Impact of in-source production of Boron on the B/C ratio in cosmic rays

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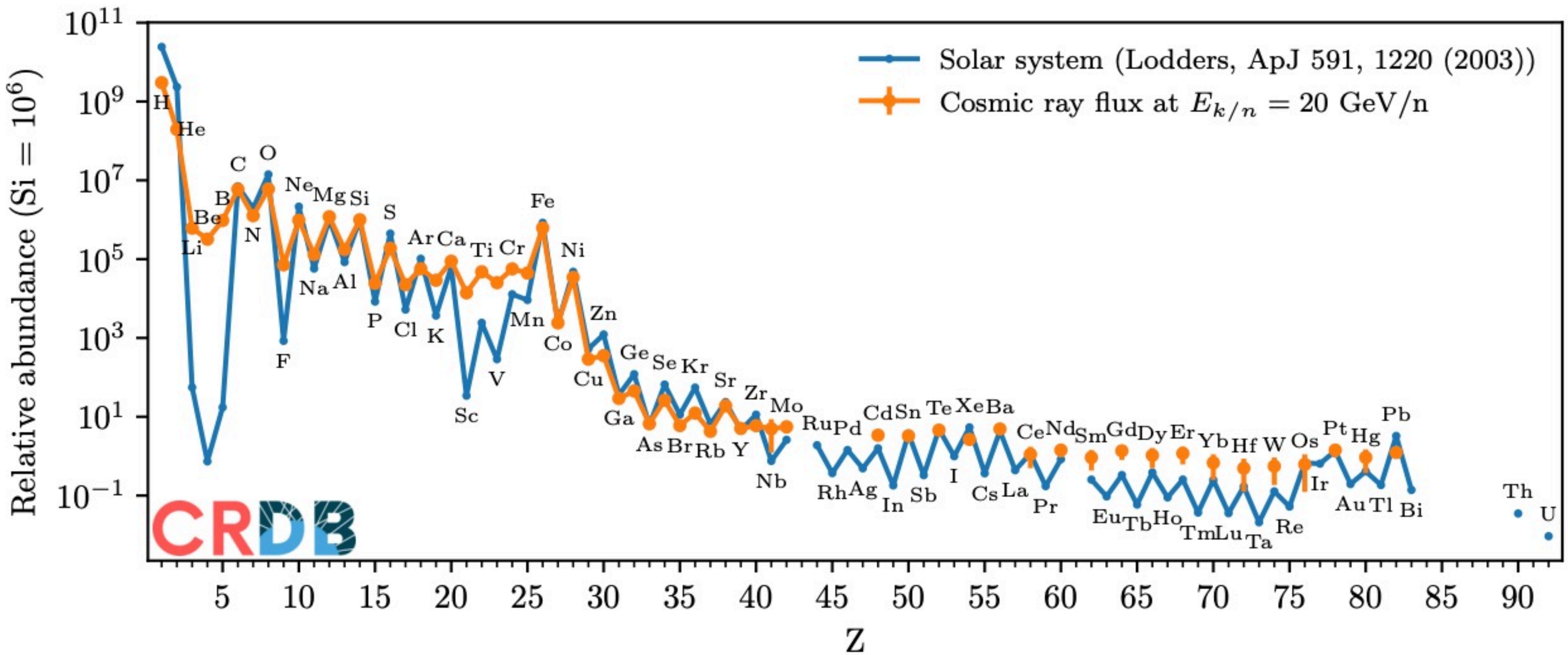
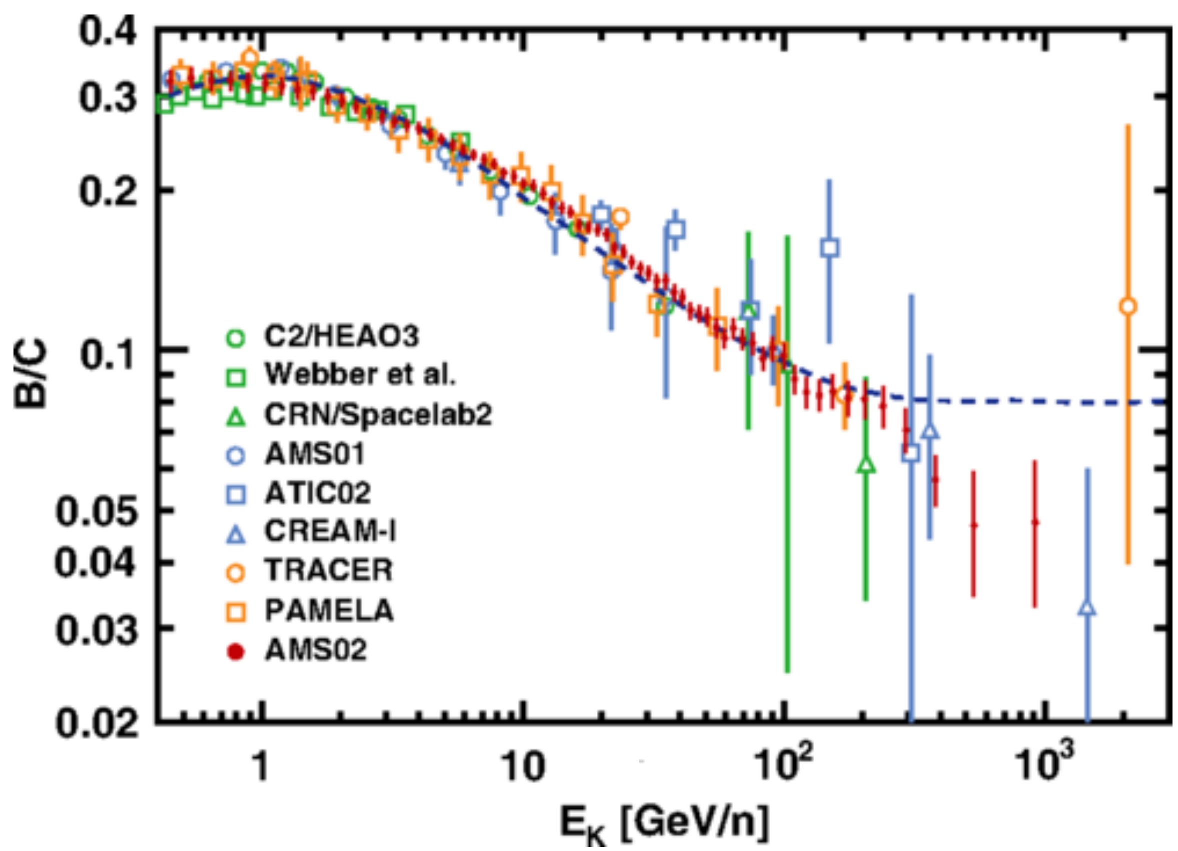
Composition



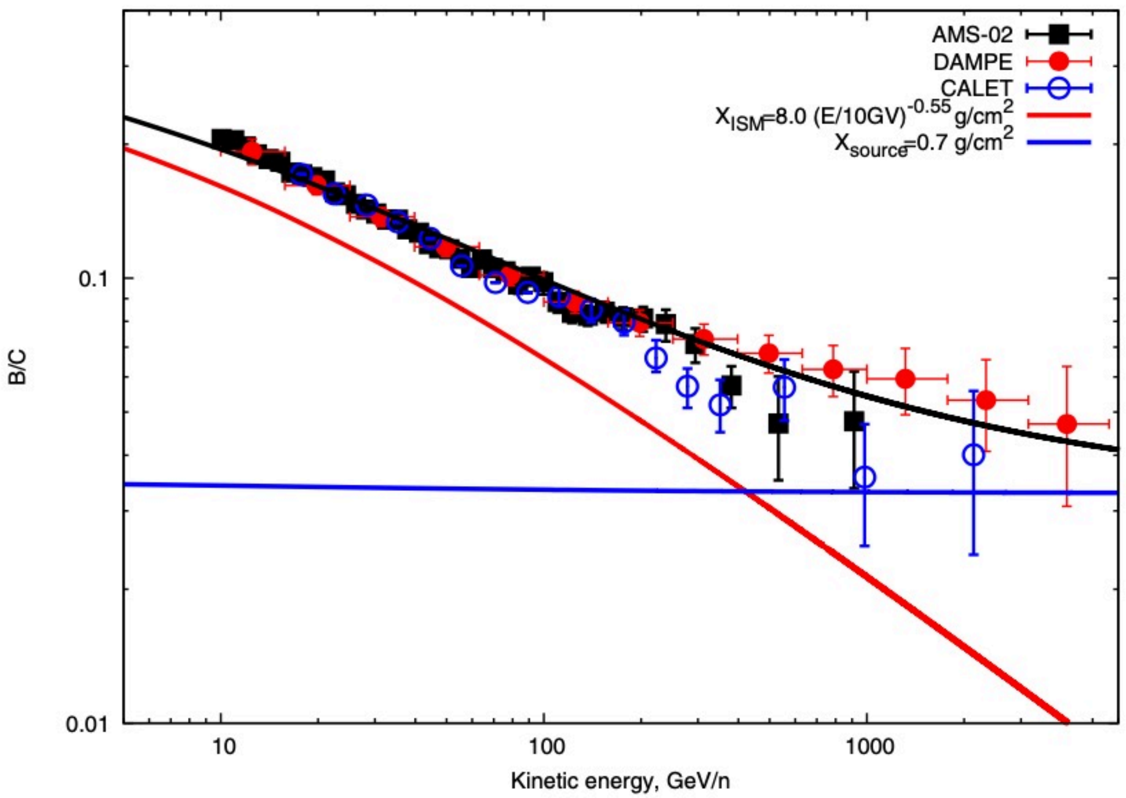
- Same abundances in CRs & in the solar system → **primaries**
- Overabundant compared to solar abundances:

→ Must have been produced during the transport → **secondaries**

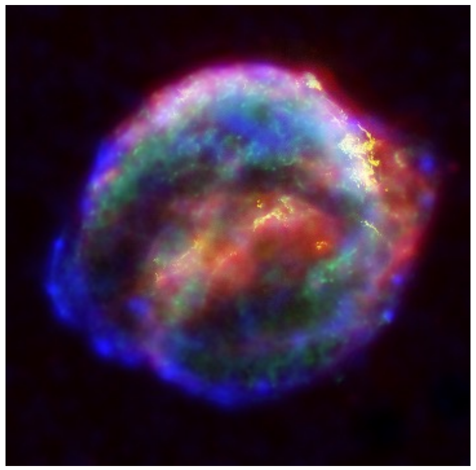
B/C Measurements



Aguilar et al., PRL 117 (2016) 231102



Yang & Aharonian, PRD 111, 083040 (2025)

