics



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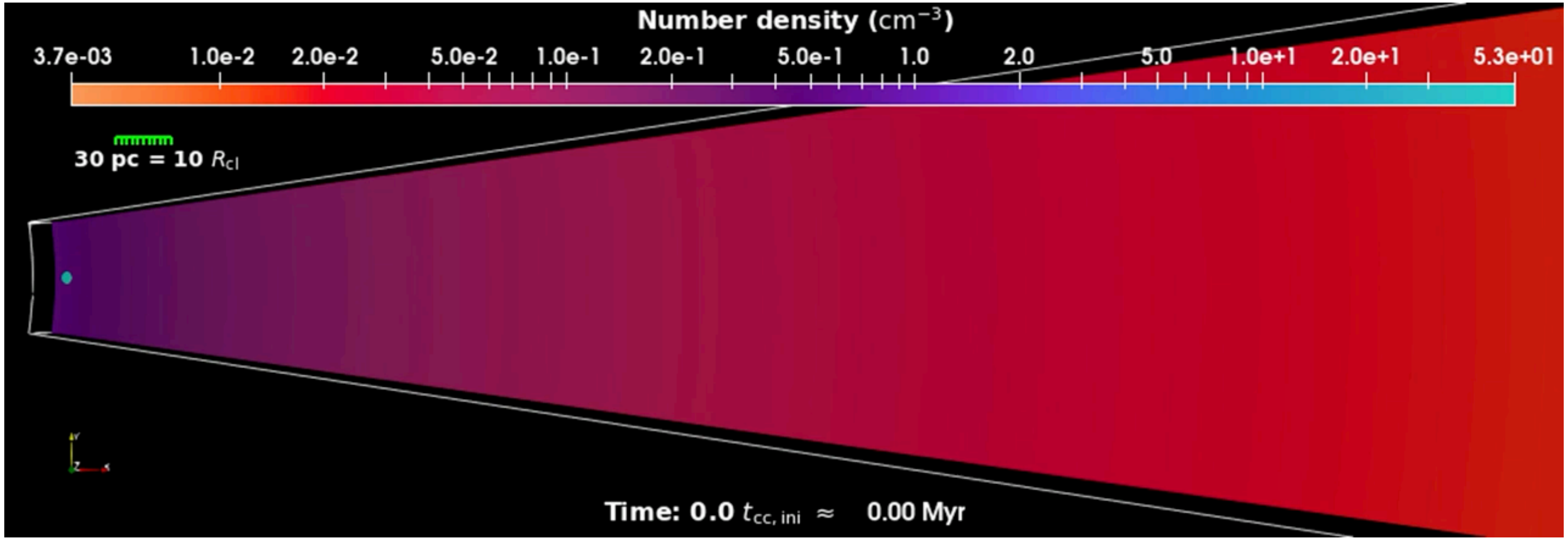

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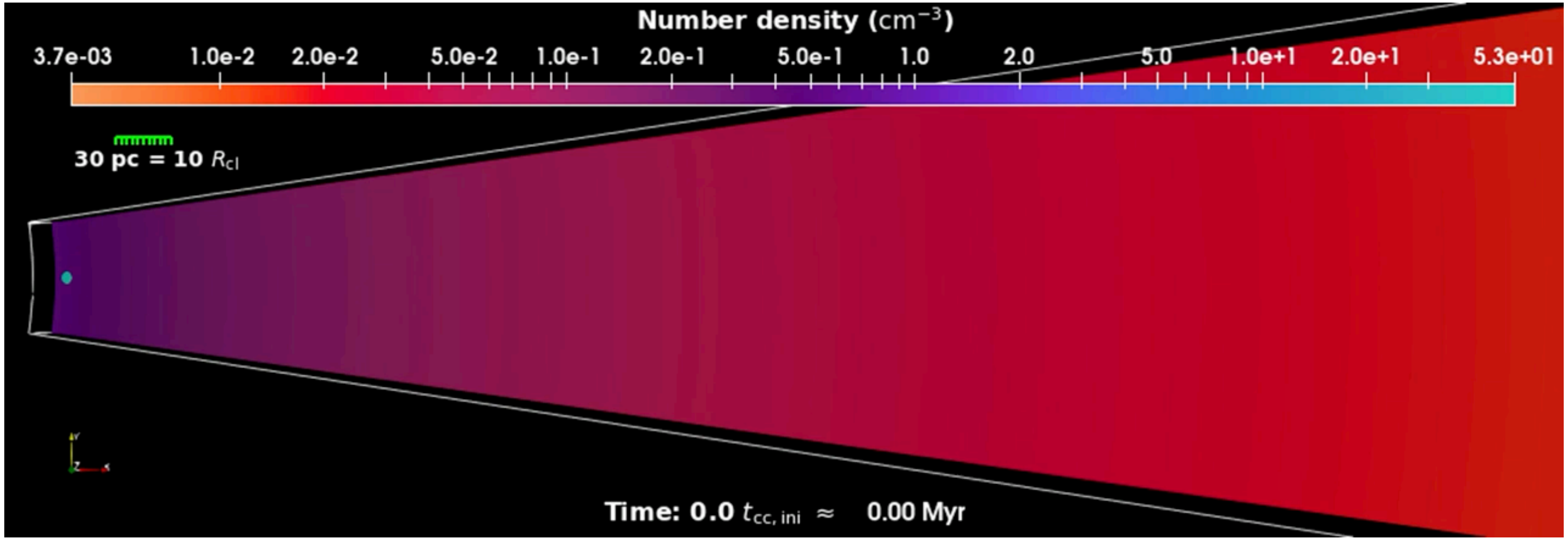

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Dutta, Sharma, MG (2025)

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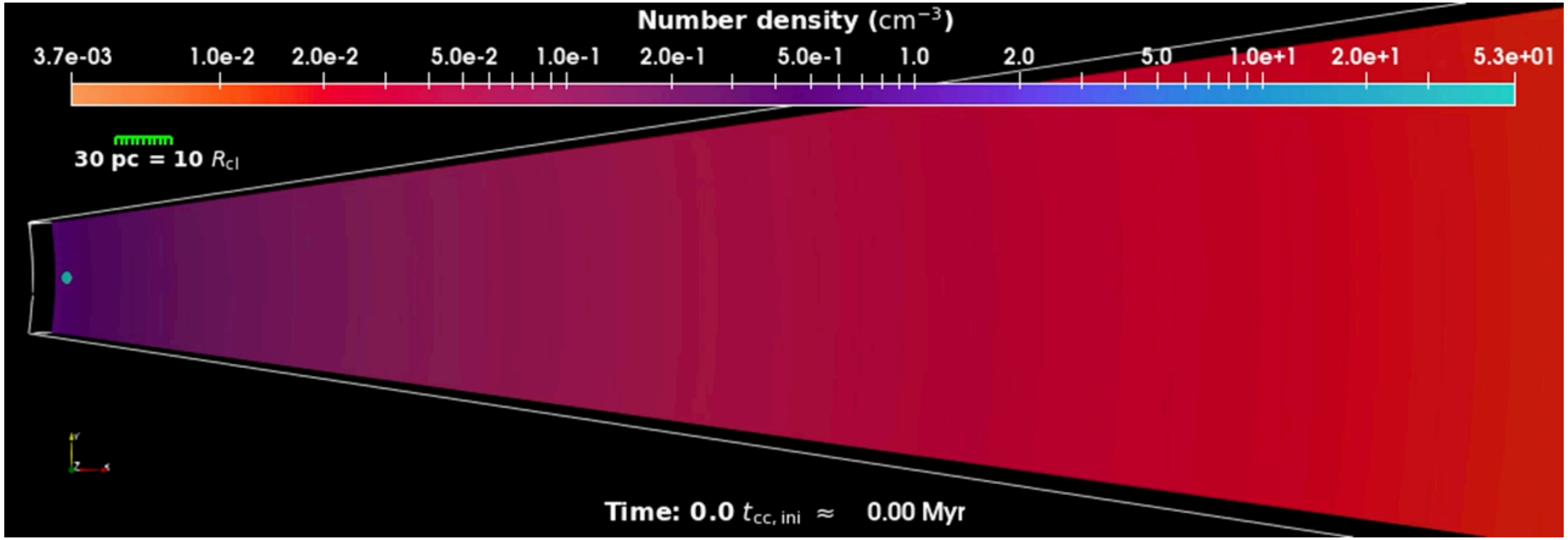
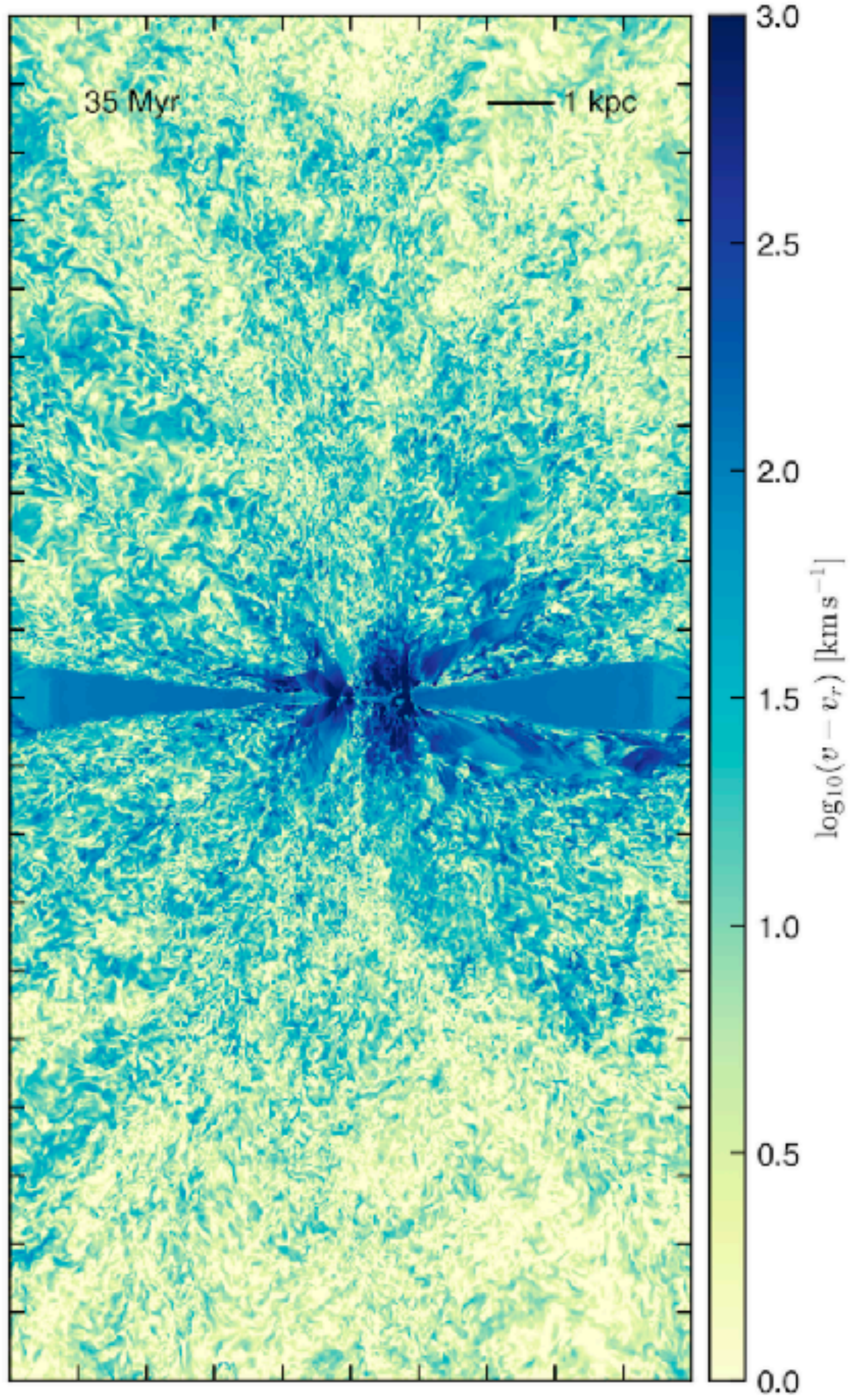


A cold cloud in a turbulent wind!

Galactic winds are not laminar!

Ritali Ghosh

Schneider et al. (2020)



Does a turbulent wind hinder "tail formation" and, thus, cold gas survival?

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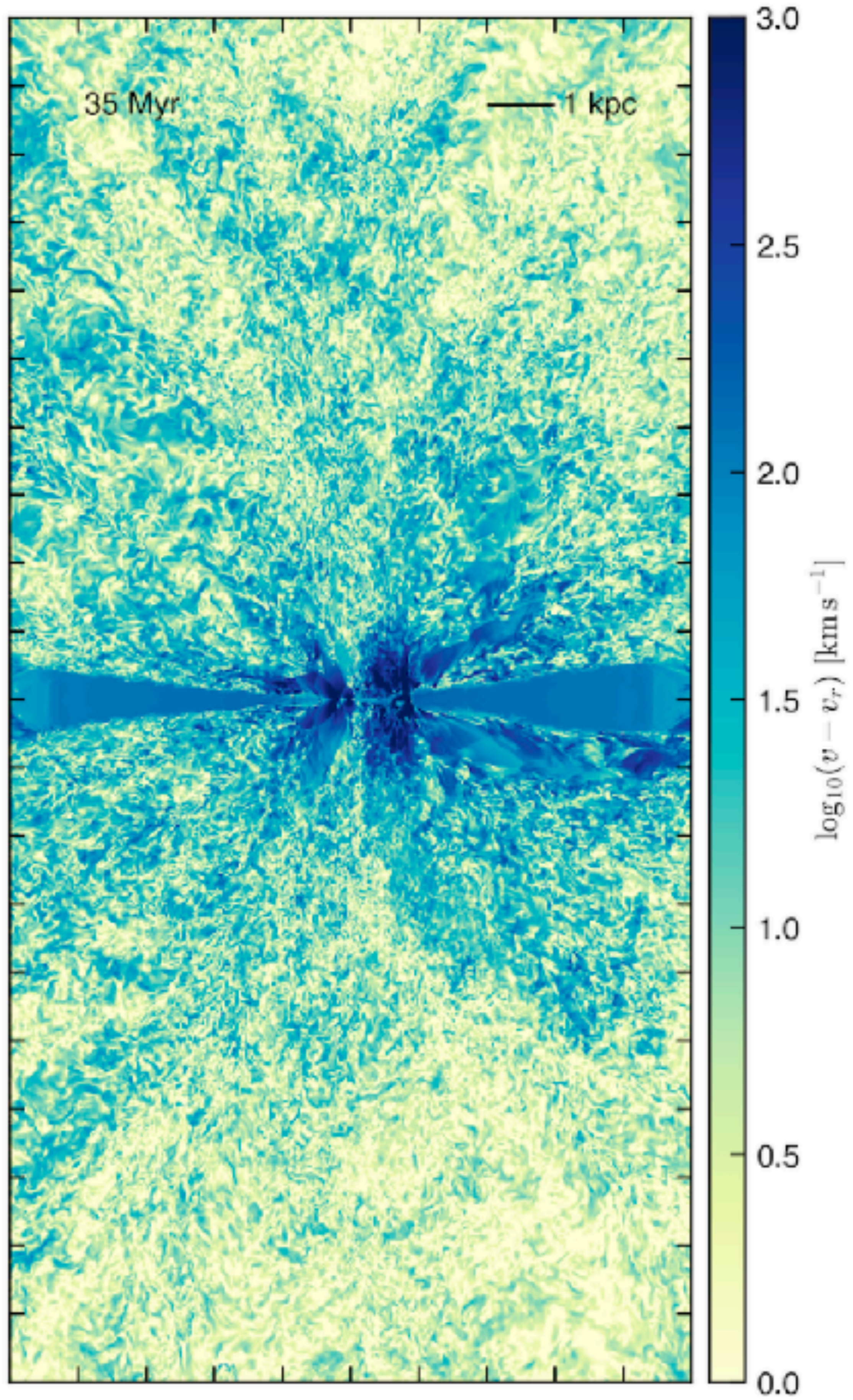

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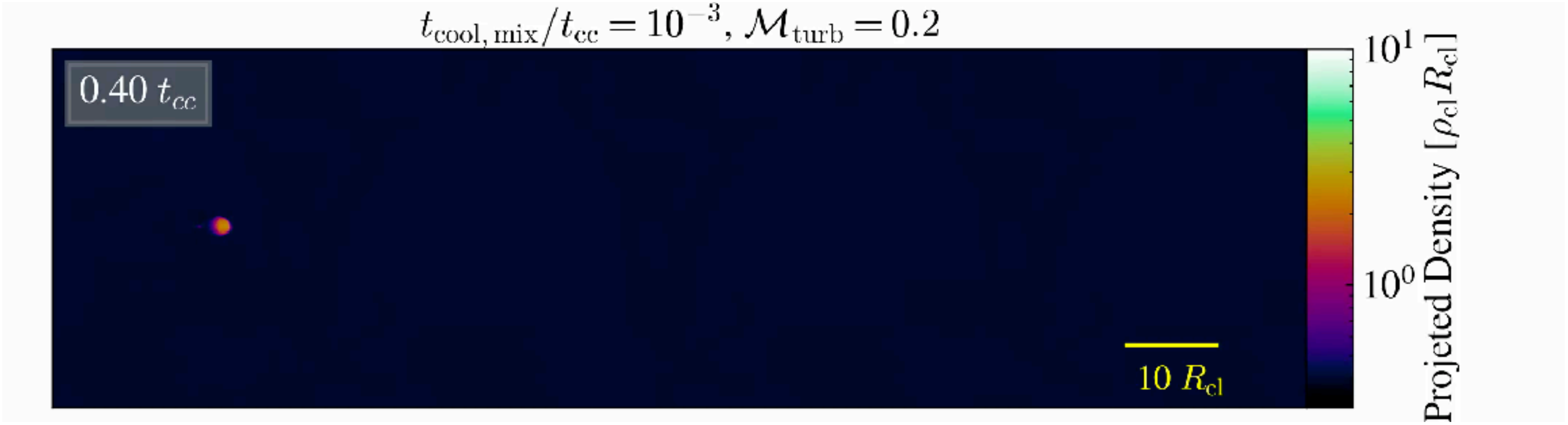

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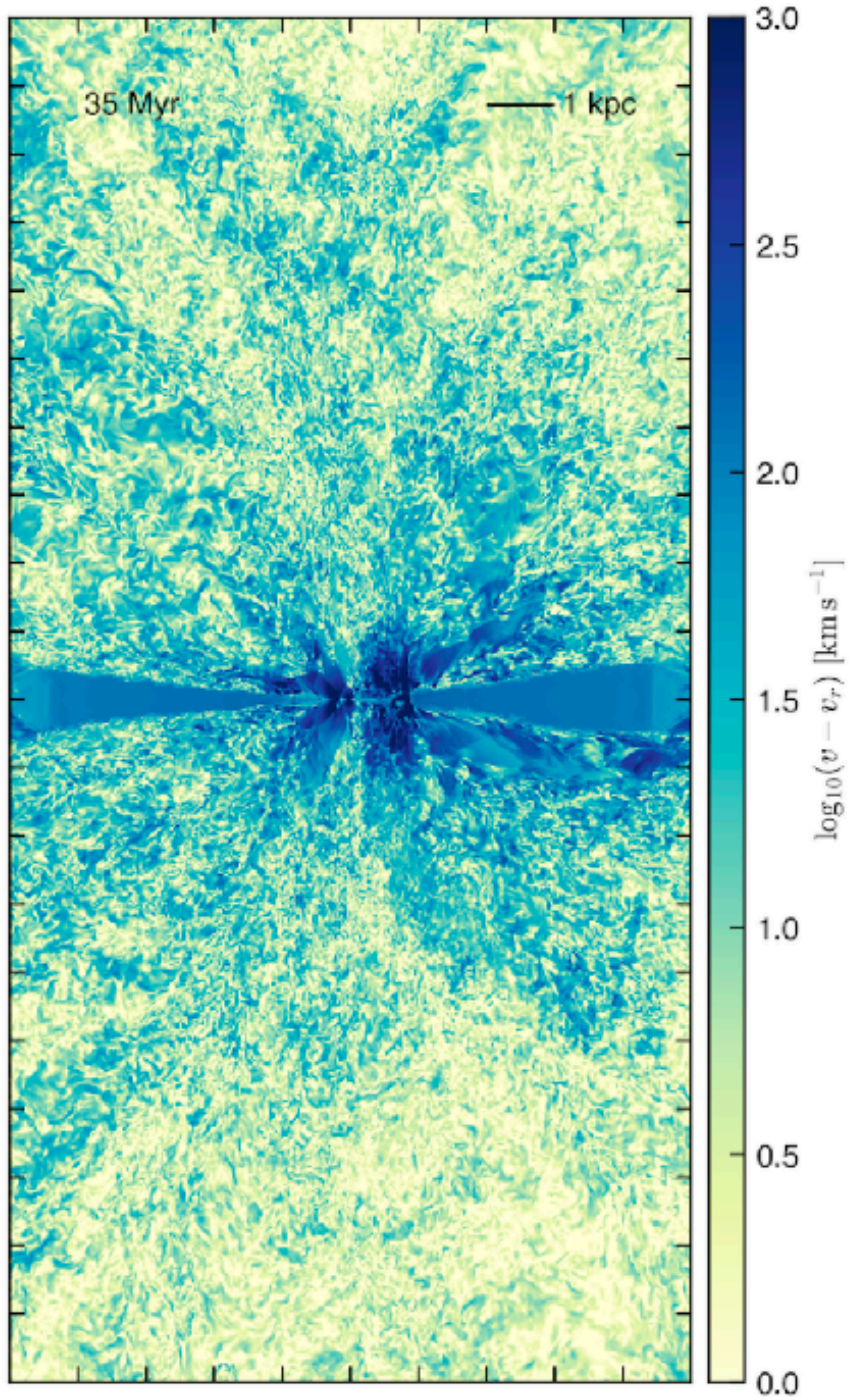

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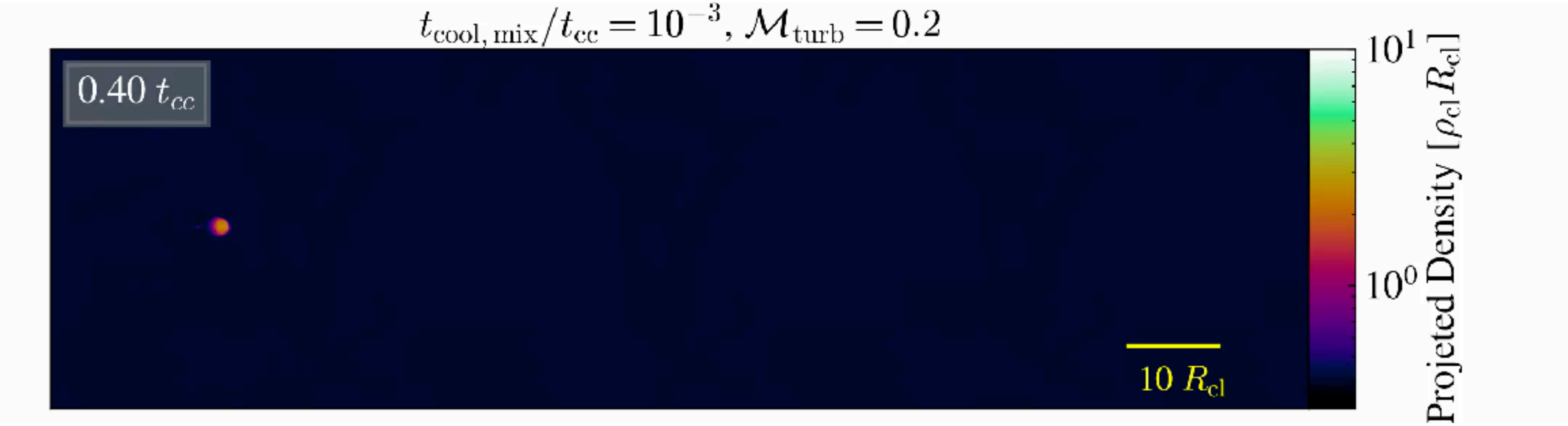
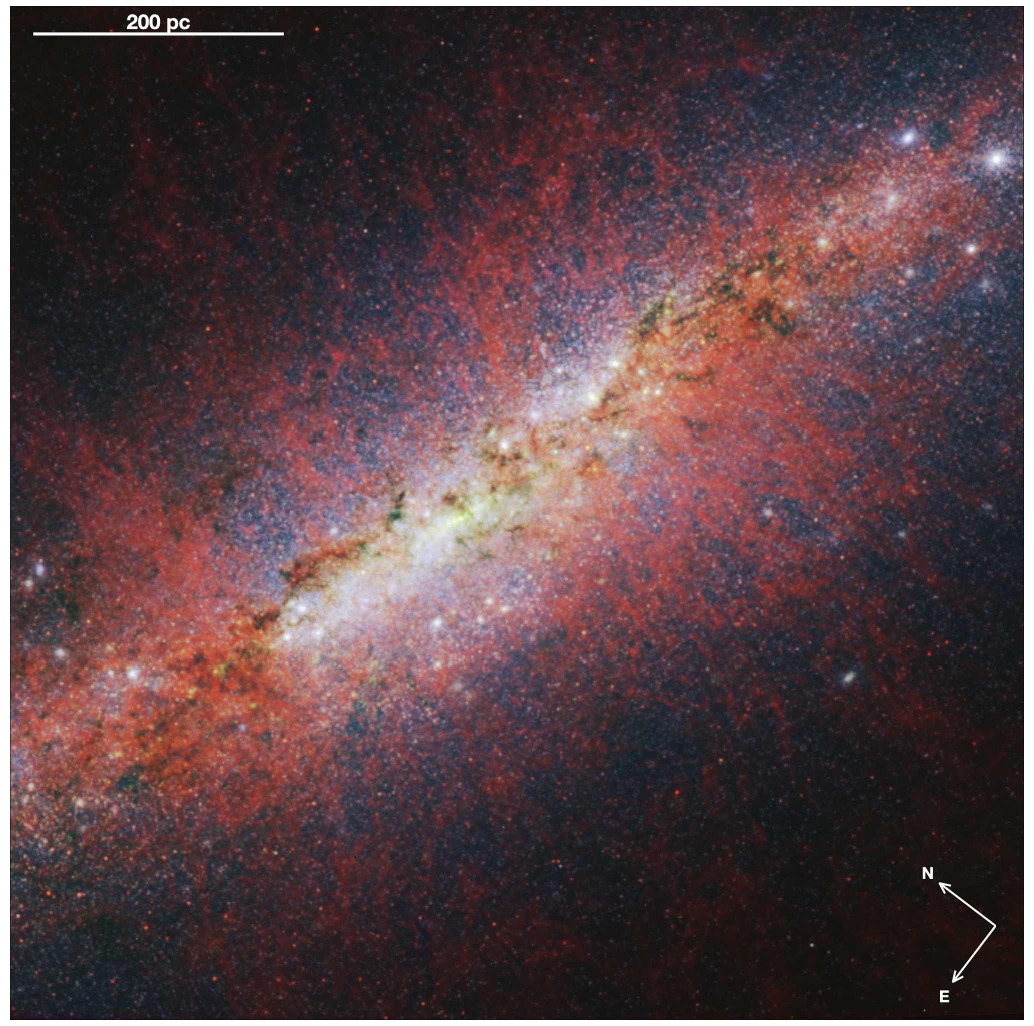




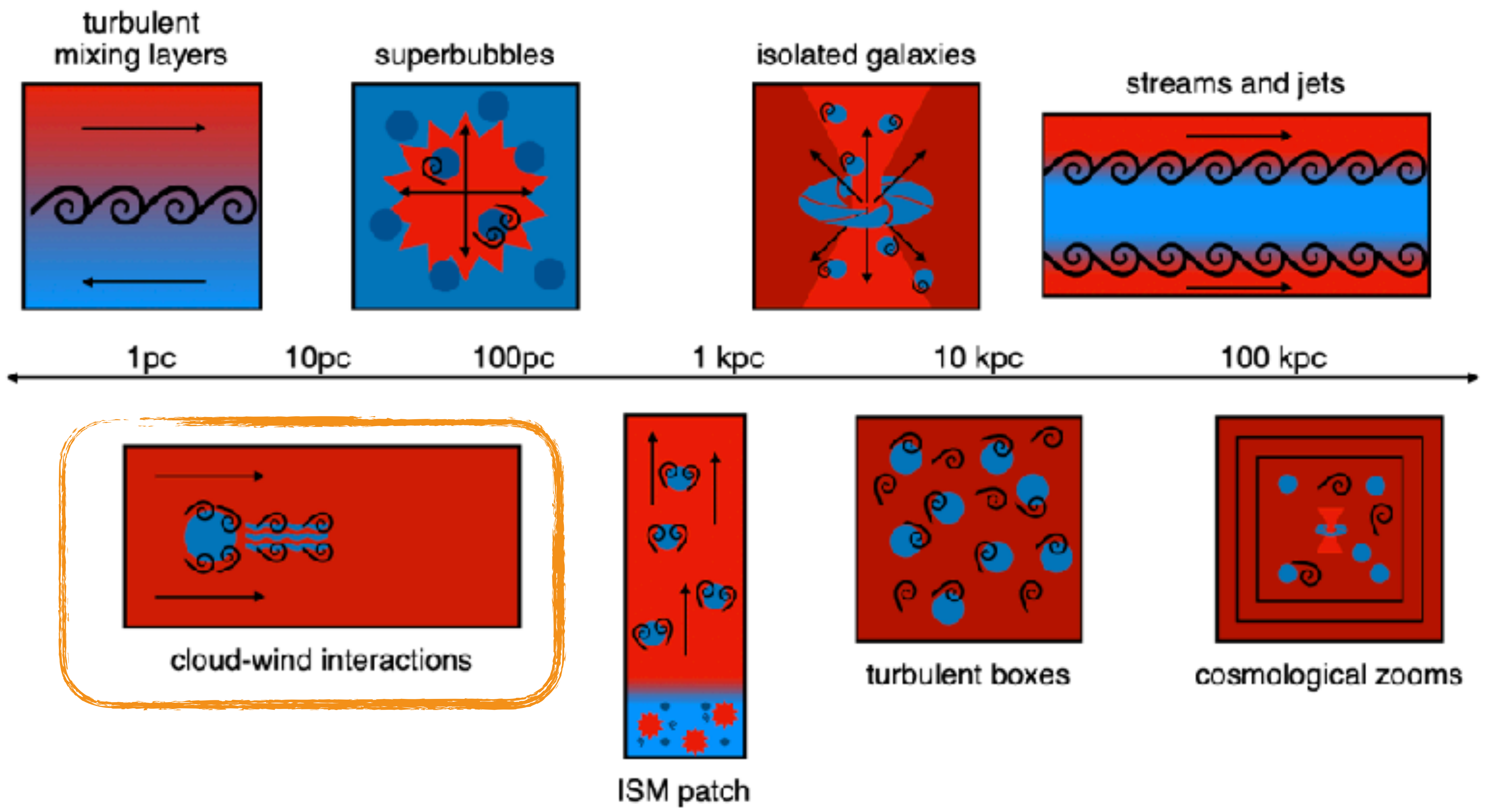
Fischer et al. (2024)

What is the morphology of the cold gas ("long tails")?

Observational signatures of turbulence in winds?

Visit her poster!

