Catastrophic cooling in super star cluster winds

(G. Tenorio-Tagle, R. Wünsch, S. Silich, J. Palouš, 2006, ApJ, accepted)

Super Star Clusters

- observed in variety of starburst galaxies at all redshifts (Ho, 1997)
- masses: $M_{\rm SC} \sim 10^5 – 10^7$ M$_\odot$
- radii: $R_{\rm SC} \sim 3 - 5$ pc
  $\rightarrow$ very compact
- age: < 500 Myr
- $L_{\rm mech} \sim 10^{38} - 10^{42}$ erg/s
- inonizing UV radiation flux:
  - *first 3 Myr . . .* $L_{\rm UV} \sim 10^{53}$ *photons·s*$^{-1}$
  - *then . . . decrease as* t^{-5}
- stellar winds and SN return $\sim 40\% M_{\rm SC}$ back into ISM

M82 - the nearby starburst galaxy

Credit: NASA, ESA, The Hubble Heritage Team

Steady state wind - adiabatic solution

(Chevalier & Clegg, 1985, Nature, 317, 44)

- energy and mass inserted at rates $L_{\rm SC}$ and $\dot{M}_{\rm SC}$, respectively; homogeneously into a sphere of radius $R_{\rm SC}$; $\dot{M}_{\rm SC} \leftrightarrow v_\infty$

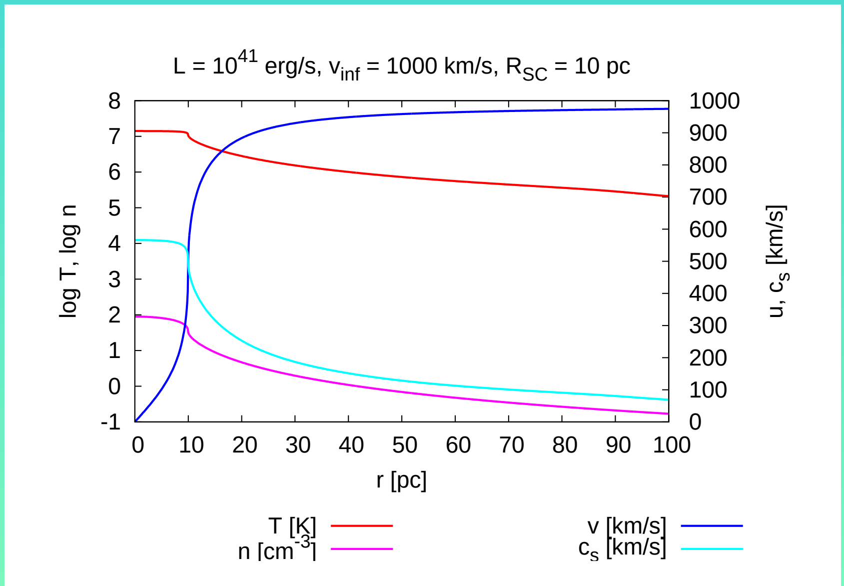
$$\frac{1}{r^2}\frac{d}{dr}\left(\rho u r^2\right) = q_m$$

$$\rho u \frac{du}{dr} = -\frac{dP}{dr} - q_m u$$

$$\frac{1}{r^2}\frac{d}{dr}\left[\rho u r^2 \left(\frac{u^2}{2} + \frac{\gamma}{\gamma - 1}\frac{P}{\rho}\right)\right] = q_e - Q$$

for $r < R_{\rm SC}$:
$q_m = (3\dot{M}_{\rm SC})/(4\pi R_{\rm SC}^3)$
$q_e = (3L_{\rm SC})/(4\pi R_{\rm SC}^3)$
elsewhere: $q_e = q_m = 0$