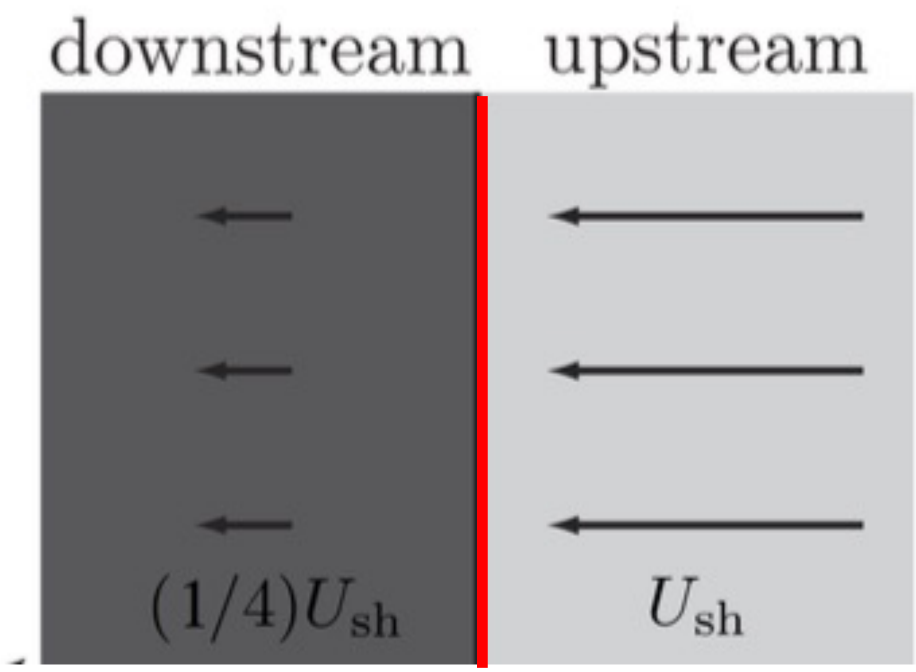


$$\langle \tau_{\rm src} \rangle \lesssim \tau_{\rm SNR} \approx 10^{4\ldots5}\,{\rm yr}$$

$$n_{\rm src} \lesssim 10\,{\rm cm}^{-3}$$

Secondaries in the source?

Diffusive Shock Acceleration



Shock rest frame

The steady-state transport equation for phase-space density f :

$$u\frac{\partial f}{\partial r} - \frac{\partial}{\partial r}D\frac{\partial f}{\partial r} - \frac{p}{3}\frac{du}{dr}\frac{\partial f}{\partial p} = 0$$

The spectrum at the shock:

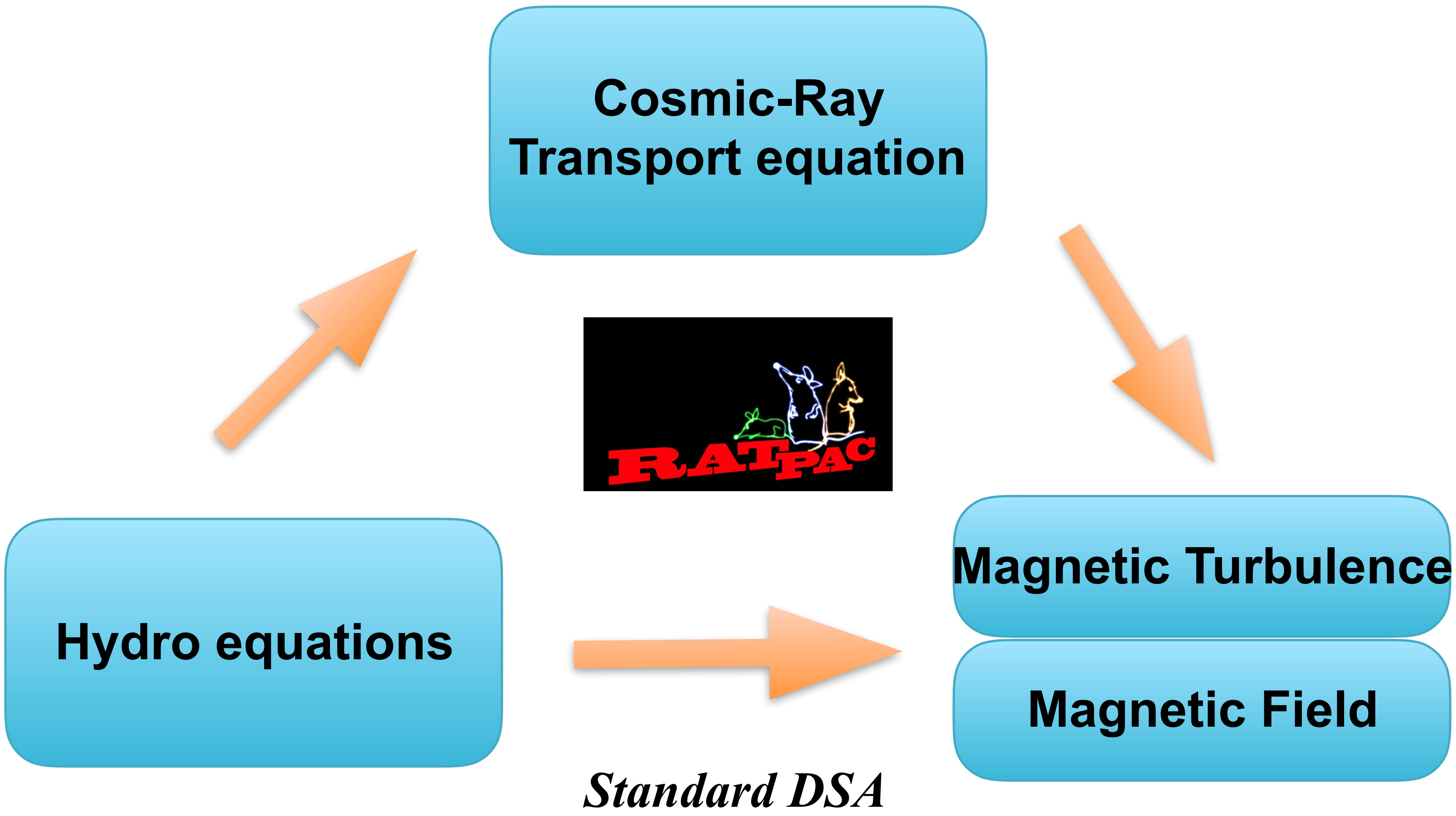
$$f(p) \propto p^{-\gamma}, \text{with} \gamma = \frac{3r}{r-1}, r = \frac{v_u}{v_d}$$

$$\text{With} r \simeq 4 : f(p) \propto p^{-4} \Rightarrow N(p) = 4\pi p^2 f(p) \propto p^{-2}$$

Strong (r = 4) shock accelerates CRs to p^{-2} spectrum!

RATPaC

Radiation Accleration Transport Parallel Code



The time-dependent transport equation

(solved in 1-D spherical symmetry in RATPaC code)

$$\frac{\partial N(p,t)}{\partial t} = \nabla \cdot \left(D\,\nabla N - \mathbf{u}\,N \right)$$

Diffusion + Convection

$$-\frac{\partial}{\partial p}\left(\dot{p}\,N - \frac{\nabla \cdot \mathbf{u}}{3}\,p\,N \right)$$

Energy loss + Acceleration

$$+Q_{\text{injection}}$$

Primary source (C, O)

$$-Q_{\text{spallation}}$$

Spallation loss (C, O)

$$+Q_{\text{secondary}}$$

Secondary source (B, Be)

Module for secondary species in RATPaC code

Methodology

The spectral production rate of secondaries:

$$\rightarrow \quad Q_{\rm sec}(p) \approx n_T \cdot N_{\rm pri}(p) \cdot \beta(p)c \cdot \sigma(p)\,.$$

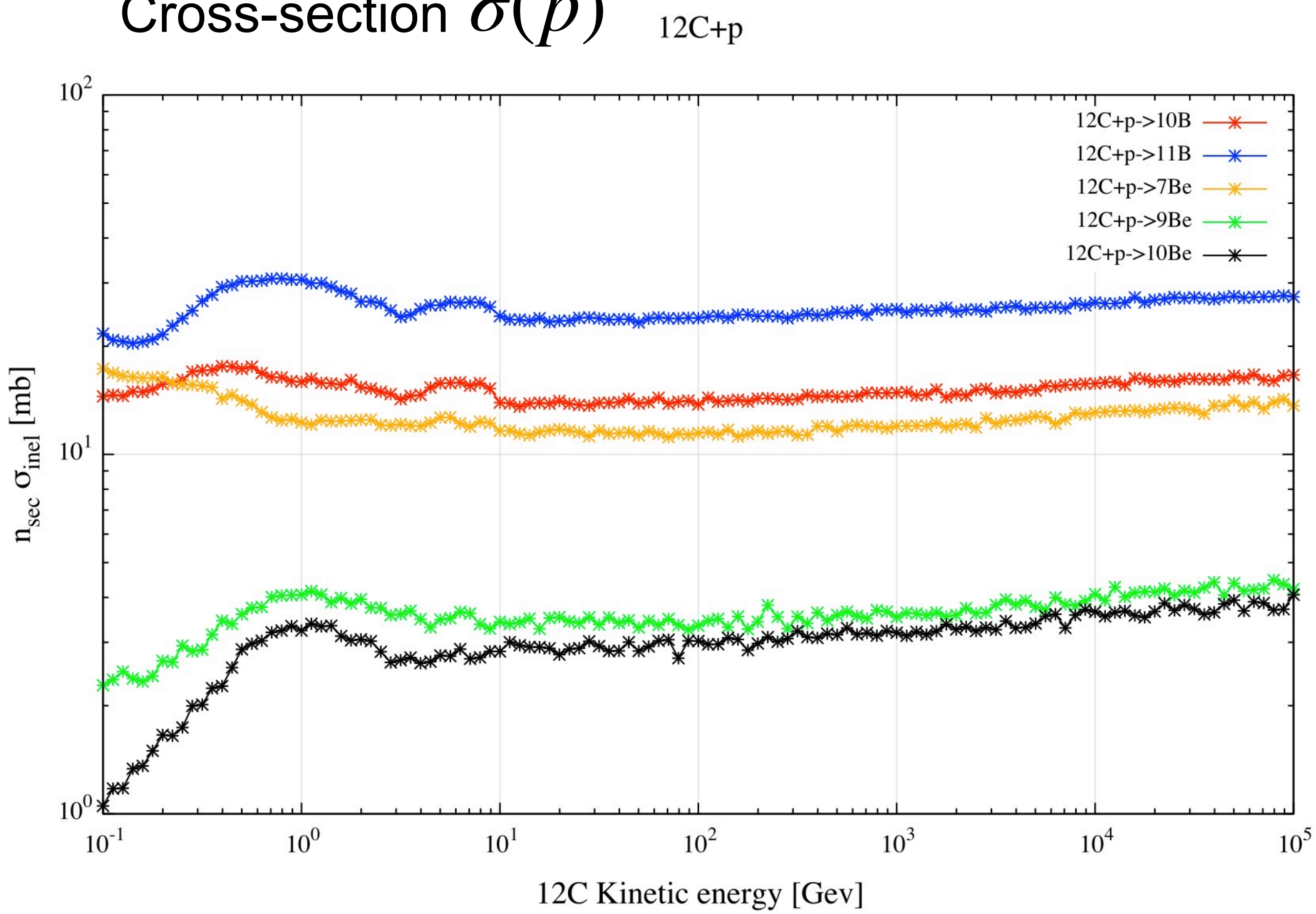
$N_{\rm pri}$ includes Nc and Nox:

