ISM heating efficiency inside clusters from 3D hydrodynamic simulations

R. Wünsch, J. Palouš, G. Tenorio-Tagle,
S. Silich, C. Muñoz-Tuñon, A. Whitworth,
F. Hueyotl-Zahuantitla

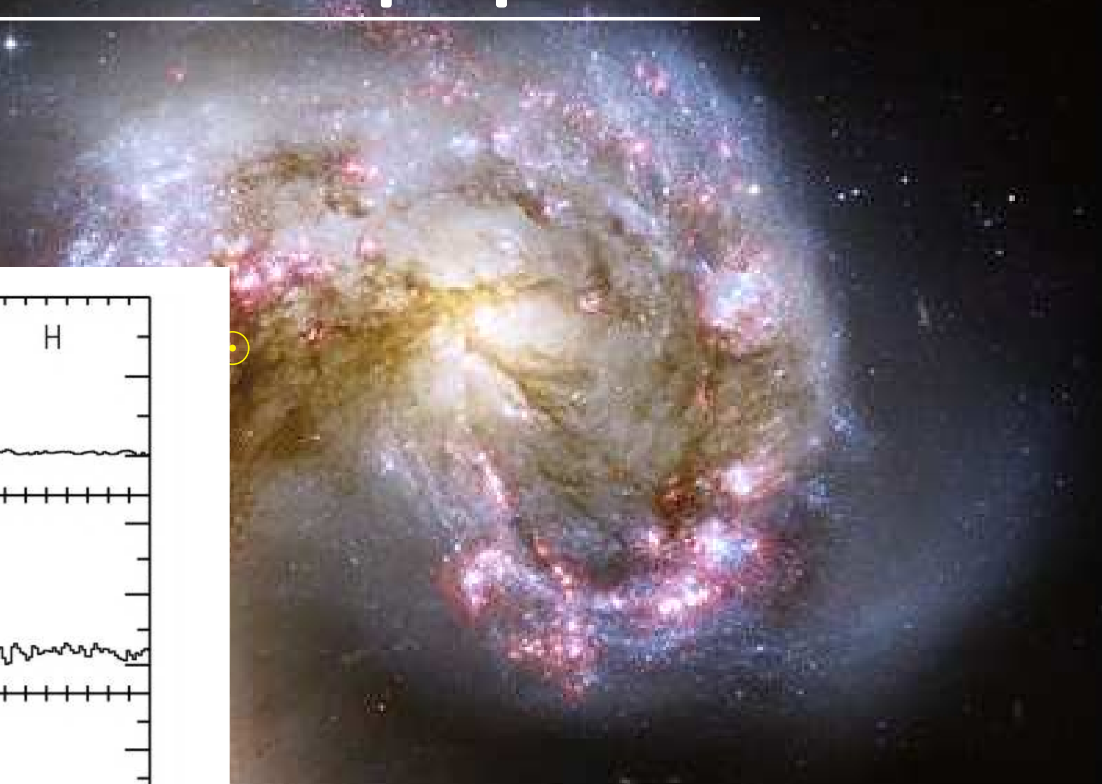
Motivation:

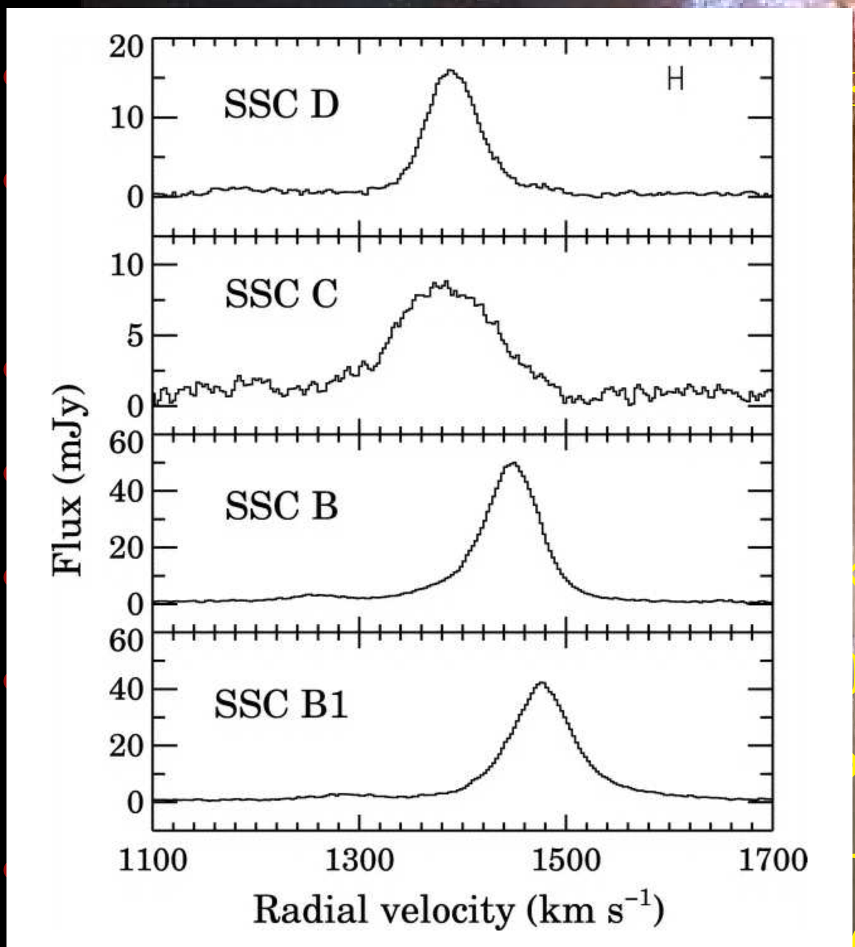
1. **Bimodal solution**
   - secondary SF in the cluster central region
   - predicts two-component line profiles, widths ratio ~ 2 (excellent agreement with observations)
2. **Critical parameter: ratio energy/mass of the reinserted matter - must be substantially lower than that of SW/SN**
   - only a fraction of mechanical energy is thermalized $\rightarrow$ heating efficiency η
   - mass loading
3. **How to calculate η from hydro simulations?**

Super star cluster properties:

- masses: $M_{\rm SC} \sim 10^5$–10^7 M$_\odot$
- radii: $R_{\rm SC} \sim 1 - 5$ pc
  $\rightarrow$ very compact
- ages: up to few Myr
- $L_{\rm mech} \sim 10^{39} - 10^{42}$ erg/s
- stars return $\sim 30\% M_{\rm SC}$ back into ISM
- UV photon fluxes: $L_{\rm UV} \sim 10^{51} - 10^{53}$ s^{-1},
  after 3Myr drops as $\sim t^{-5}$
- recombination lines: two components
  $\sim 100 - 200$ km/s and $\sim 200 - 400$ km/s

Super star cluster properties:





Gilbert & Graham (2007)

k into ISM

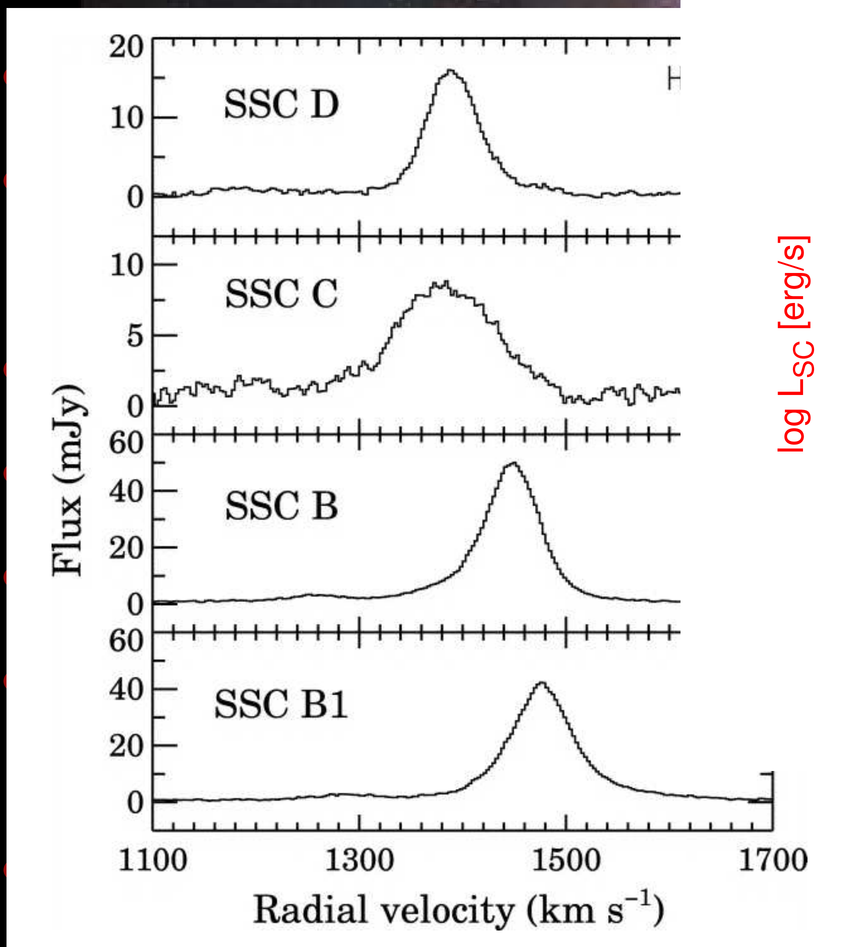
$0^{51} - 10^{53}$ s^{-1},

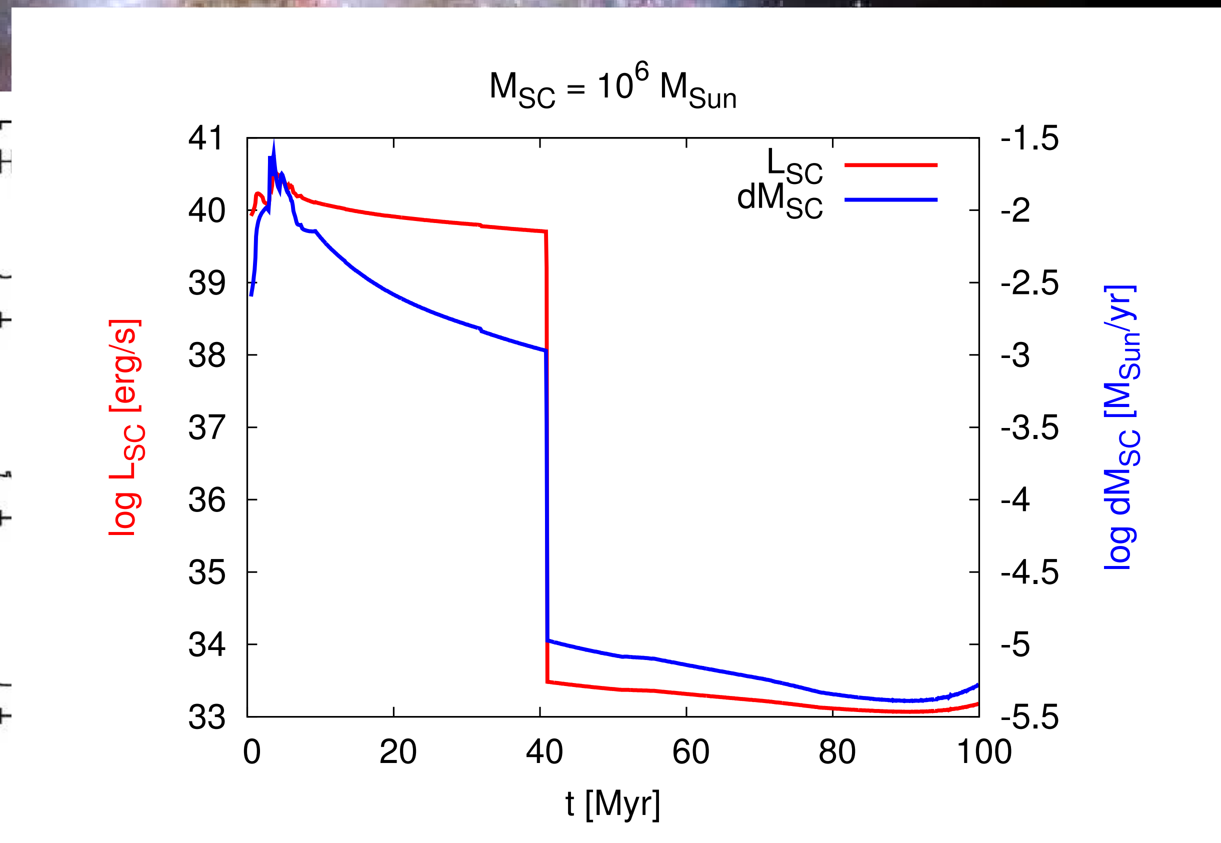
ps as $\sim t^{-5}$

nponents

$0 - 400$ km/s

Super star cluster properties:



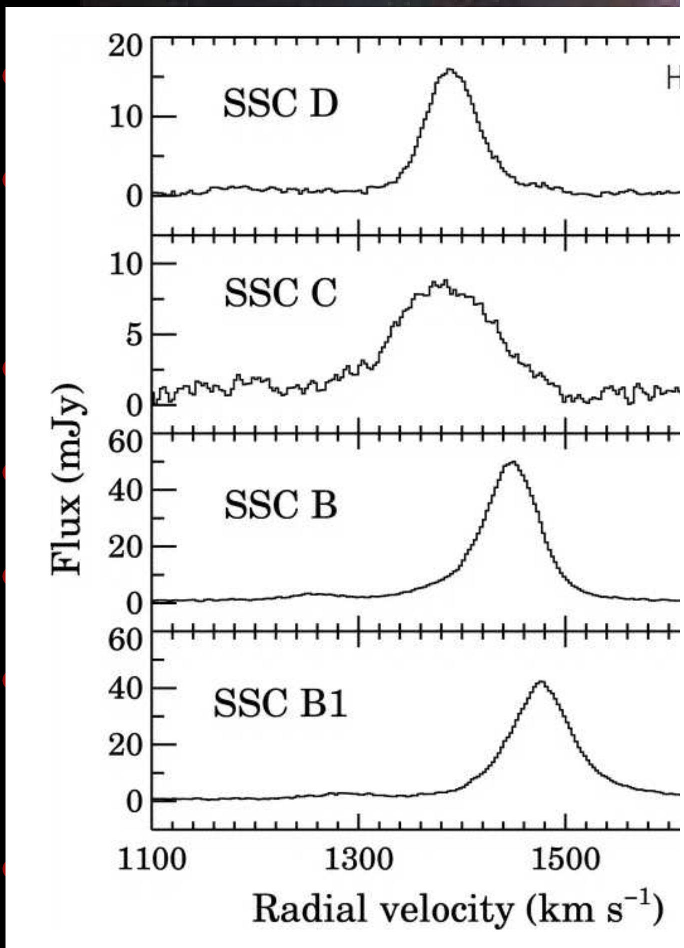


nponents

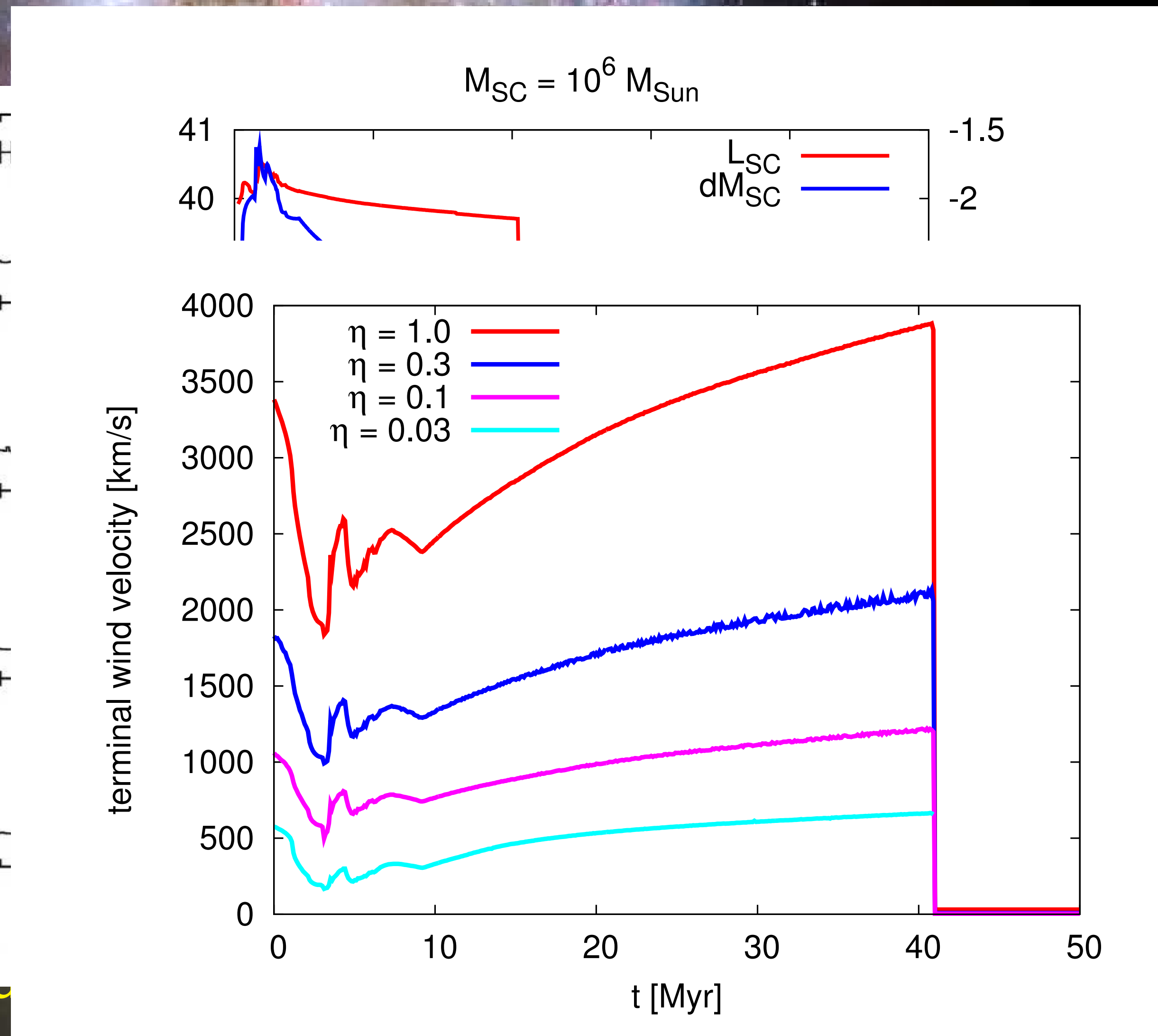
$-\ 400$ km/s

Gilbert & Graham (2007)