$$Q = n^2 \Lambda(T, z)$$

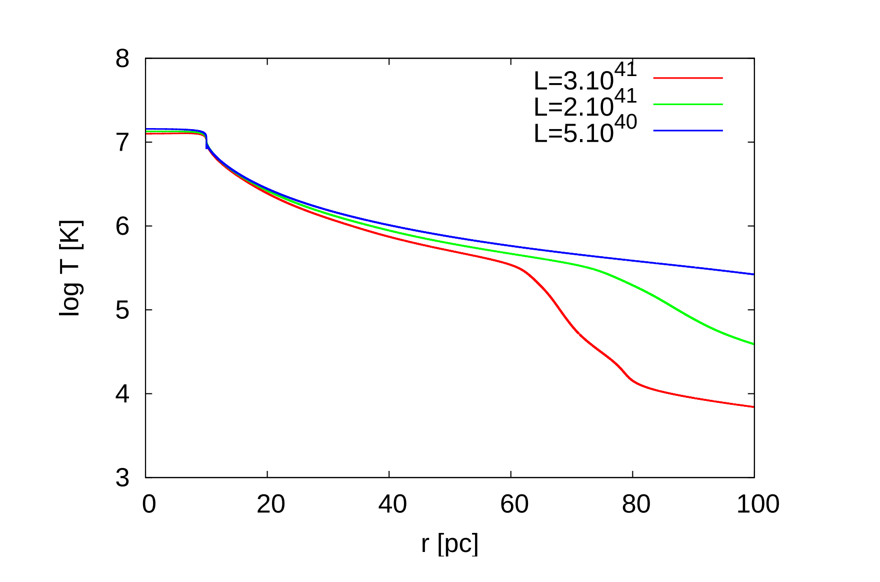


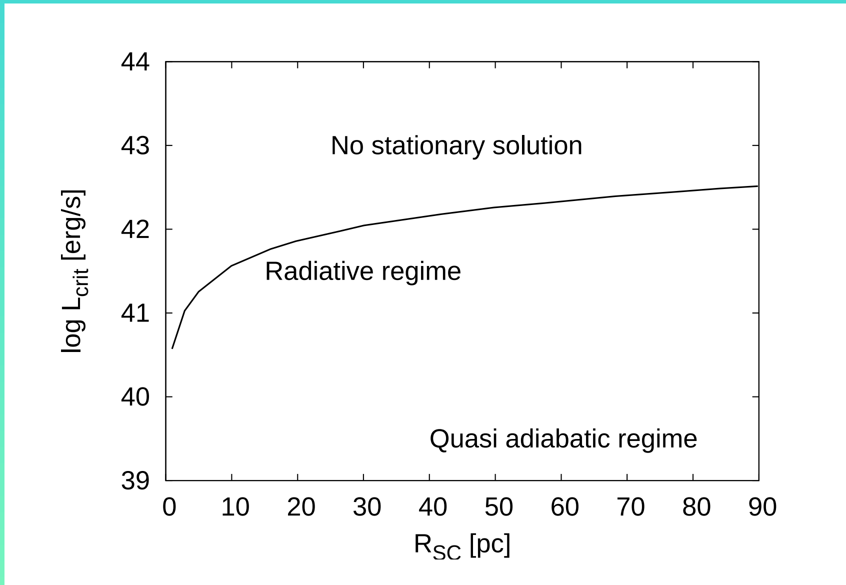
- stationary solution exists only if $R_{\rm sonic} = R_{\rm SC}$
- very extended high temperature (X-ray emitting) envelope
- not supported by observed X-ray fluxes in some cases

Radiative solution & catastrophic cooling

(Silich et al., 2004)

- for higher $L_{\rm SC}$ temperature drops to 10^4 K at some radius
- X-ray emitting region is much smaller than in adiabatic case
- P_c cannot be arbitrary large (regardless $L_{\rm SC}$)

