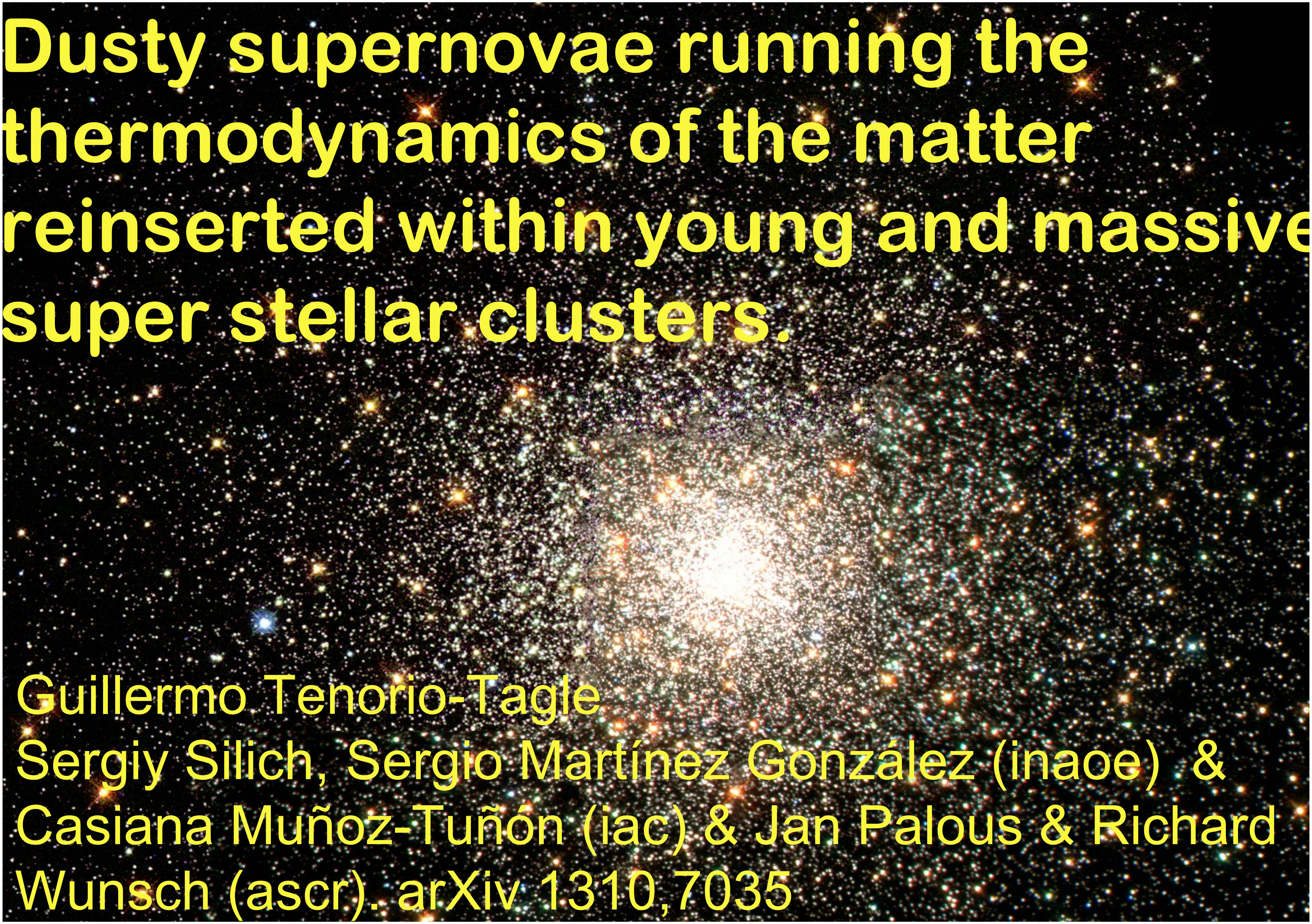
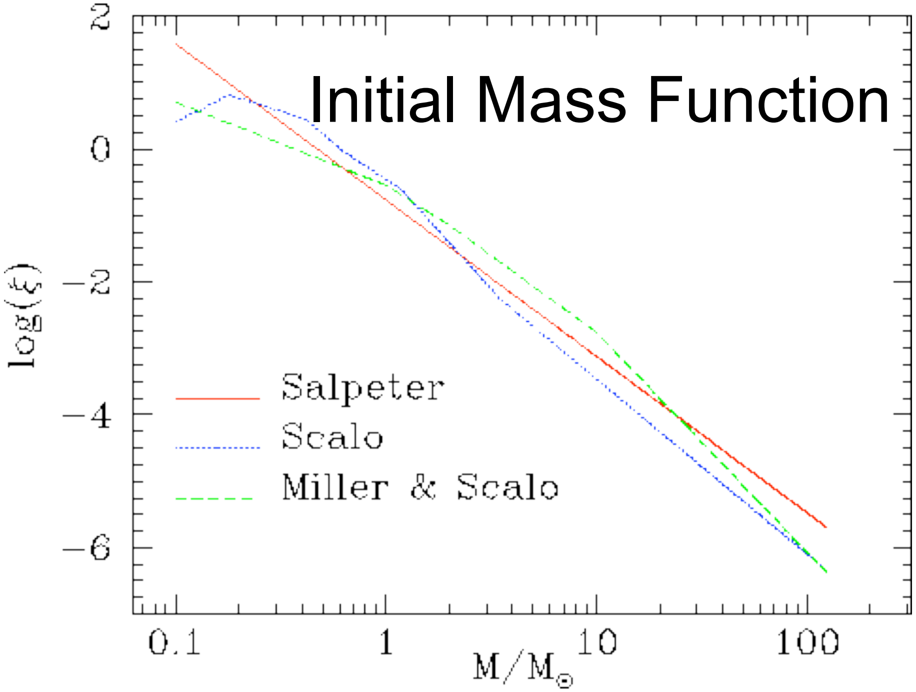


Dusty supernovae running the thermodynamics of the matter reinserted within young and massive super stellar clusters.

Guillermo Tenorio-Tagle
Sergiy Silich, Sergio Martínez González (inaoe) &
Casiana Muñoz-Tuñón (iac) & Jan Palous & Richard
Wunsch (ascr). arXiv 1310,7035

Super star clusters (SSCs) ~ old globular clusters

Westerlund 1 in the Milky Way



Young SSCs:
Age < 10 Myr
Size < 10 pc
$10^5 M_{sol} < M_{SSC} < 10^7 M_{sol}$

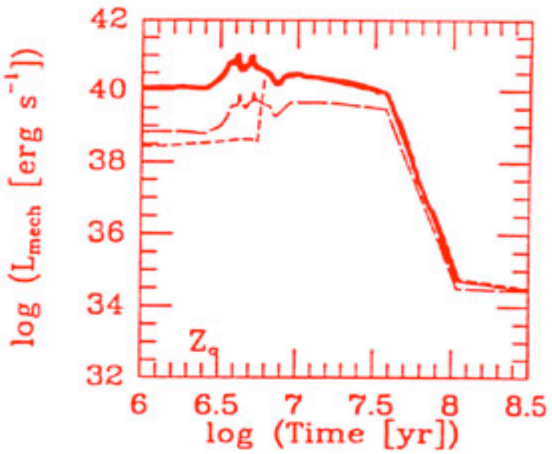
What impact do they have on their host galaxies???