Why should I care? *Galactic winds are much more complex!*



Schneider & MG (submitted)

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Simplified numerical experiments and analytical models yield…

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- (scalings for) interpretation of data
- length scale / convergence criteria
- reasons what physical mechanisms matter
- “subgrid recipes”
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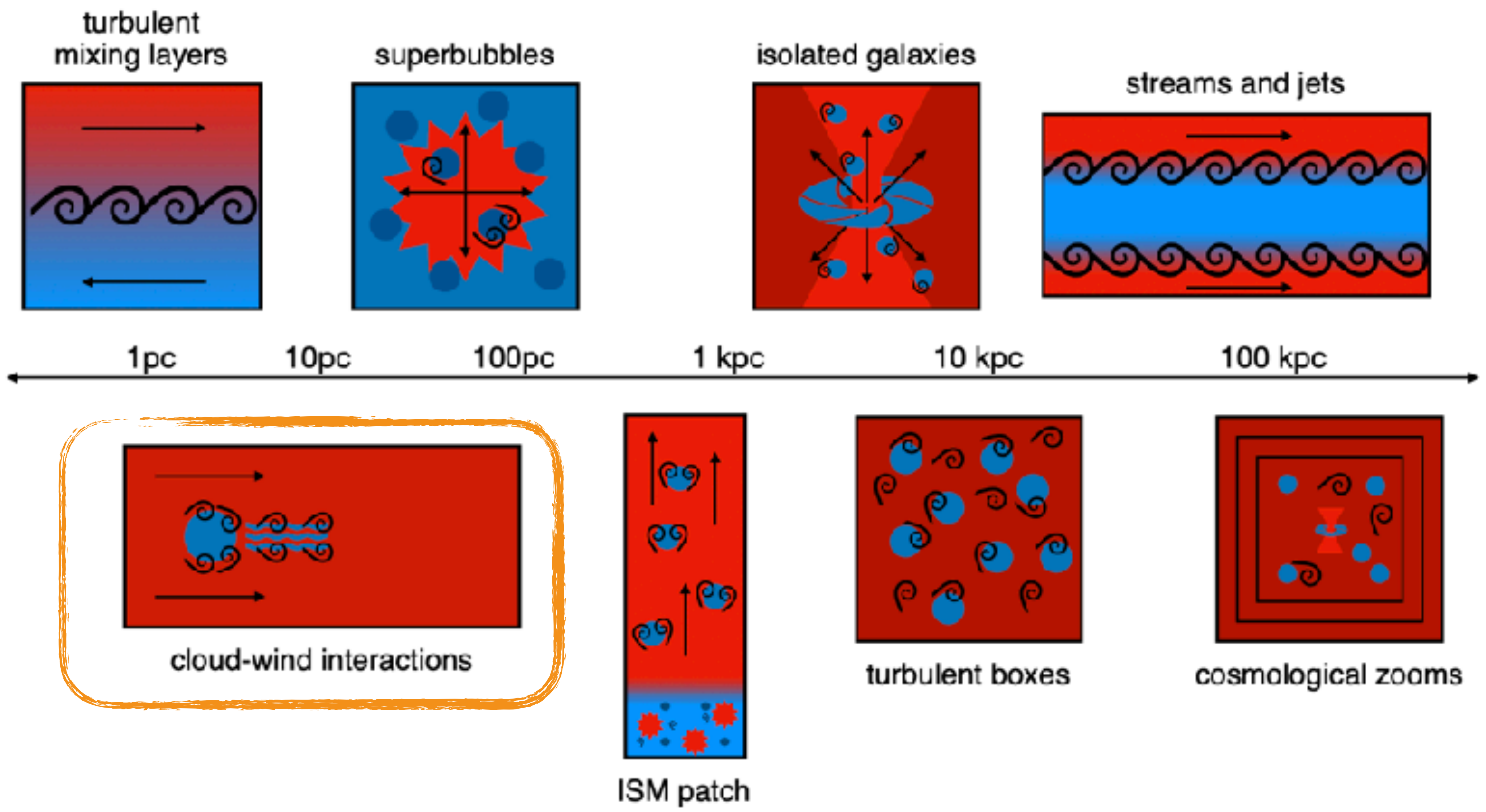

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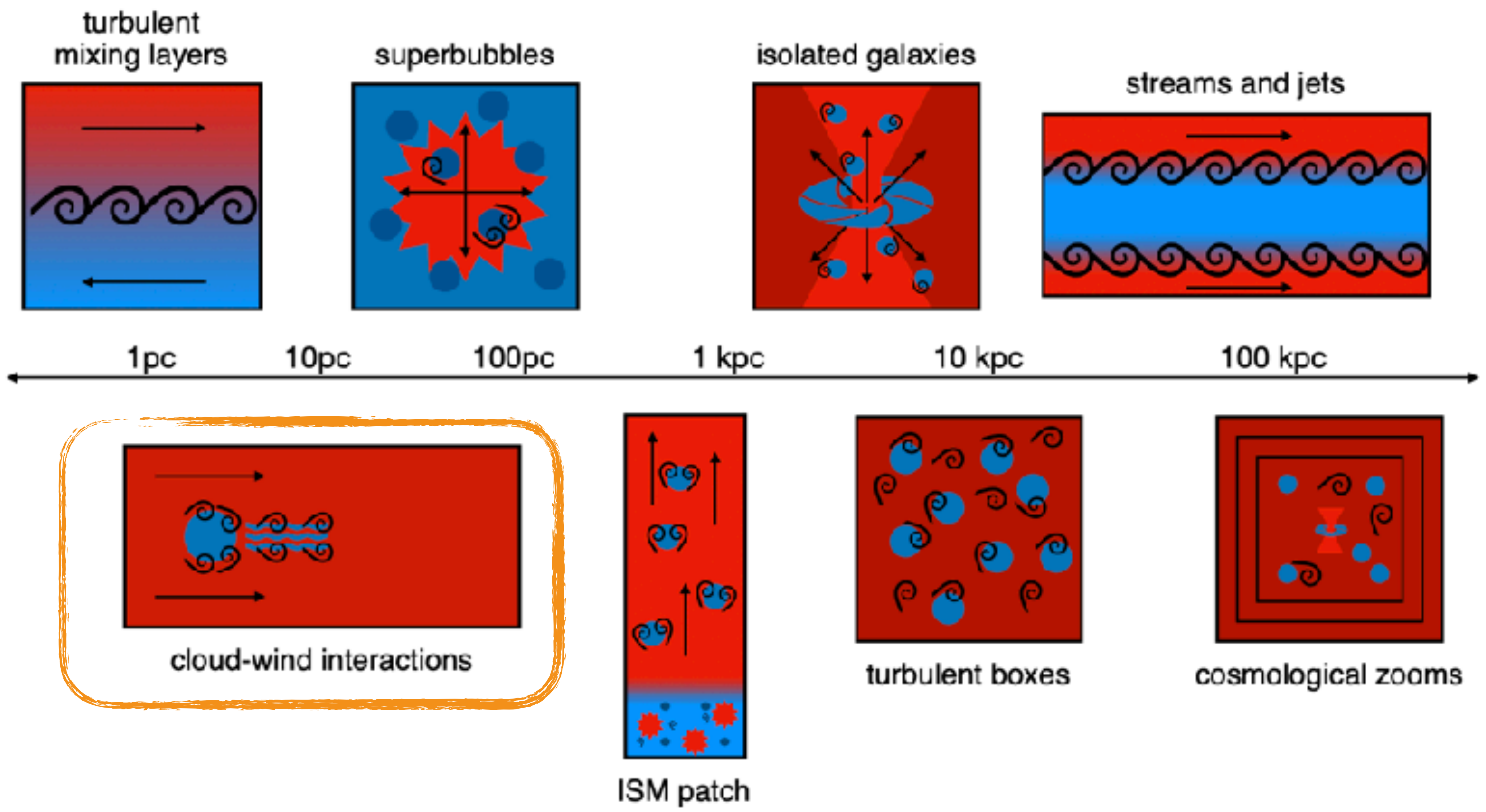

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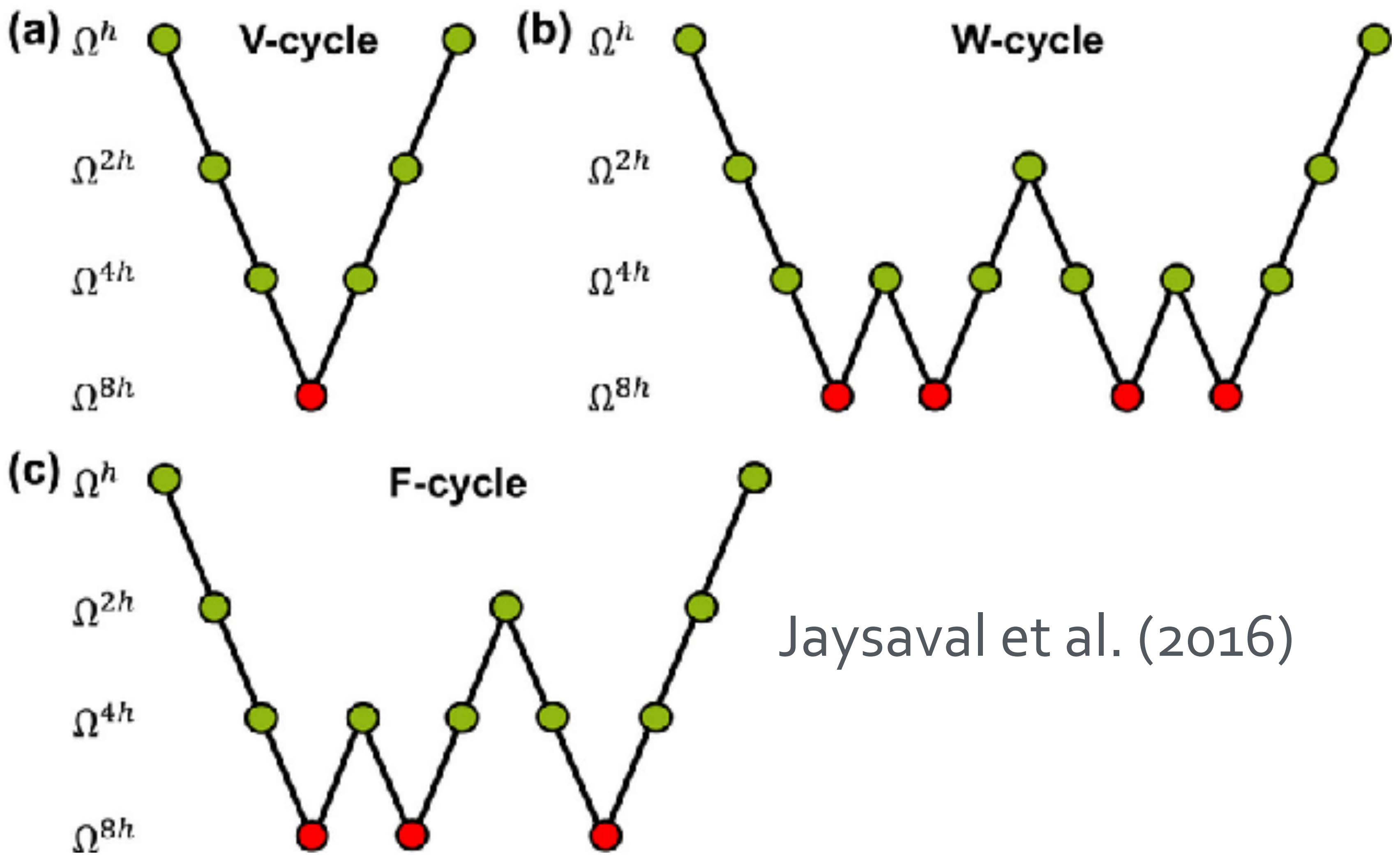

Jaysaval et al. (2016)

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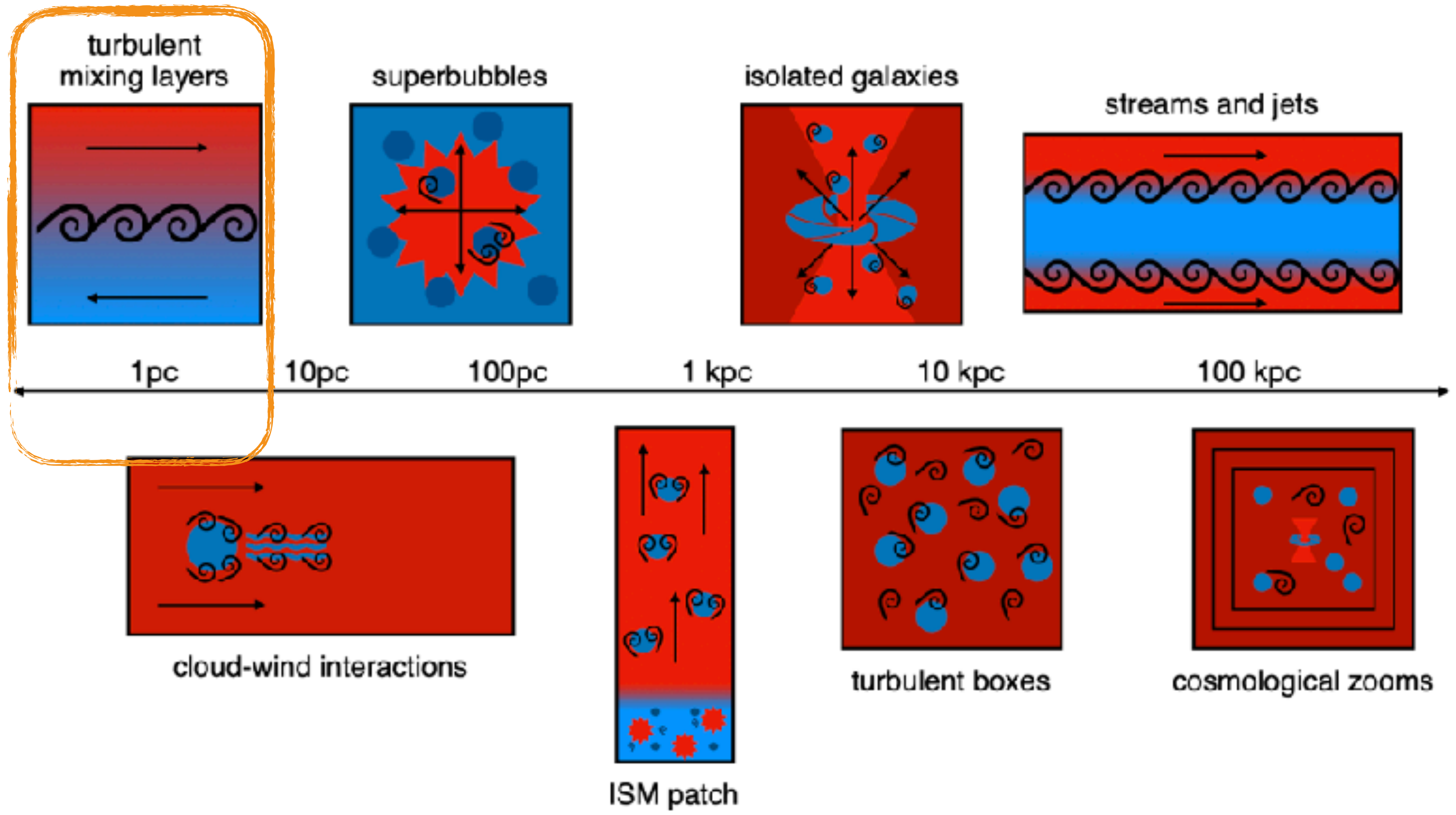

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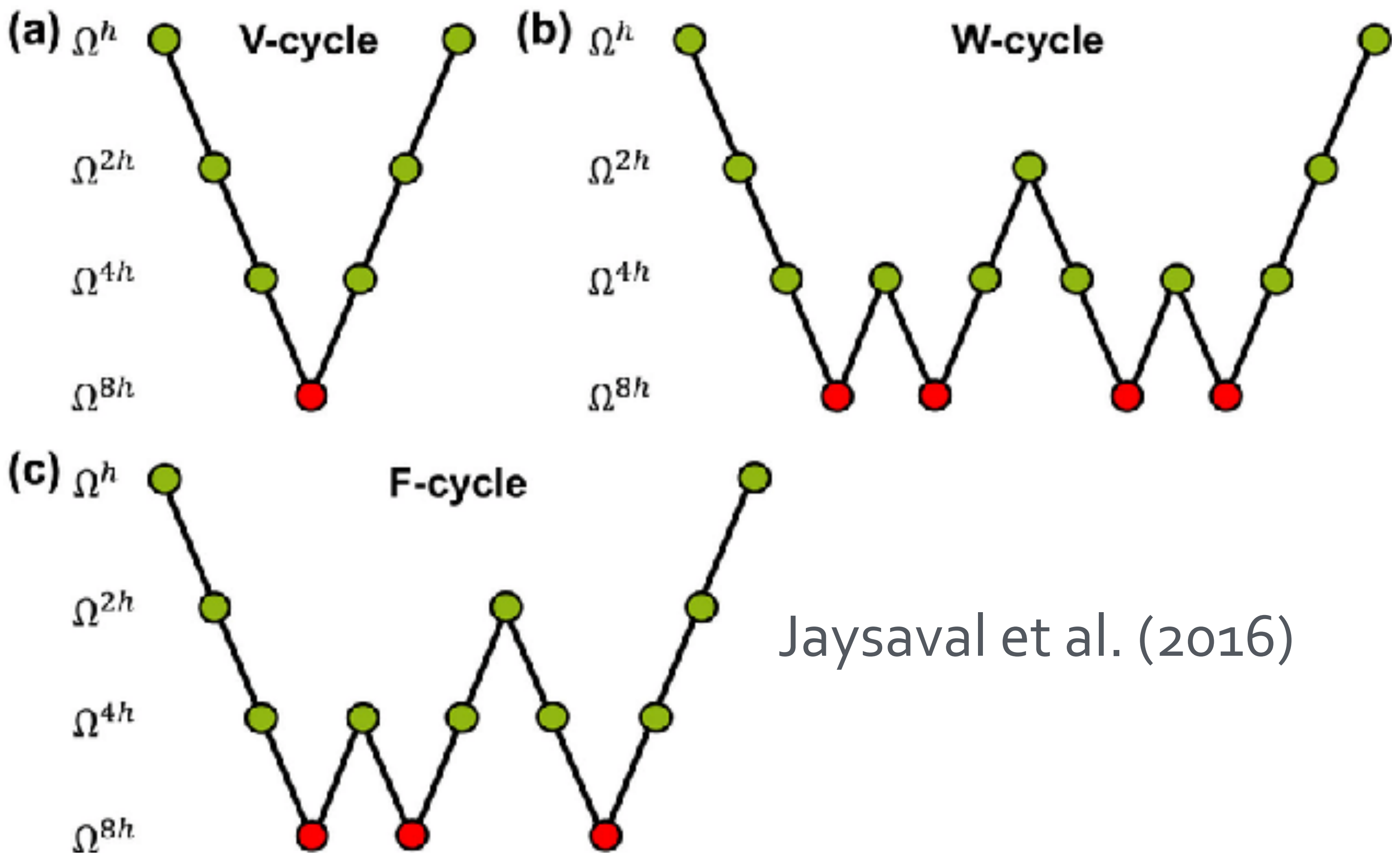

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Tan, Oh, MG (2020)

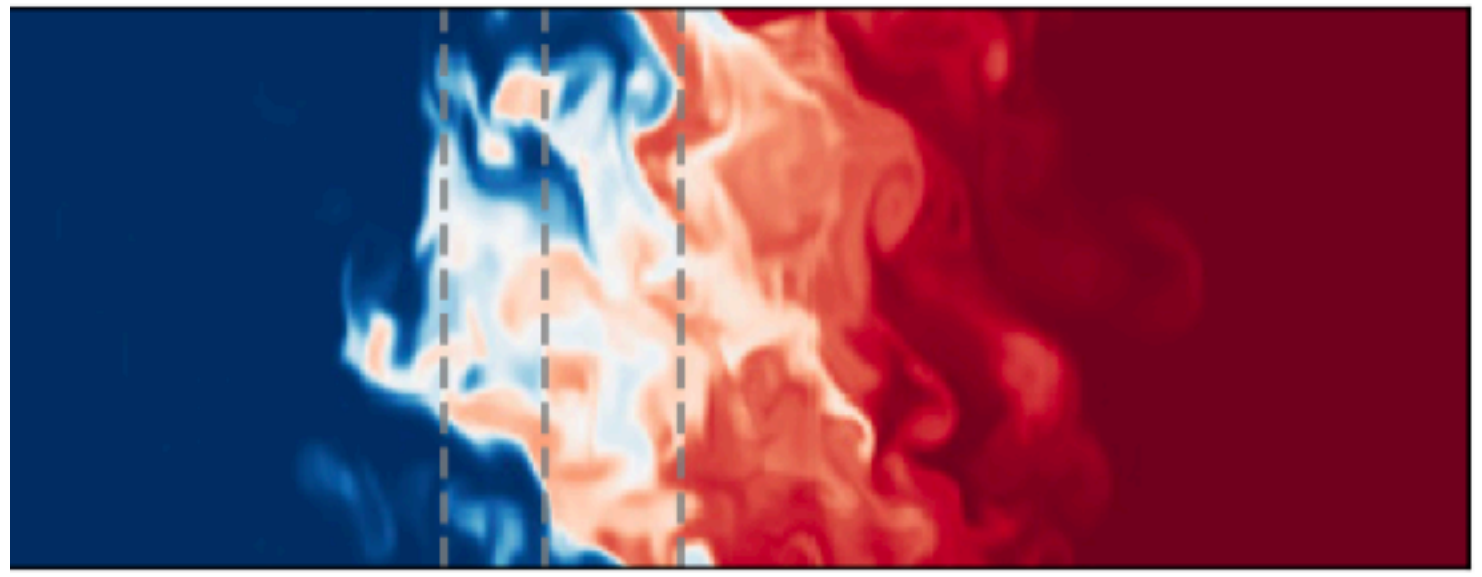
Zooming in on a turbulent mixing layer

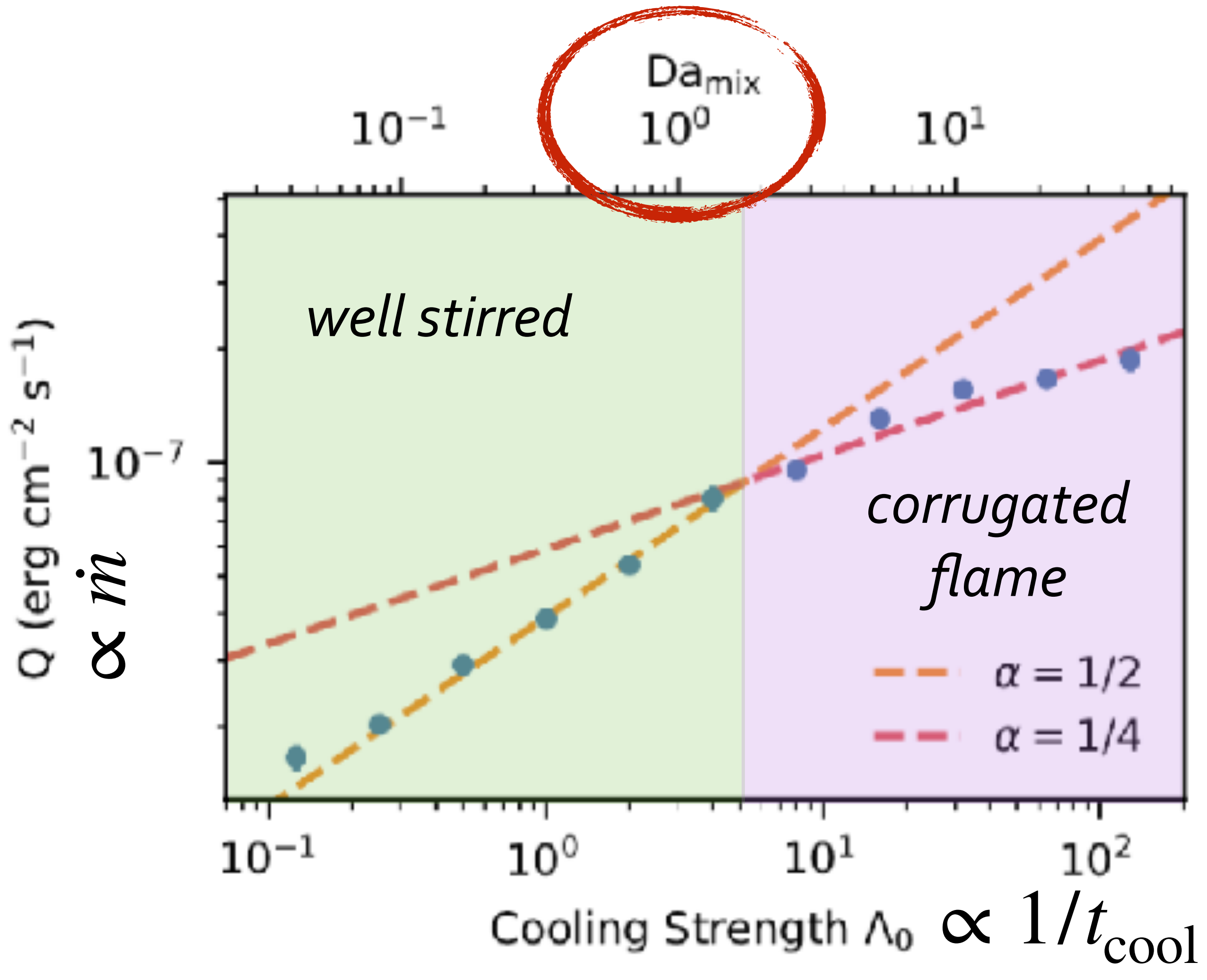
Three lessons from turbulent combustion.

1. Two distinct regimes.

Damköhler number: $\mathrm{Da} = \frac{\tau_{\mathrm{turb}}}{\tau_{\mathrm{react}}} = \frac{L}{u' t_{\mathrm{cool}}(T)}$

weak cooling





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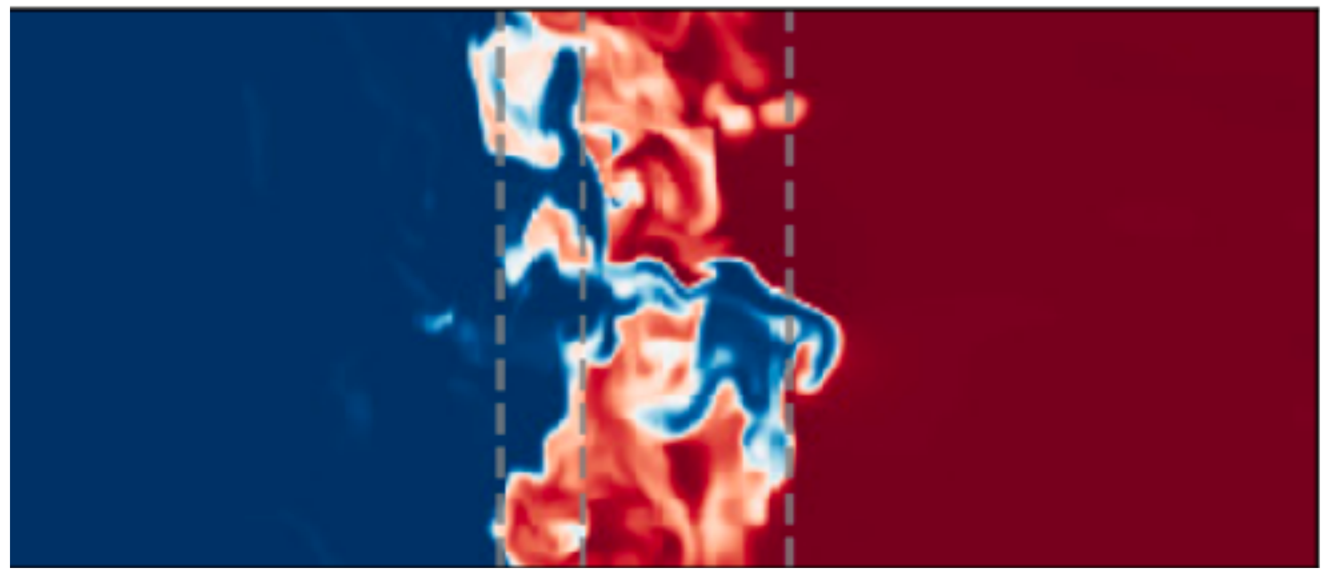

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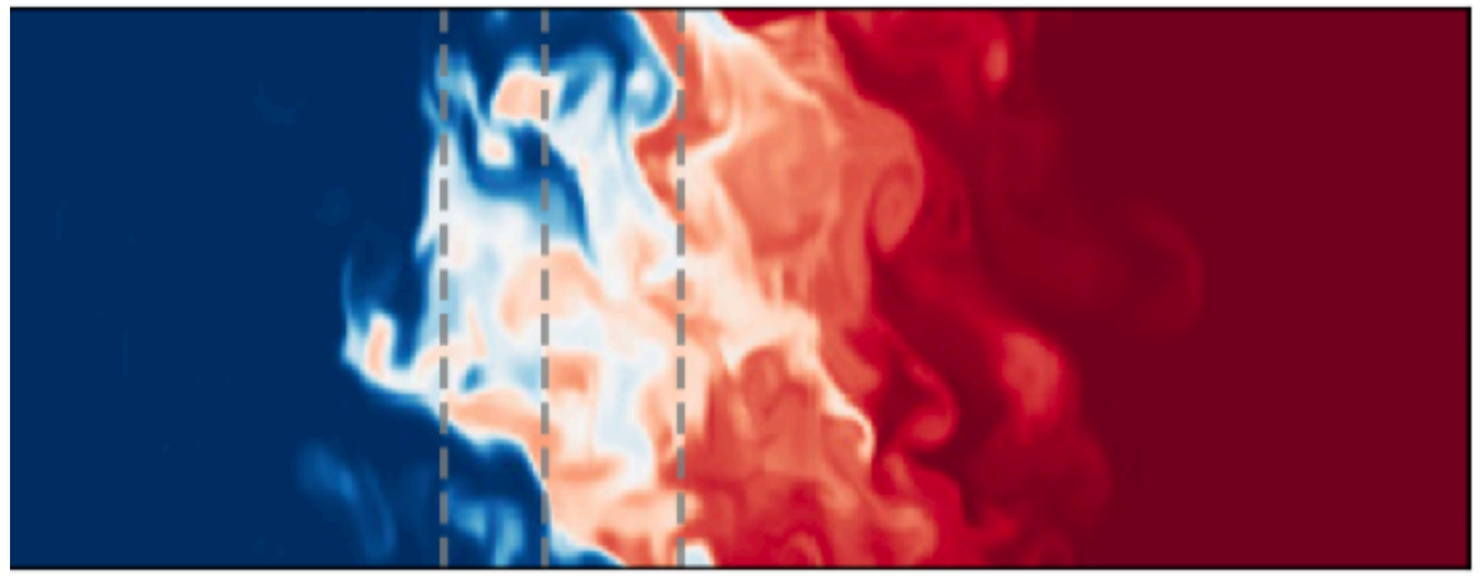

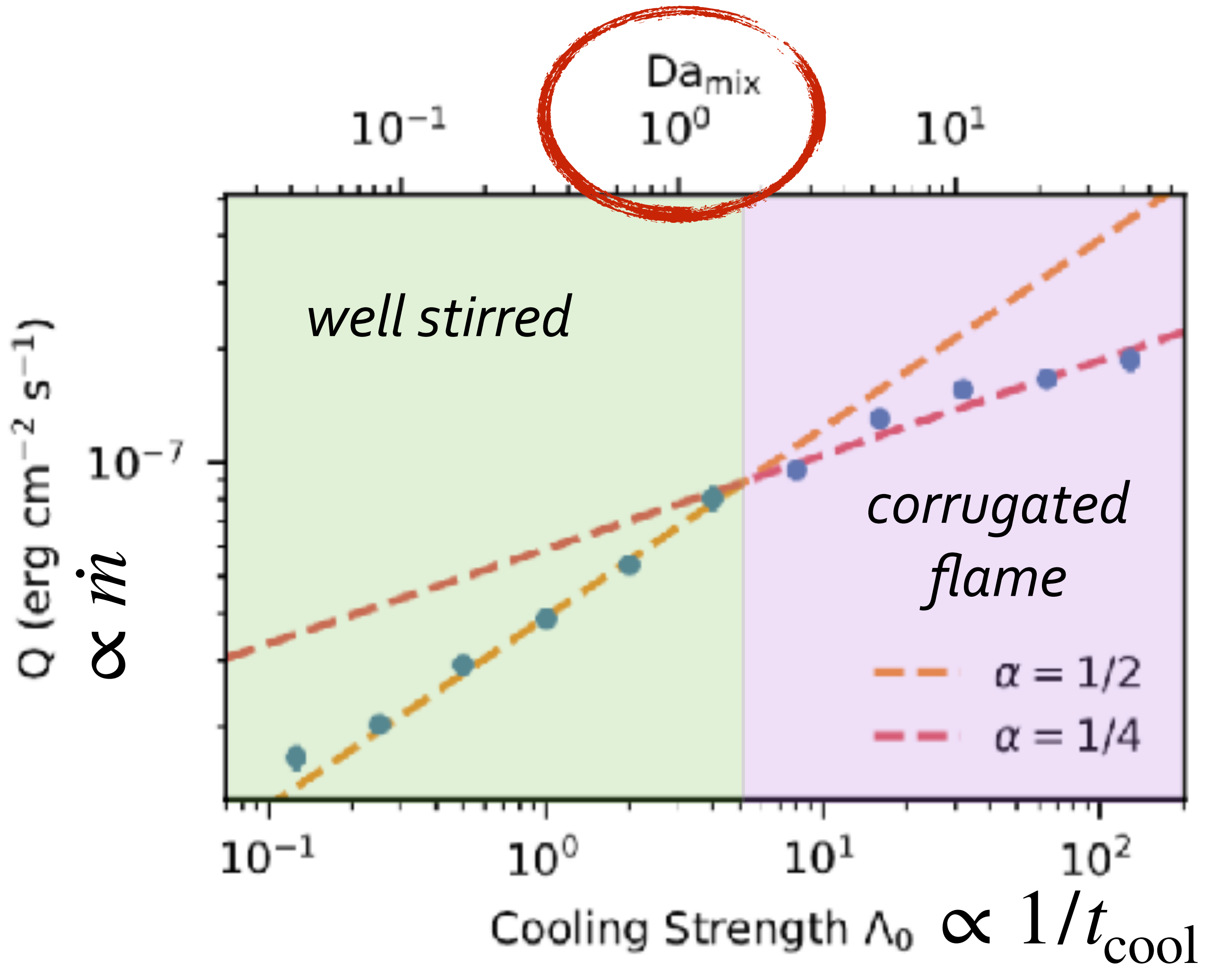

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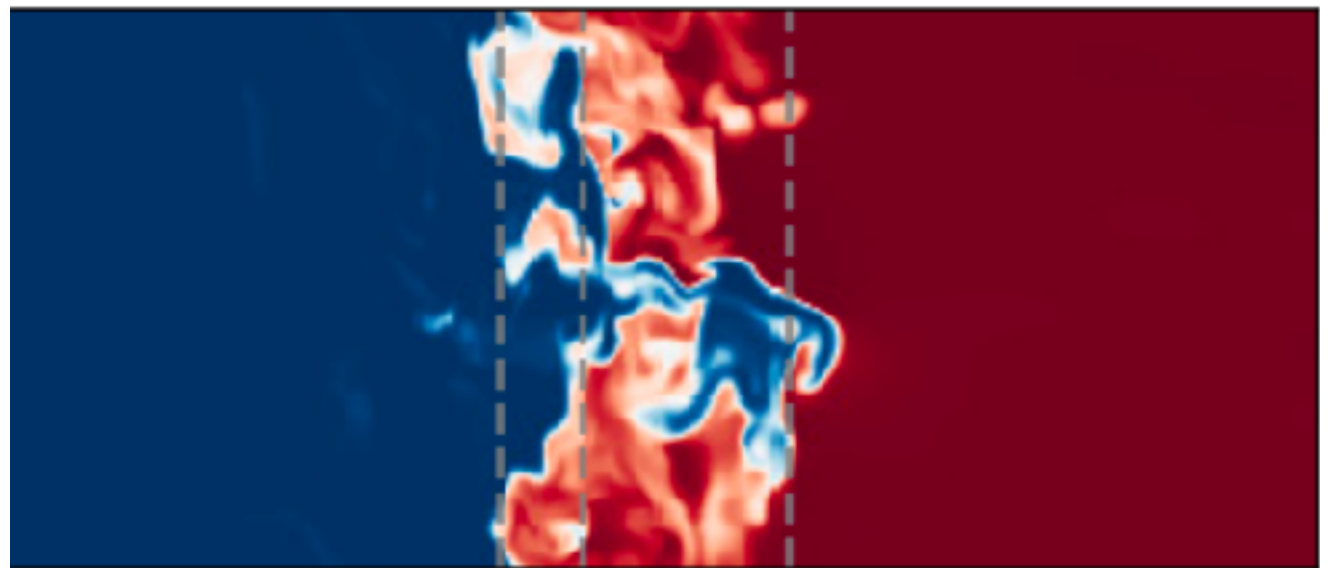

