Catastrophic cooling in super star cluster winds

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Outline:

1. Super star cluster winds
2. Semi-analytical adiabatic and radiative models
3. Catastrophic cooling
4. Numerical simulations (1D, 2D, mass outflow)

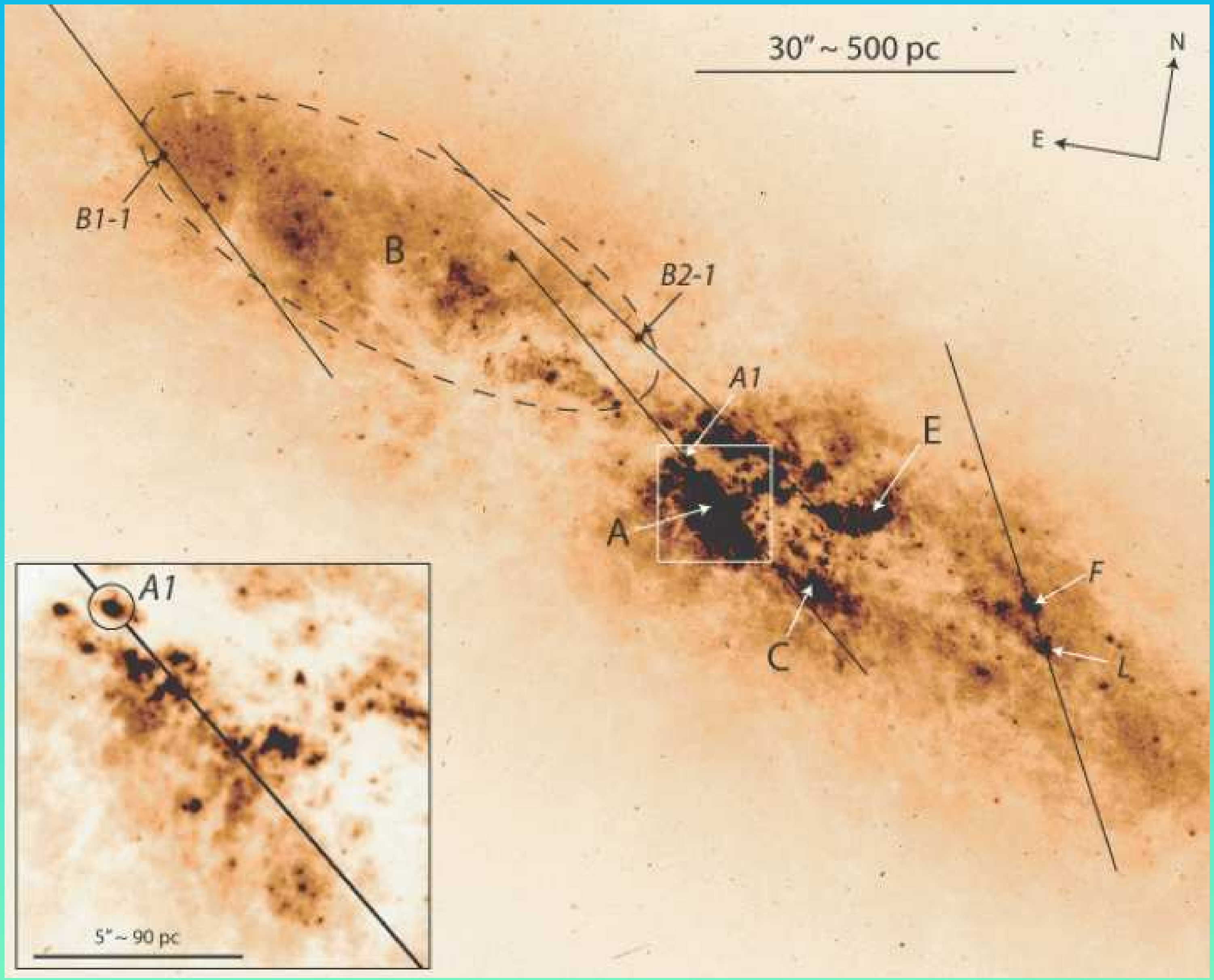
Super star clusters

- 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
- $L_{\rm mech} \sim 10^{40} - 10^{42}$ erg/s
- inonizing UV radiation flux:
  - *first 3 Myr . . .* $L_{\rm UV} \sim 10^{53}$ *photons*$\cdot$*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

SSCs in M82



HST + ACS/WFC F814W image of M82 (Smith et al, 2005)

