2D HD simulations of SSC winds

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Outline:

1. Super star clusters
   (properties, observations)
2. Physical model
   (stationary and non-stationary wind, bimodal solution)
3. Numerical code
   (ZEUS, implementation of cooling)
4. Results from wind simulations
   (1D and 2D simulations, feedback on SF)

Properties of SSCs

- massive ($10^5 - 10^7$ M$_\odot$)
  compact ($1 - 10$ pc)
  young (< 500 Myr) clusters
- observed in starburst galaxies at all redshifts (Ho, 1997)
  - *SSCs are units of starburst*
  - *M82: starburst triggered by tidal interaction with M81, cca 100 Myr ago*
- stellar winds and SN return $\leq 40\% M_{\rm SC}$ back into ISM
  - *feedback on SF*
  - *galactic superwind*
- massive stars source of ionizing radiation → UDHII regions → M82-A1 (Silich et al., 2007)

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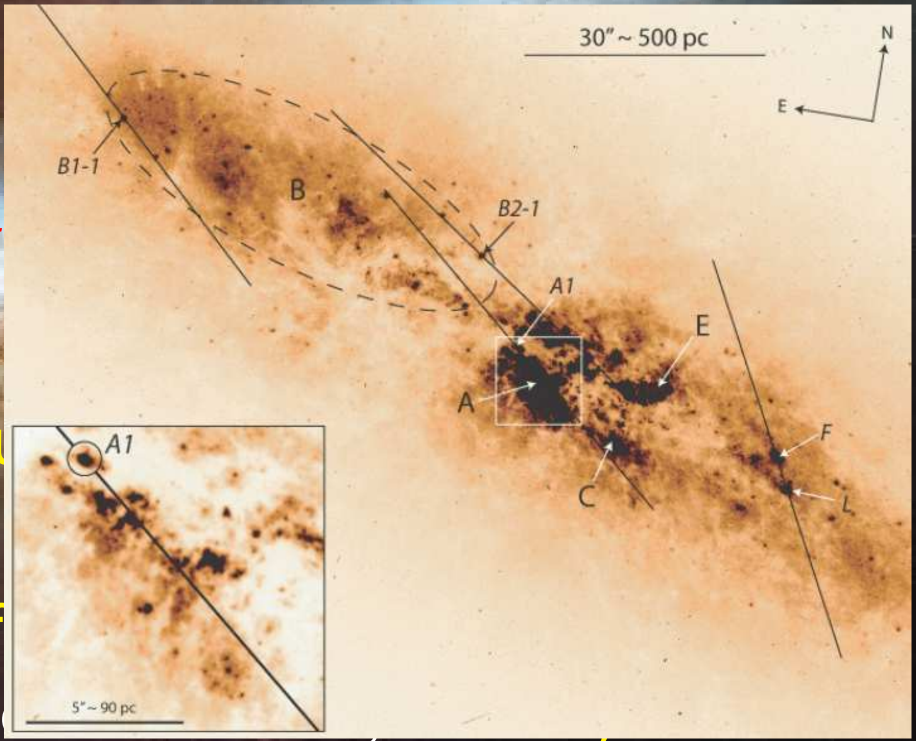
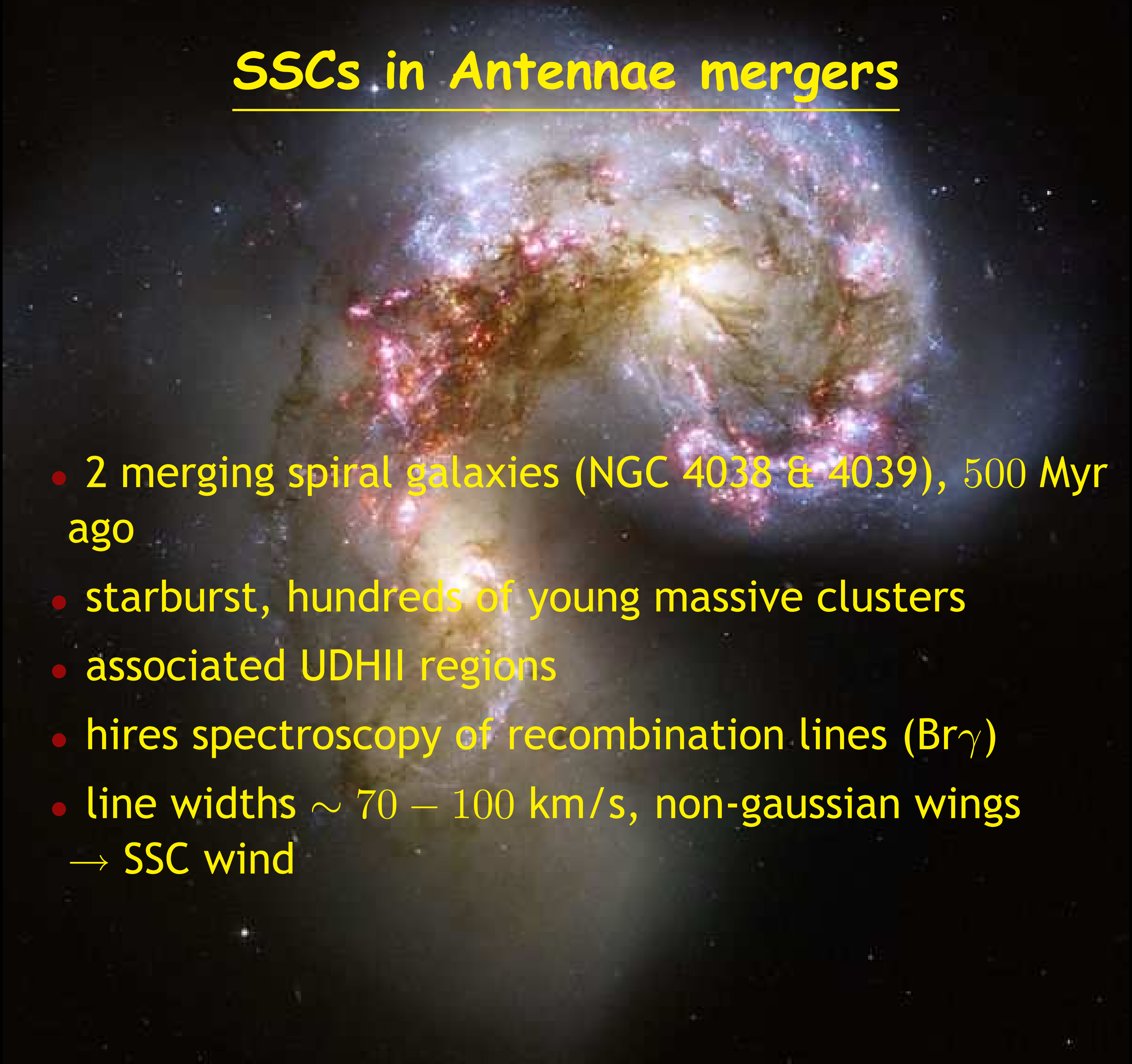