$$^{12}C + H \rightarrow B$$

$$^{16}O + H \rightarrow B$$

Total B includes B10 and B11

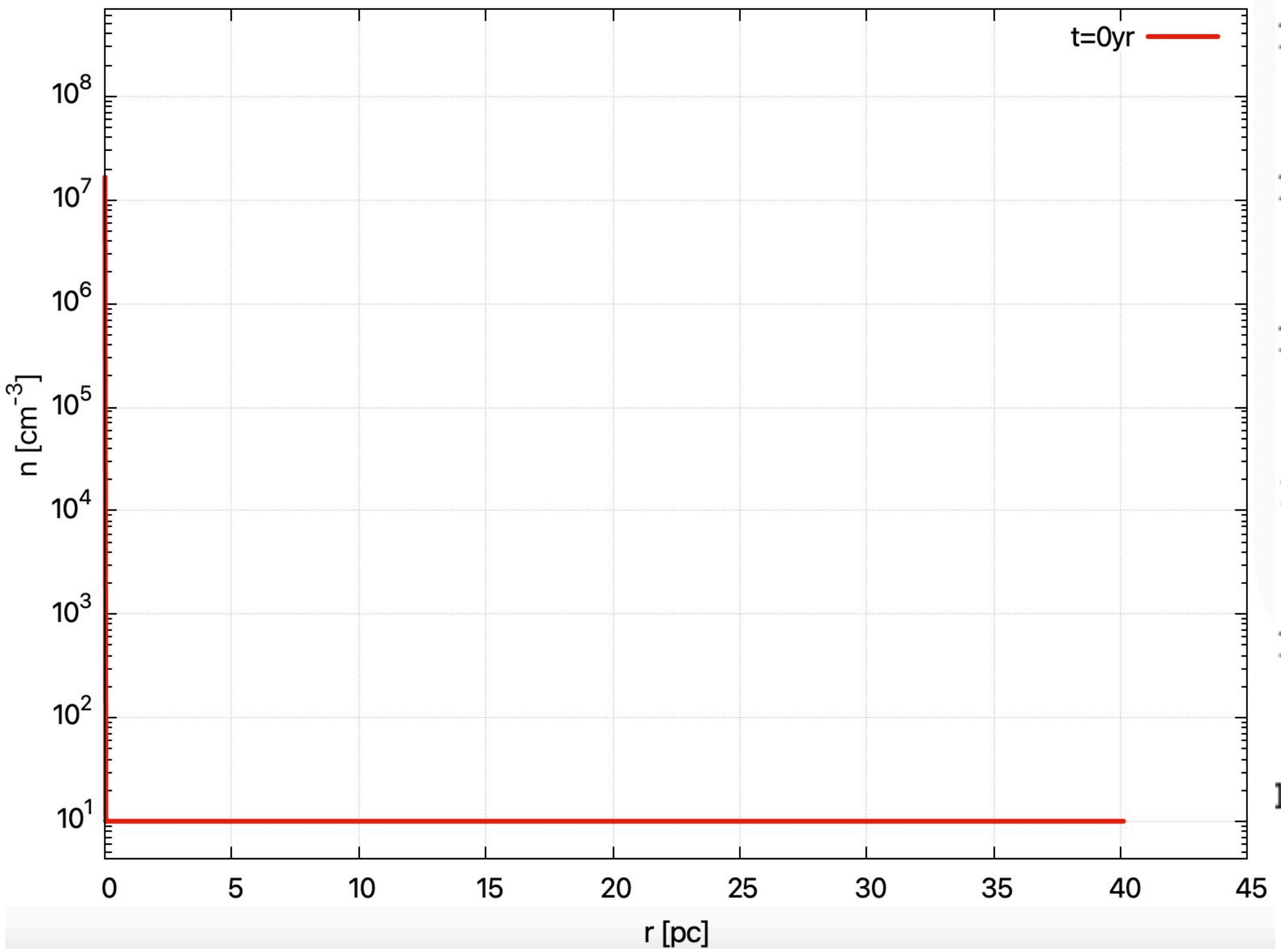
Cross-section $\sigma(p)$



(All cs numerical data are from Francesco Cerutti, CERN)

