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X-ray emission from super star clusters

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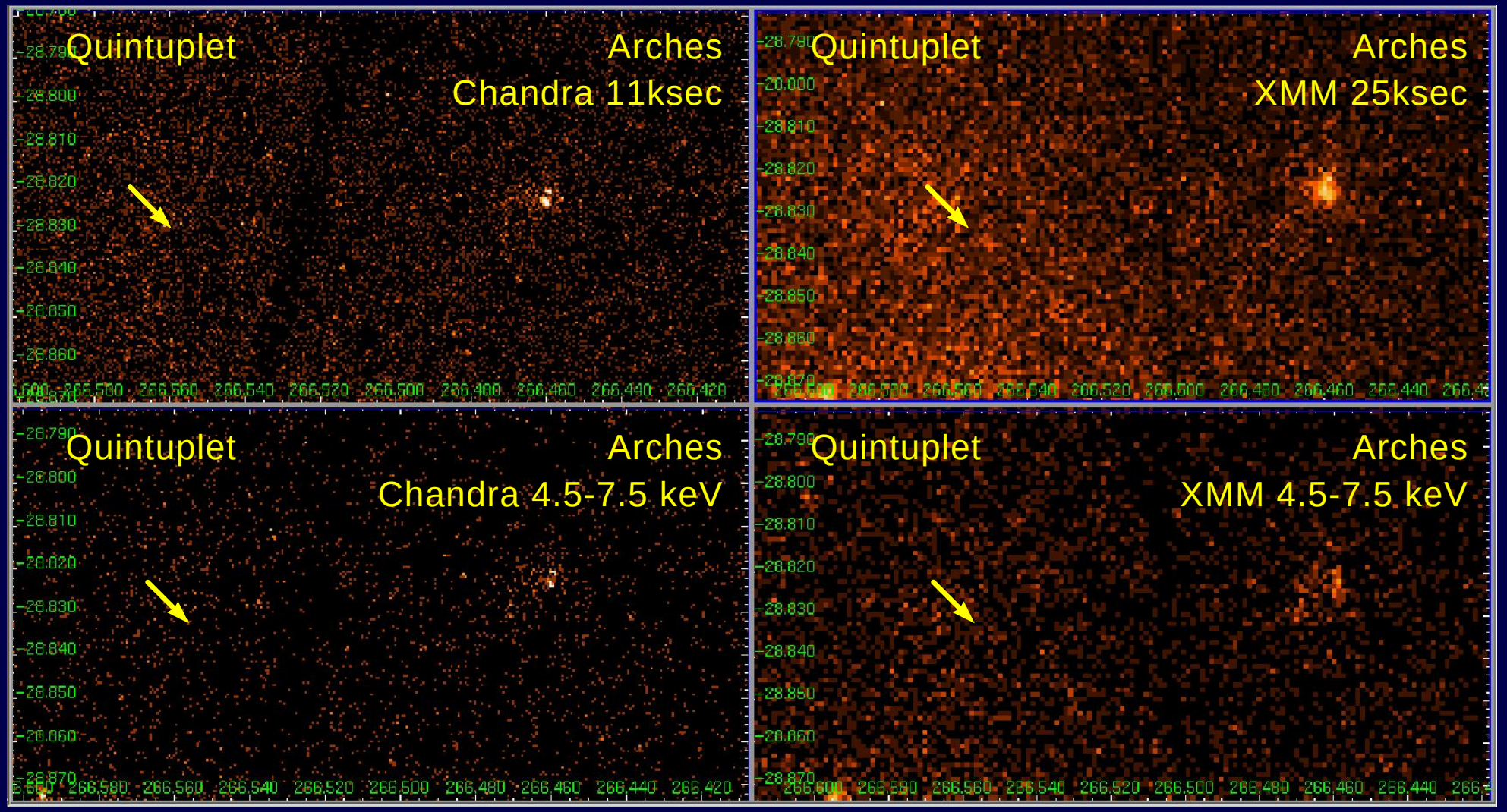
Introduction

- Super star clusters (SSC) are the most extreme cases of star formation.
- Stellar density up to $\rho_{\rm cl} \sim 10^5 M_\odot/{\rm pc}^3$. Mass from 10^4 to $10^6 M_\odot$.
- An SSC contains thousands of massive stars
- SSCs have a dramatic effect on the ISM, and in some cases intergalactic medium.
- Galactic examples: the Arches and the Quintuplet in the vicinity of the galactic center, and NGC3603.
- A few dozen SSCs are known in the Magellanic Clouds
- In *young* clusters (< 100 Myr old) no SN Ia occured yet.

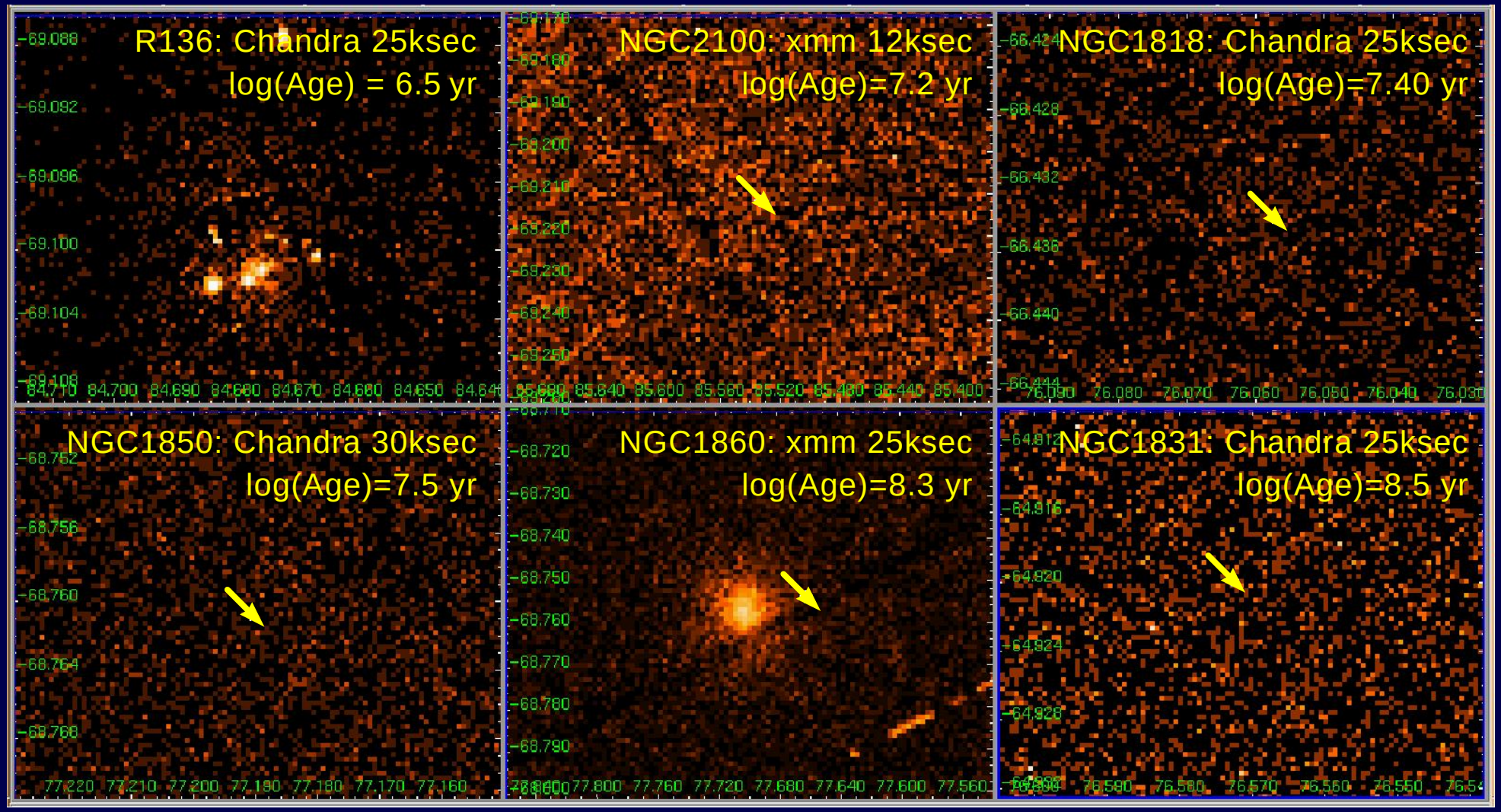
Chandra and XMM observations of Galactic Center clusters

- Arches: strong in X-rays, $M_{\rm cl} \sim 10^4 M_\odot$, 1-3 Myr old
- Quintuplet: weak in X-rays, $M_{\rm cl} \sim 10^4 M_\odot$, 3-5 Myr old