Super star cluster properties:

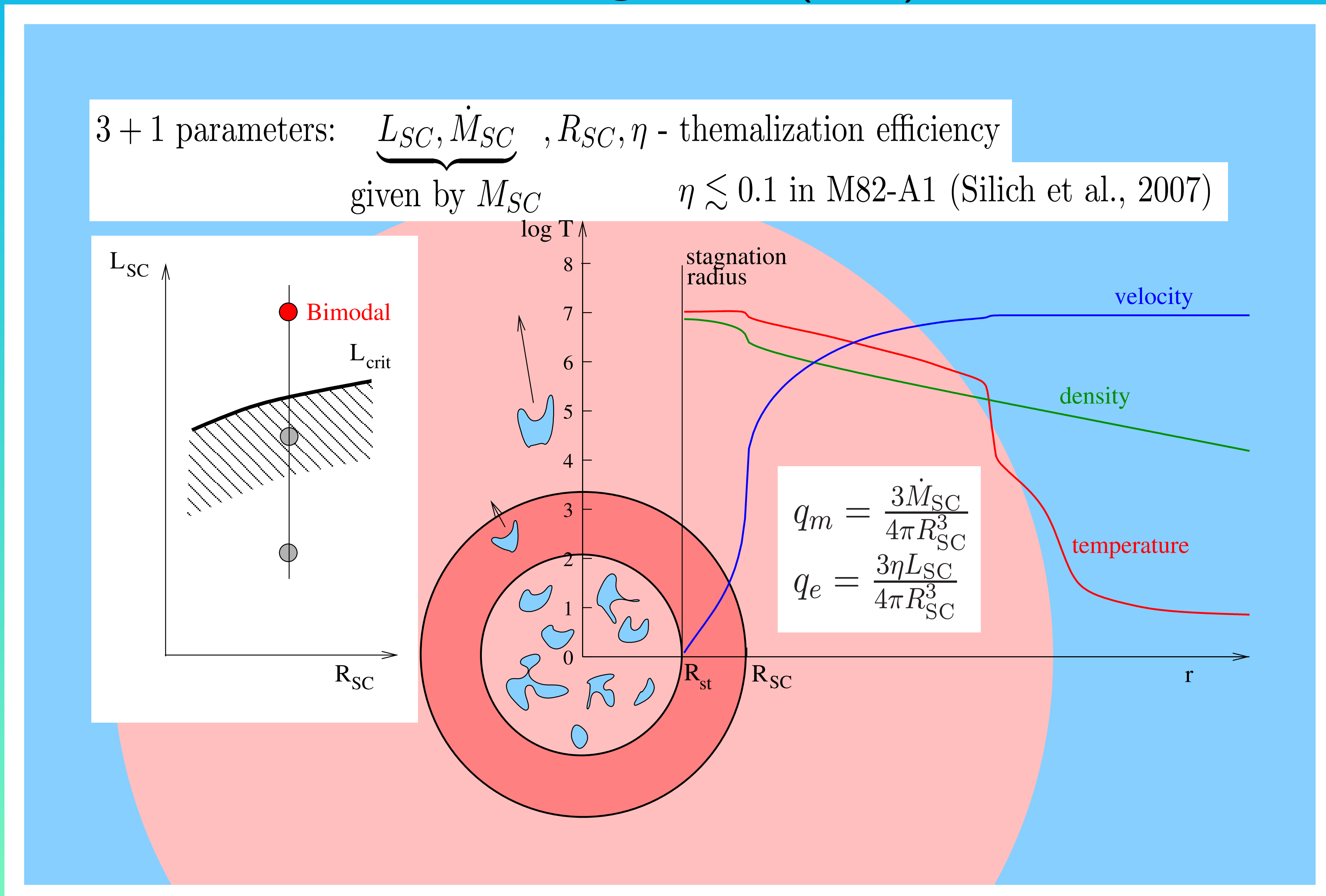


Gilbert & Graham (2007)



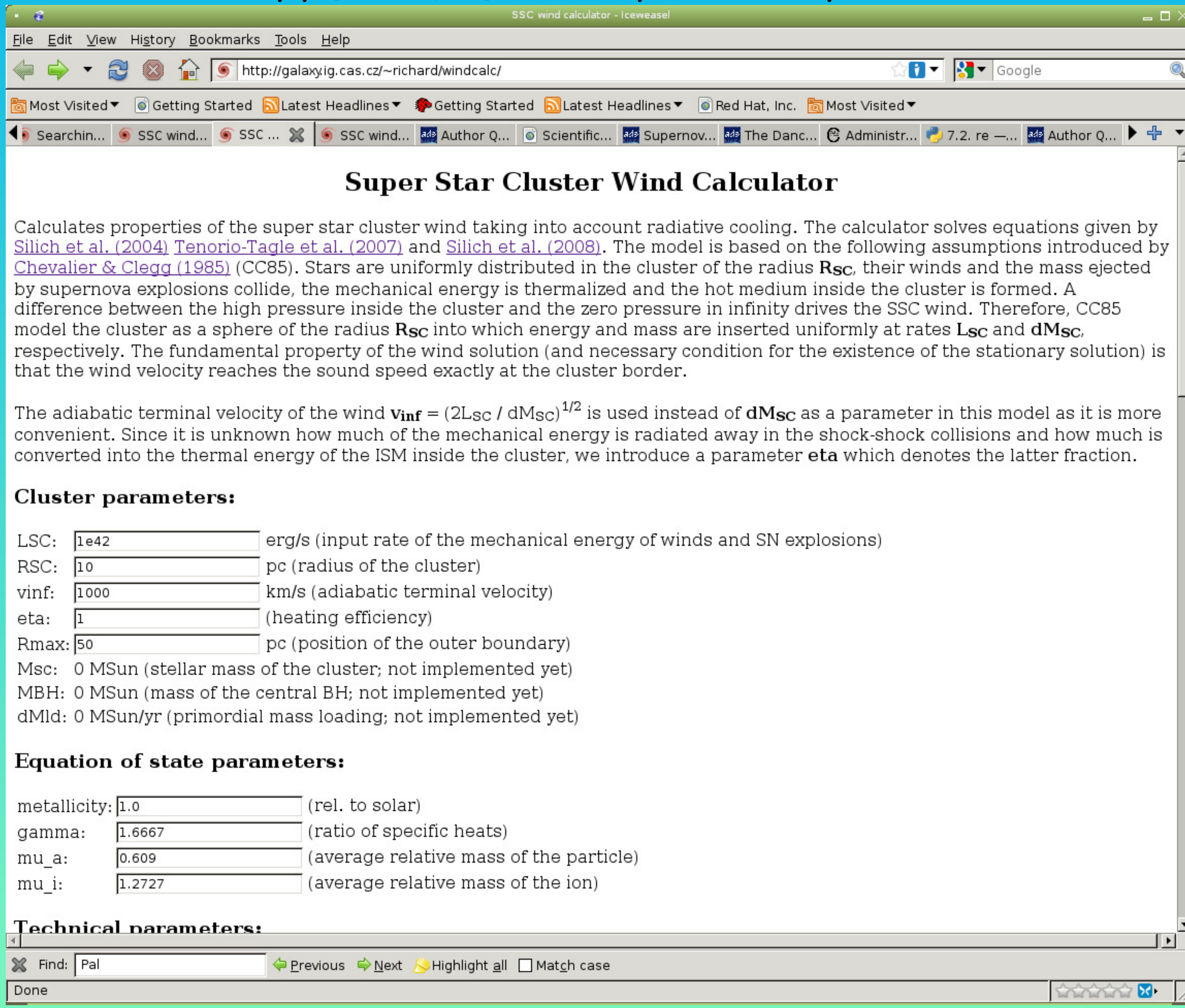
Bimodal solution

Tenorio-Tagle et al. (2007)



Web based calculator

http://galaxy.ig.cas.cz/~richard/windcalc



Super Star Cluster Wind Calculator

Calculates properties of the super star cluster wind taking into account radiative cooling. The calculator solves equations given by Silich et al. (2004) Tenorio-Tagle et al. (2007) and Silich et al. (2008). The model is based on the following assumptions introduced by Chevalier & Clegg (1985) (CC85). Stars are uniformly distributed in the cluster of the radius R_{SC}, their winds and the mass ejected by supernova explosions collide, the mechanical energy is thermalized and the hot medium inside the cluster is formed. A difference between the high pressure inside the cluster and the zero pressure in infinity drives the SSC wind. Therefore, CC85 model the cluster as a sphere of the radius R_{SC} into which energy and mass are inserted uniformly at rates L_{SC} and dM_{SC}, respectively. The fundamental property of the wind solution (and necessary condition for the existence of the stationary solution) is that the wind velocity reaches the sound speed exactly at the cluster border.

The adiabatic terminal velocity of the wind $v_{inf} = (2L_{SC} / dM_{SC})^{1/2}$ is used instead of dM_{SC} as a parameter in this model as it is more convenient. Since it is unknown how much of the mechanical energy is radiated away in the shock-shock collisions and how much is converted into the thermal energy of the ISM inside the cluster, we introduce a parameter **eta** which denotes the latter fraction.

Cluster parameters:

LSC:	1e42	erg/s (input rate of the mechanical energy of winds and SN explosions)
RSC:	10	pc (radius of the cluster)
vinf:	1000	km/s (adiabatic terminal velocity)
eta:	1	(heating efficiency)
Rmax:	50	pc (position of the outer boundary)
Msc:	0 MSun	(stellar mass of the cluster; not implemented yet)
MBH:	0 MSun	(mass of the central BH; not implemented yet)
dMld:	0 MSun/yr	(primordial mass loading; not implemented yet)

Equation of state parameters:

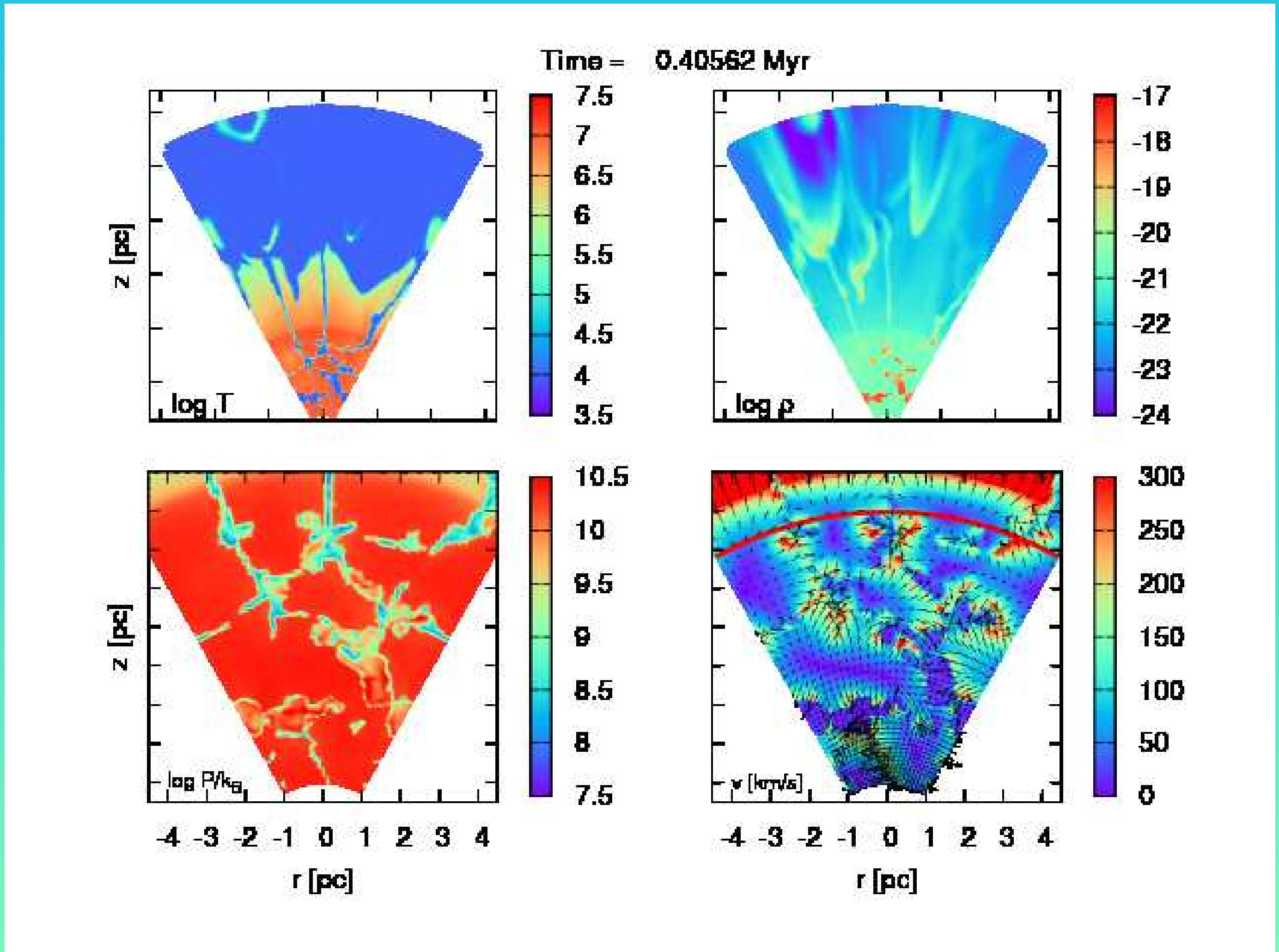
metallicity:	1.0	(rel. to solar)
gamma:	1.6667	(ratio of specific heats)
mu_a:	0.609	(average relative mass of the particle)
mu_i:	1.2727	(average relative mass of the ion)

Technical parameters:

2D hydro simulations

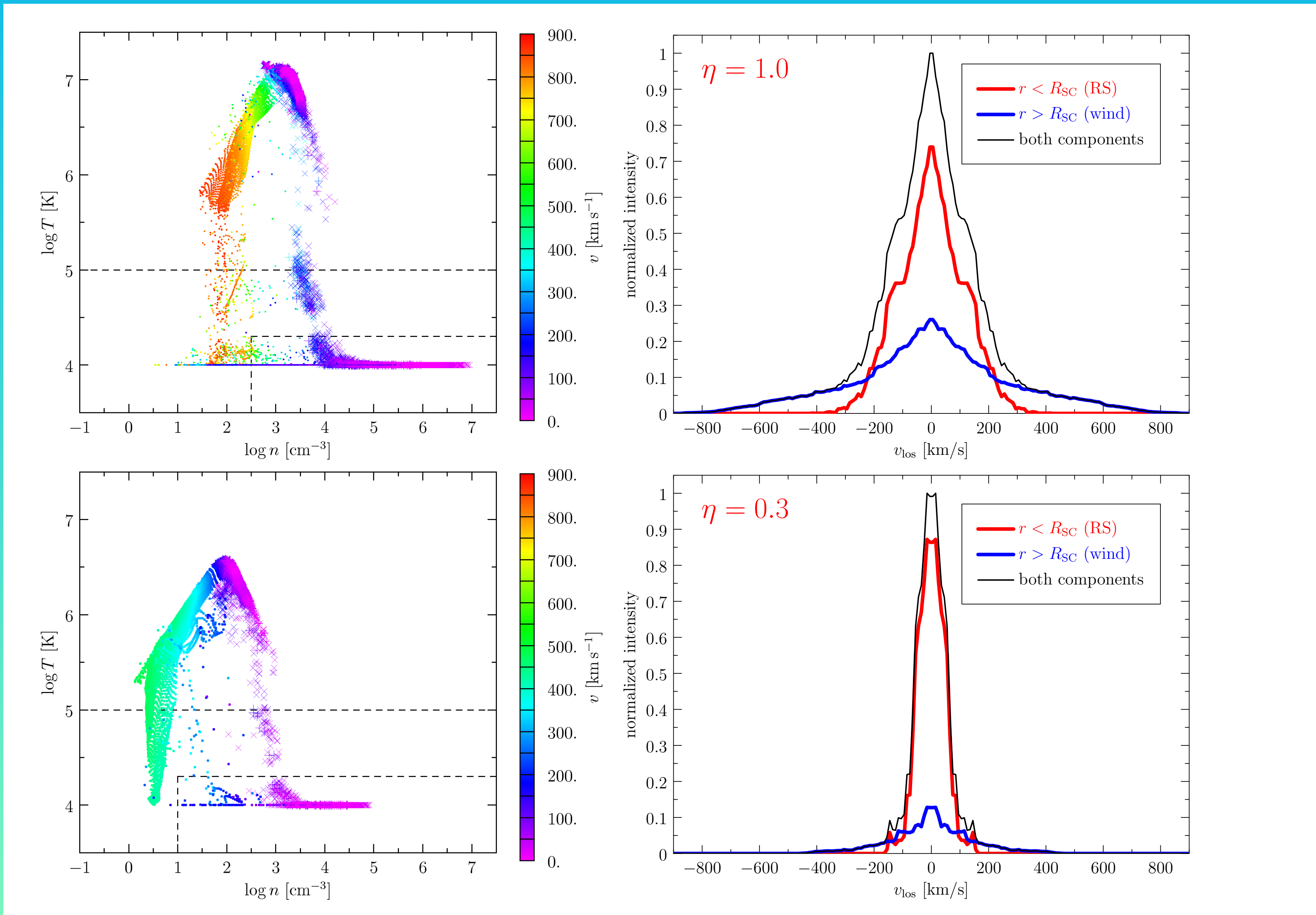
Wünsch et al. (2008)

- ZEUS, Rθ coords, open **both** R-boundaries, periodic θ-boundary
- $R_{SC} = 10$ pc, $L_{SC}/L_{\rm crit} = 20$, $\eta = 1.0$, 600×224

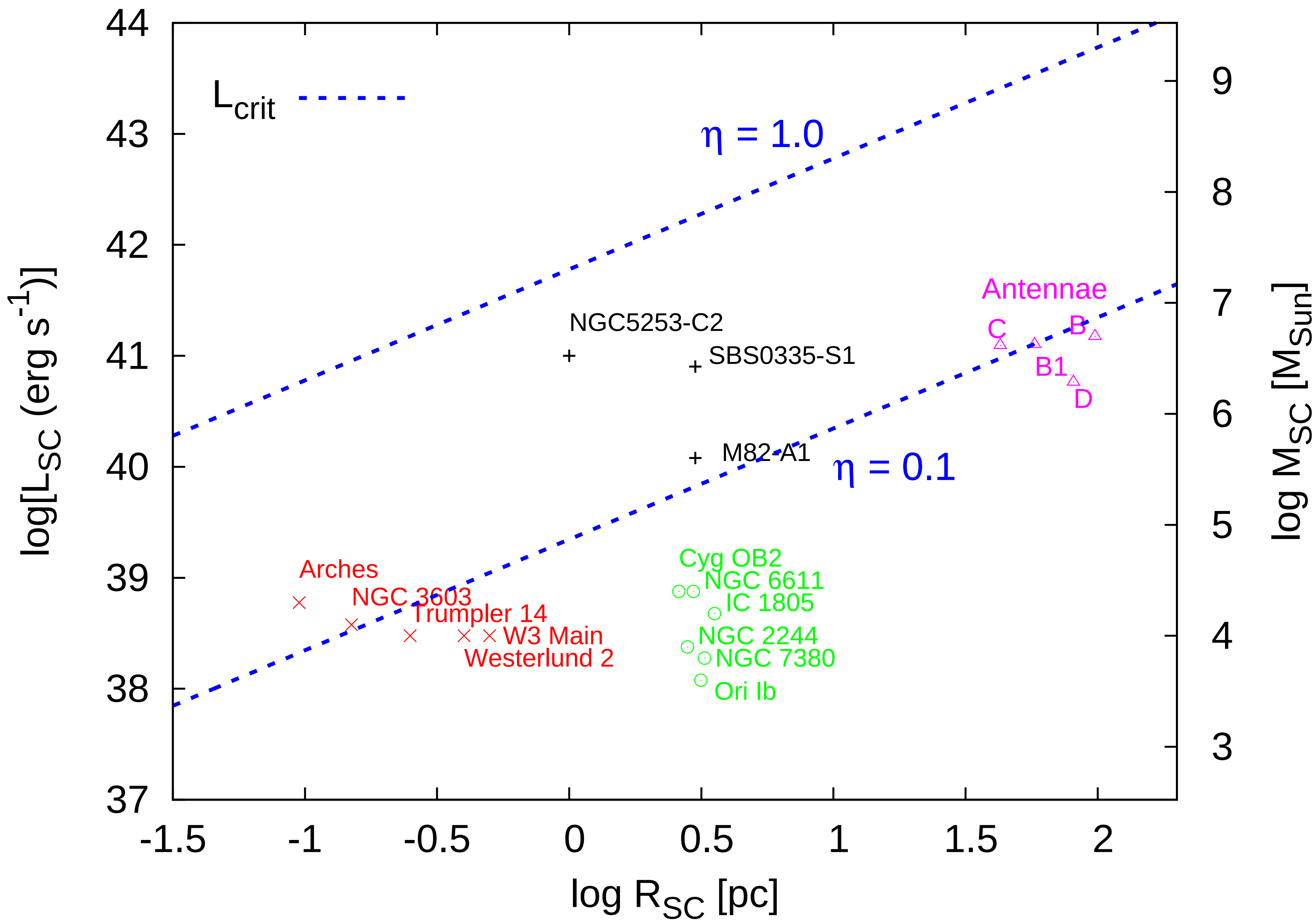


Supersonic recombination lines widths

Tenorio-Tagle et al. (2010)

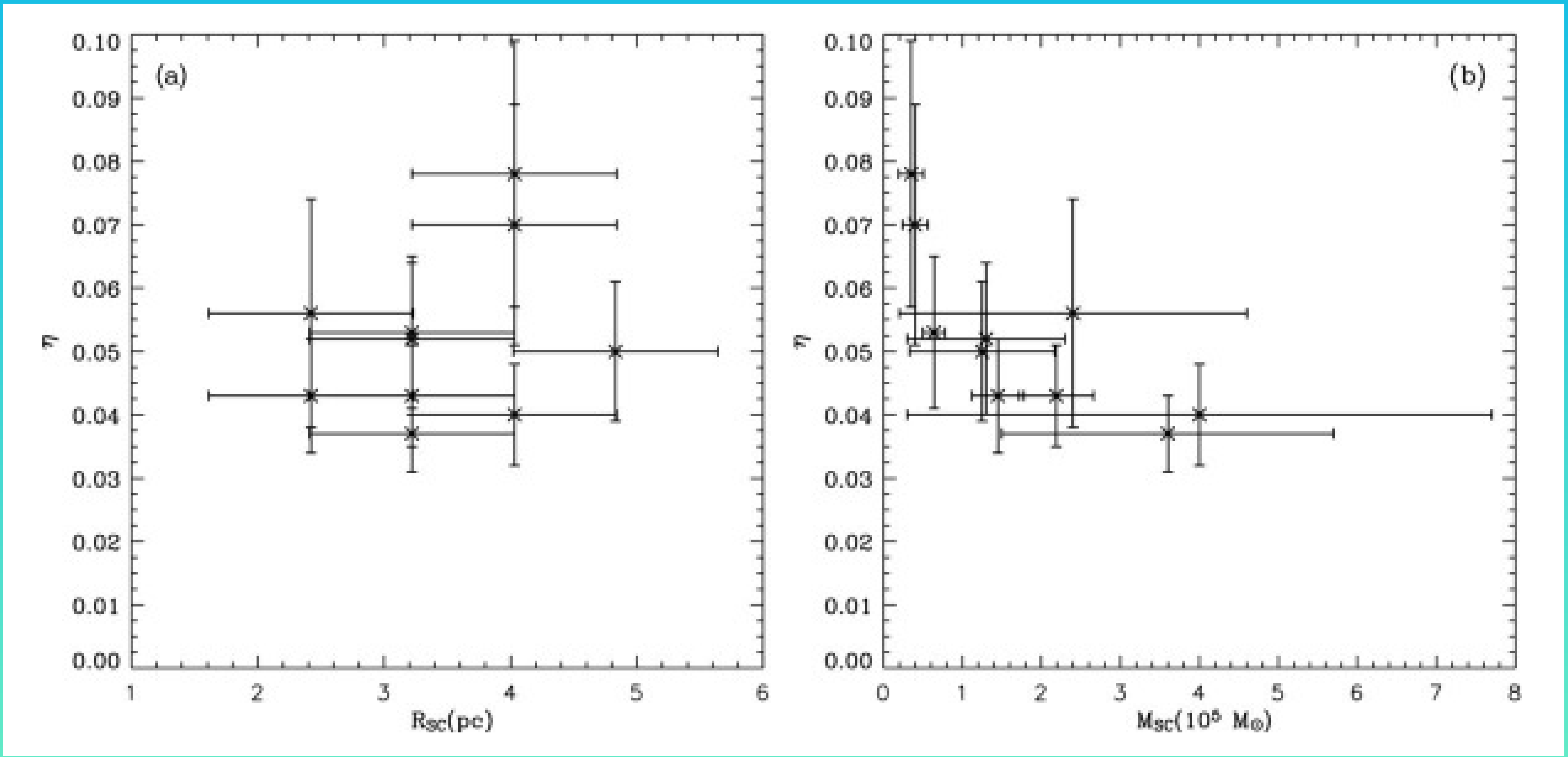


Critical luminosity and observed clusters



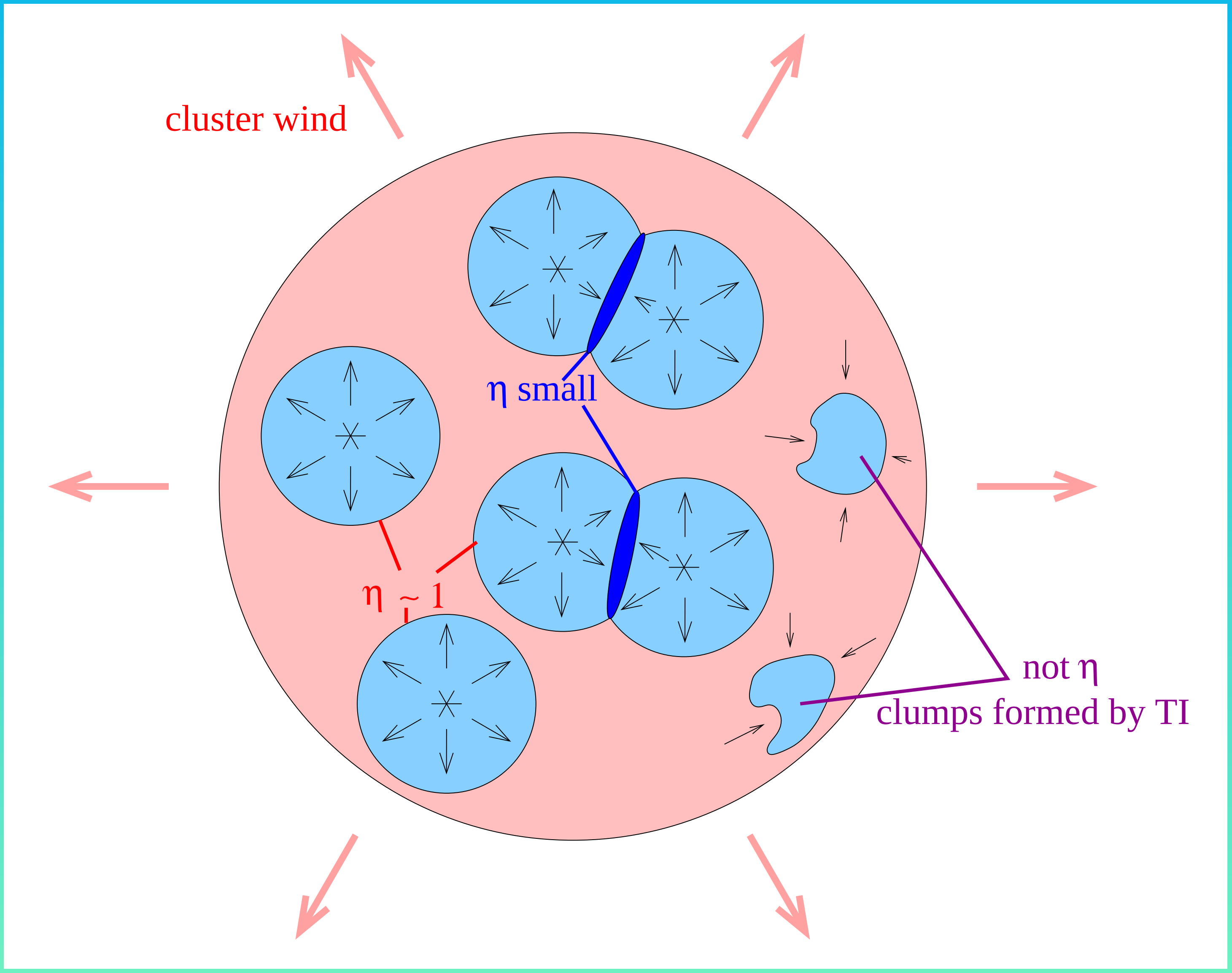
Heating efficiency in clusters in M8

Silich et al. (2009)

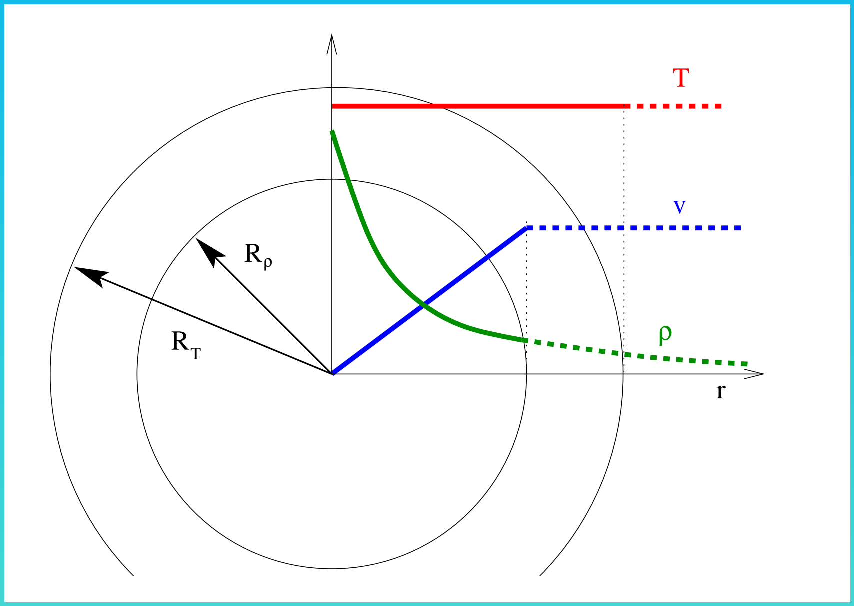


- η measured for 10 clusters in M82
- from sizes of HII regions, $\eta \lesssim 10\%$

Model for heating efficiency



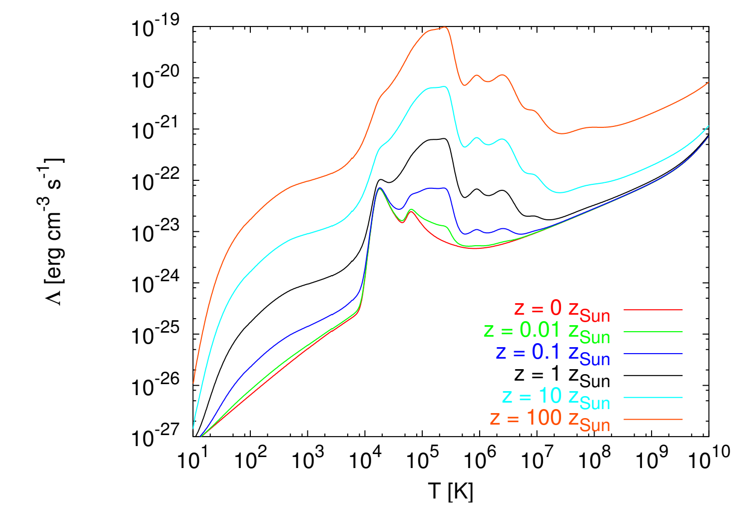
Flash model with individual sources



- Flash3.2, standard ppm Rieman solver (the unsplit solver crashes)
- Energy source: $\dot{m}$, v, T, R_ρ, R_T
- for $r < R_\rho$: $v \propto r$, $\rho \propto r^{-2}$
- for $r < R_T$: $T = \mathrm{const}$