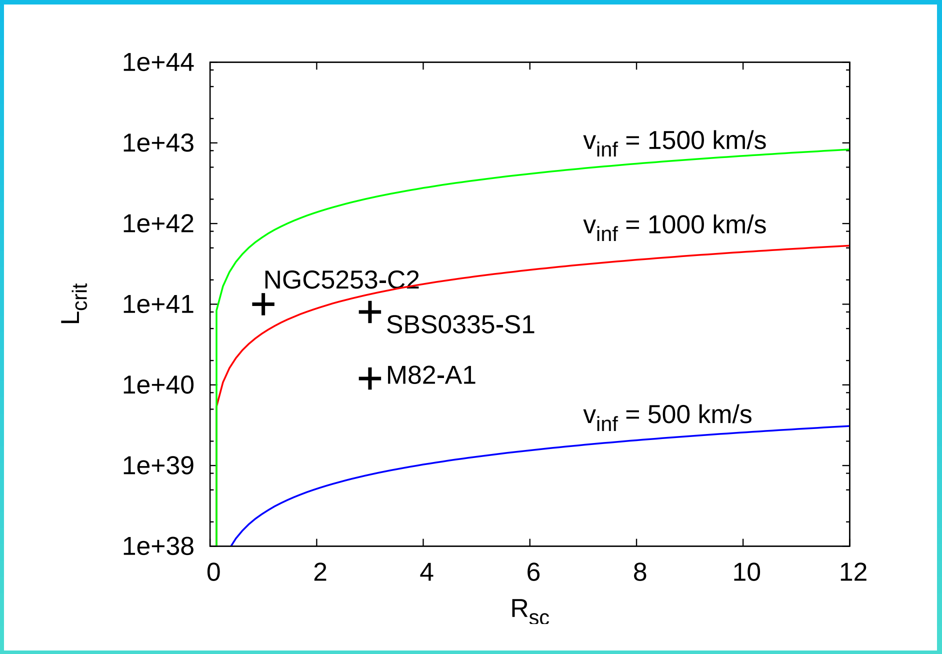


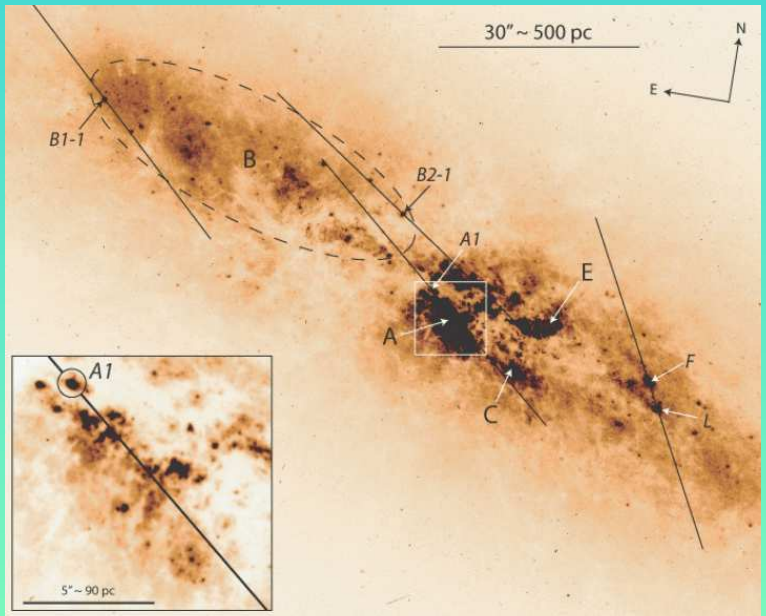


- $R_{\rm sonic} \sim P_c \Rightarrow R_{\rm sonic}$ cannot be arbitrary large $\longrightarrow$ cannot equal to $R_{\rm SC}$ for some parameters $\Rightarrow$ stationary solution does not alway exist

Catastrophic cooling & observed clusters

- most massive observed SSCs have luminosities close to $L_{\rm crit}$ curve
- uncertainty because of unknown v_∞ and metallicity





- M82-A1 associated with HII region:

$$R_{HII} = 4.5 \text{ pc}$$
$$n_{HII} = 1800 \text{ cm}^{-3}$$
$$\text{FWHM}_{HII} = 62 \text{ km/s}$$

HST + ACS/WFC F814W image of M82 (Smith et al, 2006)

Numerical model

- based on ZEUS3D v.3.4.2, new cooling implemented

Richard Wunsch - Iceweasel

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Cooling routine with "adaptive time-step refinement"

patch for the ZEUS3D hydrodynamic code

Description:

This patch for ZEUS3D v3.4.2 implements new cooling which is able to work in case of extremely fast cooling like for instance during the thermal instability of the gas. It is achieved by using more stable root finding algorithm (Brent's method) for solving the energy equation, and in particular by controlling the size of the time-step by the cooling rate.

The "cooling" time-step is defined $dt_{cool} = e/[\rho\Lambda(T,z)]$ where ρ and e are the local mass and energy densities, $\Lambda(T,z)$ is the cooling function, and **CCN** is the "cooling Courant number" - a dimensionless quantity which denotes the relative amount of internal energy that can be radiated away during dt_{cool}.

Local sub-steps for the computation of the energy equation are used to increase the code performance; the global time-step is

$$dt = \begin{cases} dt = dt_{HD} & \text{for} \quad dt_{cool} \geq dt_{HD} \\ dt = dt_{cool} & \text{for} \quad dt_{HD} > dt_{cool} \geq \delta \times dt_{HD} \\ dt = \delta \times dt_{HD} & \text{for} \quad \delta \times dt_{HD} > dt_{cool}; \rightarrow \text{local substeps } dt_{sub} = dt_{cool} \end{cases}$$

where dt_{HD} is the hydrodynamic time-step and δ (typically $\delta \approx 0.1$) is a dimensionless parameter.