HST + ACS/WFC F814W image of M82 (Smith et al, 2005)

SSCs in Antennae mergers



- 2 merging spiral galaxies (NGC 4038 & 4039), 500 Myr ago
- starburst, hundreds of young massive clusters
- associated UDHII regions
- hires spectroscopy of recombination lines (Brγ)
- line widths $\sim 70 - 100$ km/s, non-gaussian wings $\rightarrow$ SSC wind

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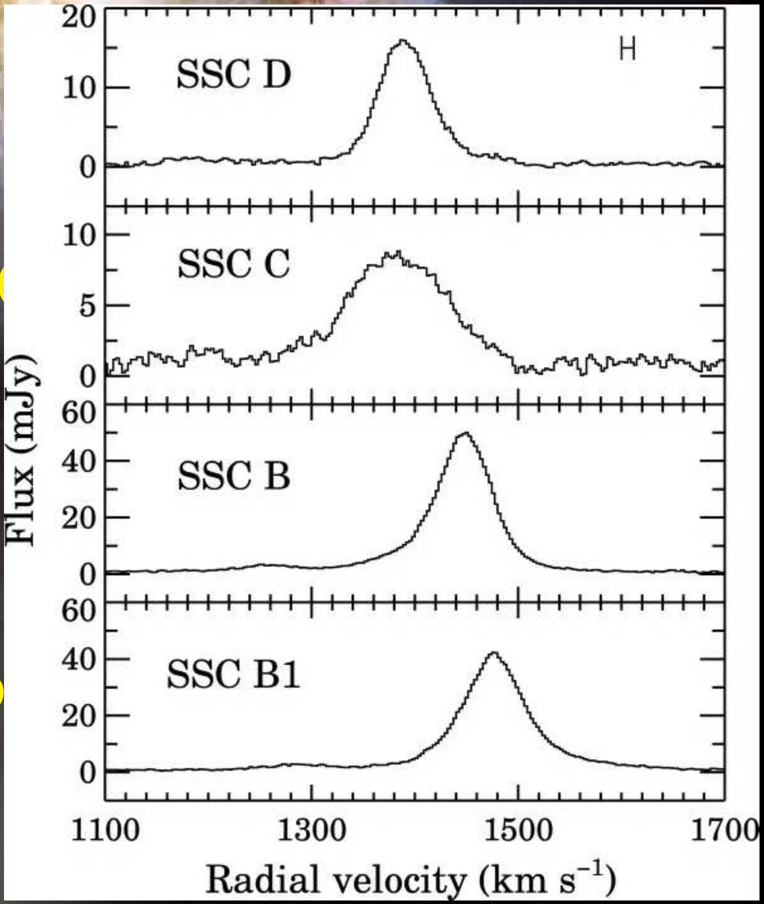


(Gilbert & Graham, 2007)

Credit: NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration Acknowledgment: B. Whitmore (STSI)

SSCs in our backyard

- R136 in LMC (30 Doradus)
- $M \sim 2 - 8 \times 10^4$ M$_\odot$, $R \sim 0.5$ pc, age~ 2 Myr
- bubbles, filaments
  - Tarantula nebula

Credit: N. Walborn (STScI) et al., WFPC2, HST, NASA

- MW: Arches, Quintuplet, NGC3603, Westerlund 1:
- $M \sim 10^5$ M$_\odot$, $R \sim 0.3$ pc, age$\sim 3.5 - 5$ Myr

Physical model of SSC wind

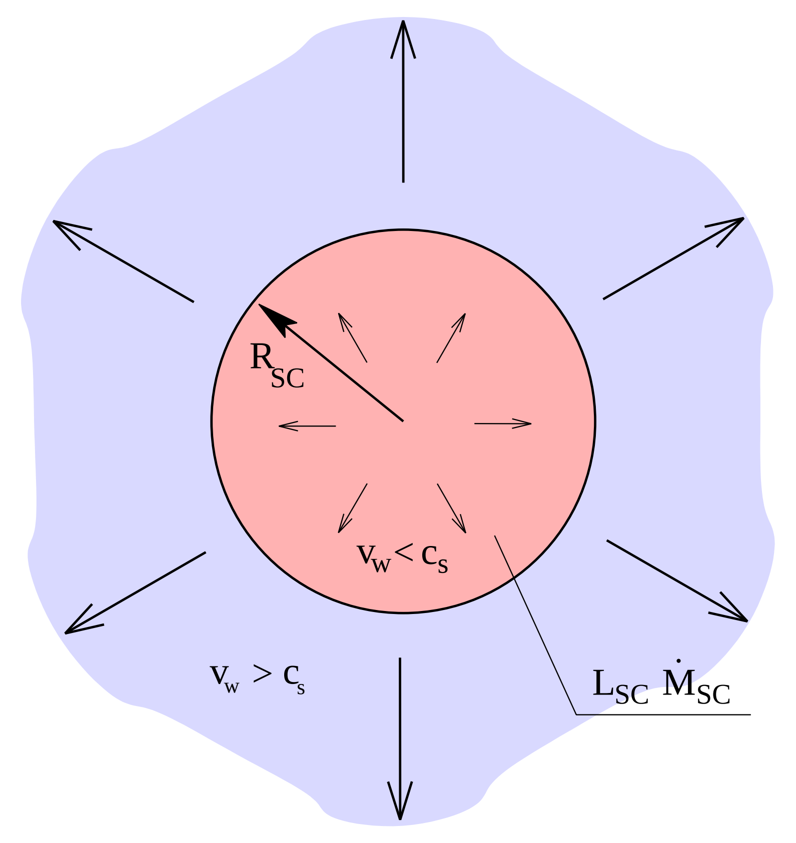
Chevalier & Clegg (1985)