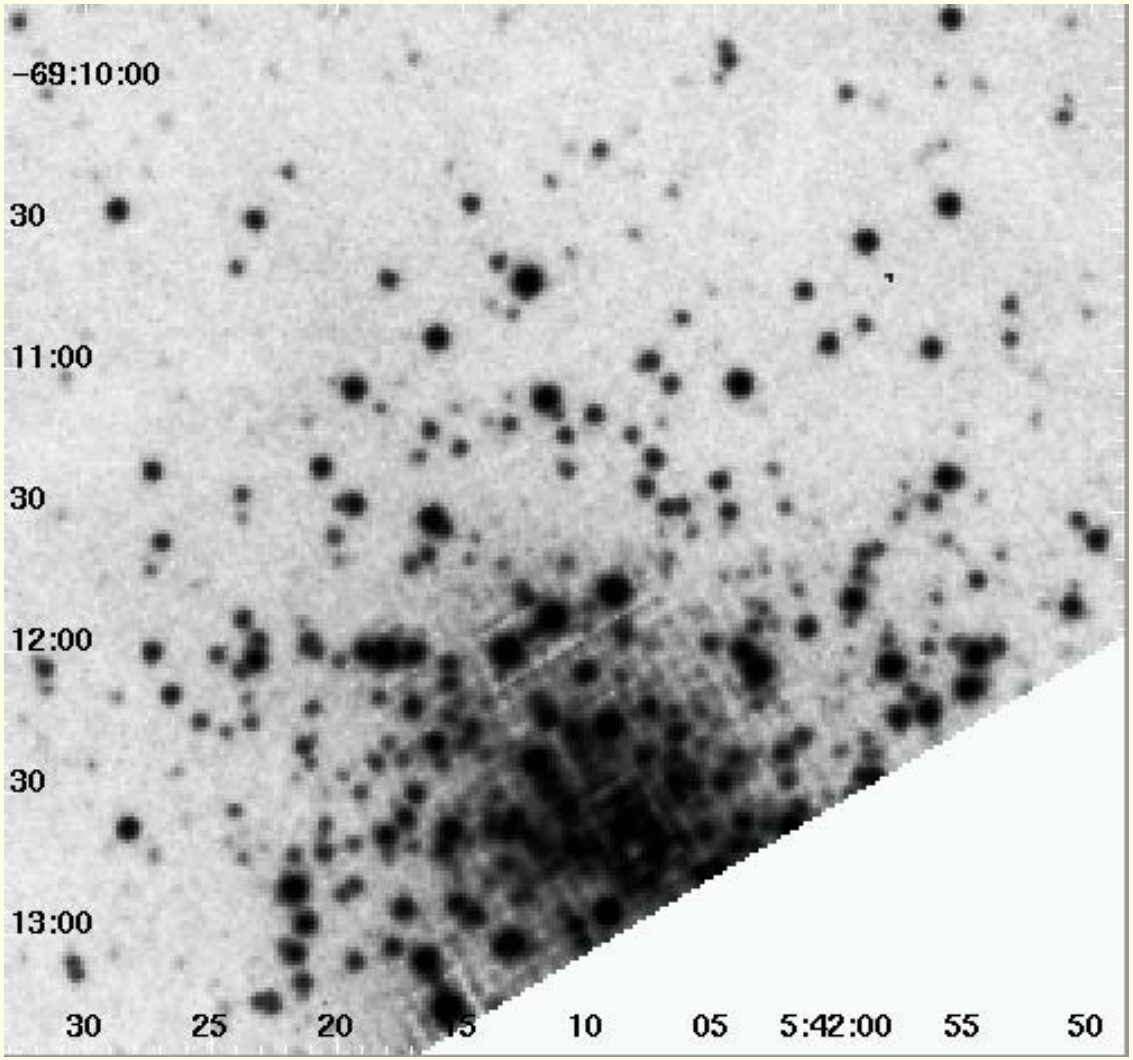
LMC clusters

A sample of LMC massive star clusters is observed with Chandra and XMM. The X-ray emission from the clusters differs significantly



Cluster ages from *Mackay & Gilmore (2003)*

XMM-Newton observation of NGC 2100

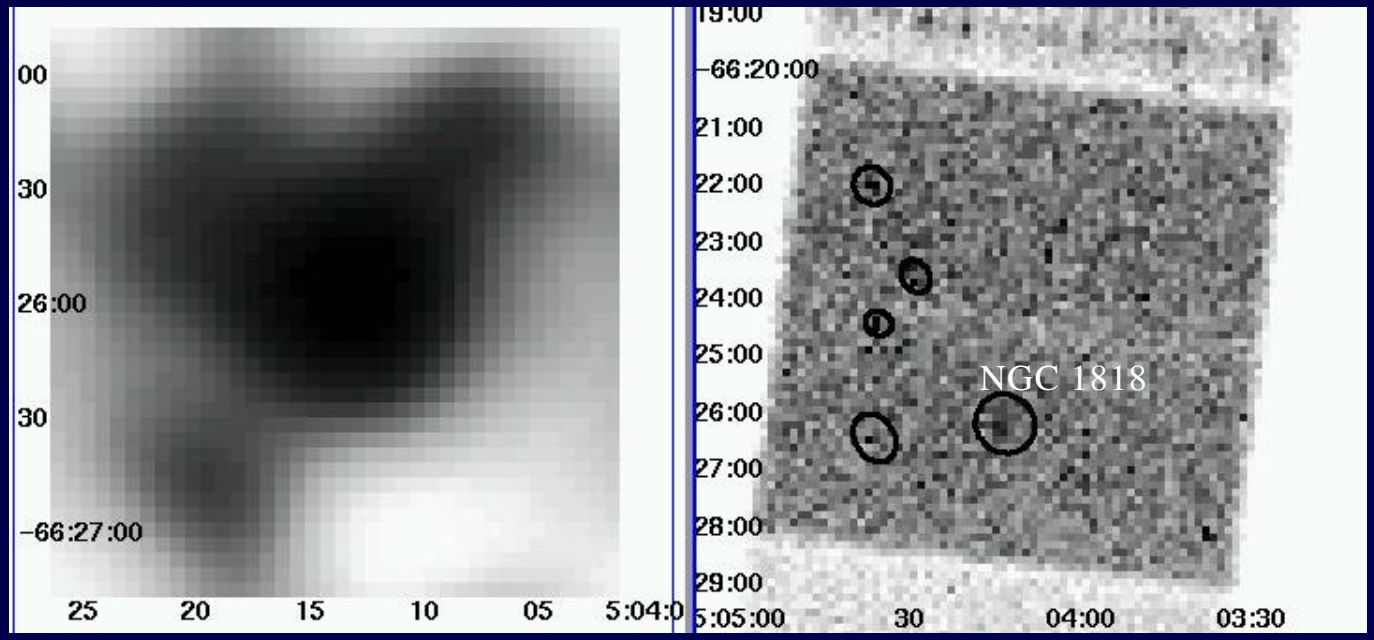


Age ≈ 10 Myr

$M_{\rm cl} \approx 2 \times 10^4 M_\odot$

NGC 2100 is clearly seen in this visual image (XMM OM camera), but not detected in X-rays

Chandra observation of NGC 1818



Age ≈ 25 Myr

$M_{\rm cl} \approx 10^4 M_\odot$

Right: Raw image; *Left:* Enlarged area with adaptively smoothed image.

- Weak source of apparently diffuse emission
- X- ray spectrum was extracted. $N_{\rm H}$ column density was constrained from a fitting of the spectrum of Seyfert I galaxy present in the FoV.
- NGC 1818 emission is fitted with multitemperature thermal plasma model.

Parameters of massive star clusters

Cluster	log Age	$\log M_{\rm cl}$	X-rays
R 136	6.5	4.40	yes, point-like
NGC 2100	7.2	4.31	non detect
NGC 1818	7.4	4.01	diffuse
NGC 1850	7.5	4.87	non detect
NGC 1860	8.3	3.90	detect
NGC 1831	8.5	4.71	non detect
NGC 3603	6.0	4.0	yes, diffuse
Arches	6.3	4.9	yes, point-like
Quintuplet	6.6	3.8	diffuse

Structural parameters of LMC clusters from Mackey and Gilmore (2003)
Data on NGC3603 from Sung et al. (2004) and Moffat et al. (2002)
Data on the Arches and Quintuplet from Figer et al.(1999), Law and Yusef-Zadeh (2004)

Properties of X-ray emission are different among star clusters of similar mass and stellar density but different age.

Modelling the X-ray emission from clusters

- Most massive young stellar clusters
- Instantaneous burst of star formation
- Solar metallicity
- Initial mass function $\xi(M) = M_0\, M^{-2.35}$
- Neglect cluster dynamics
- Only non-degenerate stars and stellar winds

Time dependend X-ray luminosity of a cluster:

$$L_{\rm X}(t) \;=\; L_{\rm X}^{\rm point}(t) \;+\; L_{\rm X}^{\rm diffuse}(t)$$

$$L_{\rm X}^{\rm point}(t) \;=\; \int_{M_{\rm min}}^{M_{\rm max}} \xi(M)\, L_{\rm X}(M,t)\, dM$$

$L_{\rm X}(M,t)$ is X-ray luminosity along isochrone of age t

$L_{\rm X}^{\rm diffuse}$ originates from mass loaded cluster wind

Mass and energy input

Mass input rate to the intracluster medium:

$$\dot{M} = \dot{M}_{*} + \dot{M}_{\mathrm{cool}}$$

- $\dot{M}_{*}$ = mass loss from massive stars and, later on, supernova explosions
- $\dot{M}_{\mathrm{cool}}$ = material ablated from protostellar (or planetary) disks (e.g. Kroupa and Bouvier 2003).