Coeval Starburst

Starbursts Synthetic Properties:

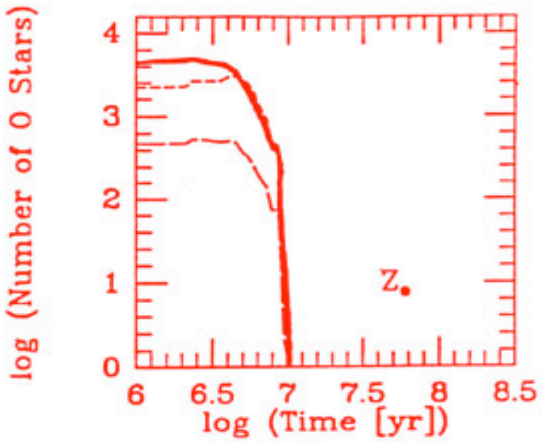
(Leitherer + Heckman 95)
IMF, $M_{low} = 1 M_\odot$, $M_{up} = 100 M_\odot$
$M_{SB} = 10^6 M_\odot \Rightarrow$

- Several thousands O stars correlated in space ($R \lesssim 100 pc$).



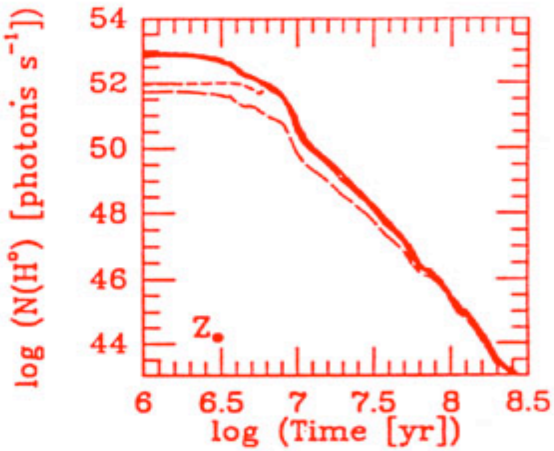
- The production of UV photons is constant for the first 3-4 Myr and then drops as t^{-5}.

$\Rightarrow t_{HII} \sim 10^7 yr < t_{SN}$.



- Massive stars undergo winds and all stars with a mass $M_* \geq 8 M_\odot$ end up as SN.

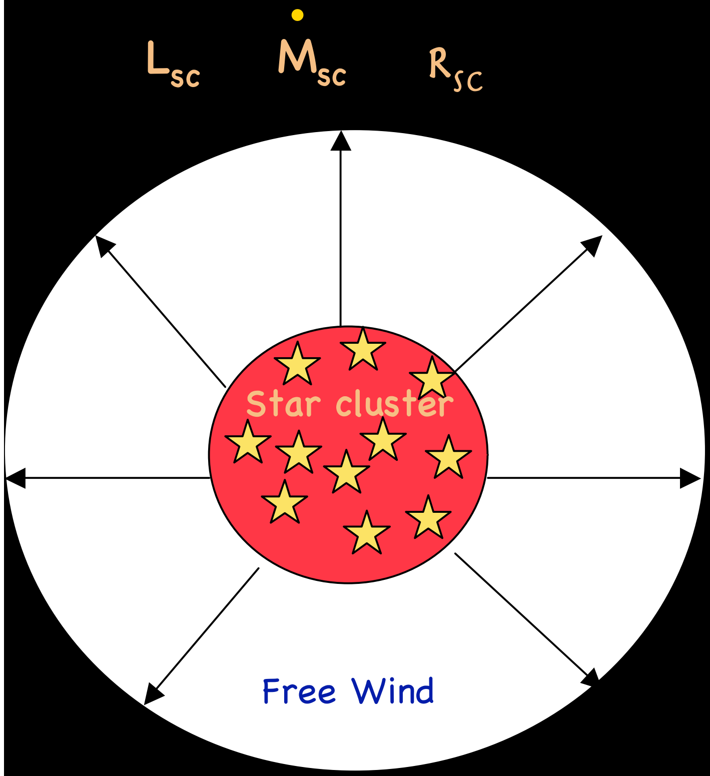
$\Rightarrow$ an almost constant L_{mech} for up to 60 Myr ($= t_{SN}$). i.e. several tens of thousands of SN.



+ scaling properties

On the hydrodynamics of the matter reinserted within SSCs

1. Super Star Cluster winds



The prototype model for SSC winds (Chevalier & Clegg 1985) is based on the assumption that massive stars are equally spaced within the SSC volume.

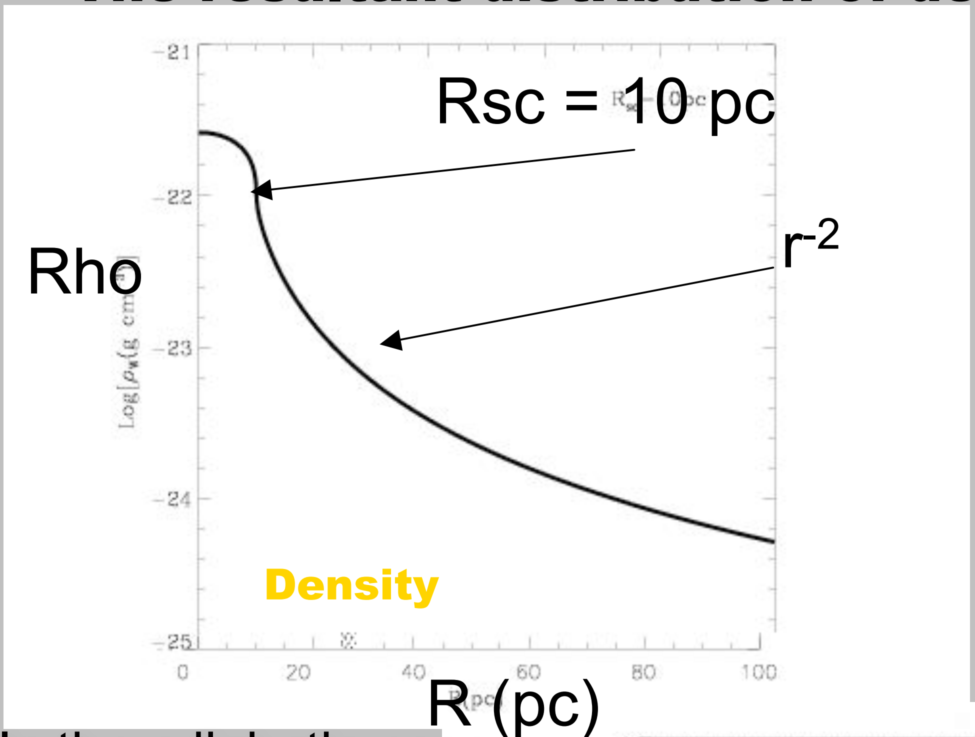
The kinetic energy deposited by massive stars is completely thermalize via random collisions of individual stellar winds and SN ejecta, within the cluster volume.

