3D hydrodynamic simulations of gas reinserted within super star clusters

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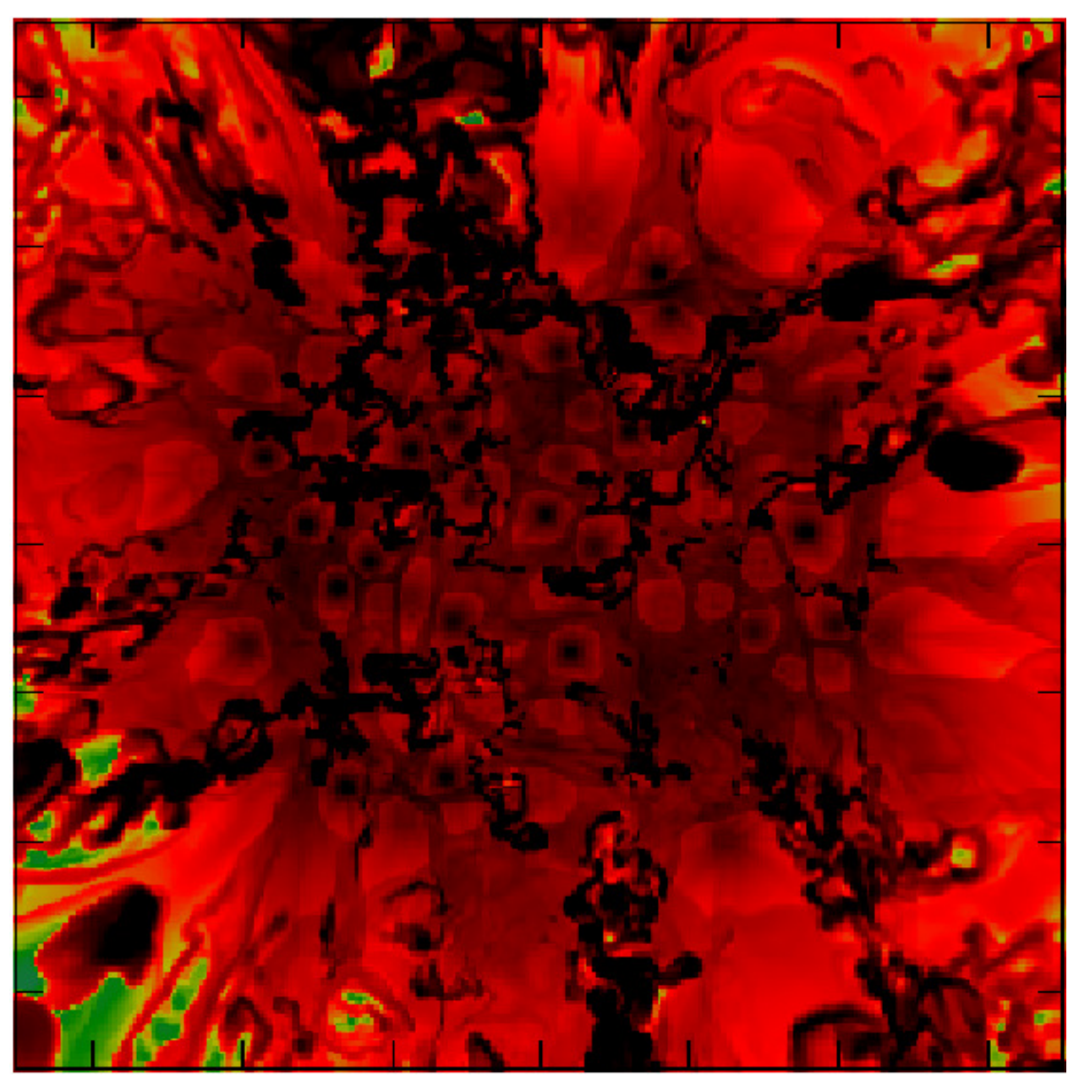
Abstract:

There are two independent observational clues that the temperature of the hot medium in Super Star Clusters (SSCs) is substantially lower than the temperature obtained if all the mechanical energy inserted by stars (SNe, stellar winds) is used to heat up the inserted gas. They are: (a) observed SSCs' recombination lines are too narrow, and (b) HII regions related with SSC are too small.