Some models in literature

analytical
spherically symmetric
adiabatic model
(Chevalier & Clegg, 1985)

adiabatic models

2D & 3D numerical models
wind−wind, wind−ISM interaction
(Canto et al., 2000)
(Raga et al., 2001)

models with cooling

2D numerical radiative solution
(Silich et al., 2003)

catastrophic cooling invented
(Silich et al., 2004)

evolution scenario
(Tenorio−Tagle et al., 2004)

catastrophic cooling
numerical & semi−analytical models
(Tenorio−Tagle et al., 2006)
(Wunsch et al., 2007)

Steady state wind

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

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

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

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

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

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

- stationary solution exists only if $R_{\rm sonic} = R_{\rm SC}$

outside of cluster: $$\frac{du}{dr} = \frac{1}{\rho}\frac{(\gamma-1)rQ + 2\gamma u P}{r(u^2 - c_s^2)}$$

inside of cluster: $$\frac{du}{dr} = \frac{1}{\rho}\frac{(\gamma-1)(q_e - Q) + q_m\{[(\gamma+1)/2]u^2 - 2c_s^2/3\}}{c_s^2 - u^2}$$

Adiabatic wind

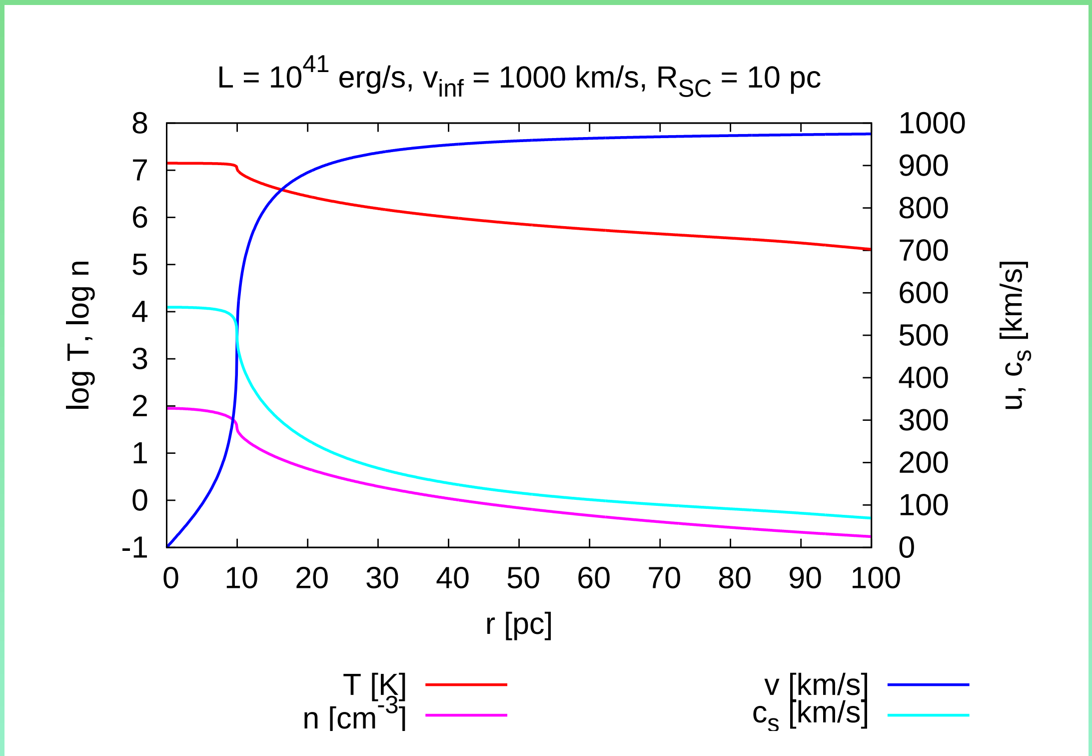
Chevalier & Clegg (1985)

- $Q = 0 \Rightarrow$ analytical formulas for the central quantities

$$\rho_c = \frac{\dot{M}_{\rm SC}}{r\pi B R_{\rm SC}^2 v_\infty}, \quad P_c = \frac{\gamma-1}{2\gamma}\frac{\dot{M}_{\rm SC} v_\infty}{r\pi B R_{\rm SC}^2}, \quad T_c = \frac{\gamma-1}{\gamma}\frac{\mu}{k_B}\frac{q_e}{q_m}$$

$$B = [(\gamma-1)/(\gamma+1)]^{1/2}[(\gamma+1)/(6\gamma+2)^{(3\gamma+1)/(5\gamma+1)}]$$