Modelling the production of B in SNR

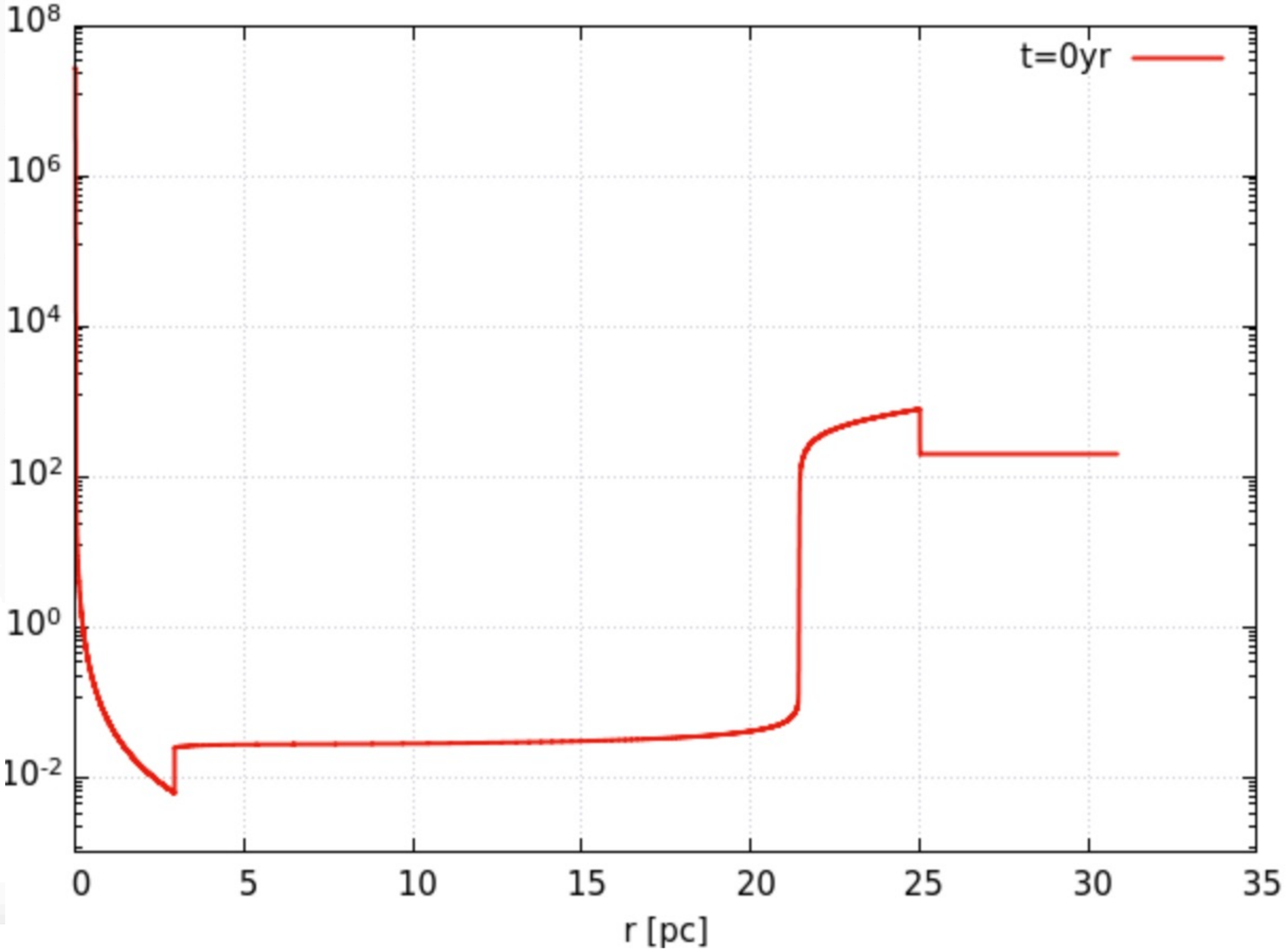
Type-Ia SNR



$$n_{\rm ISM} = 10cm^{-3}$$

Simple constant profile

Core-collaspe SNR

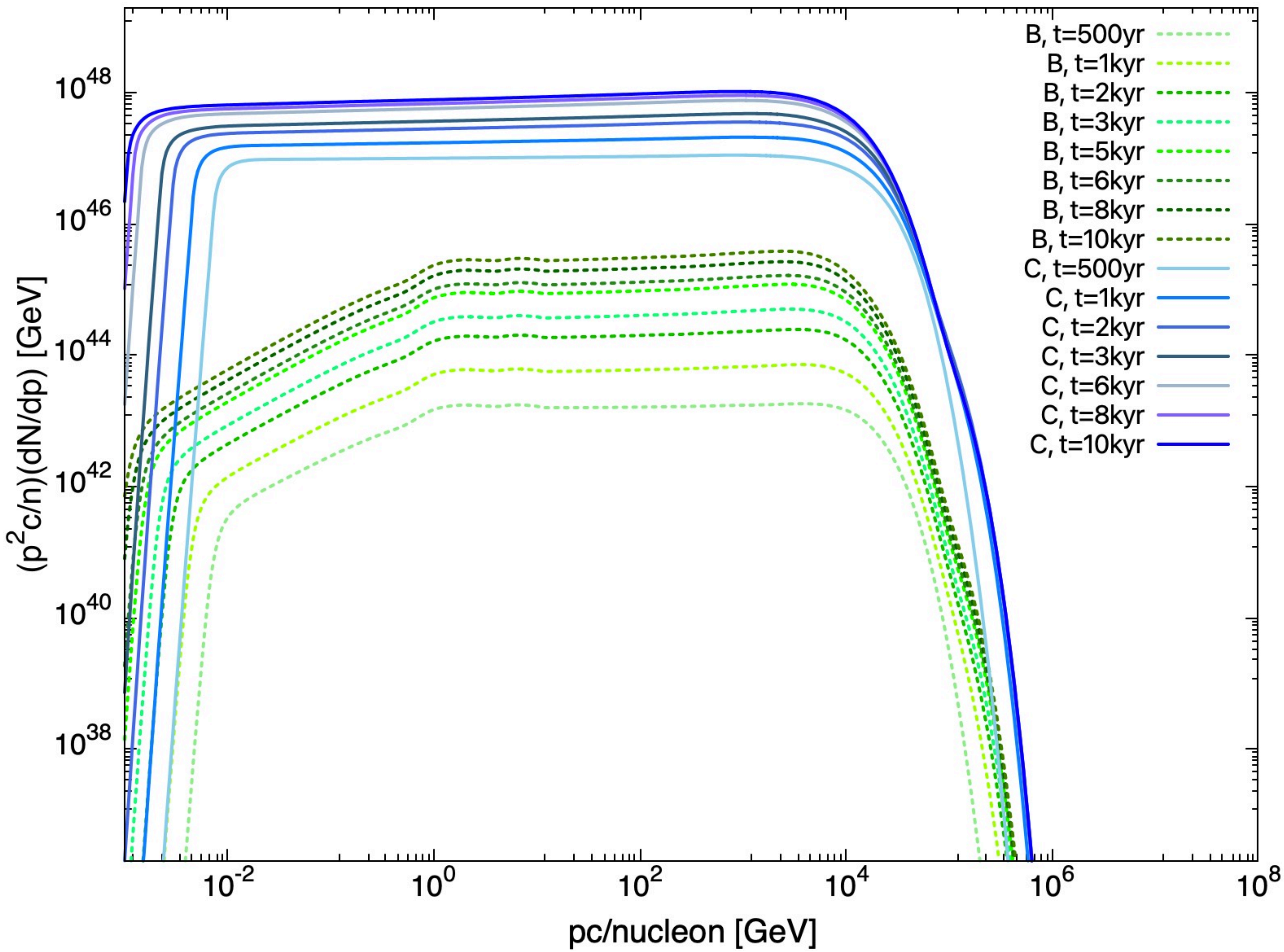


$$n_{\rm ISM} = 100cm^{-3}$$

Wind bubble structure!

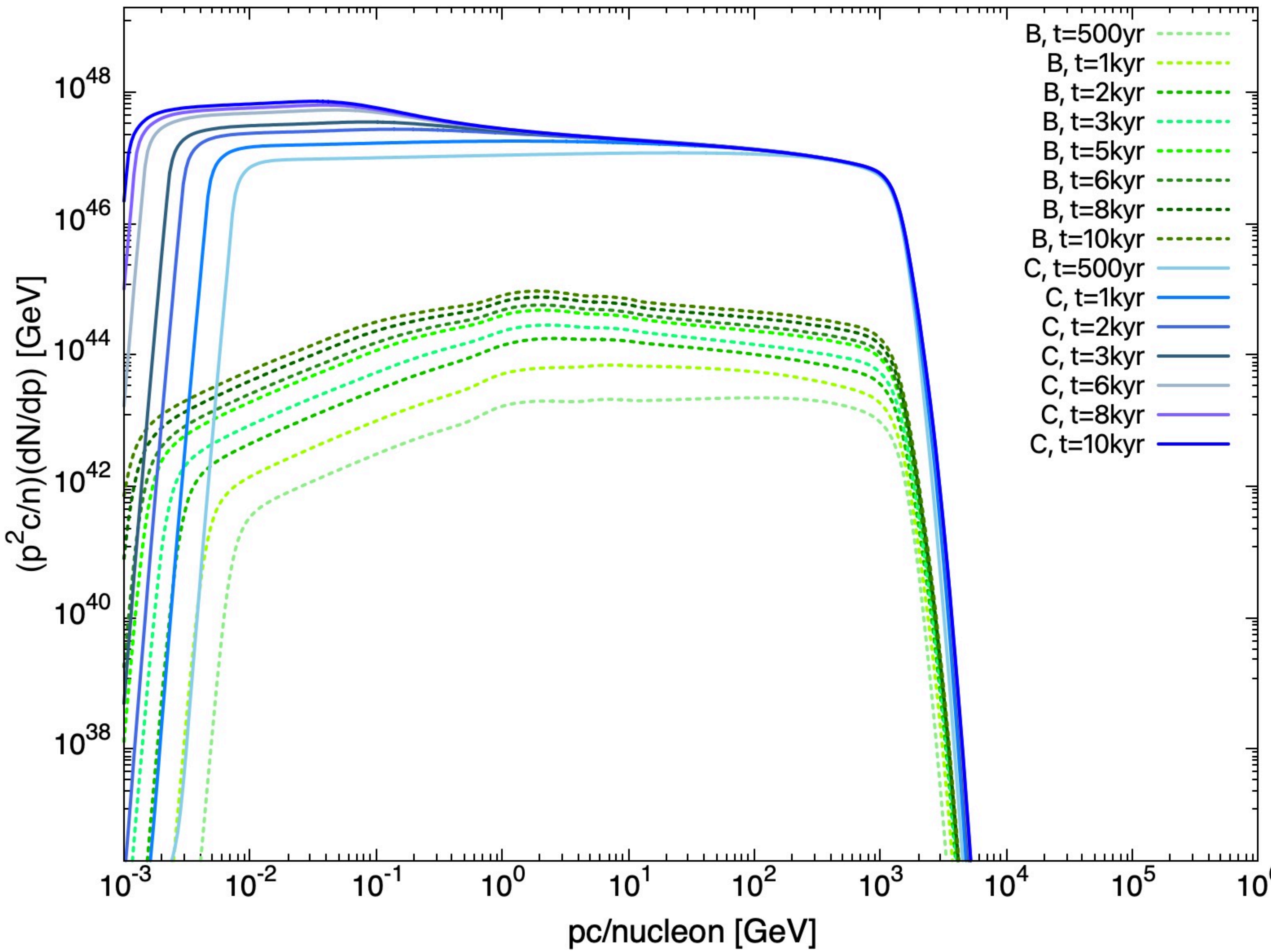
Total Momentum Spectrum

(Type-Ia with Bohm diffusion)