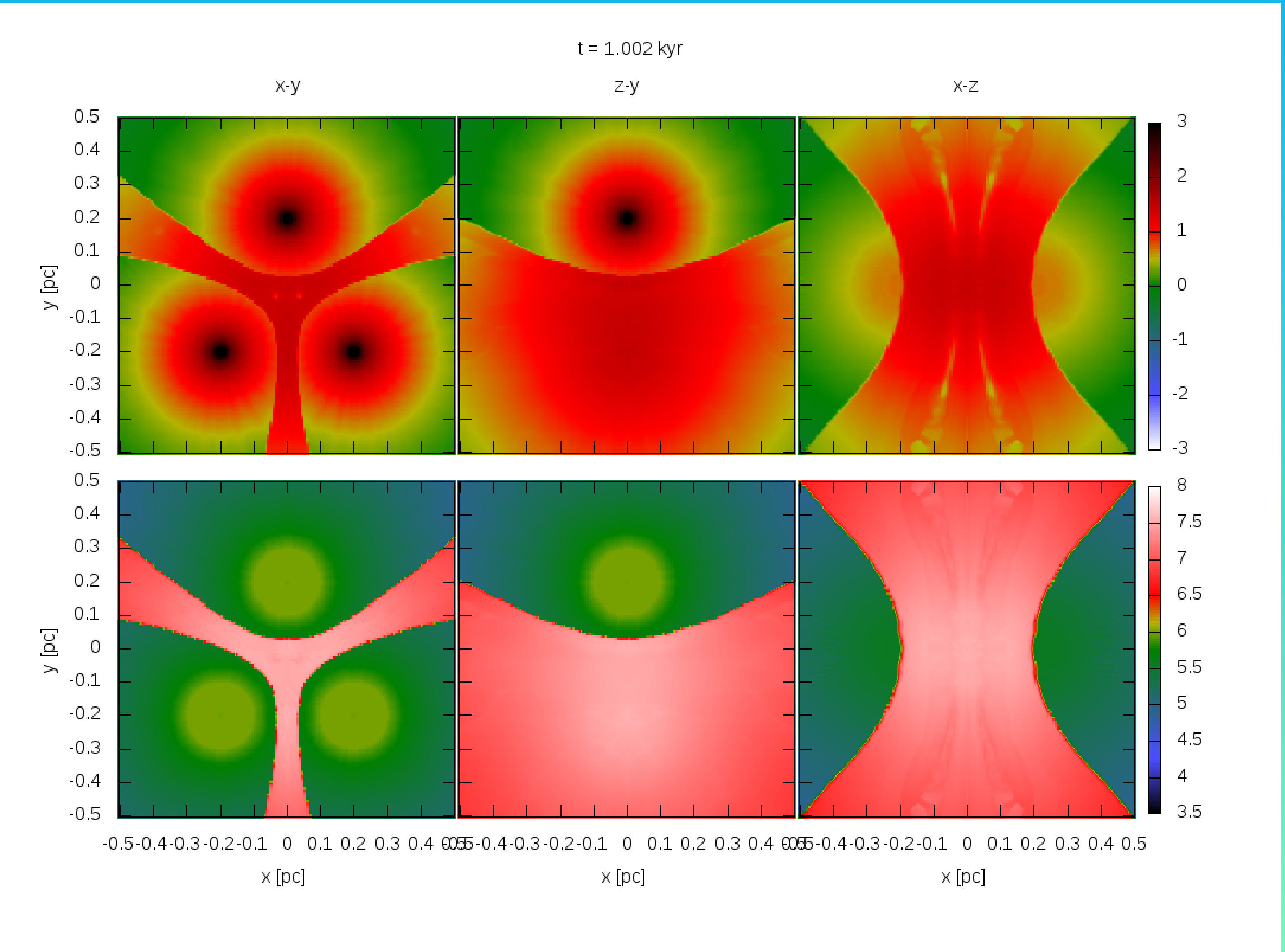
Cooling:

- time-step controlled by cooling
- limit on the minimum timestep $dt_{\mathrm{min}} \sim dt_{\mathrm{hydro}}/3$
- substeps

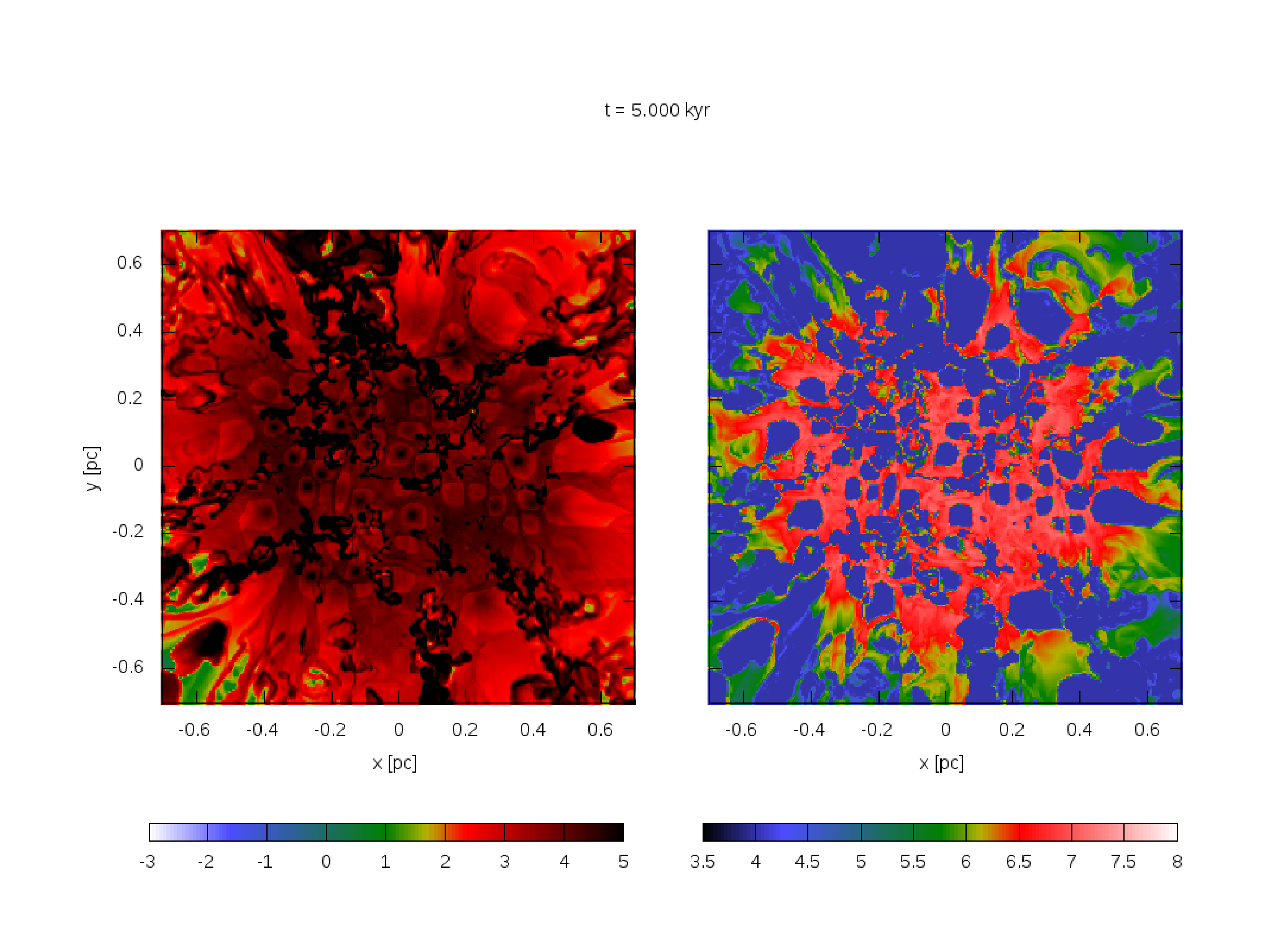


Plewa (1995)

Firsts tests - 2 and 3 stars

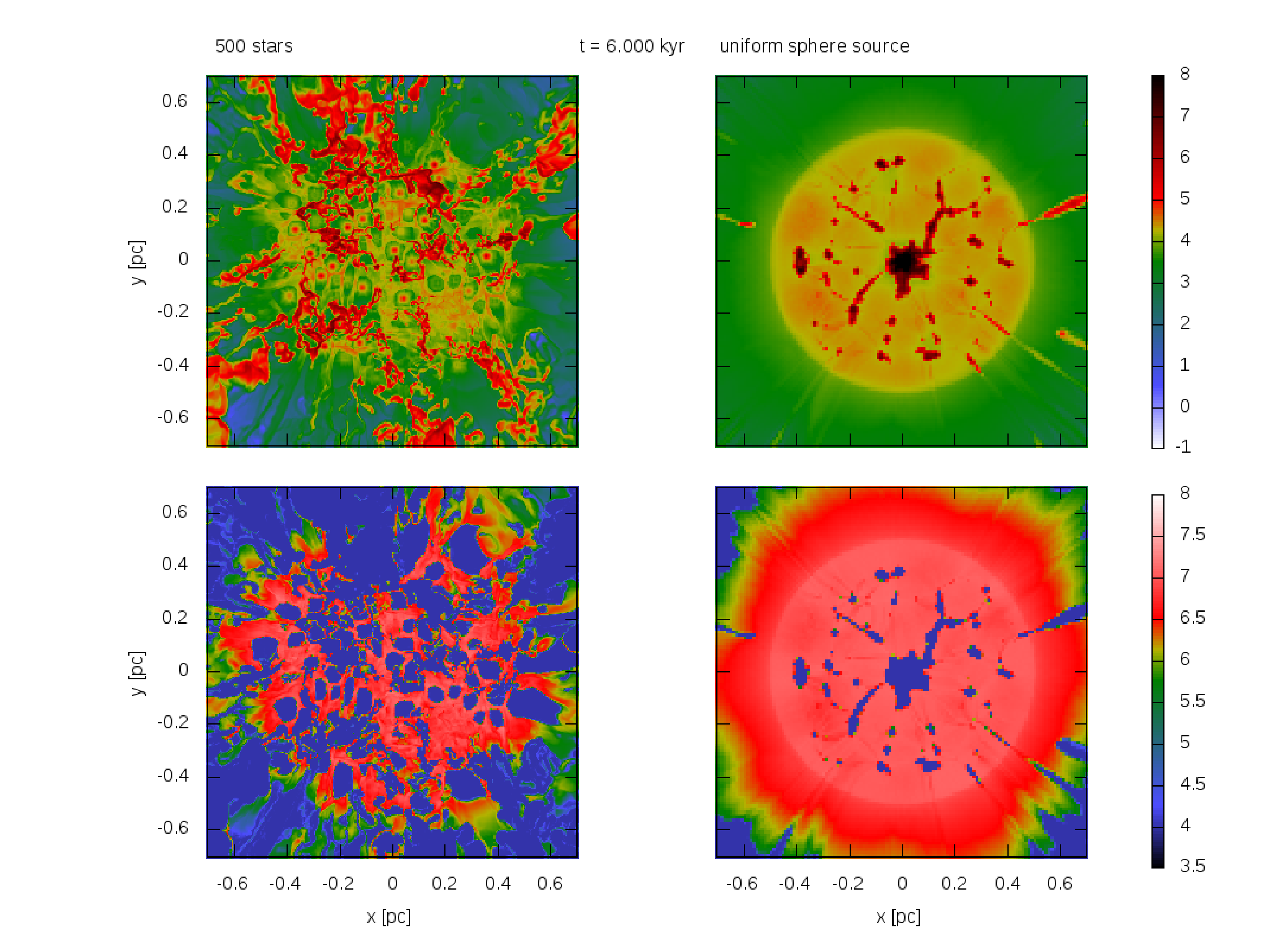


500 stars

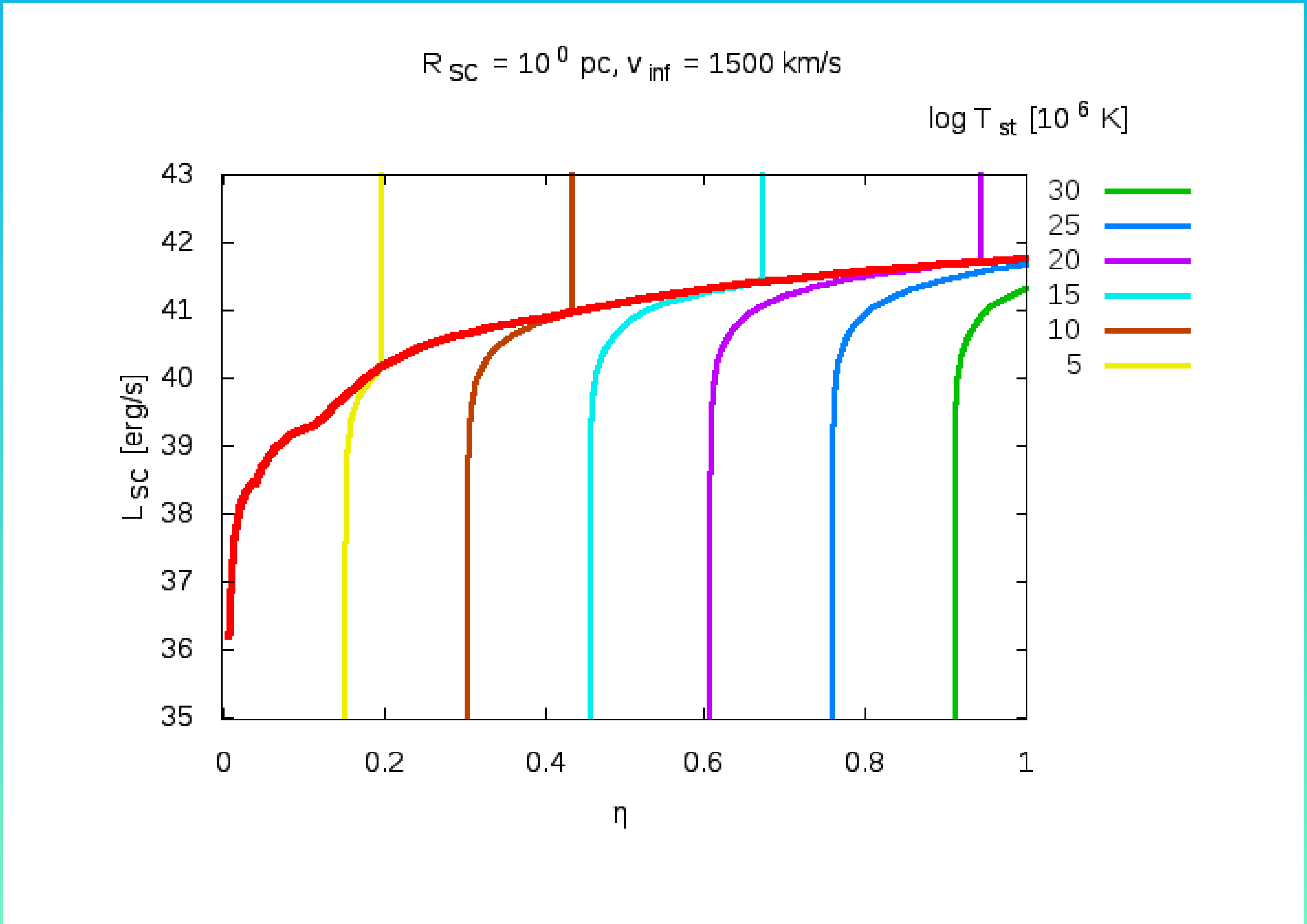


t = 5.000 kyr
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
y [pc]
-0.6 -0.4 -0.2 0 0.2 0.4 0.6
x [pc]
-0.6 -0.4 -0.2 0 0.2 0.4 0.6
x [pc]
-3 -2 -1 0 1 2 3 4 5
3.5 4 4.5 5 5.5 6 6.5 7 7.5 8

