The dynamics of superbubbles driven by star cluster winds and supernova explosion

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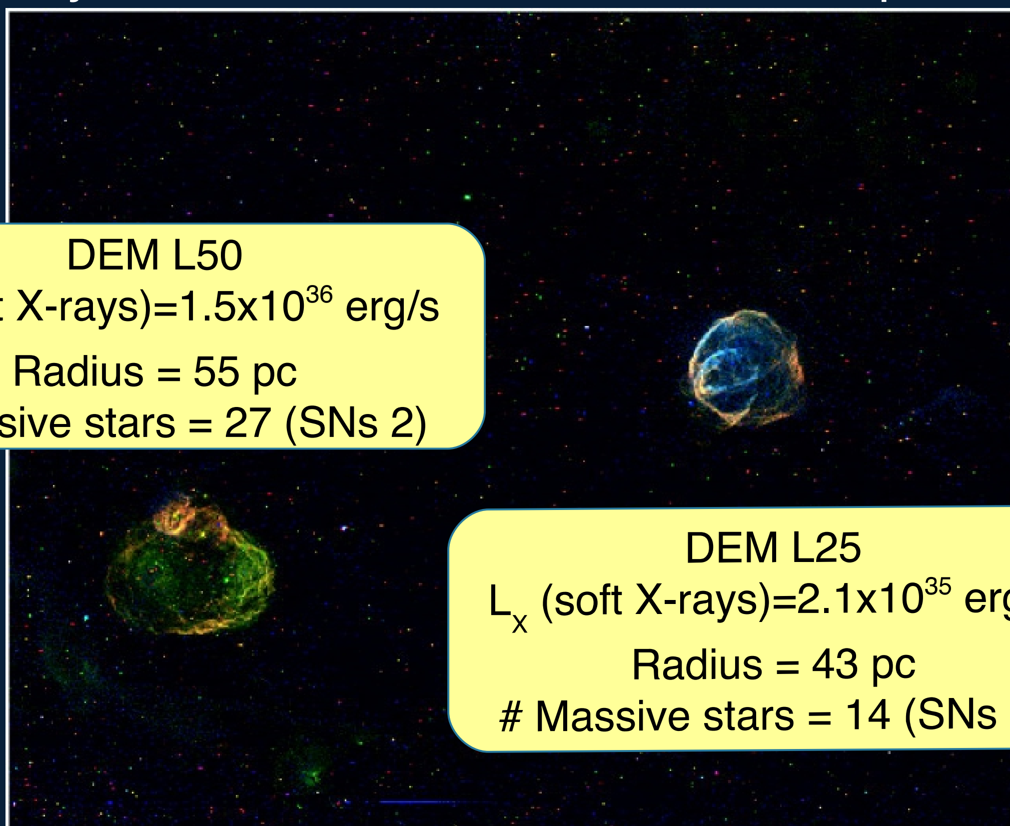
Introduction

It is well known that massive stars inject a considerable amount of mechanical energy into the interstellar medium, in form of stellar winds or supernova explosions. The energy input by the stellar winds and supernovas drive strong shocks that expand into the ISM producing a bubble.

The Large Magallanic Cloud is f lled with superbubbles with substantial soft X-ray emission, and large-diameter shells, in several cases, larger soft X-ray emission and smaller sizes than predicted by the standard model.



DEM L50
L_X (soft X-rays)=1.5×10^{36} erg/s
Radius = 55 pc
# Massive stars = 27 (SNs 2)

DEM L25
L_X (soft X-rays)=2.1×10^{35} erg/s
Radius = 43 pc
# Massive stars = 14 (SNs 2)

DEM L301 (N70)
L_X (soft X-rays)=2.4×10^{35} erg/s
Radius = 53 pc
# Massive stars = 15 (SNs 1)

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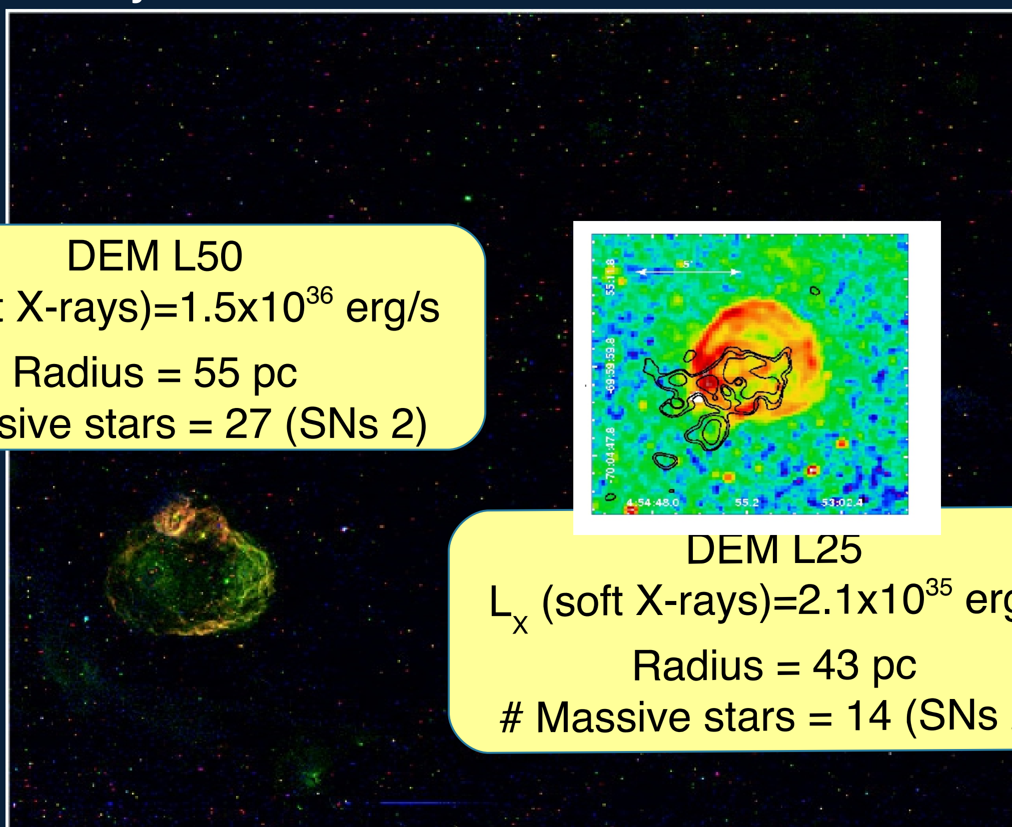

