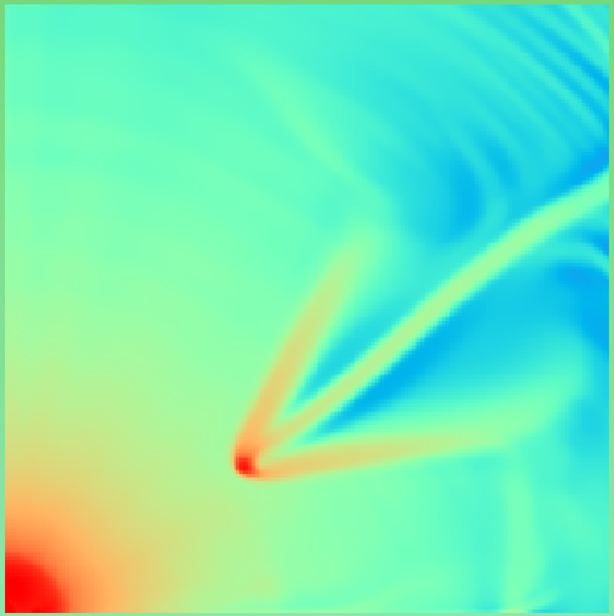
HD simulations of super star cluster winds

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

Outline:

1. Super star cluster winds
2. Semi-analytical adiabatic and radiative models
3. Catastrophic cooling
4. Numerical simulations



Super star cluster winds

- SSC recently observed in variety of starburst galaxies at all redshifts (Ho, 1997)
- masses: $M_{\rm SC} \sim 10^4 - 10^7$ $M_\odot$
- radii: $R_{\rm SC} \sim 3 - 10$ pc $\rightarrow$ very compact
- mechanical luminosities: $L \sim 10^{40} - 10^{42}$ 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
- models:
  - ▷ *spherically sym., adiabatic analytical solution* (Chevalier & Clegg, 1985)
  - ▷ *numerical adiabatic models* (Cantó et al., 2000; Raga et al., 2001)
  - ▷ *numerical models with cooling* (Silich et al., 2003)
  - ▷ *semi-analytical models of catastrophic cooling* (Silich et al., 2004)
  - ▷ *evolution of SSC winds* (Tenorio-Tagle et al., 2004)

Steady state wind

- energy and mass inserted at rates $\dot{E}_{\rm SC}$ and $\dot{M}_{\rm SC}$, respectively; homogenously 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: $q_e = q_m = 0$

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

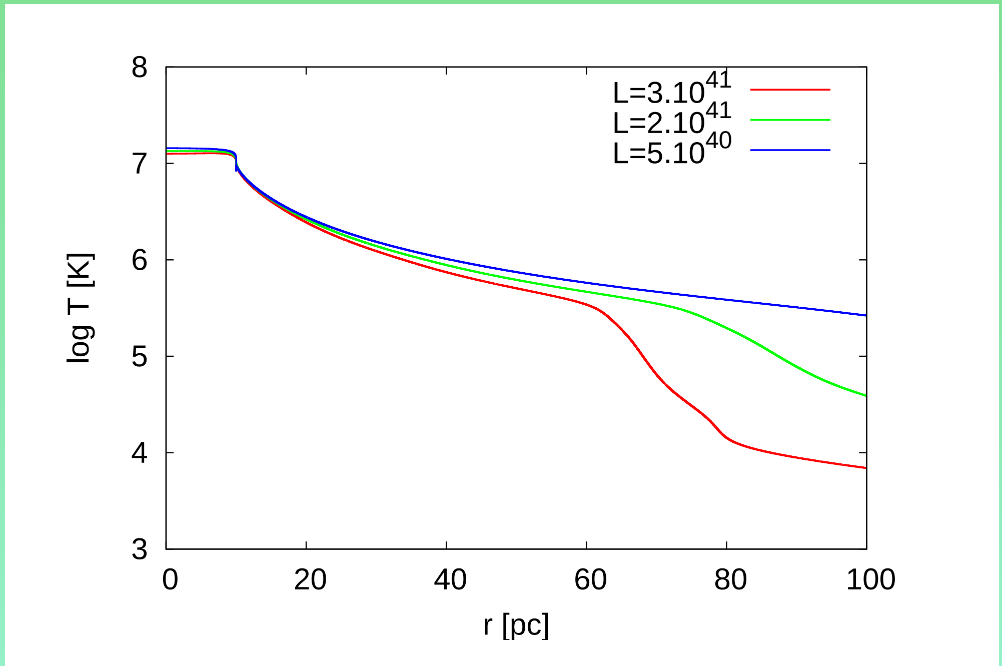
- stationary solution exists only if $R_{\rm sonic} = R_{\rm SC}$
- adiabatic case ($Q = 0$) - semi-analytical solution
  formulas for ρ_c, P_c, T_c $\rightarrow$ numerical integration
  for $r \rightarrow \infty$: $\rho \sim r^{-2}$, $T \sim r^{-4/3}$, $u \rightarrow v_\infty = \sqrt{\frac{2\dot{E}_{\rm SC}}{\dot{M}_{\rm SC}}}$
- too extended X-ray emitting (high-temperature) region