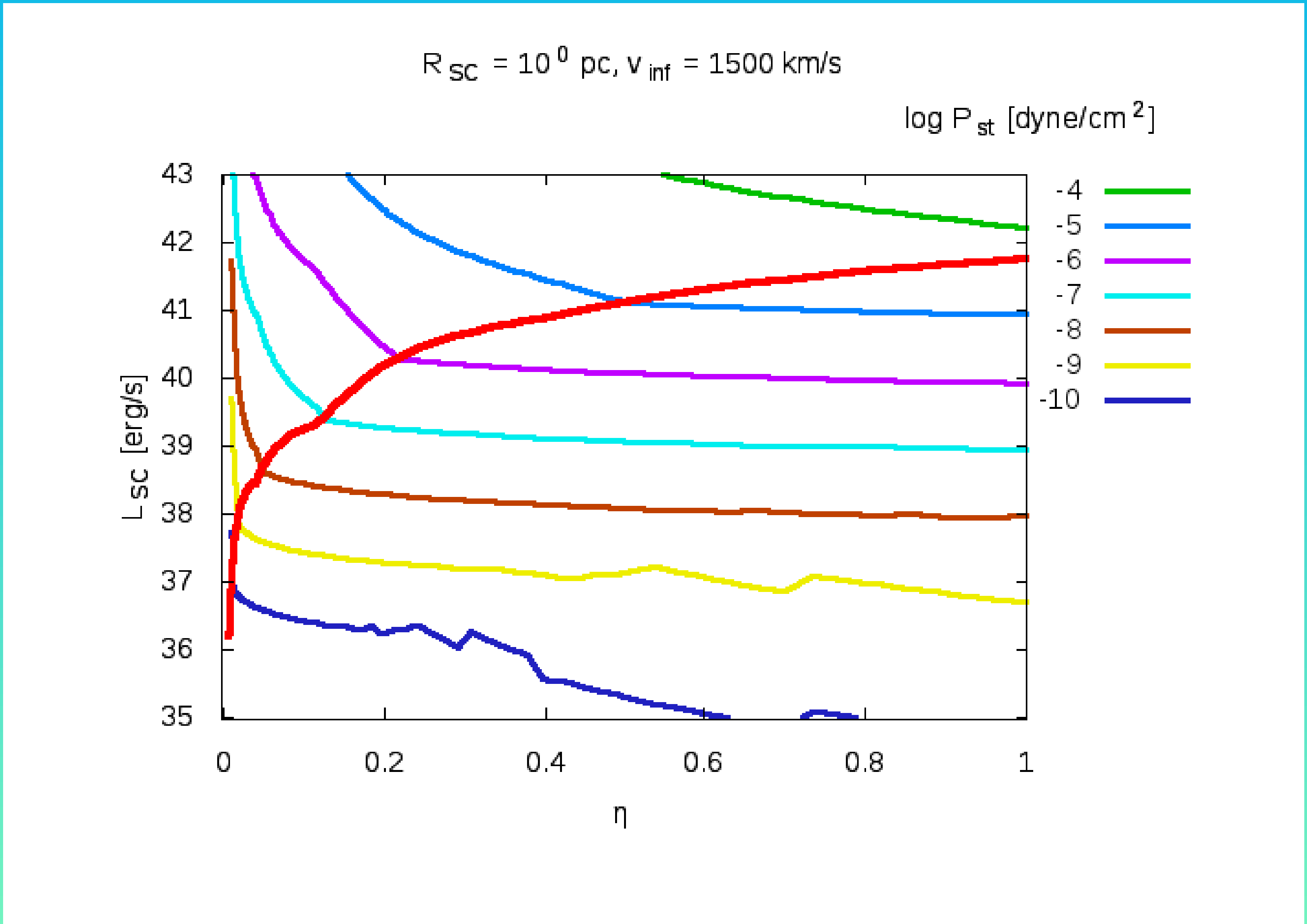
Comparison with uniform mass/energy input



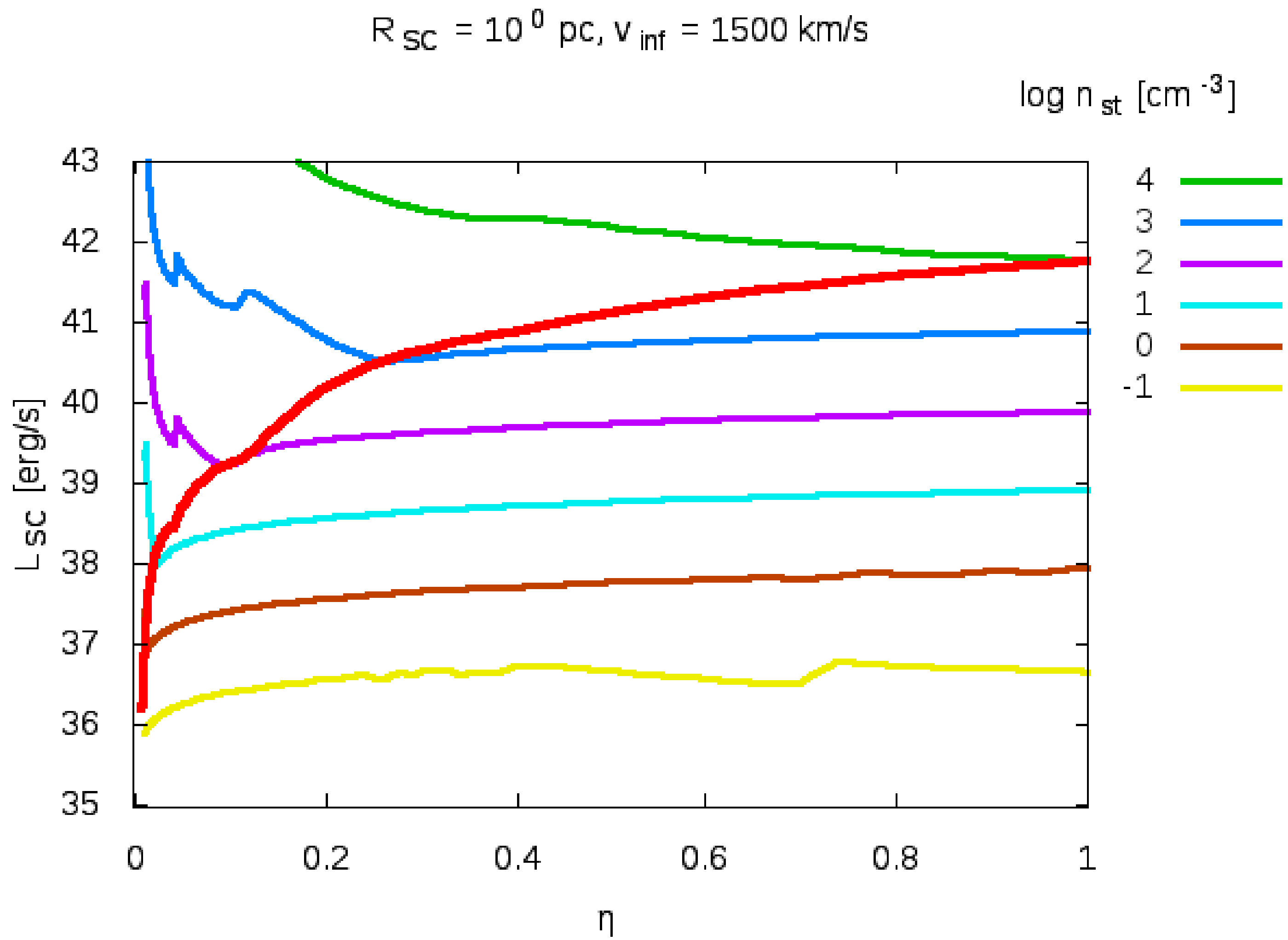
Determination of heating efficiency - temperature



Determination of heating efficiency - pressure

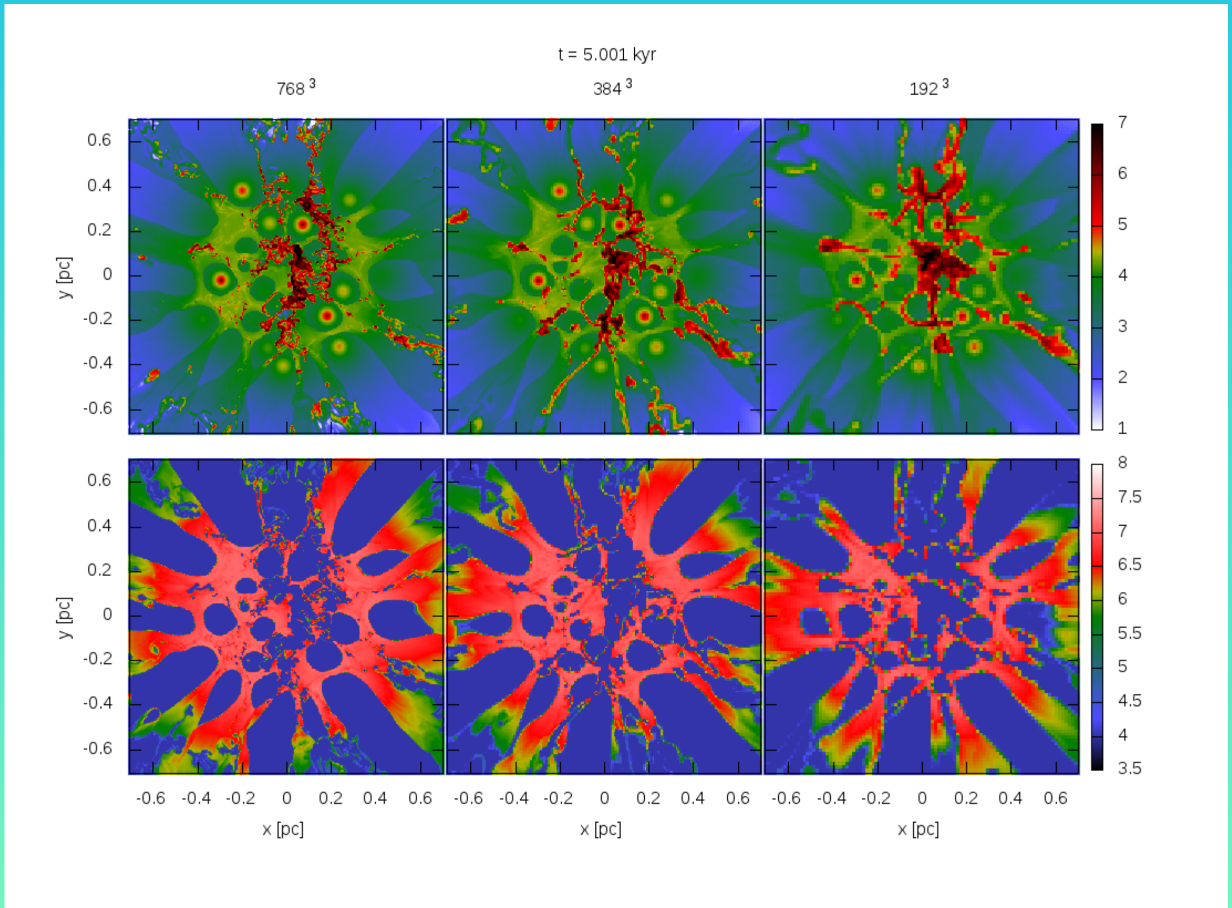


Determination of heating efficiency - density

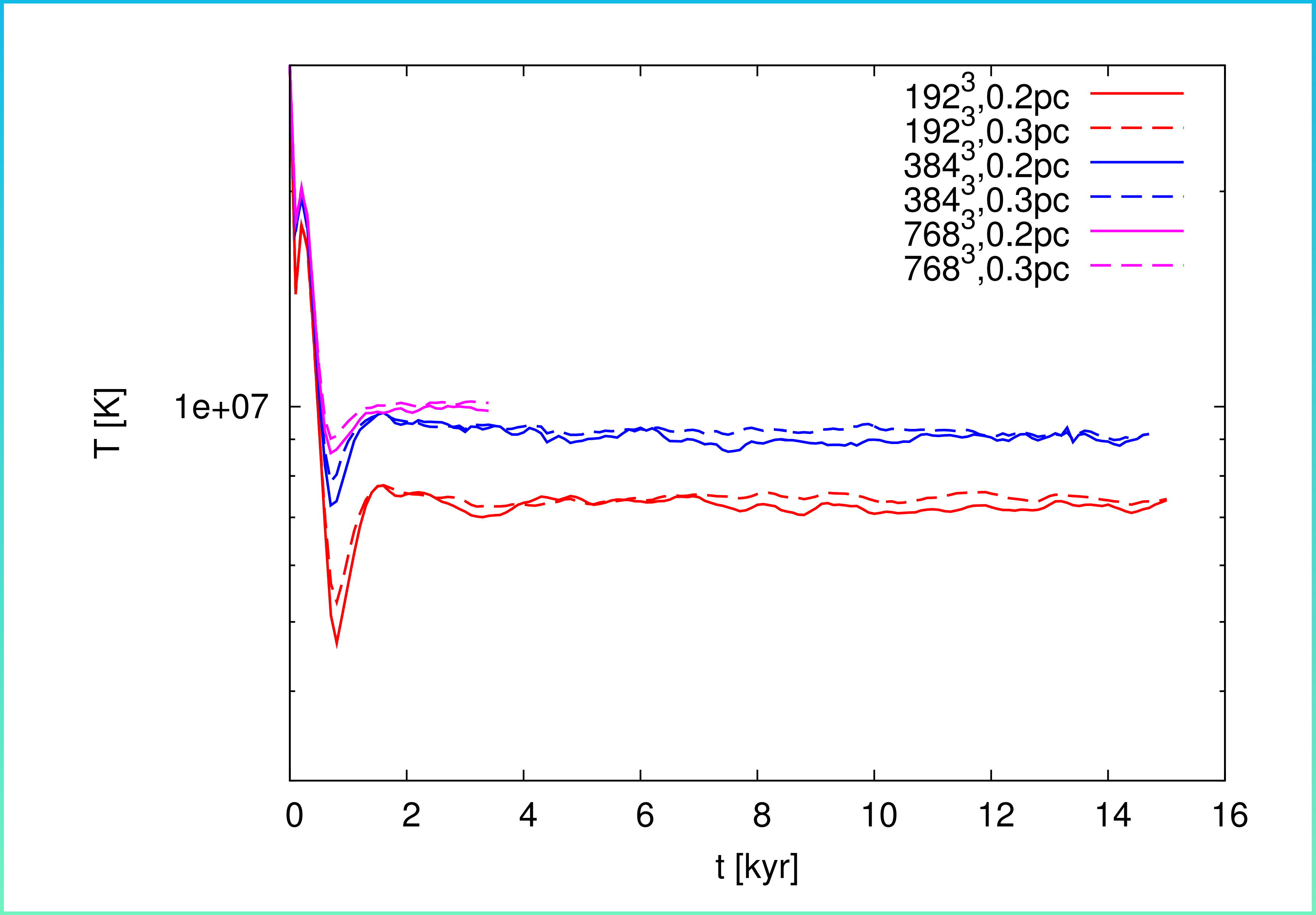


Resolution study - 100 stars

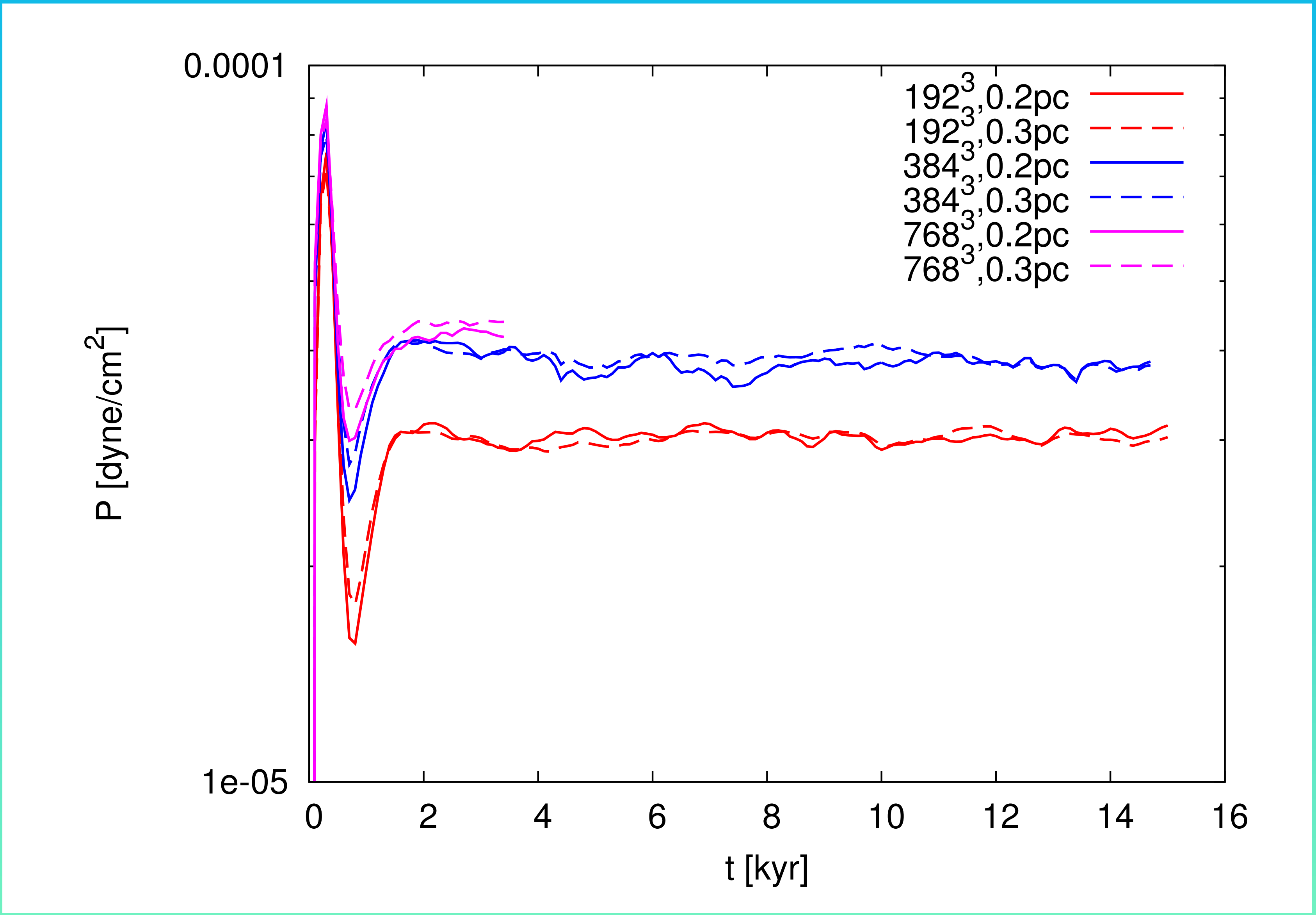
- meassured average values in spheres: 0.1, 0.2,. . . , 0.6 pc
- non-thermalized free wind excluded (velocity criterion)
- two media: warm ($T < 3 \times 10^5$) and hot ($T > 3 \times 10^5$ K)