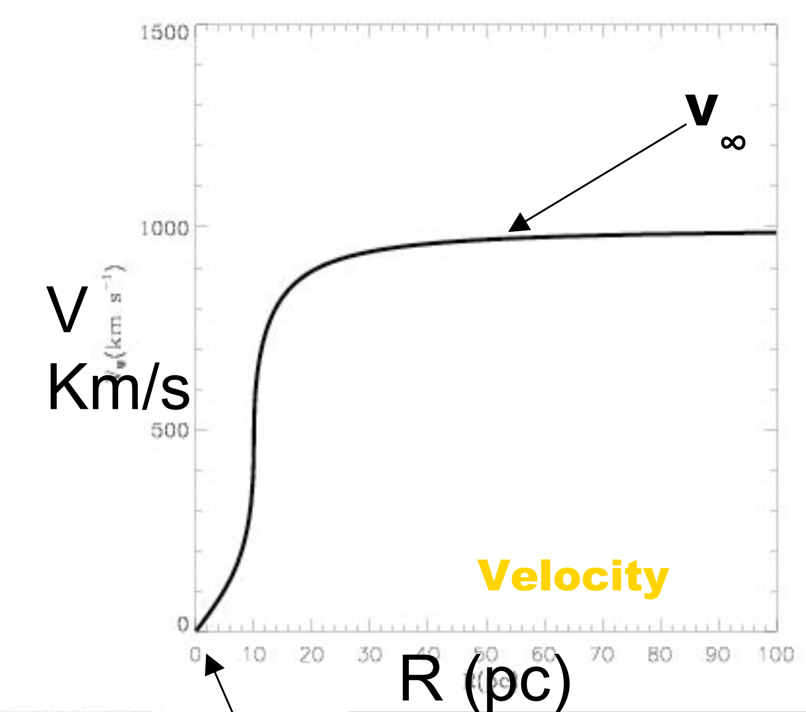
This generates the large central overpressure that accelerates the ejected matter and eventually blows it out of the star cluster in the form of a high velocity outflow – the star cluster wind.

In the adiabatic case three parameters define the distributions of the outflowing gas velocity, density, temperature and thermal pressure.

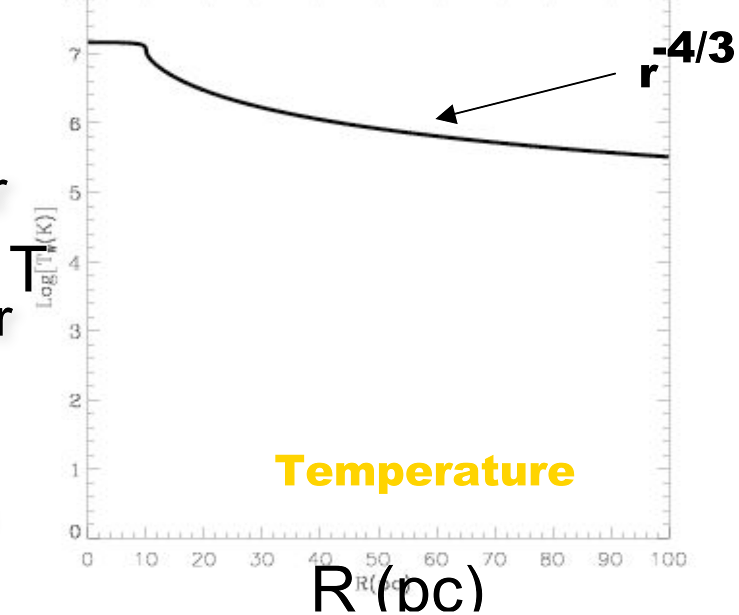
These are: The energy and mass deposition rates L_{sc} and $\dot{M}_{sc}$, and the star cluster radius R_{sc}.

The resultant distribution of density, temperature and velocity.





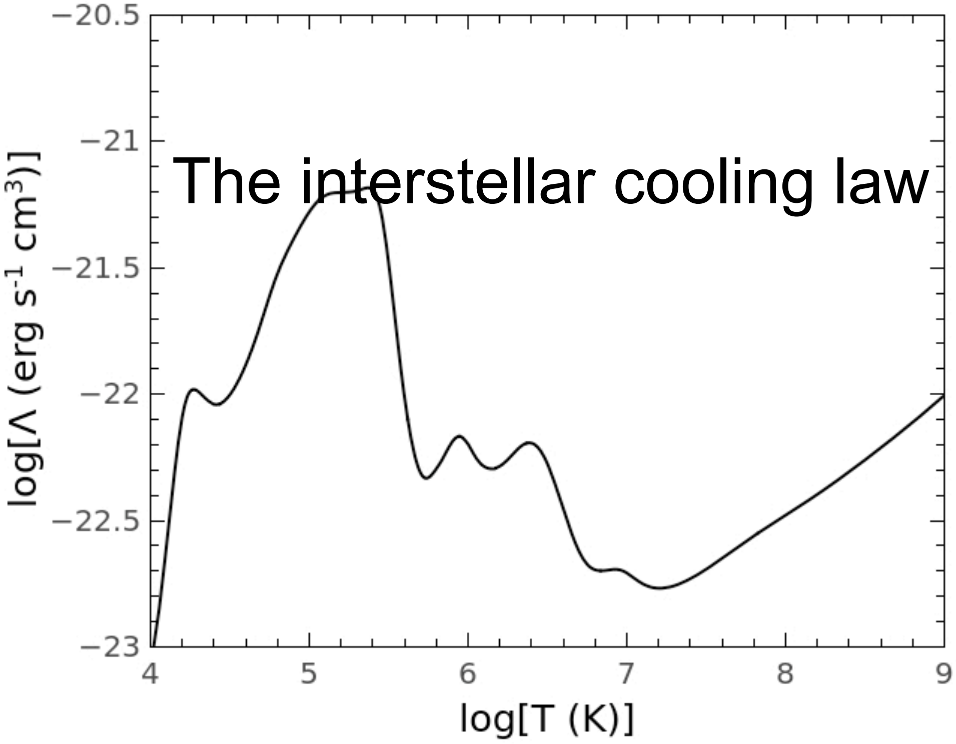
In the adiabatic case the flow reaches a stationary solution: All the deposited matter $\dot{M}$ = 4 pi R_{sc}^2rho c_s streams out as a cluster wind and the wind parameters approach their asymptotic values at large radii (R > R_{sc}).