Radiative solution
(Silich et al., 2004)

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

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

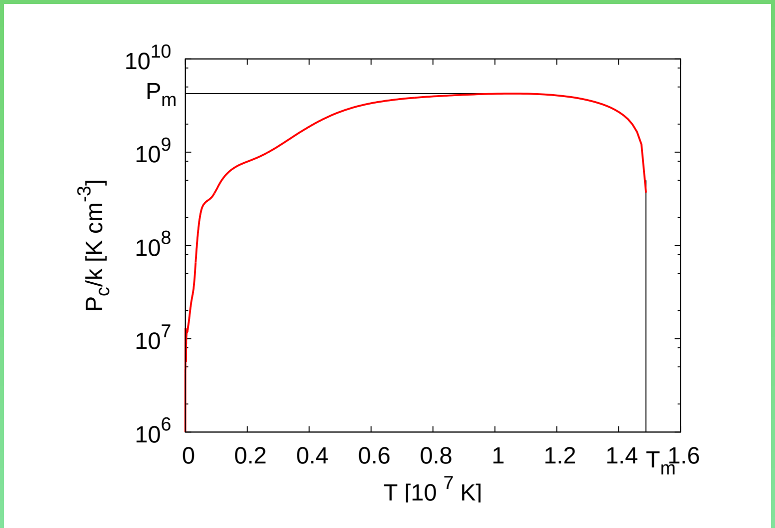
- iterative search for T_c such that $R_{\rm sonic} = R_{\rm SC} \rightarrow \rho_c, P_c \rightarrow$ numerical integration of HD eqs.

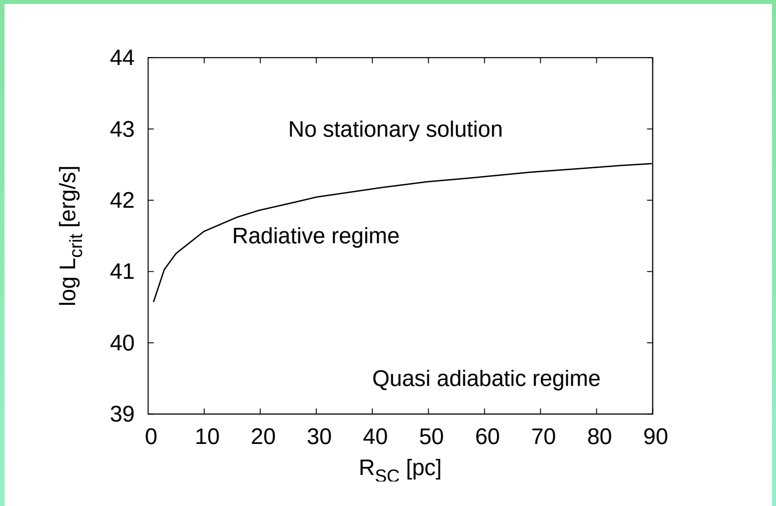


- for higher $\dot{E}_{\rm SC}$ temperature drops to 10^4 K at some radius
- X-ray emitting region is much smaller than in adiabatic case