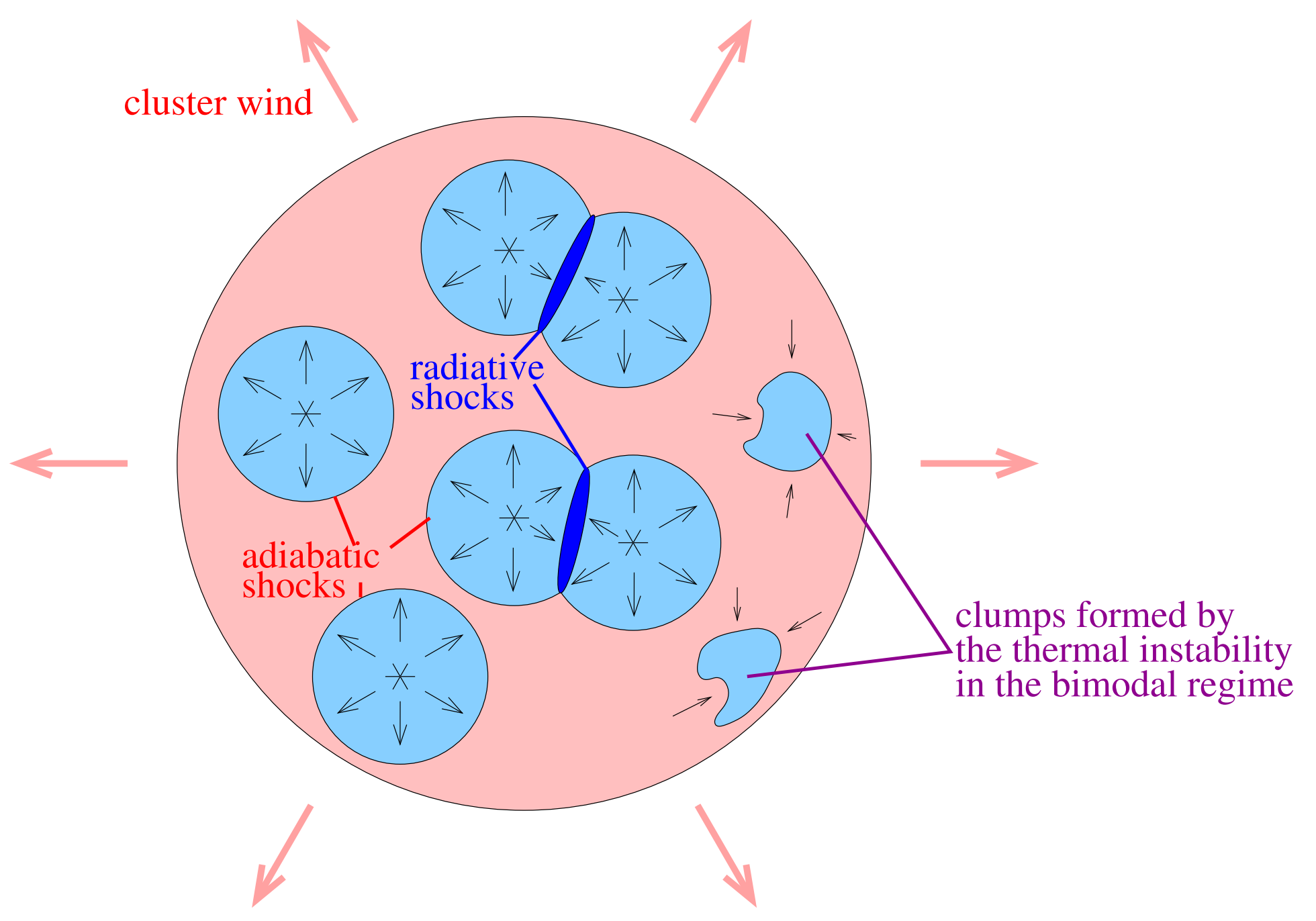
There are two mechanisms suggested to explain this discrepancy: (1) the heating efficiency ($\eta_{\rm he}$) of the thermalization process is low ($\sim 5-10\%$), and (2) mass loading ($\eta_{\rm ml}$) with the primordial gas.