Energy input rate to the intracluster medium:

- Stellar winds and SN explosions supply kinetic energy to the cluster's ISM at a rate $\dot{E}$. Some fraction α of this kinetic energy input is thermalised, heating the gas to X-ray emitting temperatures.

Modelling the evolution of cluster wind emission

$\dot{M}(t)$ and $\dot{E}(t)$

- low for a very young cluster
- increase while stars are evolving
- reach their maximum at the beginning of SNe ignition
- decline in an old cluster, when massive stars are gone

Population synthesis → $\dot{M}$, $\dot{E}$ at any epoch

$\dot{M}(t)$, $\dot{E}(t)$ → hydrodynamic Eqns. → ρ, P, T → $L_{\mathrm{X}}(t)$

Hydrodynamic solution for cluster wind

The task: solve the HD equations for a cluster wind

Self-similar solutions for the mass loaded winds from star formation regions *(Chevalier and Clegg 1985: Nature 317, 44)*

Input parameters:

- Mass input from stellar winds and SNe → $\dot{M}_*(t)$
- Mass input from planetary discs et cet. → $\dot{M}_{\rm cool}(t)$
- Total mass input $\dot{M}(t) = \dot{M}_*(t) + \dot{M}_{\rm cool}(t)$
- Mechanical energy input $\dot{E}(t)$
- Fraction $\alpha\dot{E}(t)$ is thermalized
- Cluster radius $R(t)$

HD equations solved for:

- $u(r)$ = cluster wind velocity
- $P(r)$ = pressure
- $\rho(r)$ = density

Cluster winds are *self-similar*: scalable to particular sets of parameters $(\dot{M}), \alpha\dot{E}, R$

Self-similar solutions

X – ray luminosity of cluster wind $L_{\rm X}(t) = \Lambda(T_{\rm X})\,{\rm EM}(t)$

Emission measure ${\rm EM}(t) = \int_{\rm V} \frac{\rho^2}{\mu_{\rm i}\mu_{\rm e} m_{\rm H}^2}\, dV$

Temperature of X – ray emitting gas $T_{\rm X}(t) = \frac{m_{\rm H}\mu}{k}\frac{P}{\rho}$

From scaling laws of self-similar solutions →

$$ {\rm EM}(t) \propto \frac{4\pi}{\mu_{\rm i}\mu_{\rm e} m_{\rm H}^2} \cdot \frac{\dot{M}^3}{\alpha\,\dot{E}\,R} $$

$$ T_{\rm X}(t) \propto \frac{\mu_{\rm i} m_{\rm H}}{k} \cdot \frac{\alpha\,\dot{E}}{\dot{M}} $$

where $\mu, \alpha, \dot{M}, \dot{E}$ are functions of time (on evolutionary timescale).

Population synthesis model

$\dot{M}(t)$, $\dot{E}(t)$ from Starburst99 model using appropriate metalicities *(Leitherer et al. 1999)*

Starburst99 includes:

- Inputs from stellar winds and SNe
- Evolution models from Geneva group
- Comprehensive stellar atmosphere models
- Only single stars
- Parameters: total mass $M = 10^6 M_\odot$, $M_{\rm star} = 1 \ldots 100\ M_\odot$

Accounting for binaries

(1) Majority of massive stars are binaries

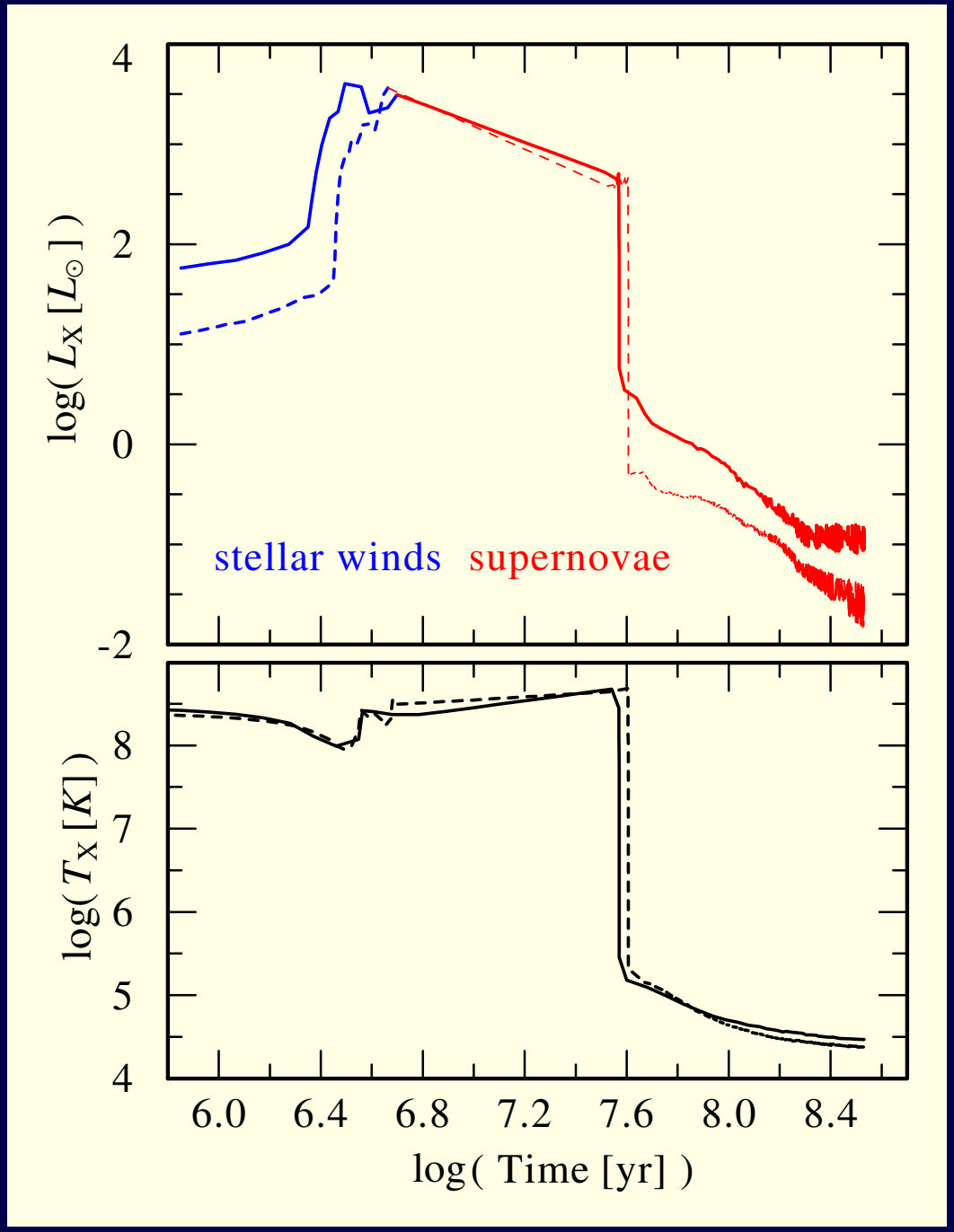
(2) Mass-loss is sum of mass-losses from its components

