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

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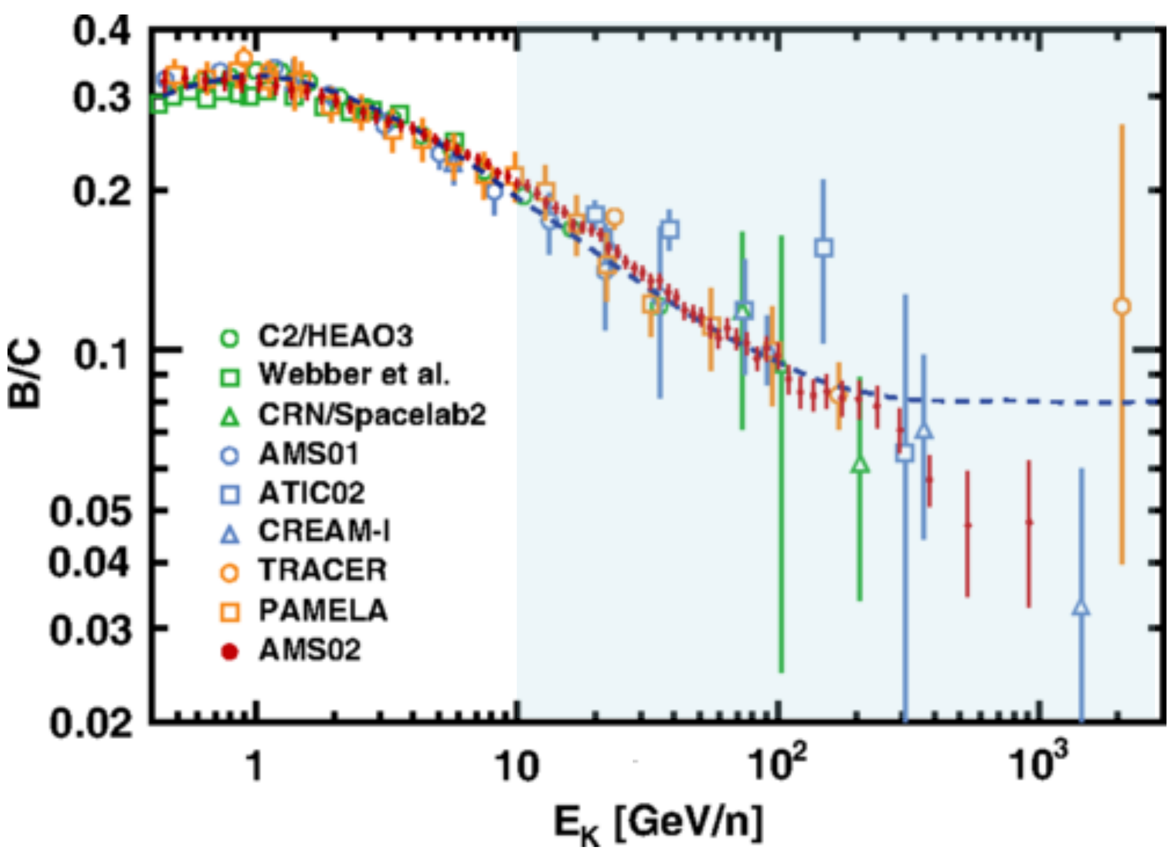
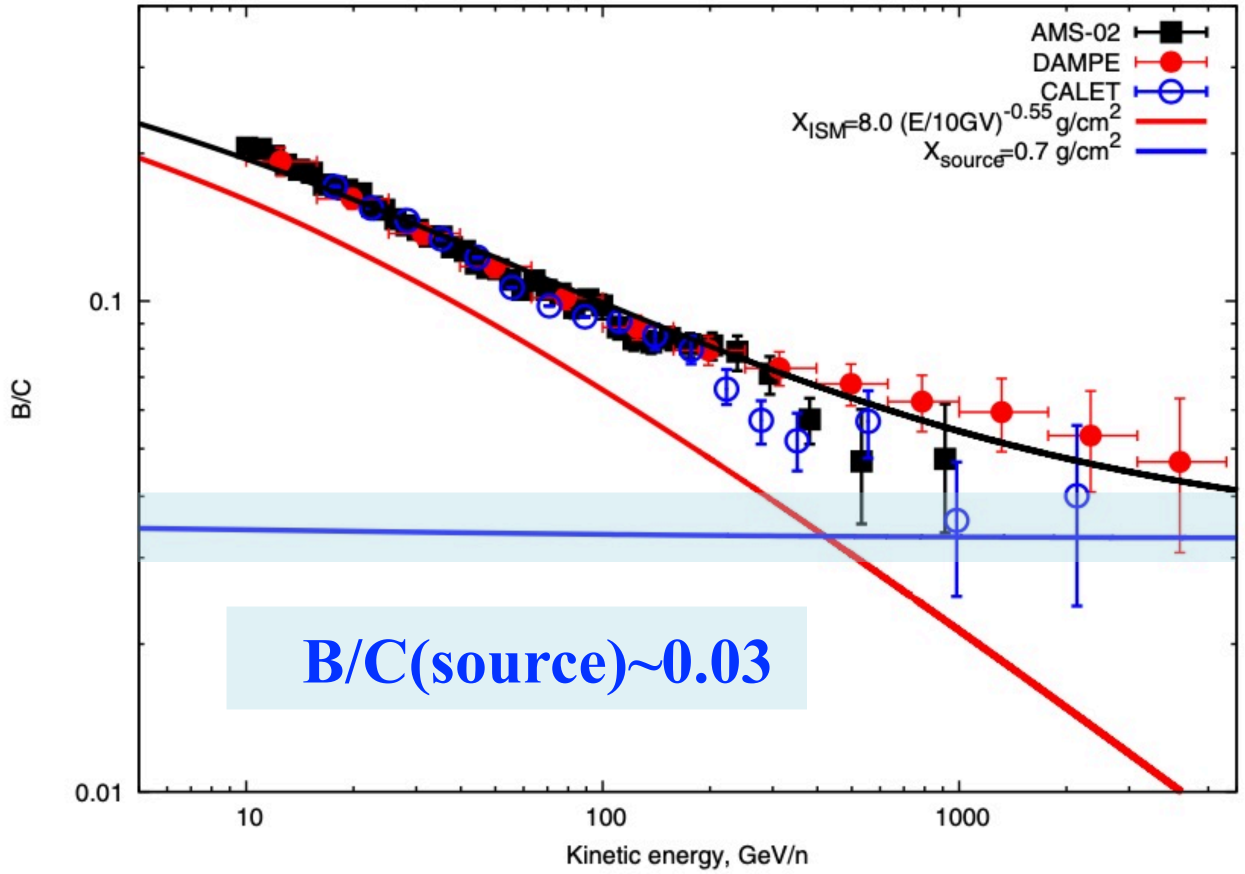
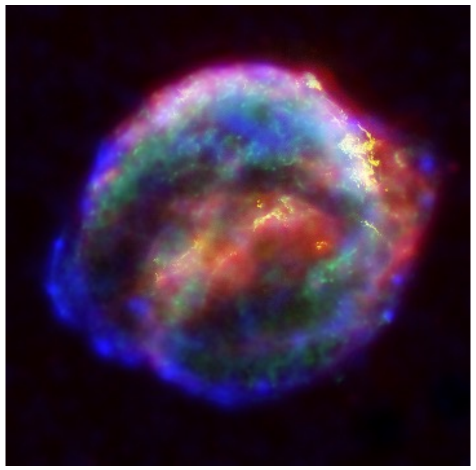
B/C Measurements



