Catastrophic cooling in super star cluster winds

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Outline:

1. Super star cluster winds
   (properties, adiabatic model)

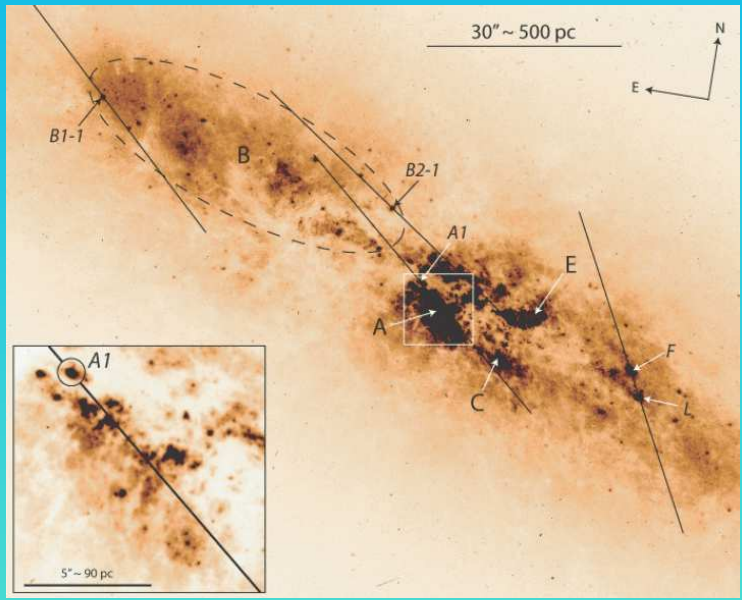
2. Influence of radiative cooling
   (radiative solution, catastrophic cooling)

3. Spherically symetric models
   (semi-analytical vs. numerical solution, outflow mass)

4. 2D (and 3D) simulations

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



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

- 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

Steady state wind

- energy and mass inserted at rates $L_{\rm SC}$ 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 $r < R_{\rm SC}$:
$q_m = (3\dot{M}_{\rm SC})/(4\pi R_{\rm SC}^3)$
$q_e = (3L_{\rm SC})/(4\pi R_{\rm SC}^3)$
elsewhere: $q_e = q_m = 0$

$$Q = n_e n_i \Lambda(T, z)$$

- 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

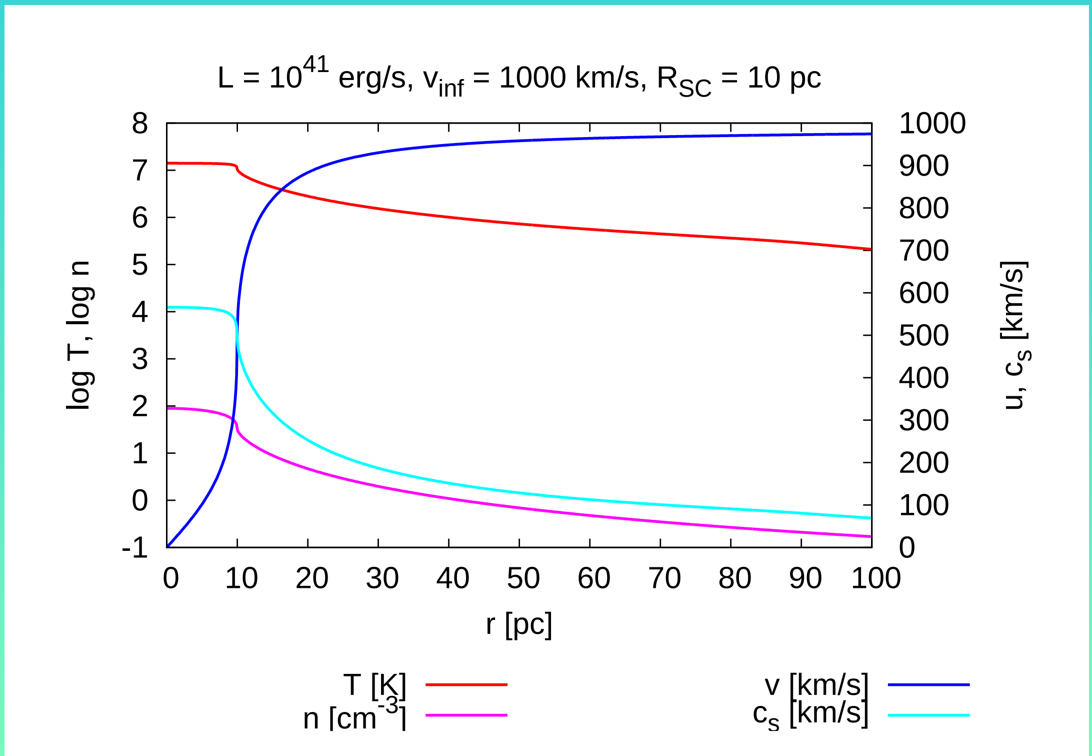
Chevalier & Clegg (1985)