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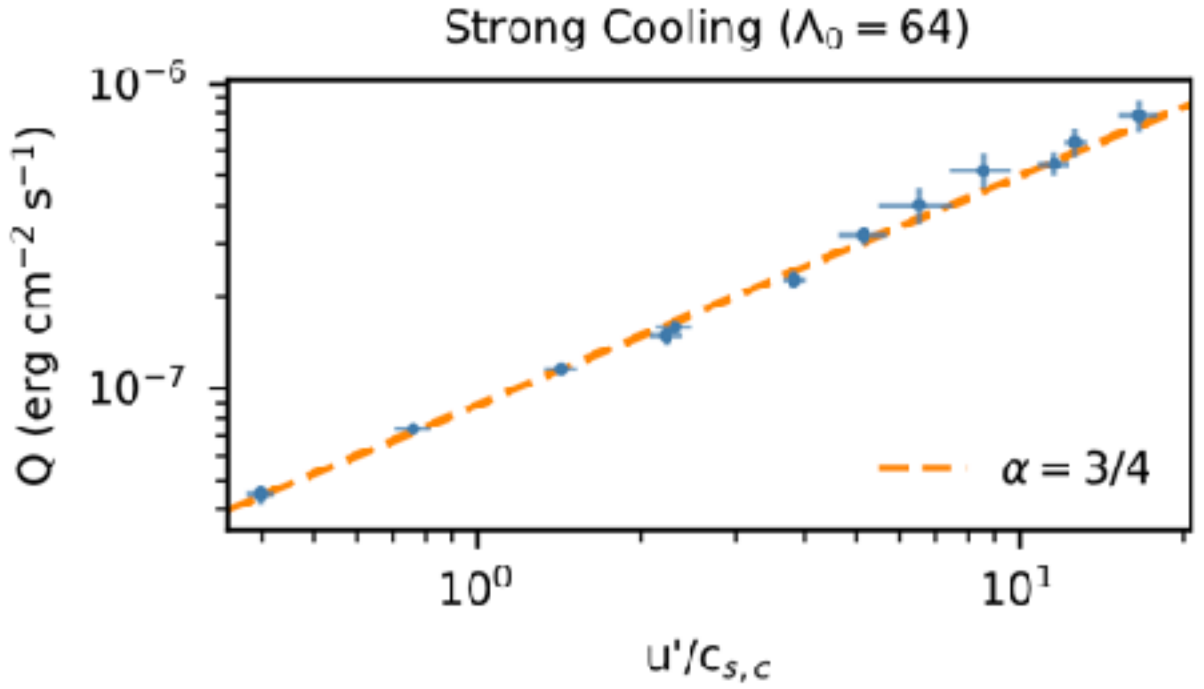

Tan, Oh, MG (2020)

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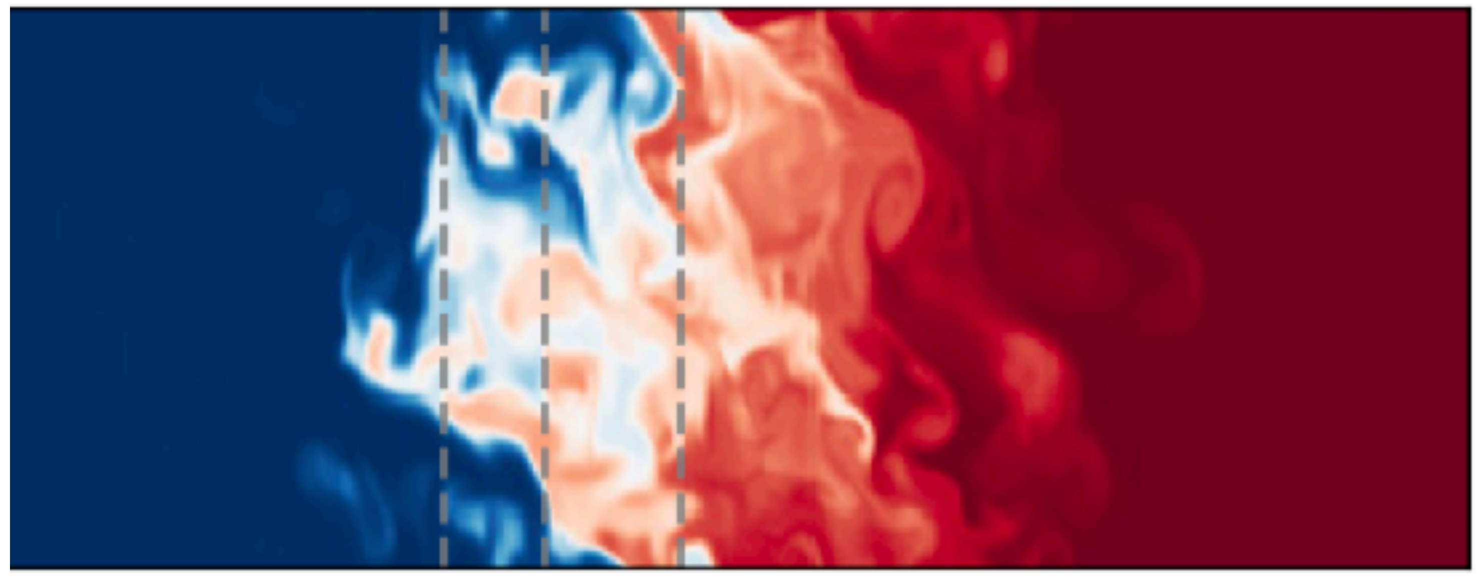

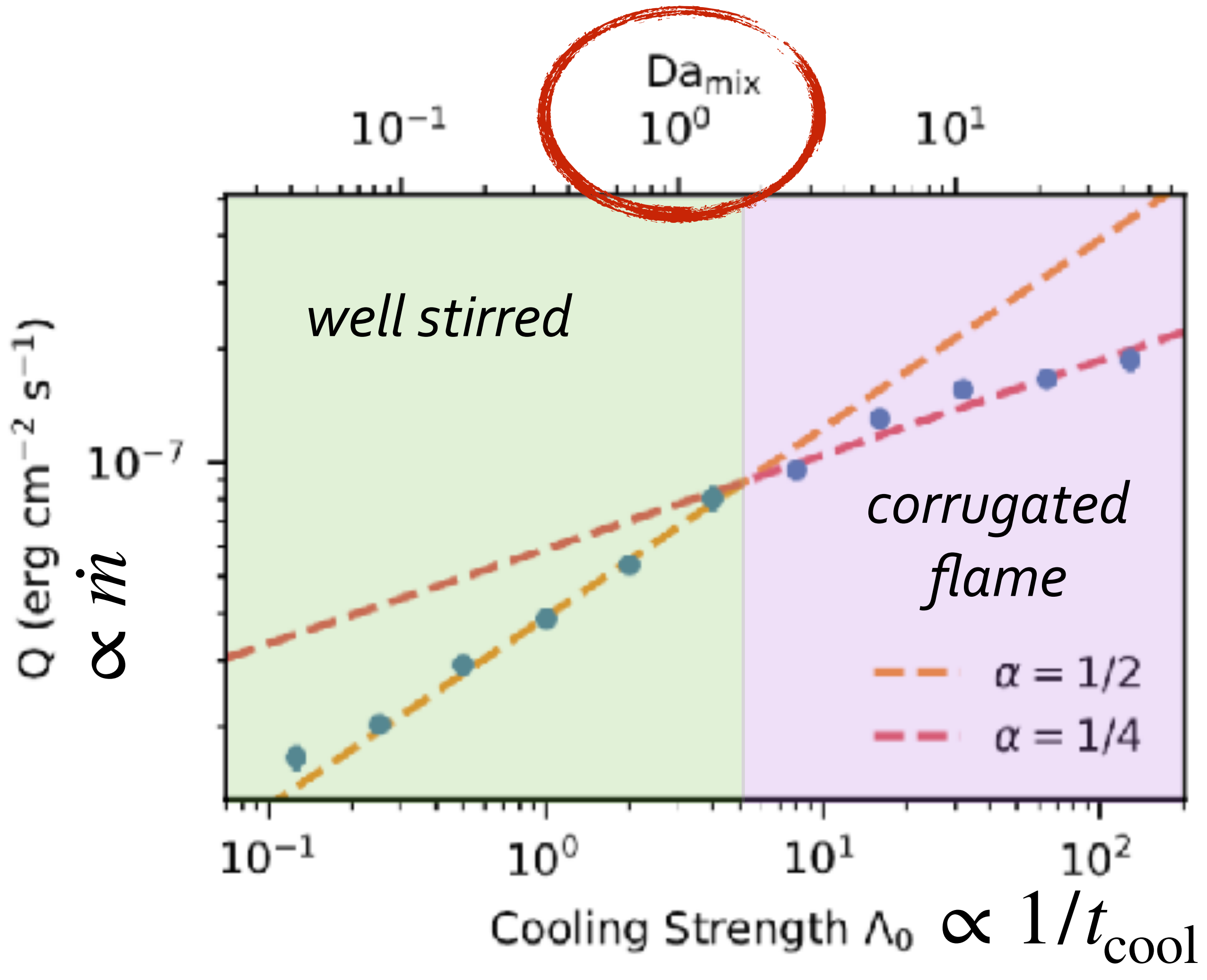

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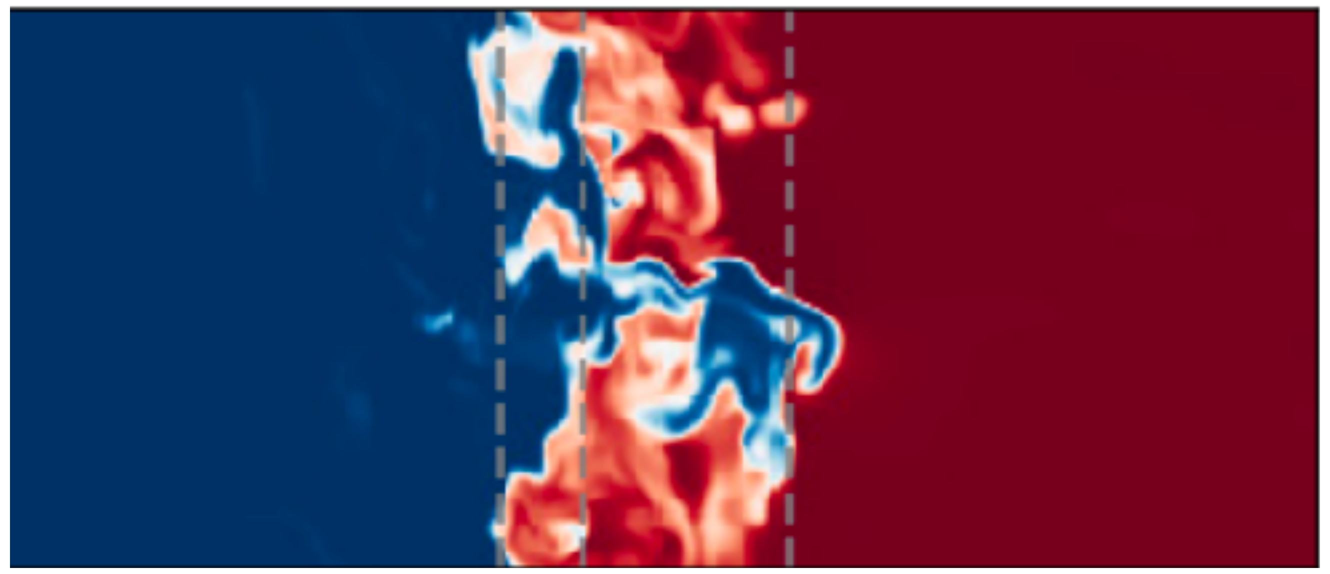

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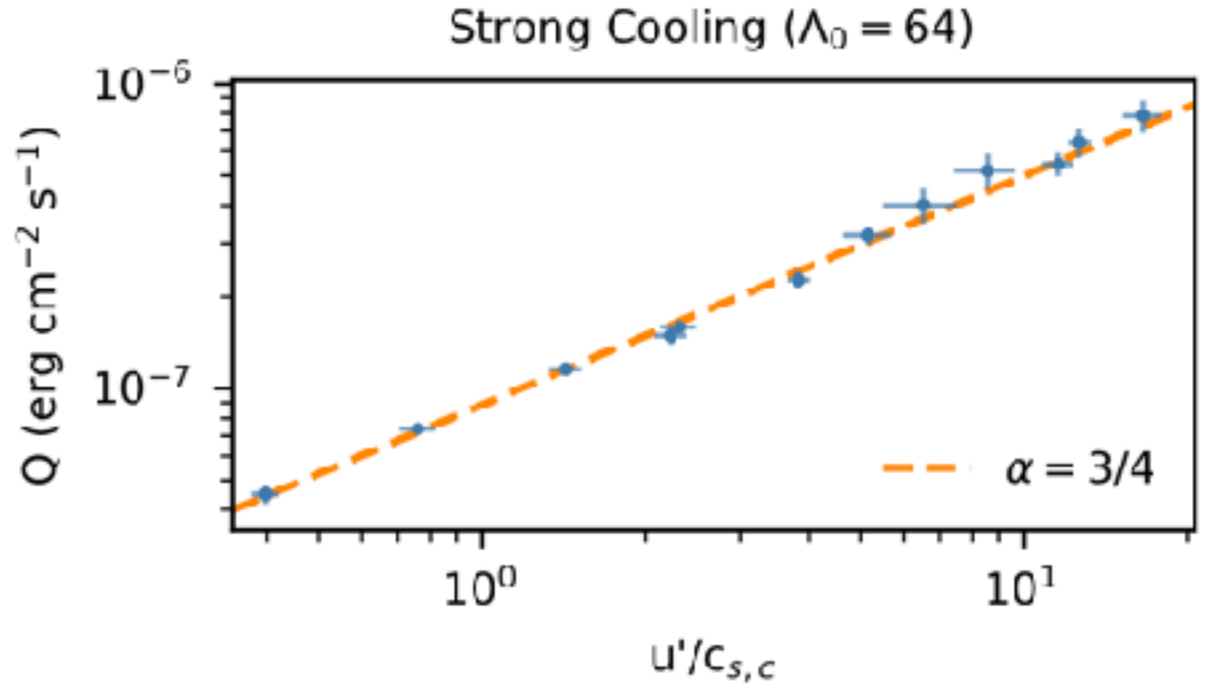
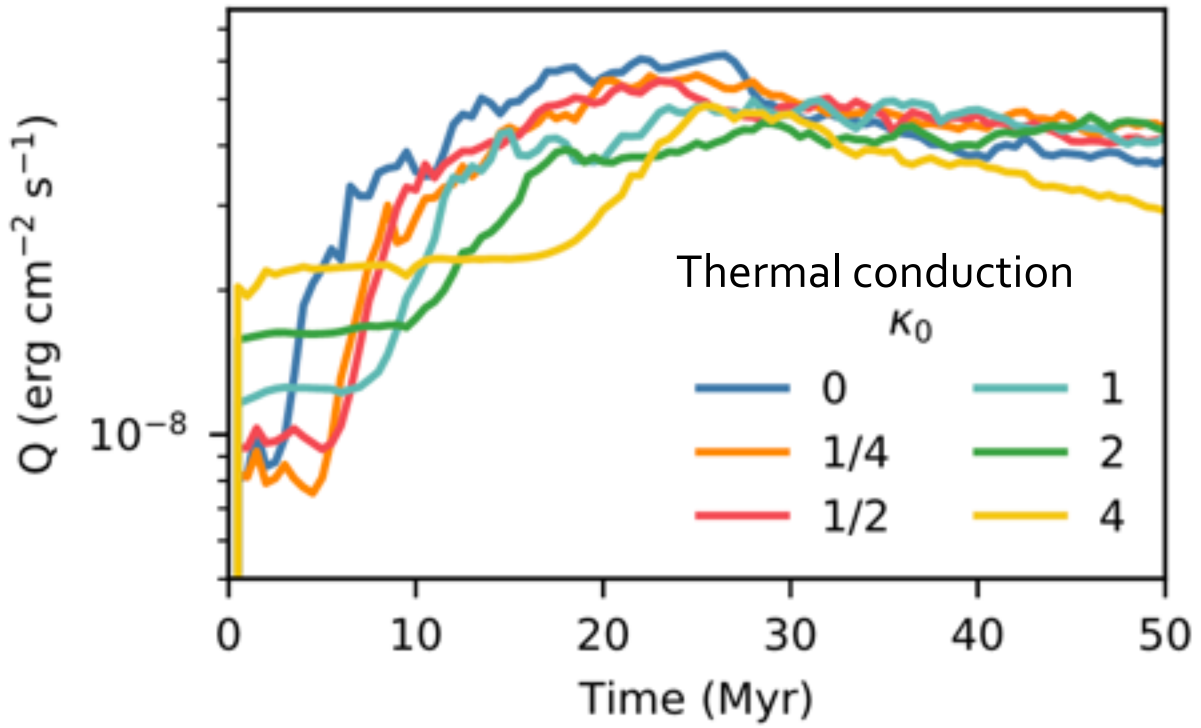


3. Turbulent diffusion dominates.



Tan, Oh, MG (2020)

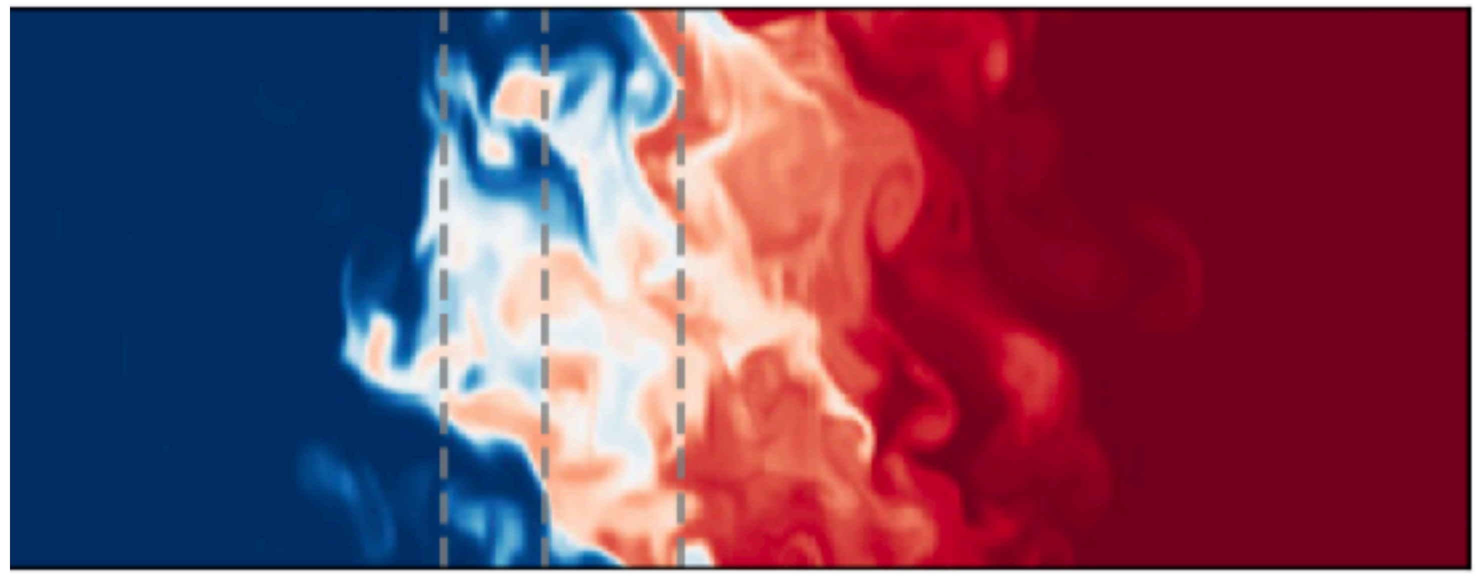
Zooming in on a turbulent mixing layer

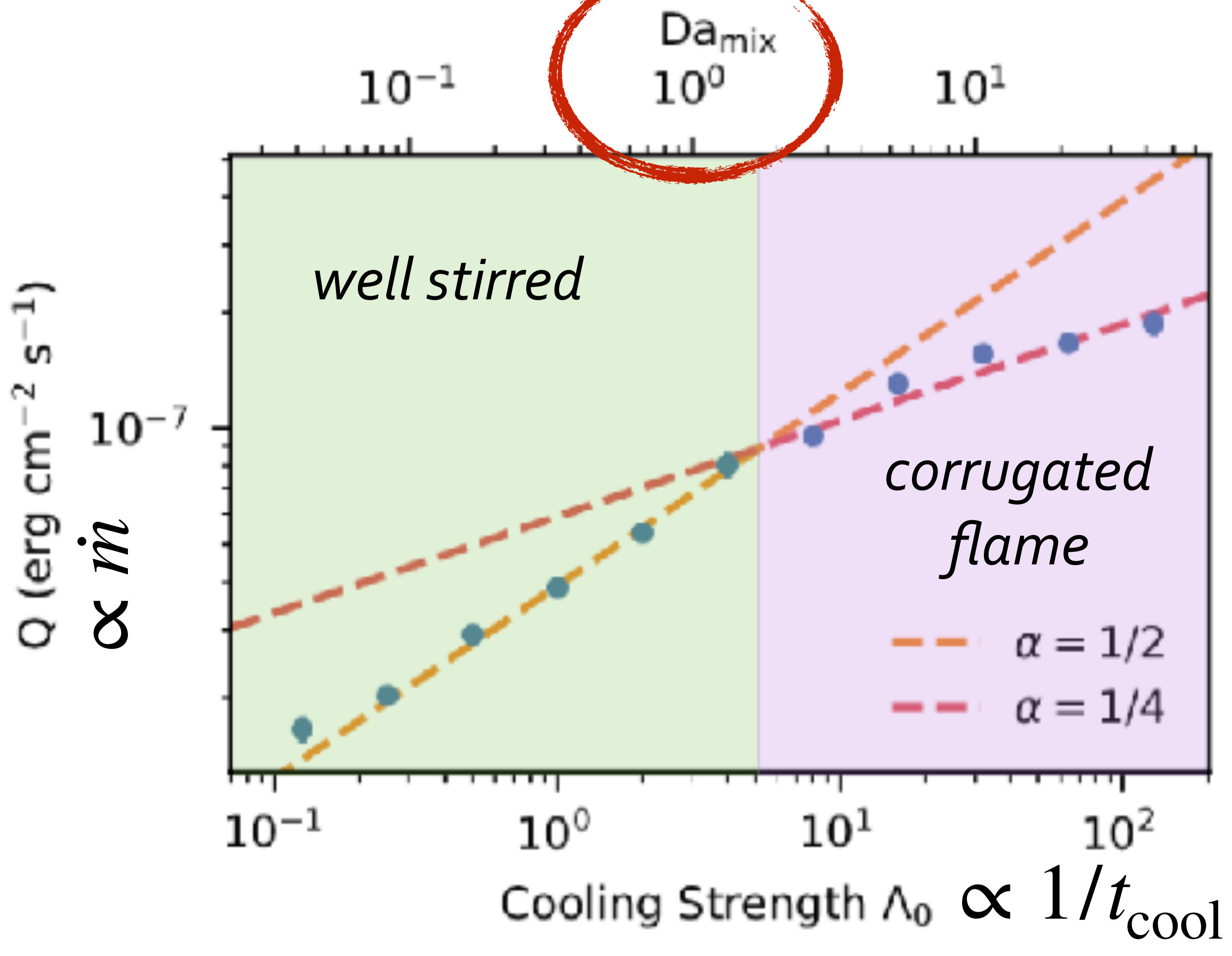
Three lessons from turbulent combustion.

1. Two distinct regimes.

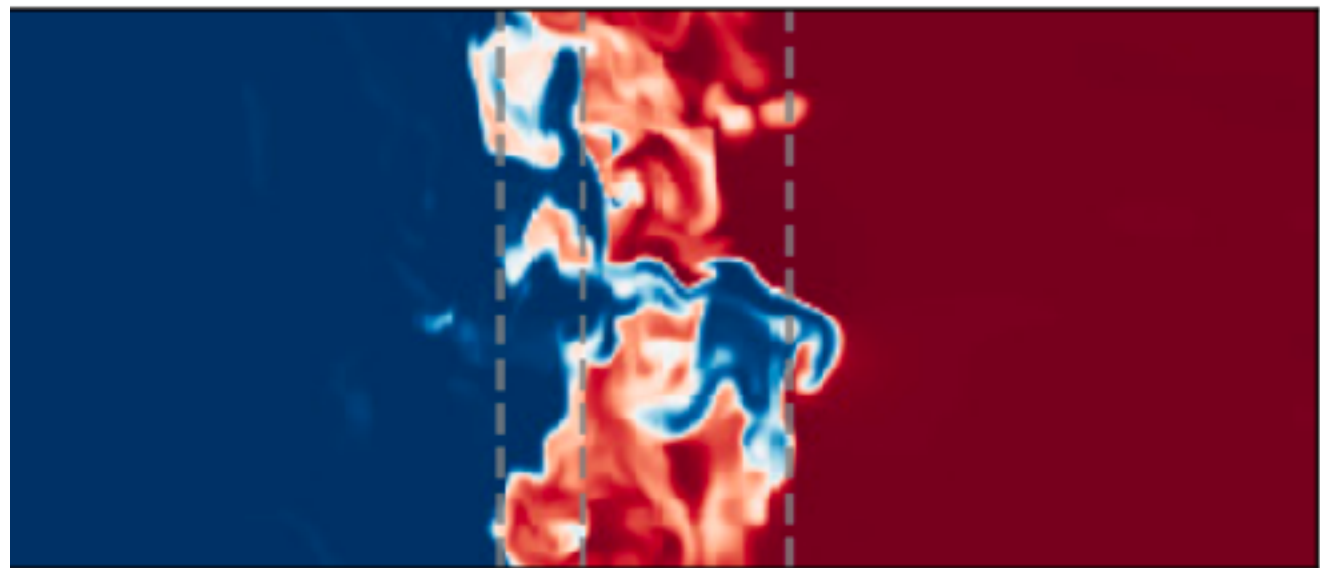
Damköhler number: $\mathrm{Da} = \frac{\tau_{\mathrm{turb}}}{\tau_{\mathrm{react}}} = \frac{L}{u' t_{\mathrm{cool}}(T)}$

weak cooling

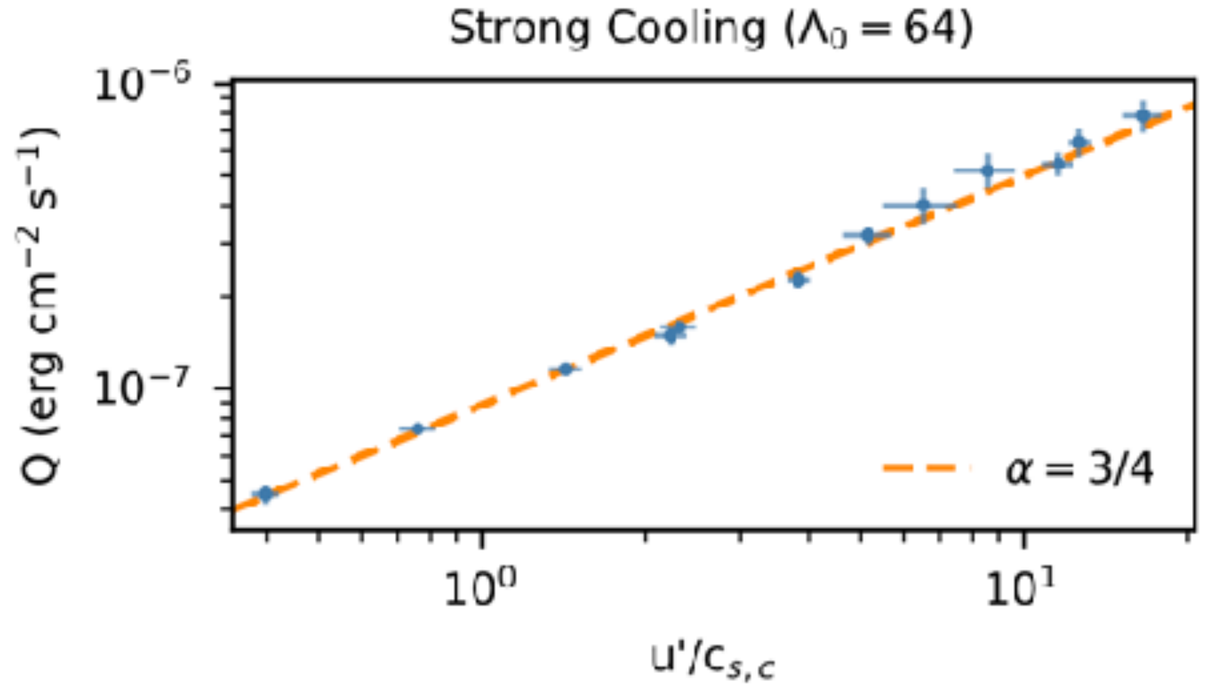




strong cooling



2. $Q(u')$ relation.



Result:
robust model for the exchange of the phases.