Catastrophic cooling

- adiabatic case: ρ_c, T_c independent
  $\rightarrow$ always can be stabilized 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 $\rightarrow$ cannot equal to $R_{\rm SC}$ for some parameters $\Rightarrow$ stationary solution does not alway exist

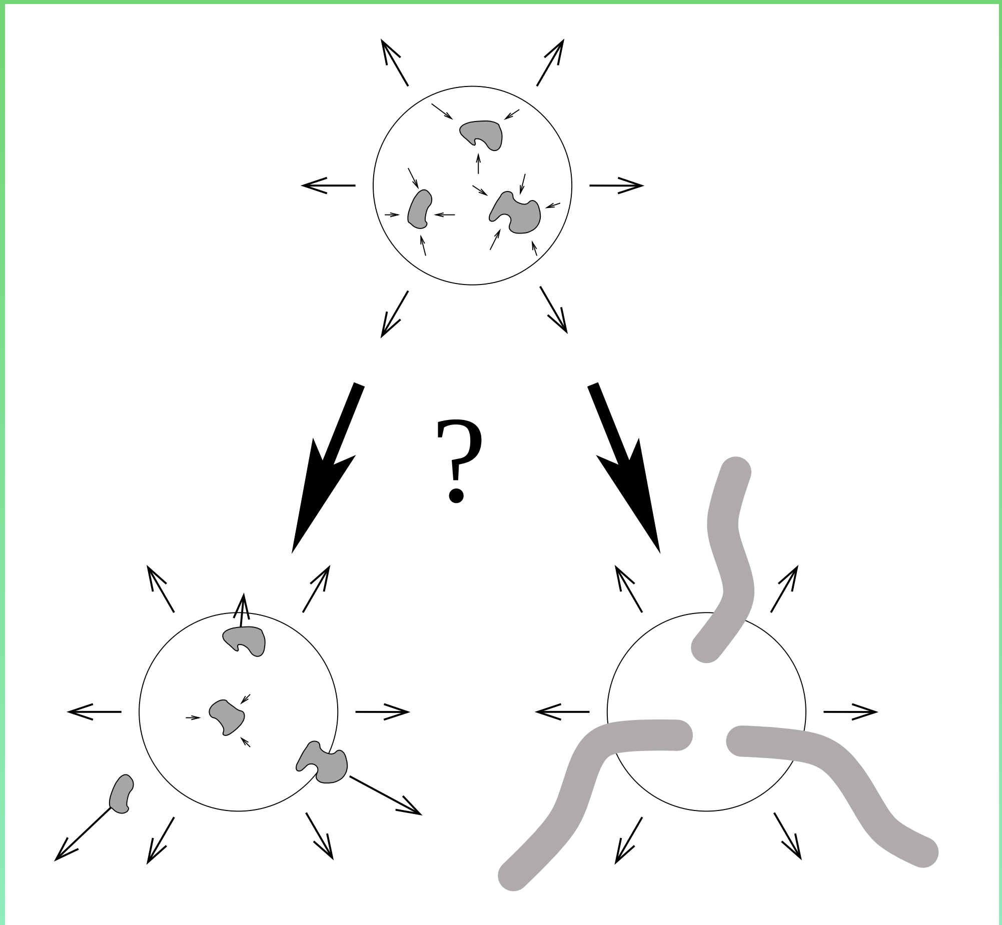
Evolution scenario

(Tenorio-Tagle et al., 2004)

- catastrophic cooling $\rightarrow T_c$ drops from 10^7 K to 10^4 K (sustained by UV radiation of massive stars)
- mass accumulation until new stationary state reached; ρ_c increases by 1.5 orders of magnitude; $\tau_{\rm m.a.} \sim 10^5$ yr
- isothermal steady state wind, $v_\infty \sim 50$ km/s; $\tau_{\rm iso} \sim 4 - 5$ Myr (until UV photon flux drops)
- another drop of T_c to ~ 100 K, mass accumulation
- massive and slow flow; $v_\infty \sim 2$ km/s - probably gravitationaly bounded
- eventually next episod of star formation