(3) Stellar winds collide

(4) Part of the wind kinetic energy is radiated away

(5) Accounted for by "thermalisation efficiency" α

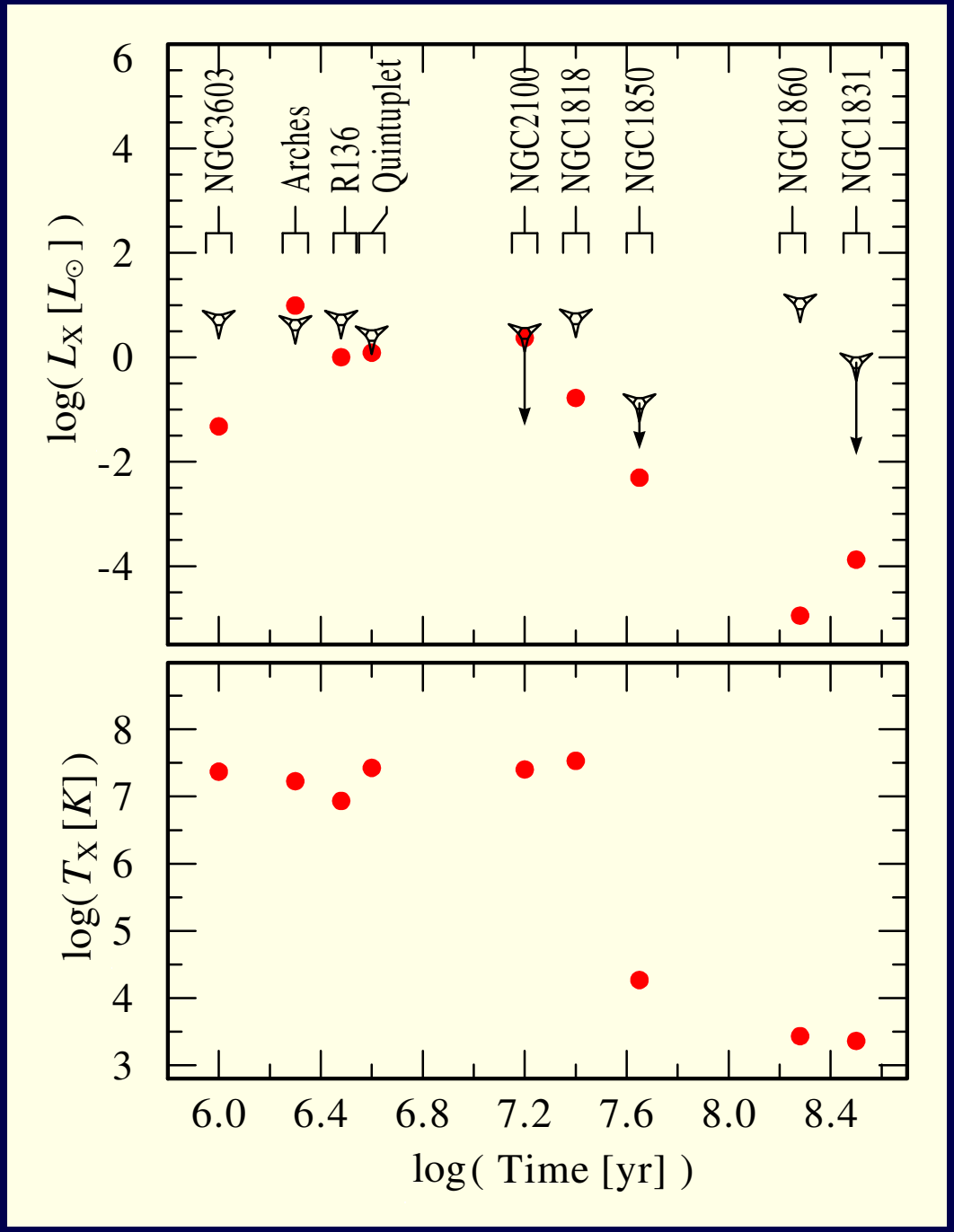
Diffuse X-ray emission from a model cluster ($M_{\rm cl} = 10^6 M_\odot$)



Luminosity of cluster wind versus cluster age for solar metallicity (solid line) and LMC metallicity (dashed line). The epochs when mass and energy input is dominated a) by stellar winds and b) by supernova explosions are indicated.

Temperature as function of the cluster age. Note that after ≈ 40 Myr of cluster evolution, the temperature becomes too low for X-ray production.

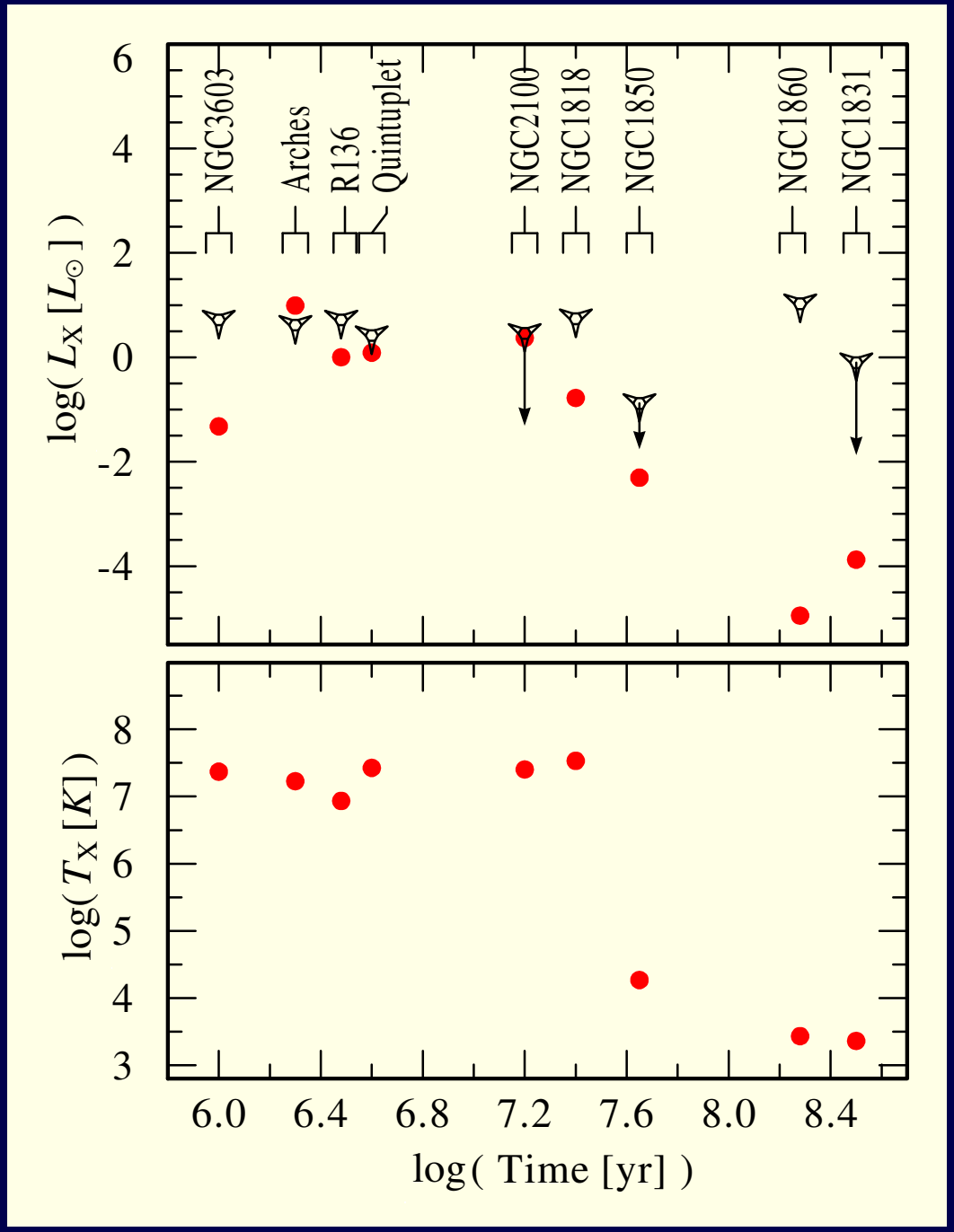
Comparison with observations



Comparison of the observed diffuse X-ray luminosities (diamonds) with individual cluster models. Circles are the model values assuming $\alpha = 0.1$ and $\dot{M}_{\rm cool} = 0.05\dot{M}_*$

Temperature infered from the individual cluster wind models. Estimates of the temperature from observaitons are not reliable.

Discrepancies between model and observations



- The observed diffuse emission cannot be attributed to the cluster wind alone.
- The estimates of the cluster ages are uncertain. The predicted X-ray luminosity is very sensitive to the cluster age.
- It is possible to fit L_X for each cluster by choosing α and $\dot{M}_{\rm cool}$. Given the quality of data this is speculative.
- NGC 1818 and 1860 - SNR?
- NGC 3603 - unresolved low-mass stars (Moffat et al. 2002)?

Stellar sources

Consider cluster of M = 10^6 $M_\odot$

In order to compute X-ray luminosity:

1. Calculate number of stars in each mass bin using IMF ($\alpha = -2.35$)

2. The duration of life for a star of given mass is from evolutionary tracks

3. Make use of mass-luminosity relation in the form

$$\frac{L_{\mathrm{MS}}}{L_\odot} = \begin{cases} 81\left(\frac{M}{M_\odot}\right)^{2.14} & M > 20M_\odot \\ 1.78\left(\frac{M}{M_\odot}\right)^{3.5} & 2 < M < 20M_\odot \\ 0.75\left(\frac{M}{M_\odot}\right)^{4.8} & M < 2M_\odot \end{cases}$$