- numerical integration of previous ODEs



for $r \to \infty$:

$$\rho \sim r^{-2}$$
$$T \sim r^{-4/3}$$
$$u \to v_\infty = \sqrt{\frac{2\dot{E}_{\rm SC}}{\dot{M}_{\rm SC}}}$$

very extended high temperature (X-ray emitting) region

Radiative solution

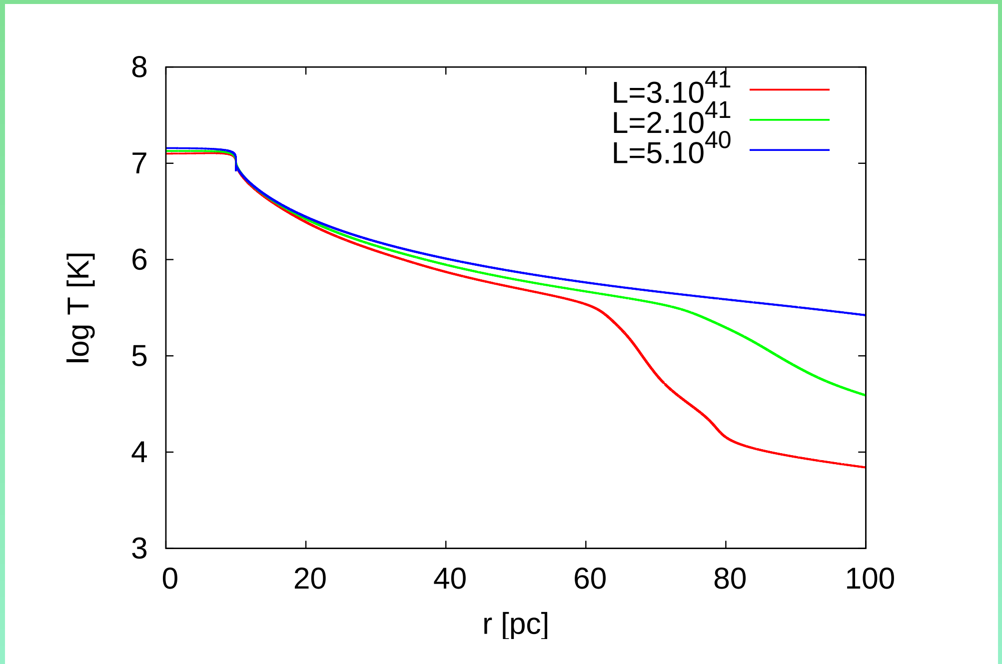
(Silich et al., 2004)

- no explicit formulas for ρ_c, T_c, but relation:

$$n_c = \sqrt{\frac{q_e - q_m c_{s,c}^2/(\gamma - 1)}{\Lambda(T_c)}}$$

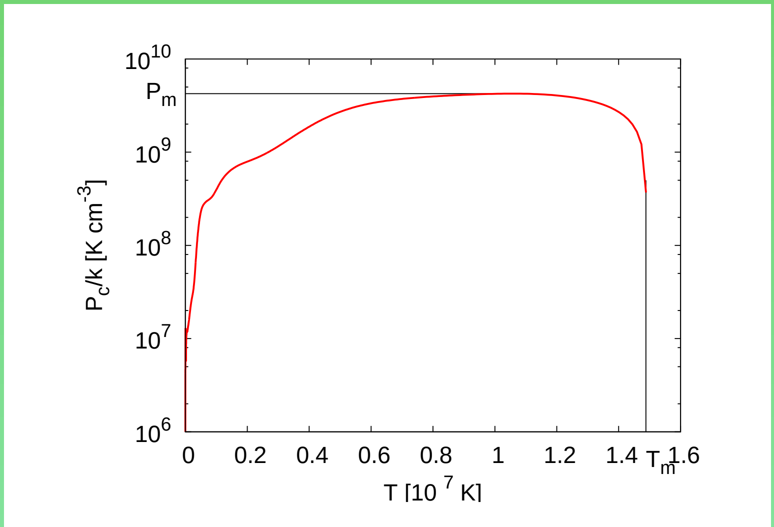
- iterative search for T_c such that $R_{\mathrm{sonic}} = R_{\mathrm{SC}} \rightarrow \rho_c, P_c \rightarrow$ numerical integration of HD eqs.