Catastrophic cooling in 2(3)D

- fast cooling and collapse occurs in some region only
- their surrounding may expand $\longrightarrow$ decrease its density and cooling rate
- cold dense clouds might be thrown out
- or dense filaments might be formed

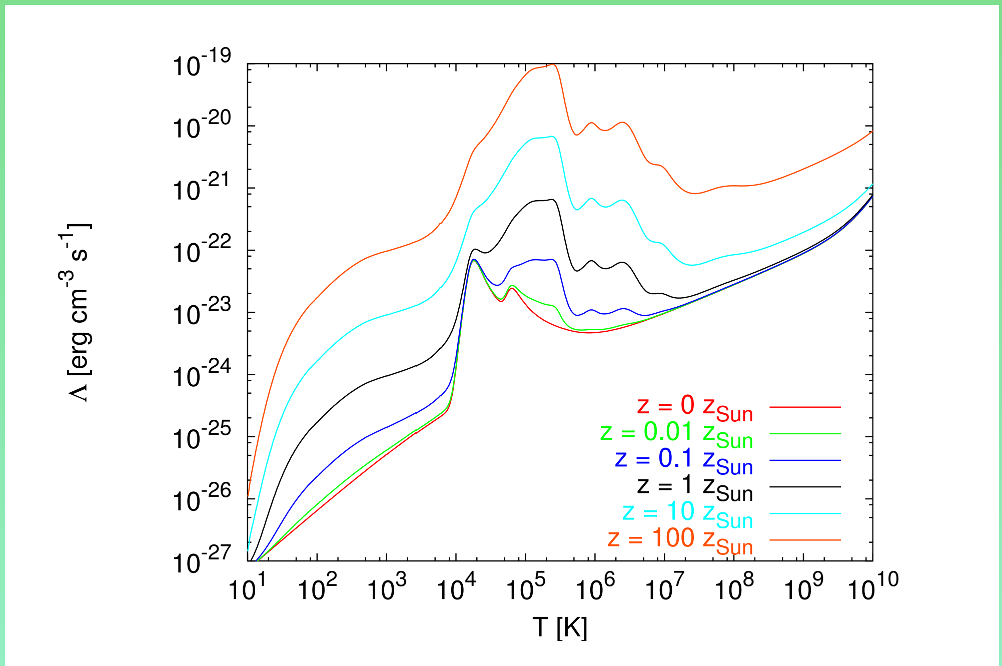


Numerical model

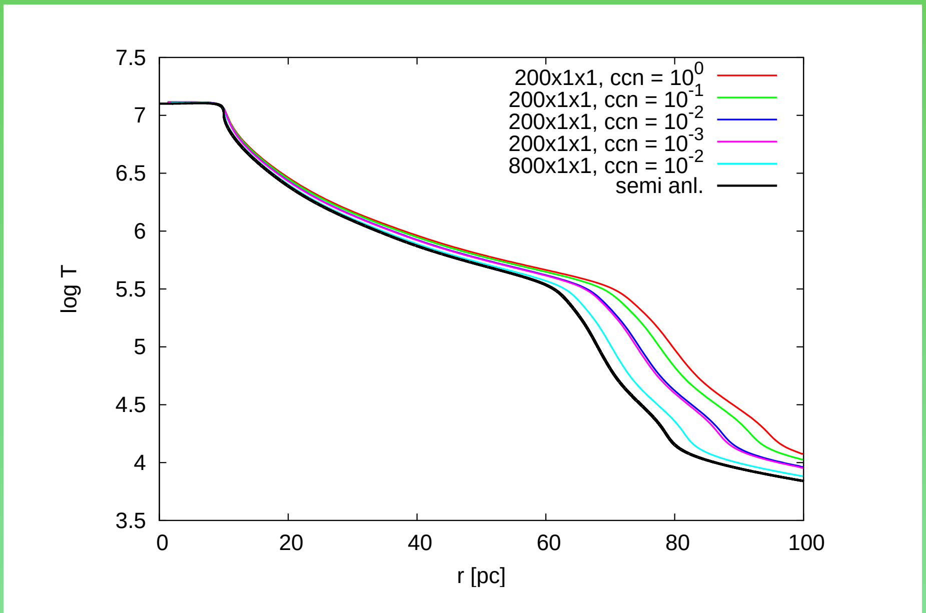
- based on ZEUS3D v.3.4.2
- grid-based Eulerian 2nd order hydrodynamic code, van Leer advection
- new cooling implemented:
  - *more up-to-date cooling function* (Ferland, 2000)
  - *equation for energy solved by Brendt algorithm (original Newton-Raphson method had problems with convergence and was too slow)*
  - *time-step controlled by cooling rate*