Aguilar et al., PRL 117 (2016) 231102



Yang & Aharonian, PRD 111, 083040 (2025)



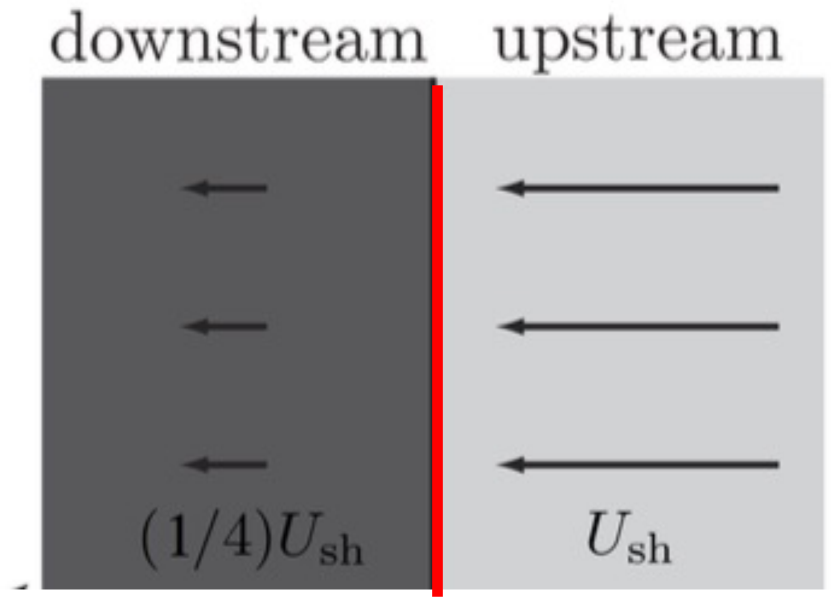
$$\langle \tau_{src} \rangle \lesssim \tau_{SNR} \approx 10^{4\ldots5}\,\mathrm{yr}$$

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

Secondaries in the source?

Diffusive Shock Acceleration

Seminal papers in 1977/78 by Krymsky; Axford, Leer, Skaldron; Blandford, Ostriker; Bell



Shock rest frame

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

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

For $x \neq 0$, $$f(x,p) = \begin{cases} g(p)\exp\left[\frac{x}{\kappa(p)/u}\right] + Y\delta(p - p_{\rm inj}), & \text{for } x < 0 \\ f_0(p), & \text{for } x > 0 \end{cases}$$

The spectrum at the shock: $f(p) \propto p^{-\gamma}$, with $\gamma = \frac{3r}{r-1}$, $r = \frac{v_u}{v_d}$

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

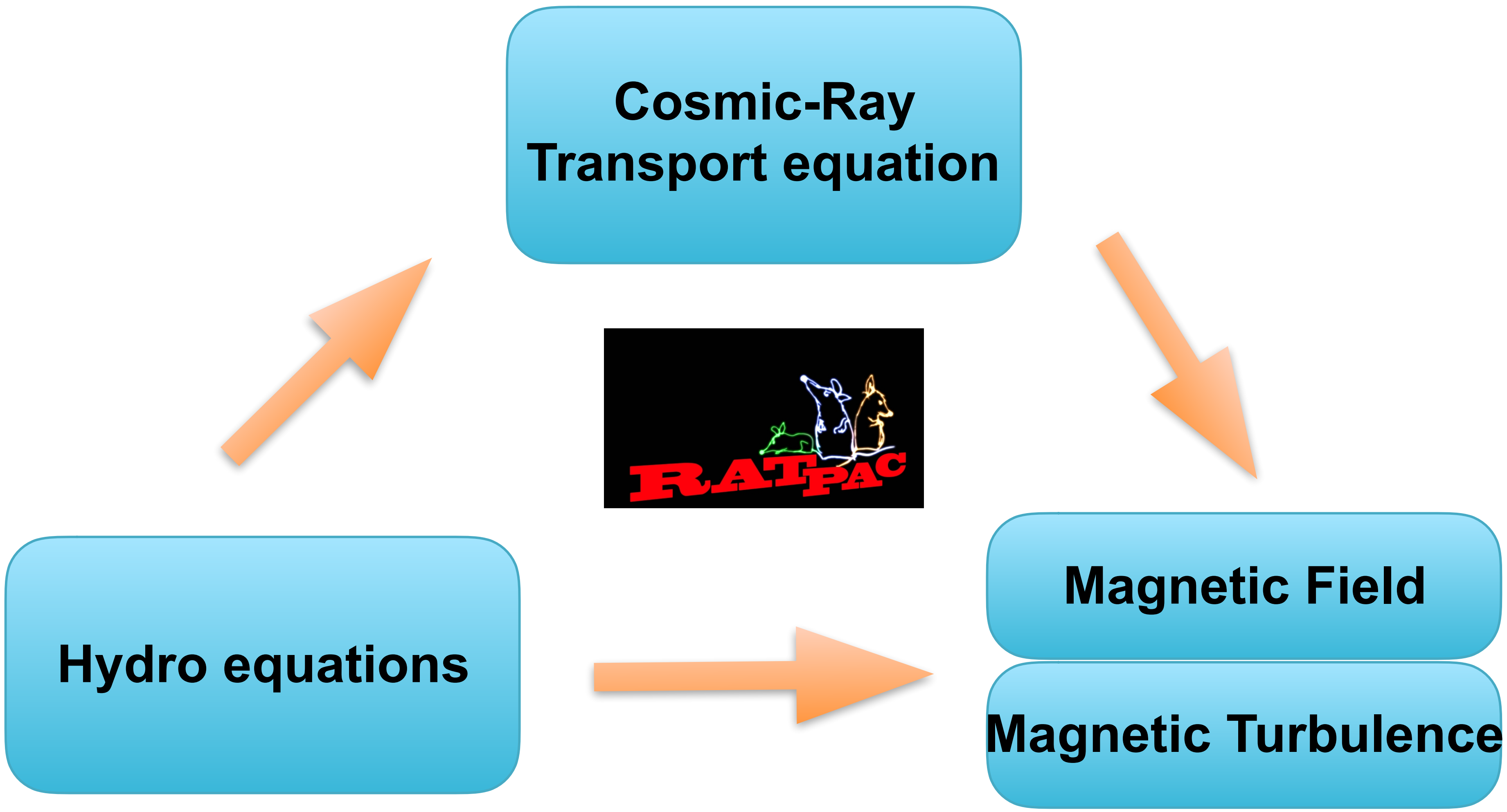
Strong (r = 4) shock accelerates CRs to p^{-2} spectrum!