4. Use correlation between X-ray and bolometric luminosity, thus between X-ray luminosity and stellar mass.

Low mass stars

Study of Orion Nebular Cluster *(Flaccomio et al. 2003)*

Low-mass stars: $M_* = 0.5 \ldots 1\ M_\odot$

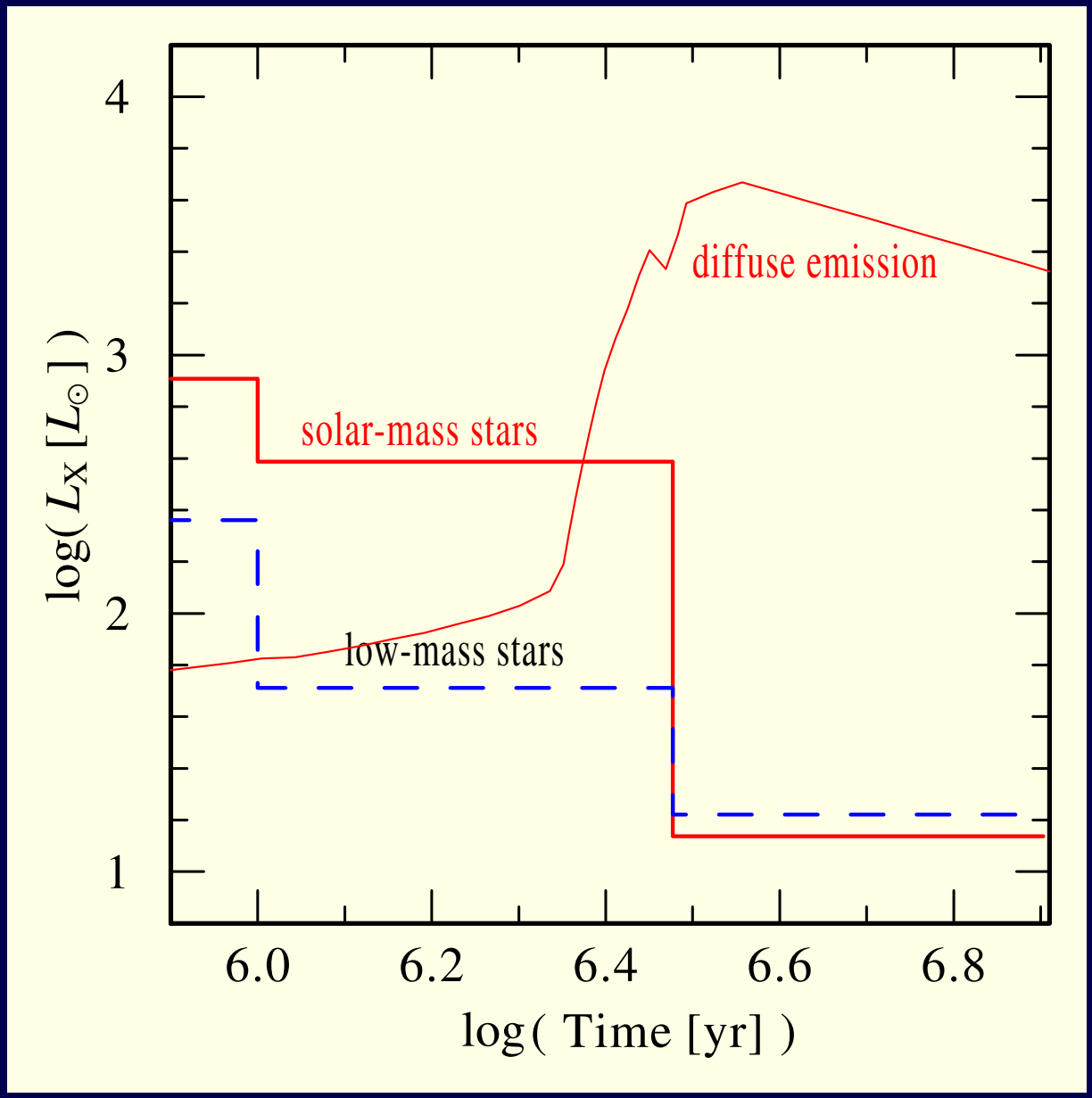
log (age) [Myr]	$\log(\langle L_X \rangle)$ [erg/s]
4.5 - 5.5	< 30.5
5.5 - 6.0	30.7
6.0 - 6.5	30.0
6.5 - 7.5	29.5

Solar-mass stars: $M_* = 1 \ldots 3\ M_\odot$

log (age) [Myr]	$\log(\langle L_X \rangle)$ [erg/s]
4.5 - 5.5	31.6
5.5 - 6.0	31.4
6.0 - 6.5	31.2
6.5 - 7.5	29.7

- Significant correlation of L_X with mass and age is observed for stars with low masses $0.1 < M_* < 3$
- For stars with masses between 3 and 10 $M_\odot$, X-ray luminosity drops dramatically. This is effect of the disappearance of convective envelope for stars more massive then 3 $M_\odot$.
- No correlation with rotation. Activity is saturated

X-rays from low- and solar-mass stars



Cluster $M_{cl} = 10^6 M_\odot$

Cumulative X-ray luminosity of low- and solar-mass stars

- For youngest stellar clusters the dominant point sources of X-rays are low-mass stars.
- Weak but very numerous X-ray sources: those objects are difficult to spatially resolve.

Stellar sources of X-ray emisison

- In young clusters (e.g. NGC 3603 ~ 1 Myr old), low-mass stars are still X-ray active
- Collective X-ray luminosity of low-mass stars in NGC 3603: $\sim 10^{34}\,\mathrm{erg\,s^{-1}}$.
- Matches the observed level of diffuse X-ray emission very well
- In older clusters, (e.g. the Quintuplet or R 136),
  - low-mass stars are less active
  - massive stars $M_* > 10\,M_\odot$ main sources of X-rays

X-ray generation in stellar winds

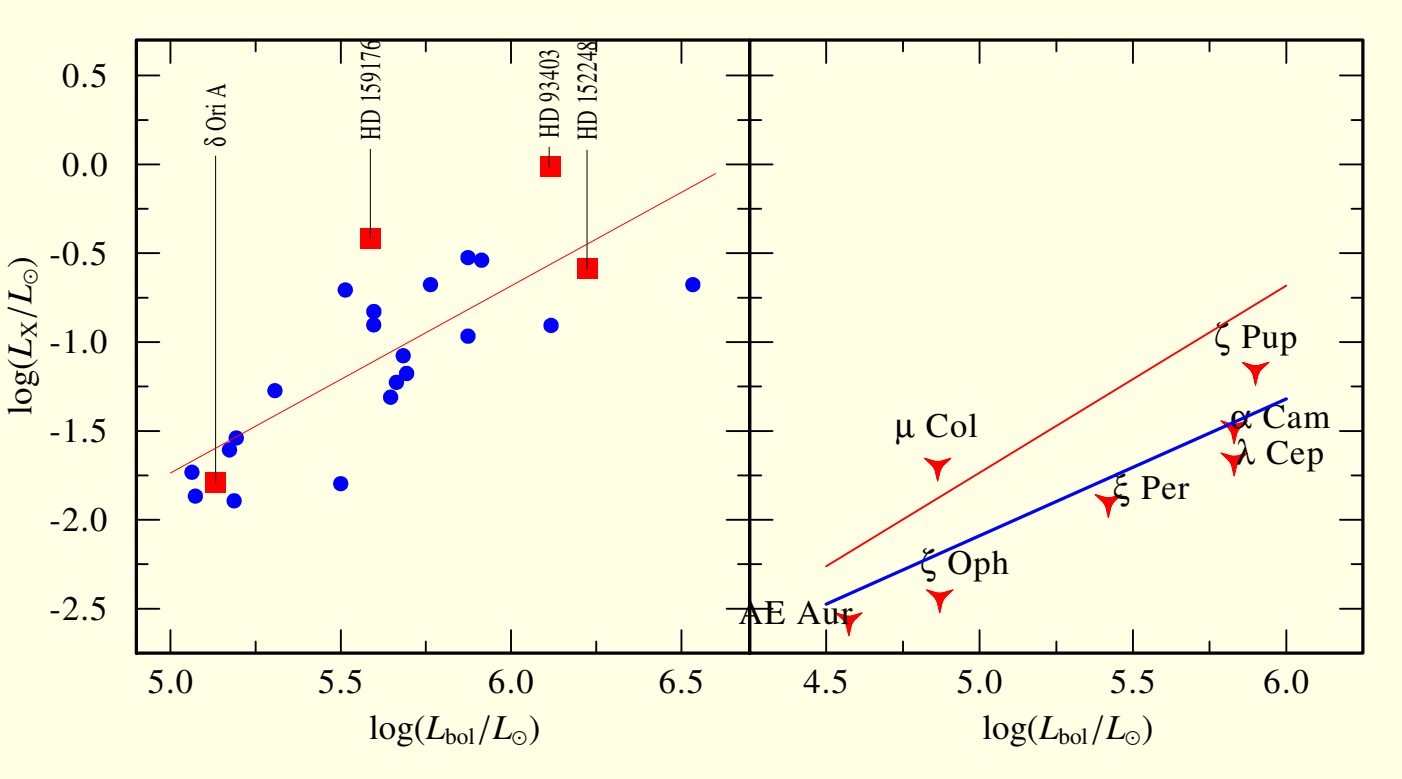
- Winds are radiatively driven
- Driving mechanism intrinsically instable; leads to the generation of strong shocks.
- Shocked plasma is heated till X-ray emitting temperatures (Feldmeier 1997).