- $Q = 0 \Rightarrow$ 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 $r \to \infty$:

$$\rho \sim r^{-2}$$

$$T \sim r^{-4/3}$$

$$u \to v_\infty = \sqrt{\frac{2L_{\rm SC}}{\dot{M}_{\rm SC}}}$$

very extended high temperature (X-ray emitting) region

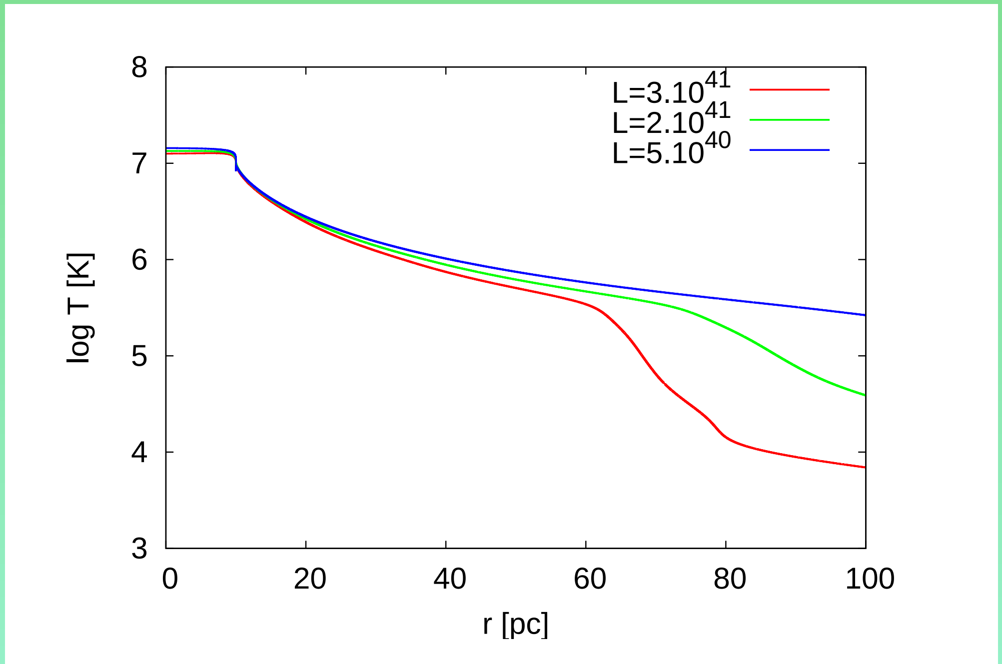
Radiative solution

Silich et al. (2004)

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

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

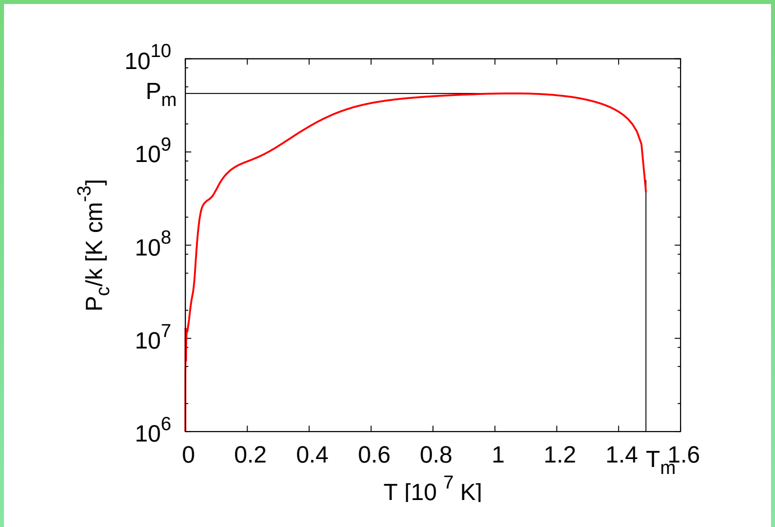
- iterative search for T_c such that $R_{\rm sonic} = R_{\rm SC} \rightarrow \rho_c, P_c \rightarrow$ numerical integration of HD eqs.