In this work we study the former one using 3D hydrodynamic simulations. We model individual stellar winds and let them collide in a subregion of cluster composed of 100 stars. Then, we measure the properties of the resulting hot shocked gas and determine the heating efficiency. We found that even for extremely high stellar densities, it is close to unity. To explain the observed low temperatures, we need to lower the heating efficiency with an unknown mechanism or to include mass loading the cluster interior with primordial gas.



Density field in the simulation with 500 stars. Mass insertion rates of wind sources were unrealistically high in order to test wind collisions in the radiative regime. Black regions are dense cold clouds formed by the thermal instability.

Low heating efficiency vs. mass loading



Model used to determine the heating efficiency ($\eta_{\rm he}$). Winds of close-to-each-other stars collide in the radiative regime and most of the mechanical energy is radiated away immediatelly. If there is no nearby star, the stellar wind forms an adiabatic shock.

Parameters of the SSC wind model:

$R_{\rm SC}$… radius

$L_{\rm SC}$… mechanical energy input rate (due to stars)

$\dot{M}_{\rm SC}$… mass input rate (due to stars)

results in mass and energy insertion rate densities:

$q_m = (1+\eta_{\rm ml})\frac{3\dot{M}_{\rm SC}}{4\pi R_{\rm SC}}, \qquad q_e = \eta_{\rm he}\frac{3L_{\rm SC}}{4\pi R_{\rm SC}}$