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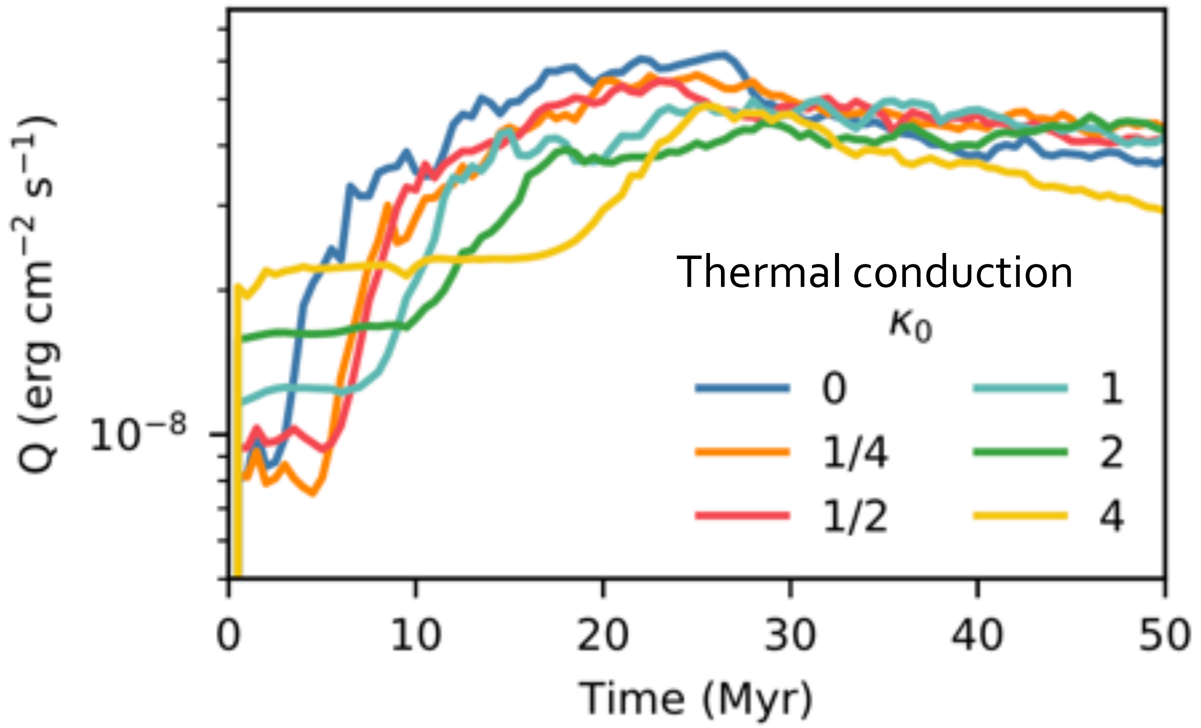
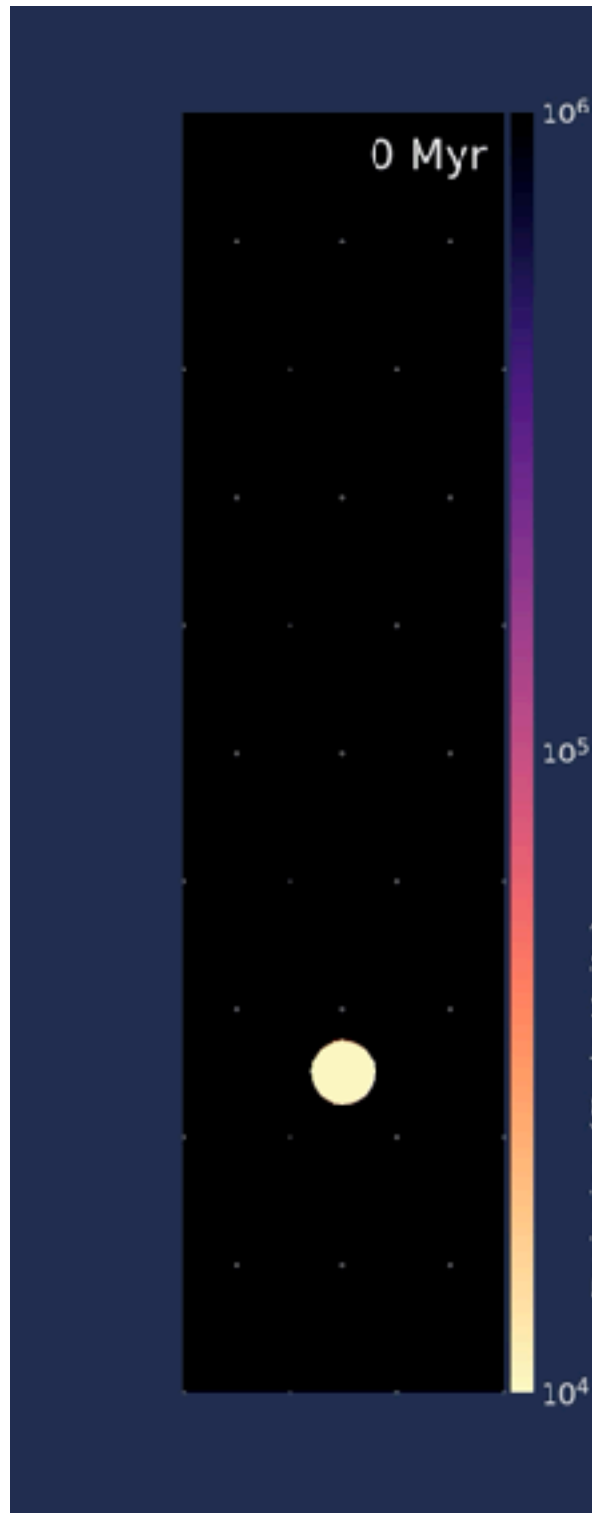
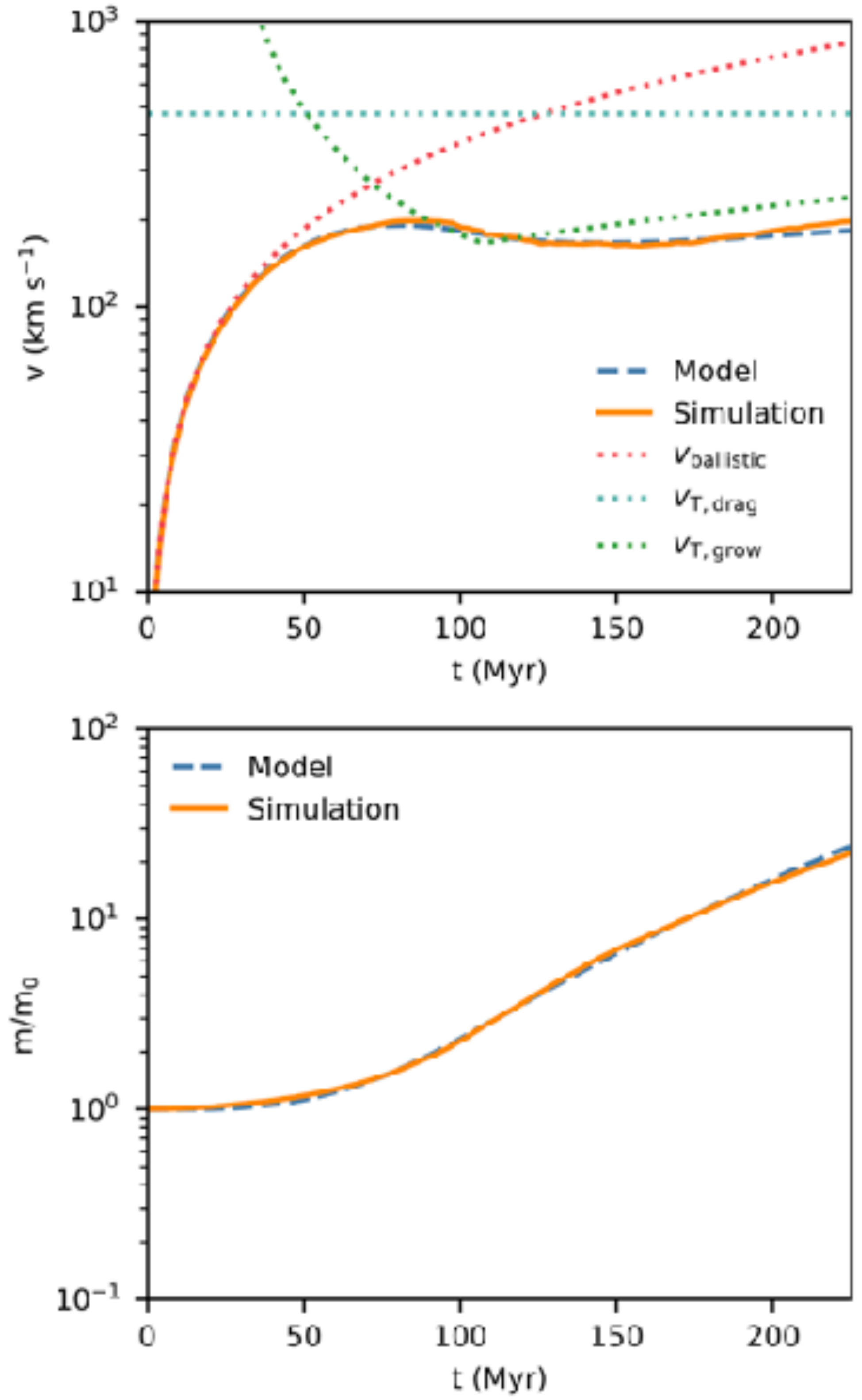


A song of ice & fire: model of mixing and cooling

Example: falling cloud

Tan, Oh, MG (2023)





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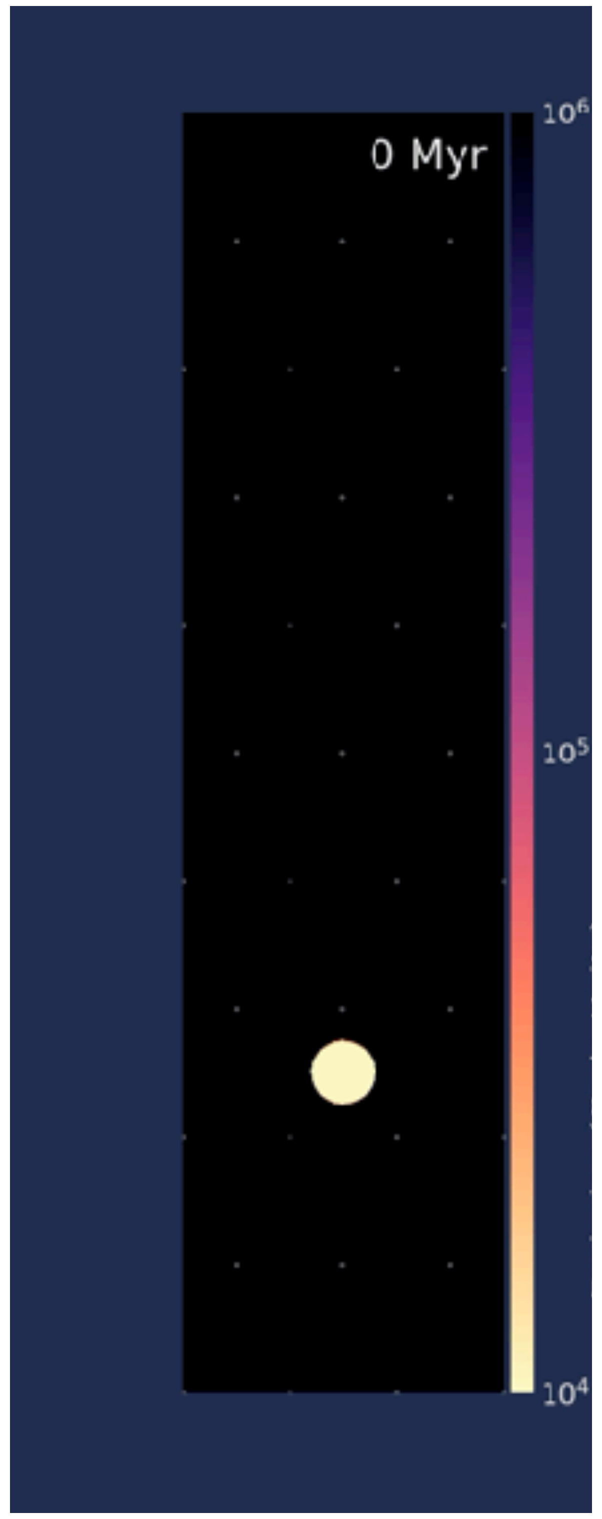

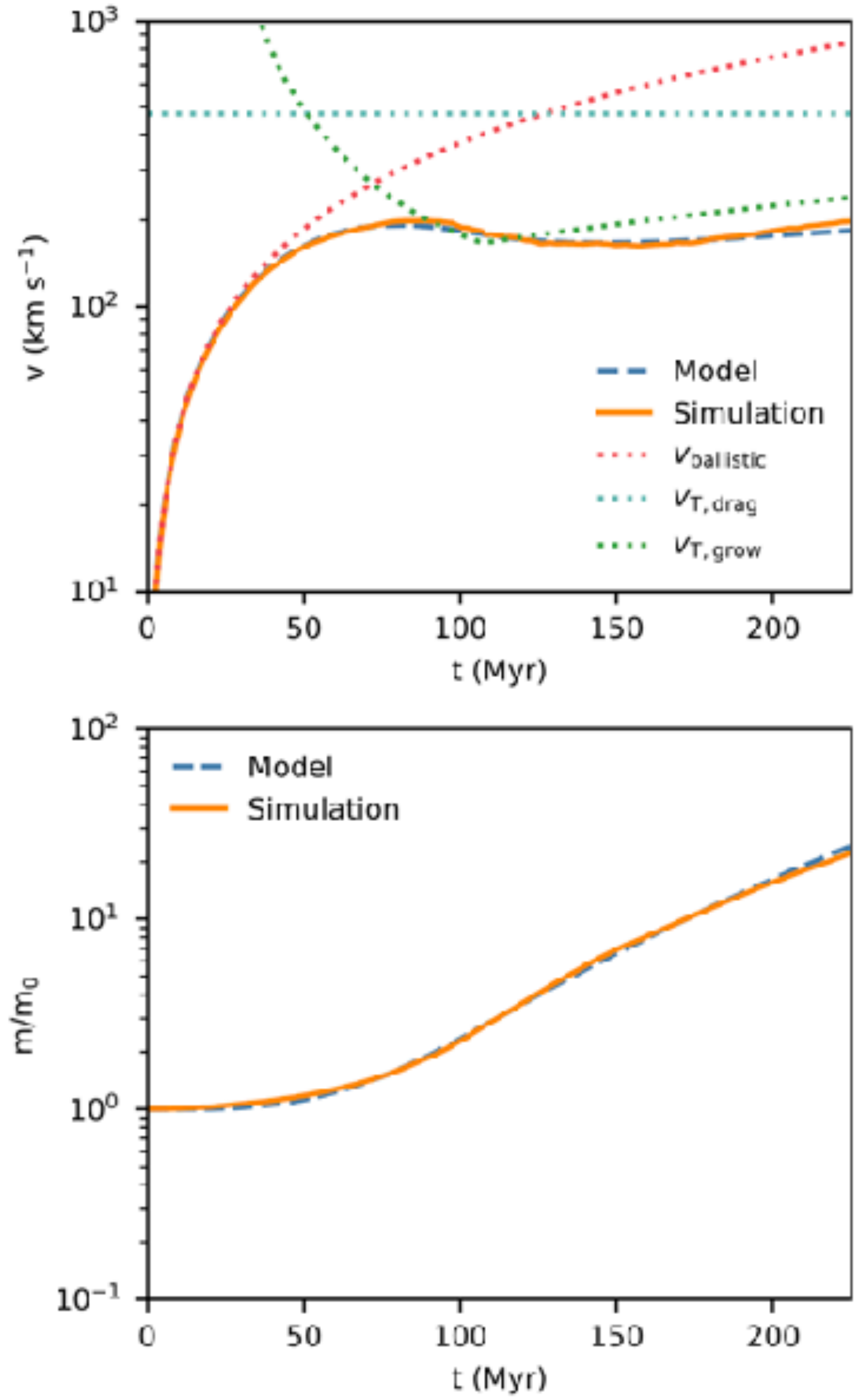

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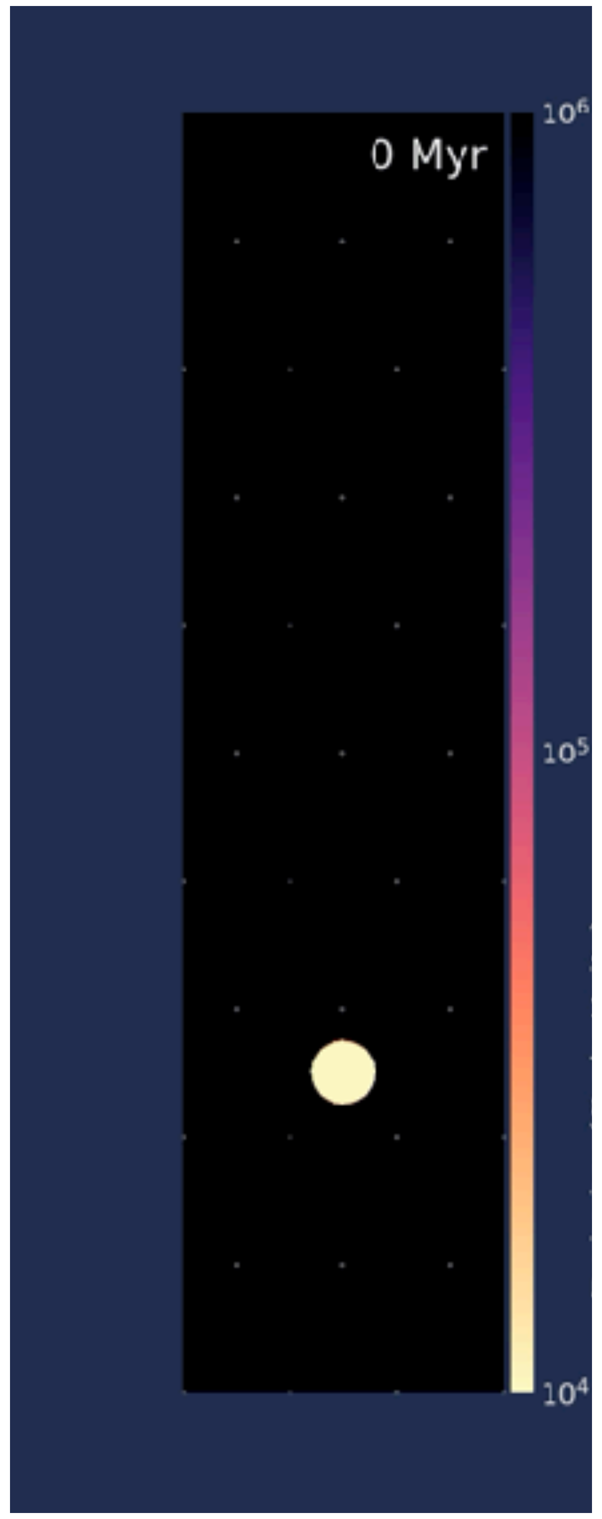

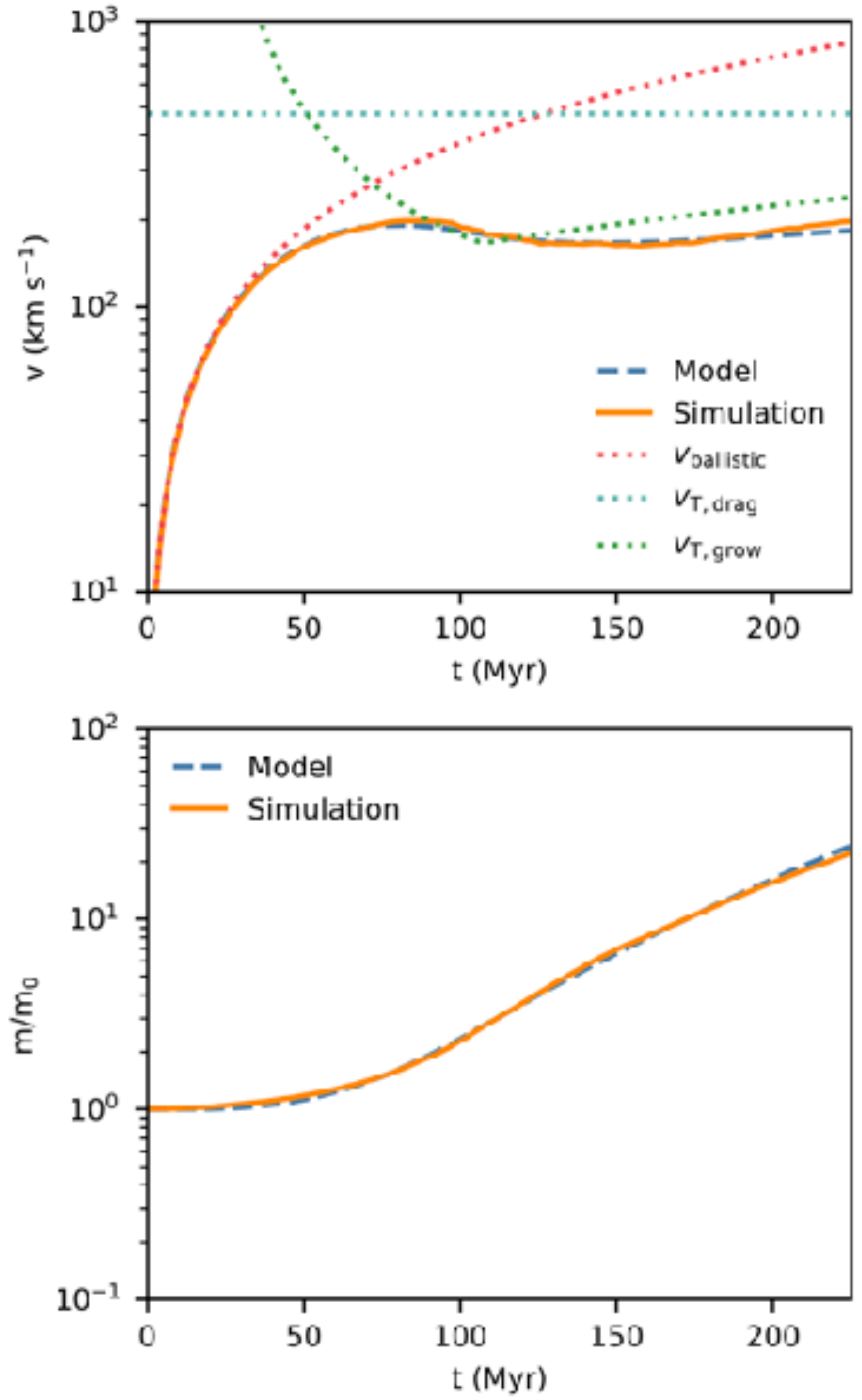

Powerful model of transfer between the phases!

And with this perfect model for mixing and cooling they lived happily ever after.

The End

A song of ice & fire: model of mixing and cooling

Tan, Oh, MG (2023)

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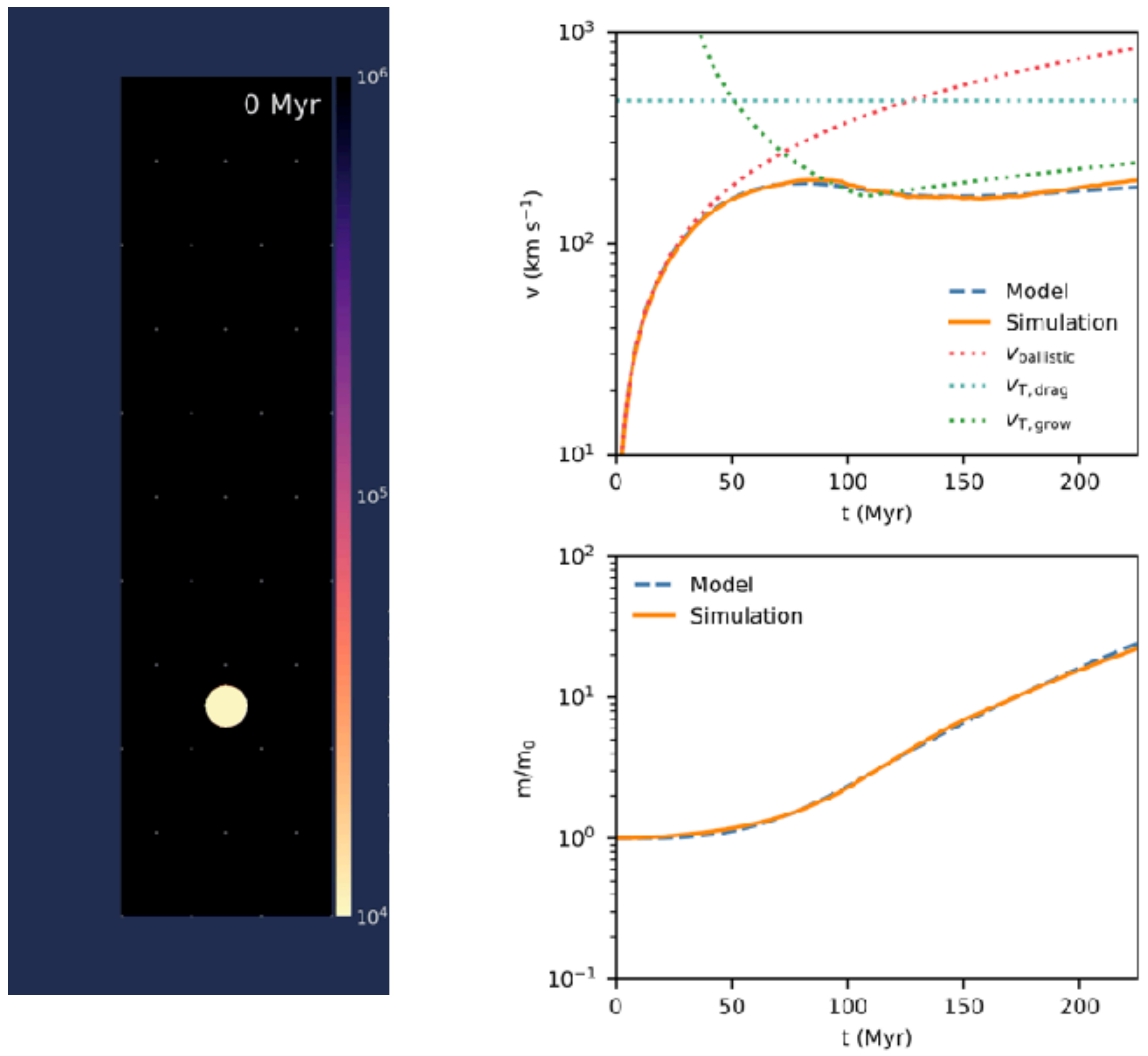

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magnetic fields

viscosity

B-fields & viscosity can hinder mixing!

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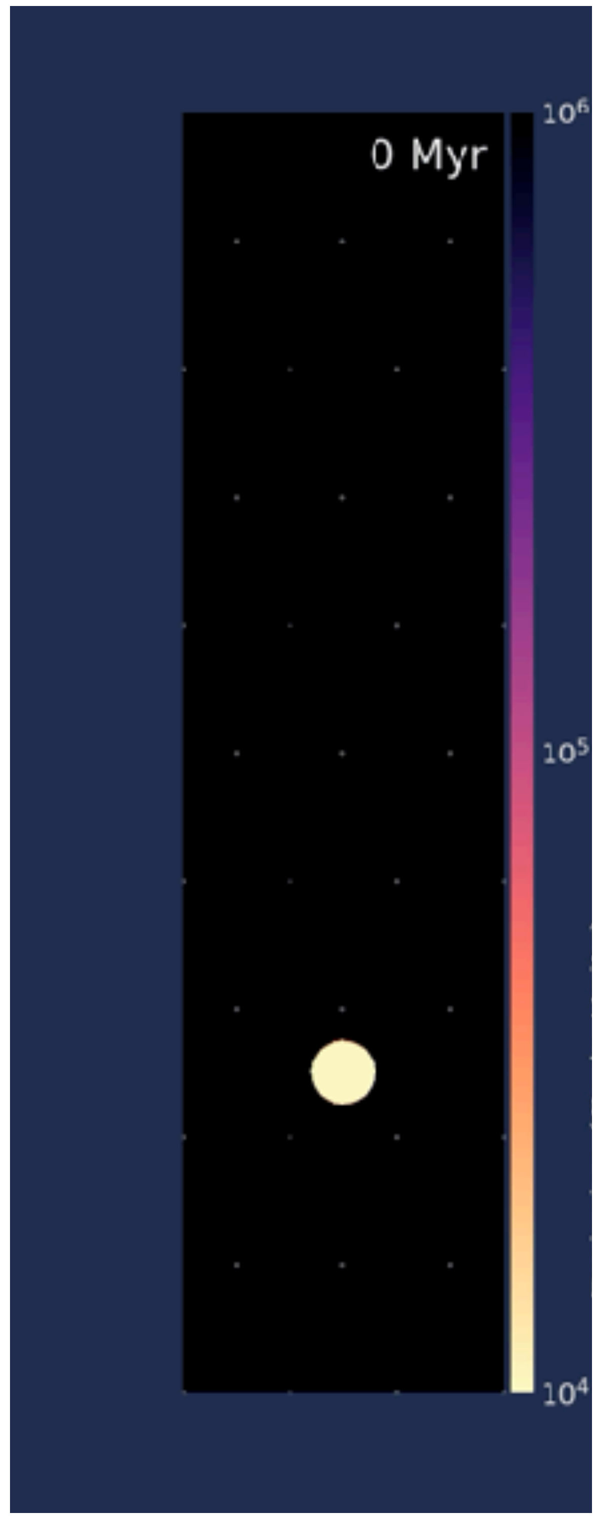

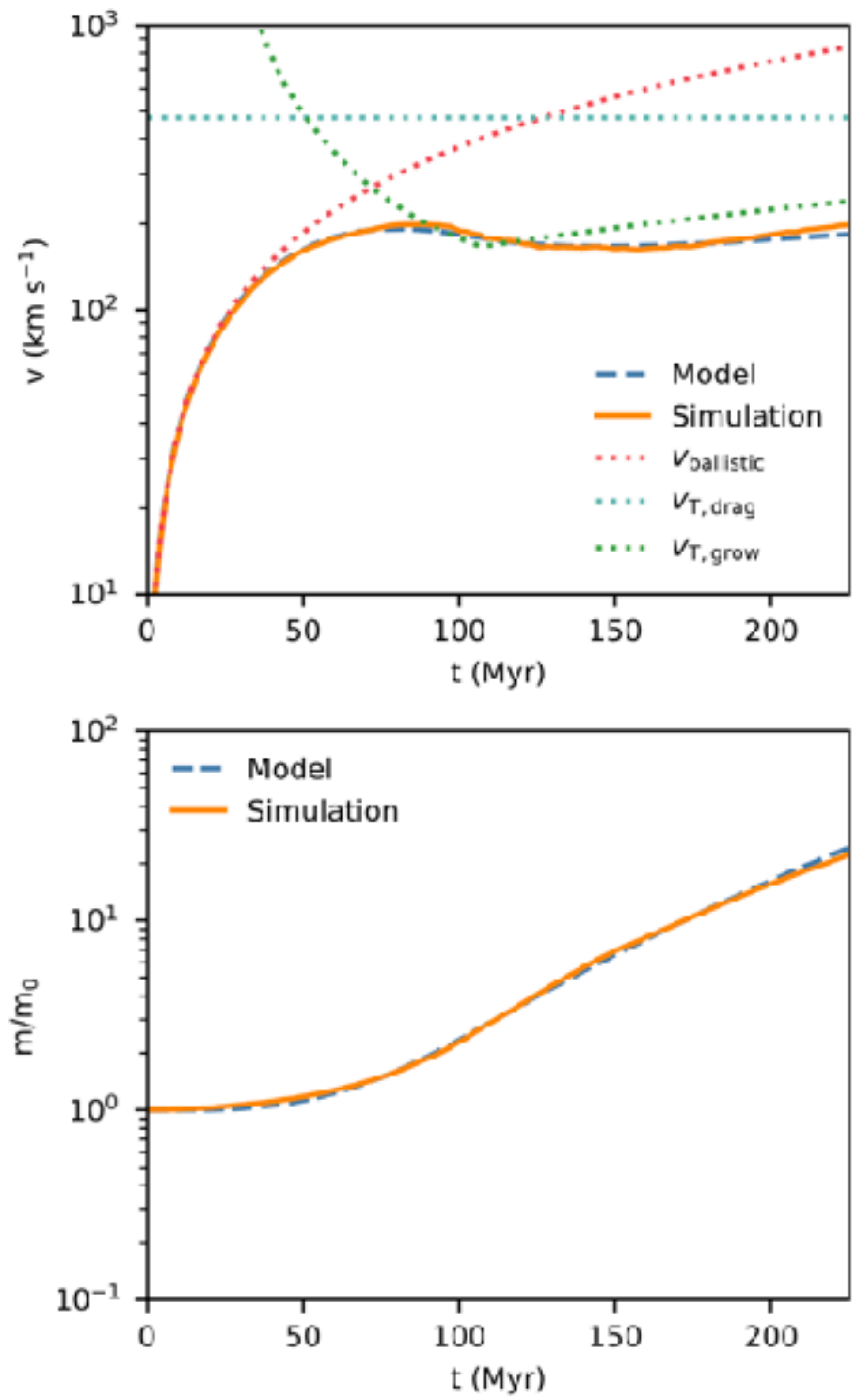

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magnetic fields
(see Hitesh's talk)

viscosity
(this talk)

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The evil powers of viscosity

Viscosity...prevents mixing!

$\eta_{\rm crit} \sim L v \rho \chi^{1/2}$ to fully suppress KHI.