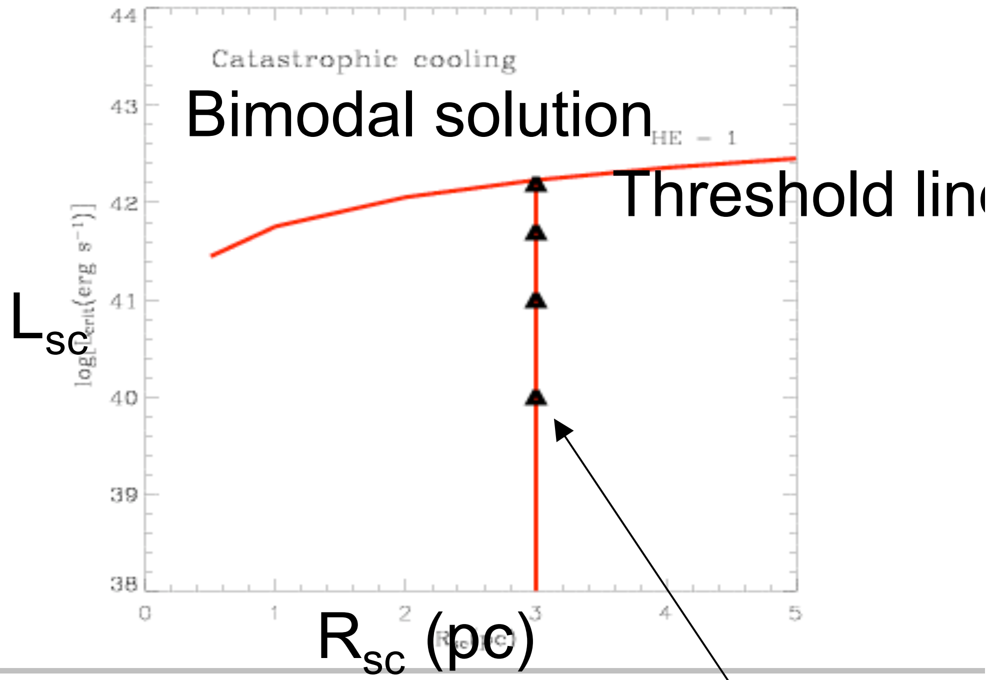


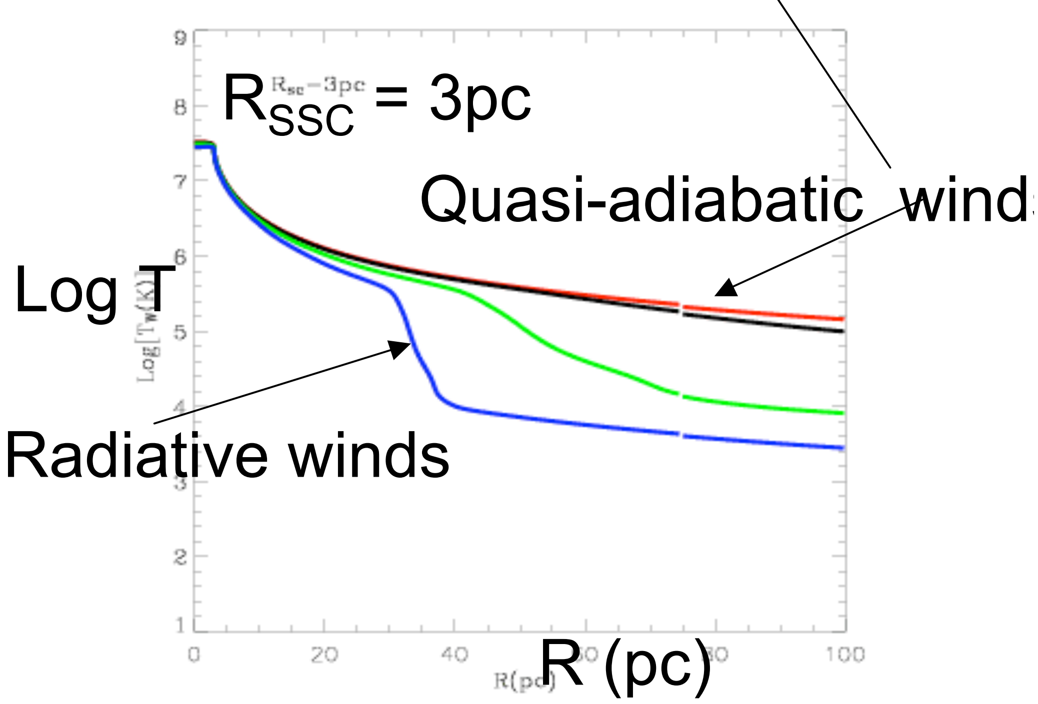
All of these solutions have the stagnation point at the center of the SSC and reach its own sound speed right at the cluster edge. But is this the end of the story???

The impact of strong radiative cooling; Q = Lambda n^2

Silich et al. 2004, ApJ 610, 226

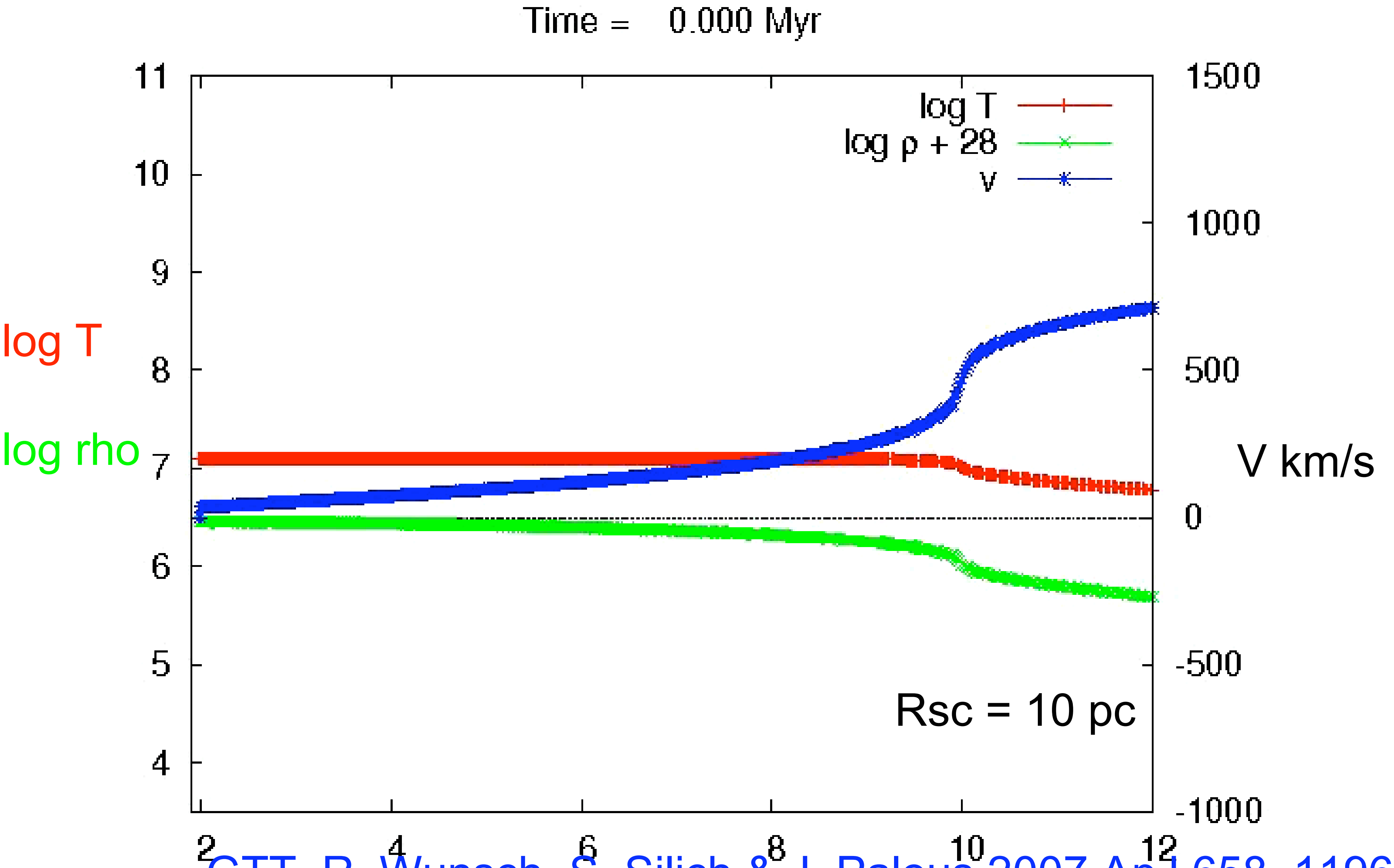






The more energetic or more massive the SSCs, the more that radiative cooling impacts on the resultant winds.