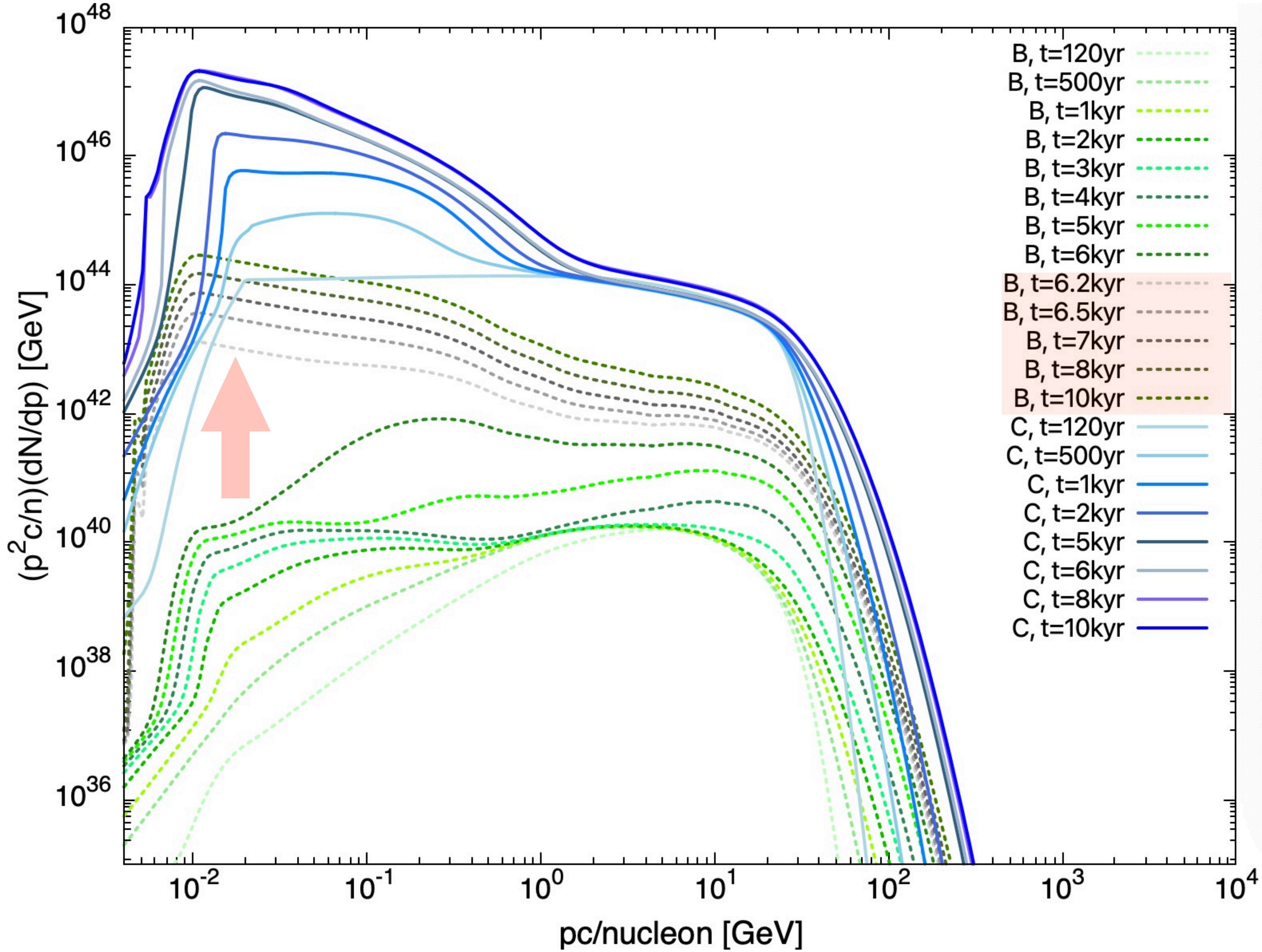
Total Momentum Spectrum

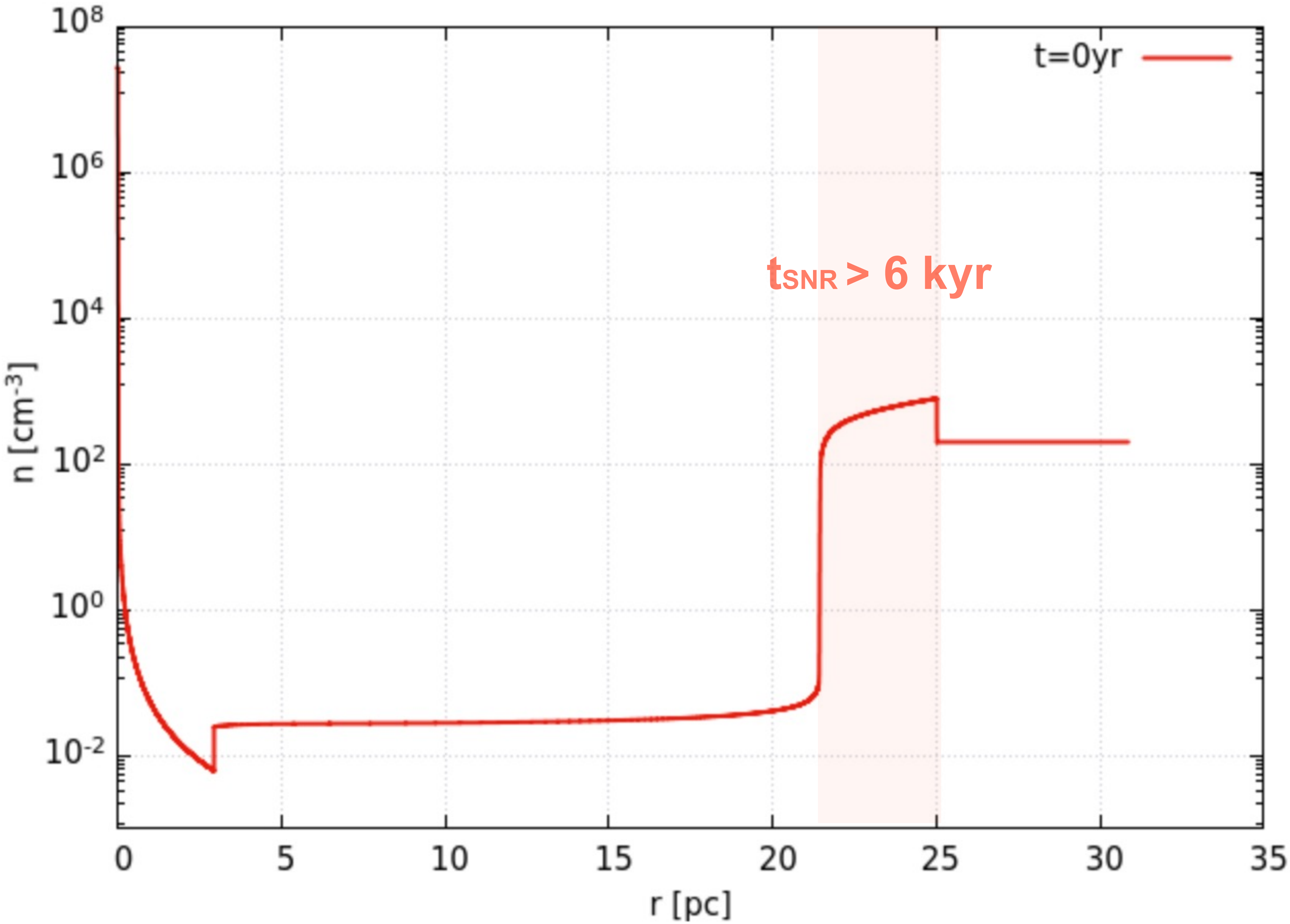
(Type-Ia with self-generated turbulence)



Total Momentum Spectrum

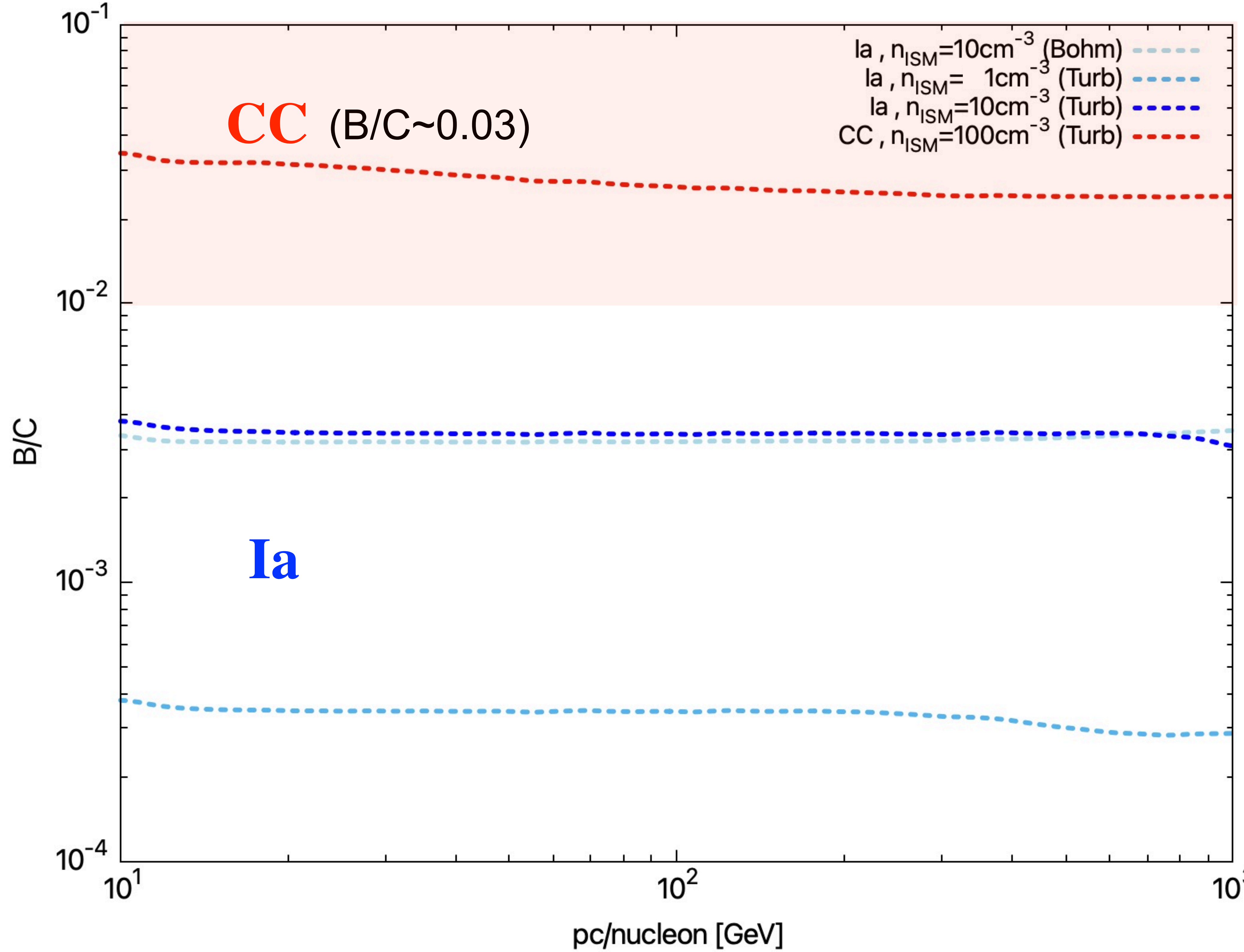
(Core-collapse with self-generated turbulence)




t=0yr
t_SNR > 6 kyr
n [cm-3]
r [pc]
10^8
10^6
10^4
10^2
10^0
10^-2
0
5
10
15
20
25
30
35

B/C ratio

t_{SNR} = 10 kyr



Summary

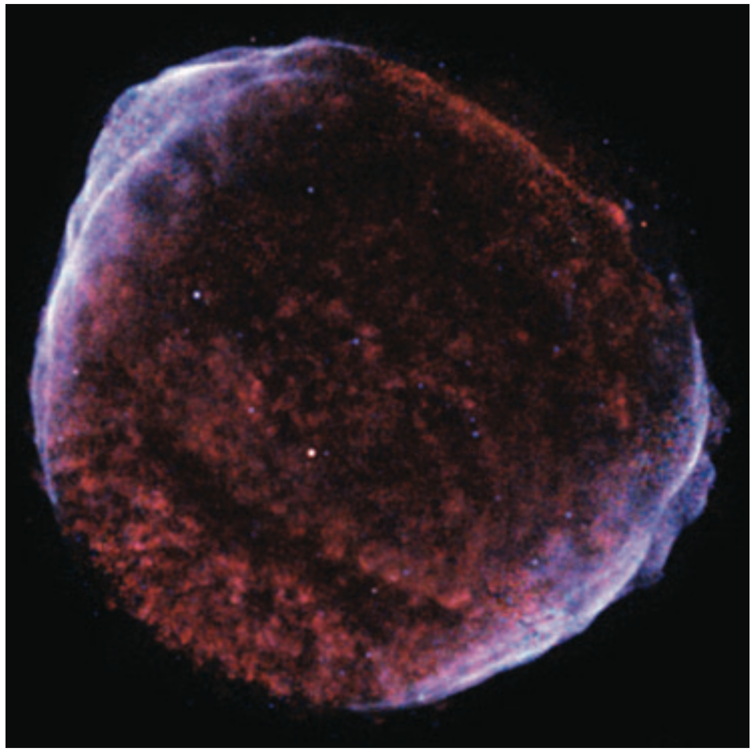
1. We first model the production of Boron in **Type Ia & CC** SNRs.