(Roediger et al. 2013)

Tirso Marin-Gilabert, MG, Oh (2025)

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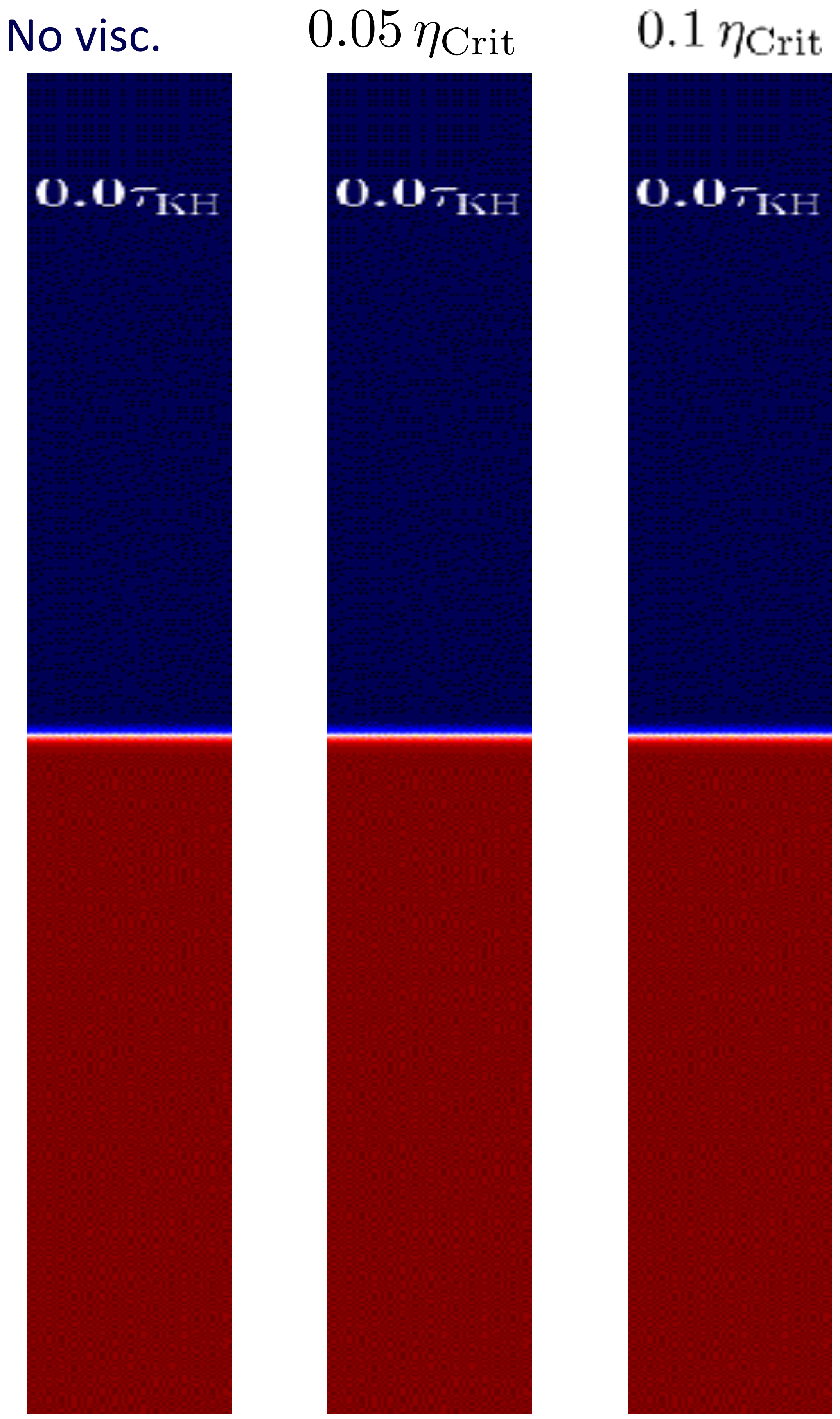

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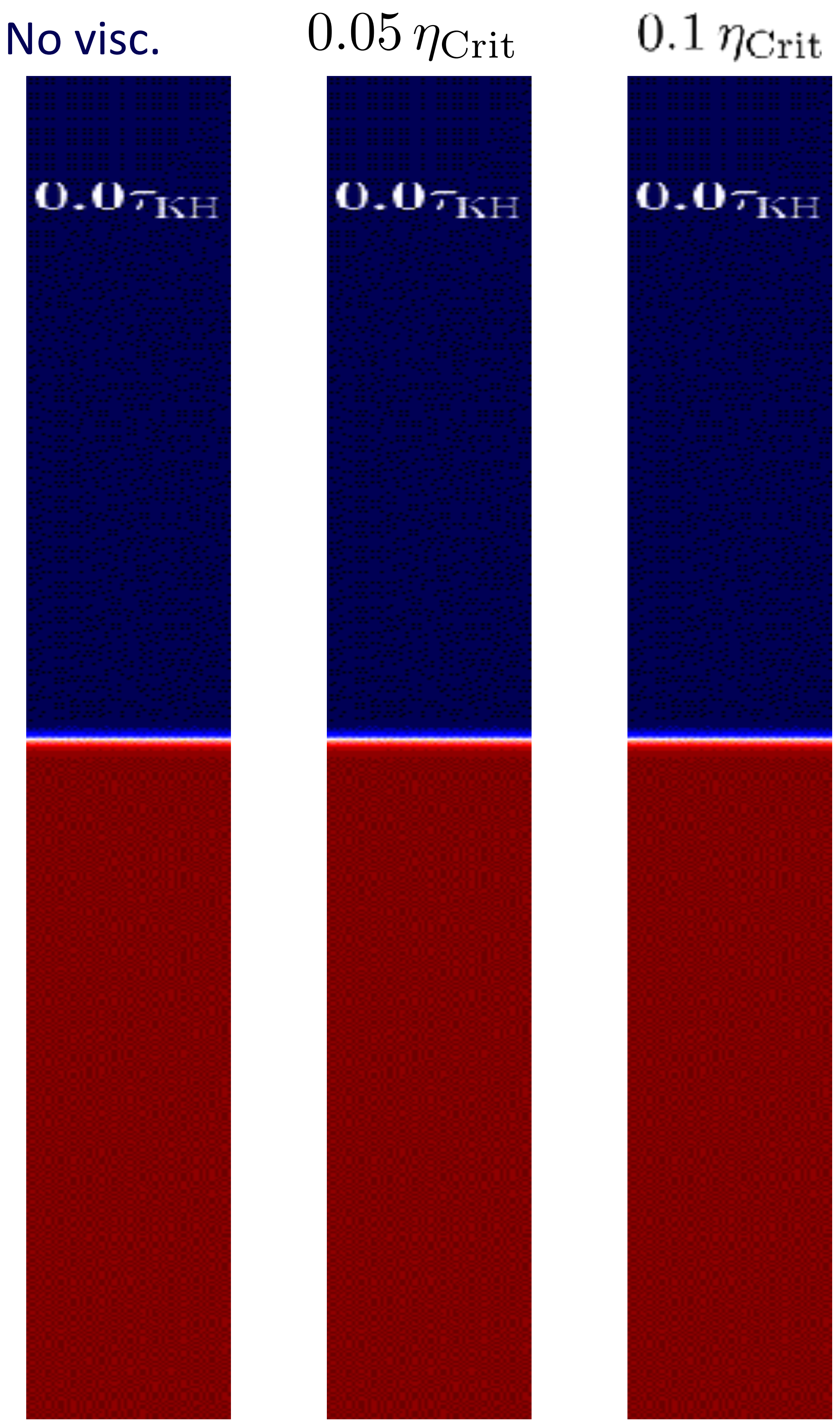
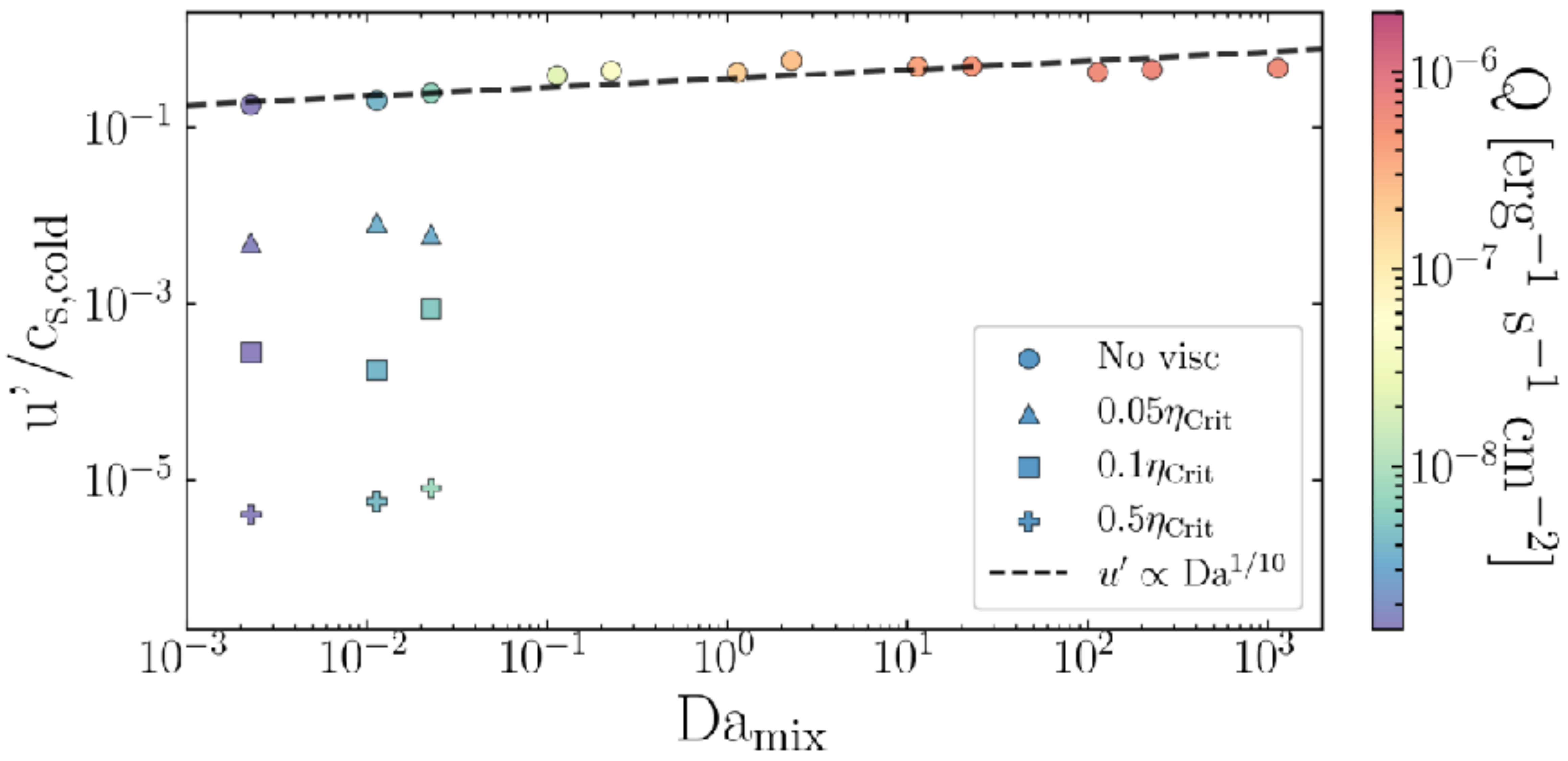


Tirso Marin-Gilabert, MG, Oh (2025)



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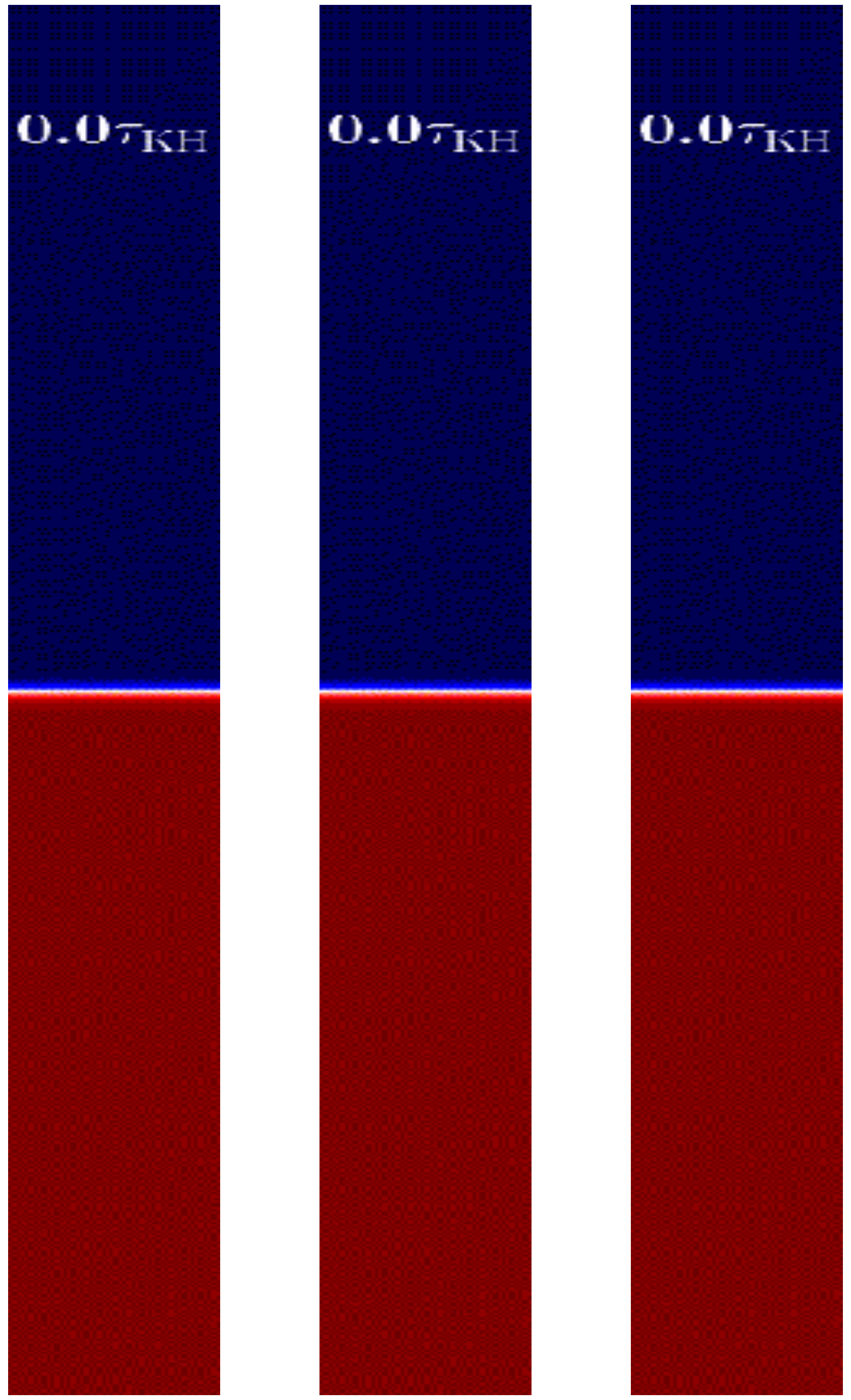
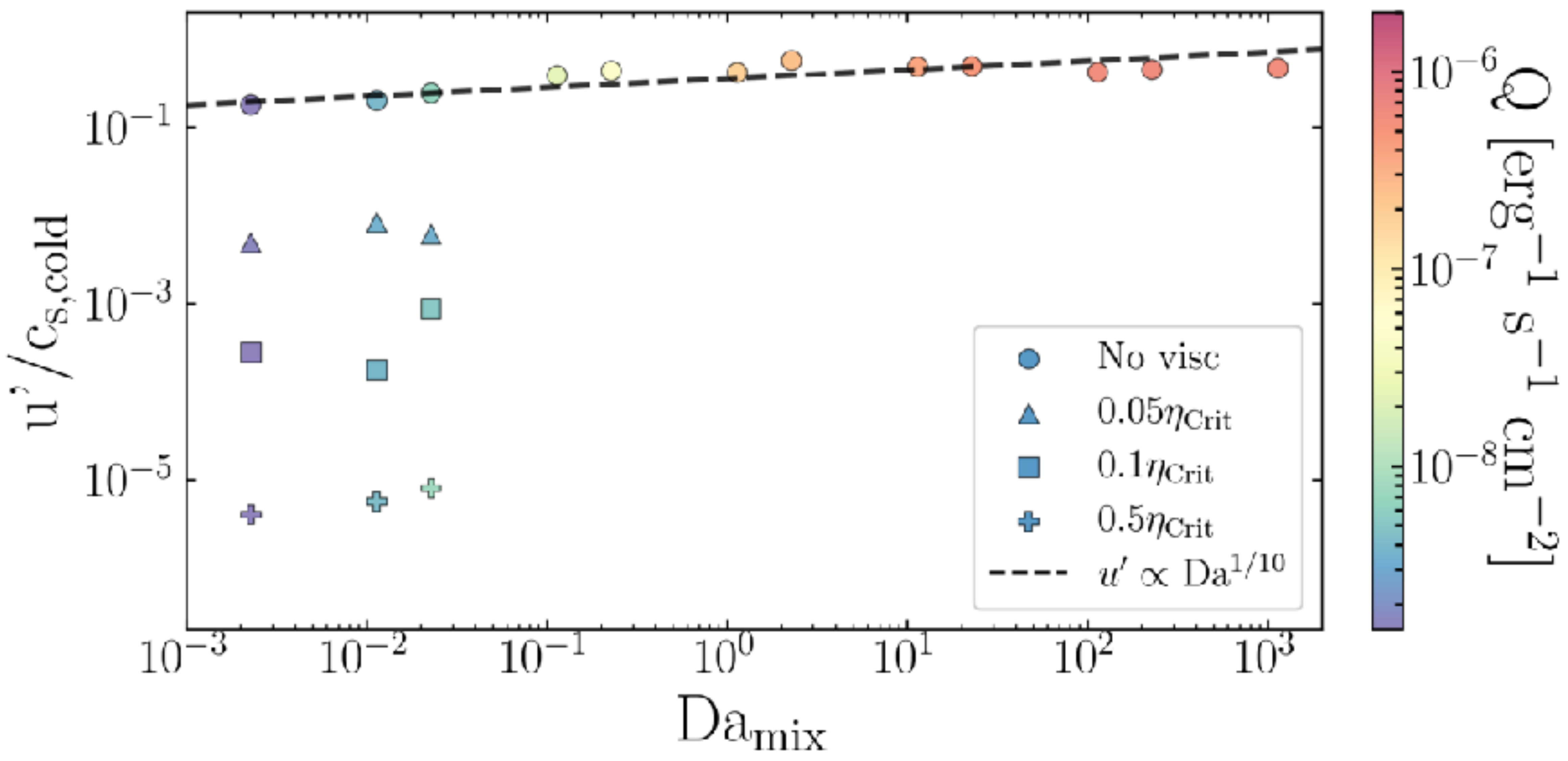
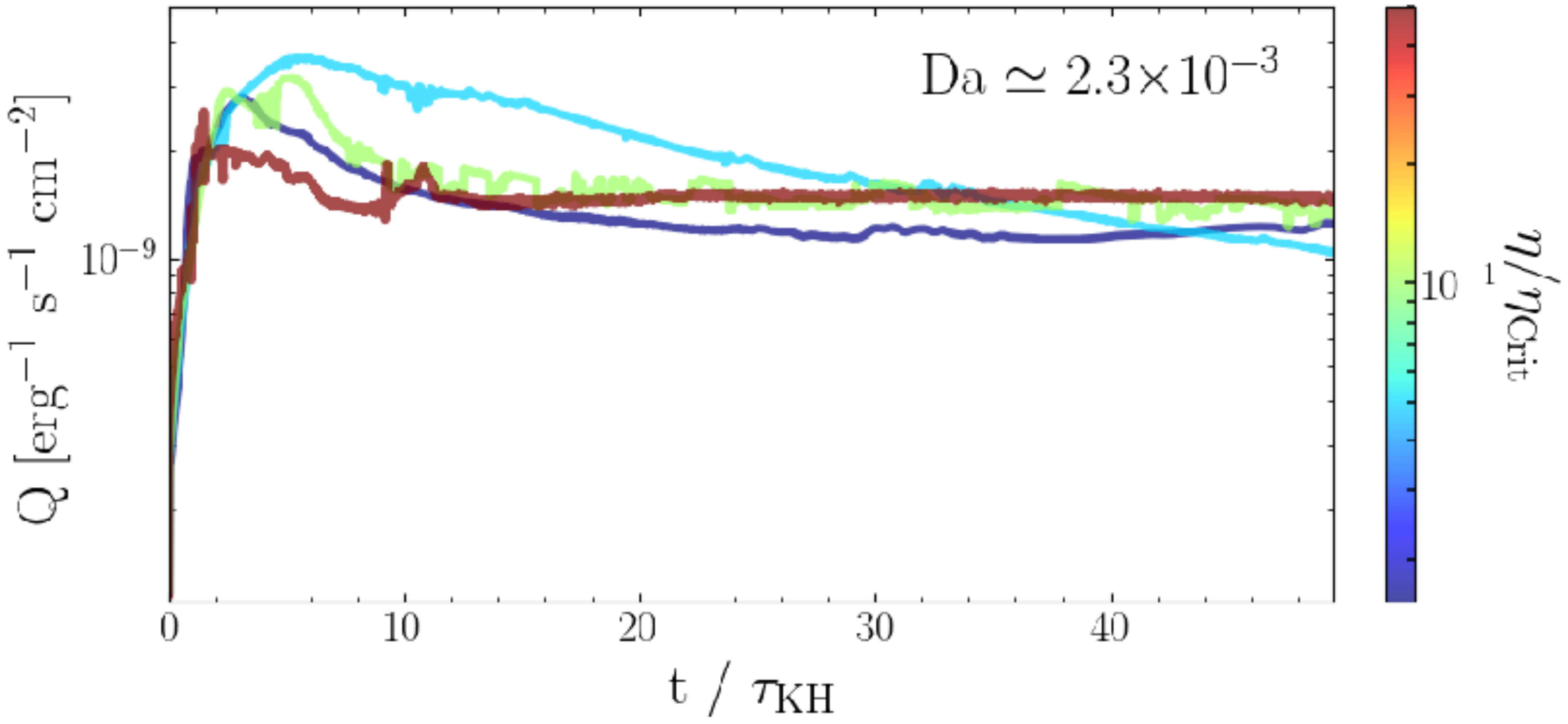
No visc. $0.05\,\eta_{\rm Crit}$ $0.1\,\eta_{\rm Crit}$





…but not cooling? (no fixed u'-Q relation as before)



Does viscosity prevent mixing?

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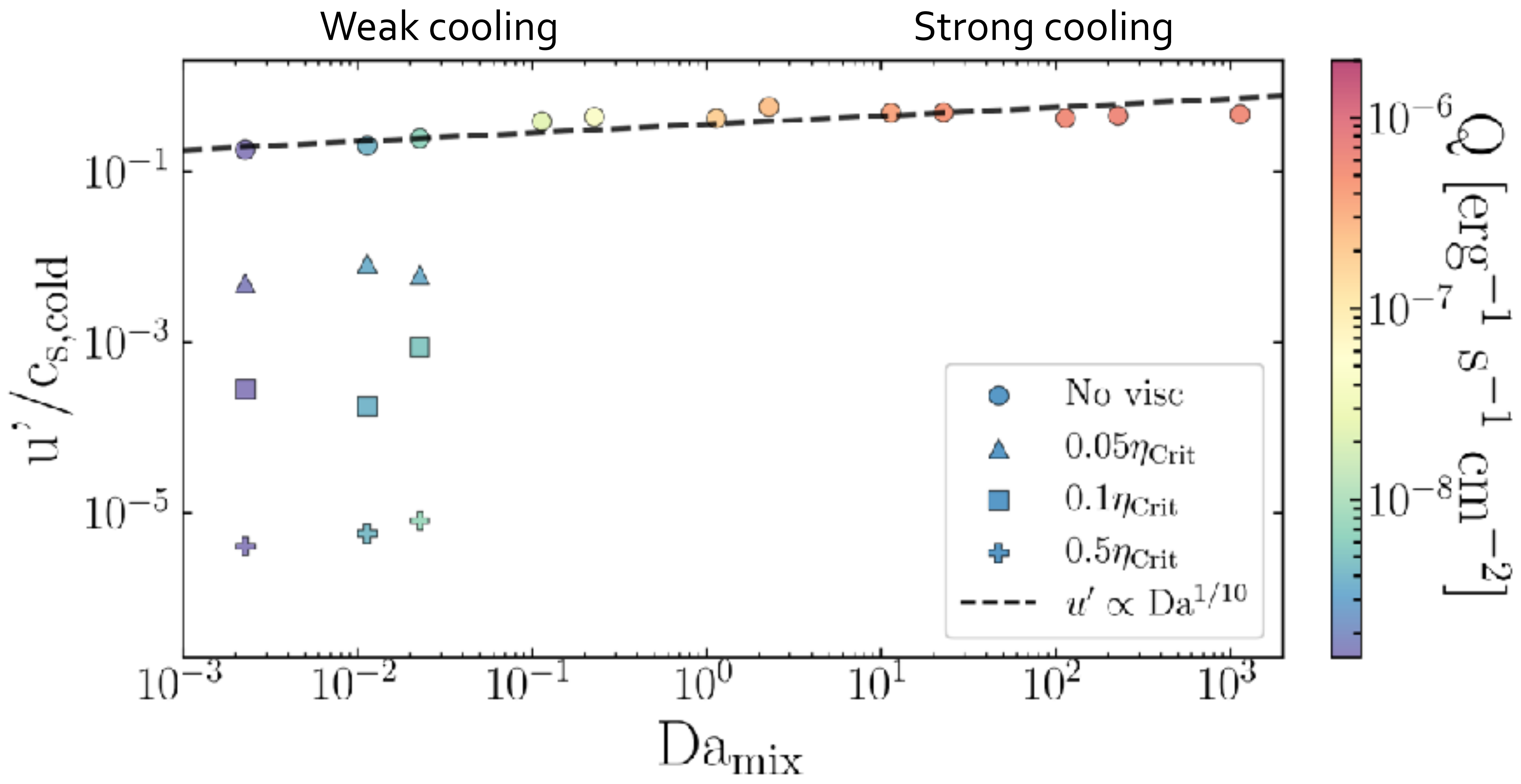

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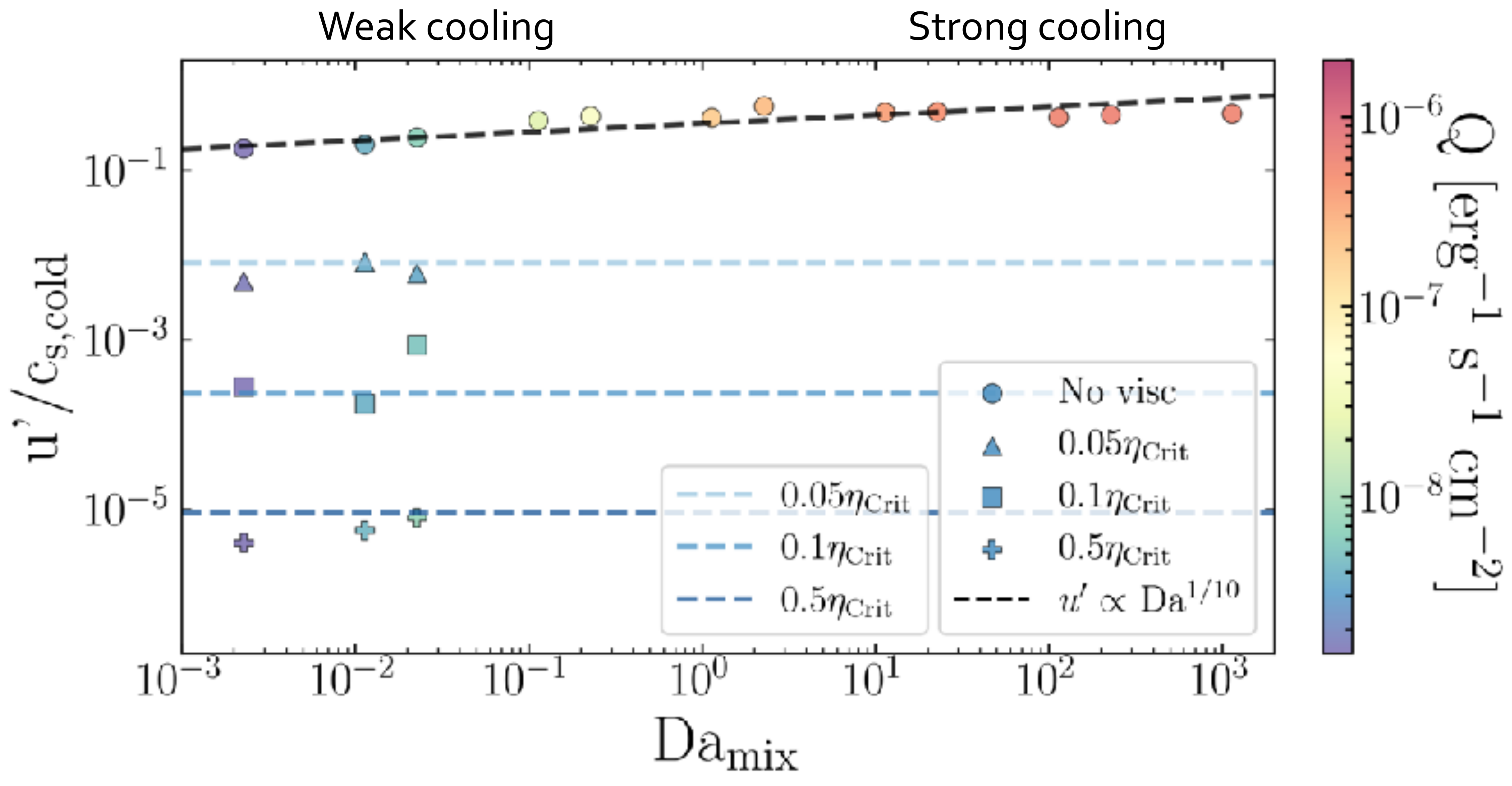

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  - …to the adiabatic value

Marin-Gilabert, MG, Oh (2025)

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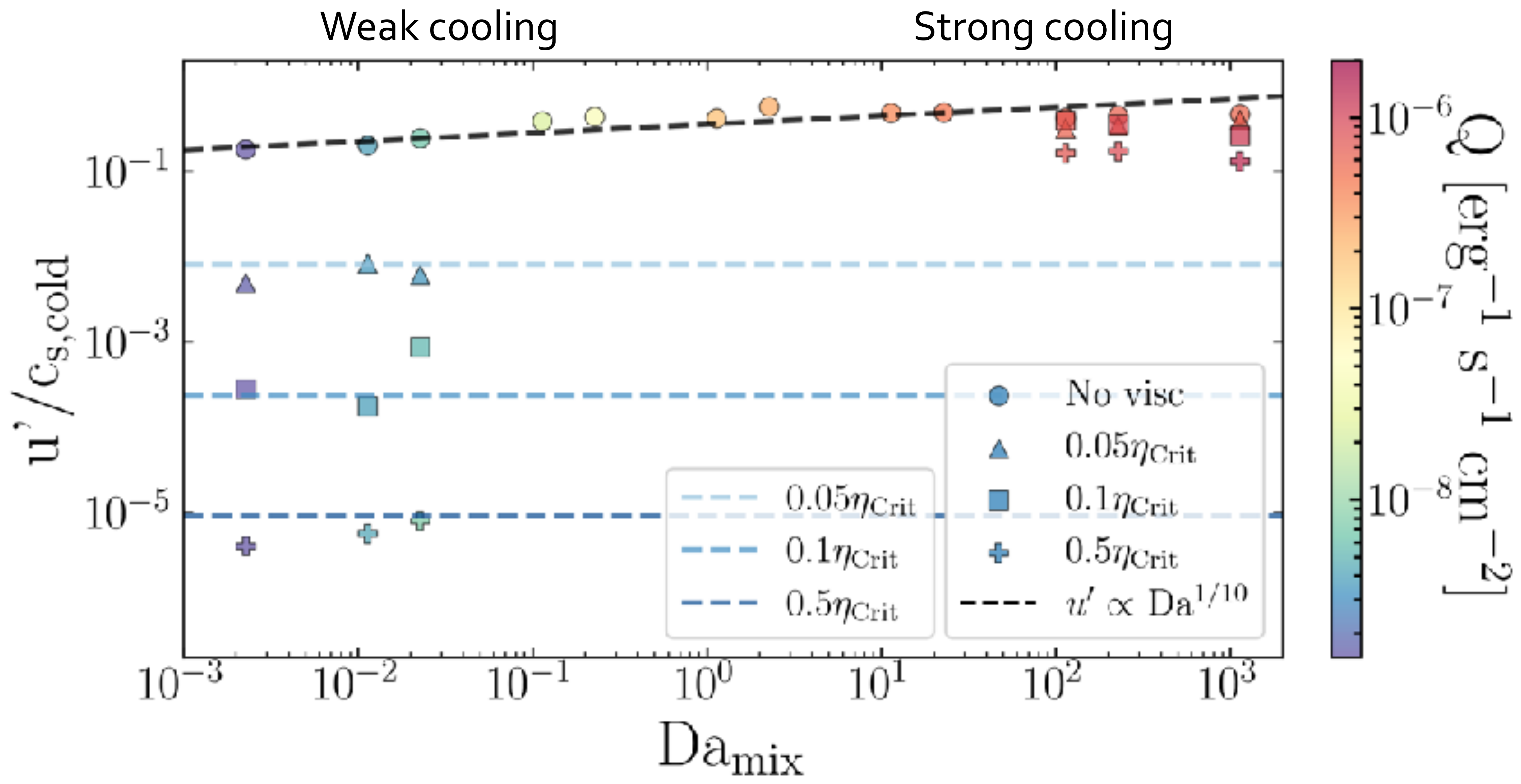