The bimodal hydrodynamic solution



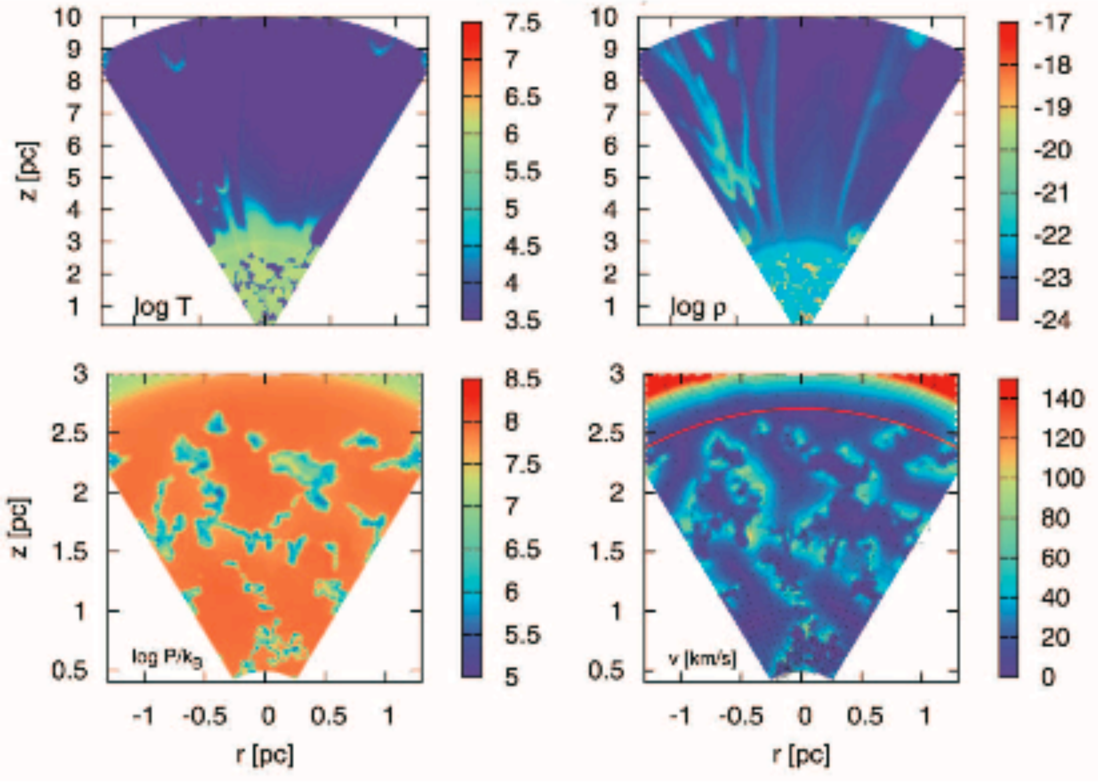
GTT, R. Wunsch, S. Silich & J. Palous 2007 ApJ 658, 1196

In the bimodal regime: Frequent and recurrent thermal instabilities occur within the SSC volume. These lead to multiple repressurizing shocks (RS). Radiative cooling moves the stagnation radius out of the cluster center and all matter reinserted within this volume losses its pressure and cannot participate in the cluster wind.

This leads to mass accumulation and to positive star formation feedback. Matter deposited in the outer zones still develops a wind.

The main outcome is that: only a small fraction of the processed matter is reinserted back into the ISM and is used instead in further generations of star formation.

Wunsch et al. 2008, ApJ 683, 683



end of the story???

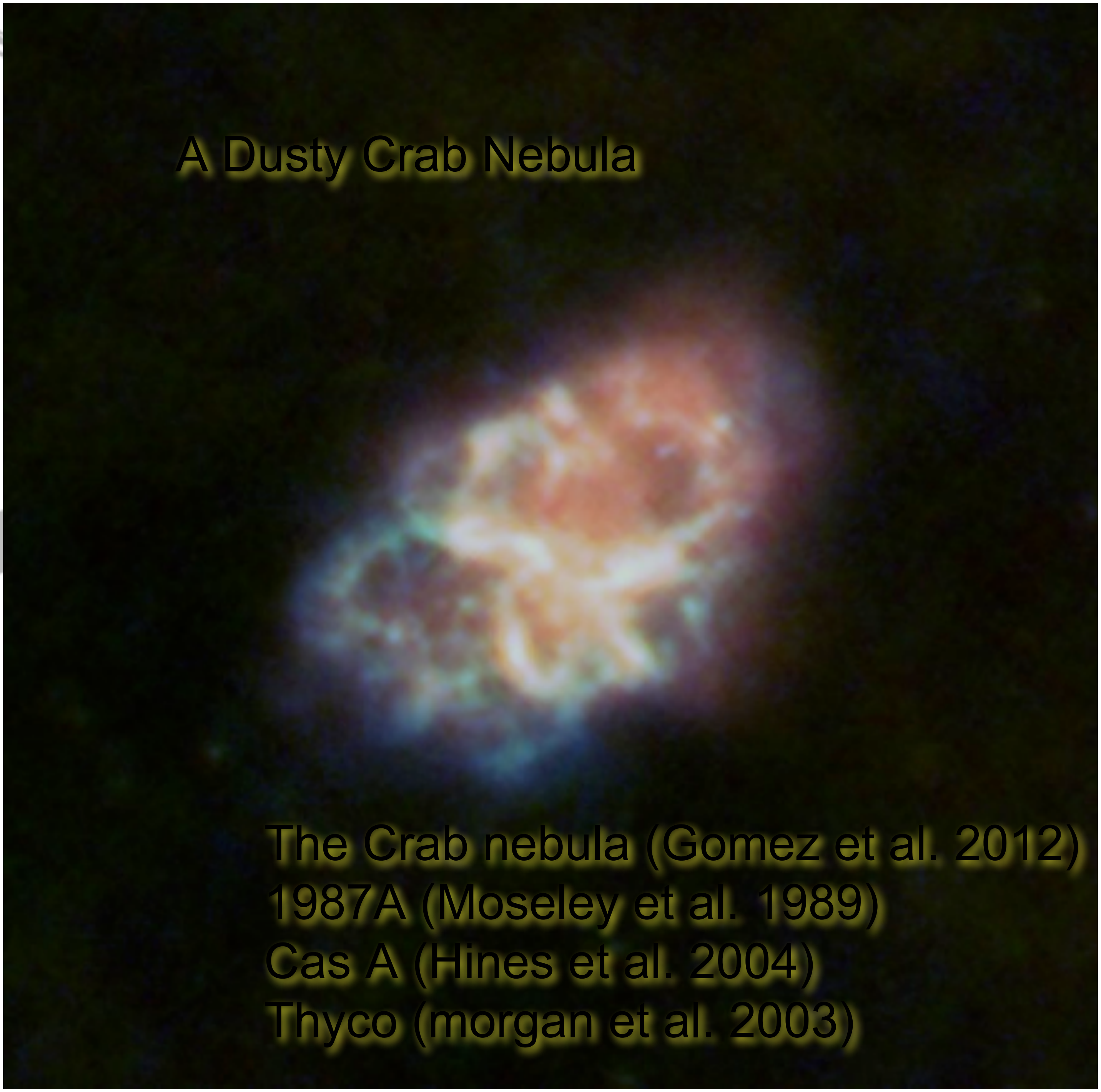
Spitzer & Herschel unveil core-collapsed SN as major dust producers!!!