- 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

Catastrophic cooling

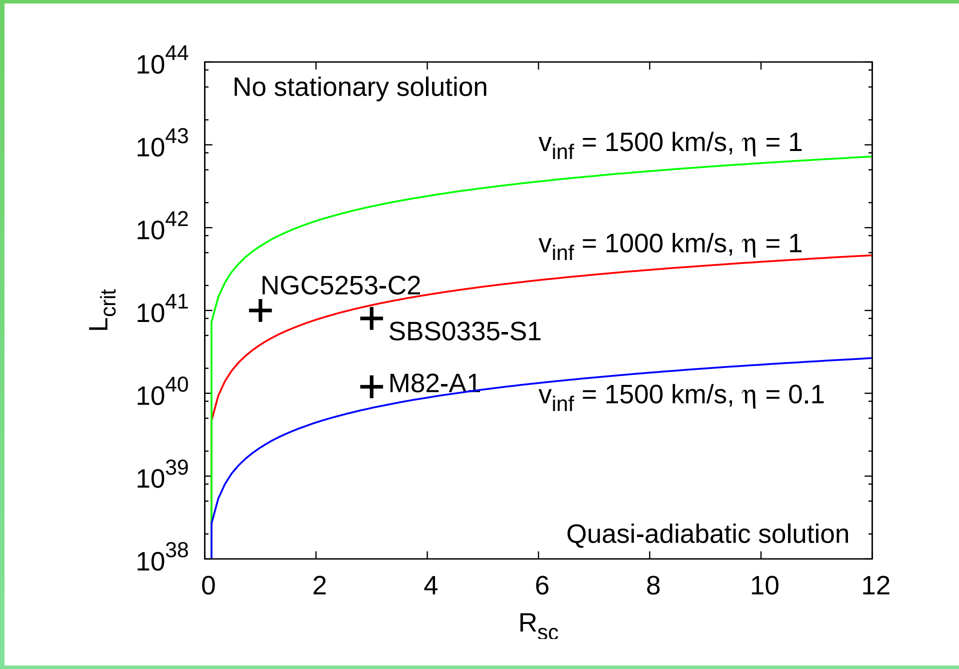
- $L_{\rm SC} \sim M_{\rm SC}$, $\rho_c \sim M_{\rm SC}$, BUT $Q \equiv \frac{de}{dt}\Big|_{\rm cool} \sim \rho_c^2 \sim M_{\rm SC}^2$
- adiabatic case: ρ_c, T_c independent
  $\rightarrow$ always can be stabilised so that $R_{\rm sonic} = R_{\rm SC}$
- radiative case:
  $T_c \rightarrow T_{\rm m} = \frac{\gamma-1}{\gamma}\frac{\mu}{k_B}\frac{q_e}{q_m}$: $\rho_c, P_c \rightarrow 0$
  $T_c < T_{\rm m}$: P_c increases for decreasing T_c, but there is a maximum of P_c

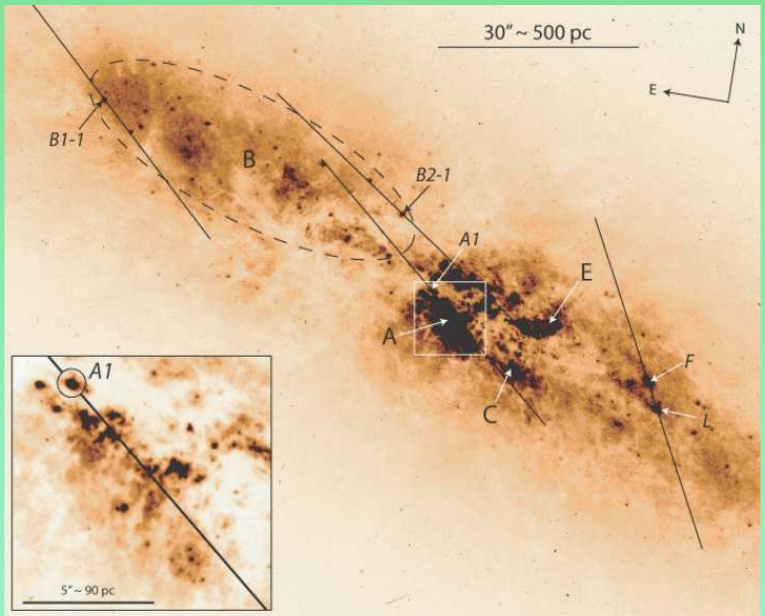


- $R_{\rm sonic}(P_c) \Rightarrow R_{\rm sonic}$ cannot be arbitrary small $\rightarrow$ cannot always equal to $R_{\rm SC} \Rightarrow$ stationary solution does not alway exist

$L_{\rm crit}$ curve

- no stationary solution for $L > L_{\rm crit}(R_{\rm SC}, v_\infty, \eta)$
- clusters with $L \sim L_{\rm crit}$ observed!
- uncertainty in v_∞ and η - thermalization efficiency





- M82-A1 associated with HII region:

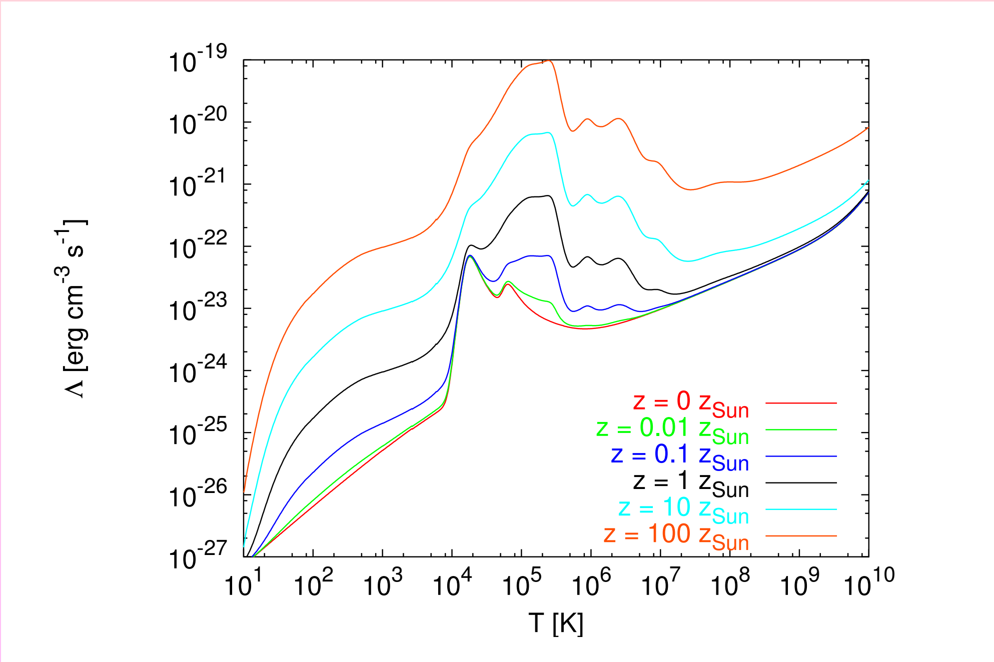
$R_{SC} = 3$ pc $\quad R_{HII} = 4.5$ pc

$L_{SC} = 10^{40}$ erg/s $\quad n_{HII} = 1800$ cm^{-3}

FWHM$_{HII} = 62$ 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)`

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

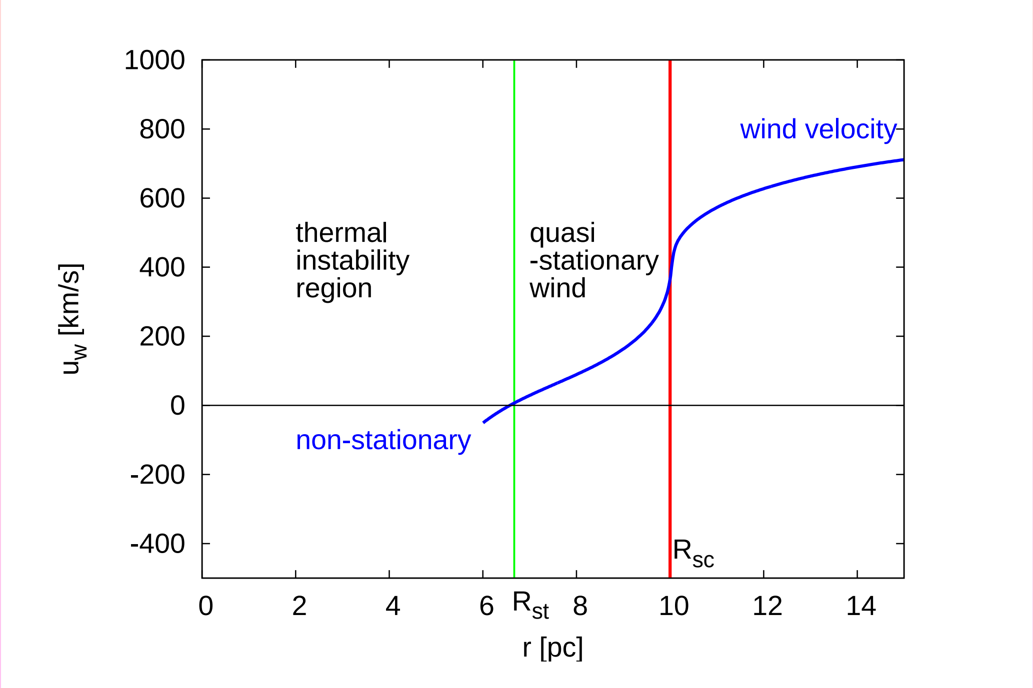
- CCN - "Cooling Courant Number" (typically 0.25)
- $dt_{\rm cool}$ too small in some places ($dt_{\rm cool} \sim 10^{-3} dt_{\rm HD}$)
  $\Rightarrow$ **local** sub-steps $dt_{\rm sub} \le dt_{\rm cool}$