RATPaC

Radiation Accleration Transport Parallel Code

Tested code in development since 2012

- 15+ papers
- 225+ citations



Standard DSA

Equations in RATPaC

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

$$\frac{\partial N(p,t)}{\partial t} = \nabla \cdot \left(D\, \nabla N - \mathbf{u}\, N \right) - \frac{\partial}{\partial p}\left(\dot{p}\, N - \frac{\nabla \cdot \mathbf{u}}{3}\, p\, N \right) + S - L_{\mathrm{spa}} + Q_{\mathrm{sec}}$$

Diffusion + Convection | Energy loss + Acceleration | Primary injection | Primary loss | Secondary injection

$$\frac{\partial E_W}{\partial t} = -\left(v\, \nabla_r E_W + c\, \nabla_r v E_W \right) + k^3\, \nabla_k D_k \nabla_k \frac{E_W}{k^3} + 2(\Gamma_g - \Gamma_d) E_W$$

Advection | Compression | Cascading | Growth+Damping

$$\frac{\partial}{\partial t}\begin{pmatrix} \rho \\ \mathbf{m} \\ E \end{pmatrix} + \nabla \cdot \begin{pmatrix} \rho \mathbf{v} \\ \mathbf{m}\mathbf{v} + P\mathbf{I} \\ (E+P)\mathbf{v} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ L \end{pmatrix} \qquad E = \frac{\rho v^2}{2} + \frac{P}{\gamma - 1}, \qquad \gamma = \frac{5}{3}$$

Methodology

The spectral production rate of secondaries:

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

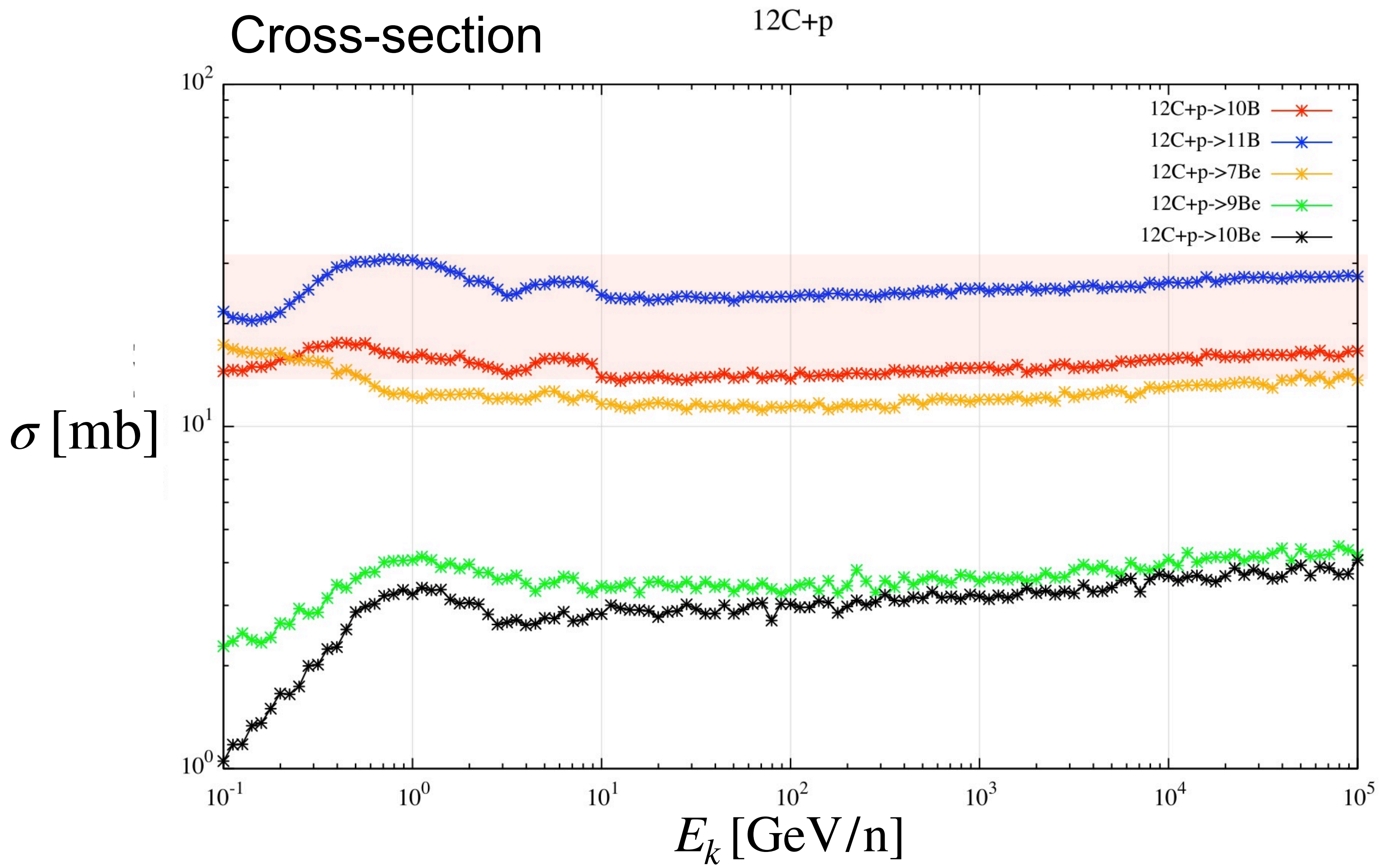
N_{pri} includes Nc and Nox:

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

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

Total B includes **B10** and **B11**

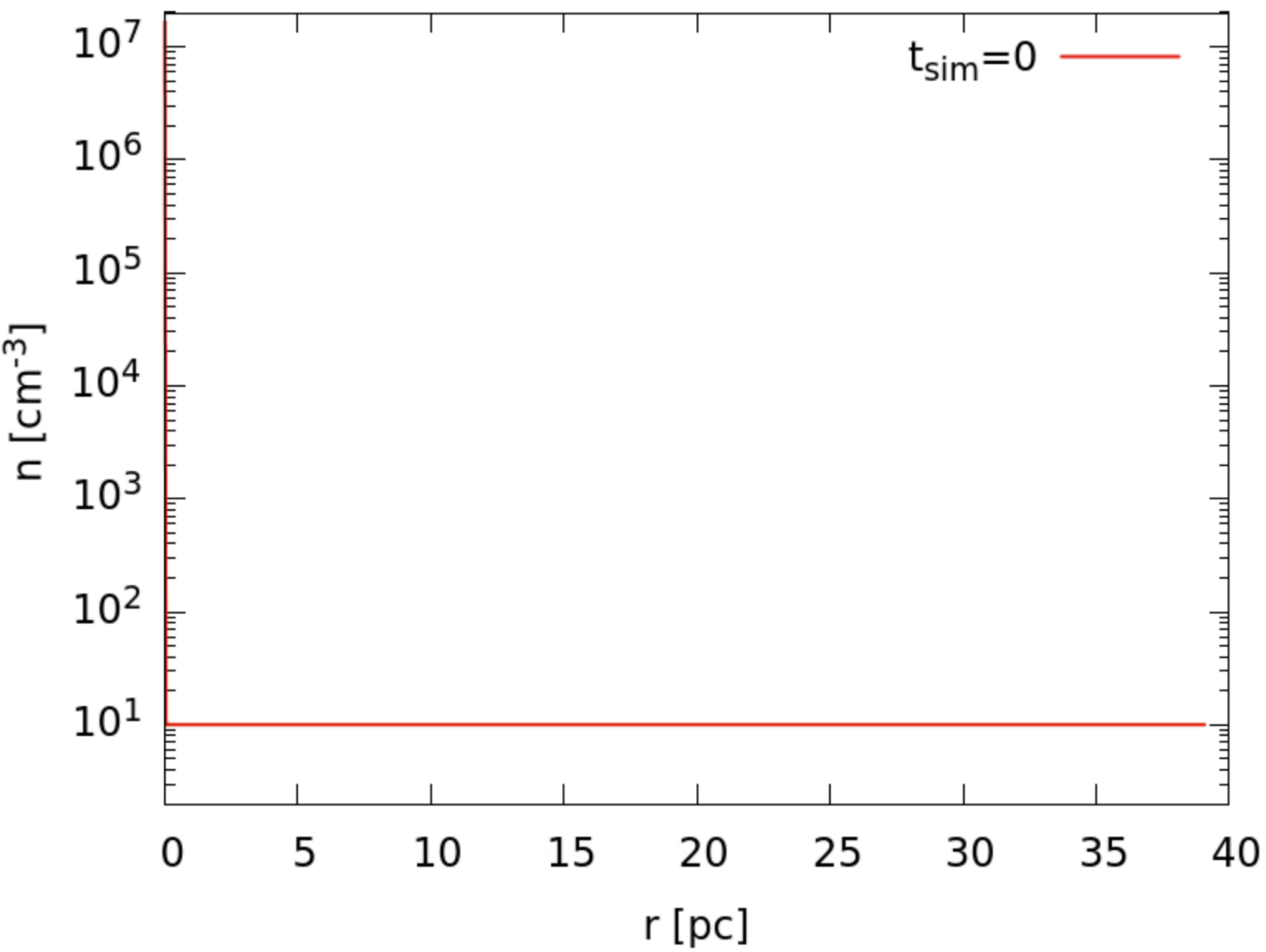
Cross-section



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

Modelling the production of B in SNR