2. In the SNRs, we have a **flat B/C ratio** in the energy range up to 1TeV/n, reaching the range of measurements.

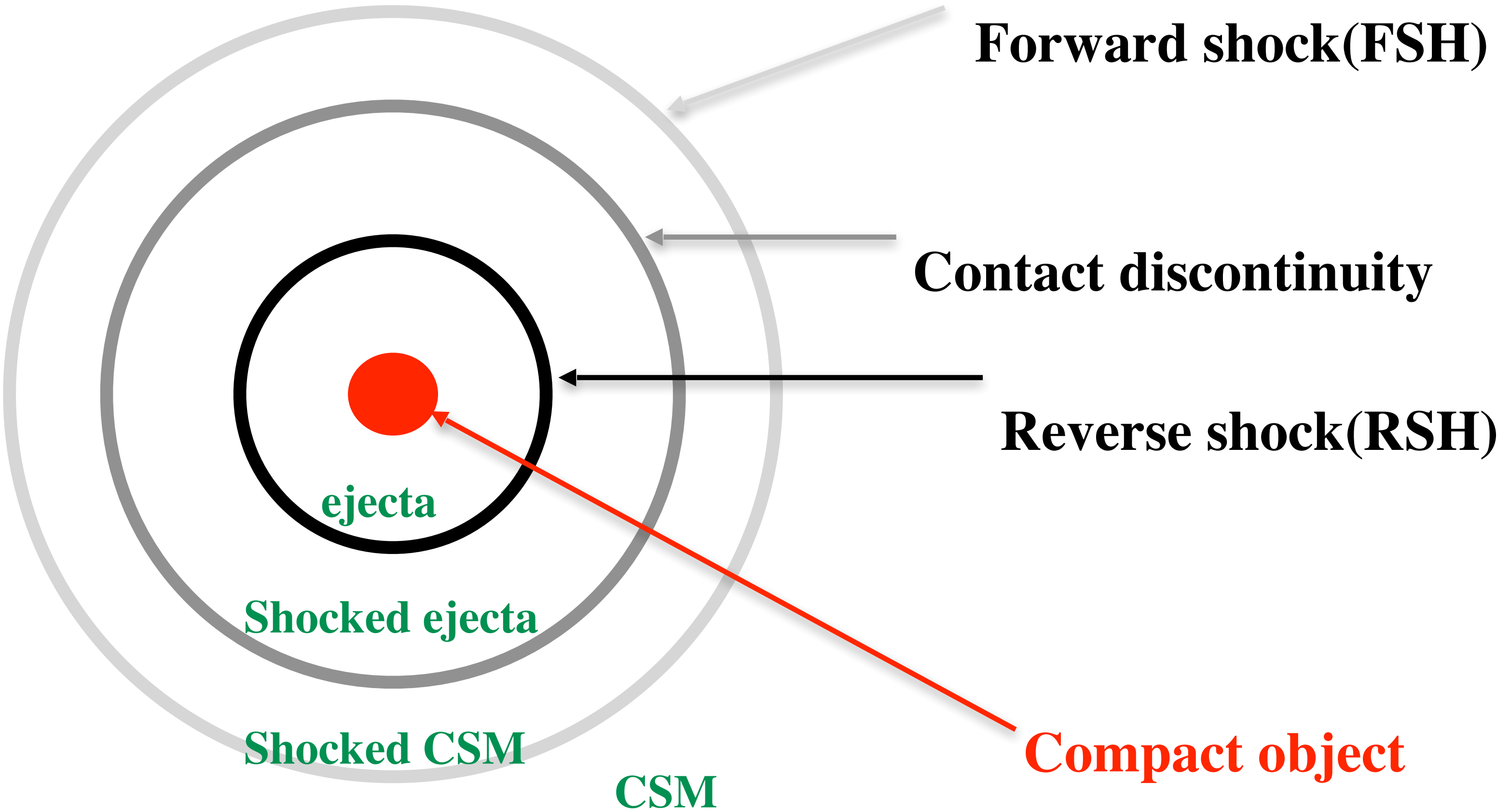
3. The in-source B/C ratio: **~0.01**, depending on the diffusion model, the density of the source region, and the acceleration time.

Backup

1). Theoretical:



SN 1006



(Normal Structure of SNR)

Four phases of supernova renmant:

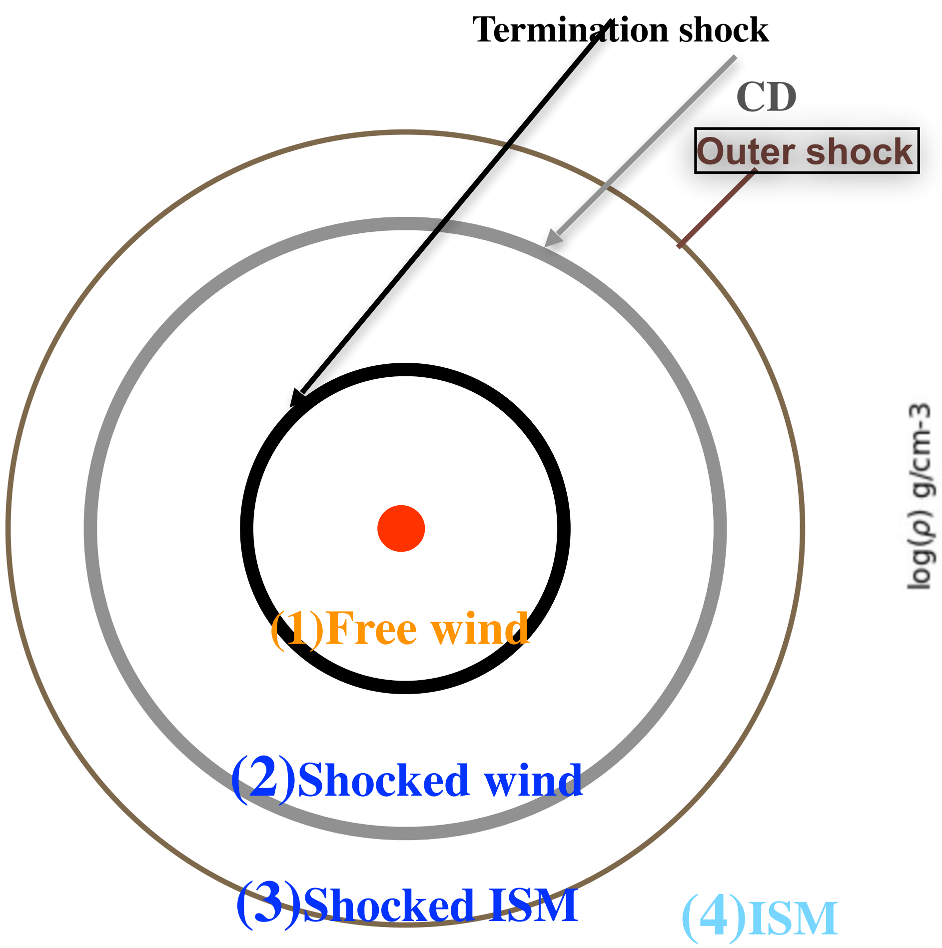
- Free expansion phase: E_explosion transfers to E_kinetic.
- Sedov-Taylor phase: SNR expands adiabatically, RSH moves inward.
- Radiative phase: FSH slows down, T_downstream drops.
- Dissipative phase: SNR merges into CSM and shocks disappear.

Stellar wind-blown bubble

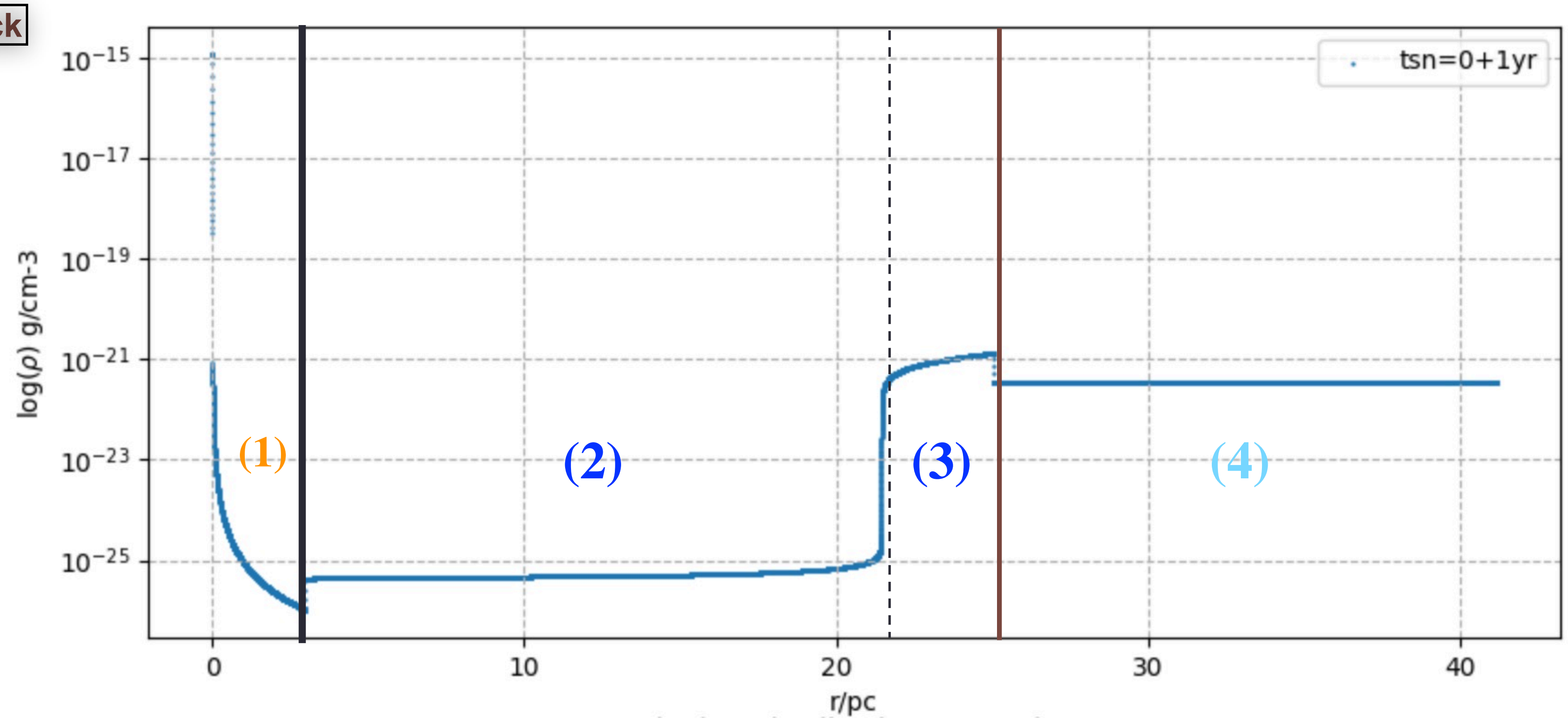
(NGC 7635)