$M_{dust} \sim f_{dust} M_{SN}$

$0.02 < f_{dust} < 0.05$

Todini& Ferrara 2001
Bianchi & Schneider 2007
Nozawa et al. 2003

…and there are tens of thousands of type II SN in young SSCs…



A Dusty Crab Nebula

The Crab nebula (Gomez et al. 2012)
1987A (Moseley et al. 1989)
Cas A (Hines et al. 2004)
Thyco (morgan et al. 2003)

Dust cooling of hot gas

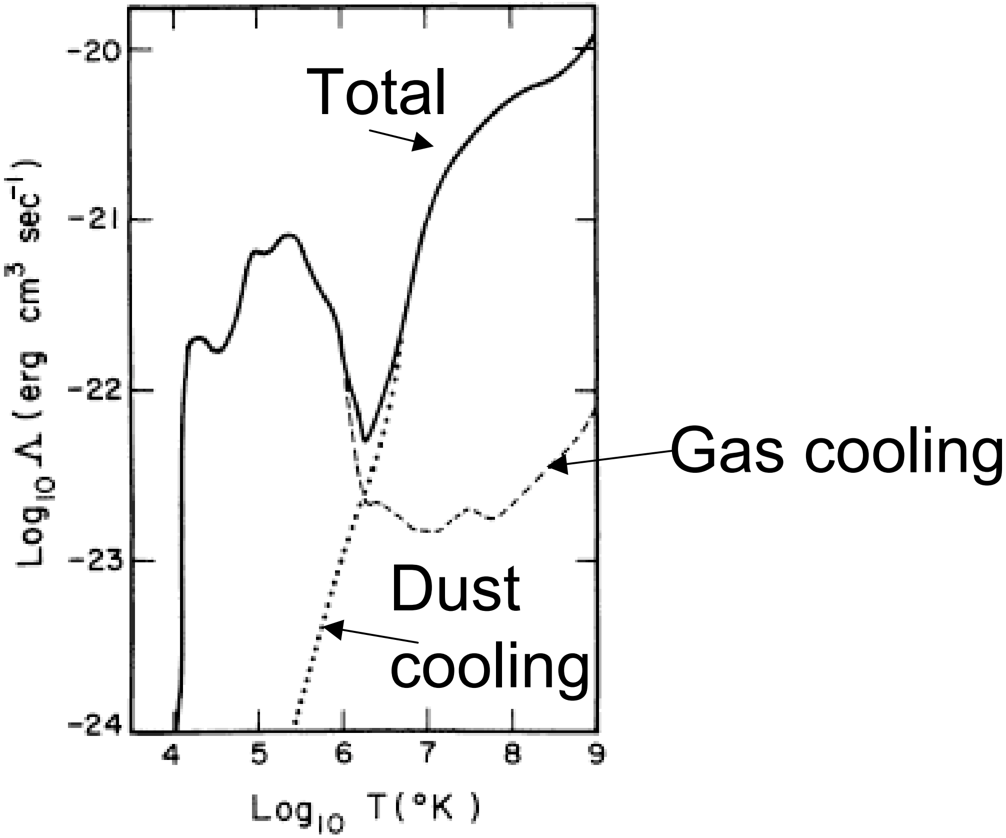


FIG. 1.—Cooling curve for collisionally ionized gas, containing cosmical abundances of heavy elements and graphite grains ($\sigma_g n_g = 3 \times 10^{-22}$ n cm^2, $a = 0.1$ μ). Dashed curve denotes contribution by gas alone; dotted curve, by grains alone.

Ostriker & Silk 1973, ApJ 184, L113

Draine, B. T. 1981, ApJ 245, 880

Dwek, E. 1987, ApJ 322, 812; 1981; etc

Smith et al. 1990 ApJ 475, 864

Montier & Giard 2004, Guillard et al. 2010 … etc, etc

The stationary presence of dust within young stellar clusters

One simply must account for the dust production rate $\dot{M}_d$ as well as for the rate at which all other processes may lead to its depletion within the flow.

$$\dot{M}_d - \frac{M_d}{\tau_d} - \dot{M}_g \frac{M_d}{M_g} = 0, \tag{1}$$

where τ_d is the characteristic dust destruction time scale. Hereafter we will assume that the dust mass input rate $\dot{M}_d$ is in direct proportion to the gas mass input rate, $\dot{M}_d = \alpha \dot{M}_g$, as dust is here assumed to be injected (via SN) together with the gas (which comes from winds and SN).

$$Z_d = \frac{M_d}{M_g} = \frac{\alpha \tau_d \dot{M}_g}{M_g} \left(1 + \frac{\tau_d \dot{M}_g}{M_g}\right)^{-1}, \tag{2}$$

The mass of the reinserted gas within the star cluster radius (R_{SC}) is:

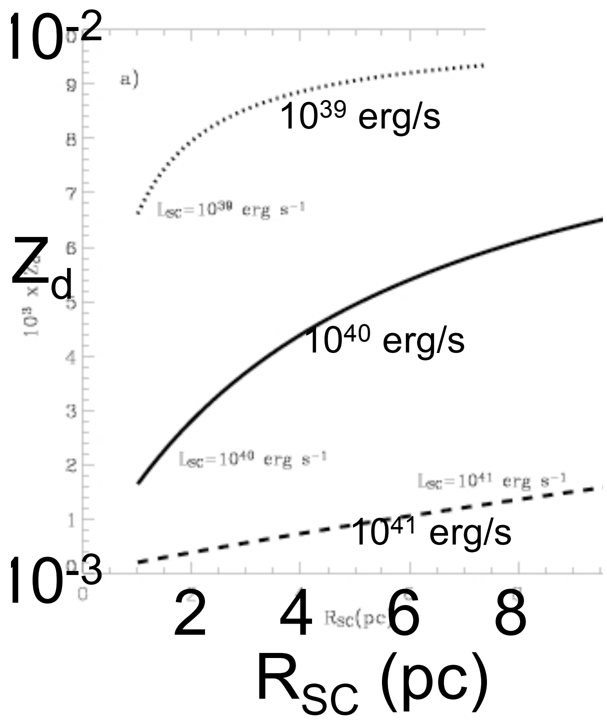
$$M_g = 4\pi \int_0^{R_{SC}} \rho(r) r^2 \mathrm{d}r = \frac{f_g R_{SC} \dot{M}_g}{3 c_s}. \tag{3}$$

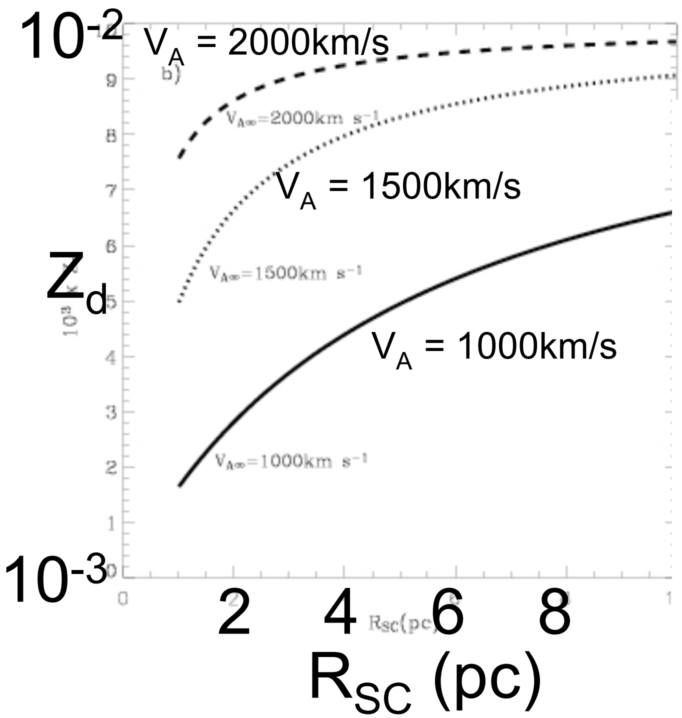
The factor $f_g \approx 2$ in equation (3) takes into account the fact that the gas density within the cluster is not uniform, it drops from the center outwards to reach the value $\rho_s = \dot{M}_{SC} / 4\pi c_s R_{SC}^2$ at the star cluster surface where c_s is the sound speed at the star cluster edge ($c_s \approx v_\infty/2$), v_∞ is the wind terminal speed.