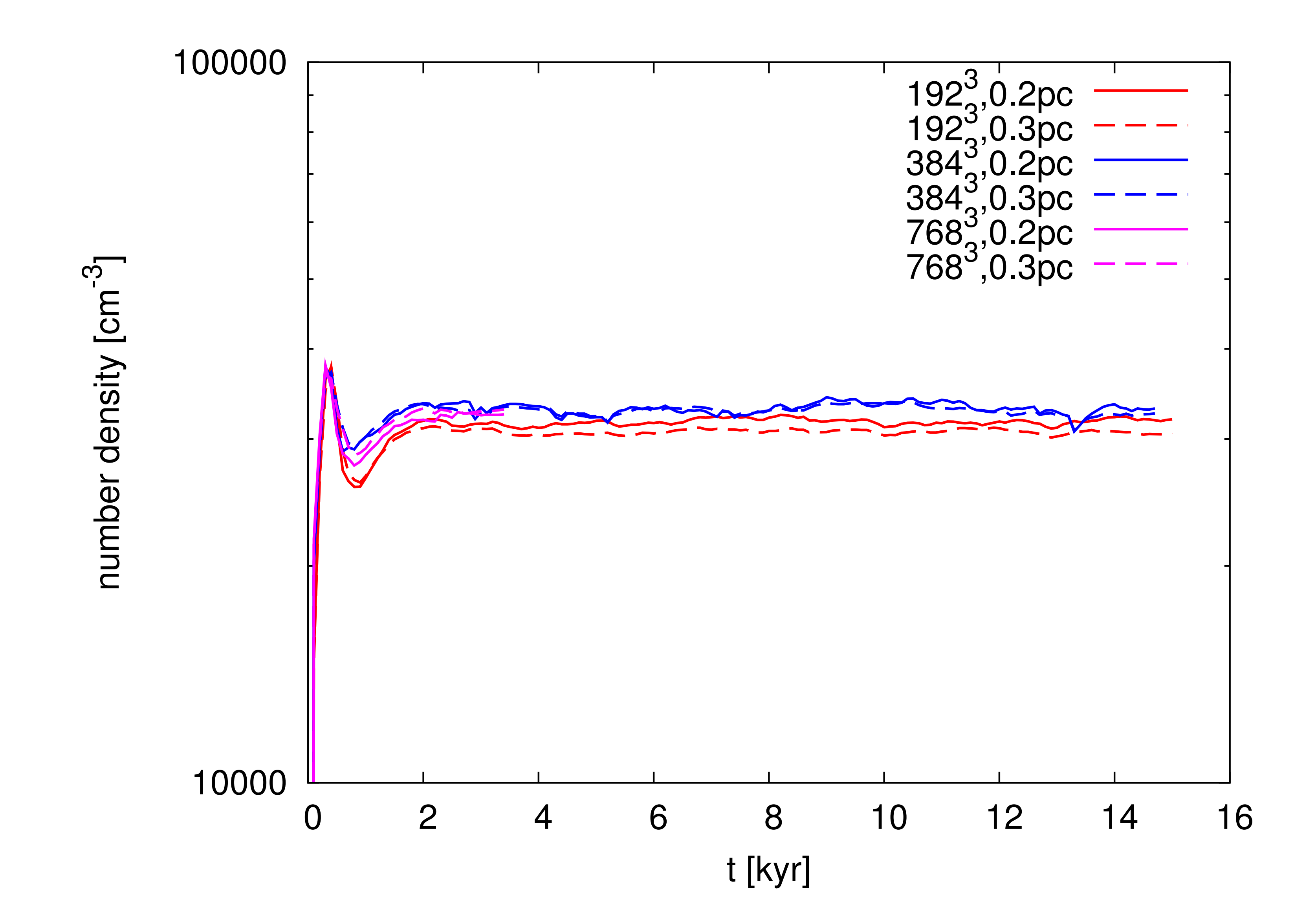
Temperature inside the cluster



Pressure inside the cluster



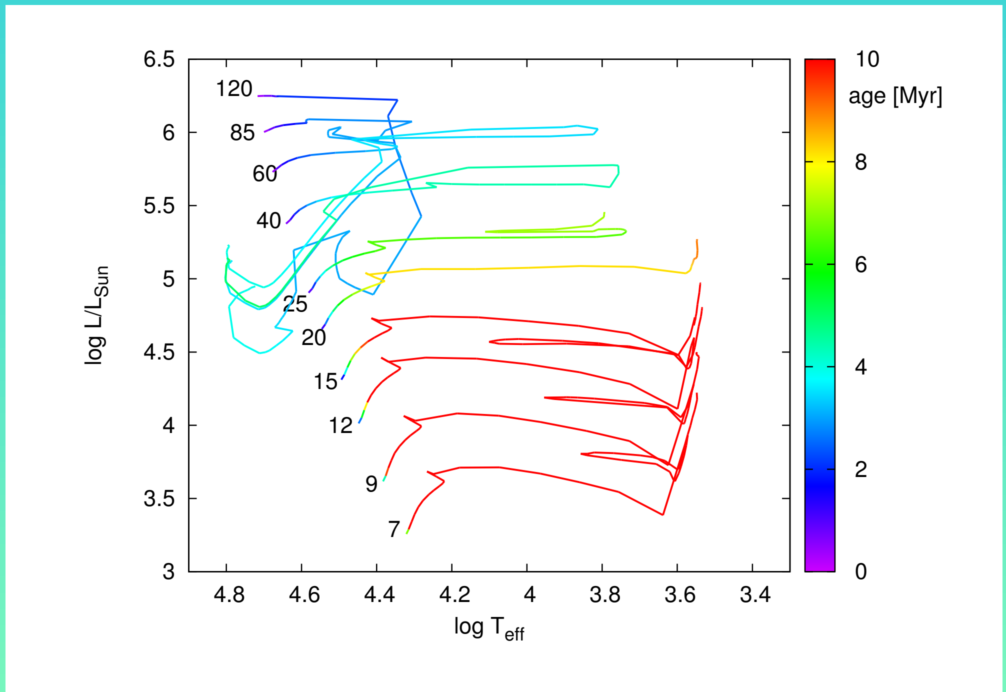
Density inside the cluster



Stellar wind properties from SB99

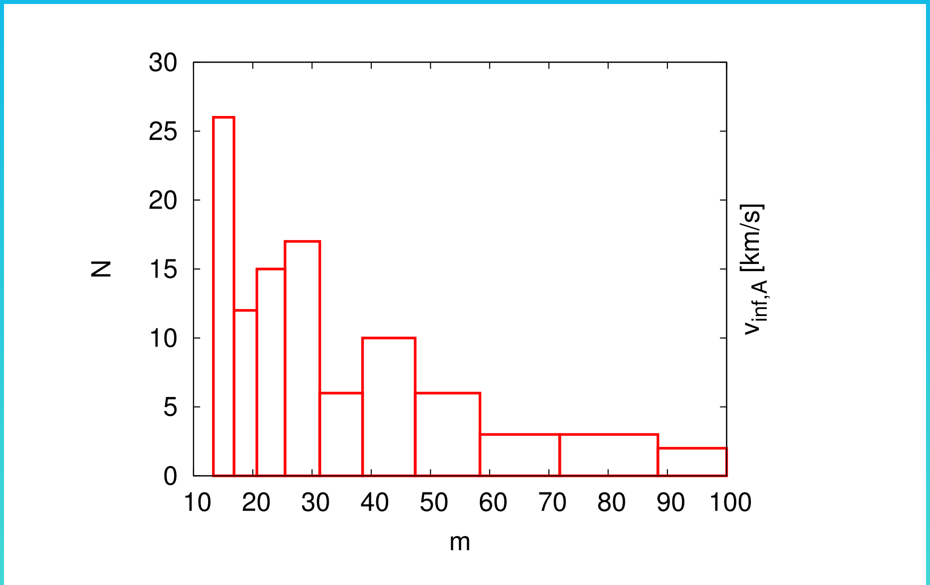
Leitherer et al. (1999)

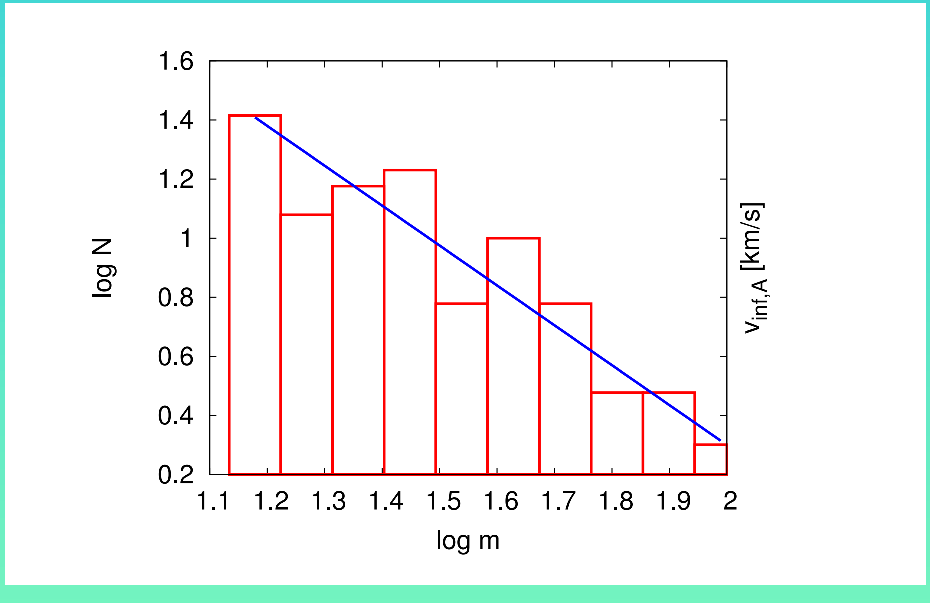
- based on Starburst99 v5.1 data tables
- each wind source is a star with $15\ \mathrm{M}_\odot < M < 120\ \mathrm{M}_\odot$
- time dependent mass loss rate and wind velocity (given by evolutionary tracks)
- mass distribution: Salpeter IMF