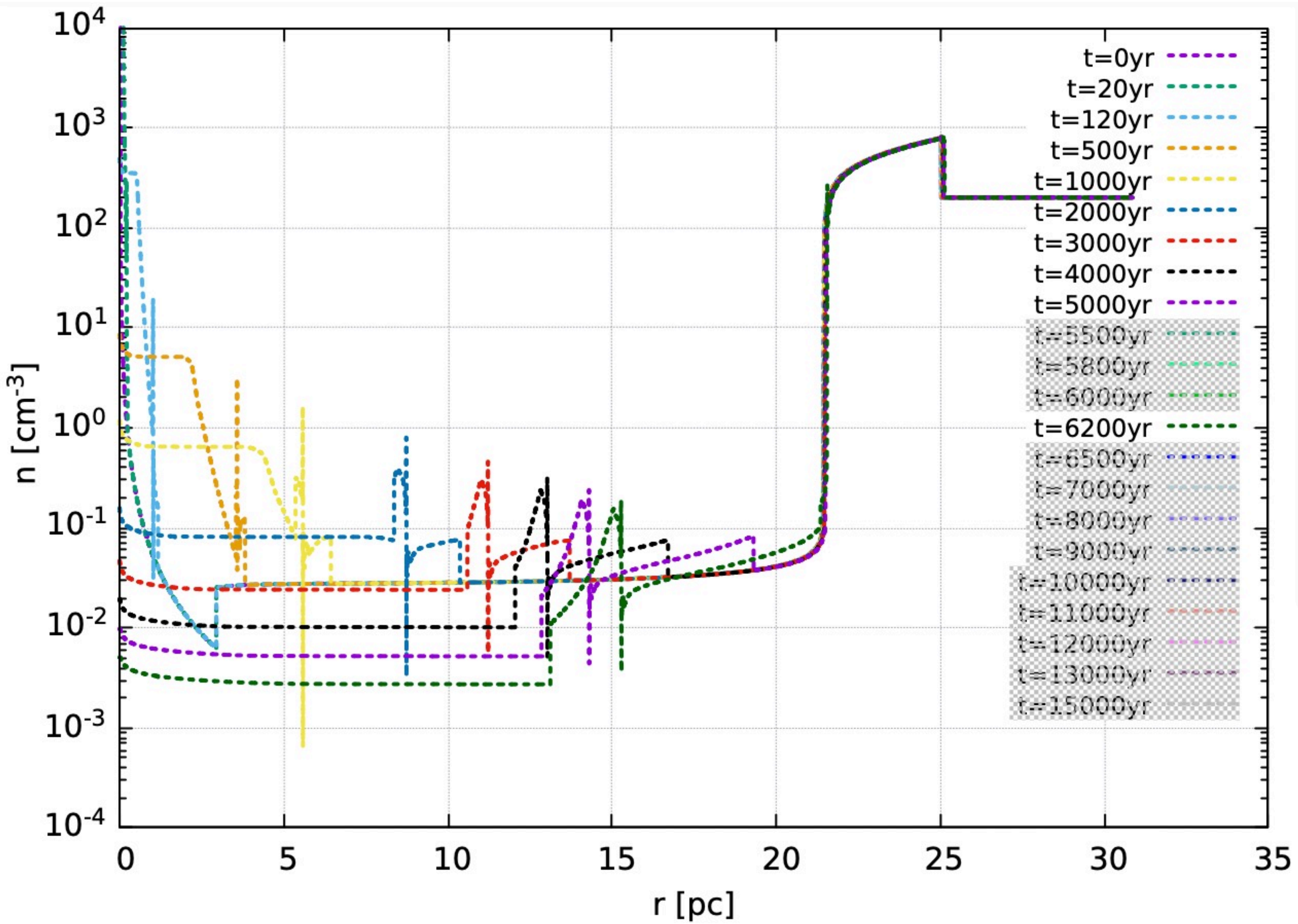
Wind bubbles have a **two-shock** structure. The wind density (ρ_{wind}) related to mass-loss rate, stellar radius, and wind velocity by,

$$\rho_{\text{wind}} = \frac{\dot{M}}{4\pi R^2 V_{\text{wind}}}$$

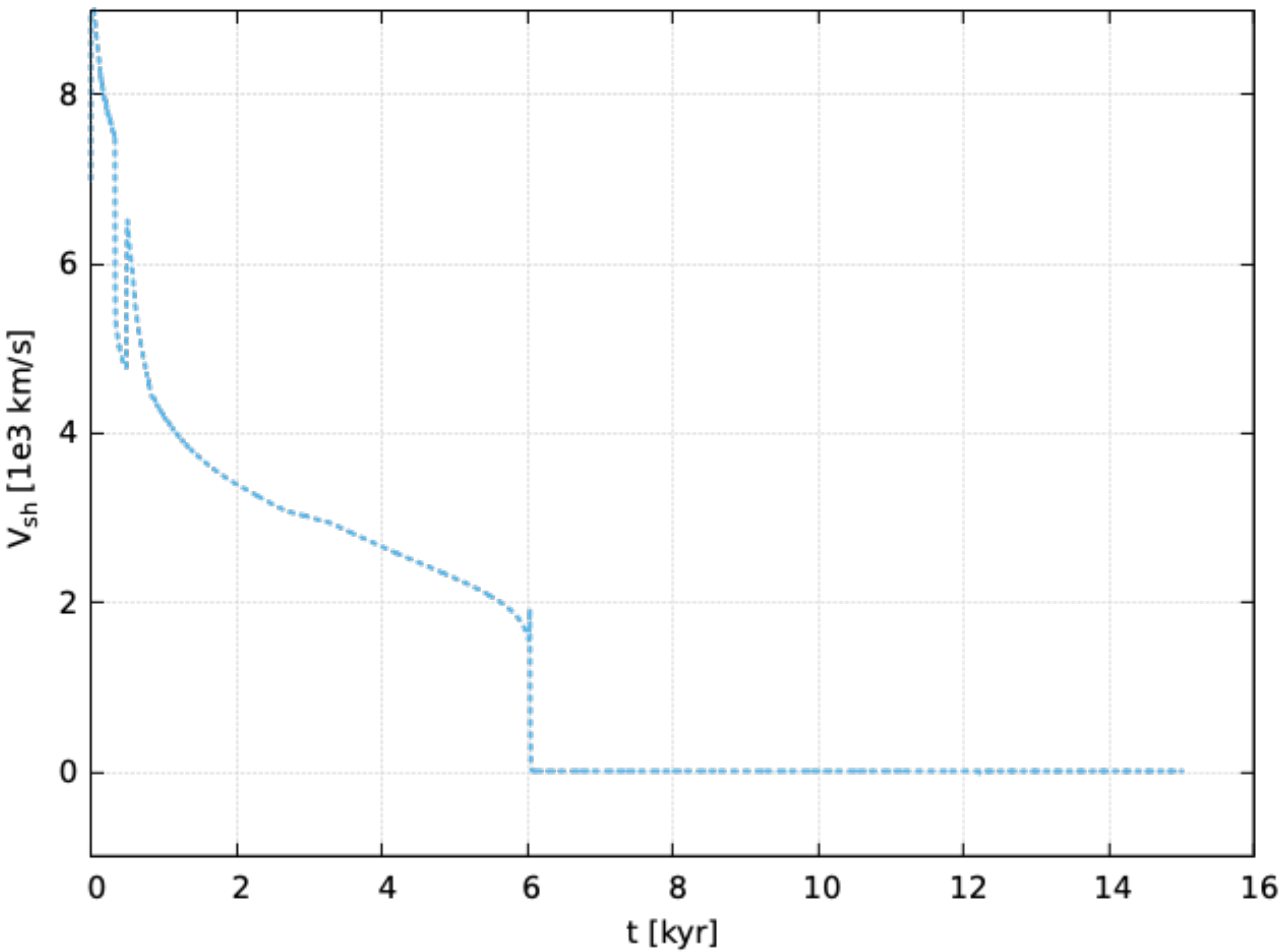


(Structure of WB)

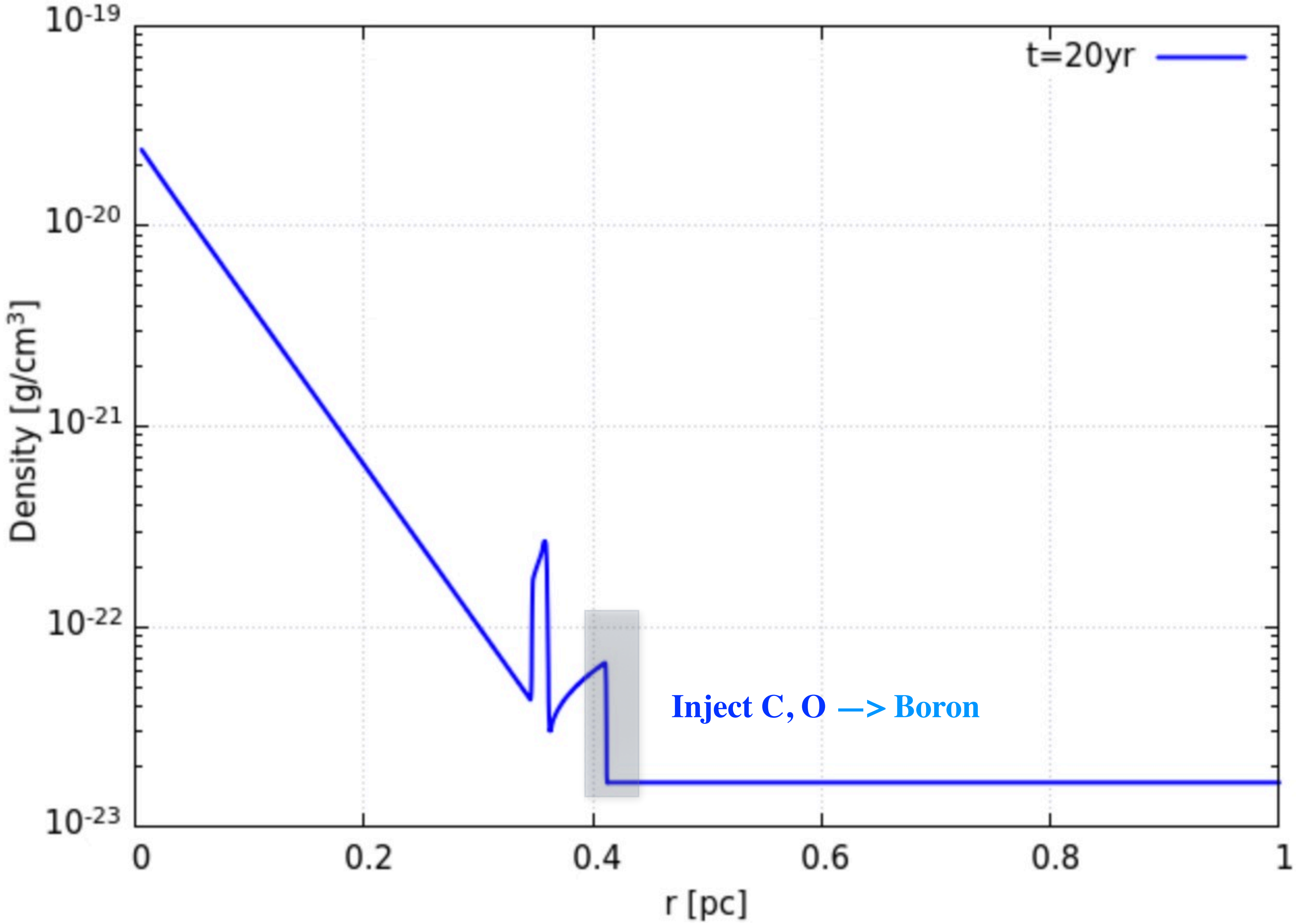




10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
n [cm^{-3}]
0
5
10
15
20
25
30
35
r [pc]
t=0yr
t=20yr
t=120yr
t=500yr
t=1000yr
t=2000yr
t=3000yr
t=4000yr
t=5000yr
t=5500yr
t=5800yr
t=6000yr
t=6200yr
t=6500yr
t=7000yr
t=8000yr
t=9000yr
t=10000yr
t=11000yr
t=12000yr
t=13000yr
t=15000yr