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

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

Bimodal behaviour

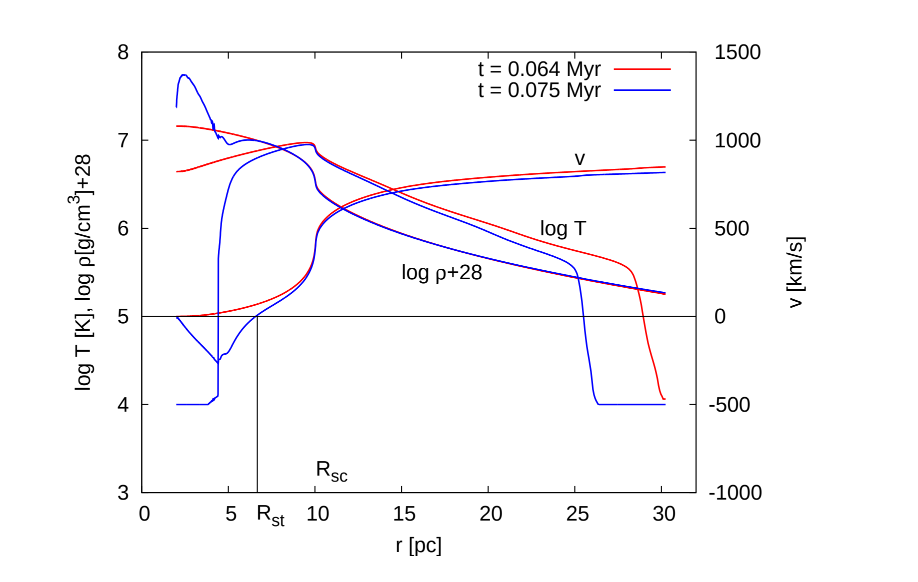
- cluster divided into two regions by so called "stagnation radius" $R_{\rm st}$ ($u(R_{\rm st}) = 0$)
- $r > R_{\rm st}$: quasi-stationary wind with $u = c_s$ at $R_{\rm SC}$
- $r < R_{\rm st}$: non-stationary region - suffers from the thermal instability

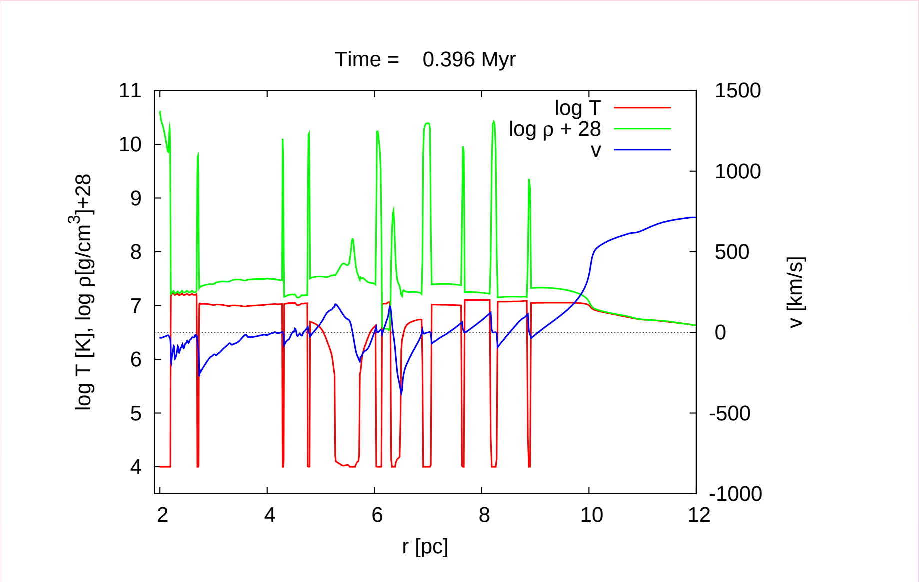


1D numerical simulations

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





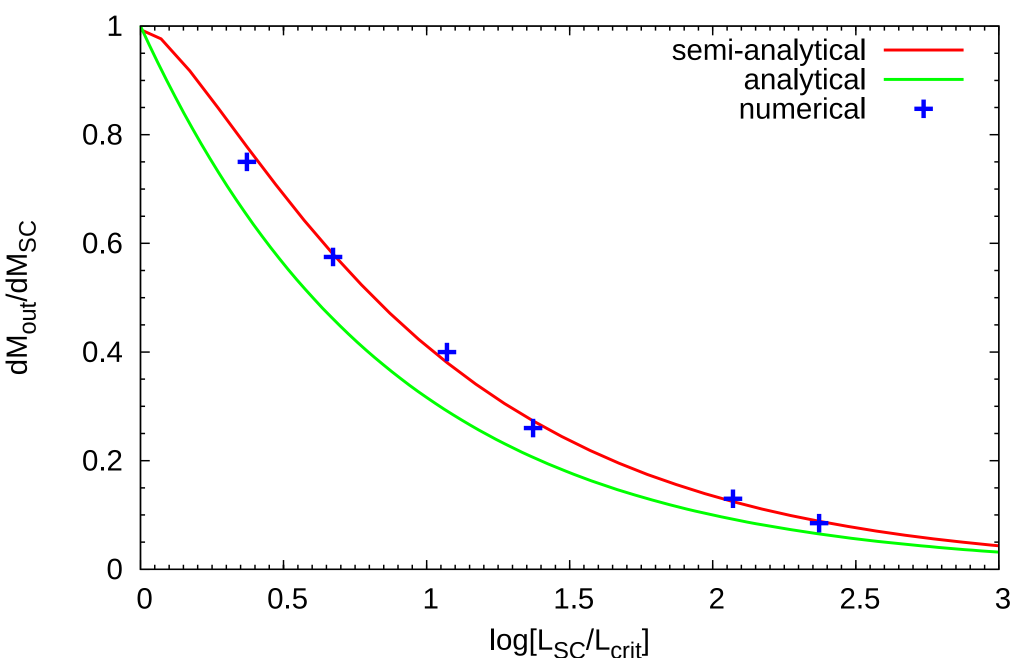
Higher $L_{\rm SC}$ (10^{43} erg/s)