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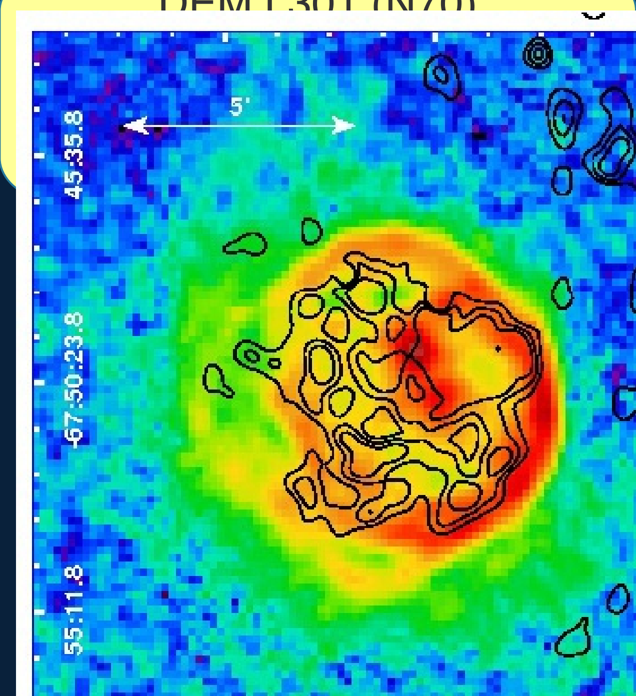
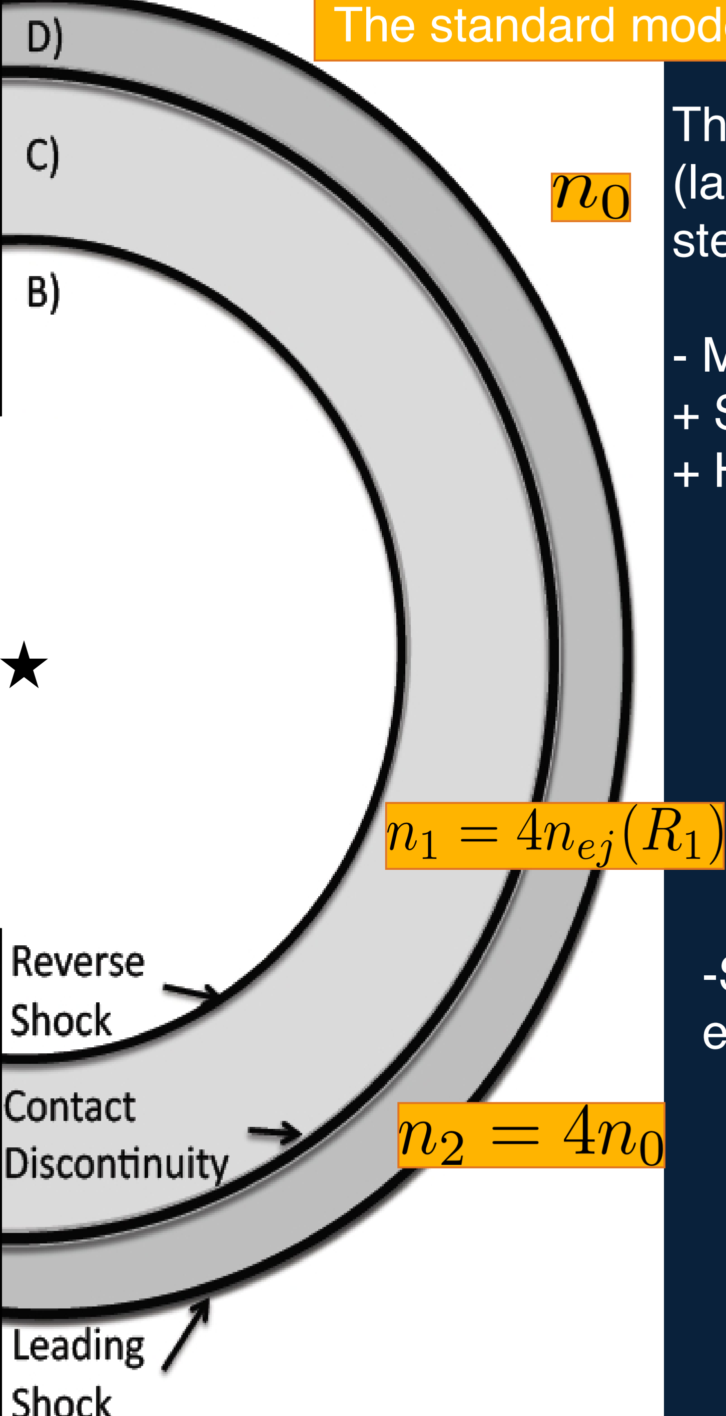


The standard model for a bubble



The standard model (Weaver et al. 1977) and (later Chu et al. 1990 & 1995) for a bubble driven by stellar winds

- MAIN ASSUMPTIONS:
+ Single stellar wind
+ Homogeneous interstellar medium density.