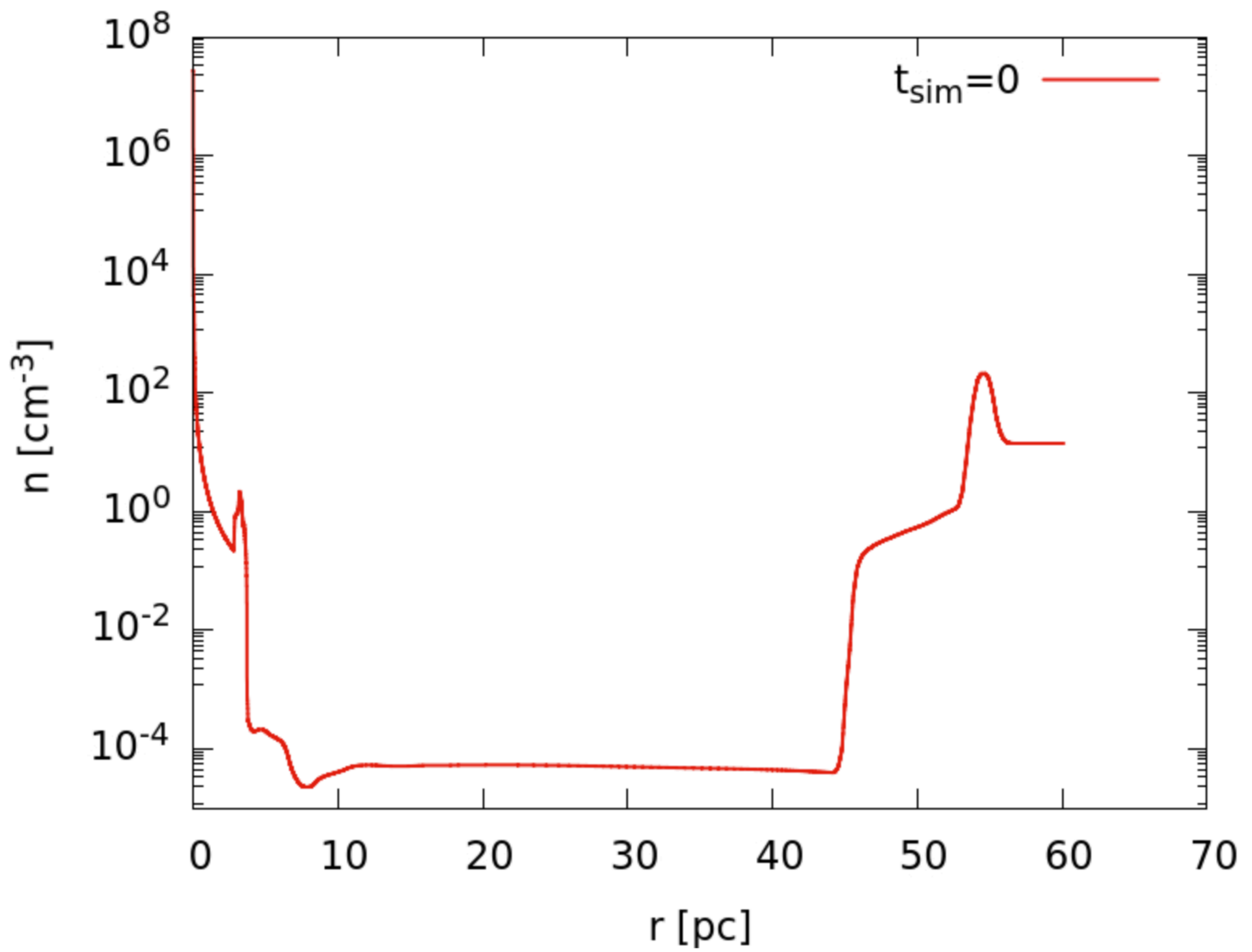
Type-Ia SNR



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

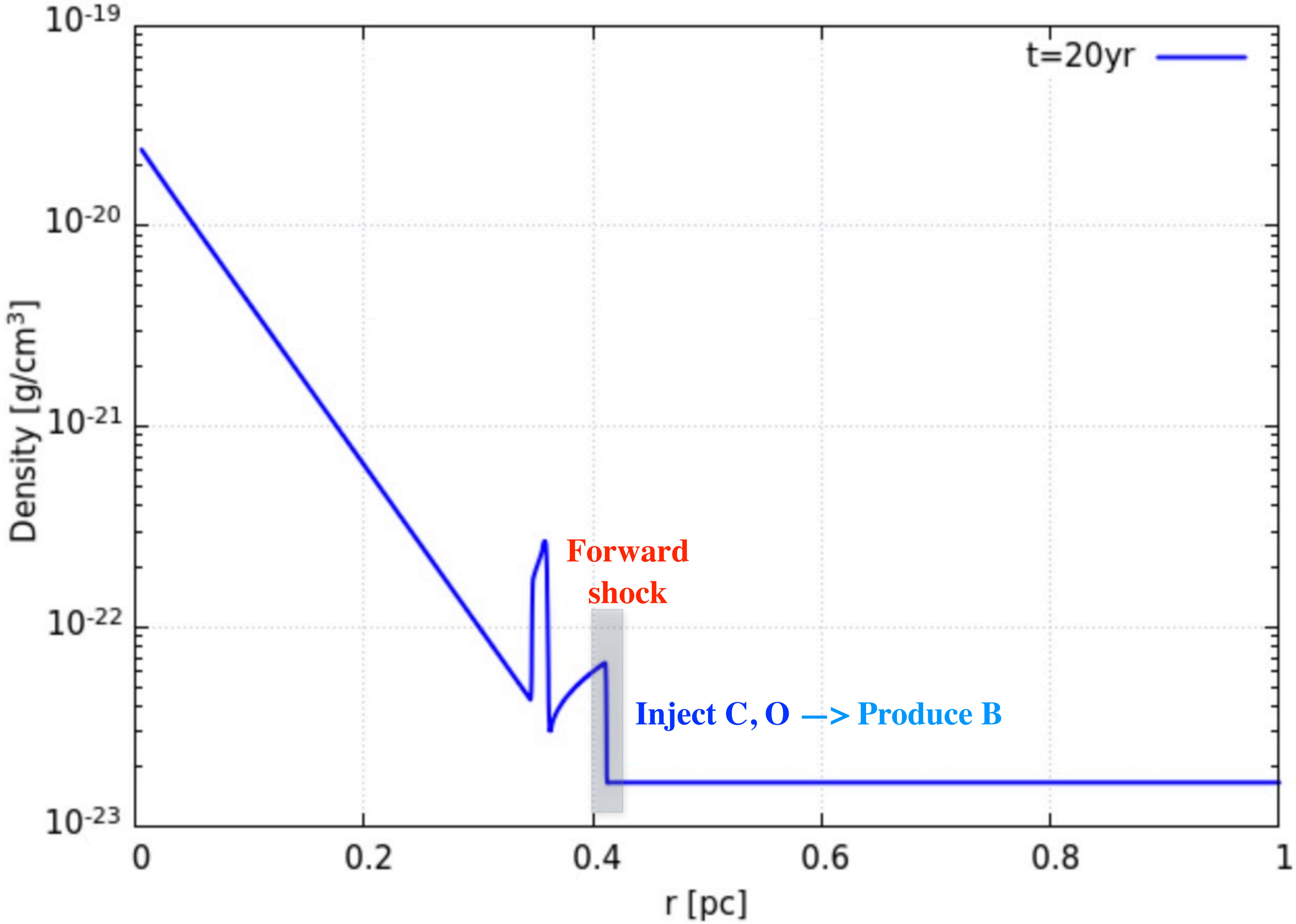
Simple constant profile

Core-collaspe SNR



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

Wind bubble structure!