Stellar wind sources

- **Evolution of massive stars**
  - OB star on main sequence $\dot{M}_{\rm O} \sim 10^{-6..-7}\, M_\odot\, {\rm yr}^{-1}$
  - Significant mass loss (stellar wind, LBV outbursts, mass transfer in a close binary)
  - Wolf-Rayet phase: $\dot{M}_{\rm WR} \sim 10^{-5..-6}\, M_\odot\, {\rm yr}^{-1}$
  - WN phase, revealing CNO-burning products at its surface
  - WC phase, revealing the He-burning products

- **Correlation between $L_{\rm X}$ and $L_{\rm bol}$**
  - Based on Rosat All- Sky Survey: $L_{\rm X} \approx 10^{-7}\, L_{\rm bol}$ (Berghöfer et al. 1997)
  - Explained by invoking the wind-momentum luminosity relation (Owocki and Cohen 1999; Kudritzki and Puls 2000)
  - Which $L_{\rm X}$ for binaries ?

$L_X \propto L_{bol}$ correlation for O stars

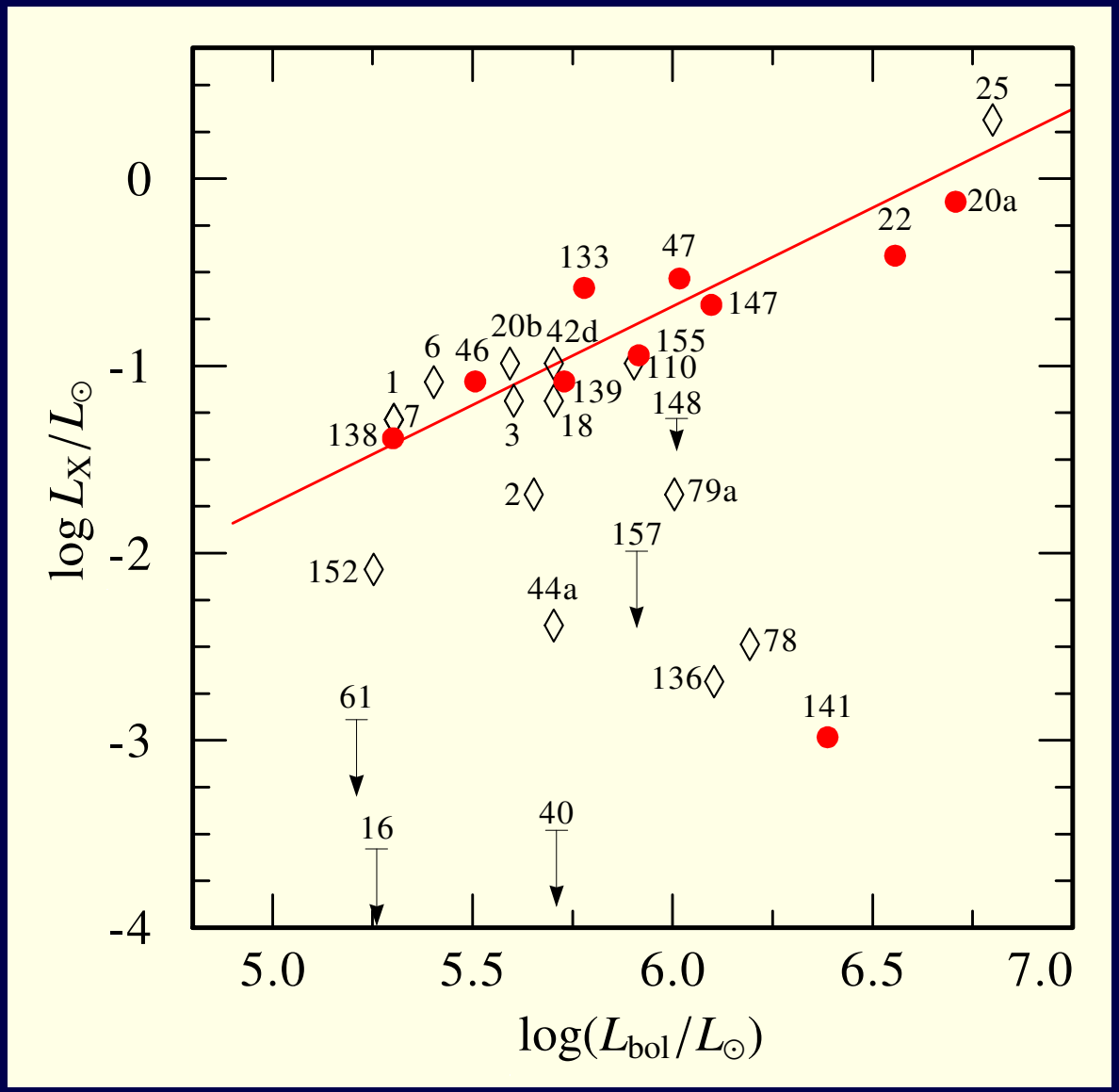


Rosat pointings, or XMM/Chandra observations.
O+O spectroscopic binaries (left)
Single runaway O stars (right)

- $\log L_X = 1.05 \log L_{bol} - 7.00$ for binaries

We may apply the correlation $\log L_X \approx \log L_{bol} - 7$ for O stars, disregarding whether they are single or binaries.

X-ray observations of single WN stars



Diamonds: putatively single WN stars. No correlation is seen.

Circles: WN spectroscopic binaries. Correlation is similar to the one for O type binaries

Arrows: upper limits for non detections.

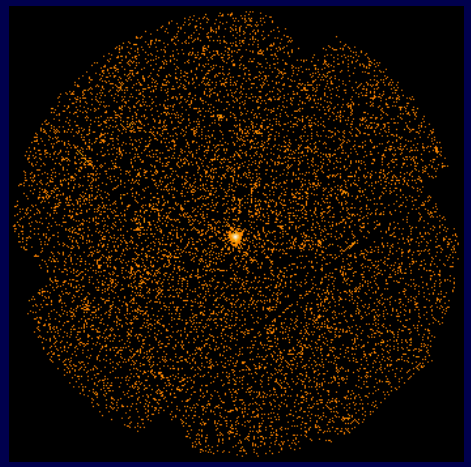
No WN8 type star was ever observed in X-rays.

WN8: Non-radiatively driven stellar winds? Fast rotators? Thorn-Zhitkov objects? Good candidates for GRB progenitors?

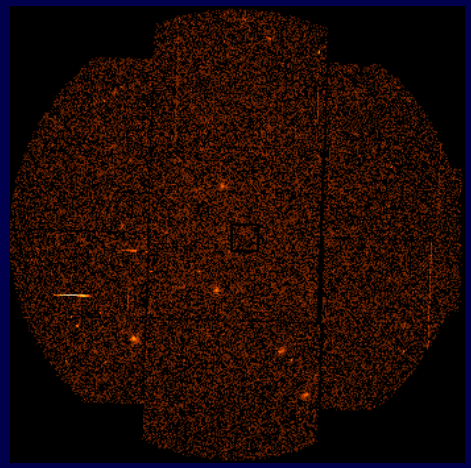
X-ray observations of single WC stars

- There has not been ever any confident X-ray detection of a single WC star *(Oskinova et al. 2003)*
- Only 20% of binaries containing WC stars are X-ray sources
- In general, WR stars are not significant X-ray emitters and can be ignored when addressing emission from rich stellar clusters
- Observations with XMM-Newton:

ζ Pup (O-type)