- dense cold standing shells are formed through collisions of shocks

Mass outflow (Wünsch et al., 2007)

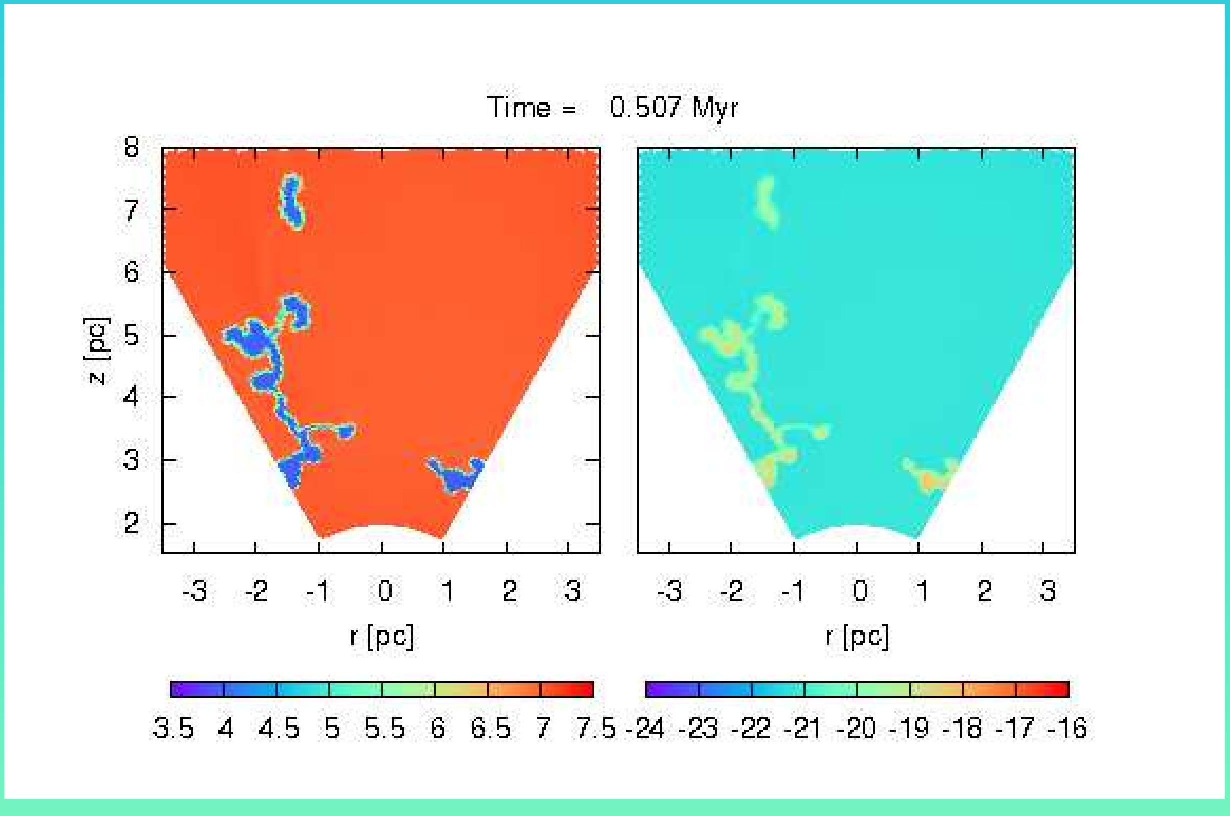
- 1D simulations in perfect agreement with semi-anl. results
- based on idea of the stagnation radius we found an approximate analytical solution: $\frac{\dot{M}_{out}}{\dot{M}_{SC}} = \frac{R_{SC}^3 - R_{st}^3}{R_{SC}^3} = \left(\frac{L_{crit}}{L_{SC}}\right)^{1/2}$

$$L_{crit} = \frac{6(\gamma-1)\pi\eta\alpha^2\mu_i^2 R_{SC} v_\infty^4}{(\gamma+1)\Lambda_{st}} \left(\frac{\eta v_\infty^2}{2} - \frac{c_{st}^2}{\gamma-1}\right), \alpha = \frac{\rho_{\rm SC}}{\rho_{\rm st}} \sim \text{const} \sim 0.3$$