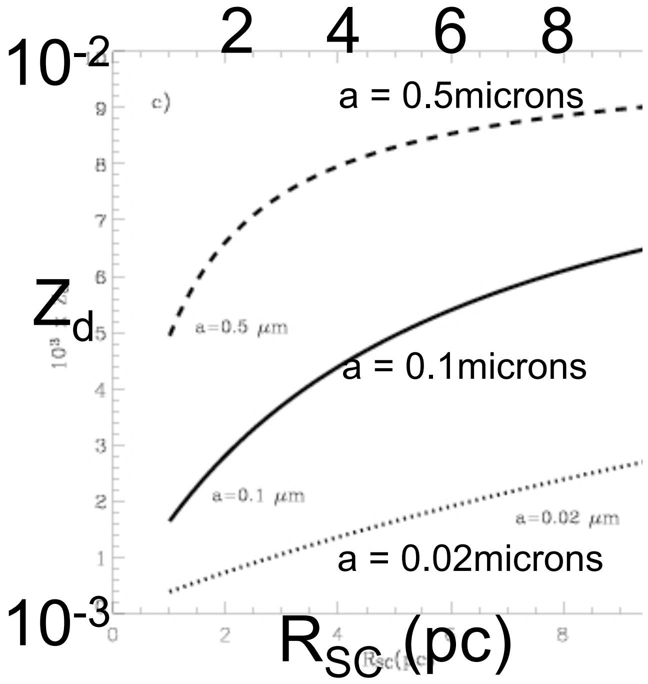
$$Z_d = \frac{M_d}{M_g} = \frac{3 \alpha \tau_d c_s}{f_g R_{SC}} \left(1 + \frac{3 \tau_d c_s}{f_g R_{SC}}\right)^{-1}. \tag{4}$$

The dust life-time against sputtering at temperatures above 10^6 K is given by Draine & Salpeter (1979): $\tau_d = 10^6 a/n(yr) = B/n(sec)$, where $B = 3.156 \times 10^{13} a$, a is the size of the considered dust grains in μm and n is the average nucleon number density in the gaseous phase. Taking into account that the average density of the reinserted matter is within a factor f_g larger than at the star cluster surface ($n = f_g \dot{M}_{SC}/2\pi\mu_i v_\infty R_{SC}^2$), one can obtain:

$$Z_d = \frac{M_d}{M_g} = \frac{3\pi\alpha B\mu_i R_{SC} v_{A\infty}^4}{2f_g^2 L_{SC}} \frac{L_{out}}{L_{SC}} \left(1 + \frac{3\pi B\mu_i R_{SC} v_{A\infty}^4}{2f_g^2 L_{SC}} \frac{L_{out}}{L_{SC}}\right)^{-1}, \qquad (5)$$







Following Dwek & Werner (1981), we calculate the cooling function due to gas-grain collisions as

$$\Lambda_d = \frac{1.4 m_H Z_d}{\langle m_d \rangle} \left(\frac{32}{\pi m_e} \right)^{1/2} \pi a^2 (kT)^{3/2} \left[h_e + \frac{11}{23} \left(\frac{m_e}{m_H} \right)^{1/2} h_n \right], \tag{6}$$

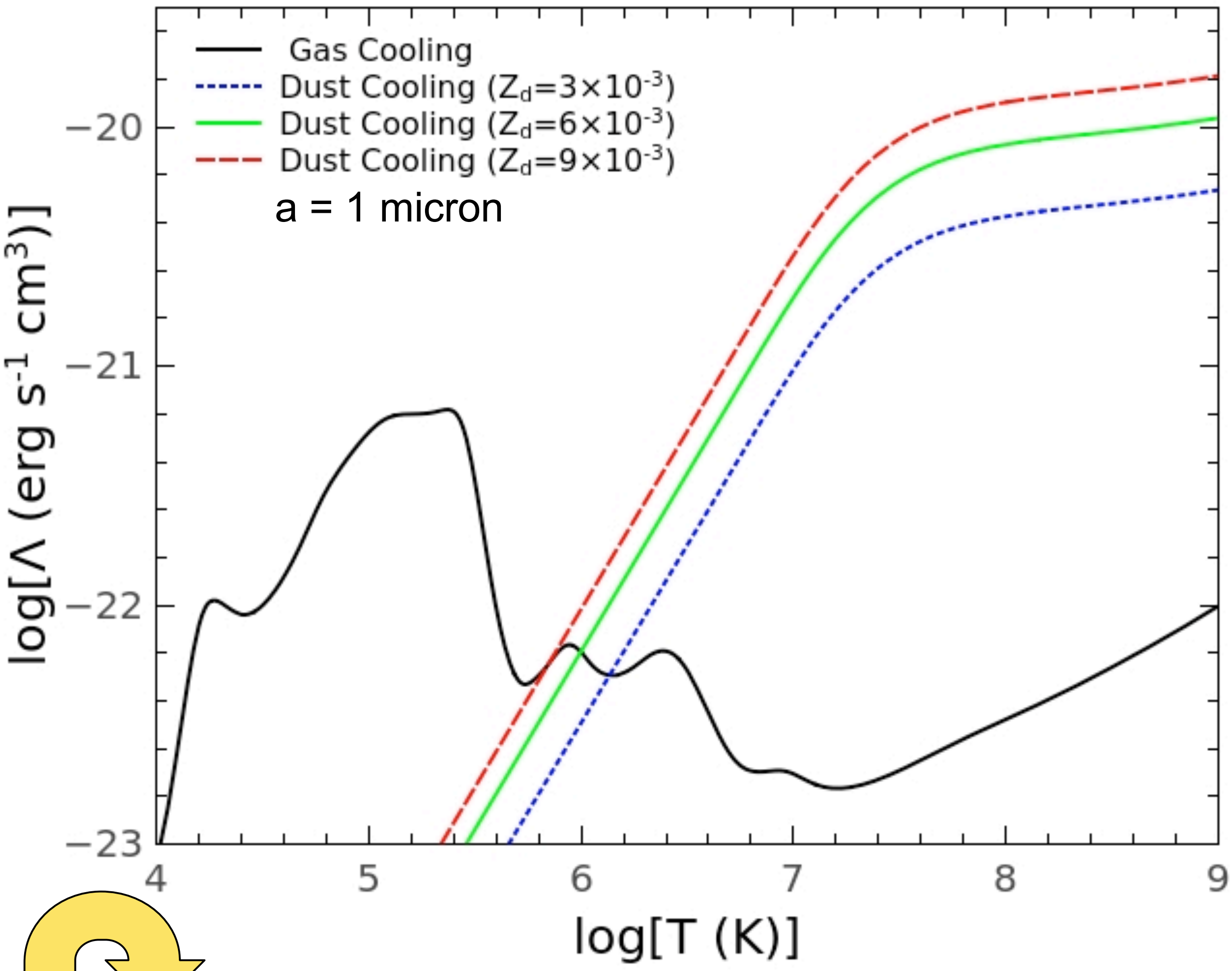
where h_e and h_H are the effective grain heating efficiencies due to incident electrons and incident nuclei, given by

$$h_e = 1 - \int_0^\infty (z + x_e)[(z + x_e)^{3/2} - x_e^{3/2}]^{2/3} \mathrm{d}z, \tag{7}$$

$$h_n = 1 - (1 + E_H/2kT) exp(-E_H/kT), \tag{8}$$

where m_H is the proton mass, $\langle m_d \rangle = 4/3\pi\rho_d a^3$ is the mass of the dust grains, $x_e = E_e/kT$, $E_e = 23a^{2/3}(\mu\mathrm{m})$ keV and $E_H = 133a(\mu\mathrm{m})$ keV. It was assumed that the dust grains have no charge and that all of them have the same size a and density $\rho_d = 3$ g cm^{-3}.