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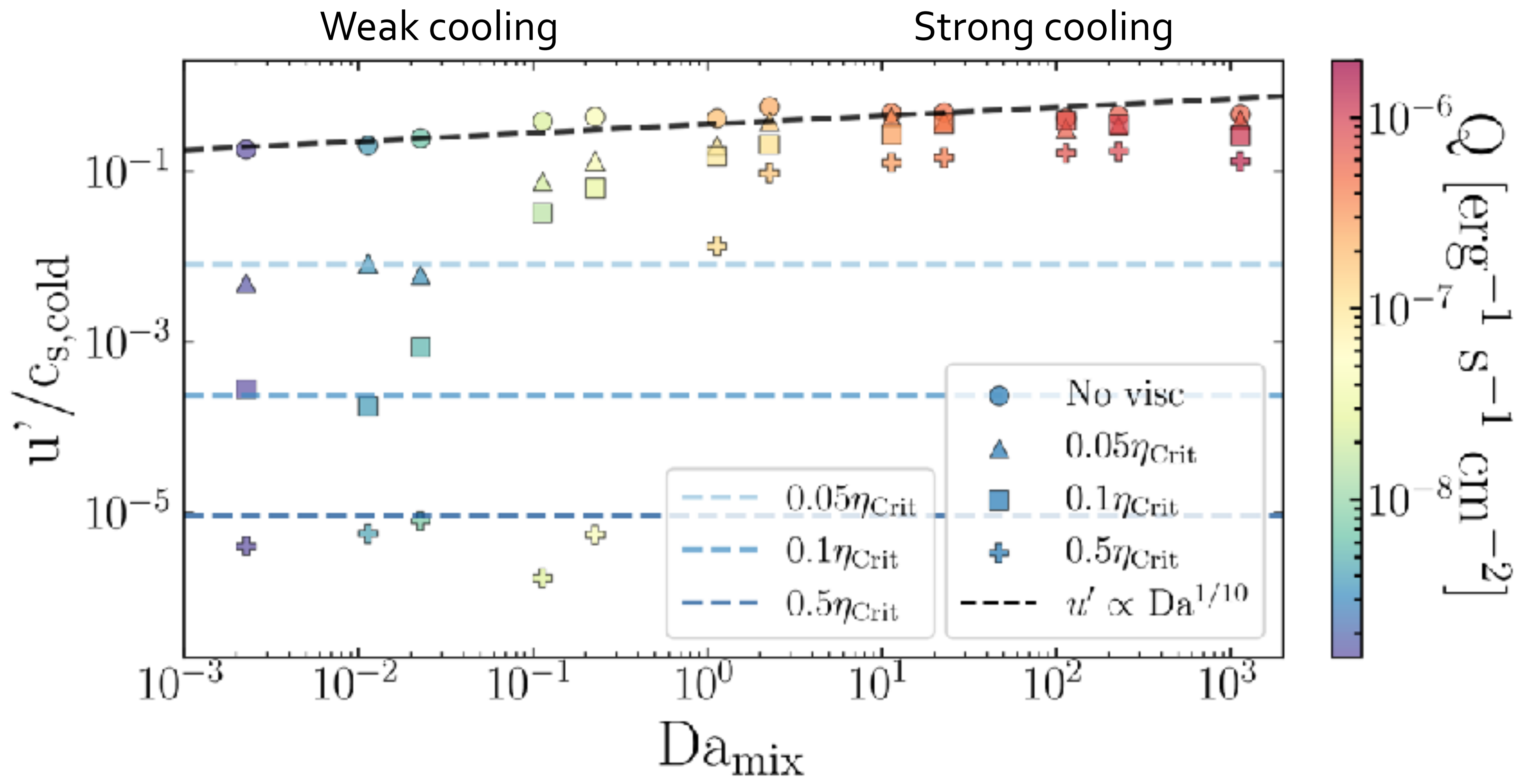

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(cf. Tan et al. 2020, Fielding et al. 2020)

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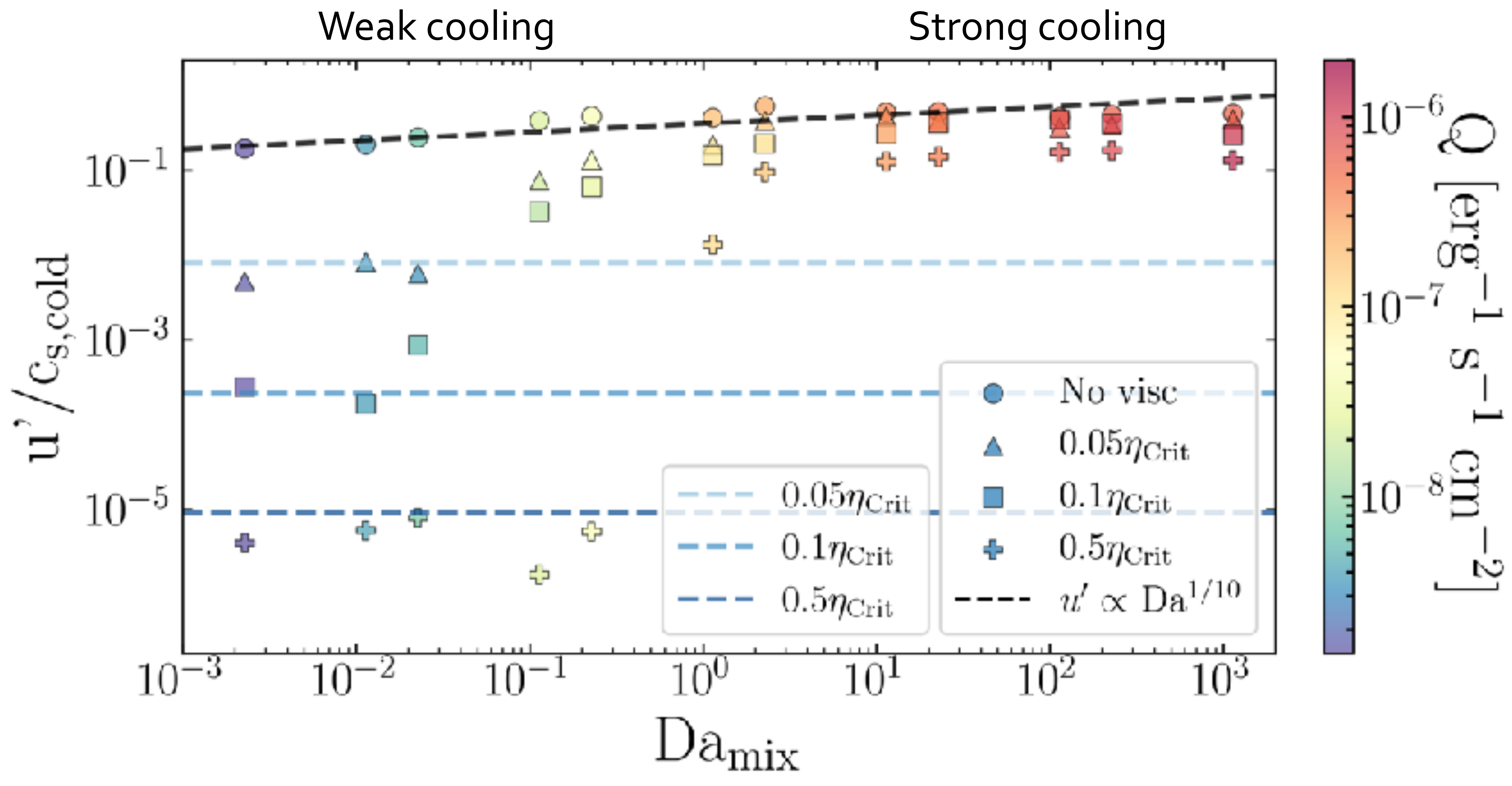

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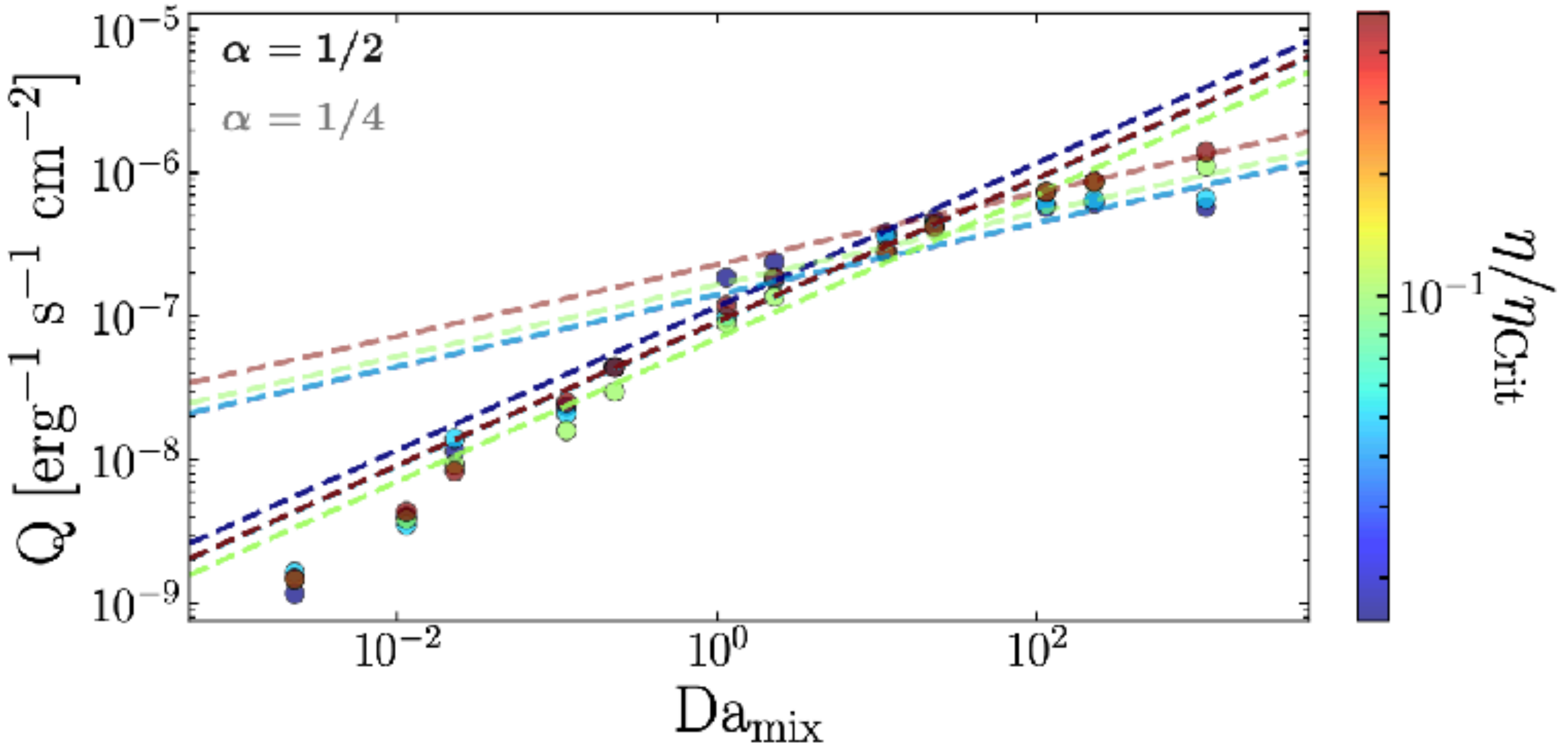

In both regimes the mass transfer rates are not affected by viscosity!

🤔

The (non-)effect of viscosity

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In the **weak cooling** regime $t_{\rm mix} \ll t_{\rm cool} \rightarrow$ *cooling* is the bottleneck (unaffected by ν)!

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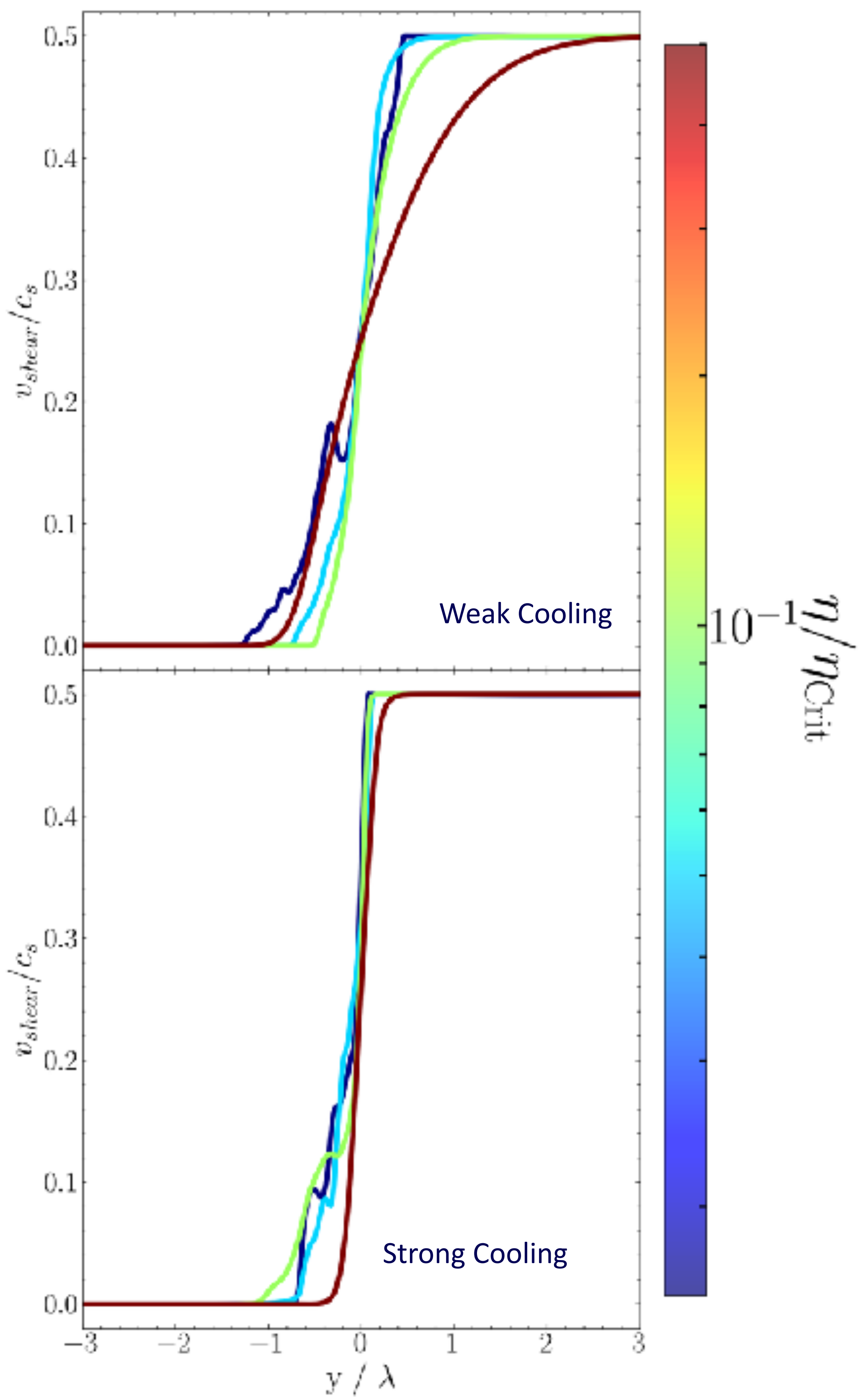
- in pressure equilibrium this leads to a sharp velocity profile



Marin-Gilabert, MG, Oh (2025)

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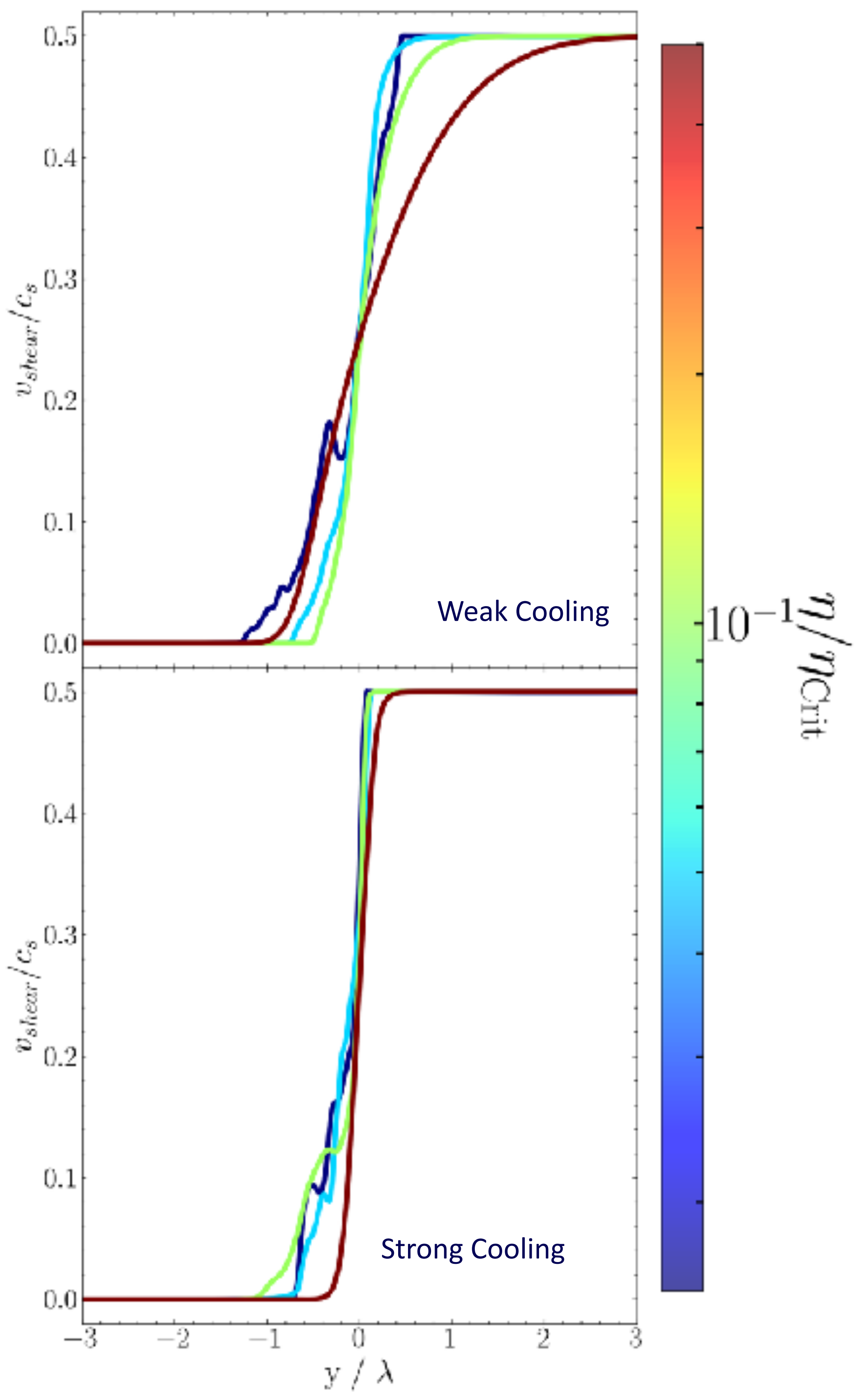

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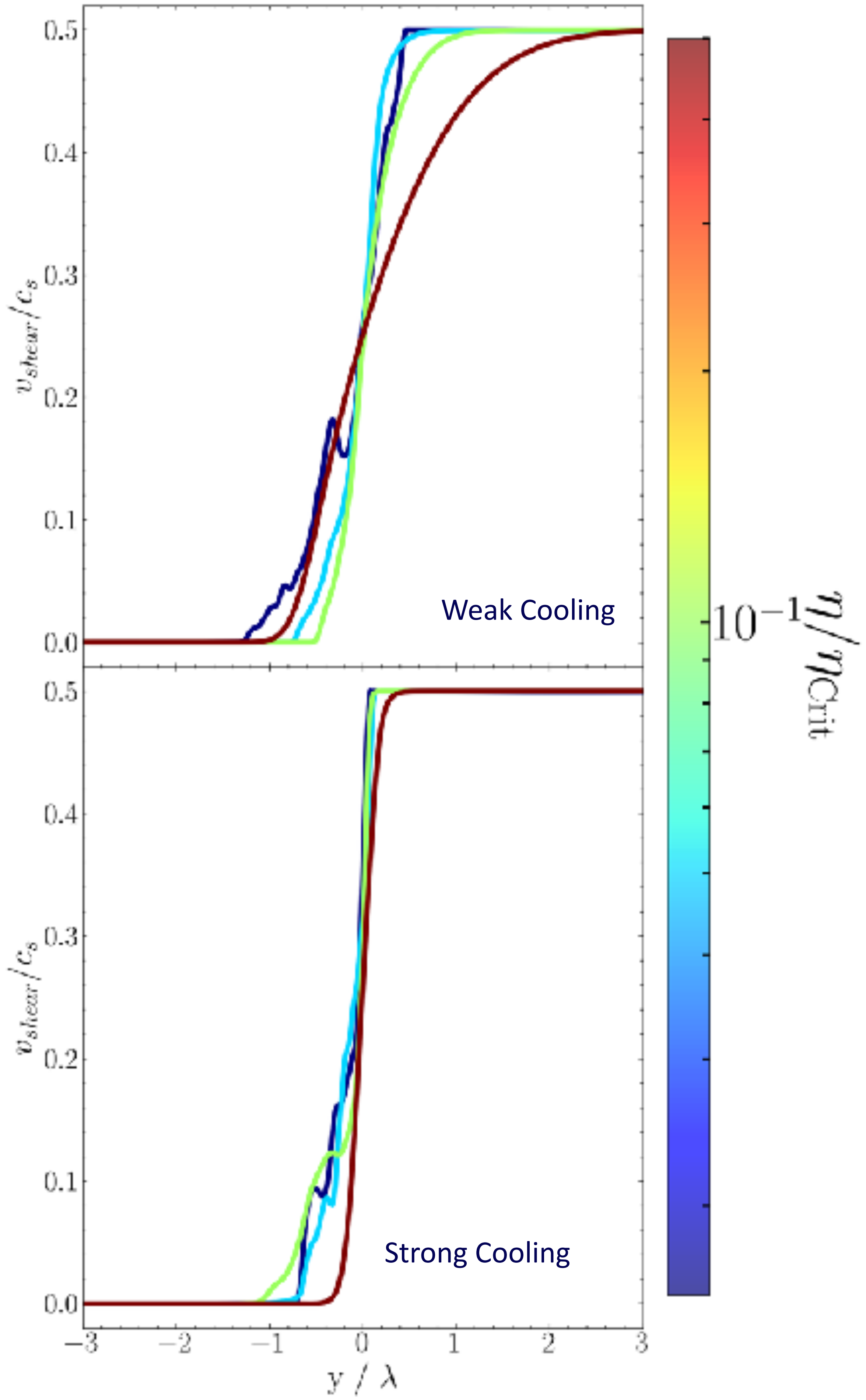

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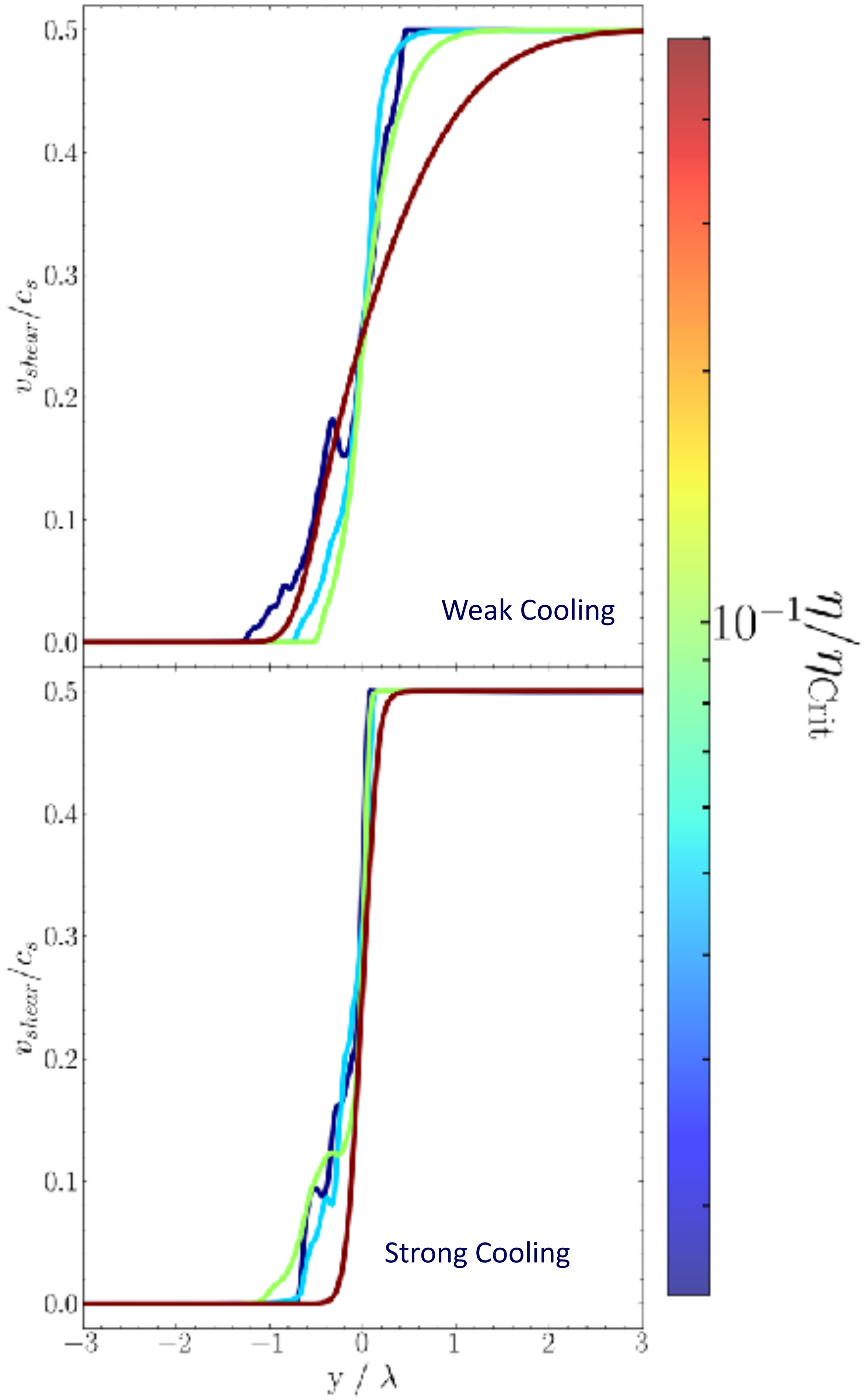

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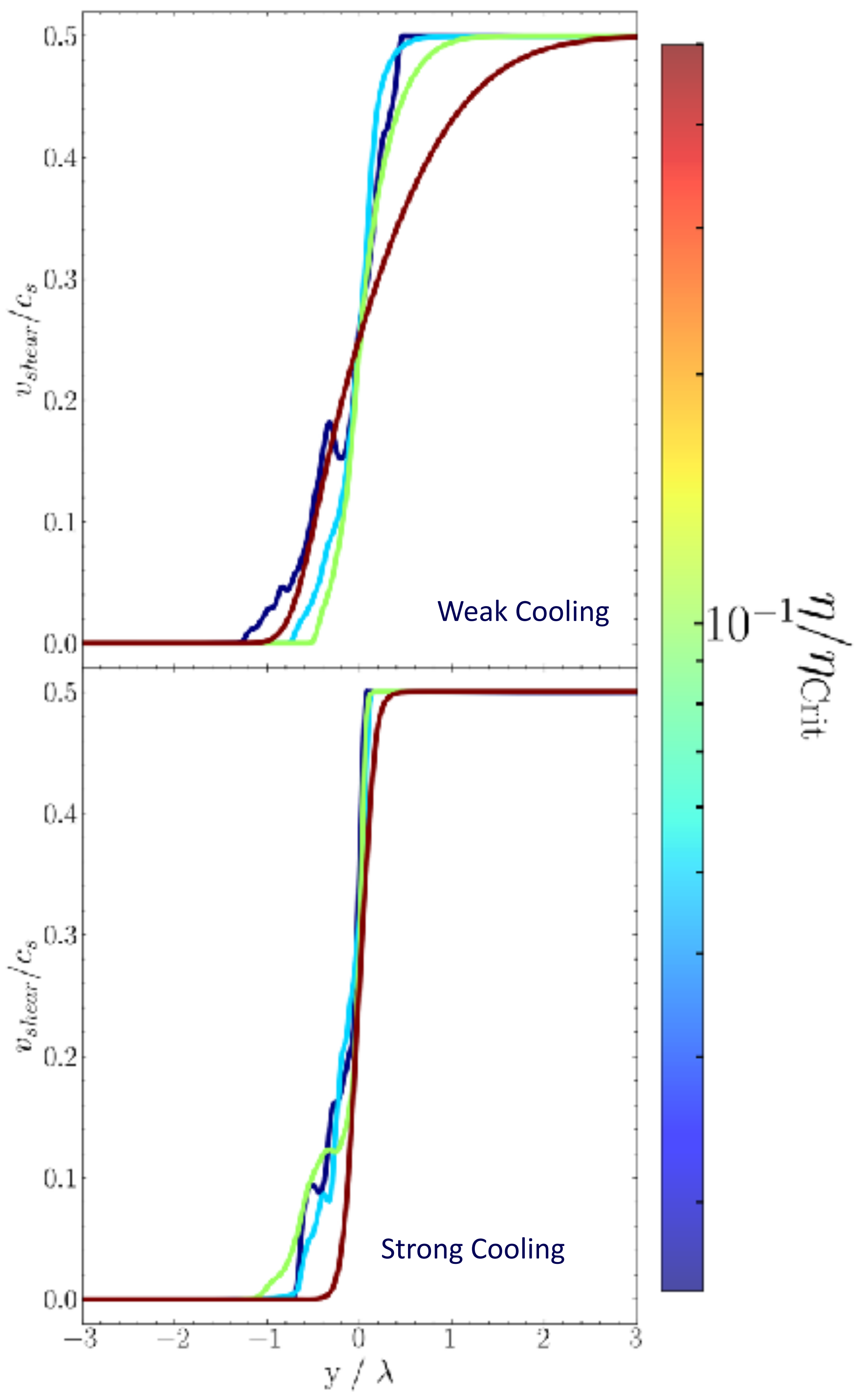