- SW and SN energy thermalized (efficiency η)
- 4 parameters:

  η, $R_{\rm SC}$, $L_{\rm SC}$ and $\dot{M}_{\rm SC}$
- $L_{\rm SC}$ and $\dot{M}_{\rm SC}$ coupled:

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

  if a stellar population assumed



- Catastrophic cooling: (Silich et al., 2004)

  energy input rate: $L_{\rm SC} \propto M_{\rm SC}$

  cooling rate: $\left.\frac{de}{dt}\right|_{\rm cool} \propto \rho^2 \propto \dot{M}_{\rm SC}^2 \propto M_{\rm SC}^2$

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: $q_e = q_m = 0$

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

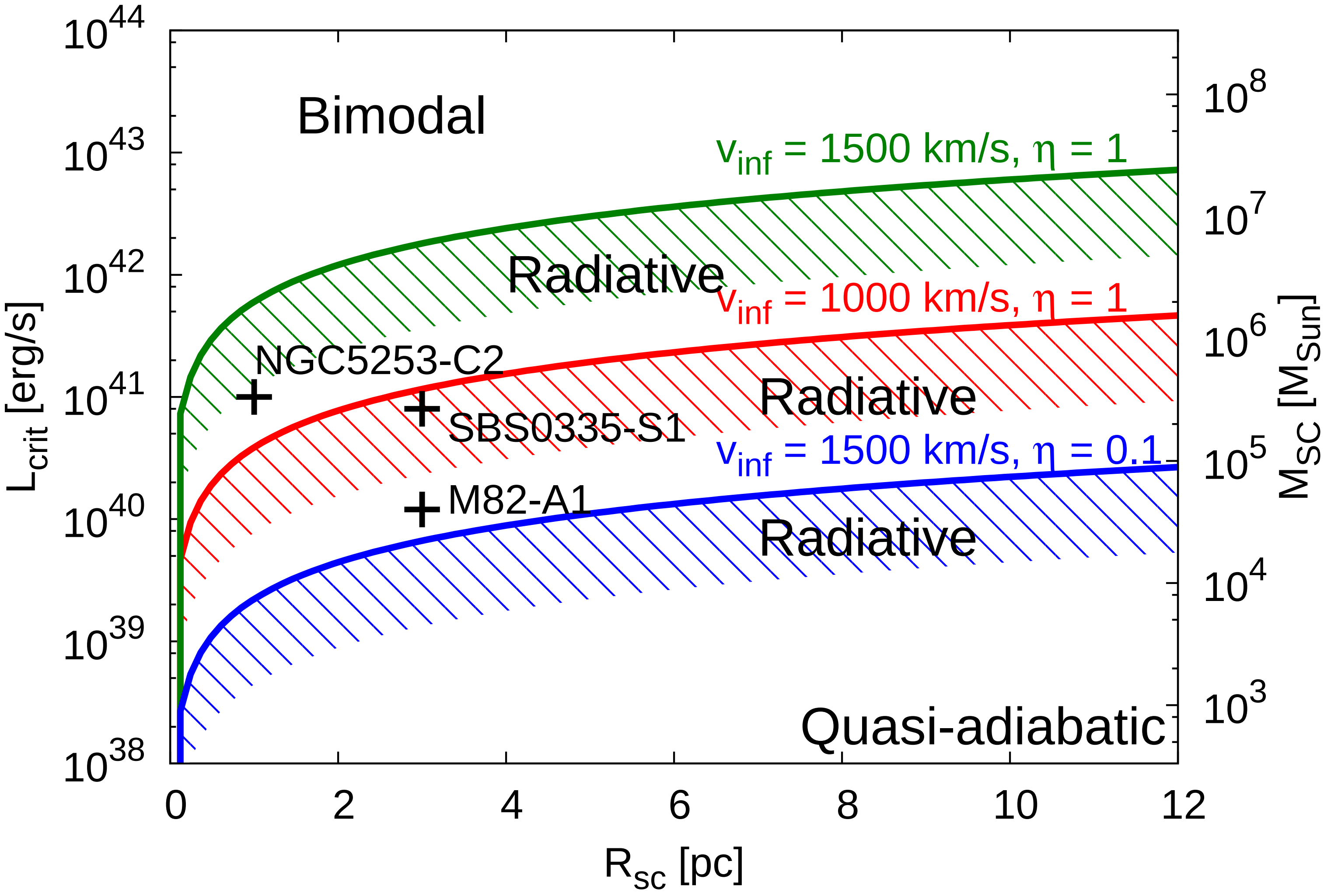
- stationary solution exists only if $R_{\rm sonic} = R_{\rm SC}$

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

Critical luminosity

- stationary solution for $L_{SC} < L_{\rm crit}(R_{\rm SC}, v_{a,\infty}, \eta, Z)$