$$L_w = \frac{1}{2}\dot{M}V_\infty^2$$

$$R = (42\,\mathrm{pc})L_{\mathrm{w}37}^{1/5} n_0^{-1/5} t_6^{3/5}\ ,$$

$$V = \frac{dR}{dt} = (0.59\,\mathrm{km\,s^{-1}})R_{\mathrm{pc}}/t_6$$

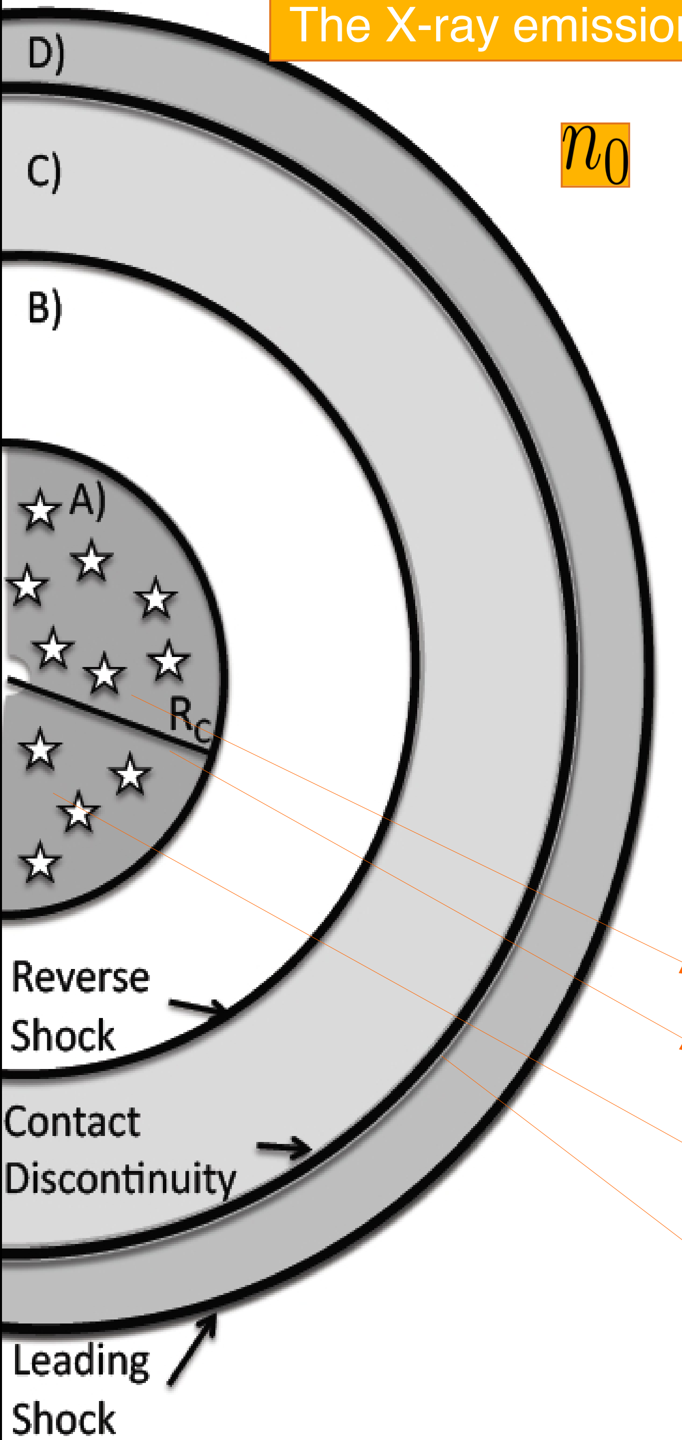
-Soft-Xray luminosity, is coming from the internal and external shells

$$L_X = 3.29 \times 10^{34} I(\tau)\xi L_{37}^{33/35} n_0^{17/35} t_6^{19/35} \quad [\mathrm{erg\,s^{-1}}],$$

$$I(\tau) = \frac{125}{33} - 5\tau^{1/2} + \frac{5}{3}\tau^3 - \frac{5}{11}\tau^{11/3},$$

$$\tau = 0.16 L_{37}^{-8/35} n_0^{-2/35} t_6^{6/35},$$

The X-ray emission in a superbubble



+ Multiple stellar winds.
+ Homogeneous interstellar medium density.
+ The gravitational potential is neglected.

$$L_w = \sum \frac{1}{2}\dot{M}V_\infty^2$$

Hard-Xray luminosity (2-10 keV) is coming from the cluster volume

Soft-Xray luminosity (0.1 – 2 keV) is coming from the region of shocked gas

$$L_X = 3.29 \times 10^{34} I(\tau)\xi L_{37}^{33/35} n_0^{17/35} t_6^{19/35} \quad [\mathrm{erg\,s^{-1}}],$$

$$L_{X,A+B} = 3.8 \times 10^{34}\Phi \frac{L_{38}^2}{R_{c,1}V_{1000}^6} \quad [\mathrm{erg\,s^{-1}}],$$

What is the influence of the stellar distribution?

How does the gas metallicity affect the superbubble evolution and X-ray emission?

Does the supernova explosion accelerate the external shell?

Can the thermal conduction change the dynamics of the external shell, and increase the density of the internal shell?

THE X-RAY EMISSION

The X-ray luminosity excess can be explained when a clumpy interstellar medium is considered (Jaskot et al. 2001) or when the wolf-rayet stage is considered in the stellar cluster evolution (Rogers & Pittard 2014).

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THE EXPANSION VELOCITY

High-velocity and Low-velocity (Oey 1996)

-High-velocity superbubbles are characterized by a shell expansion velocity $v_s > 25$ km s^{-1}. The problem lies in the fact that it is virtually impossible to obtain expansion shell velocities in excess of 25 km s^{-1} (if the stellar winds are the only source of mechanical energy injection).

Silich & Franco 1998 used a gradient in the ISM density and the evolution of the superbubbles can be accelerated. However, with these models the soft and hard x-ray luminosity can not be reproduce it.

THEN!!!!!

->An extra energy input rate is necessary.

->We explore possible mechanism that can simultaneously reproduce the hard and soft X-ray emission, the rapid expansion of high velocity superbubbles and the sizes reported in the observations.

The numerical code

With the purpose of exploring the effect of:
-> the SN explosions (on/off center),
-> metallicity
-> stellar distribution
-> thermal conduction
in the superbubbles

We perform a series of numerical simulations, and obtain the X-ray emission and the expansion velocity of the shells.

We used the HUACHO code to perform the numerical simulations. The code solves the HD equations on a 3D Cartesian mesh including radiative cooling and isotropic thermal conduction.

Conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + \mathbf{I}P) = 0,$$

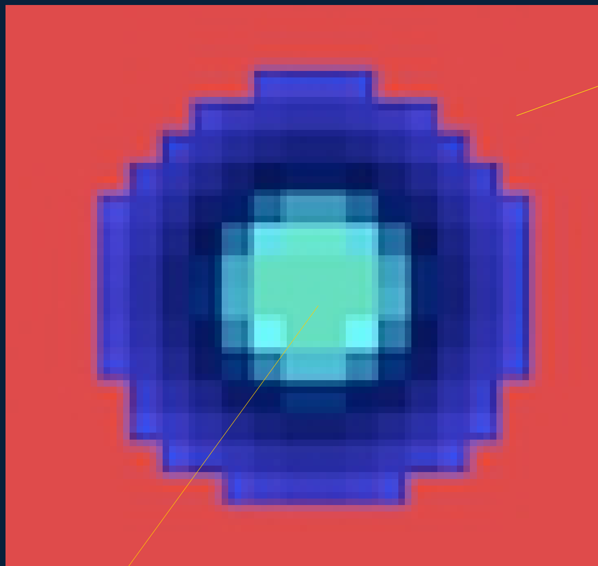
$$\frac{\partial E}{\partial t} + \nabla \cdot [\mathbf{u}(E+P)] = L_{\mathrm{rad}}(Z,T) + \nabla \cdot \mathbf{q},$$

where, , u, T, P and E are the mass density, velocity, temperature, thermal pressure and energy density.

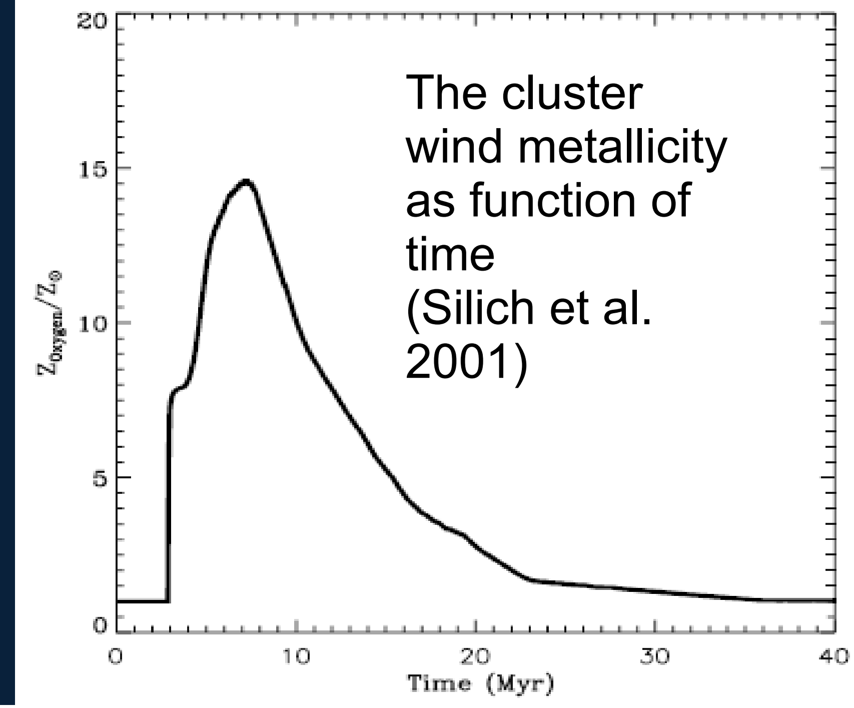
The numerical simulations contain:

+ 15 Massive stars in a cluster with radius Rc=10 pc.
+ Stellar winds with v=1000 km/s, dM/dt=10^{-6} Msun/yr
+ a 140^3 pc (256^3 pixels) grid
+ Interstellar (or circumstellar) density=2 cm^{-3}
+ Interstellar medium metallicity =0.3 Z_{sun}
+ Stellar wind metallicity = 3 Z_{sun}
+ Supernova remnant metallicity =10 Z_{sun}

=0.3 Z_{sun}



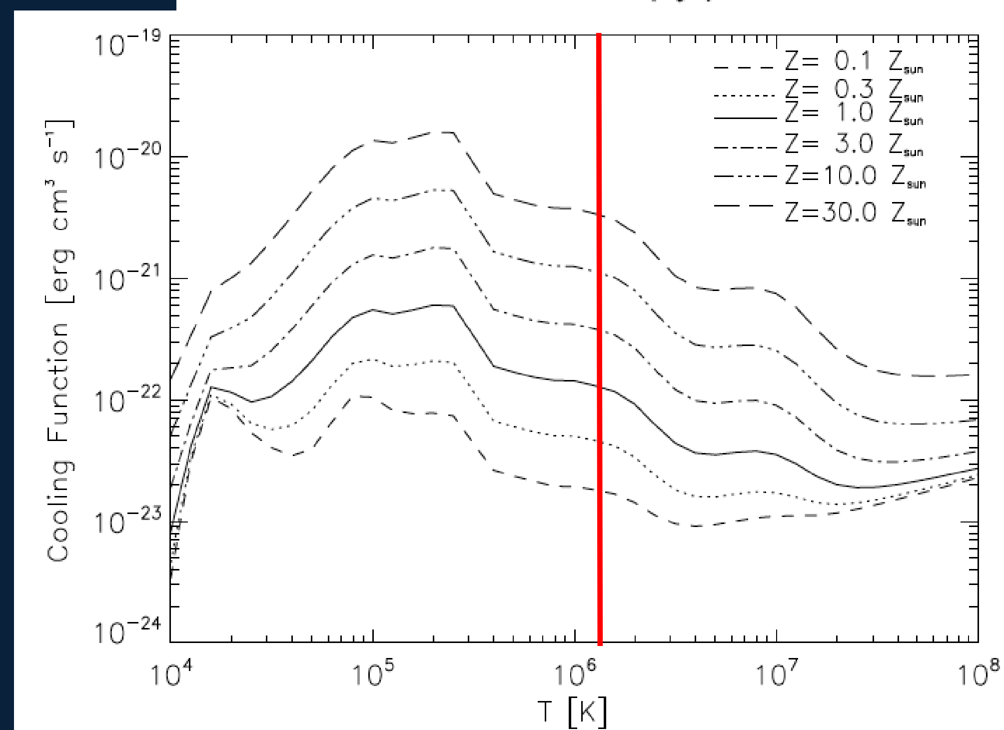
=3 Z_{sun}



The cluster wind metallicity as function of time (Silich et al. 2001)