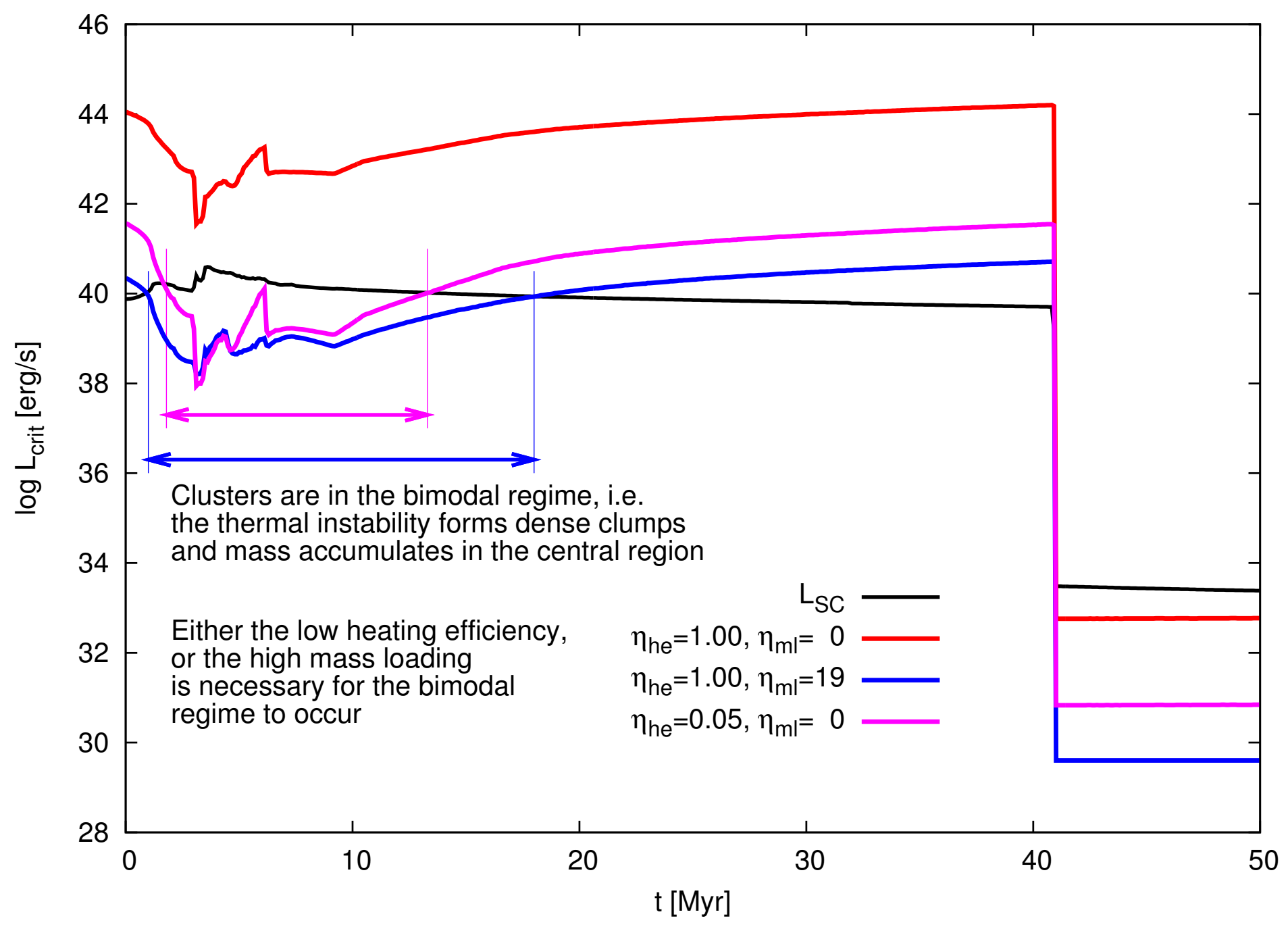
where

$\eta_{\rm ml} \in (0,\infty)$… mass loading

$\eta_{\rm he} \in (0,1)$… heating efficiency

The terminal wind velocity is an important quantity, because it determines line widths. If we account for the heating efficiency and the mass loading, the adiabatic terminal wind velocity $v_{\rm A,\infty} \equiv \sqrt{2L_{\rm SC}/\dot{M}_{\rm SC}}$ changes to

$$v_{\rm he,ml,\infty} = \left(\frac{\eta_{\rm he}}{1+\eta_{\rm ml}}\right)^{1/2} v_{\rm A,\infty}$$