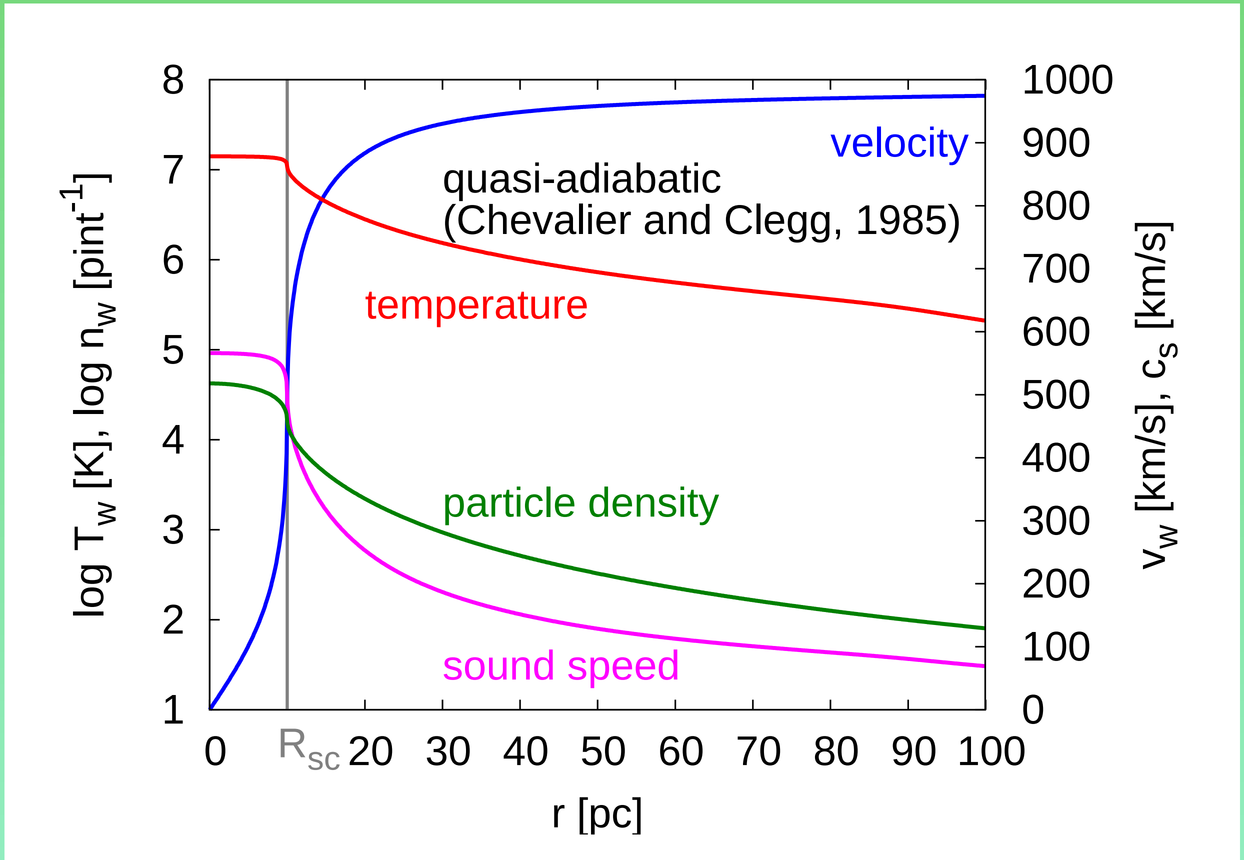


Adiabatic wind

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

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

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



for $r \to \infty$:

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

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

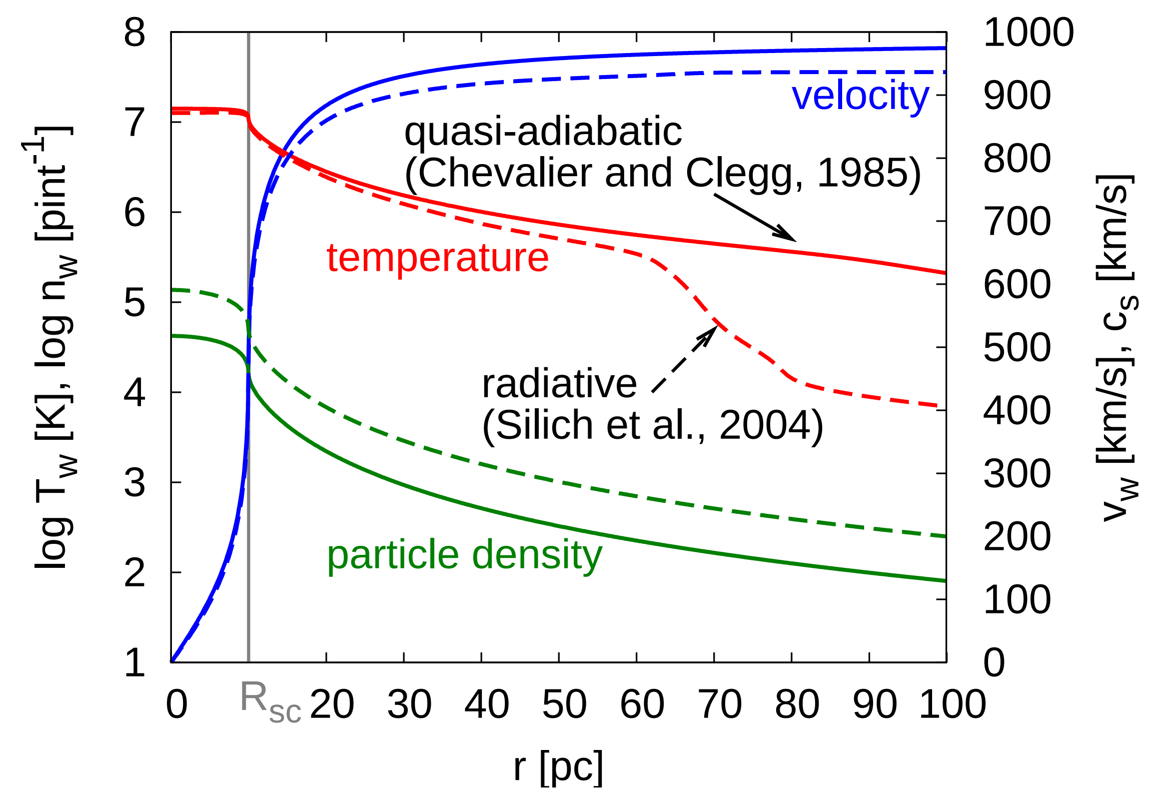
$u \to v_\infty = \sqrt{\frac{2 L_{SC}}{\dot{M}_{SC}}}$