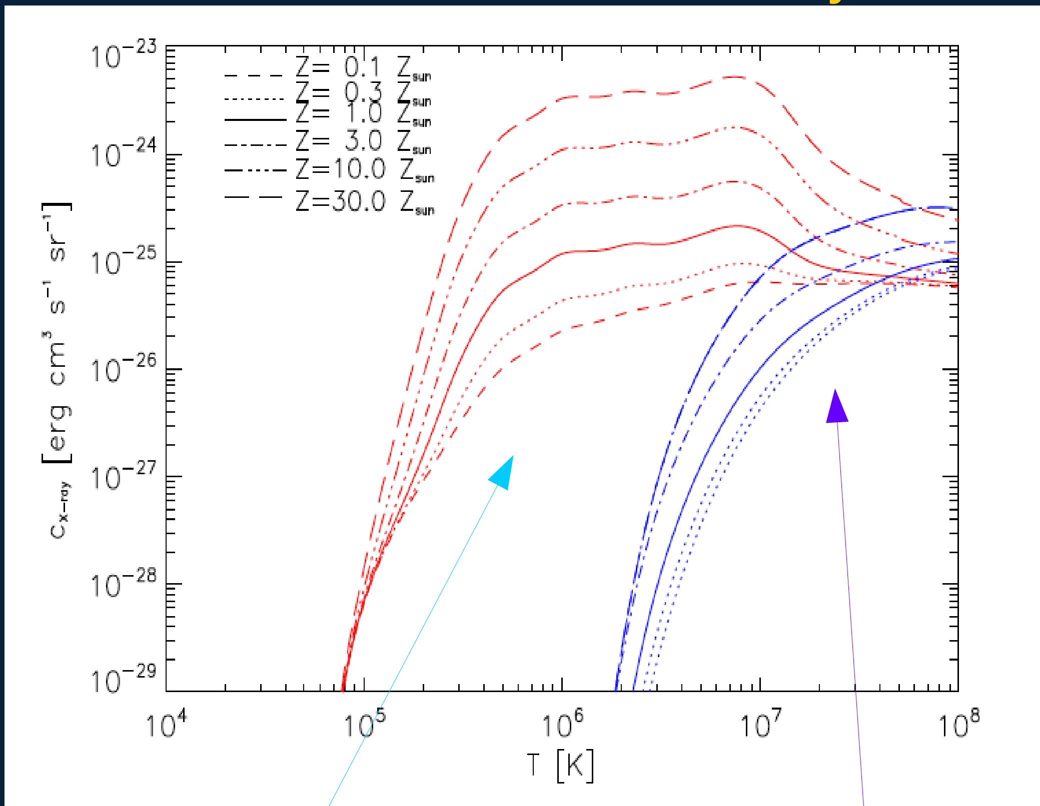
Advection equation

$$\frac{\partial Z\rho}{\partial t} + \nabla \cdot (Z\rho\mathbf{u}) = 0$$



Cooling function for different metallicites

The soft and hard – X ray emission coeff icients as function of metallicity and temperature



The soft and hard X-ray emission coeff icients, for a given metallicity, were computed and integrated over energy bands using the CHIANTI atomic database and its associated IDL software. We have computed the coeff icients for various metallicities (0.1, 0.3, 1, 3, 10 and 30 Zsun) and over a range of temperature from 10^4 to 10^9 K.

Soft X-ray coefficients

Hard X-ray coefficients

Thermal soft (0.1-2 keV, in red line) and hard (2-10 keV, in blue lines) X-ray emission coefficients for a range of metallicities between 0.1 and 30 Zsun.

The total luminosity is given by

$$L_X = \int n^2(R)\Lambda_X(Z,T)d^3R \ ,$$

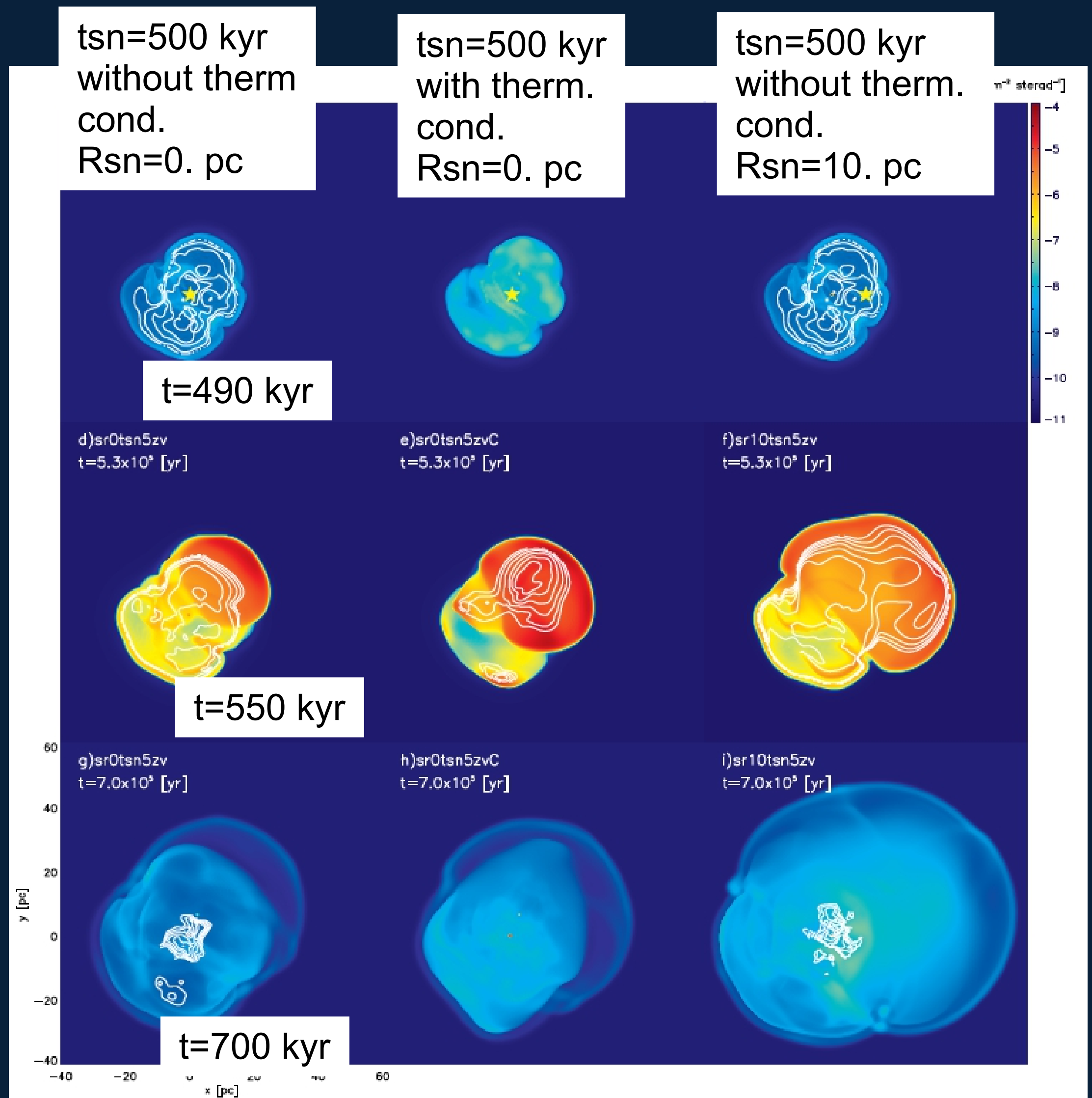
where, 'n' is the numerical density and Λ_X is the X-ray coef.