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

$CCN \ldots$ *cooling Courant number* $\sim 0.01 - 1$

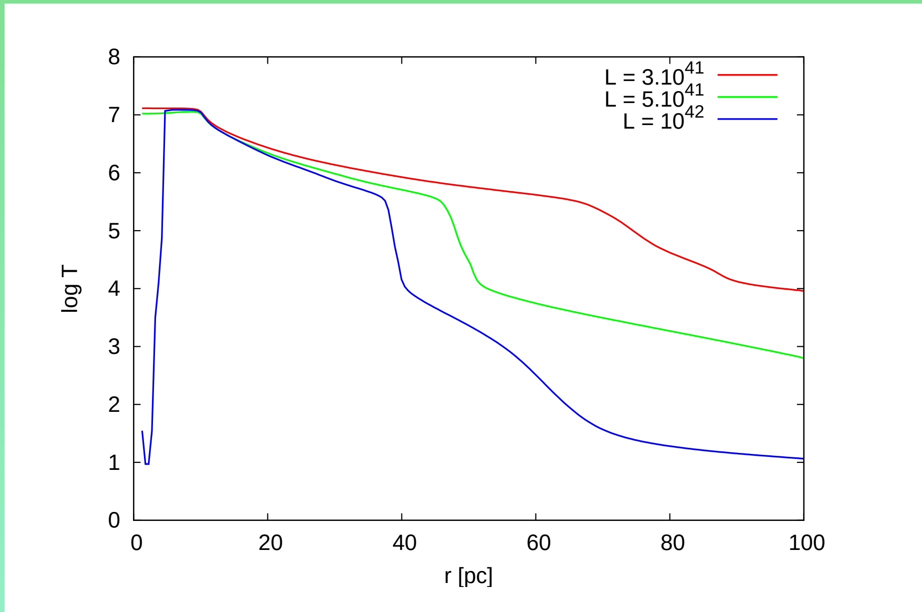


1D models



Parameters:

- $R_{\rm SC} = 10$ *pc*
  $v_\infty = 1000$ *km/s*
  $\dot{E}_{\rm SC} = 3 \cdot 10^{41}$ *erg/s*
- *200x1x1, 800x1x1*
- $CCN = 0.01, 0.1, 1.0$
- *convergence, good agreement with semianalytical model*



Parameters:

- $R_{\rm SC} = 10$ *pc*
  $v_\infty = 1000$ *km/s*
  $\dot{E}_{\rm SC} = 3 \cdot 10^{41}, 5 \cdot 10^{41}, 10^{42}$ *erg/s*
- *200x1x1*
- *mass accumulation*

Future

- UV ionizing radiation of the cluster (maintains T=10000K in $R_{\rm str}$)
- gravitational potential of the cluster
- evolution of metalicity

References

Chevalier, R. A., Clegg, A. W., 1985, Nature, 317, 44

Cantó, J., Raga, A. C., Rodríguez, L. F., 2000, ApJ, 536, 869

Raga, A. C., Velázquez, P. F., Cantó, J., Masciadri, E., Rodríguez, L. F., 2001, ApJ, 559, L33

Silich, S., Tenorio-Tagle, G., Muñoz-Tuñón, C., 2003, ApJ, 590, 791

Silich, S., Tenorio-Tagle, G., Rodríguez-González, A., 2004, ApJ, 610, 226

Tenorio-Tagle, G., Silich, S., Rodríguez-González, A., Muñoz-Tuñón, C., 2004, ApJ, 620, 217

Ferland, G. J., 2000, RevMexAA, 9, 153