very extended high temperature (X-ray emitting) region

Radiative solution

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

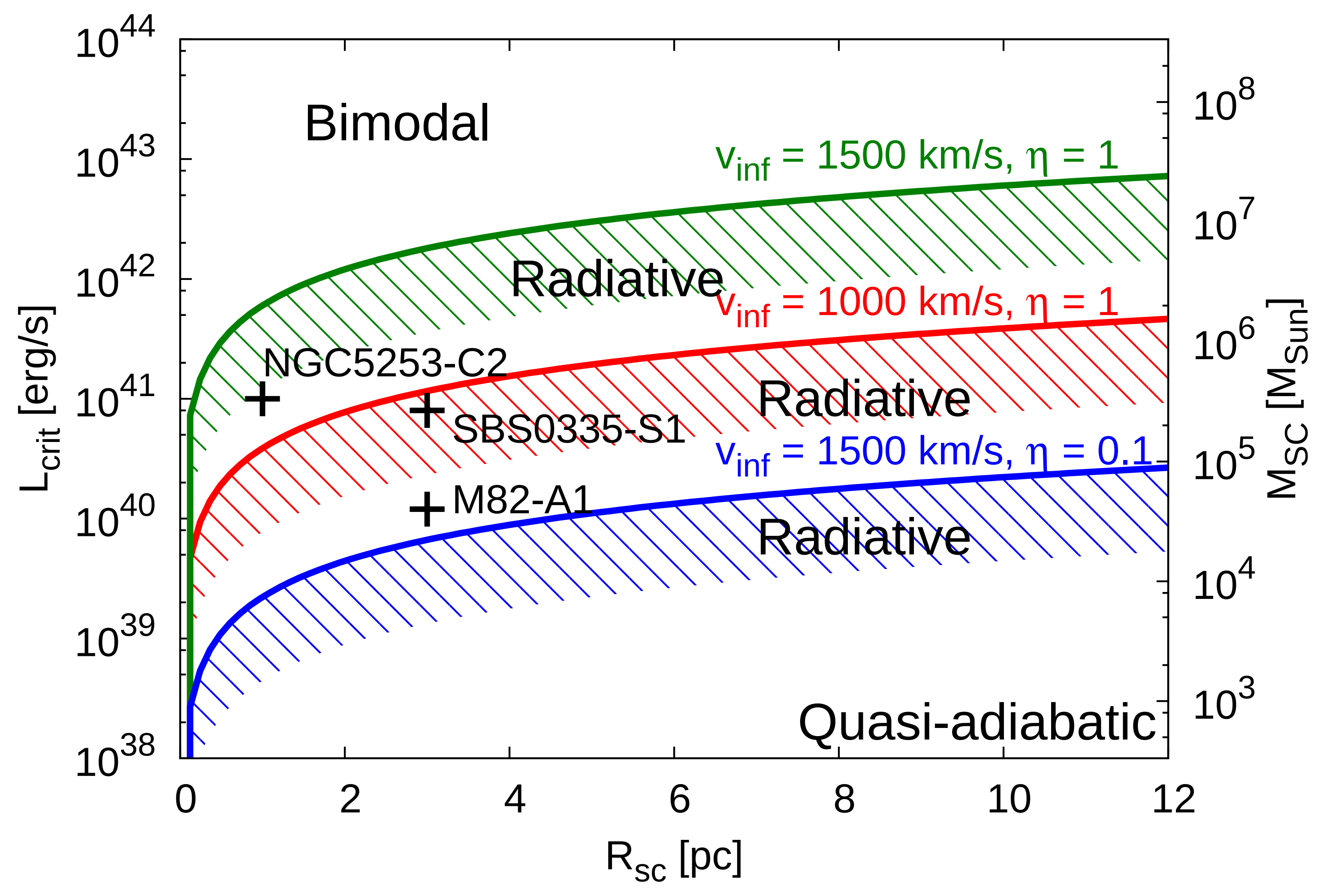
$$n_c = \sqrt{\frac{q_e - q_m c_{s,c}^2/(\gamma - 1)}{\Lambda(T_c)}}$$



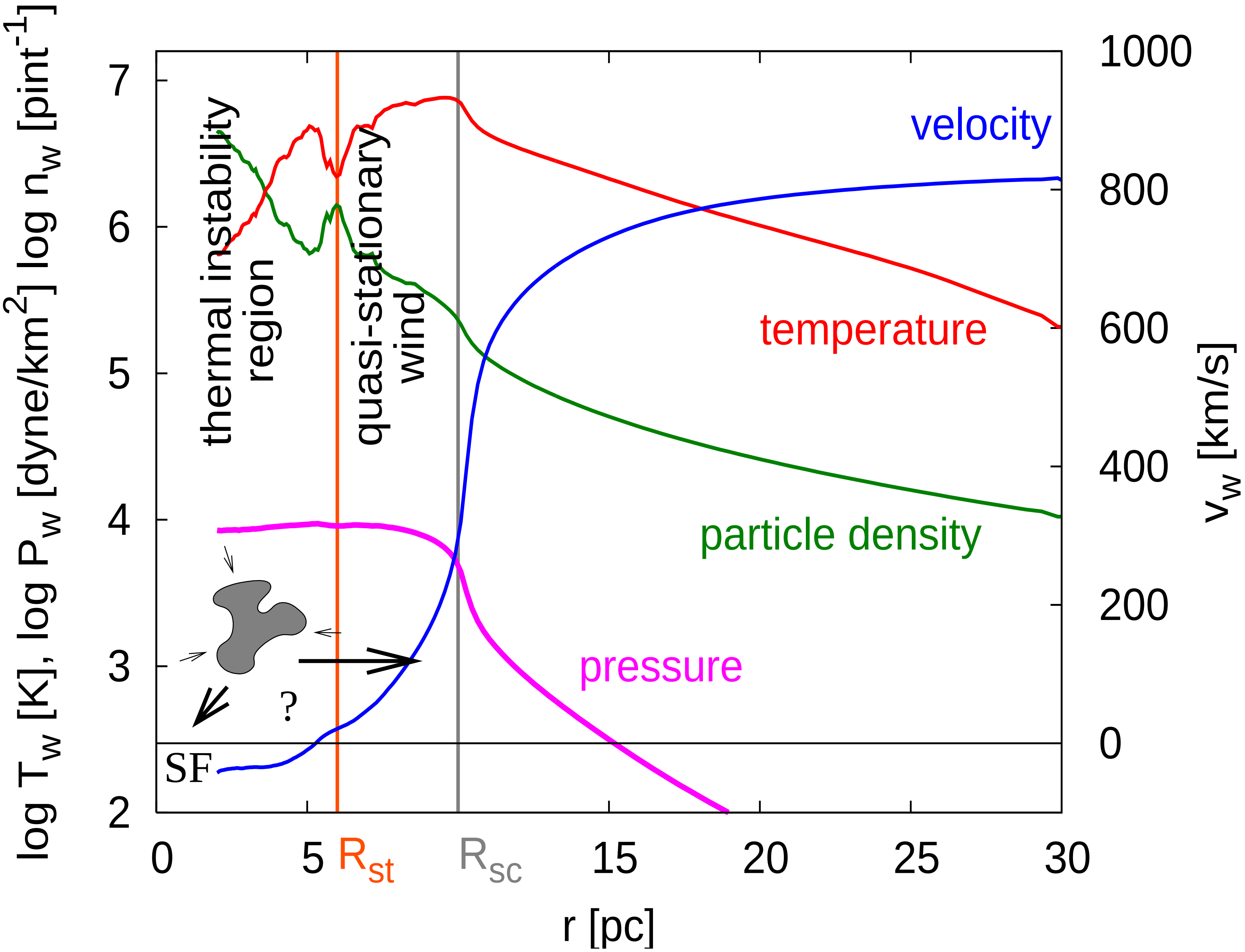
- iterative search for T_c such that $R_{\text{sonic}} = R_{\text{SC}}$ $\rightarrow \rho_c, P_c$ $\rightarrow$ numerical integration of HD eqs.