The numerical simulation results:

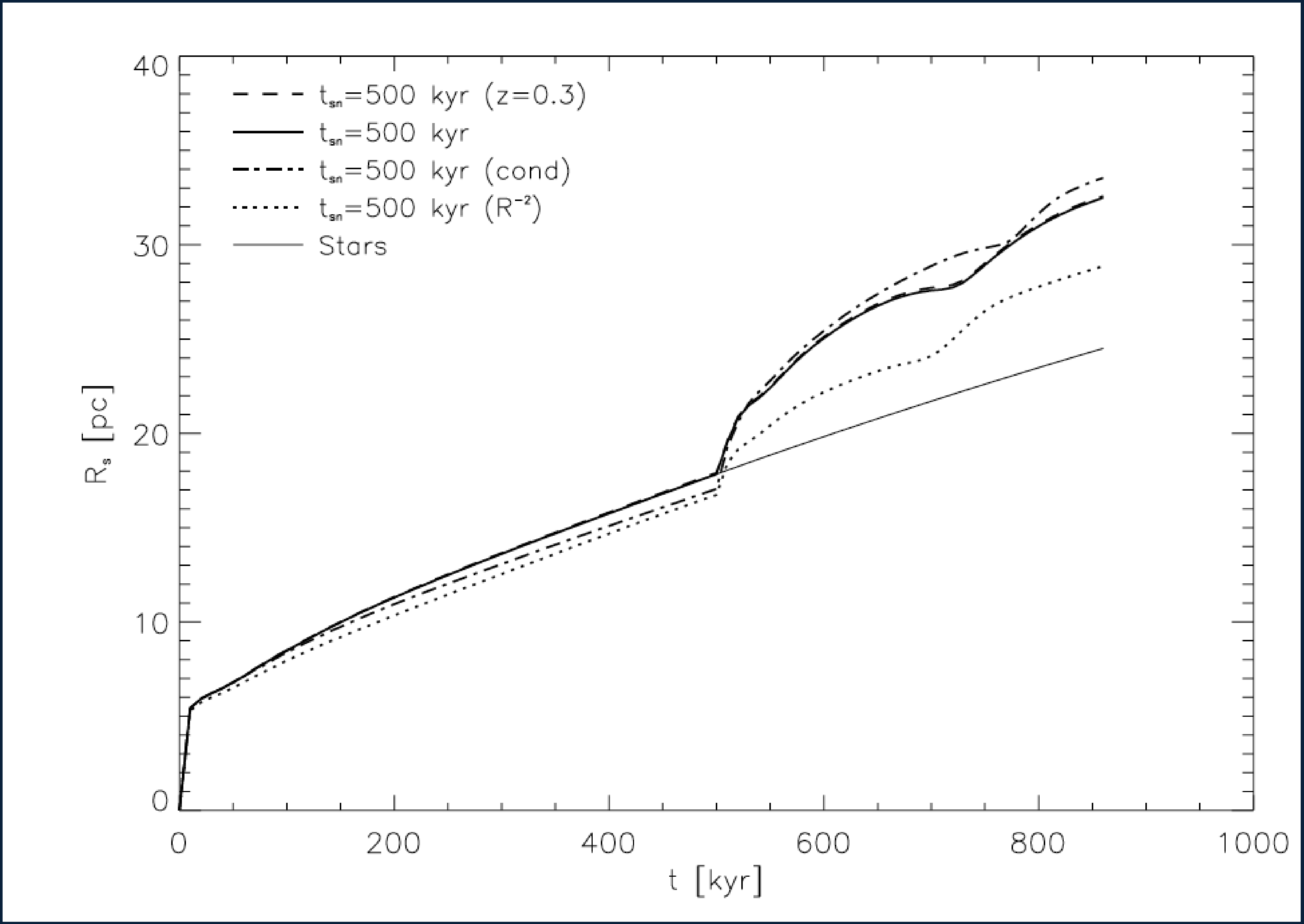
Comparison of the X-ray emissivity in the soft (color maps) and hard (contours) bands for different stages of the evolution and different models.

Following the time sequence in the columns, one can see that the supernova ejecta reaches the edge of the wind bubble and pushes it further into the ambient medium. Due to the particular position of the stars in these models, the gas distribution inside the wind bubble favors the expansion toward the upper right corner of the simulation.

The blow-out is more pronounced in this direction, the effect being larger if the SN explodes off-center (at the edge of the cluster).