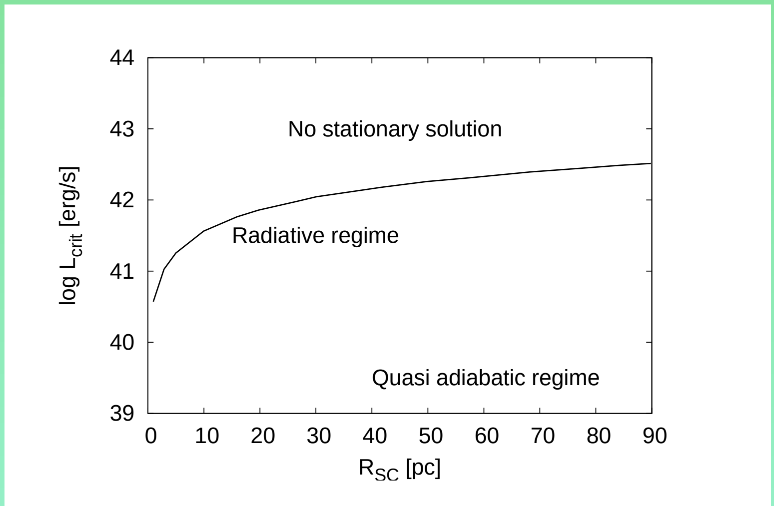
- for higher $\dot{E}_{\mathrm{SC}}$ temperature drops to 10^4 K at some radius
- X-ray emitting region is much smaller than in adiabatic case



Catastrophic cooling

- adiabatic case: ρ_c, T_c independent
  $\longrightarrow$ always can be stabilised so that $R_{\rm sonic} = R_{\rm SC}$
- radiative case:
  $T_c \rightarrow T_{\rm m} = \frac{\gamma - 1}{\gamma} \frac{\mu}{k_B} \frac{q_e}{q_m}$: $\rho_c, P_c \rightarrow 0$
  $T_c < T_{\rm m}$: P_c increases for decreasing T_c, but there is a maximum of P_c