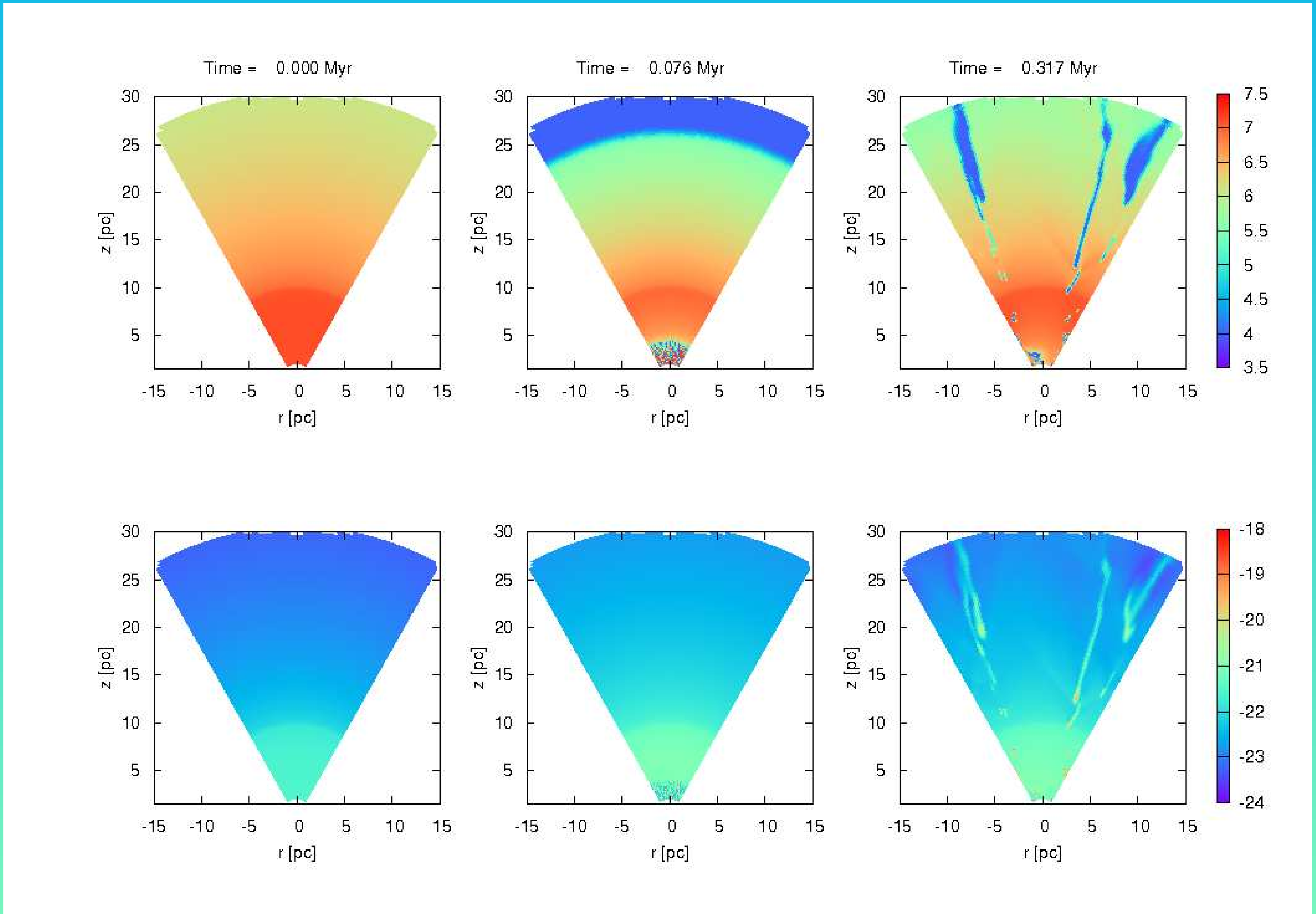


2D simulations

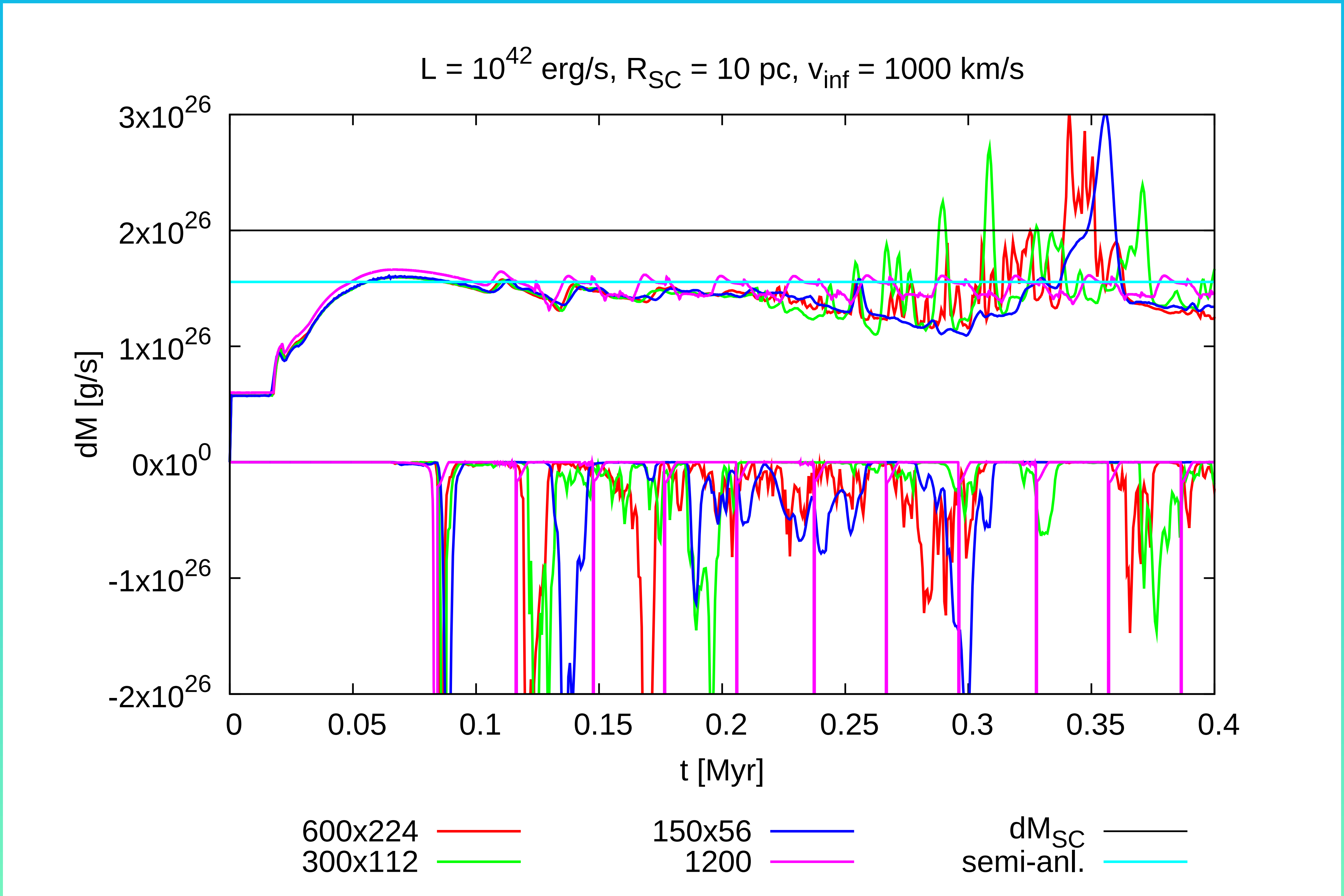
- random perturbations to break the spherical symmetry
- gravity of the cluster - point mass M_{SC}
- parameters: 300×112, $M_{SC} = 10^6 M_\odot$
  $R_{SC} = 10$ pc, $L_{SC} = 10^{42}$ erg/s, $v_\infty = 1000$ km/s



2D simulation - ejected clumps



Mass outflow - 2D



Computed models

L_{SC} [erg/s]	dim	grid	M_{SC}	$\dot{M}_{IB}/\dot{M}_{SC}$	$\dot{M}_{OB}/\dot{M}_{SC}$
10^{42}	1	semi-anl.	0	-22%	78%
10^{42}	1	1200	0	-21%	77%
10^{42}	2	150x56	0	-12%	76%
10^{42}	2	300x112	0	-11%	78%
10^{42}	2	600x224	0	-14%	77%
10^{42}	2	150x56	10^6	-14%	78%
10^{42}	2	300x112	10^6	-15%	80%
10^{42}	3	150x56x56	10^6	-15%	70%
10^{43}	1	semi-anl.	0	-73%	27%
10^{43}	1	1200	0	-21%	31%
10^{43}	2	300x112	10^6	-45%?	25%?
10^{44}	1	semi-anl.	0	-91%	8.8%
10^{44}	1	1200	0	-53%	8.7%
10^{44}	2	300x112	10^6	?	?

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

References

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

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

Ho, L. C., 1997, RMxAA, 6, 5

Plewa, T., 1995, MNRAS, 275, 145

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

Suttner, Smith, M. D., Yorke, H. W., Zinnecker, H., 1997, A&A, 318, 595

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

Tenorio-Tagle, G., Wünsch, R., Silich, S., Palouš, J., 2006, ApJ, 658, 1196

Wünsch, R., Tenorio-Tagle, G., Silich, S., Palouš, J., 2007, ApJ, practically accepted