Initial settings:

E_{ej} = 10^{51} erg

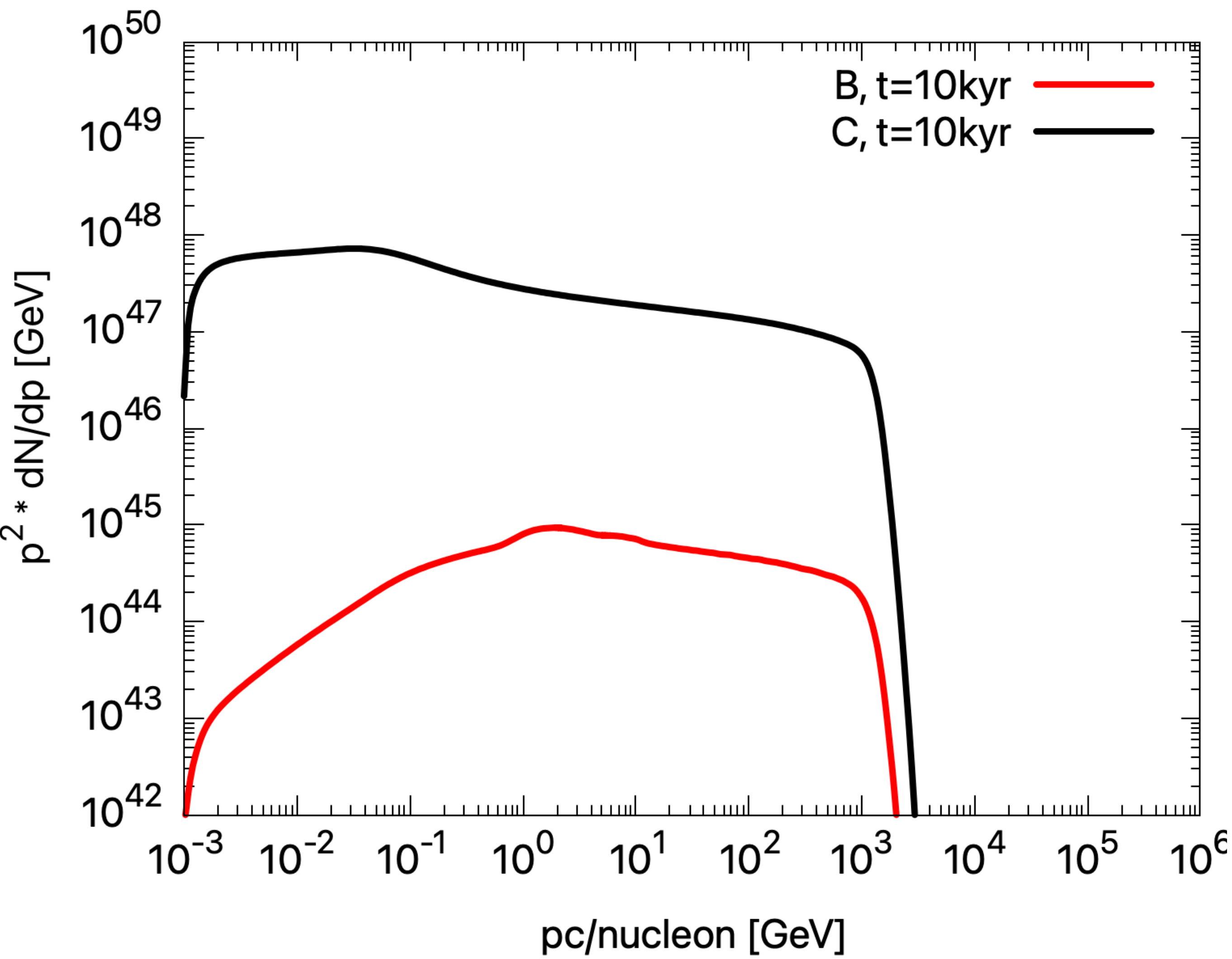
M_{ej} = 1.4 $M_{\odot}$, n_{ISM} = 10 cm-3

T_{ej}=10000 K

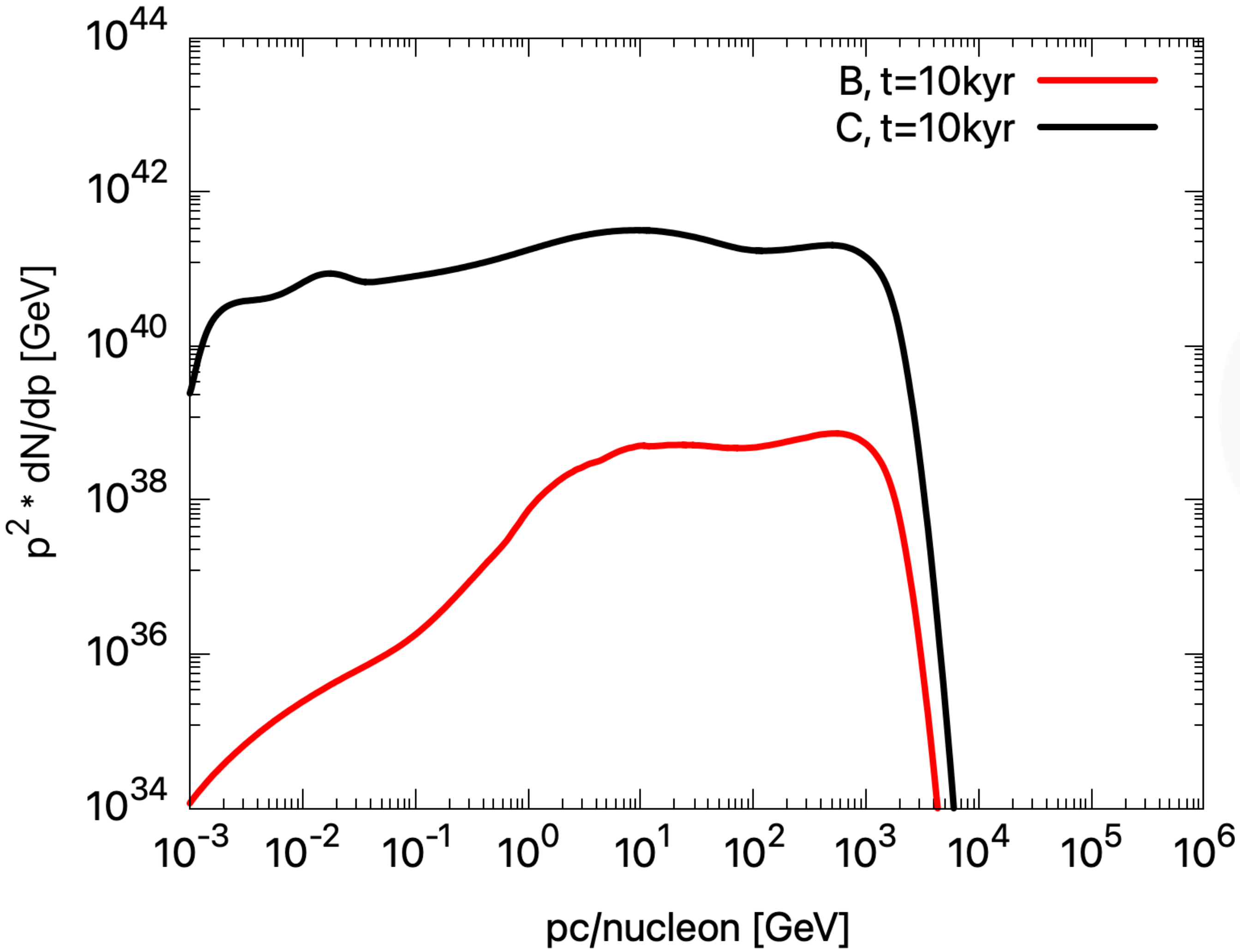
$$Q_B = n_H \cdot N_C \cdot v_C \cdot \sigma_{C-B} + n_H \cdot N_{OX} \cdot v_{OX} \cdot \sigma_{OX-B}$$