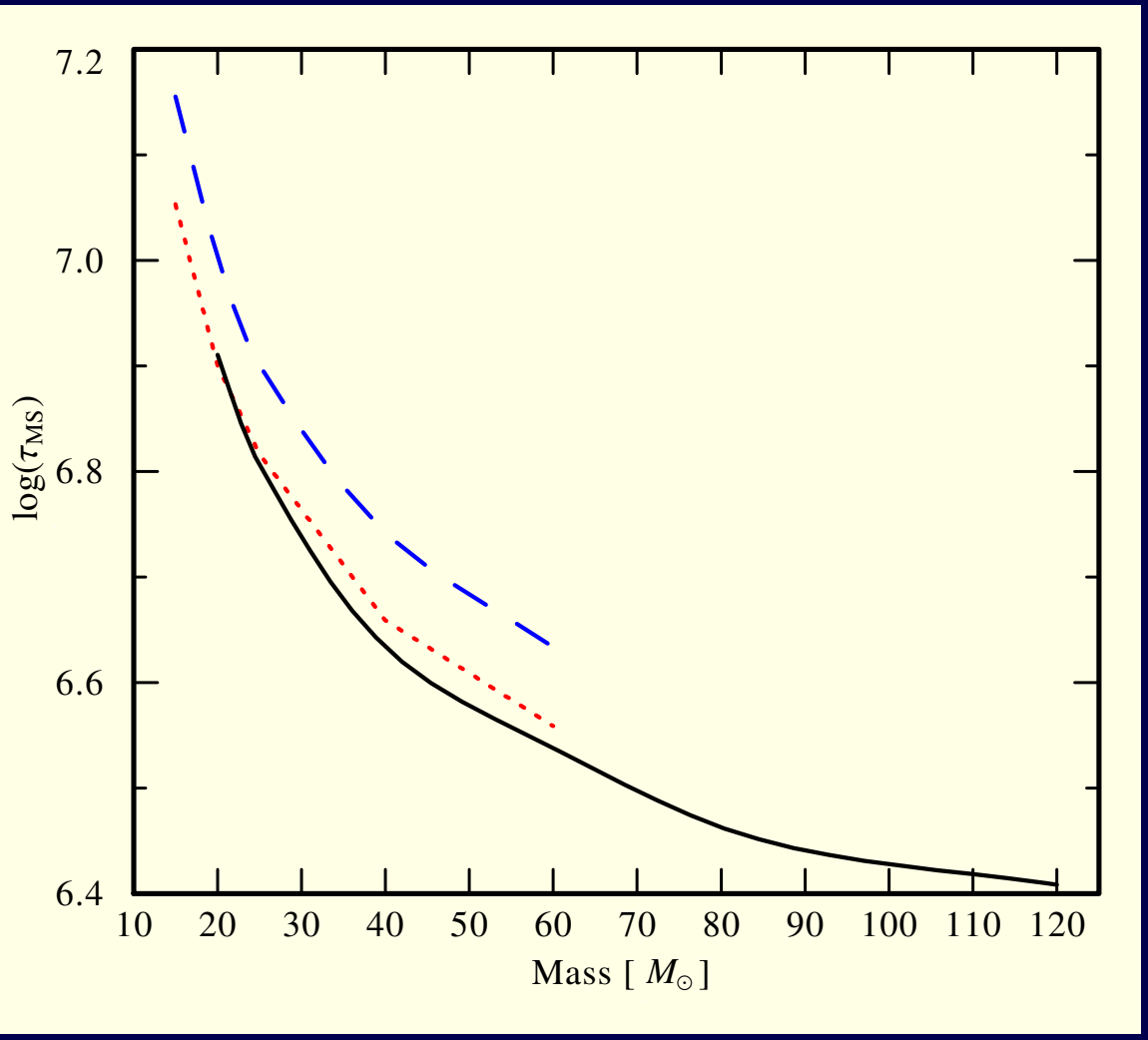


WR 1 (WN)



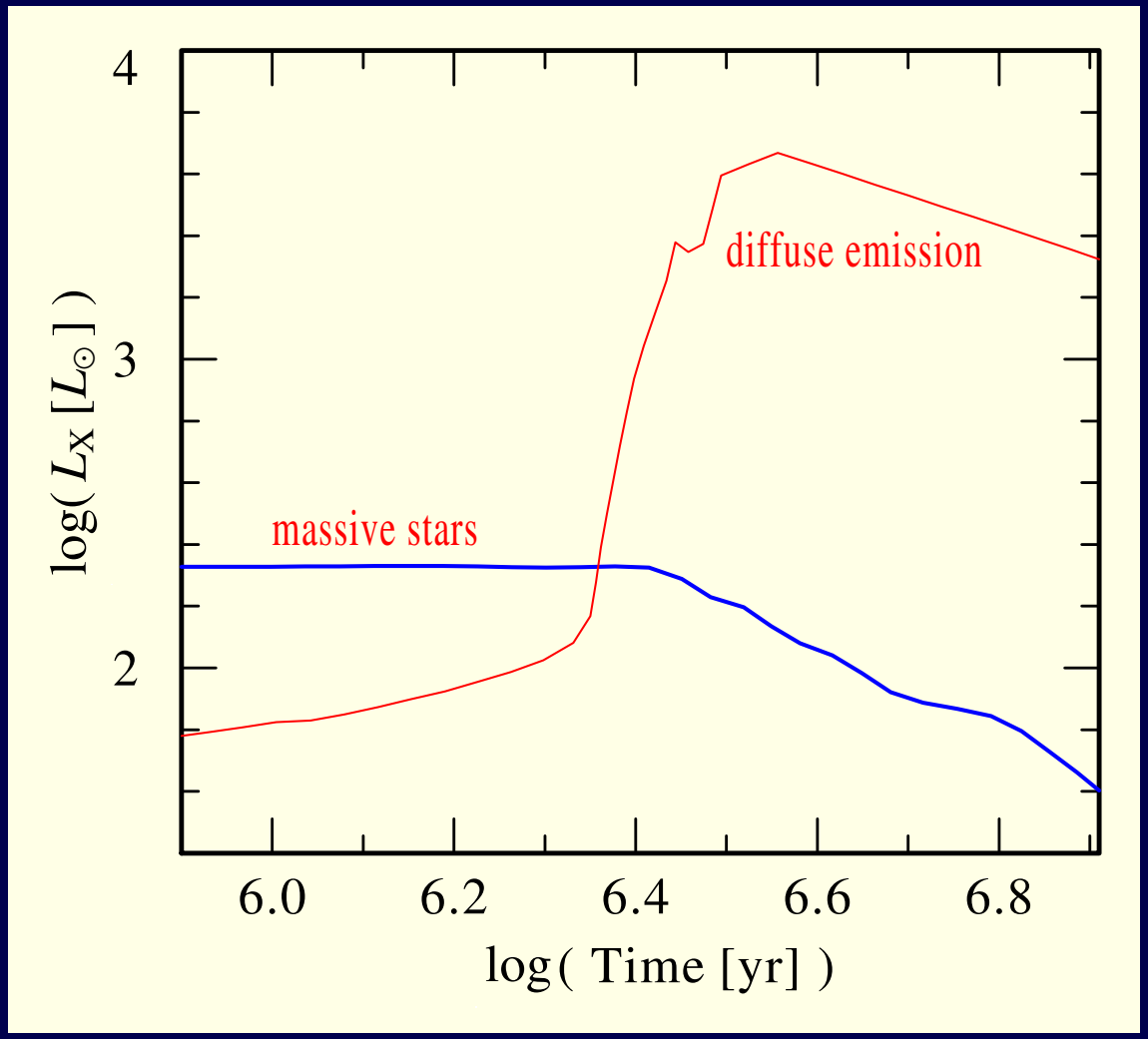
WR 114 (WC)

Lifetime in H-burning stage



The dashed line represents the evolutionary models with rotation $v_{\rm rot} = 300 {\rm km\,s^{-1}}$ and thin solid line is for the models without rotation. The thick line (Massey 2003) used in this work.

X-rays from massive stars



Evolution of the cumulative X- ray luminosity of massive stars $M > 8M_\odot$ in the $10^6 M_\odot$ cluster.

Strong decline after ≈ 2 Myr, when the most massive stars end their lives by core collapse.

The cluster wind is fed by massive stars: $L_{\rm X}^{\rm diff} \propto \dot{M}^3 \propto N_*^3$. The collective stellar luminosity $L_{\rm X}^* \propto N_*$. Ratio of cluster wind to stellar emission is smaller for less massive clusters.

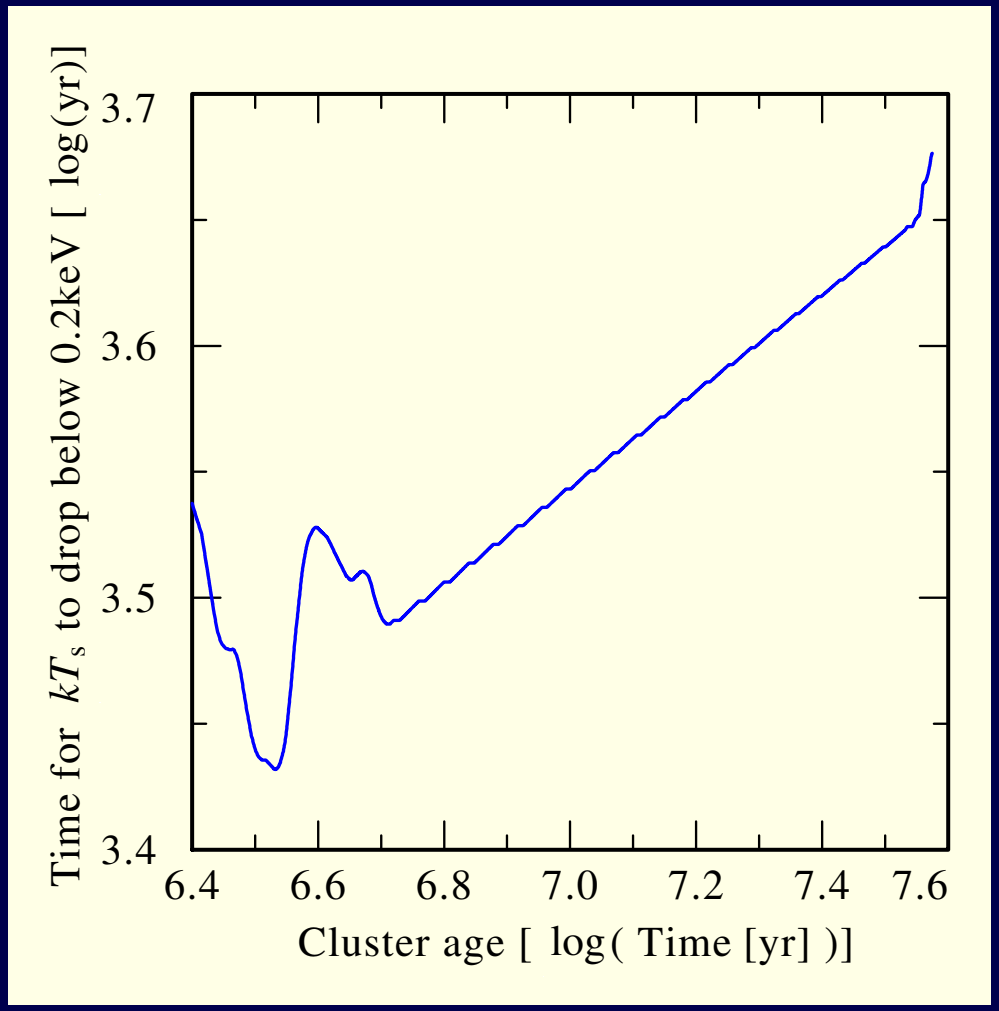
X-ray emision from young supernova remnants