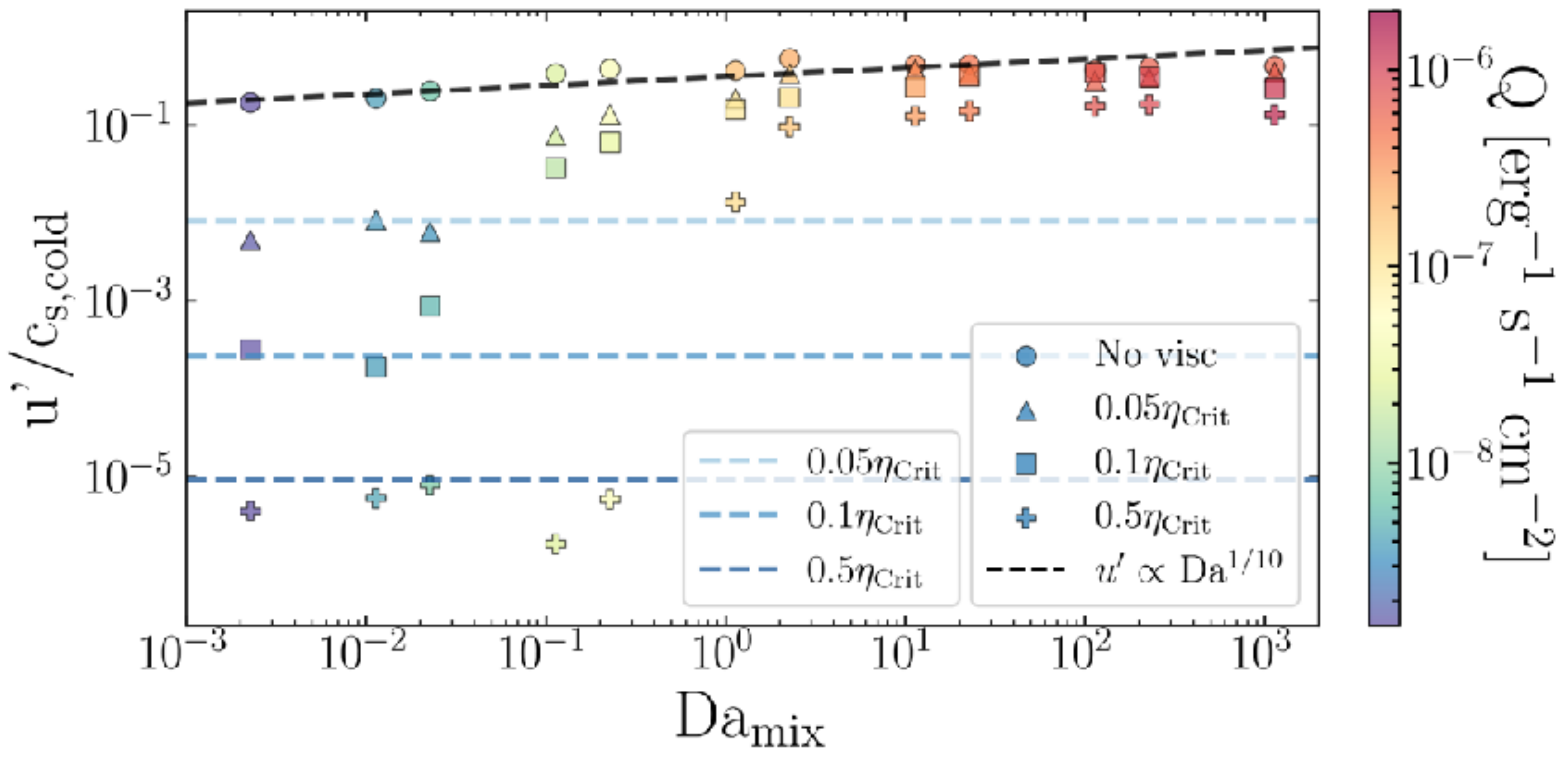

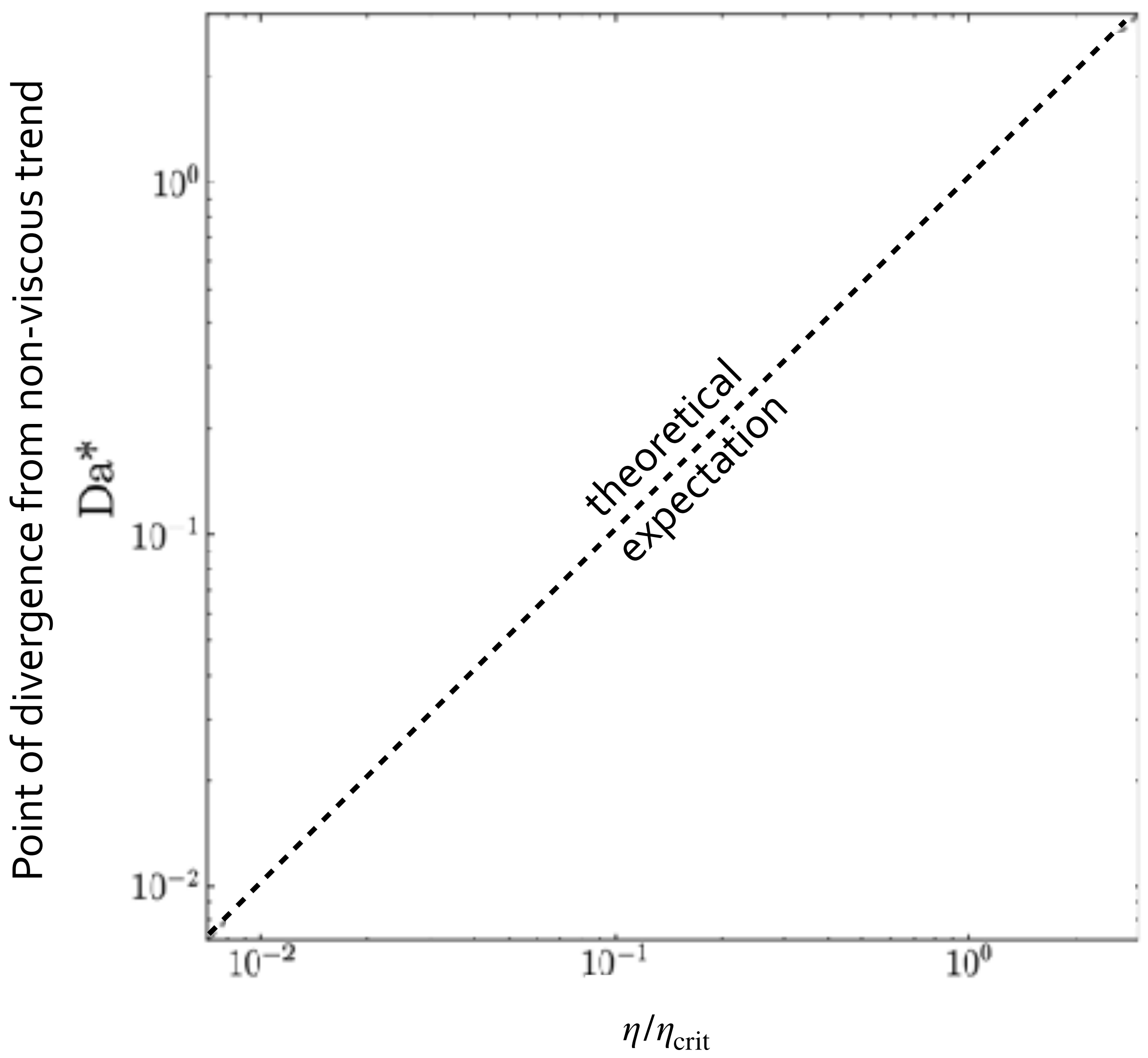

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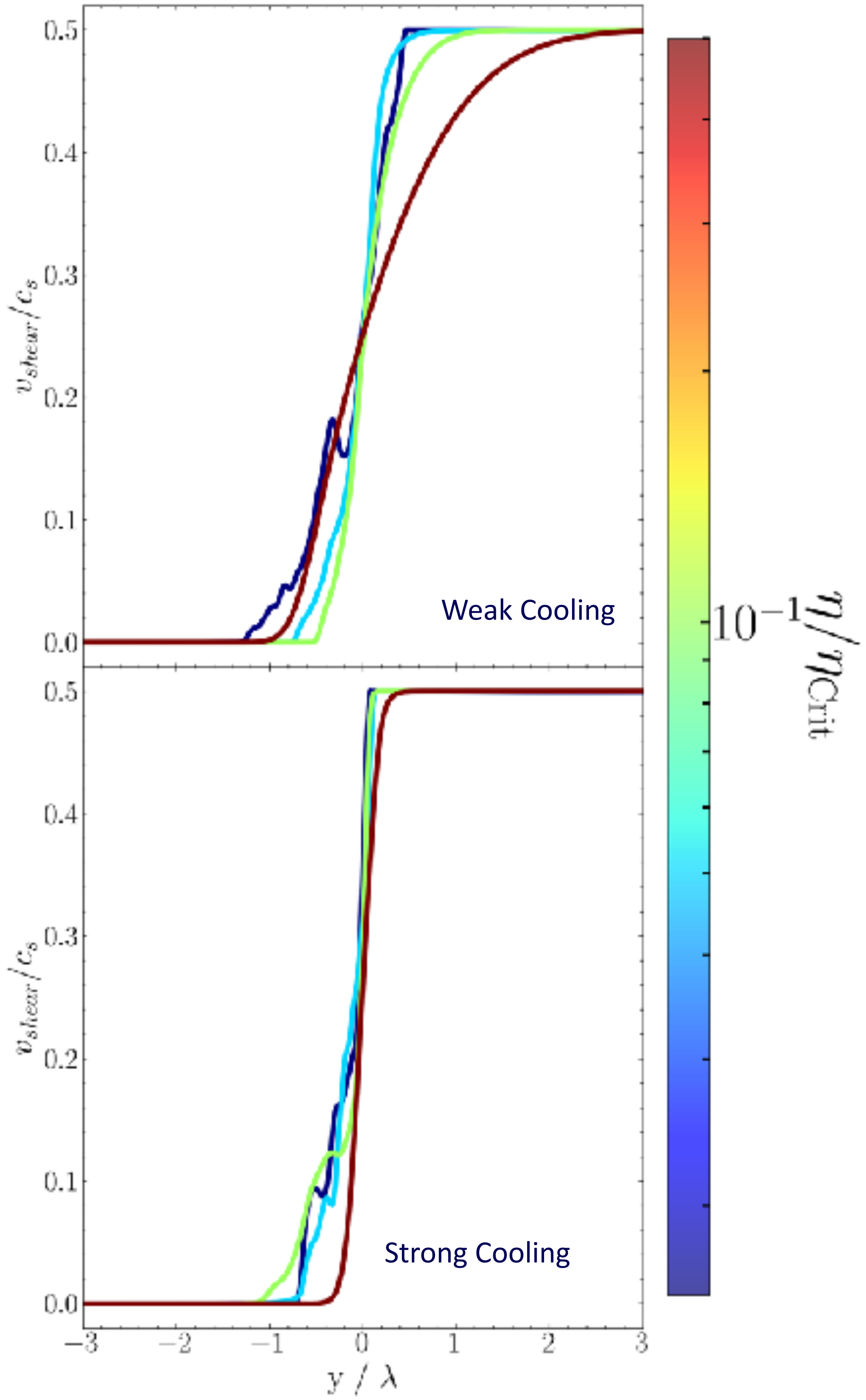

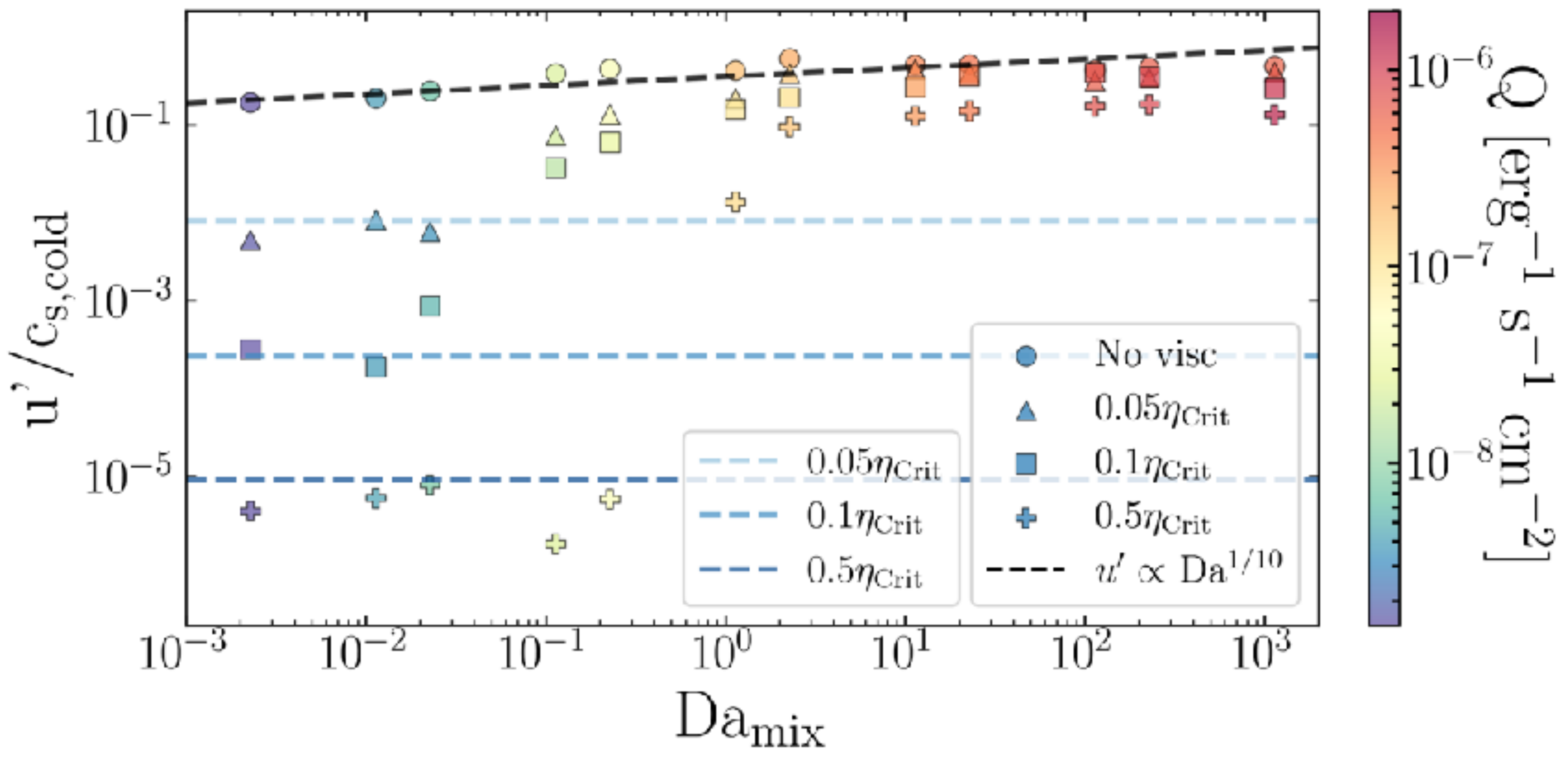

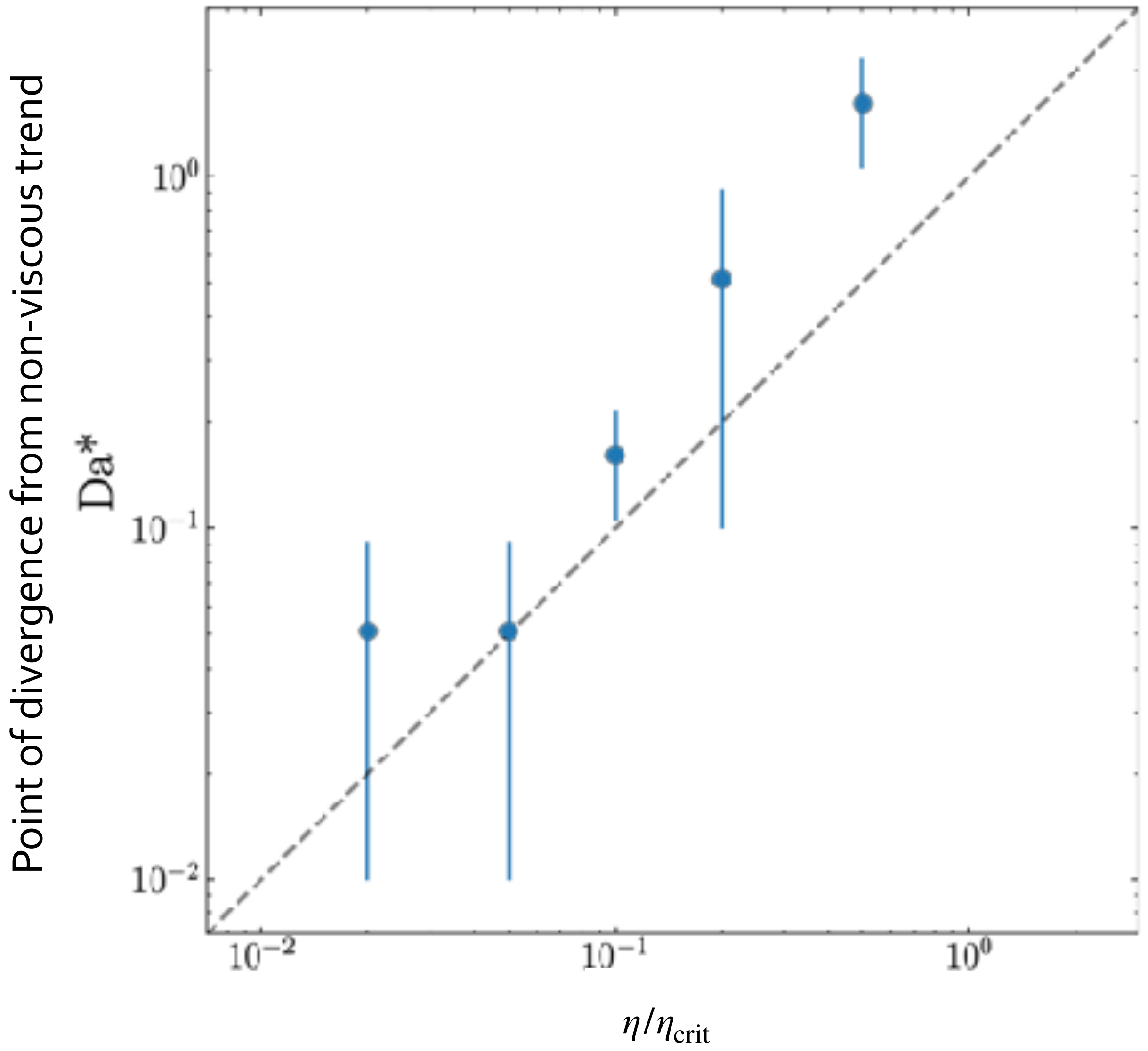

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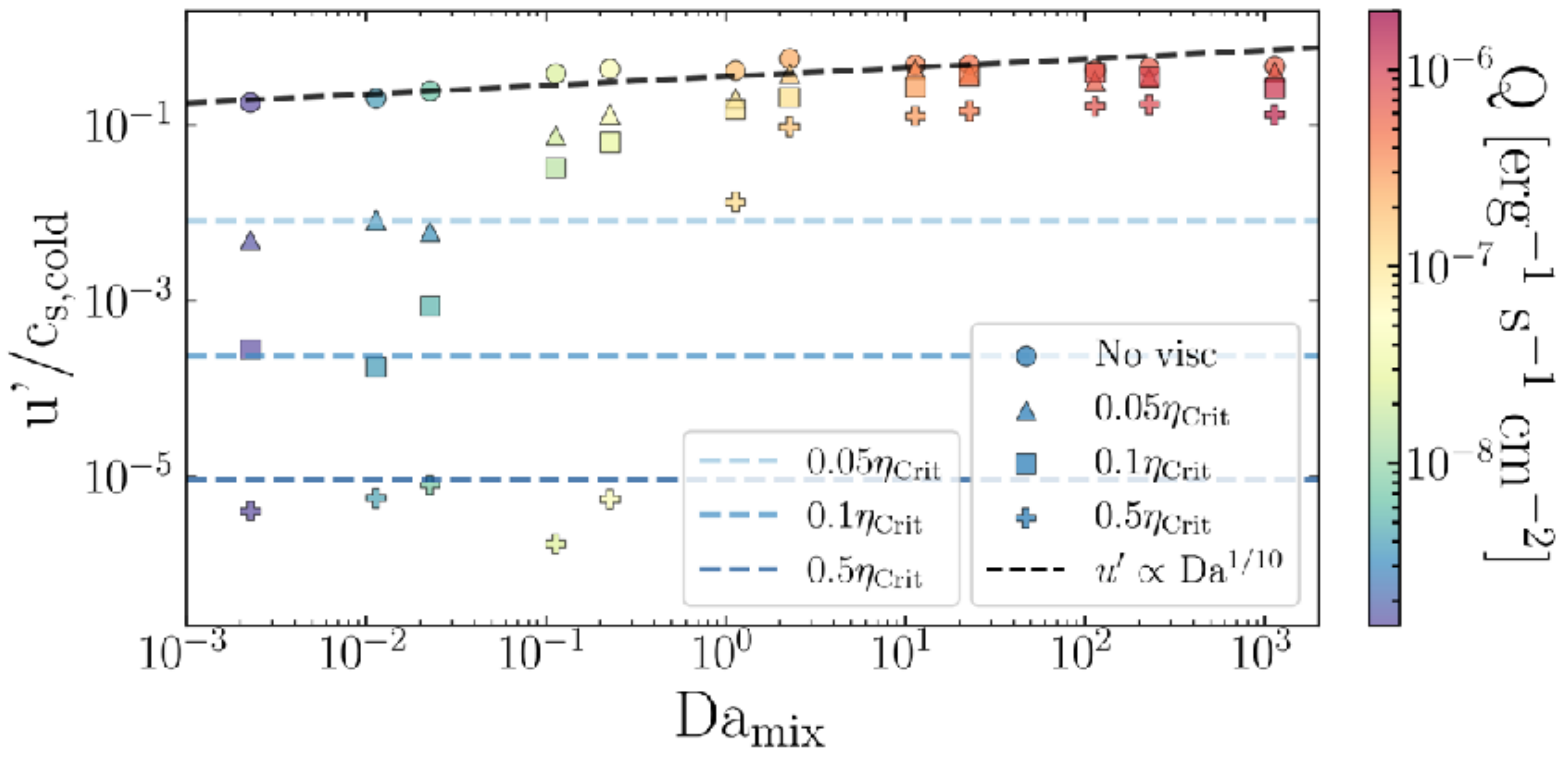
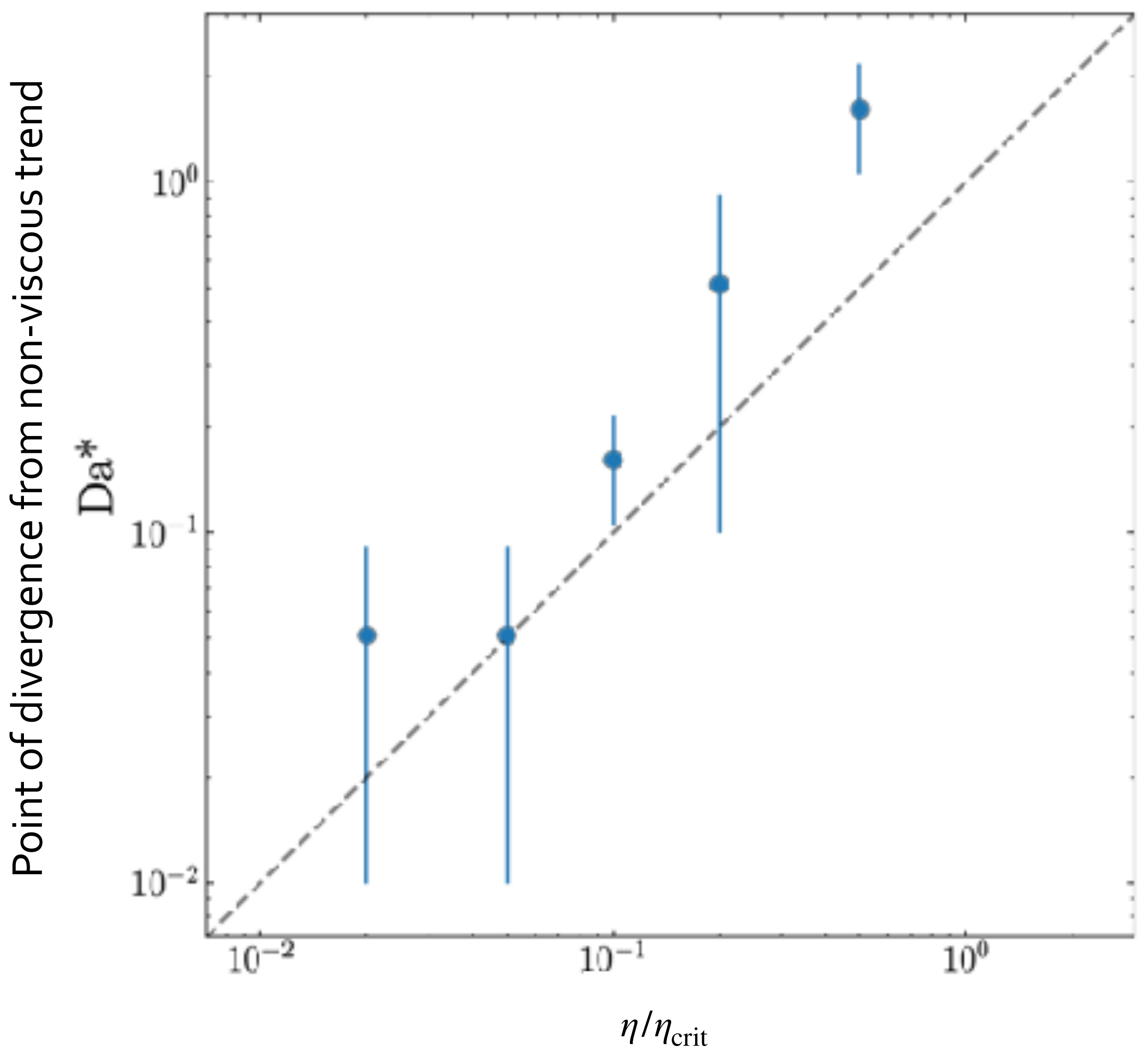
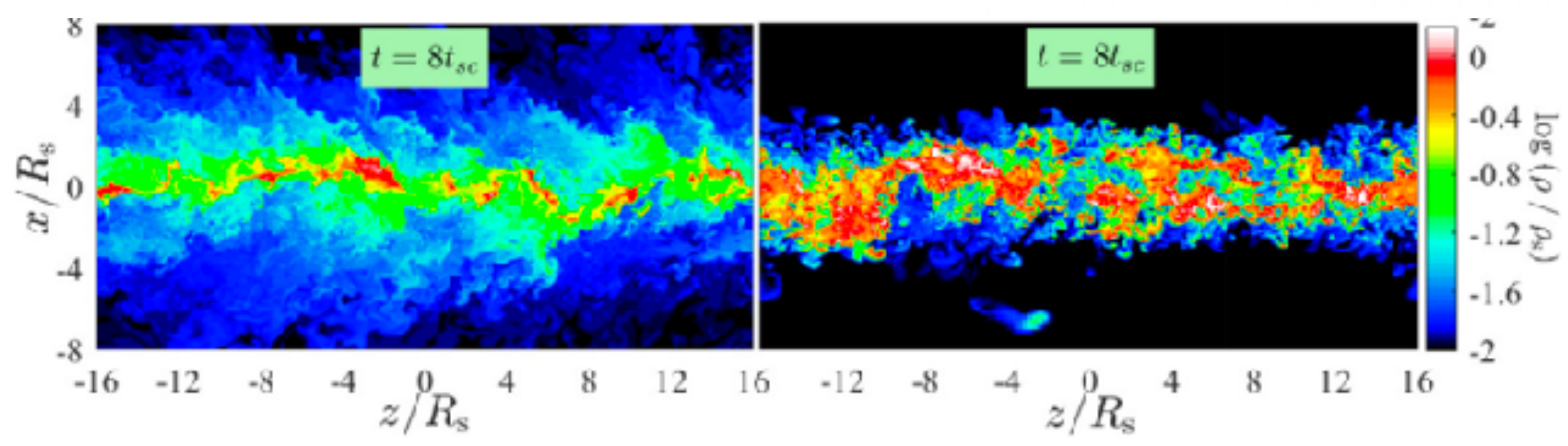
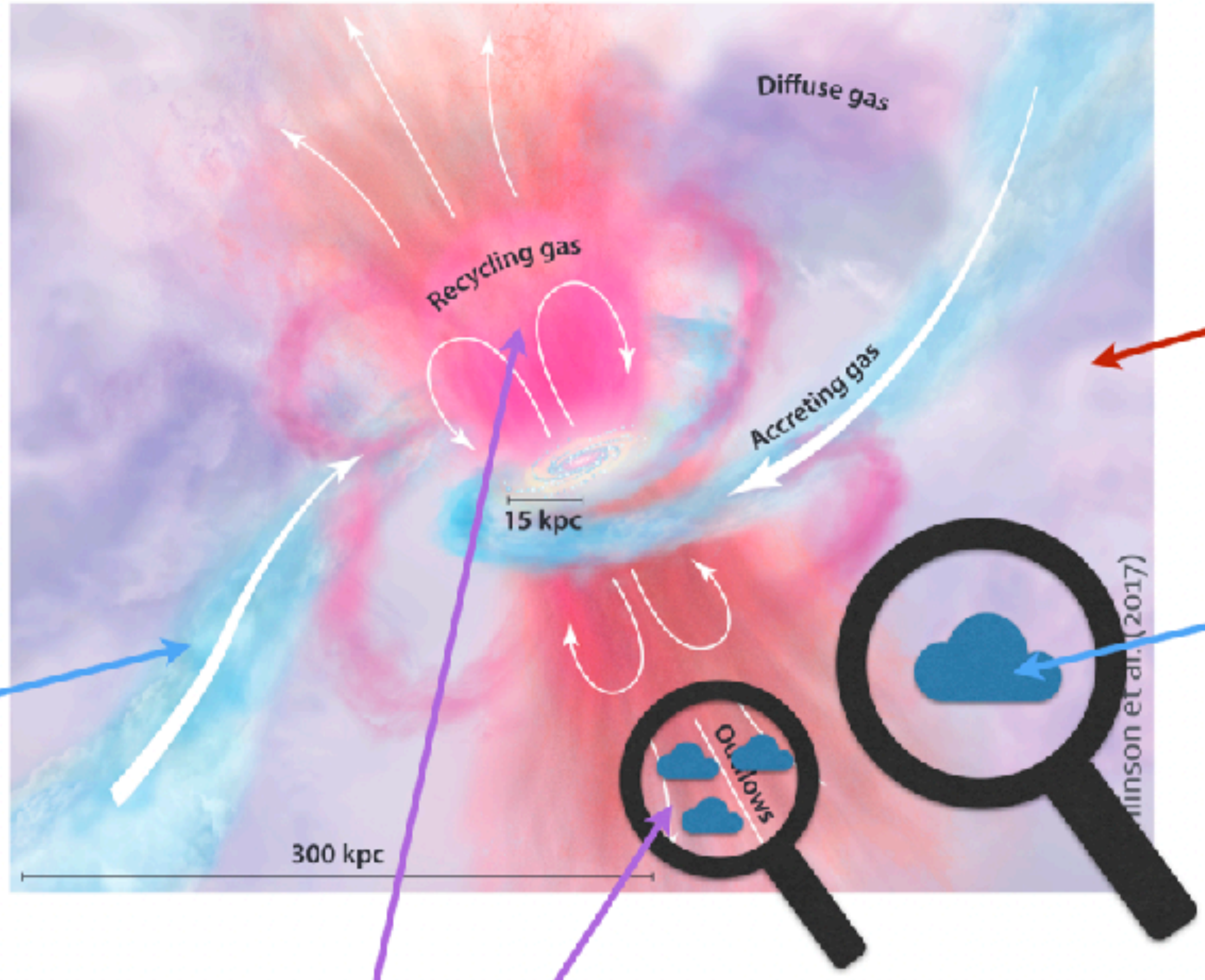


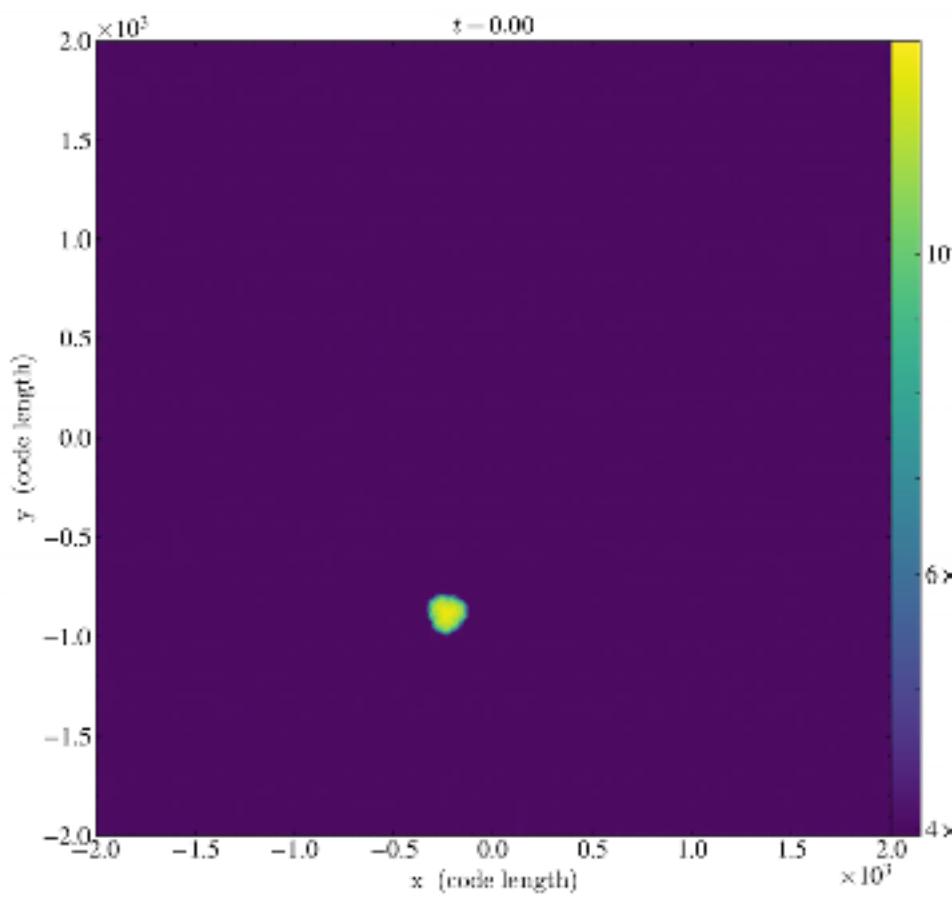


The (non-)impact of viscosity on the multiphase CGM

Mandelker et al. (2020)