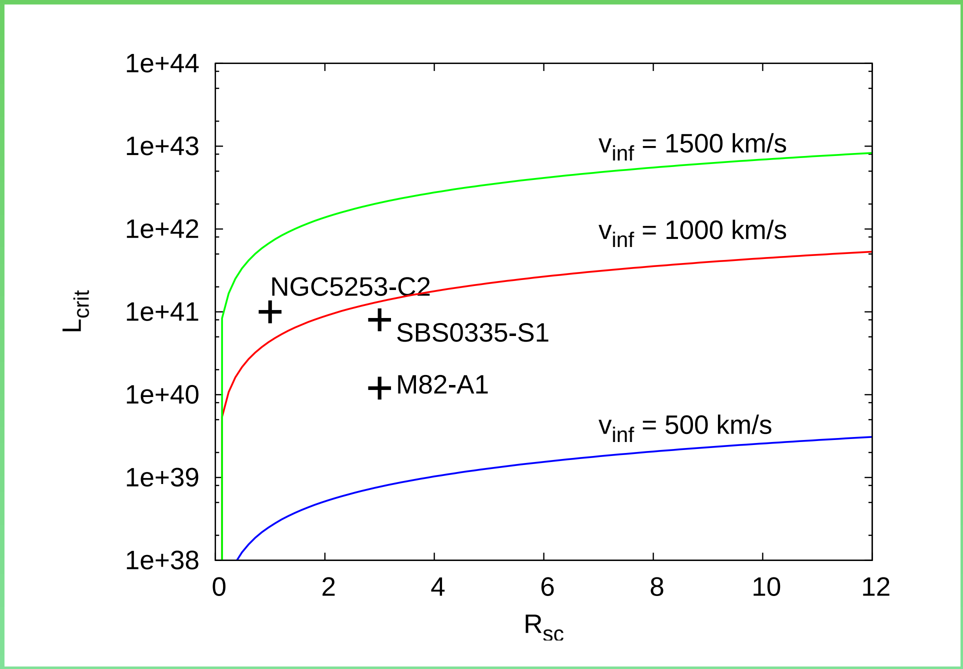


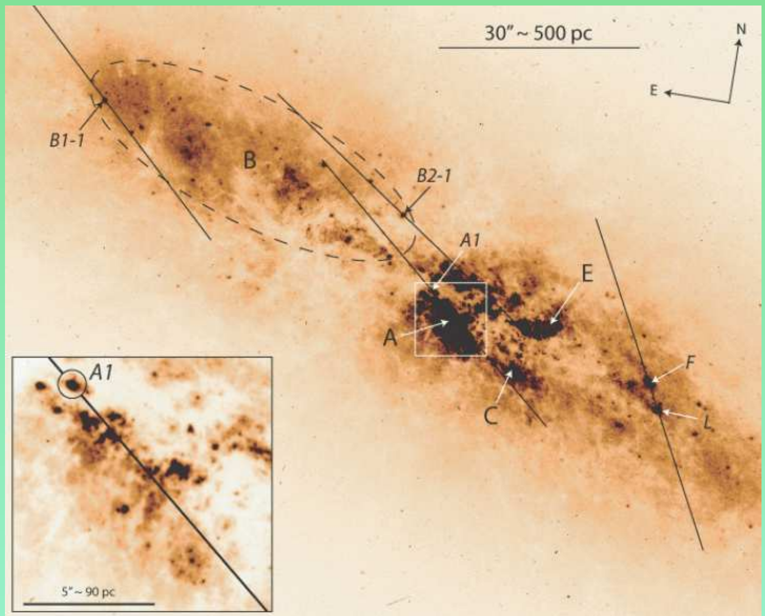


- $R_{\rm sonic} \sim P_c \Rightarrow R_{\rm sonic}$ cannot be arbitrary large $\longrightarrow$ cannot equal to $R_{\rm SC}$ for some parameters $\Rightarrow$ stationary solution does not alway exist

Observed clusters

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





- M82-A1 associated with HII region:

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

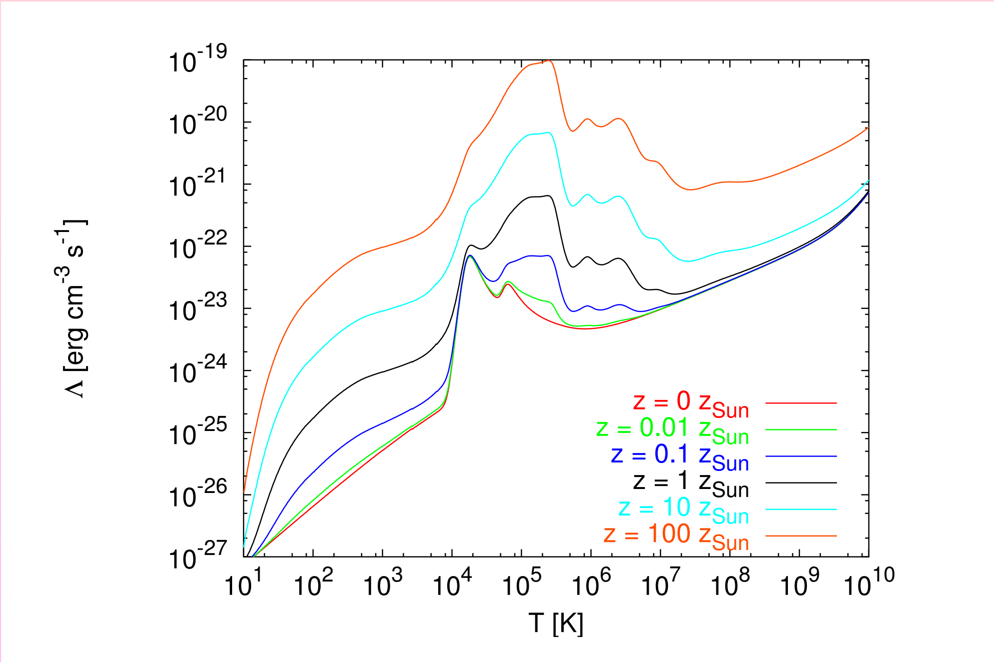
Numerical model

- based on ZEUS3D v.3.4.2
- grid-based Eulerian 2nd order hydrodynamic code, van Leer advection
- advantage of radially scaled grid (in 2D regular cells in spherical coords)
- new cooling implemented:

  ▷ *more up-to-date cooling function* `(Plewa, 1995)`

  ▷ *equation for energy solved by Brendt algorithm (original Newton-Raphson method had problems with convergence and was too slow)*

  ▷ *time-step controlled by cooling rate*



Implementation of cooling

- cooling time-step (limit on the relative amount of internal energy which can be radiated away during 1 time-step) (e.g. Suttner et al., 1997)

$$dt_{\rm cool} = {\rm CCN} \times \frac{e}{\rho^2 \Lambda(T,z)}$$

- CCN - "Cooling Courant Number" (typically 0.1)
- $dt_{\rm cool}$ too small in some places ($dt_{\rm cool} \sim 10^{-3} dt_{\rm HD}$)
  $\Rightarrow$ **local** sub-steps $dt_{\rm sub} \leq dt_{\rm cool}$