Total Momentum B-C Spectrum

Type-Ia SNR



Core-collaspe SNR



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

$$T_{SNR} = 10kyr$$

B/C(TeV)~0.001

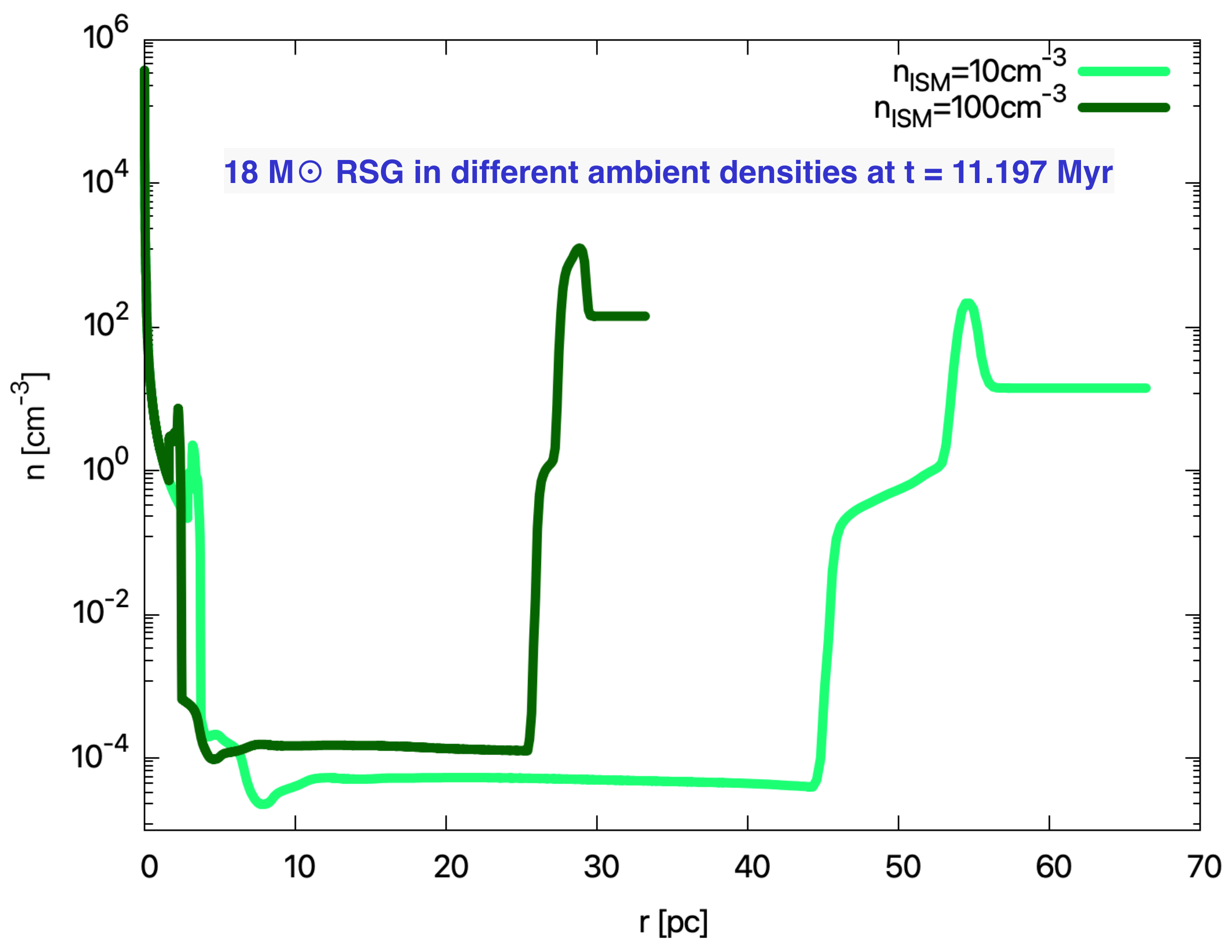
Simutation Runs

Type-Ia

Runs	$n_{\rm ISM}$	Diffusion	Magnetic field
R-1	1.0	*Turb*	TRA$(B_{up} = 5\mu G)$
R-2	10.0	*Turb*	TRA$(B_{up} = 5\mu G)$
R-3	100.0	*Turb*	TRA$(B_{up} = 5\mu G)$