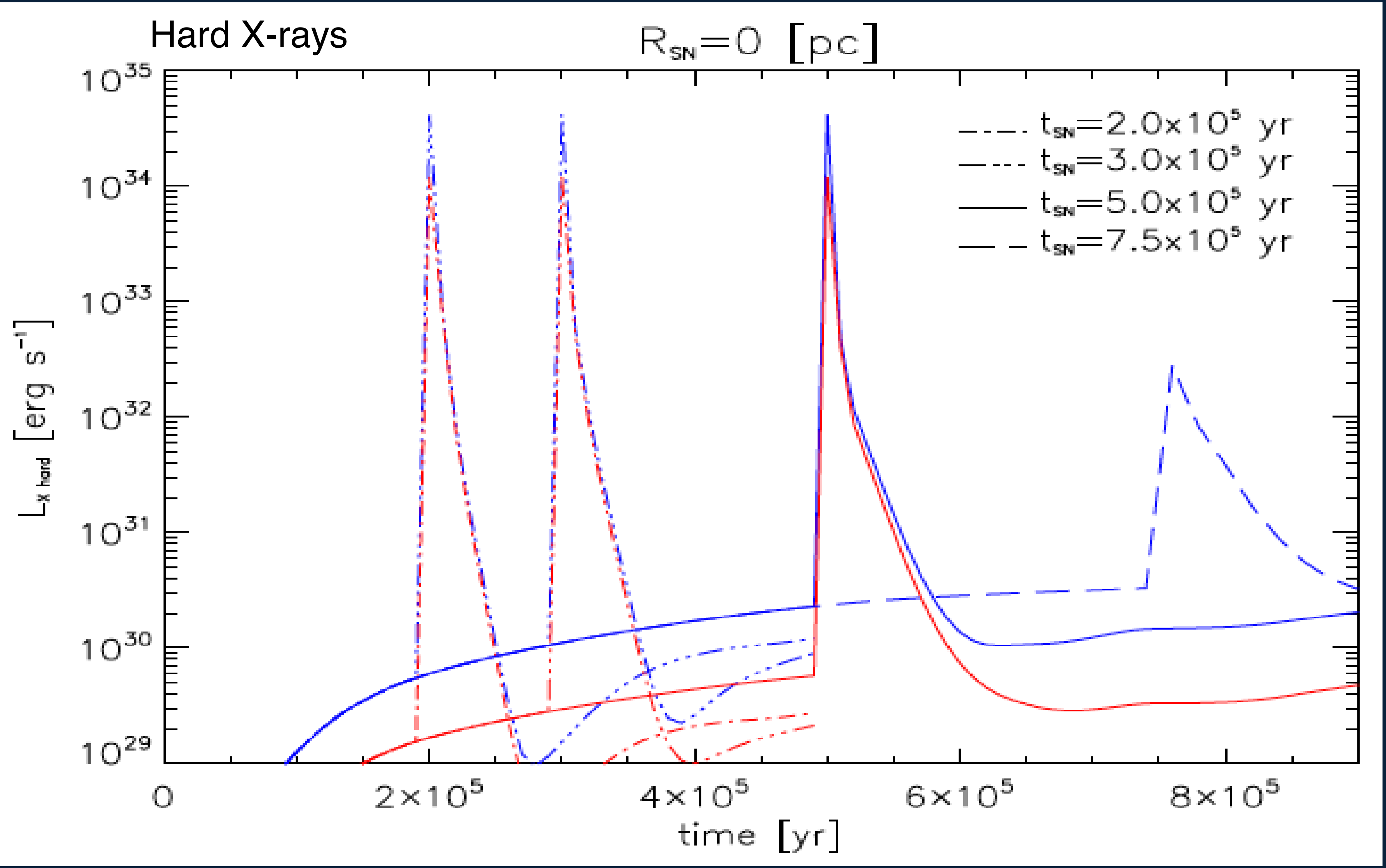


The Radius of the external shell

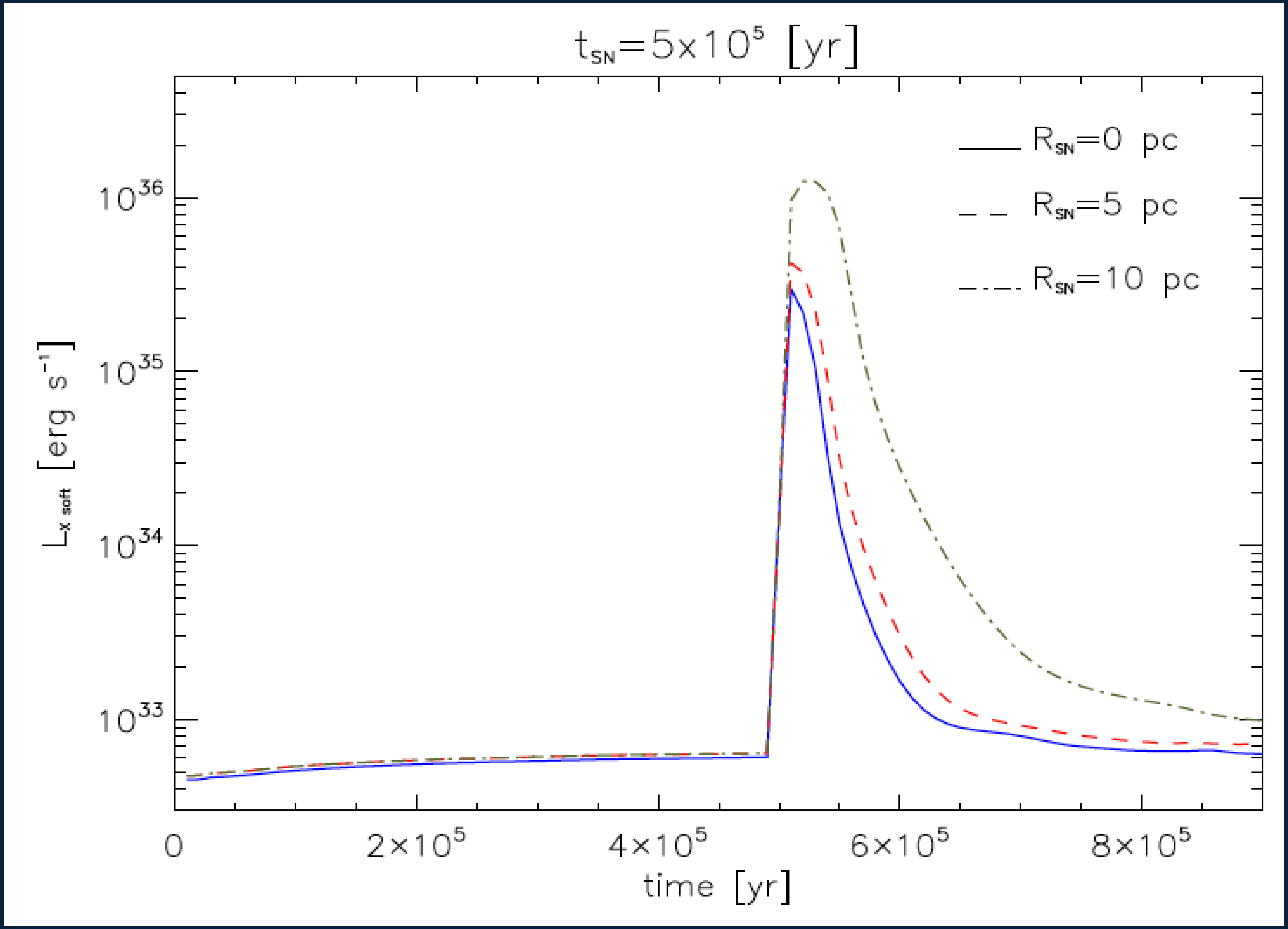


Considering the different metallicities

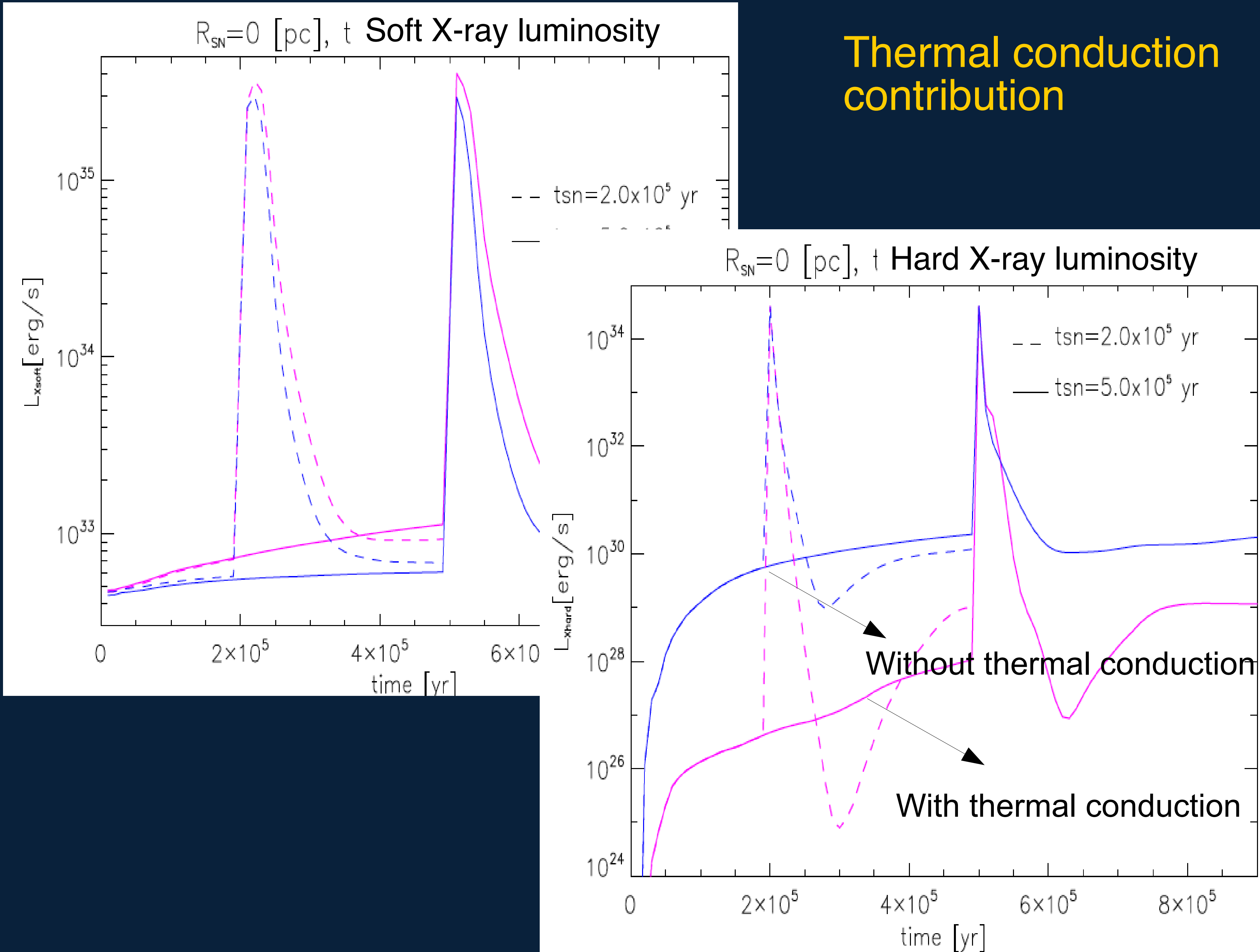
The metallicities only affect the hard X-ray luminosity:



On- and off-center supernovas



Thermal conduction contribution



Conclusions

- An important increase in the maximum soft X-ray luminosity is produced when the ejecta of an off-center SN collide with the dense shell of swept up interstellar medium left behind by the interaction with the cluster wind (10^{36} erg/s can be attained). A high expansion velocity of the shell is also produced. This scenario reproduces well the observations of high X-ray luminosity bubbles in the LMC

- In order to reproduce the shell radius we need to consider an no-homogeneous stellar distribution.

- Our models show that the effect of considering the metallicity of the winds and supernova remnant is negligible for the soft X-ray emission and for the expansion velocity of the shell but is important for the hard X-ray luminosity.

- The models with thermal conduction result in a noticeable contribution to total luminosity of soft X-rays (with an increase by factor ~1.25 with respect to models without conduction). For the hard X-rays, the thermal conduction has a larger effect on the total emission (by factor of 2.6). The f inal radius of the shells is 10% larger than in models without thermal conduction.