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

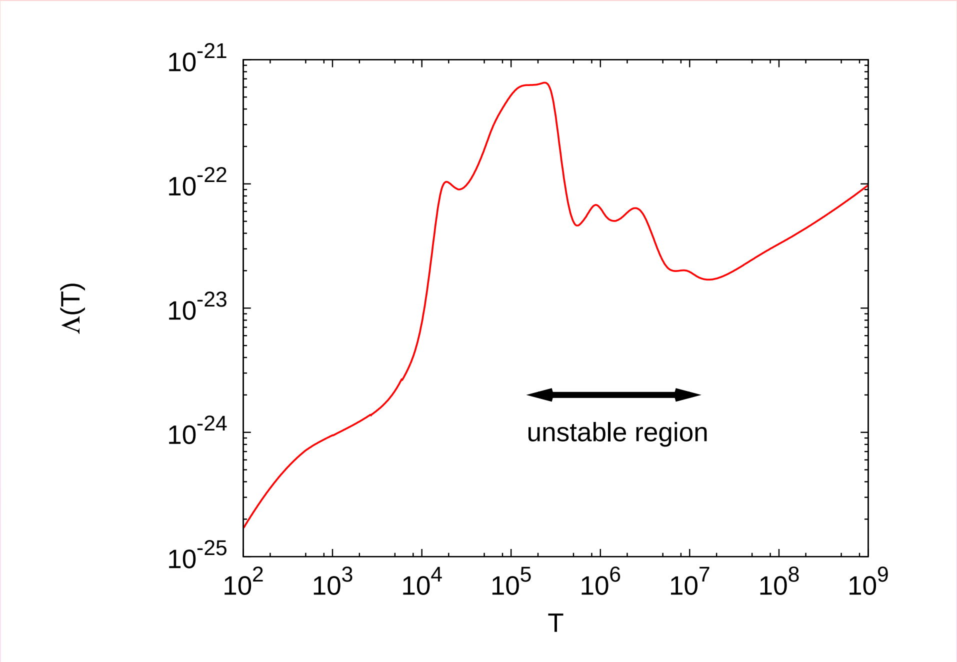
- δ - safety factor (typically 0.1)
- code publically available `http://richard.wunsch.matfyz.cz`

Supercritical clusters - 1D

- cluster divided into two regions by so called "stagnation radius" $R_{\rm st}$ ($u(R_{\rm st}) = 0$)
- $r > R_{\rm st}$: quasi-stationary wind with $u = c_s$ at $R_{\rm SC}$
- $r < R_{\rm st}$: non-stationary region - suffers from the thermal instability

Thermal instability

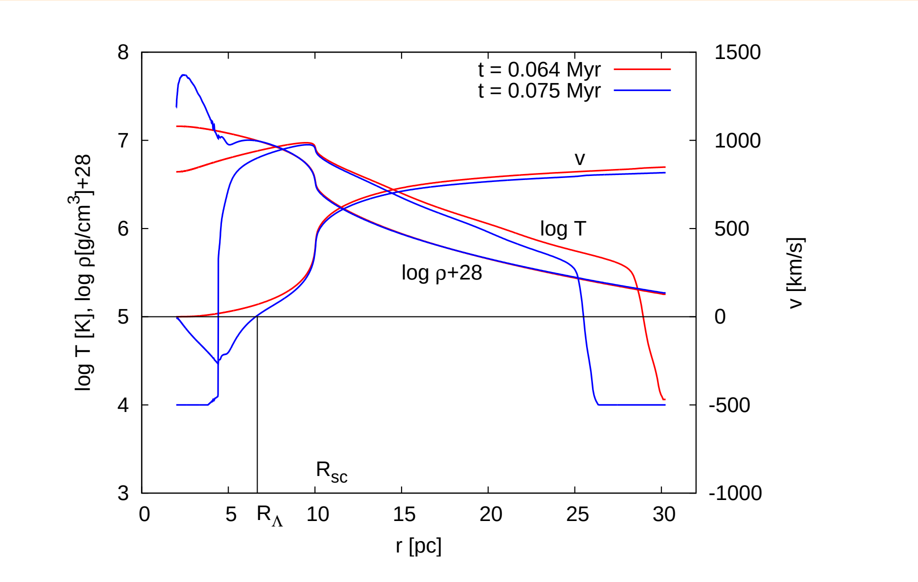
- drop in temperature leads to the more efficient cooling $\rightarrow$ positive feedback