8
6
4
2
0
V_{sh} [1e3 km/s]
0
2
4
6
8
10
12
14
16
t [kyr]



Initial settings:

E_{ej} = 10^{51} erg

M_{ej} = 1.4 $M_{\odot}$, n_{ISM} = 10 cm-3

T_{ej}=10000 K, Tsim=1yr

Cross-sections data:

(All cs numerical data are from Francesco Cerutti, CERN)

Carbon reaction channel:

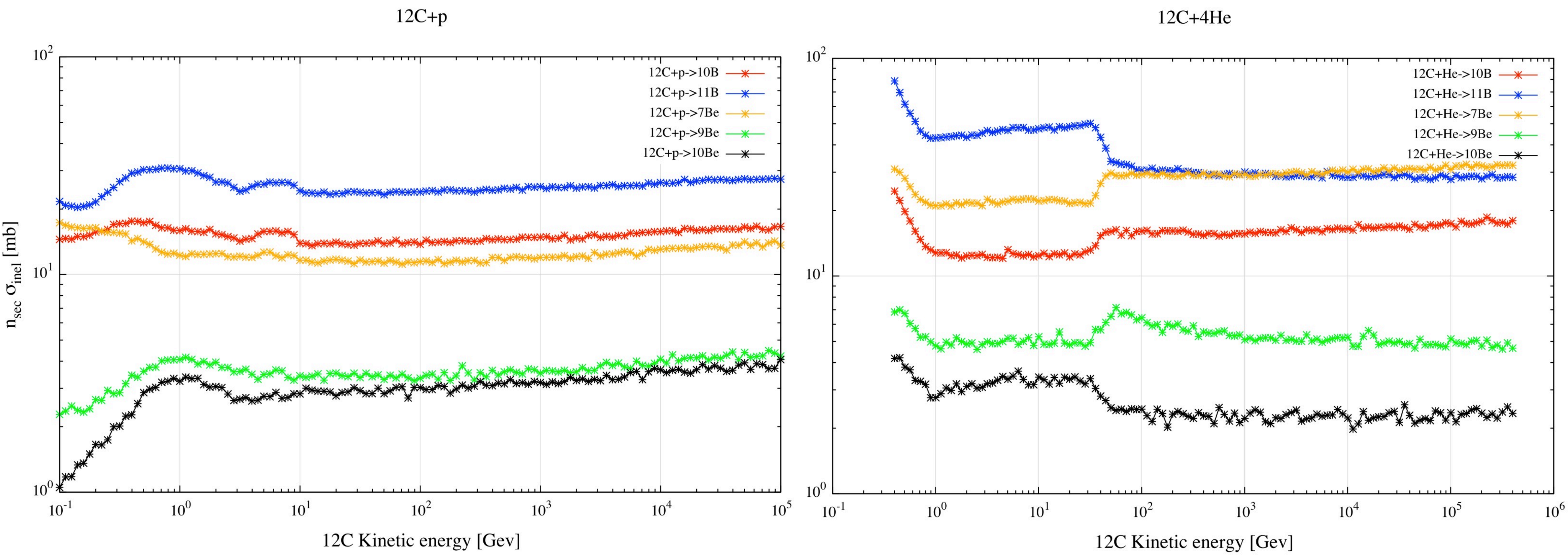


Fig.1. Inclusive cross sections for the production of spallation nuclei in collisions of ***^{12}C* with H and *^{4}He*** nuclei. The plots show the cross sections for the production of ***B (^{10}B , ^{11}B), Be (^{7}Be , ^{9}Be, ^{10}Be)***

Oxygen reaction channel:

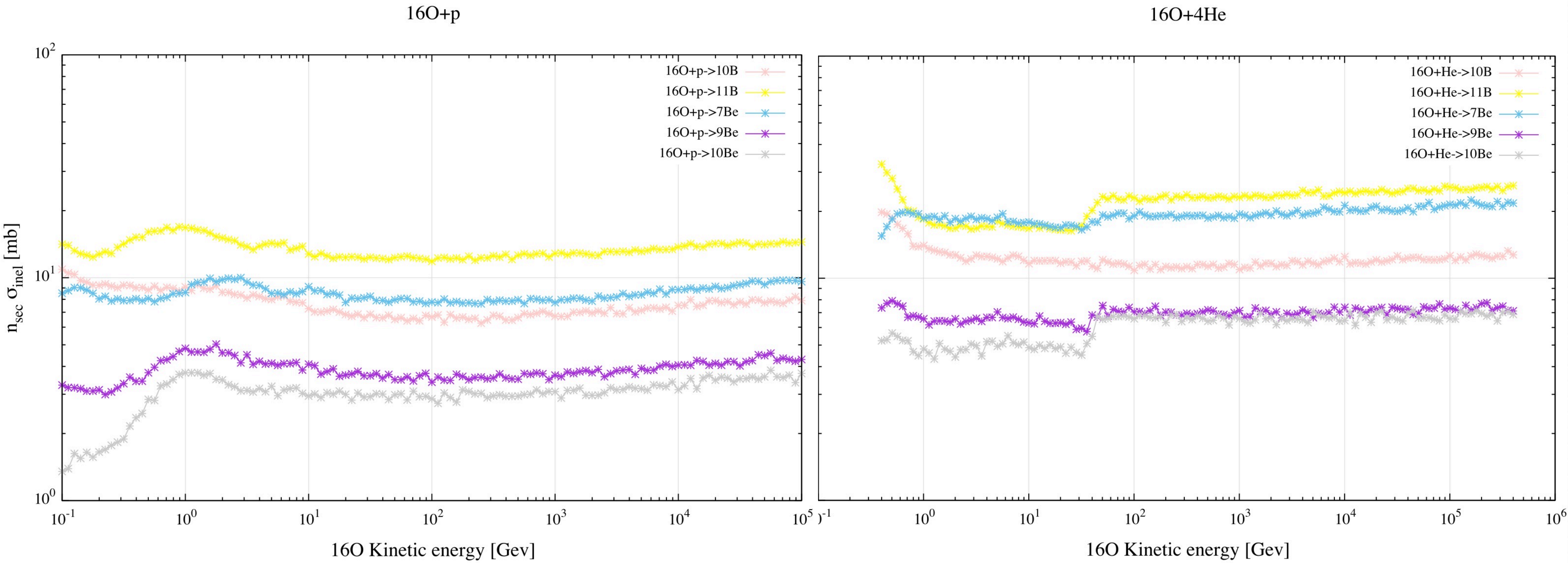
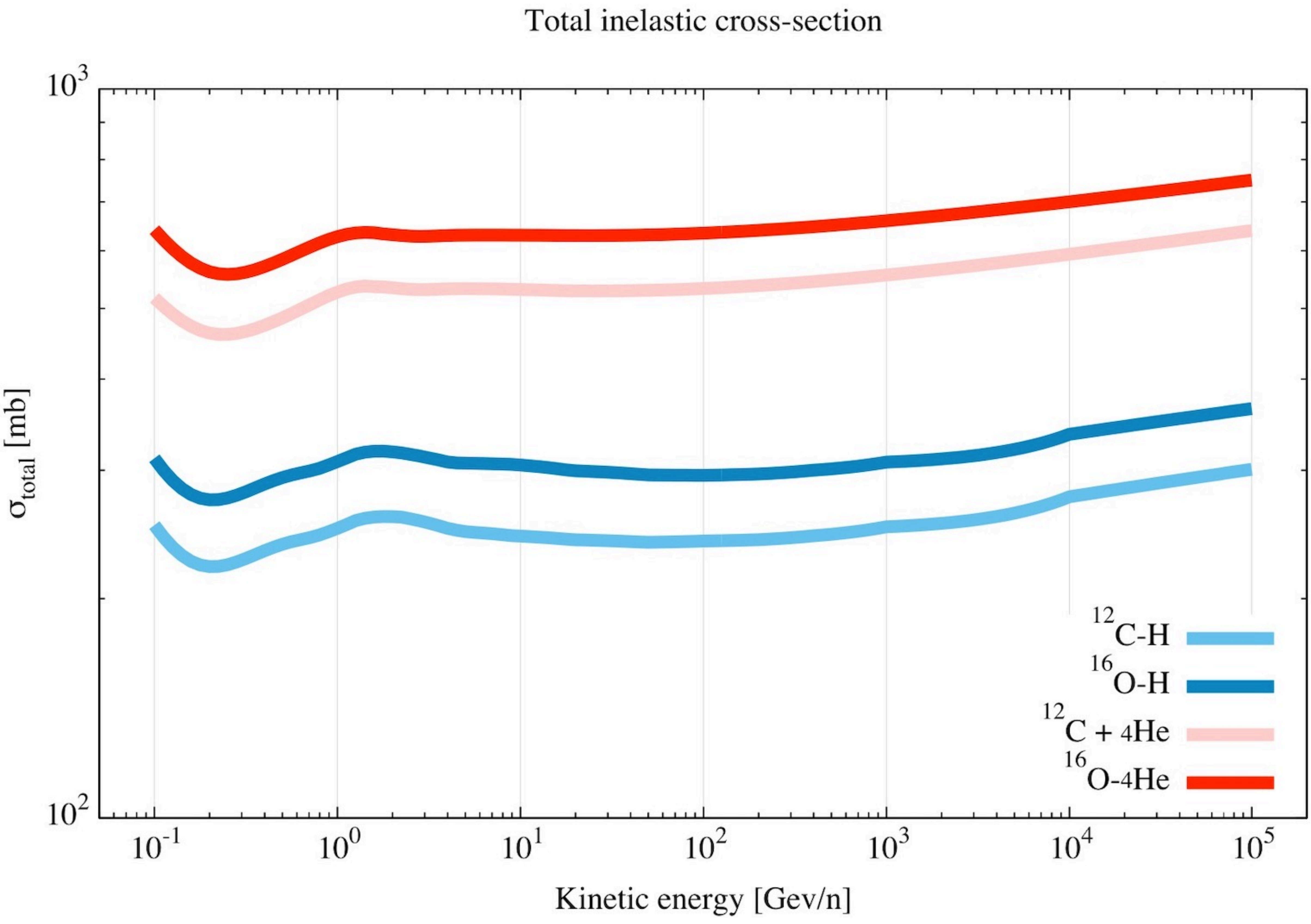


Fig.2. Inclusive cross sections for the production of spallation nuclei in collisions of ***^{16}O* with p and *^{4}He*** nuclei.

The plots show the cross sections for the production of ***B (^{10}B , ^{11}B), Be (^{7}Be , ^{9}Be, ^{10}Be)***


Total inelastic cross-section
σ_{total} [mb]
10^3
10^2
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
Kinetic energy [Gev/n]
^{12}C-H
^{16}O-H
^{12}C + 4He
^{16}O-4He