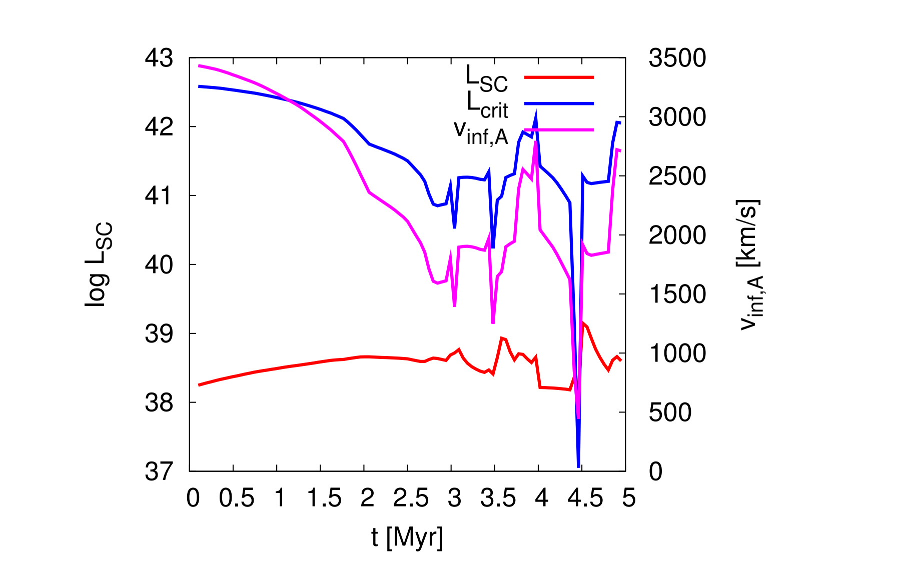


Cluster with "realistic" wind sources

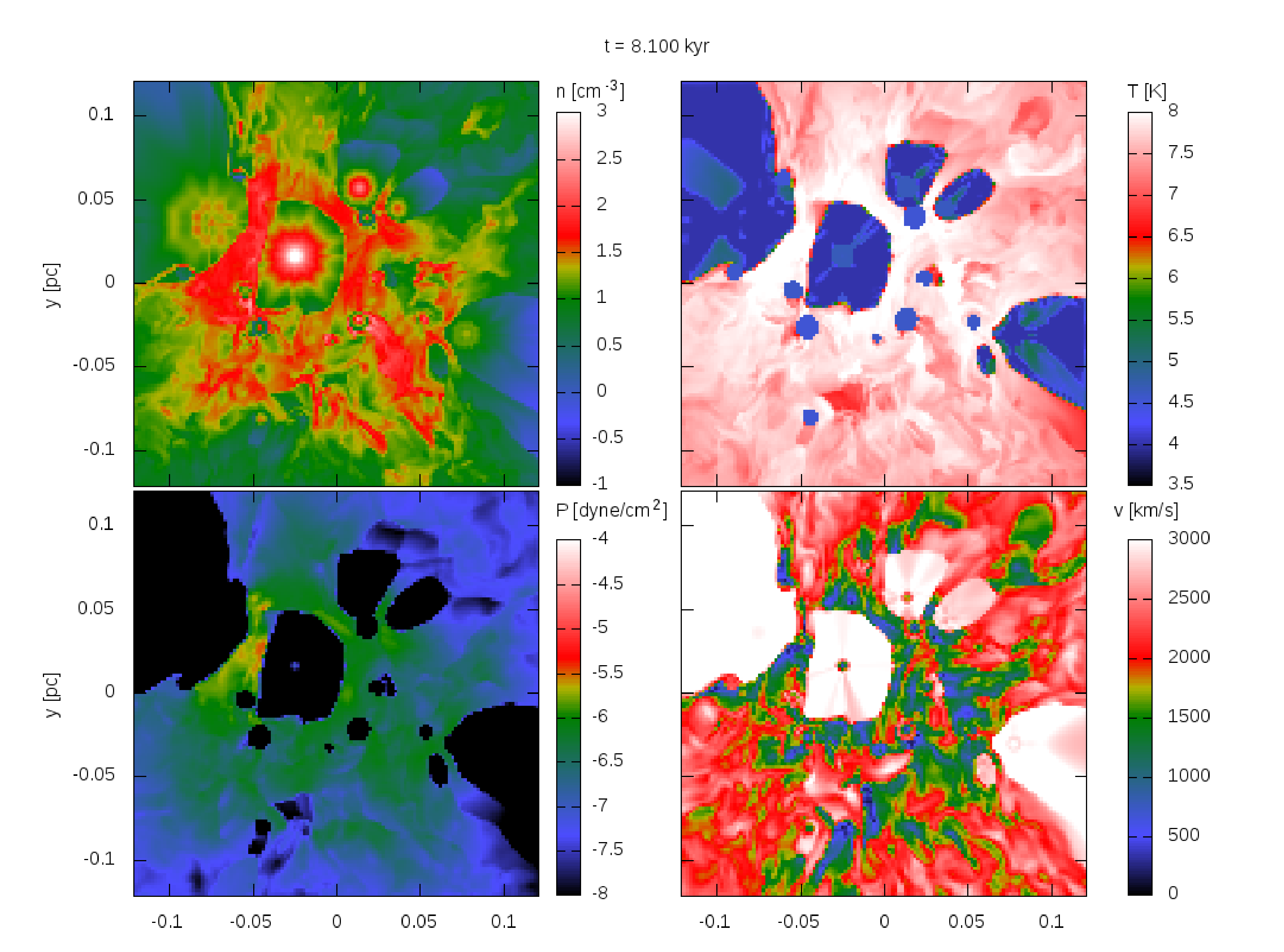
$R_{SC} = 0.1$ pc
$t = 0$





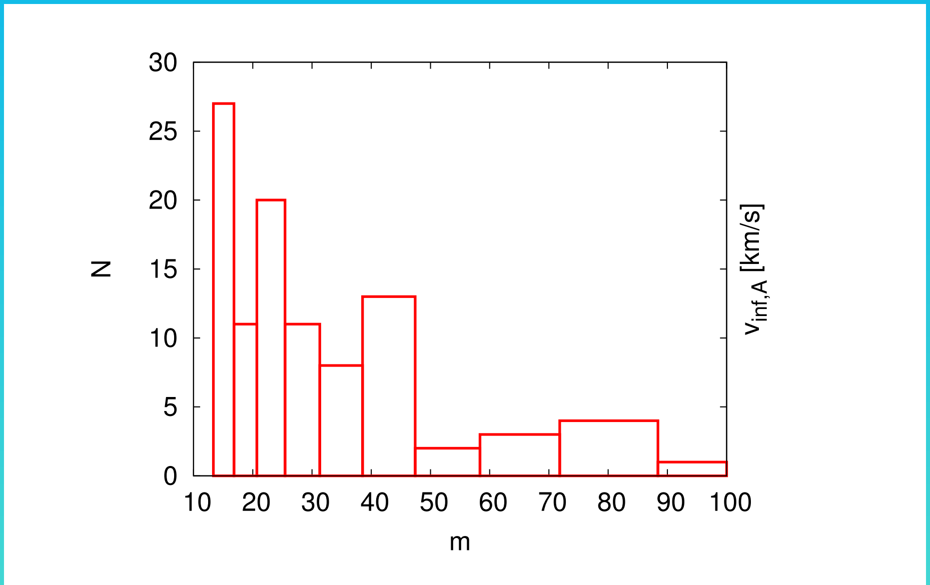


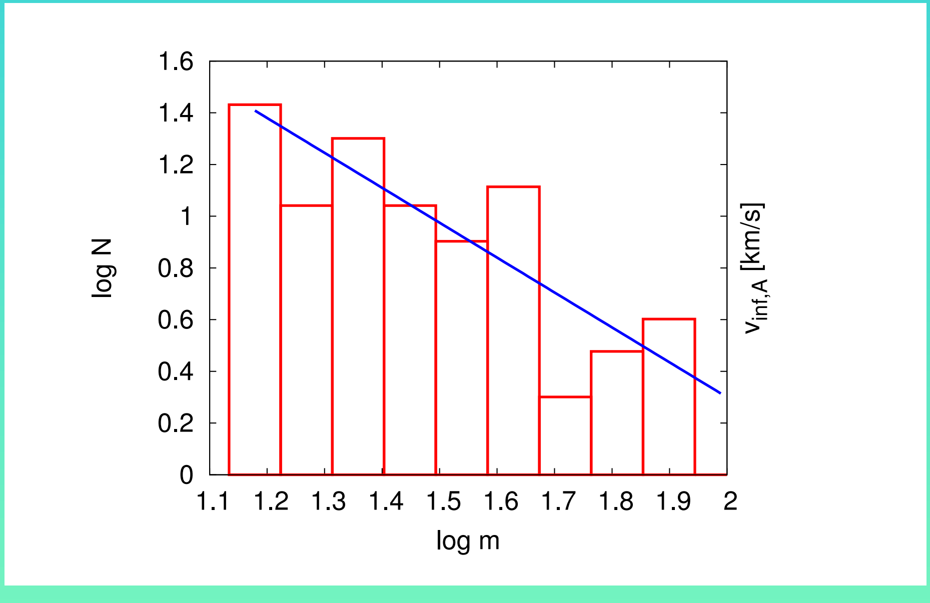
$R_{SC} = 0.1$ pc, $t = 0$

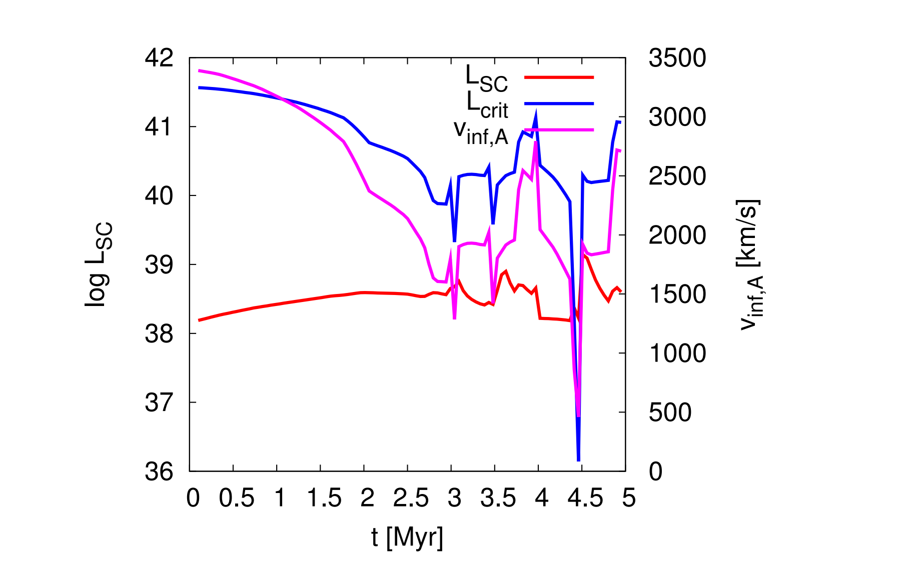

t = 8.100 kyr
n [cm -3]
3
2.5
2
1.5
1
0.5
0
-0.5
-1
T [K]
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
P [dyne/cm 2]
-4
-4.5
-5
-5.5
-6
-6.5
-7
-7.5
-8
v [km/s]
3000
2500
2000
1500
1000
500
0
y [pc]
0.1
0.05
0
-0.05
-0.1
-0.1
-0.05
0
0.05
0.1

Cluster with "realistic" wind sources 2

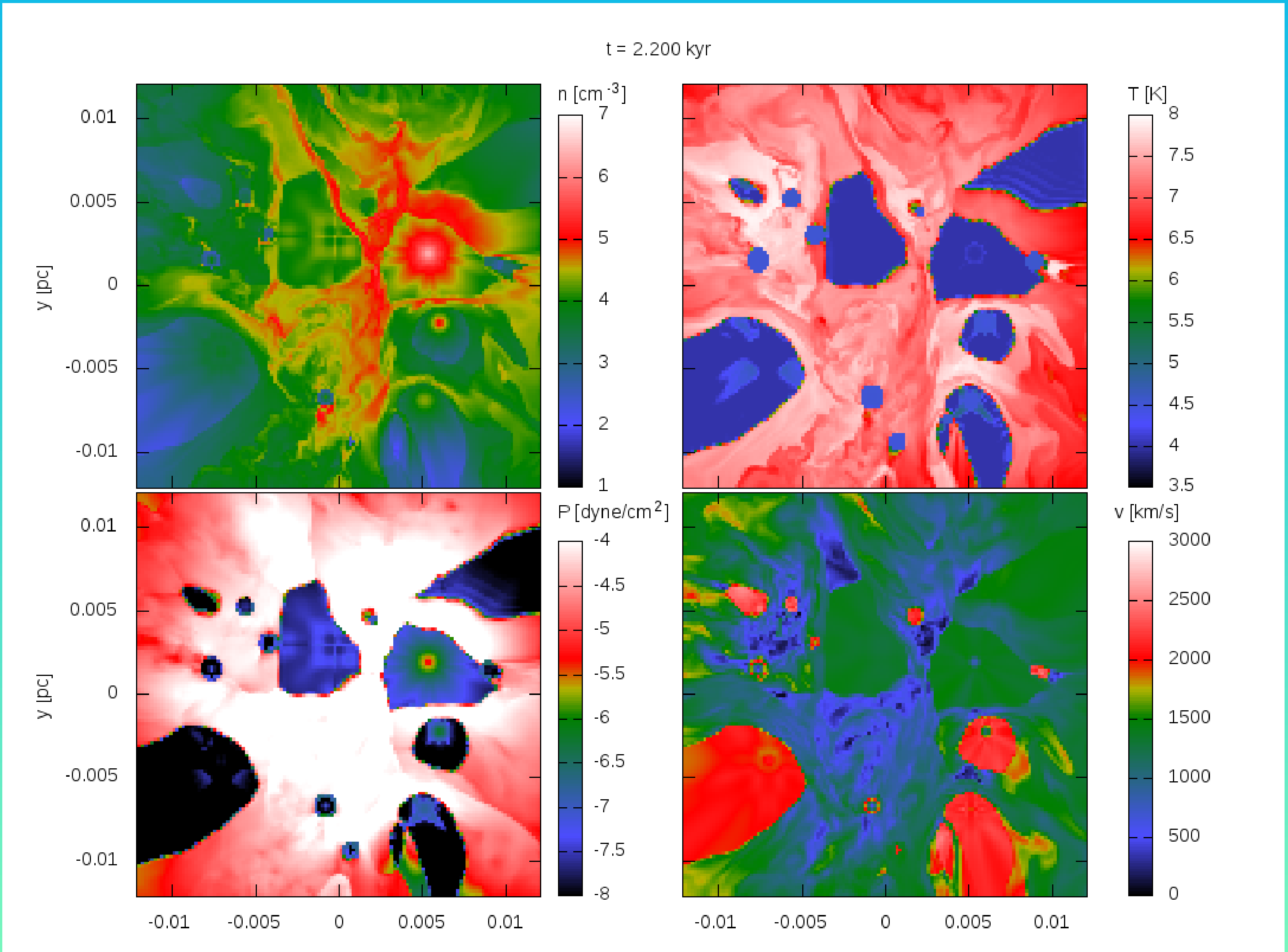
$R_{SC} = 0.01$ pc
$t = 3$ Myr





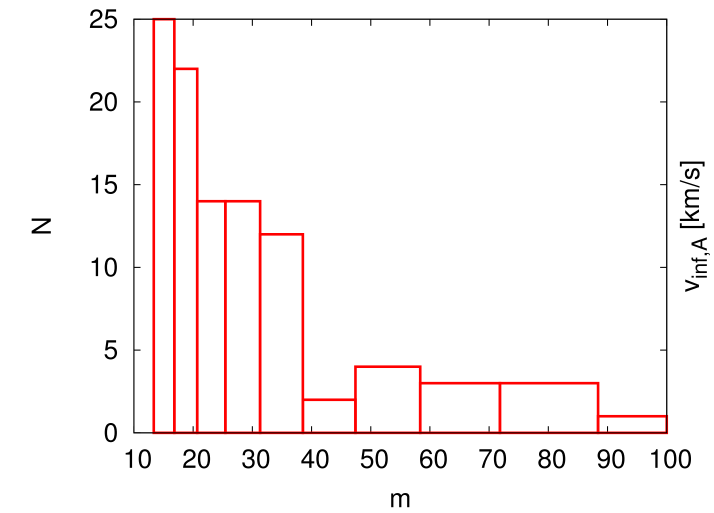


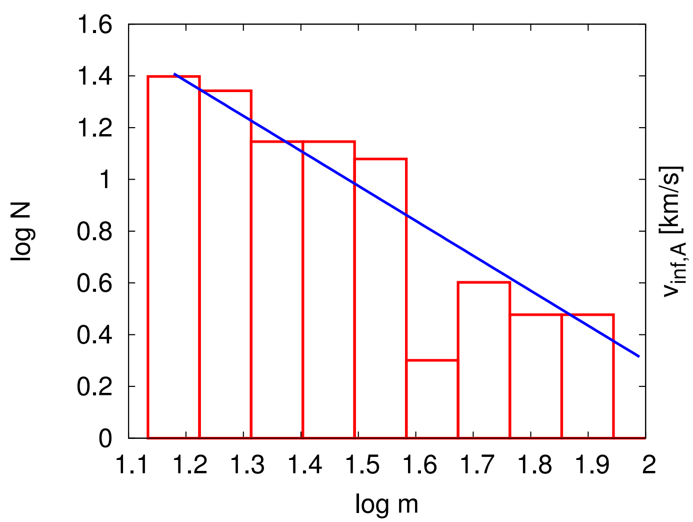
$R_{\rm SC} = 0.01$ pc, $t = 3$ Myr

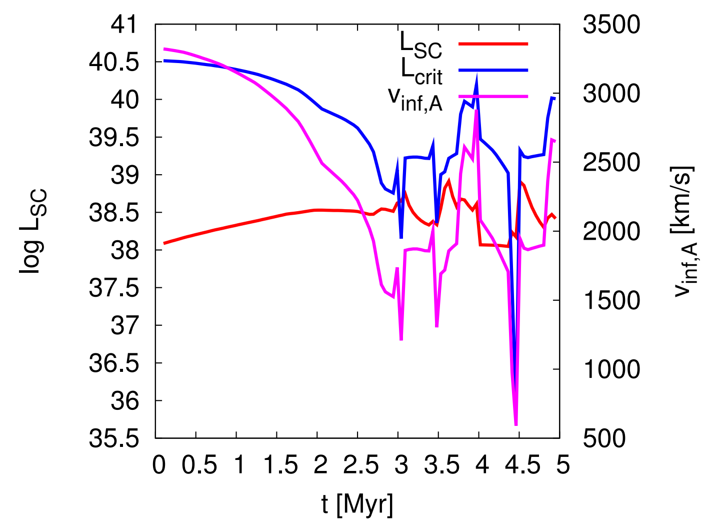


Cluster with "realistic" wind sources 3

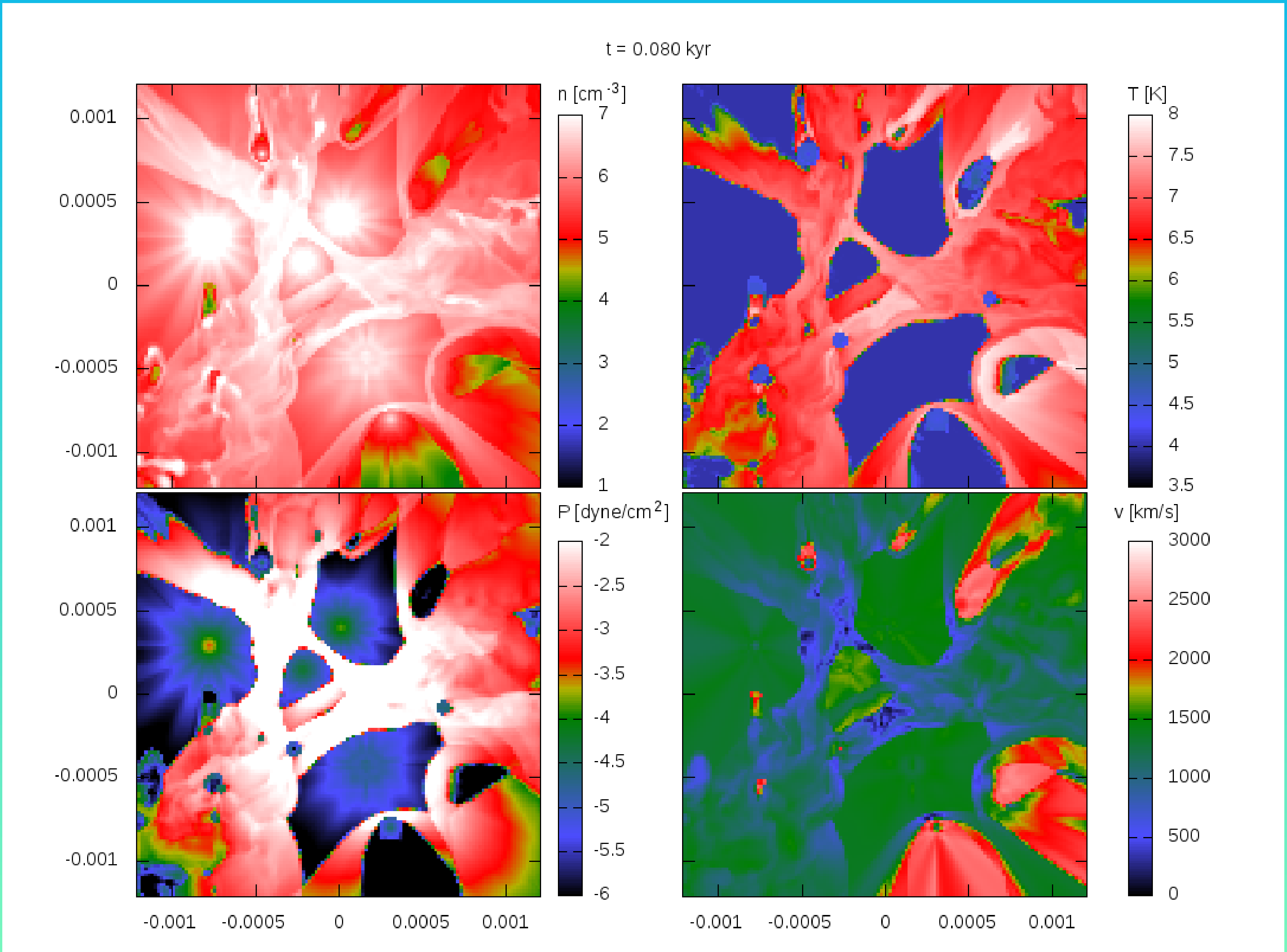
$$R_{\mathrm{SC}} = 0.001\ \mathrm{pc}$$
$$t = 3\ \mathrm{Myr}$$