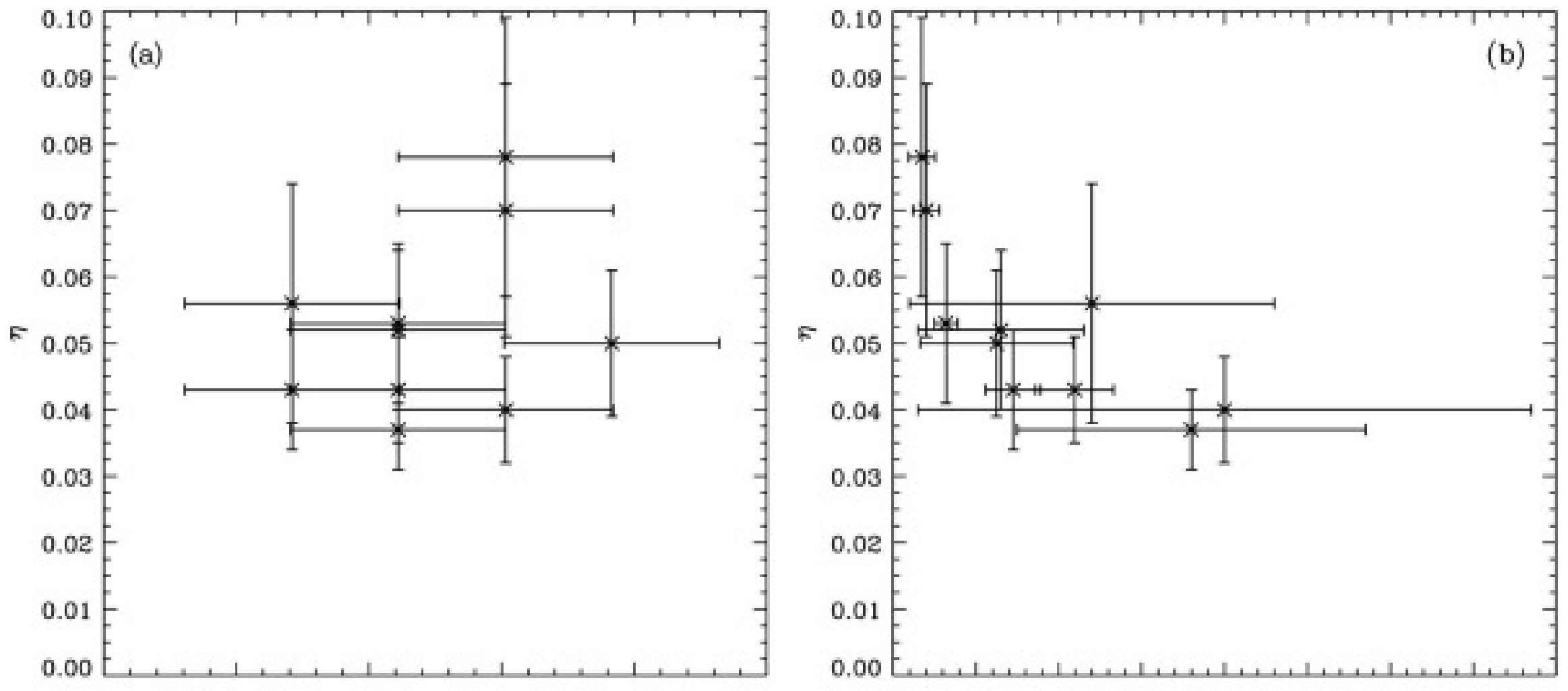


The heating efficiency and/or mass loading are critical parameters which determine if the cluster is in the bimodal regime or not. In the former case the mass reinserted by stars accumulates in the central region where it may feed secondary star formation. The cluster is in the bimodal regime if $L_{\rm SC} > L_{\rm crit}(\eta_{\rm ml},\eta_{\rm he})$. The figure above shows time evolution of $L_{\rm SC}$ and $L_{\rm crit}$ for the cluster with 10^6 M$_\odot$ and three combinantions of $\eta_{\rm he}$ and $\eta_{\rm ml}$.