This procedure does not let the global time-step decrease below $\delta \times dt_{HD}$. However, the accuracy in solving the equation of energy is ensured by the sub-steps of size dt_{cool} which are only applied to fast cooling regions.

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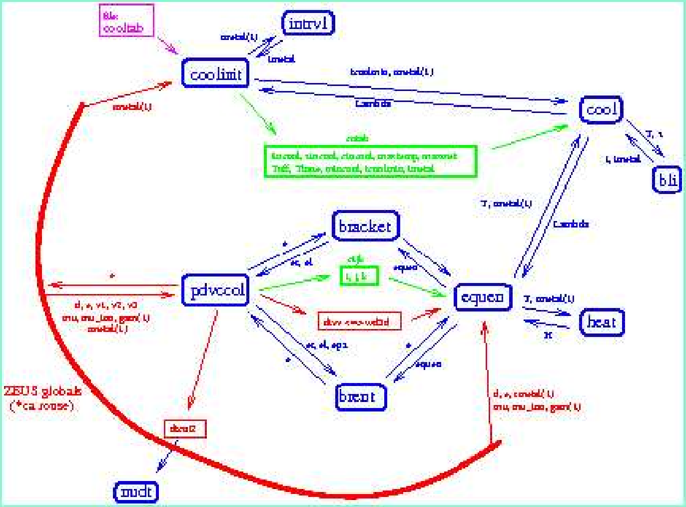
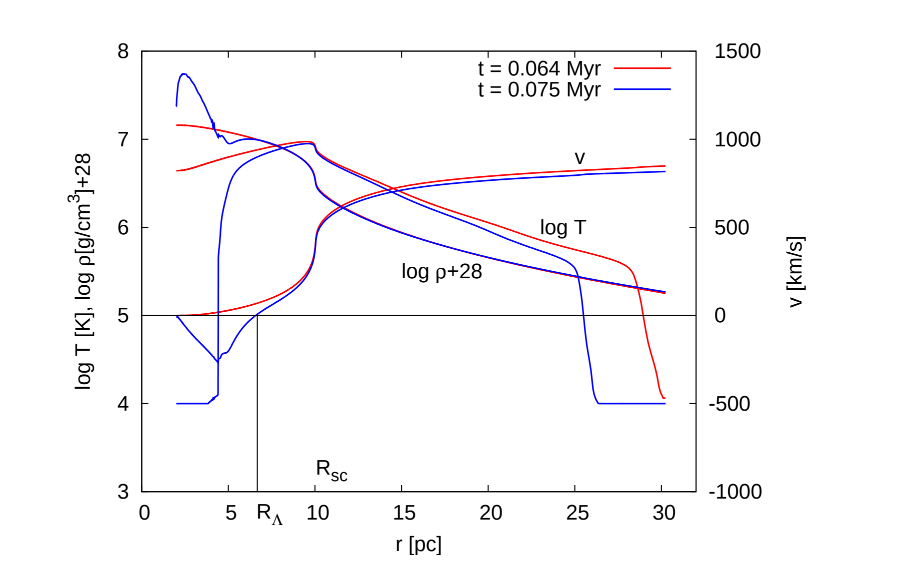
Diagram of subroutine calls

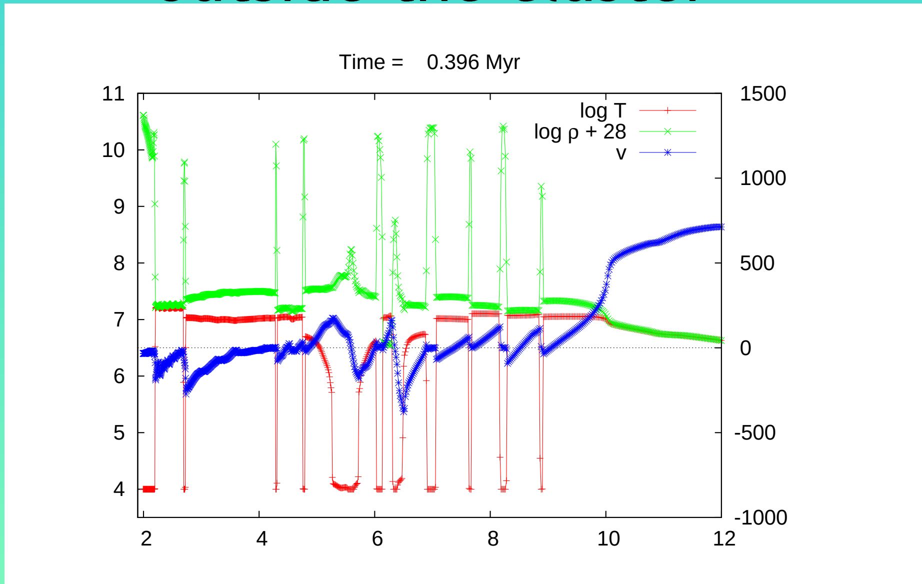


Supercritical clusters - 1D

Lower $L_{\rm SC}$ (10^{42} erg/s)