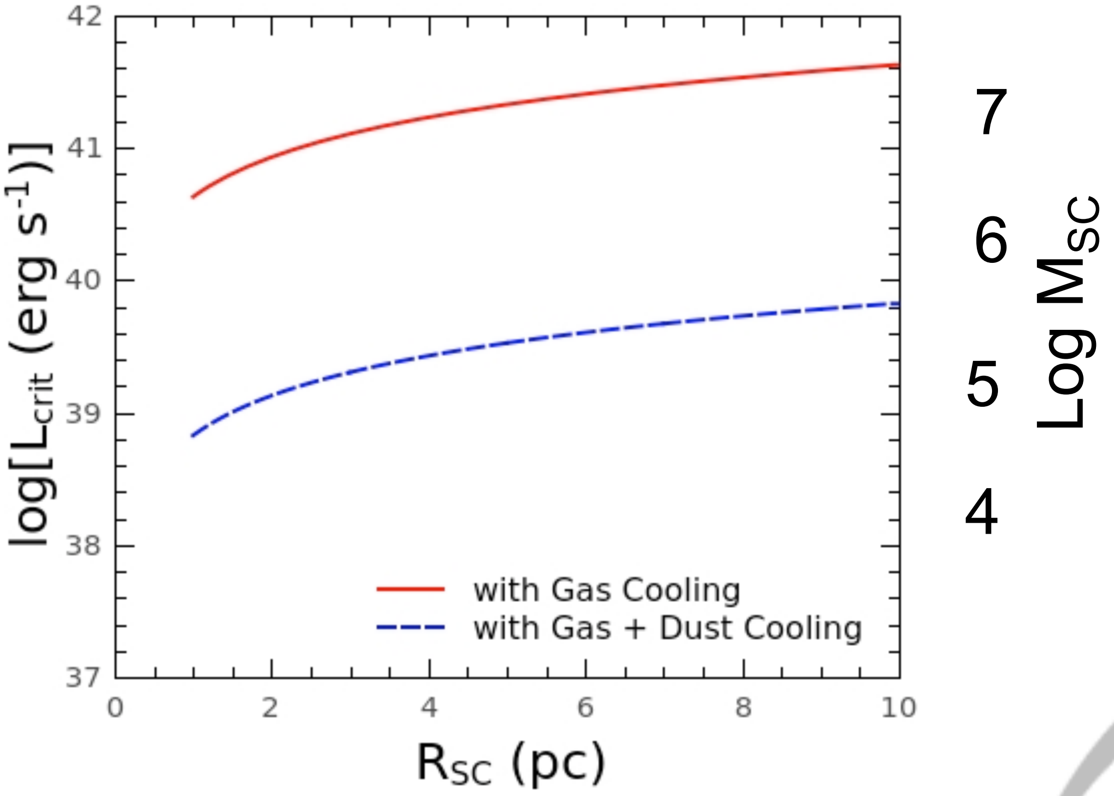
The gas and the dust cooling curves



And now!!!

Select SSC and dust parameters. Find Zd using eq. 5
Determine the dust cooling curve.
Using gas plus dust cooling find the critical line.

The new critical line!!!



CONCLUSIONS

Observational and theoretical evidence point at an efficient condensation of refractory elements into dust in the ejecta of core-collapsed SN.

The several tens of thousands of type II SN expected in young and massive SSCs has led us to postulate a continuous presence of dust in the SSCs volume.

This has led to the likely range of dust to gas mass ratios,

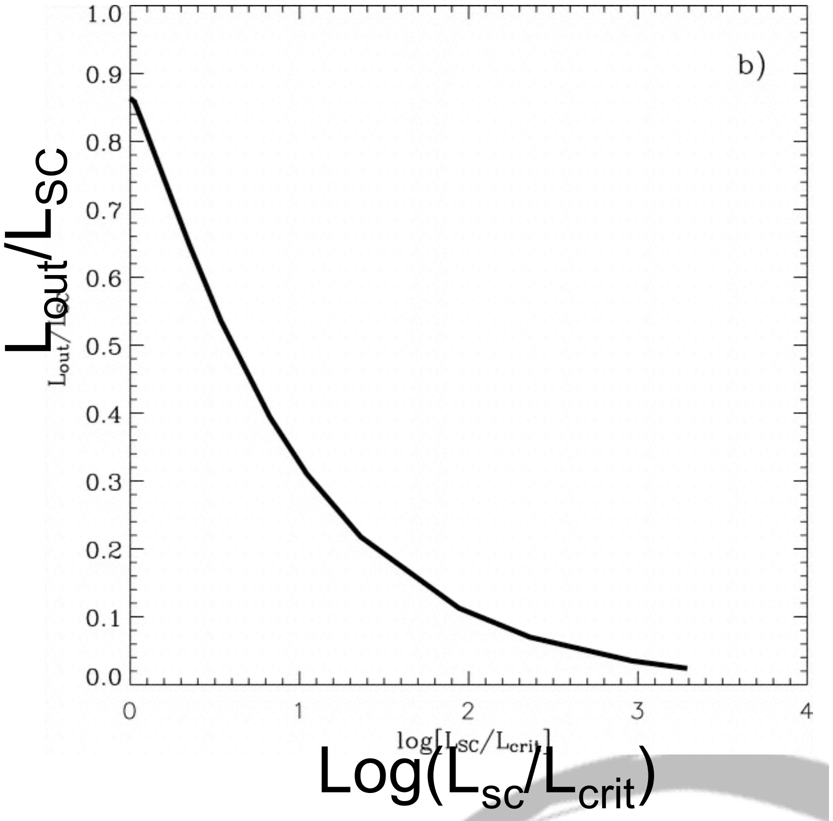
$Z_d \sim 10^{-3} - 10^{-2}$,

what has allowed us to calculate the dust cooling law within young and massive SSCs.

Dust cooling effectively lowers the location of the critical line, found in the mechanical luminosity vs size plane, when using only gas cooling. The new location, about two orders of magnitude lower, implies that young, massive and compact SSC with a mass $M_{SSC} > 10^5\, M_{sun}$ experience the bimodal solution.

CONCLUSIONS

The implication of assuming gas and dust cooling is that for young, massive and compact stellar clusters only a small fraction of their mechanical luminosity, as inferred from synthesis models (as in SB99), impacts the surrounding ISM.



Massive, compact and young clusters inject into the ISM only a small fraction of their processed metals, while the accumulated reinserted matter eventually surpasses the Jeans Limit. This is expected to lead to an extreme mode of positive star formation feedback, to further generations of stars, with the matter reinserted by massive stars.