Critical luminosity

- bimodal solution for $L_{SC} > L_{\rm crit}(R_{\rm SC}, v_{a,\infty}, \eta, Z)$

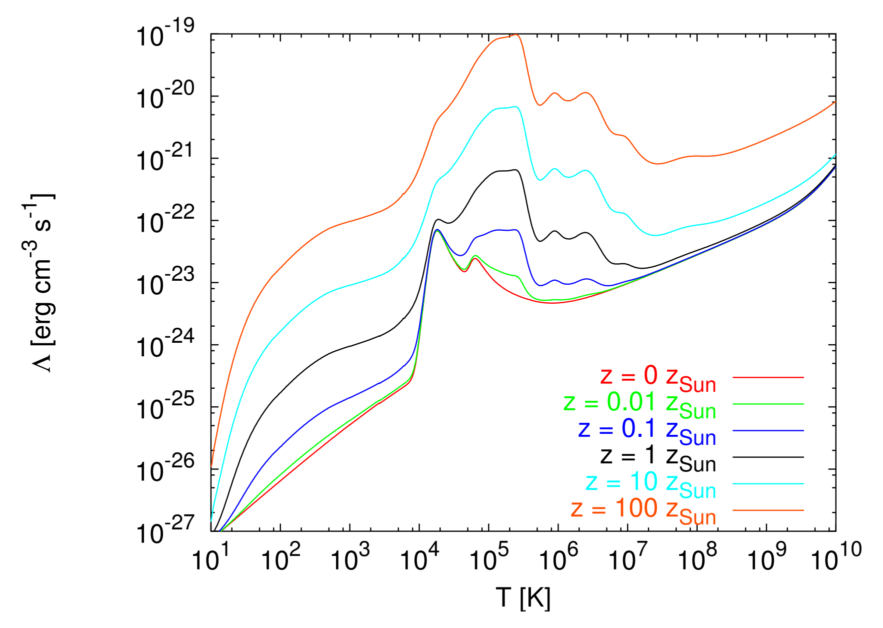


Bimodal solution



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)`

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

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

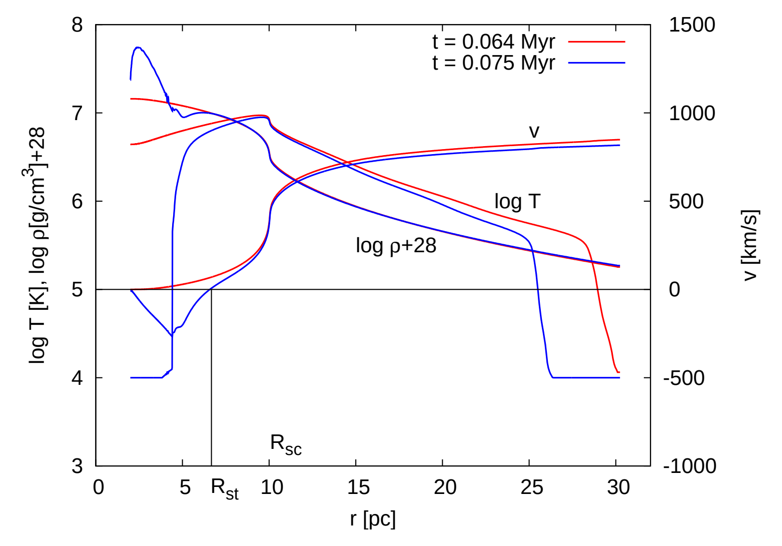
$$dt = \begin{cases} dt = dt_{\mathrm{HD}} & \text{for} \quad dt_{\mathrm{cool}} \ge dt_{\mathrm{HD}} \\ dt = dt_{\mathrm{cool}} & \text{for} \quad dt_{\mathrm{HD}} > dt_{\mathrm{cool}} \ge \delta \times dt_{\mathrm{HD}} \\ dt = \delta \times dt_{\mathrm{HD}} & \text{for} \quad \delta \times dt_{\mathrm{HD}}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

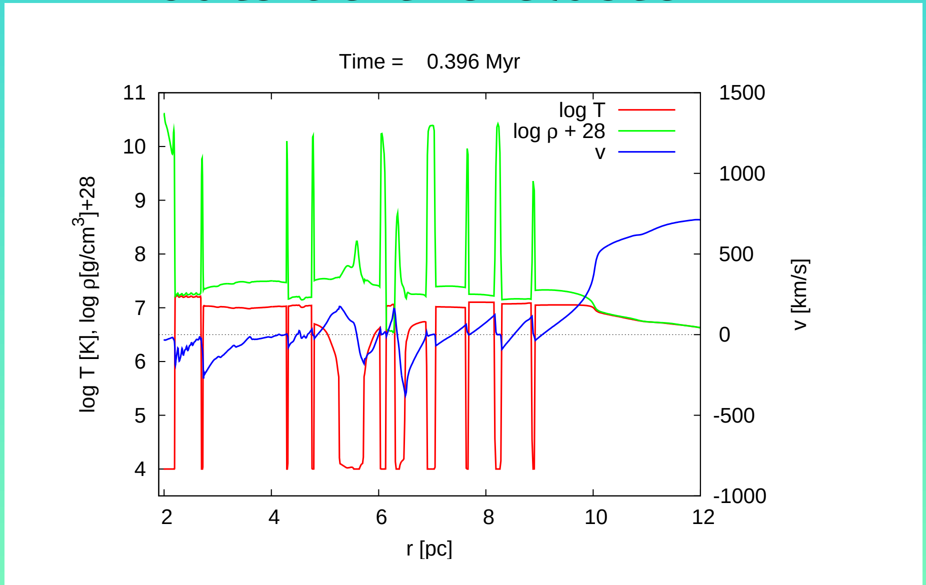
- δ - safety factor (typically 0.1)
- code publically available `http://richard.wunsch.matfyz.cz`