- inner cluster region oscillates between 2 states with higher (10^7 K) and lower (10^4 K) temperature
- periodic shifts of $R_{\rm st}$ and temperature drop region outside the cluster

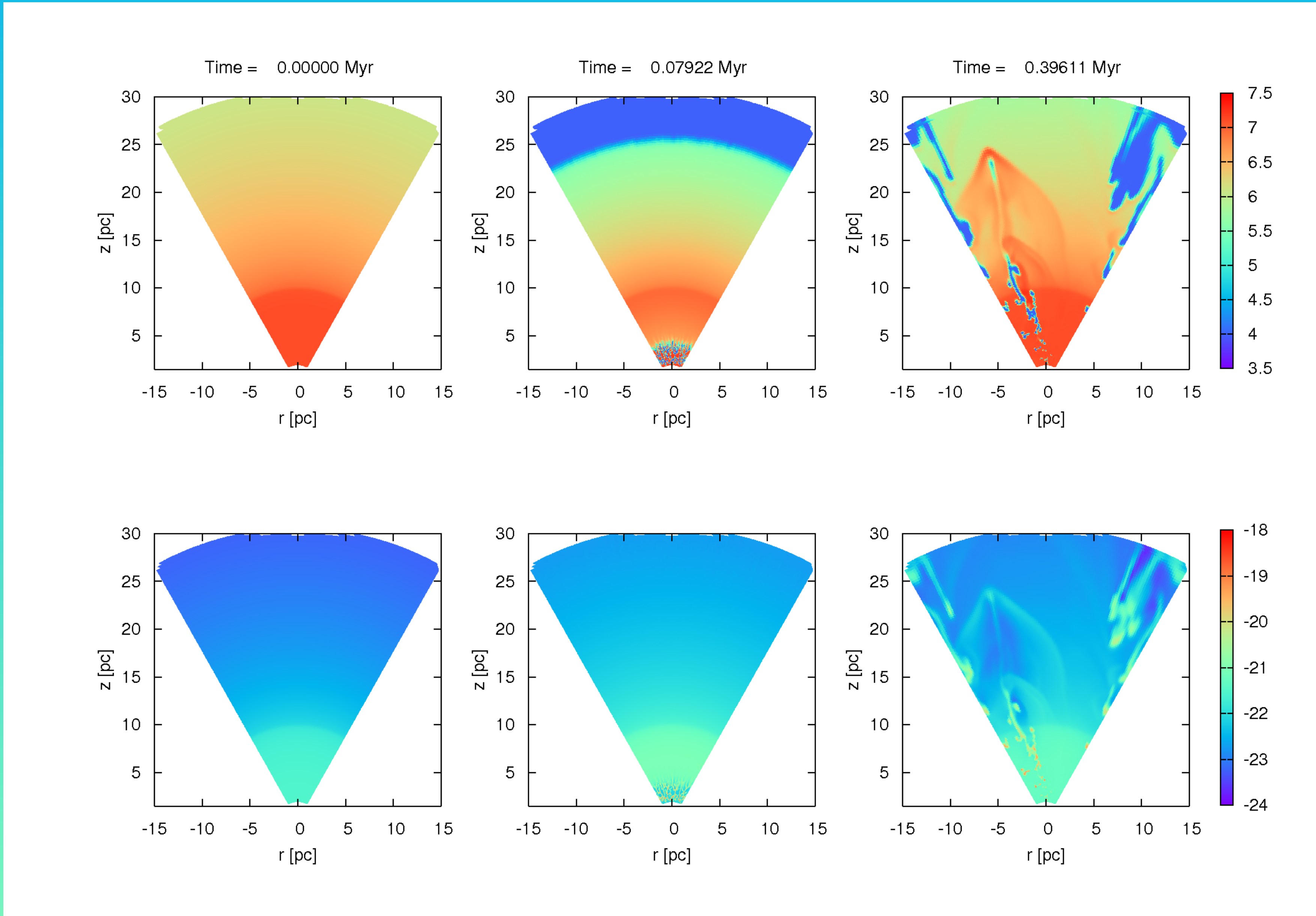




Higher $L_{\rm SC}$ (10^{43} erg/s)