- The highly supersonic expansion of the envelope shocks the ISM. The expansion is uniform, with $v \propto r$.
  Time=few $\times 10^2$ years. $\times 10^2$ years.
- A complete sample of recent nearby SNe has been observed with ROSAT (Bregman et al. 2003). Probability of a SN being brighter then $6 \times 10^{38} \mathrm{erg/s}$ is less than to 50%
- The rate of bright SNR in a $10^6 M_\odot$ cluster older than 3 Myr is $\sim 10^{-4}$ per year. We may observe such SNR in up to 10 per cent of the young clsuters.
- The young SN remnants are likely to totally dominate both, point and diffuse X-ray emisison of a stellar cluster

Sedov-Taylor solution

- A few hundreds years after the SN, the swept-up mass becomes greater than the ejected mass: adiabatic blast-wave (Sedov-Taylor solution).
- The postshock temperature $kT_{\rm s} \propto (E/n_0)^{1/5} t^{-6/5}$, where E is the SN explosion energy, n_0 is the number density of the preshock ISM, and t is the SNR age (Borkowski et al. 2001).
- Emission measure of the remnant: EM $\propto n_0^2\, t^{6/5}$. The emissivity depends on $T_{\rm s}$, electron temperature, abundances, and the ionisation state of the gas.
- Cluster wind solution → Number density of the preshock ISM n_0 → SNR spectrum and n_0 → SNR spectrum and cooling time.

Cooling time for a SNR



Time for the shock temperature kT_s of a SNR in Sedov-Tayler phase to drop below 0.2 keV, as function of the model cluster age. $T_e = 0.5T_s$ and $E = 10^{51}\,\mathrm{erg\,s^{-1}}$.

The remnant cools at $< 10^4$ years. During this time the remnant luminosity is comparable to the luminosity of the whole cluster, and its radius comparable with the cluster radius.

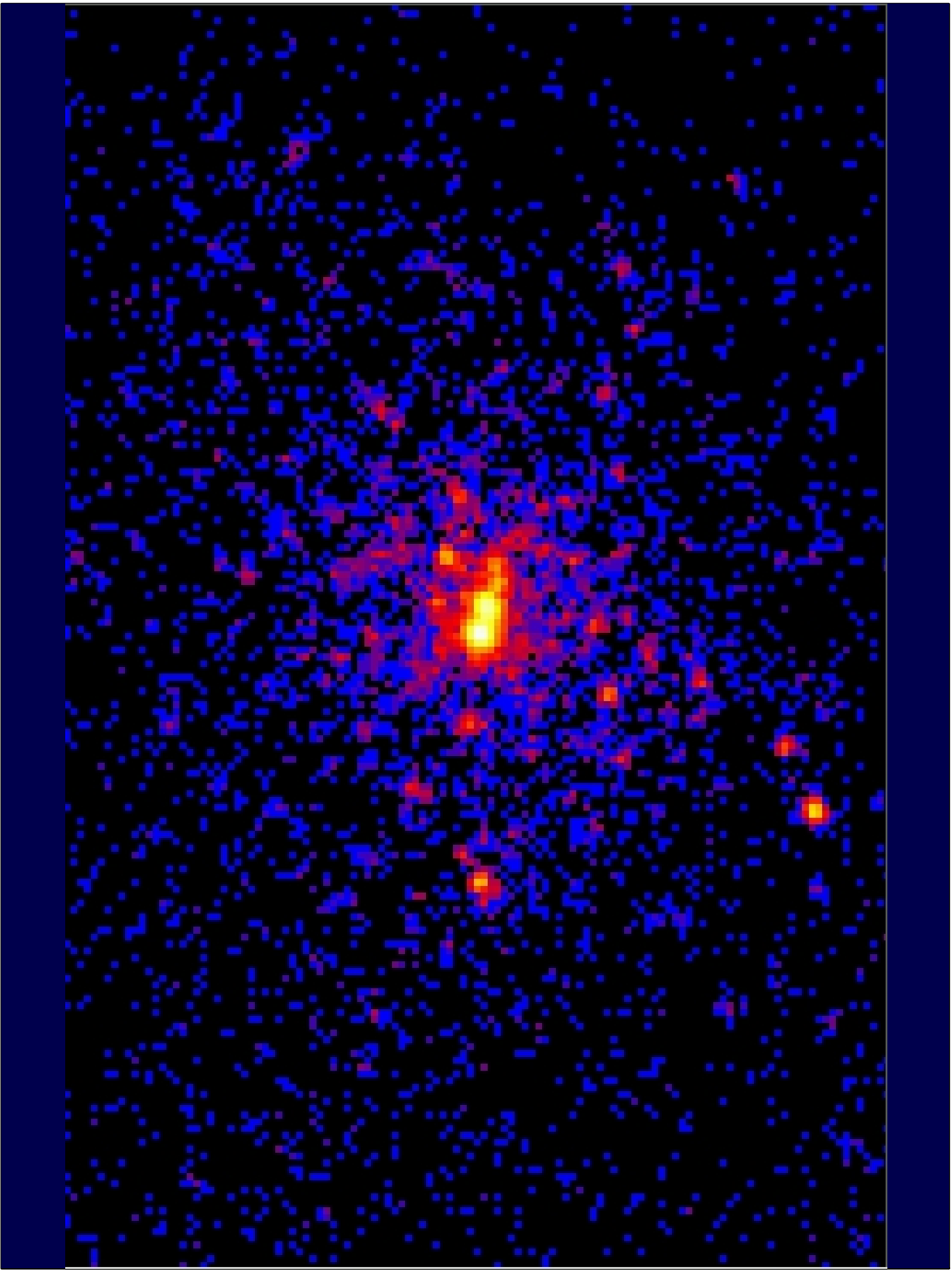
It is plausible to explain the enhanced level of diffuse X-ray emission in the LMC clusters NGC 1860 and NGC 1831 by the presence of an old SNR

High-Mass X-ray Binaries.

- After ≈ 2 Myr of evolution the most massive stars end their lives by a core collapse and a supernova explosion. Black holes are formed from stars with initial masses above $\sim 21 M_{\odot}$, while neutron stars result from stars with lower masses (Woosley et al. 2002).
- Population synthesis studies predict that $\sim 2-5\%$ of all OB stars must produce HMXB (e.g. Helfand and Moran 2001). The lifetime of a HMXB is limited by the nuclear time-scale of the optical companion $(\sim 20$ Myr).
- HMXB = point source with luminosity $> 10^{35} \mathrm{erg\ s^{-1}}$
- Five LMC clusters in our sample are expected to have 1-3 HMXB. None of them shows X-ray point sources which are bright enough
- There is disagrement between predicted and observed number of HMXB

High-Mass X-ray Binaries.

- Recent Chandra observations of interacting and starburst galaxies confirmed the decrepancy (Kalogera et al. 2005)
- The point sources do not seem to coincide with the SSC stellar that can easily form systems capable of such emission.
- What is wrong?
  - Supernovae kicks estimates?
  - XMHB ejection from star clusters?
  - Clusters dynamics?
  - Massive star evolution scenario?

Conclusions

- X-ray emission of cluster wind is governed by stellar evolution. Low for young clusters it rises steeply when massive stars evolve to WR stage, characterized by energetic stellar winds.
- Powered further by supernova explosions, the diffuse emission of a cluster wind is nearly constant during about 40 Myr. When the supernova rate drops, the cluster wind ceases.
- X-ray active low-mass stars are the dominant sources of X- rays in clusters younger than ≈ 2 Myr. Evolved massive stars are insignificant sources of X-rays.
- SNR may become a dominant source of X-ray emission, albeit for a relatively short time.
- There is disagrement between predicted and observed number of HMXB