Hot gas inside SSCs seems to be colder than it should be

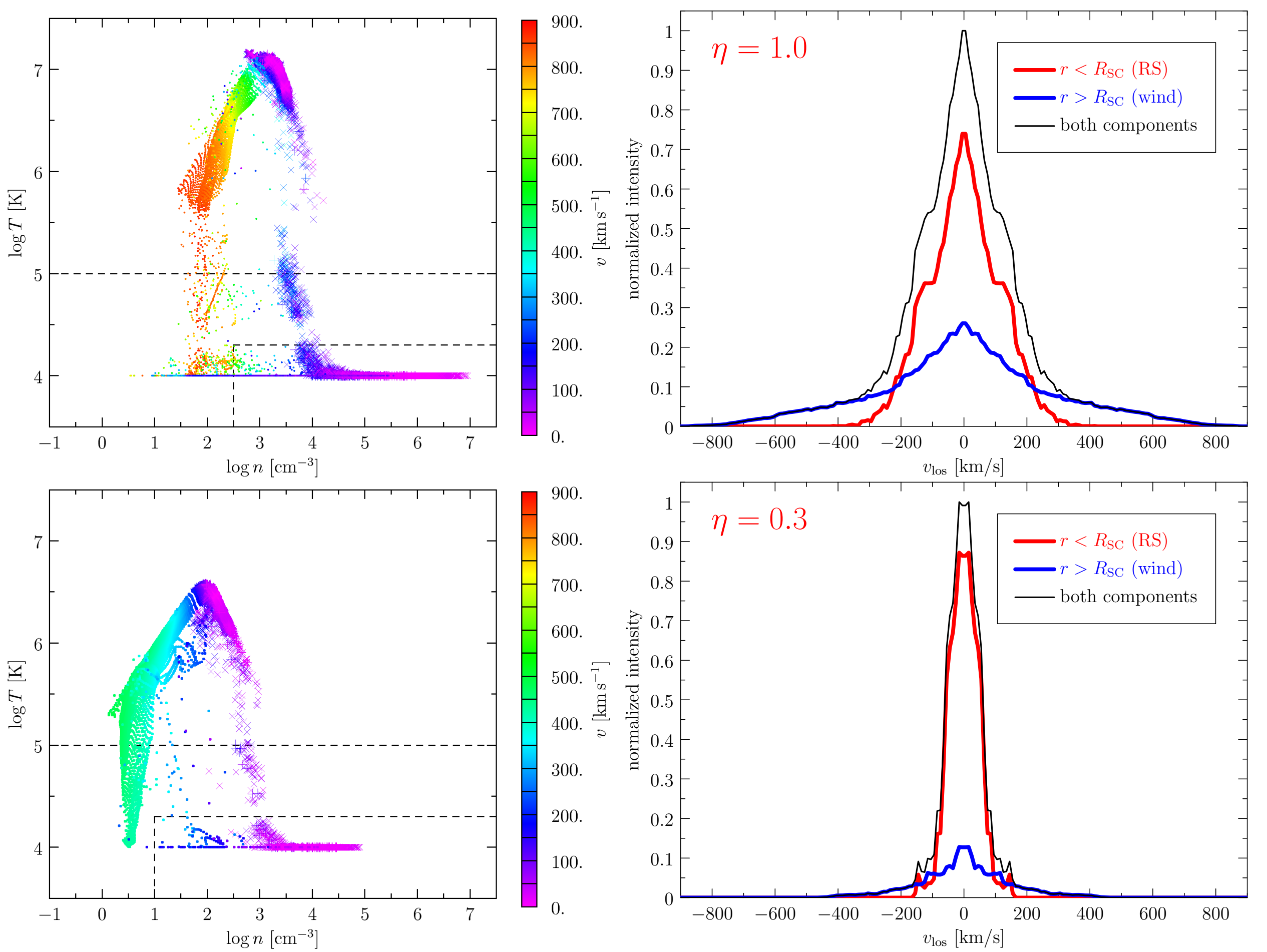
Thermal pressure of the hot gas inside the cluster drives the SSC wind. Therefore, the wind parameters depend on the gas temperature which depends on the heating efficiency and/or the mass loading. Small sizes of HII regions overlapping with SSCs and narrow recombination lines suggest that either the heating efficiency is small ($\eta_{\rm he} < 10$ %) or the mass loading is high ($\eta_{\rm ml} > 10$).

Sizes of HII region in M82:



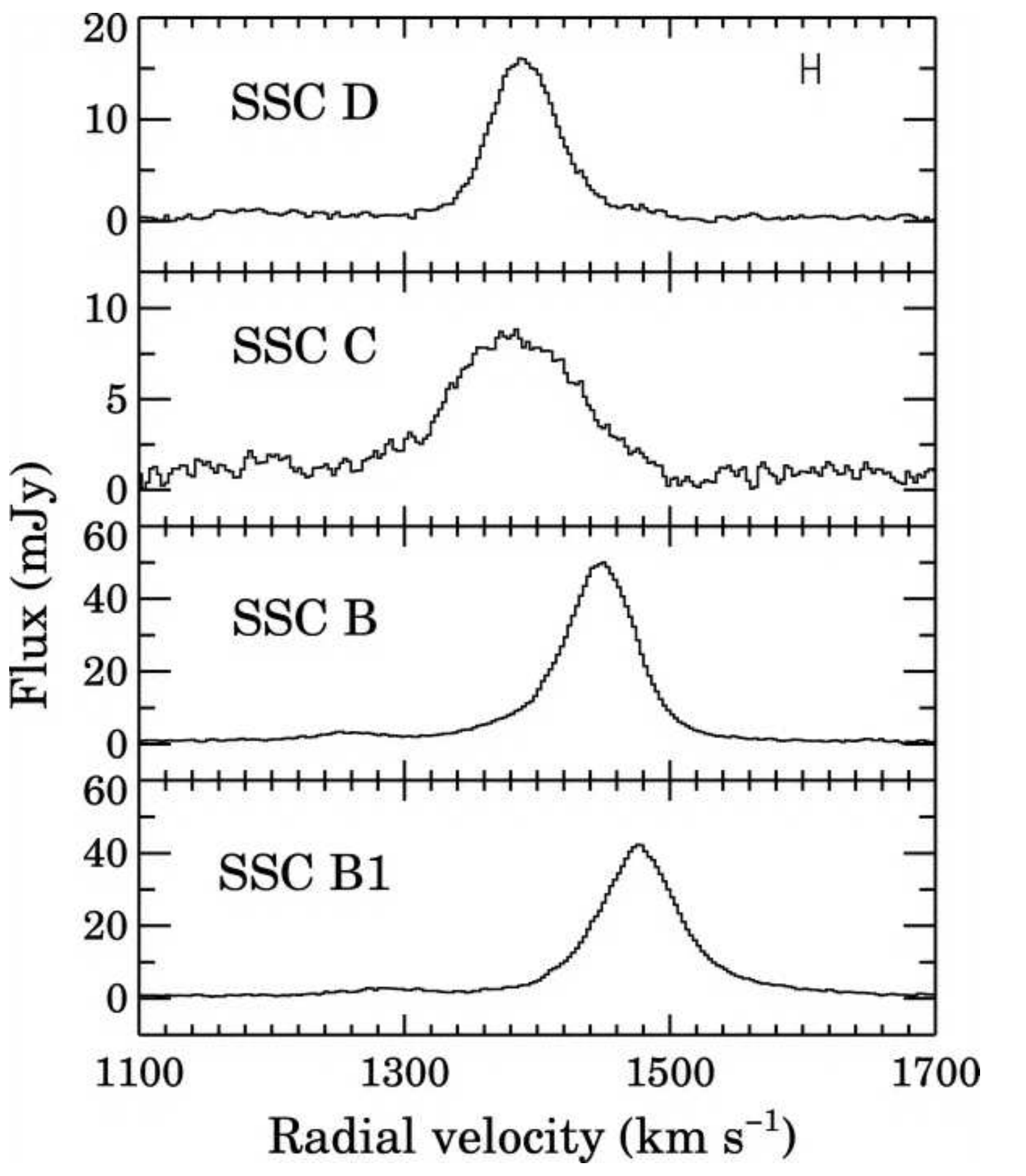
The heating efficiency measured for 10 SSCs in the M82 galaxy from sizes of overlapping HII Regions. In all casses $\eta_{\rm he} < 10$ %. See Silich et al. (2009) for details.

SSC's recombination line widths in simulations:



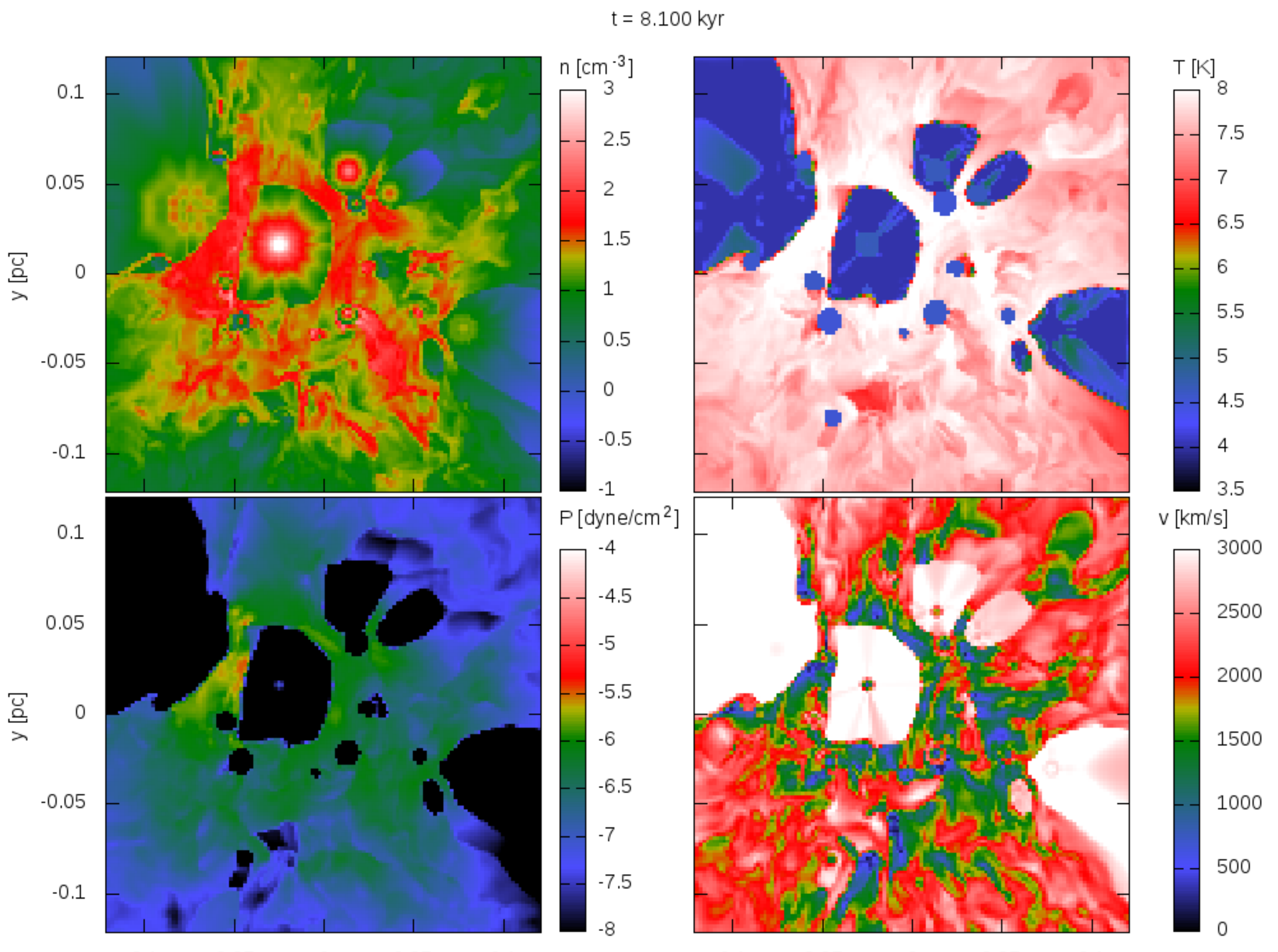
Left panels show density-temperature-velocity diagrams of the reinserted gas in simulated clusters for two different heating efficiencies: $\eta_{\rm he} = 1.0$ (top) and $\eta_{\rm he} = 0.3$. Right panels show resulting line profiles. See Tenorio-Tagle et al. (2010).

…and in the Antennae:



Bracket-γ line profiles of several SSCs observed in Antennae colliding galaxies. See Gilbert & Graham (2007).

Meassuring the heating efficiency from simulations



Simulation setup:

100 wind sources were randomly distributed into spheres with radii 0.1, 0.01 and 0.001 pc. Their parameters were chosen to resemble stellar winds with masses given by the Salpeter IMF and ages 0 and 3 Myr. Properties of the hot shocked medium were determined and the heating efficiency $\eta_{\rm he}$ was meassured. It was close to 1 in all the simulations. The four panels on the left show the particle density, temperature, pressure and velocity magnitude in one of the simulations

Conclusions

- We performed 3D hydrodynamic simulations of super star clusters modelling collisions of individual stellar winds in order to measure the heating efficiency of the gas. In all our simulations, the heating efficiency was always close to 1.
- Therefore, we conclude that it is unlikely that the low heating efficiency is responsible for the lower-than-expected temperature inside SSCs.
- This make the mass loading a more favourable mechanism for lowering the SSC internal temperature, and we will explore this in the future.

References:
A. M. Gilbert, J. R. Graham, 2007, ApJ, 668, 168
Silich, Tenorio-Tagle, Torres-Campos, Muñoz-Tuñón, Monreal-Ibero, Melo, 2009, ApJ, 700, 931
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