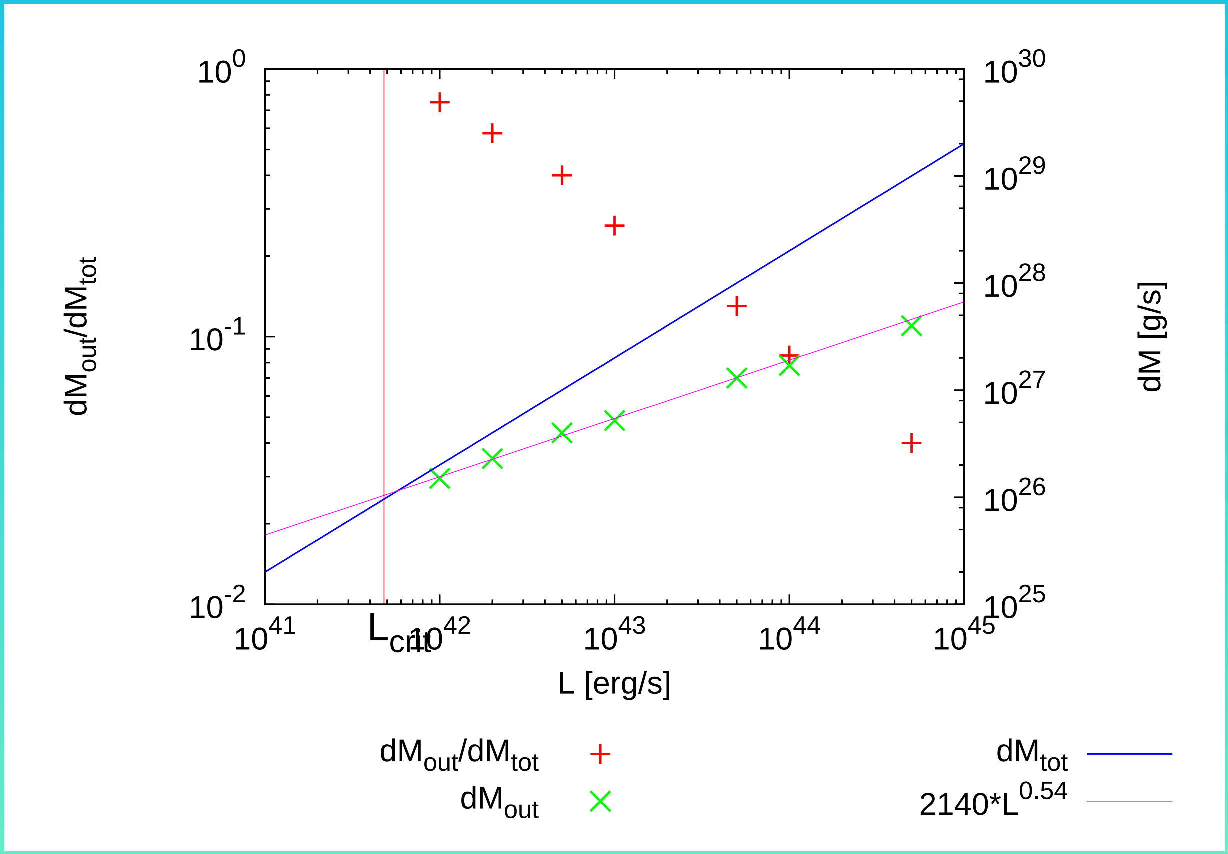
- dense cold standing shells are formed through collisions of shocks

Supercritical clusters - 2D



Mass outflow

- although $R_{\rm st} \rightarrow R_{\rm SC}$ for $L_{\rm SC} \rightarrow \infty$, the amount of mass outflowing from the cluster grows with $L_{\rm SC}$



$$\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm SC}} \approx \left(\frac{L_{\rm SC}}{L_{\rm crit}}\right)^{-0.46}$$

Summary

- the radiative cooling may substantially change the radial temperature profile of the SSC wind, making the high-temperature (X-ray emitting) region smaller
- winds in very massive and compact SSCs (above $L_{\rm crit}$ curve) may become thermally unstable in the central region
- the thermally unstable material collapses into dense cold clumps and part of it may eventually feed the subsequent star-formation there
- the outer region of the cluster is still able to produce the quasi-stationary wind, though less powerful than predicted by the adiabatic model

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