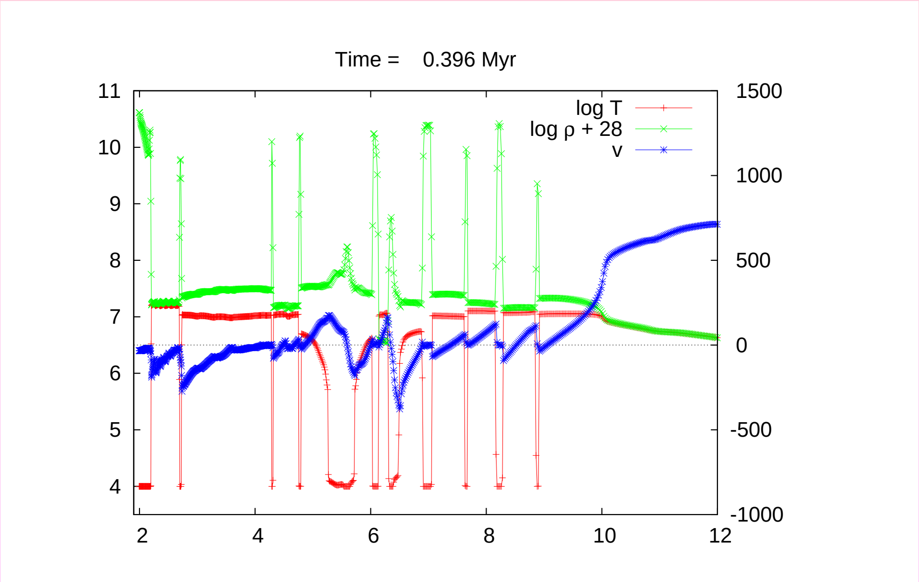


Supercritical clusters - 1D

Lower $\dot{E}_{\rm SC}$ (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

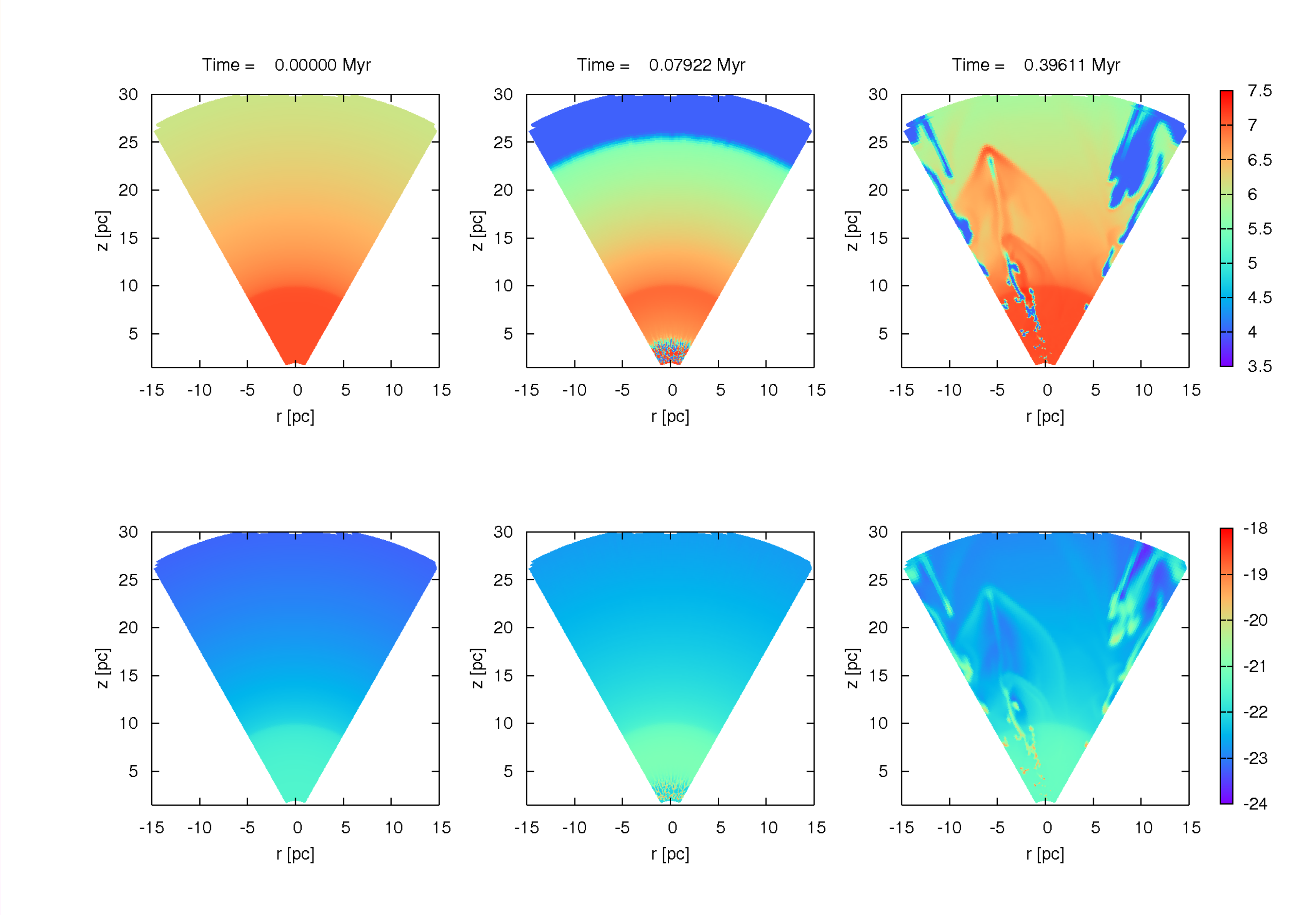




Higher $\dot{E}_{\rm SC}$ (10^{43} erg/s)

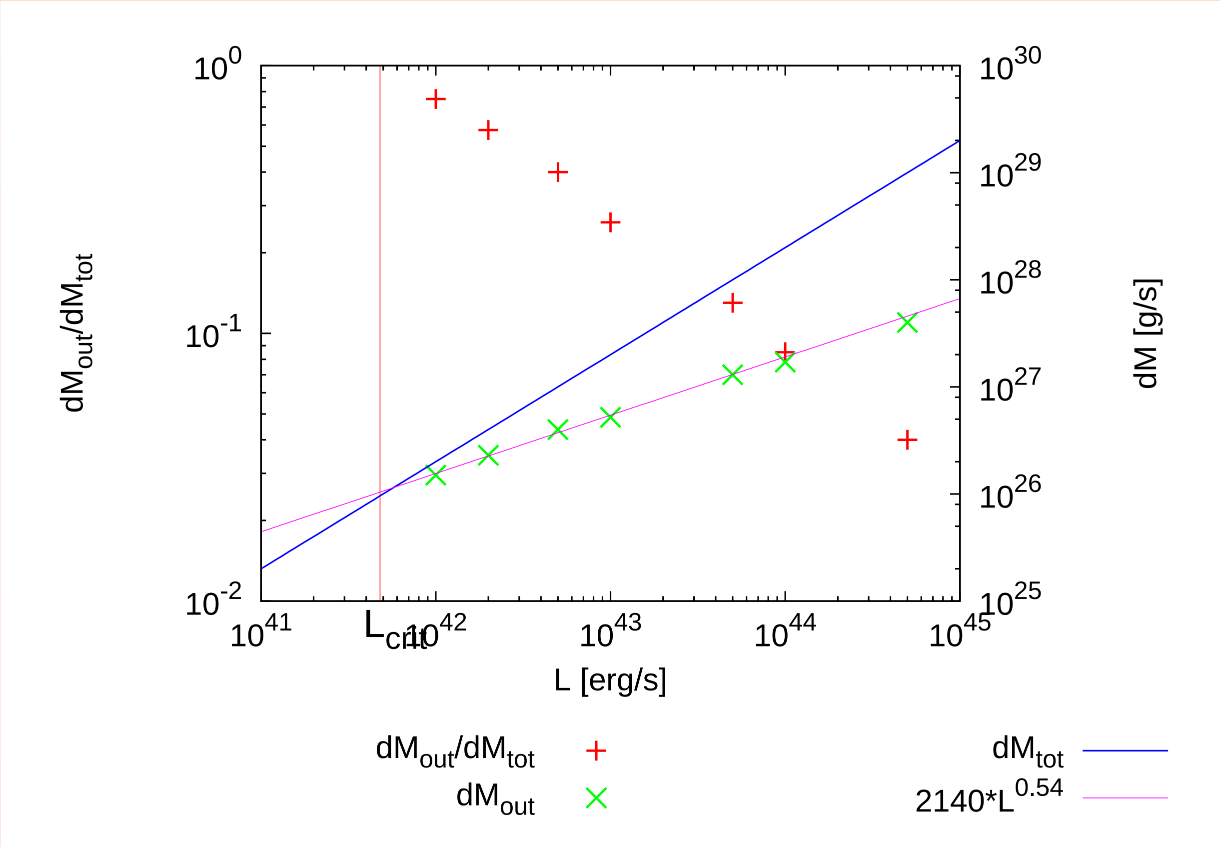
- dense cold standing shells are formed through collisions of shocks

Supercritical clusters - 2D



Mass outflow

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



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

Conclusions

- 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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