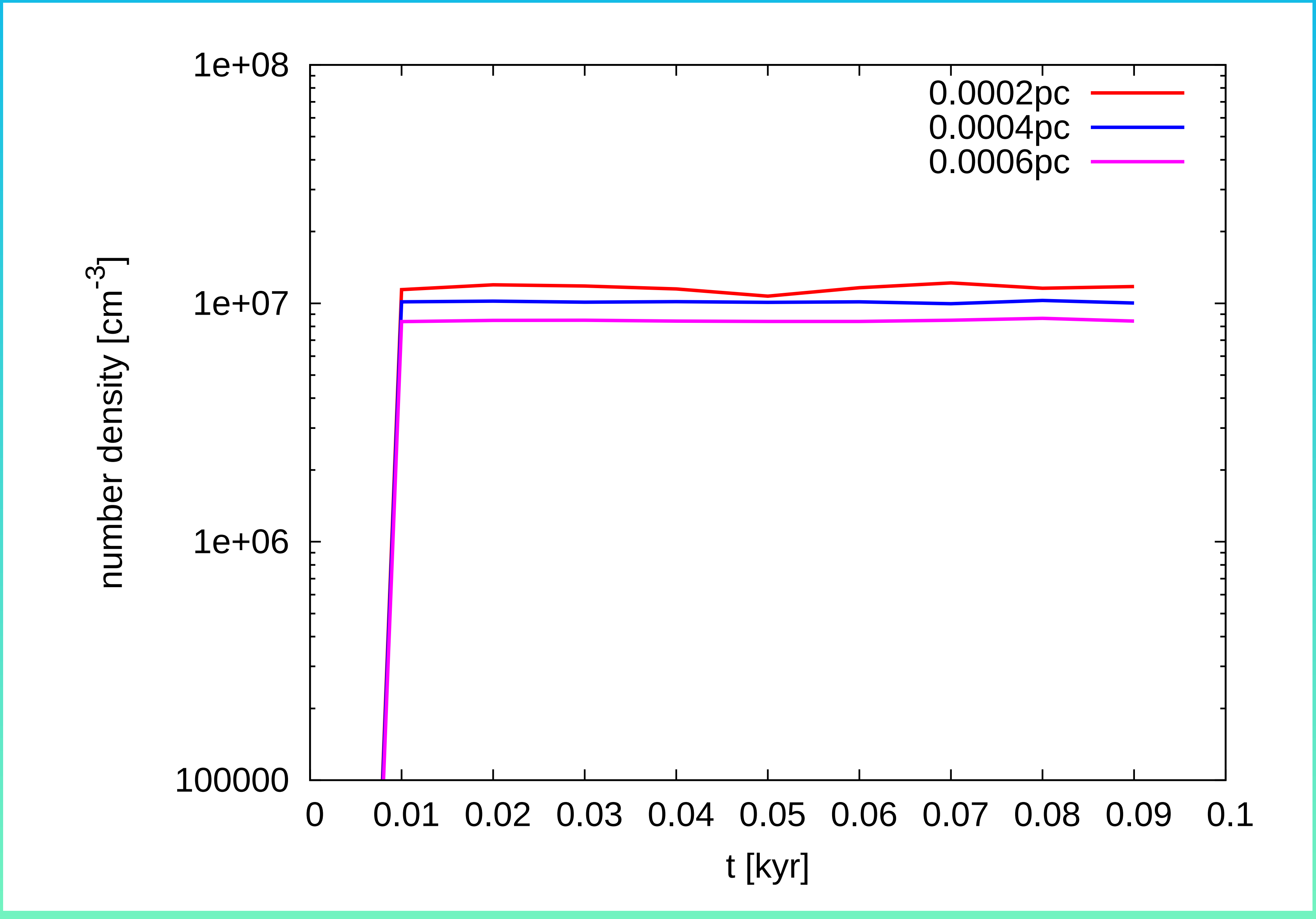




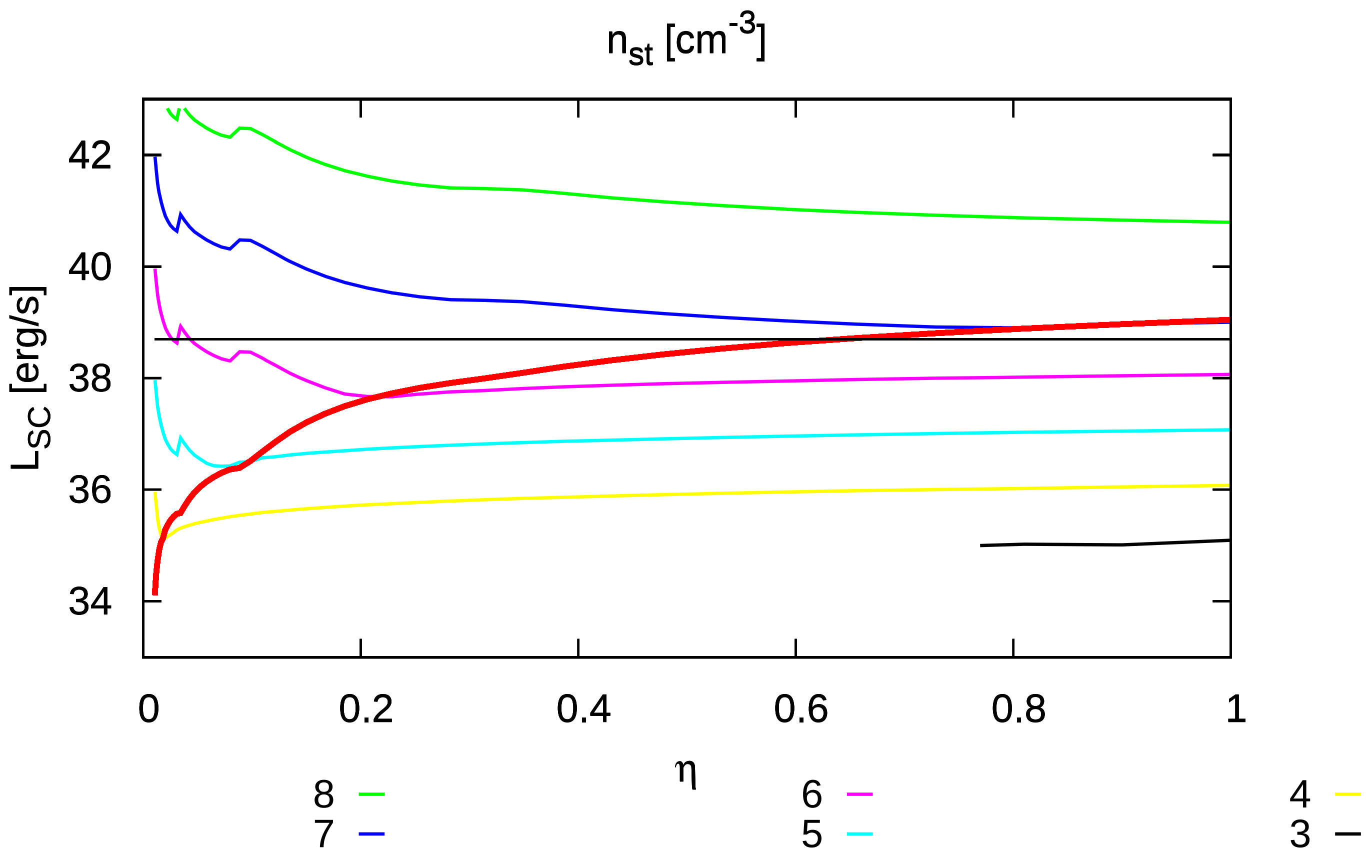
$R_{\mathrm{SC}} = 0.001$ pc, $t = 3$ Myr



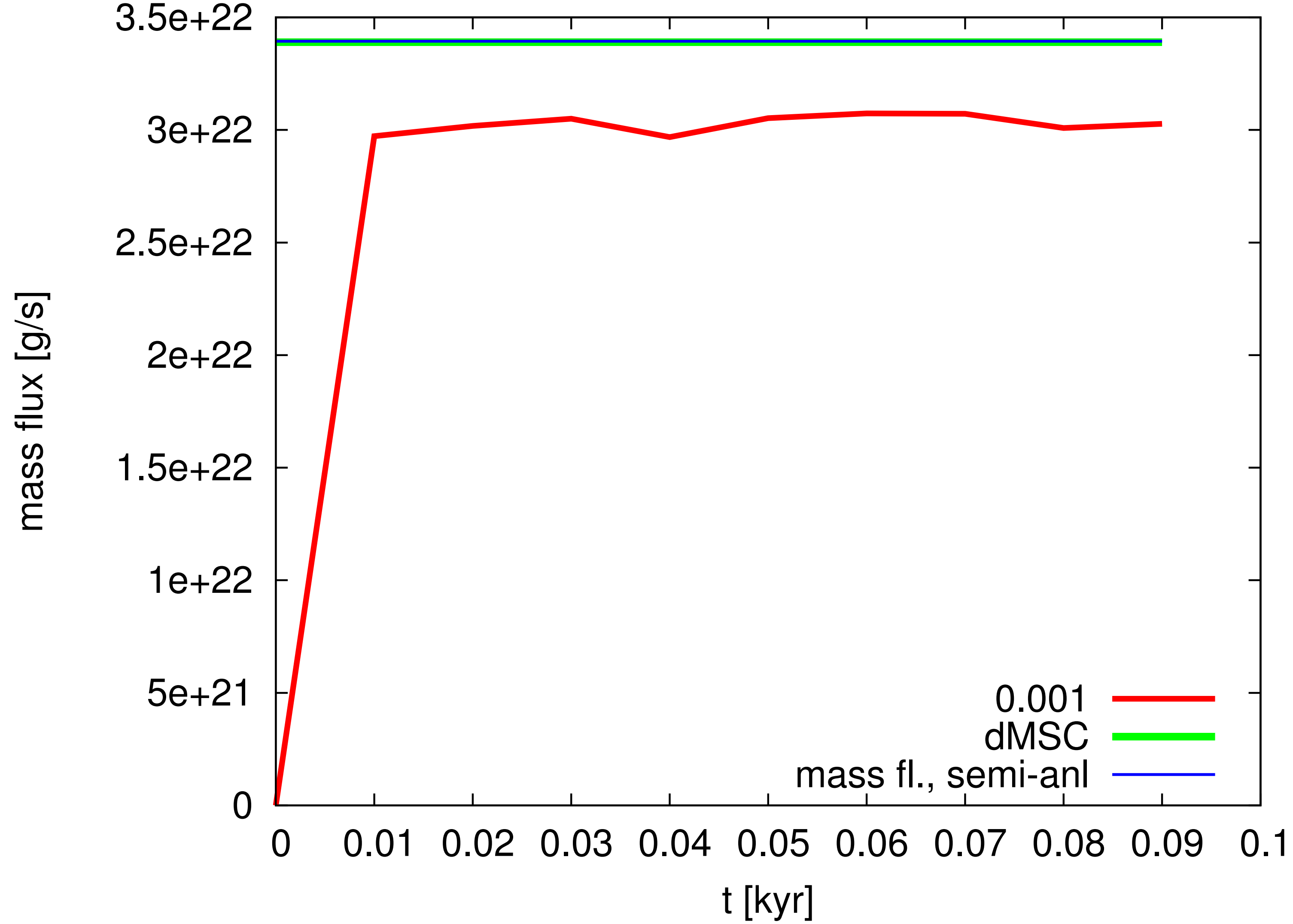
$R_{\rm SC} = 0.001$ pc, time evolution of density



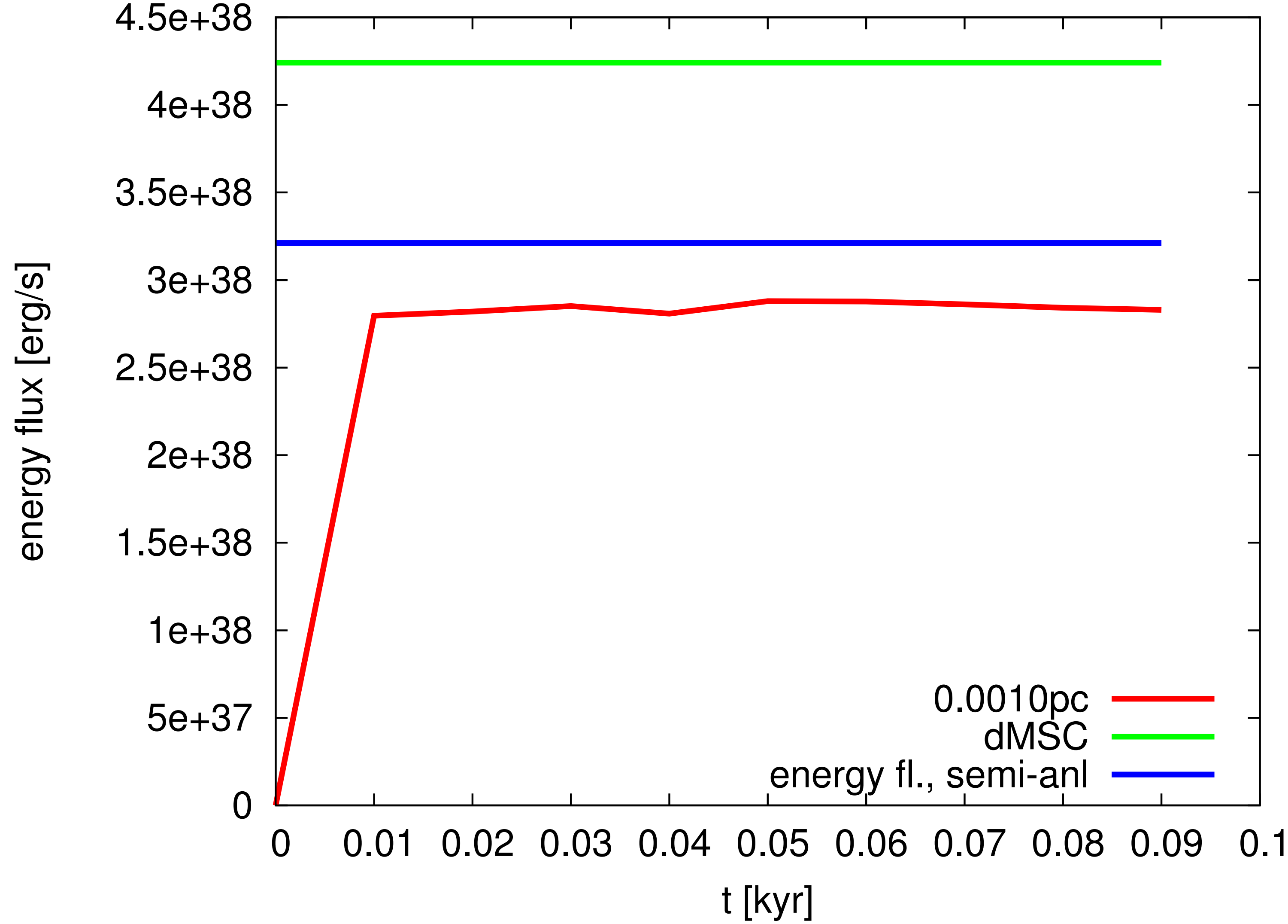
$R_{\rm SC} = 0.001$ pc, density($L_{\rm SC}, \eta$)



$R_{\rm SC} = 0.001$ pc, mass flux



$R_{\rm SC} = 0.001$ pc, energy flux



Summary

- massive compact clusters may evolve in the bimodal regime
  - ▷ outer quasi-stationary wind region
  - ▷ inner thermal instability region, seconday SF
- energy/mass ratio in the hot gas is the critical parameter
  - ▷ heating efficiency: observations suggest $\eta \lesssim 10\%$
- 3D models: uniform E&M insertion vs. individual sources
  - ▷ in general, the IS model confirms Chevalier & Clegg approximation
  - ▷ there are differences - freely floating clumps vs. filaments
- messuring the heating efficiency in simulations
  - ▷ based on properties (density) of the hot medium inside the cluster
  - ▷ very difficult to get $\eta < 1$ with "realistic" stellar properties
  - ▷ other ways making η small: primordial gas, SNe, binaries . . . any ideas?

References

R. A. Chevalier, A. W. Clegg 1985, Nature, 317, 44
A. M. Gilbert, J. R. Graham, 2007, ApJ, 668, 168
T. Plewa 1995, MNRAS, 275, 145
S. Silich, G.Tenorio-Tagle, A.Rodríguez-González 2004, ApJ, 610, 226
S. Silich, G.Tenorio-Tagle, C. Muñoz-Tuñón 2007, ApJ, 669, 952
S. Silich, G.Tenorio-Tagle, A. Torres-Campos, C. Muñoz-Tuñón, A. Monreal-Ibero, V. Melo, 2009, ApJ, 700, 931
G. Tenorio-Tagle, R. Wünsch, S. Silich, J. Palouš 2007, ApJ, 658, 1196
G. Tenorio-Tagle, R. Wünsch, S. Silich, C. Muñoz-Tuñón, J. Palouš 2010, ApJ, 708, 1621
R. Wünsch, S. Silich, J. Palouš, G. Tenorio-Tagle 2007, A&A, 471, 579
R. Wünsch, G. Tenorio-Tagle, J. Palouš, S. Silich, 2008, ApJ, 683, 683