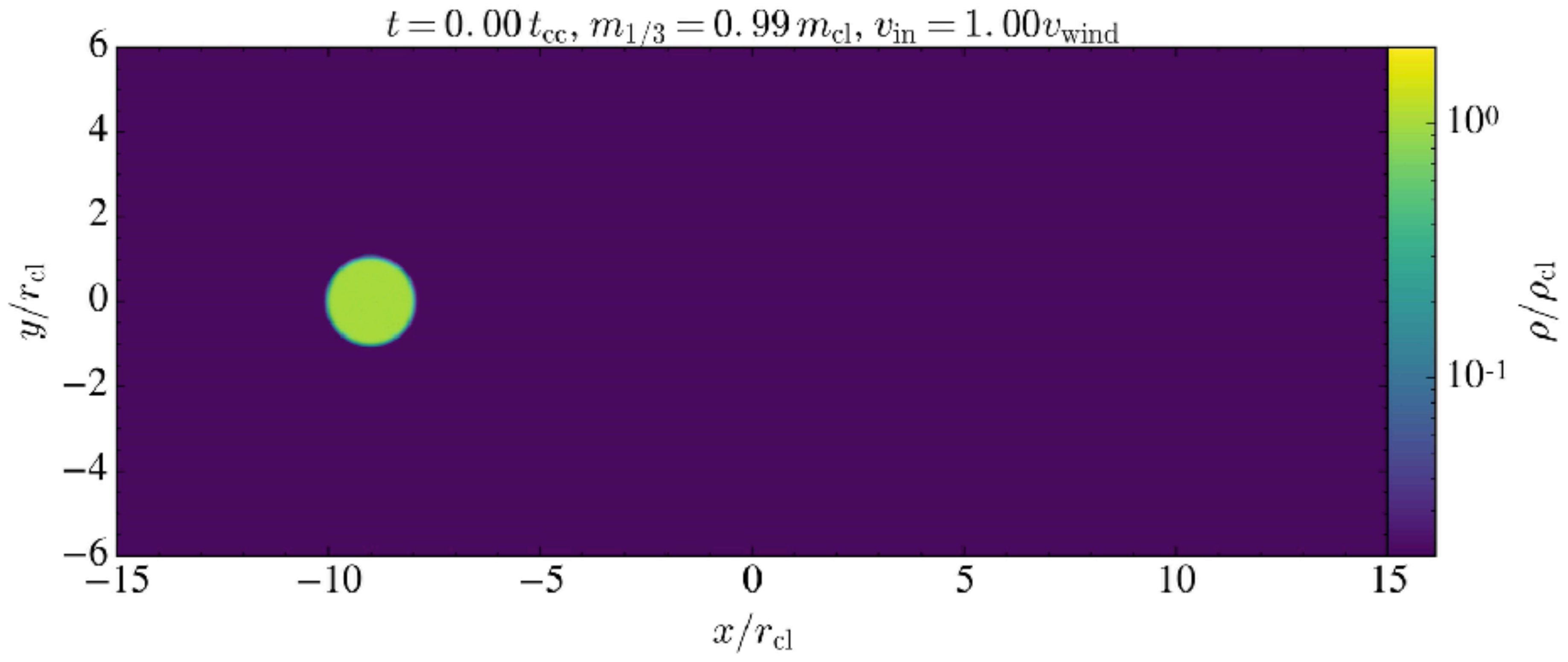


hot $T \sim T_{\rm vir} \sim 10^6$ K gas halo

small ($\lesssim$ 10s pc) cold ($\sim 10^4$ K) gas clouds

cold ($\sim 10^4$ K) streams (at higher z) fueling galaxies

multiphase ($\sim 10^{6-8}$ K vs. 10^{1-4} K) galactic winds and fountain flows



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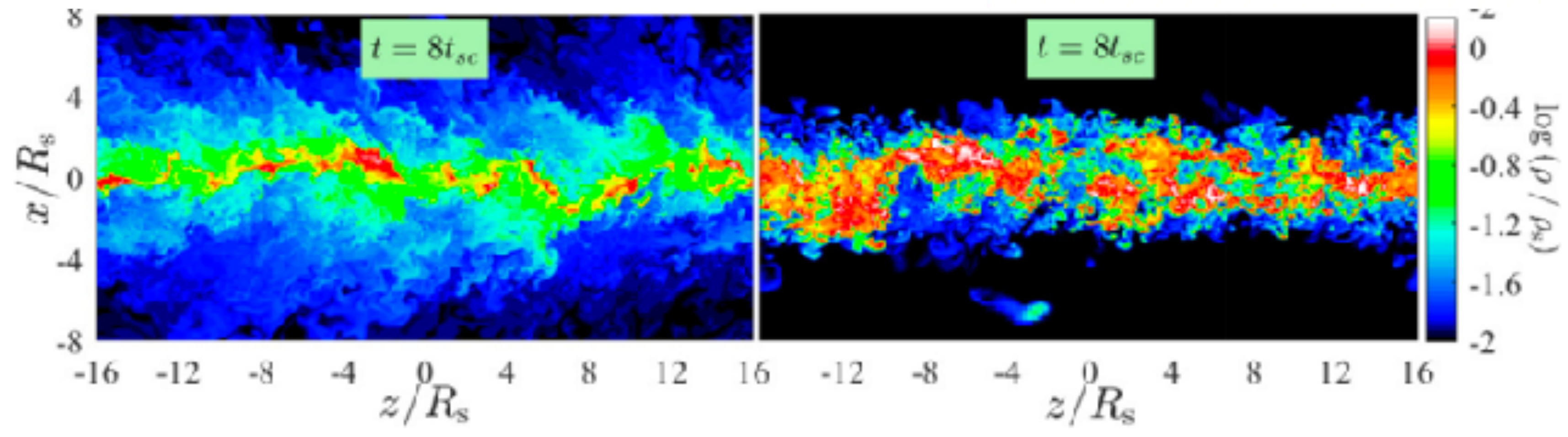

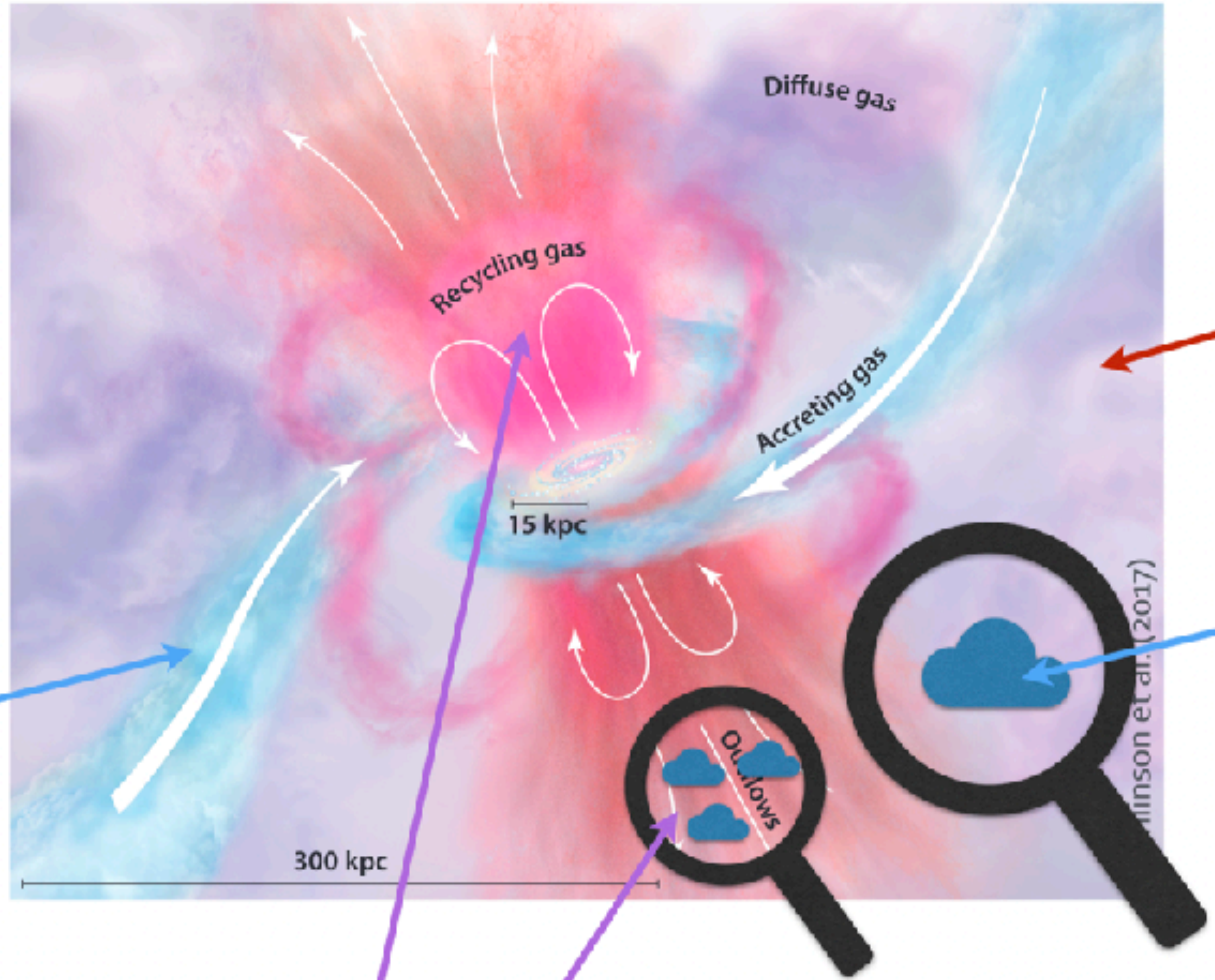

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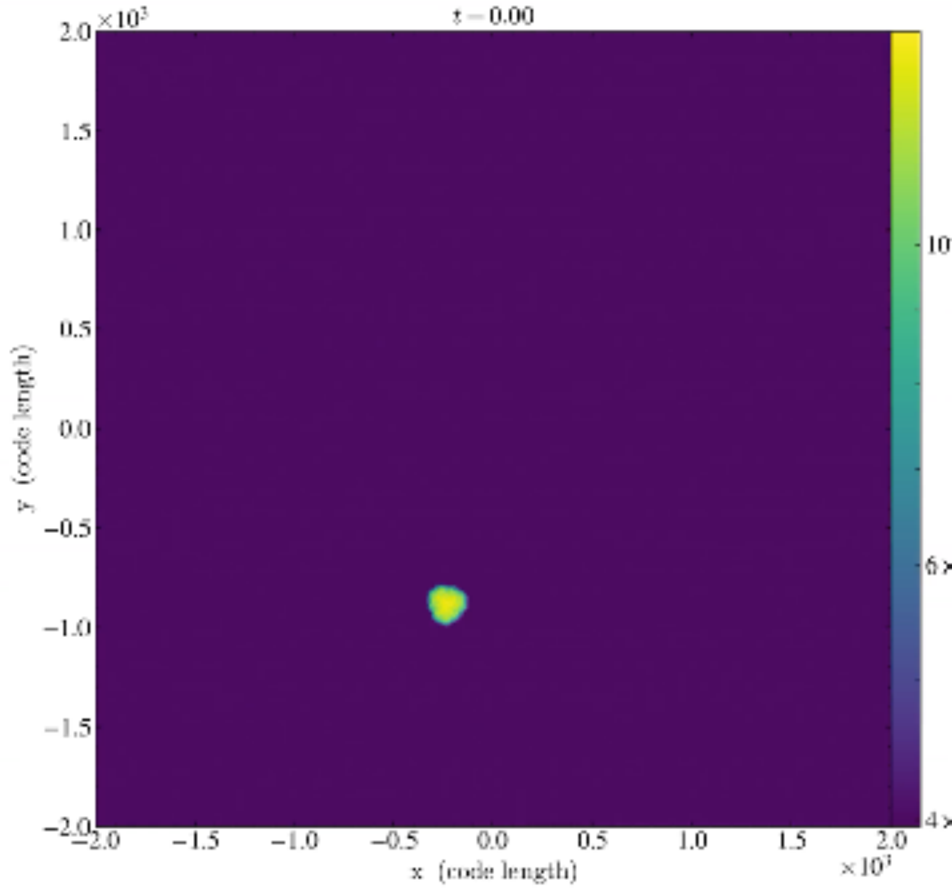

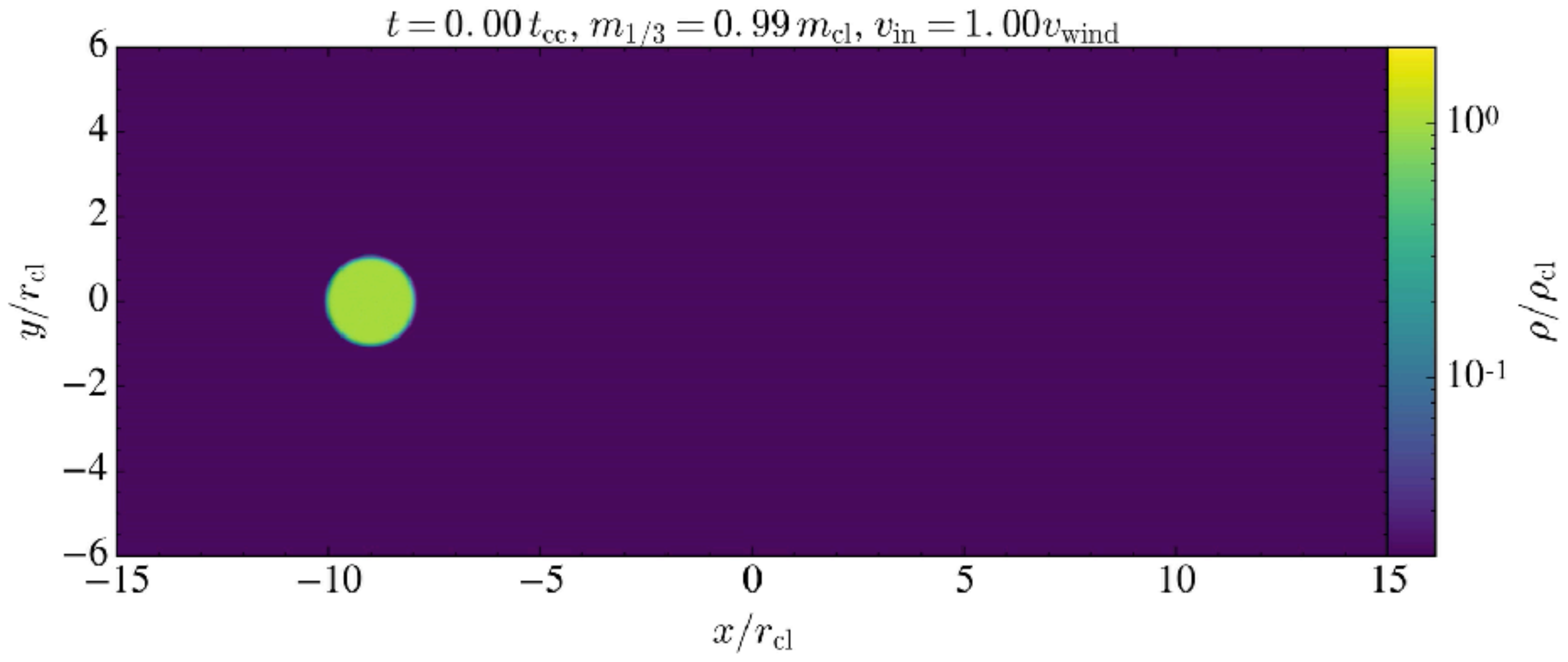

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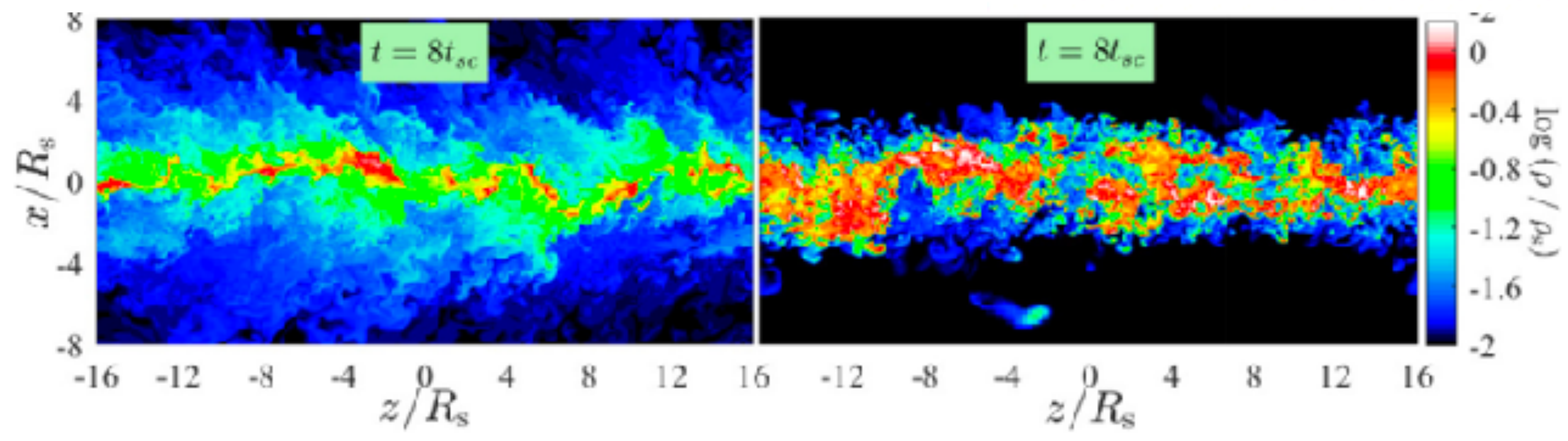

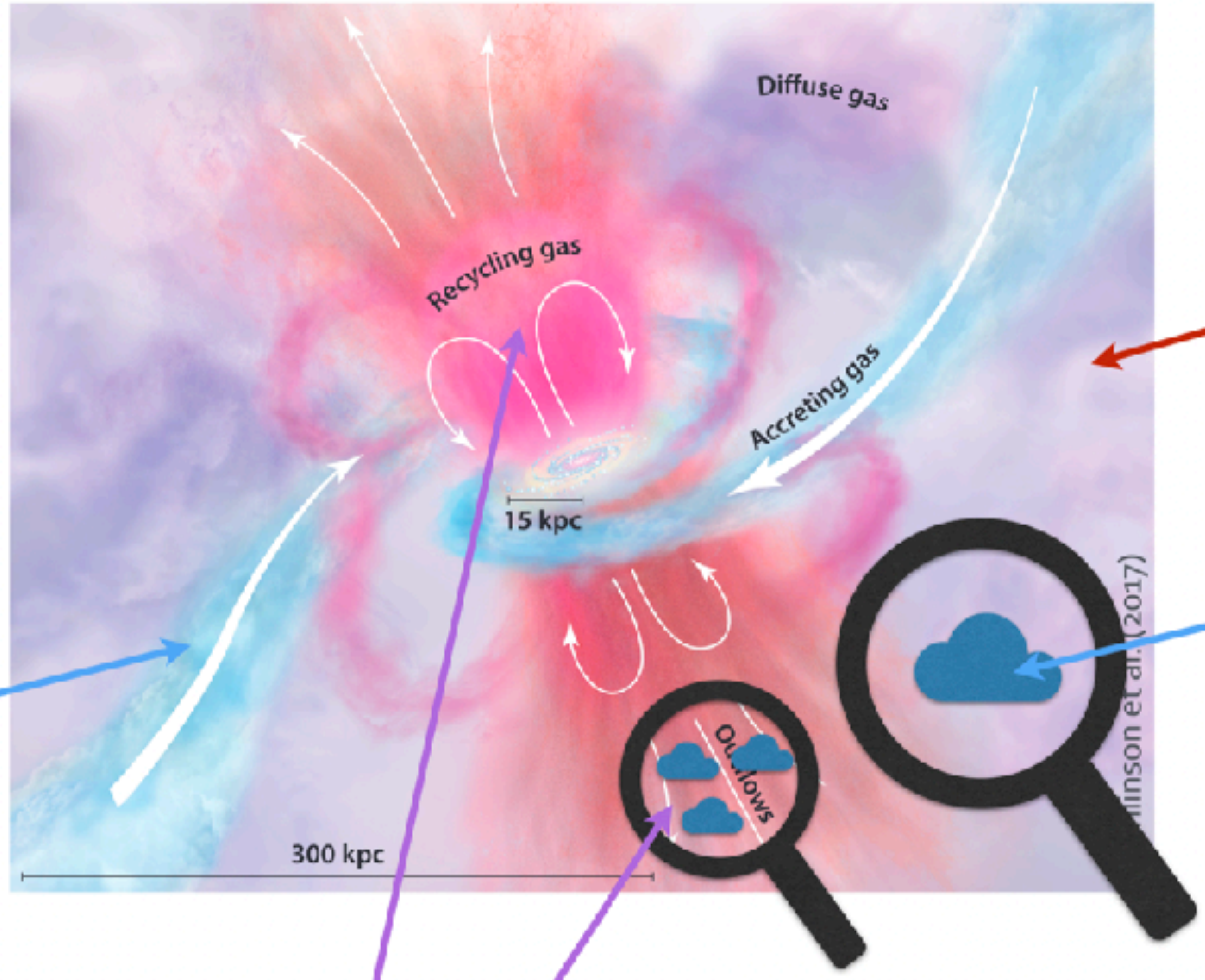

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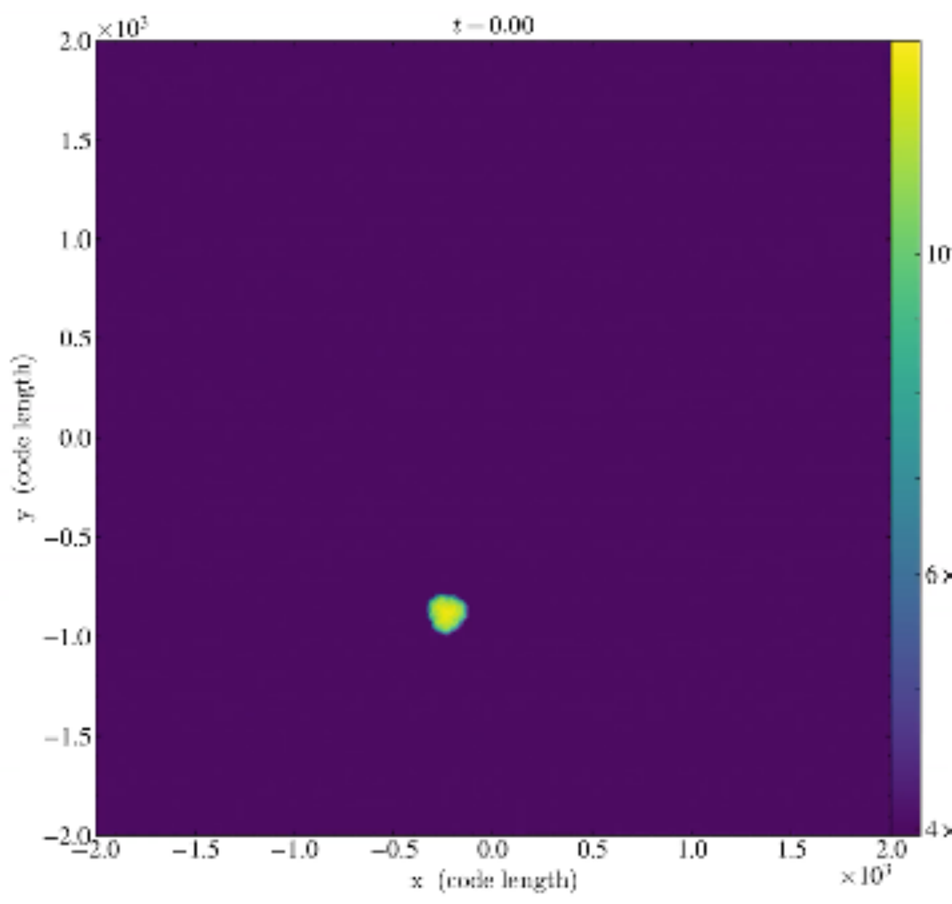
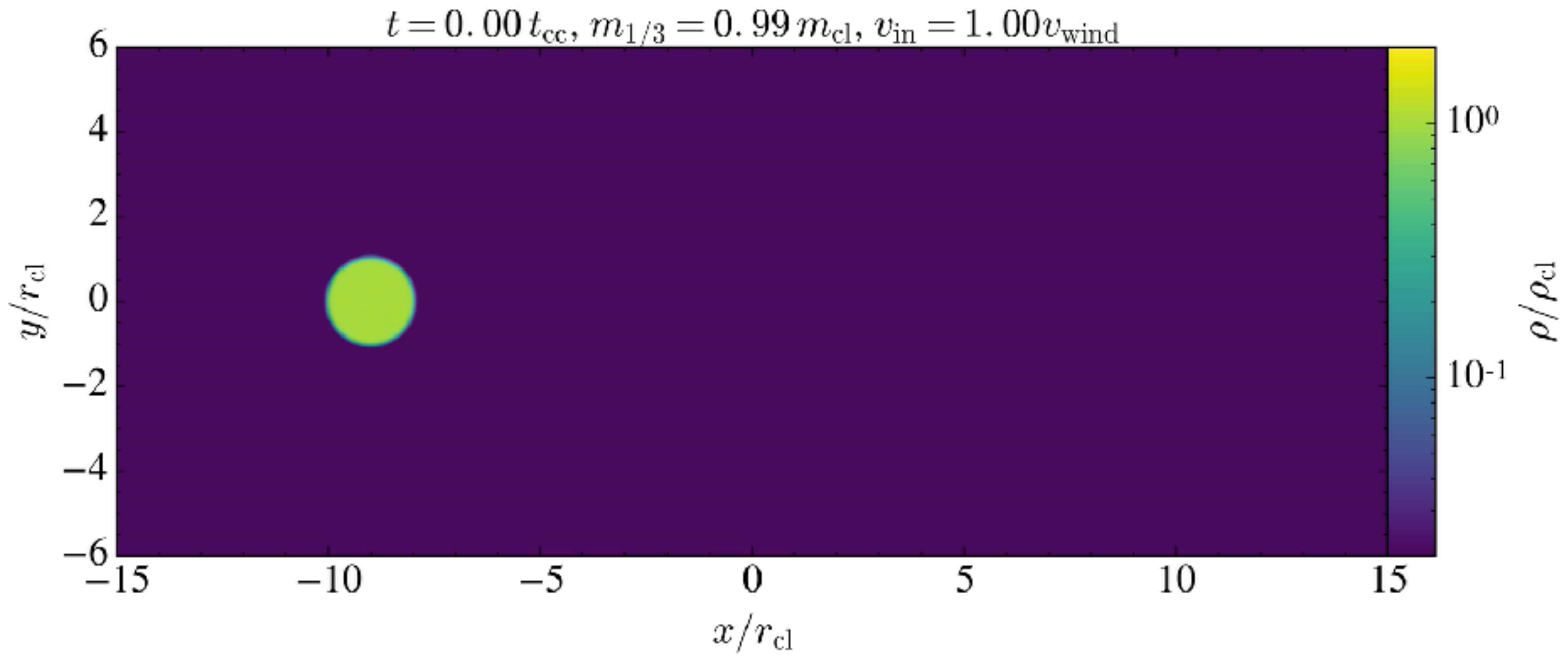
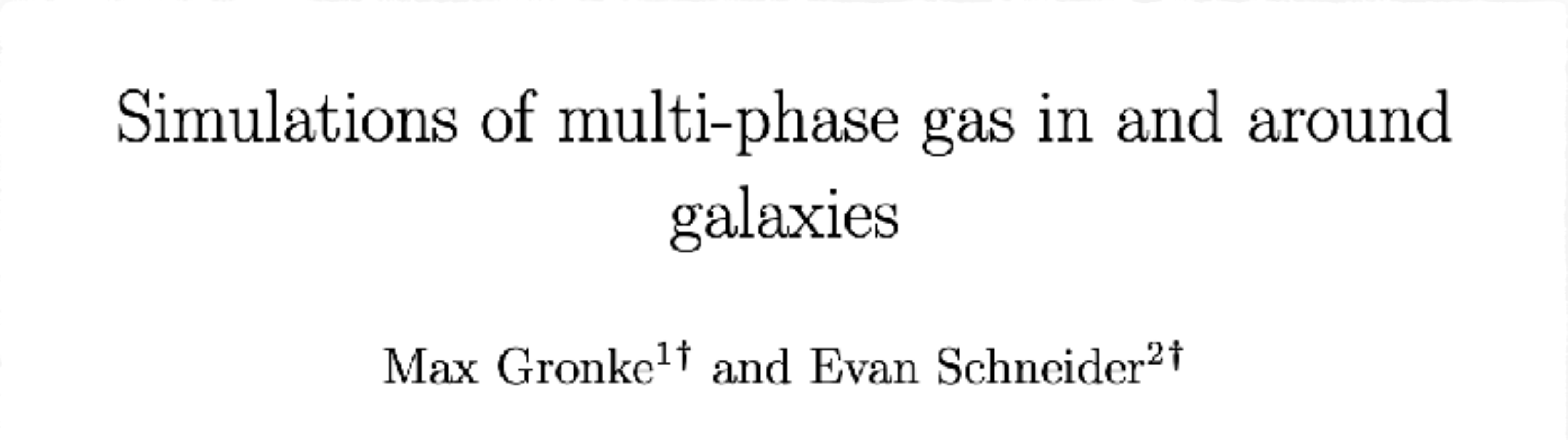




Don't worry about viscosity!

Multiphase gas dynamics



Simulations of multi-phase gas in and around galaxies

Max Gronke[1†] and Evan Schneider[2†]

…on the arXiv soon!

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- Volker Springel

Multiphase gas dynamics

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...on the arXiv soon!

"Writing a review is to science what playing golf is to sport."
- Volker Springel

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Summary & conclusion

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Appendix

Temperature dependent viscosity

$$\eta_{\rm Hot} = \eta_{\rm Cold} \left(\frac{T_{\rm Hot}}{T_{\rm Cold}} \right)^{5/2} = \eta_{\rm Cold}\, \chi^{5/2} \,. \tag{35}$$

$$\nu > \nu_{\rm Crit} = \frac{\lambda\, \Delta v_{\rm shear}}{100} \frac{(\rho_{\rm hot}\, \rho_{\rm cold})^{1/2}}{(\rho_{\rm hot} + \rho_{\rm cold})} \,.$$

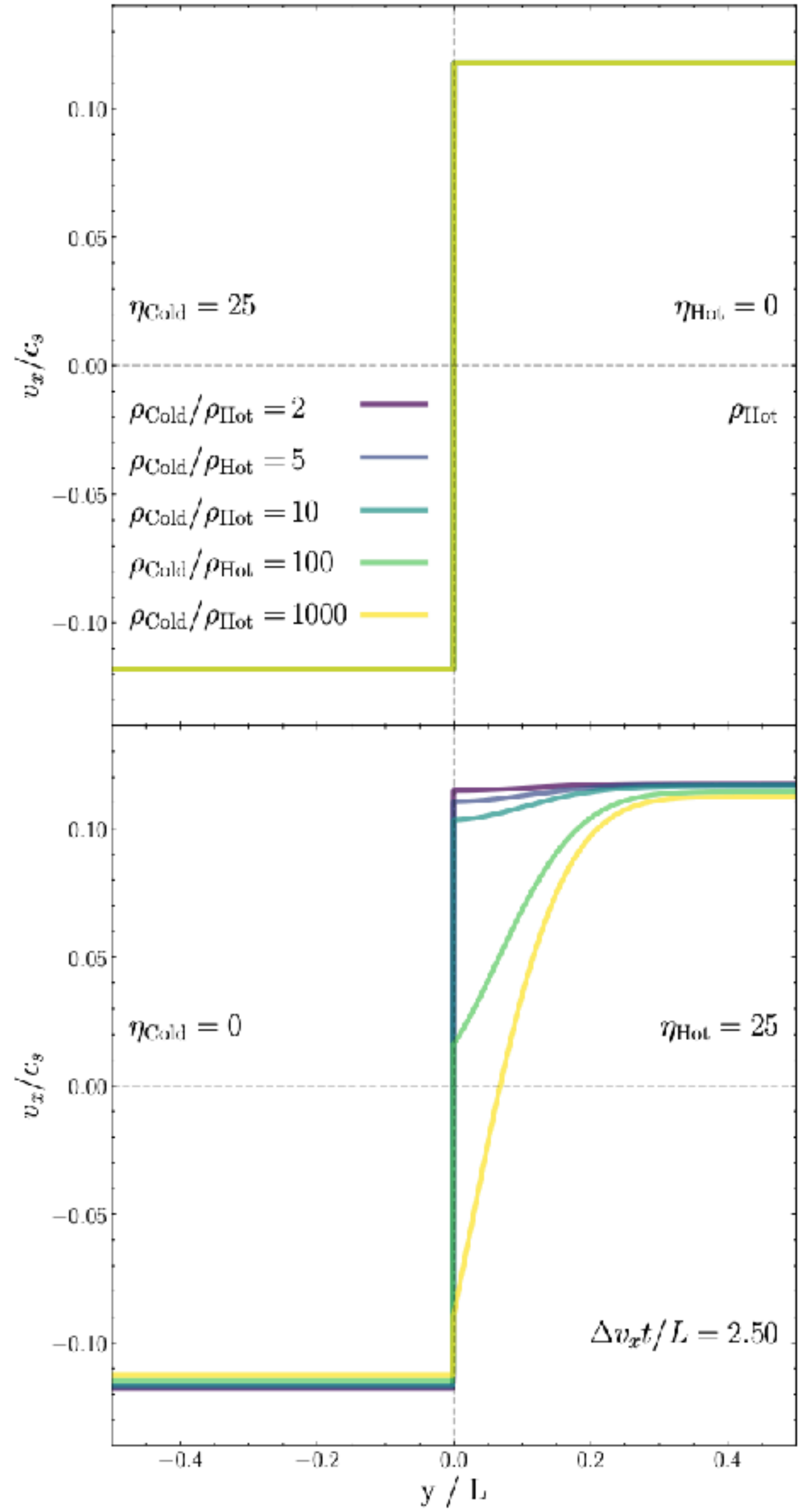

Fig. 14. Velocity profile of 1D simulations. *Top panel*: Only the cold gas ($y < 0$) is viscous. *Bottom panel*: Only the hot gas ($y > 0$) is viscous.