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

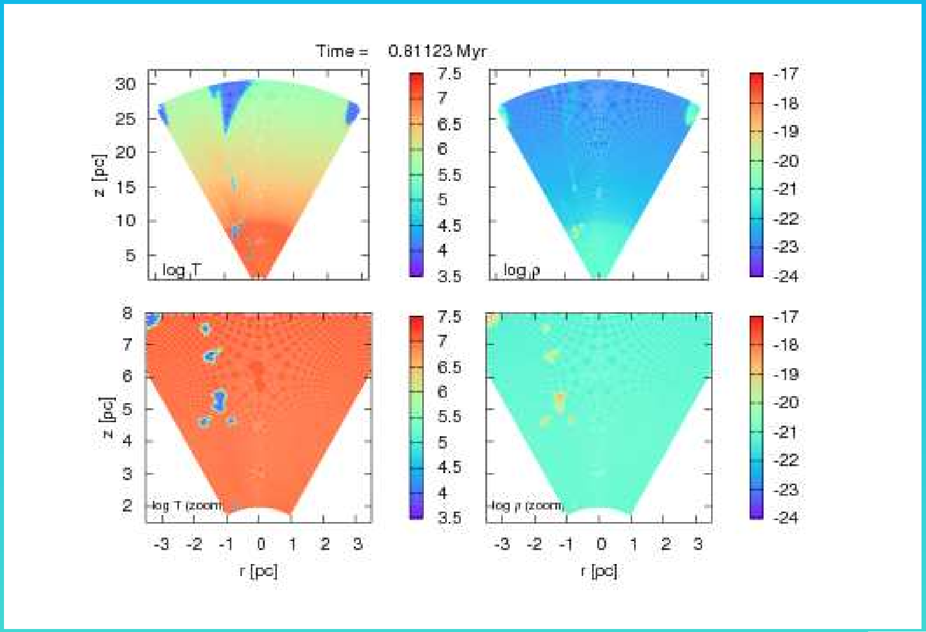




Higher $L_{\rm SC}$ (10^{43} erg/s)

- dense cold standing shells are formed through collisions of shocks

2D Numerical simulations



Slightly above $L_{\rm crit}$:

$R_{\rm SC} = 10$ pc

$L_{\rm SC} = 10^{42}$ erg/s

$= 2L_{\rm crit}$

$v_{a,\infty} = 1000$ km/s

$T_{\rm min} = 10^4$ K

Fairly above $L_{\rm crit}$:

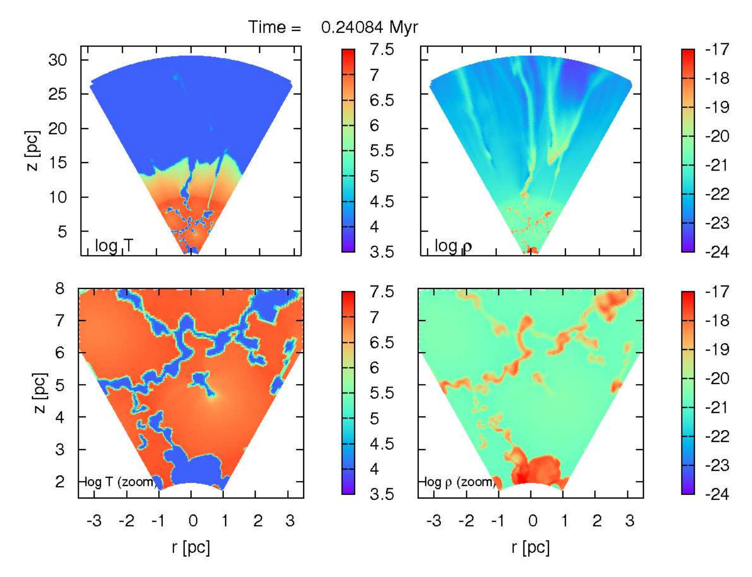
$R_{\rm SC} = 10$ pc

$L_{\rm SC} = 10^{43}$ erg/s

$= 20L_{\rm crit}$

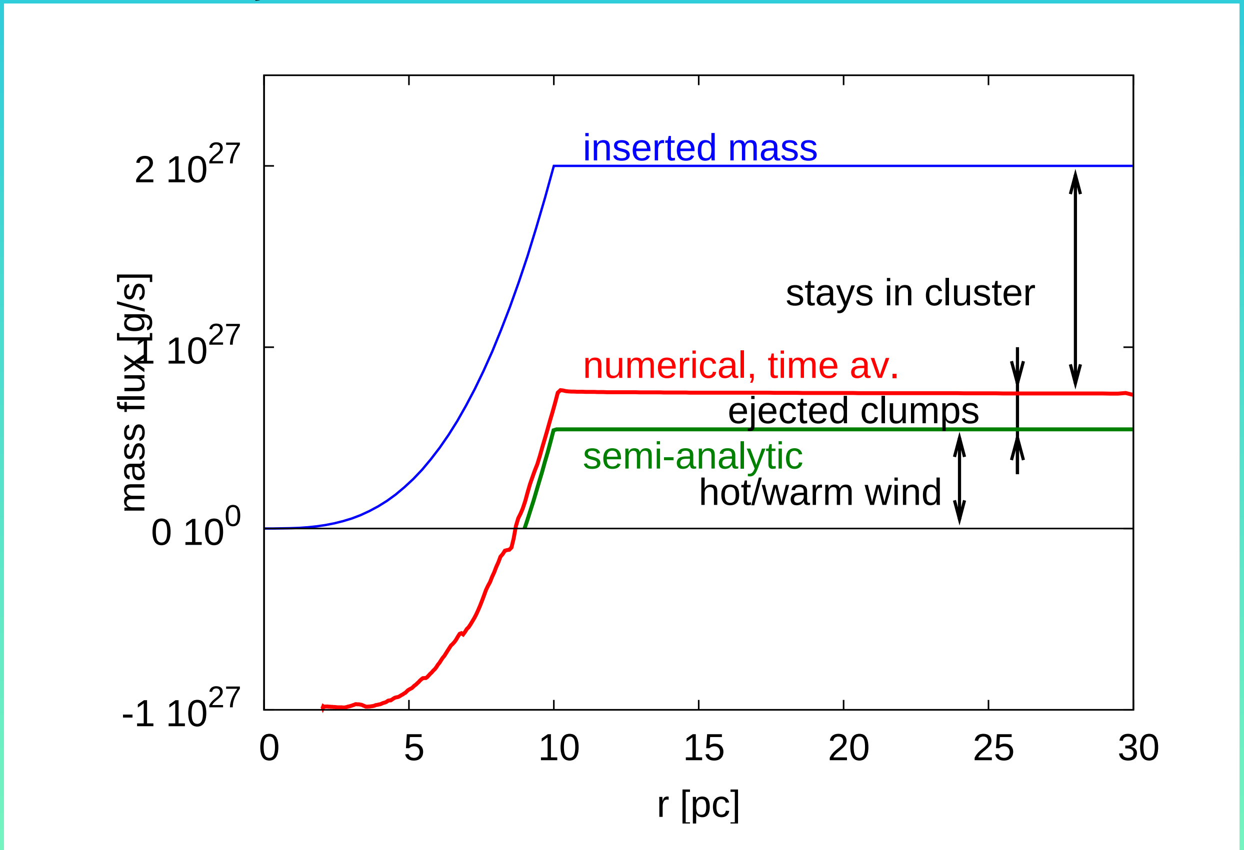
$v_{a,\infty} = 1000$ km/s

$T_{\rm min} = 10^4$ K

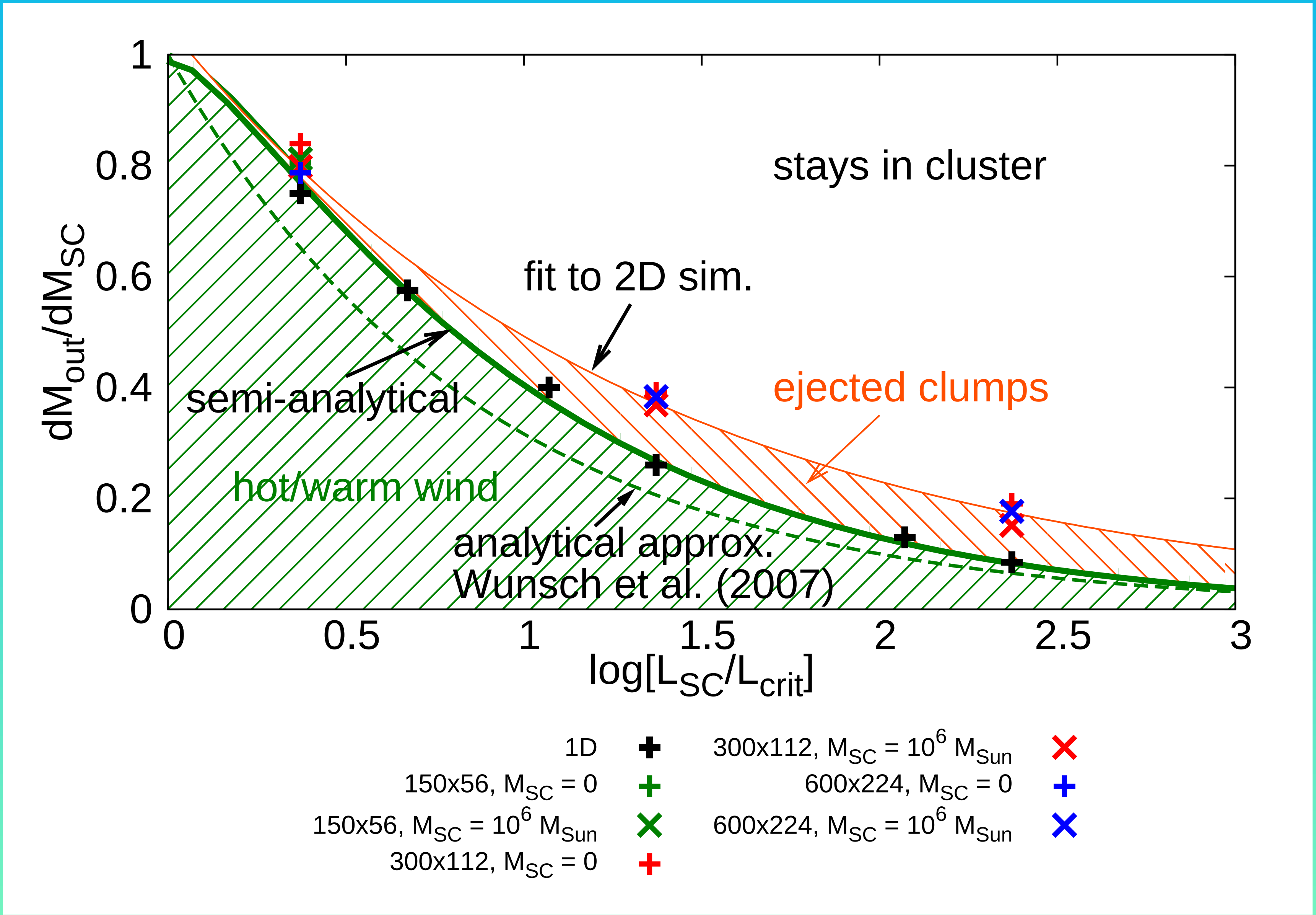


Mass flux as function of radius

- semi-anl: includes hot/warm wind only
- numerical: includes both hot/warm wind and clumps
- substantial amount of mass stays inside cluster
  → eventually available for SF



Outflow from the cluster for different models



Conclusions

- 2D simulations confirm bimodal behaviour: outer part of cluster produces the quasi-stationary wind, thermal instability forms dense warm clumps in the inner region
- warm 10^4 K outflow from the cluster consits of two components: originally hot wind that cools down and ejected clumps formed in the central region
- ejected clumps carry only small amount of inserted mass (10% or less), most of mass inserted below R_{st} stays in the cluster

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