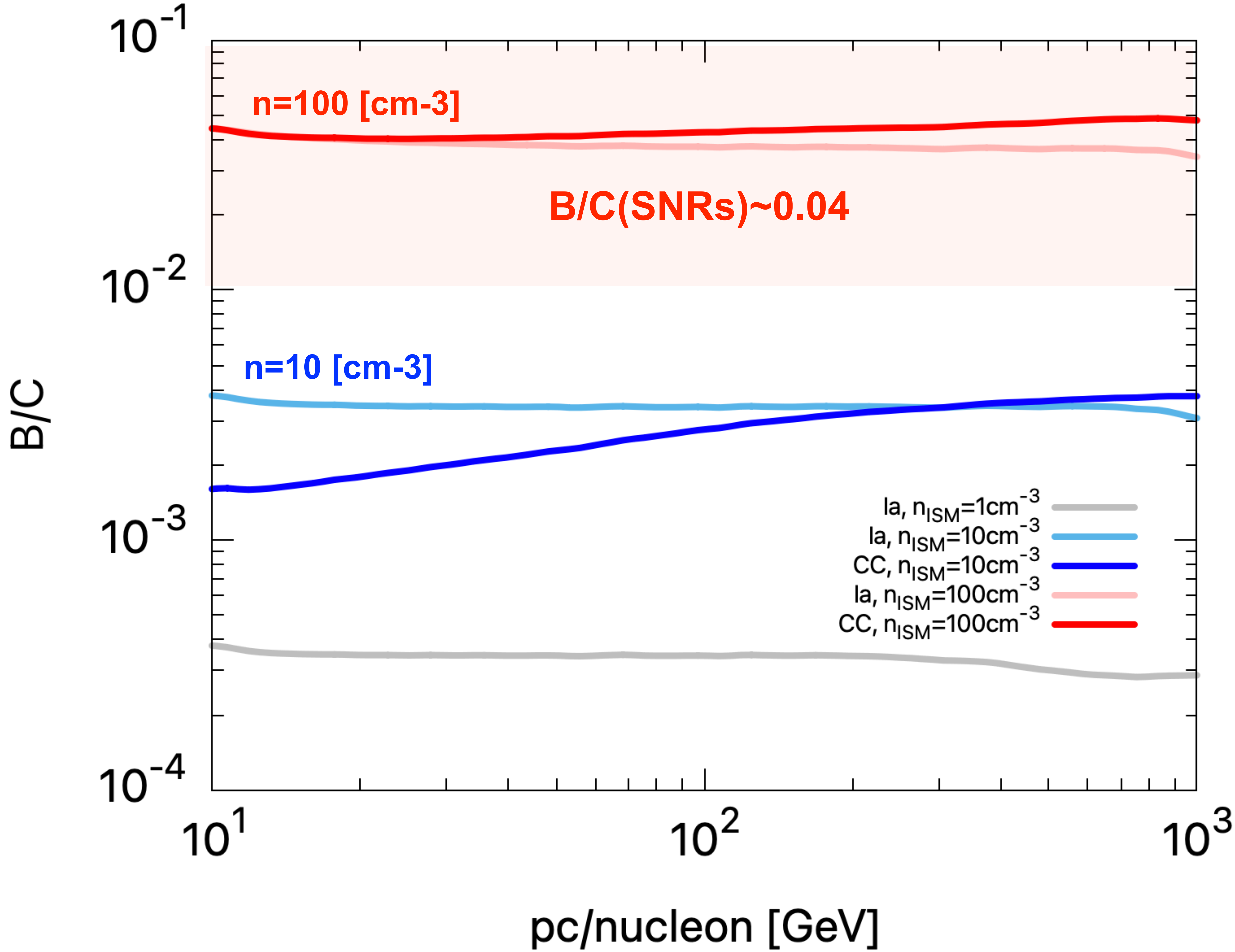
Core-collaspe

Runs	$n_{\rm ISM}$	Diffusion	Magnetic field
R-4	10.0	*Turb*	TRA$[\mathrm{B_0(r)}](\mathrm{B_{up}} = 5\mu\mathrm{G})$
R-5	100.0	*Turb*	TRA$[\mathrm{B_0(r)}](\mathrm{B_{up}} = 5\mu\mathrm{G})$



ALL Wind-Bubble Data are from Jonathan Mackey, DIAS

In-source B/C ratio (T_{SNR}=10kyr)



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: **~** 10^{-2}, depending on the diffusion model, the density of the source region, and the acceleration time.

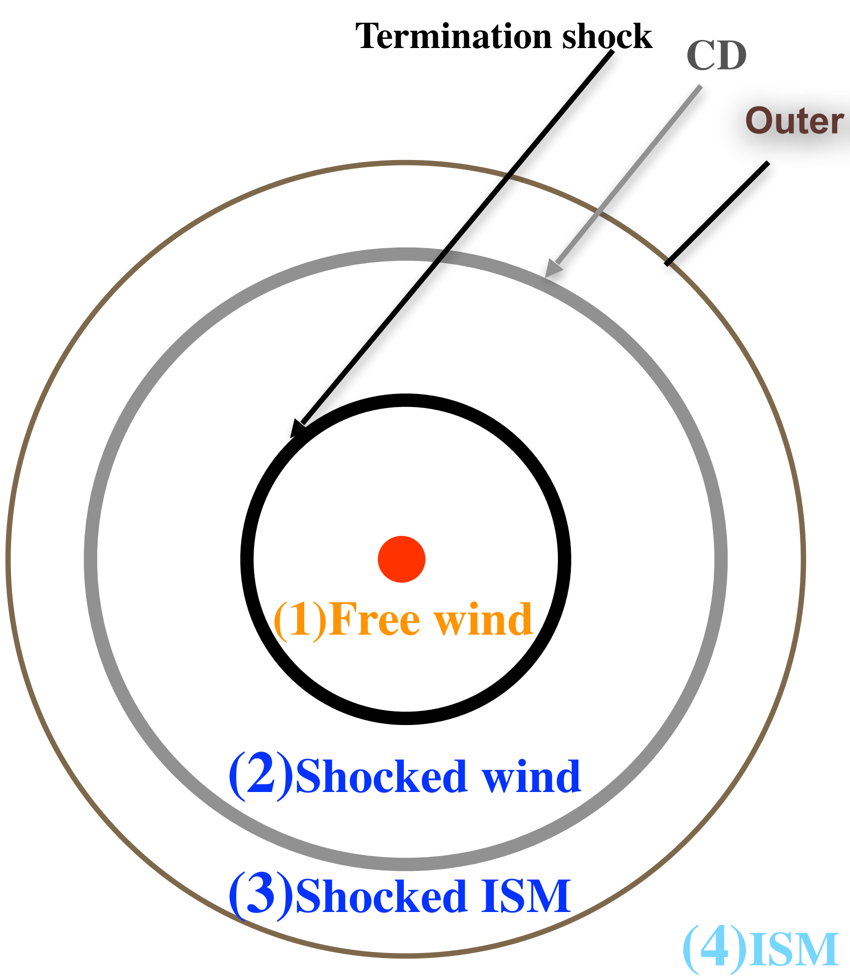
Backup

Stellar wind-blown bubble

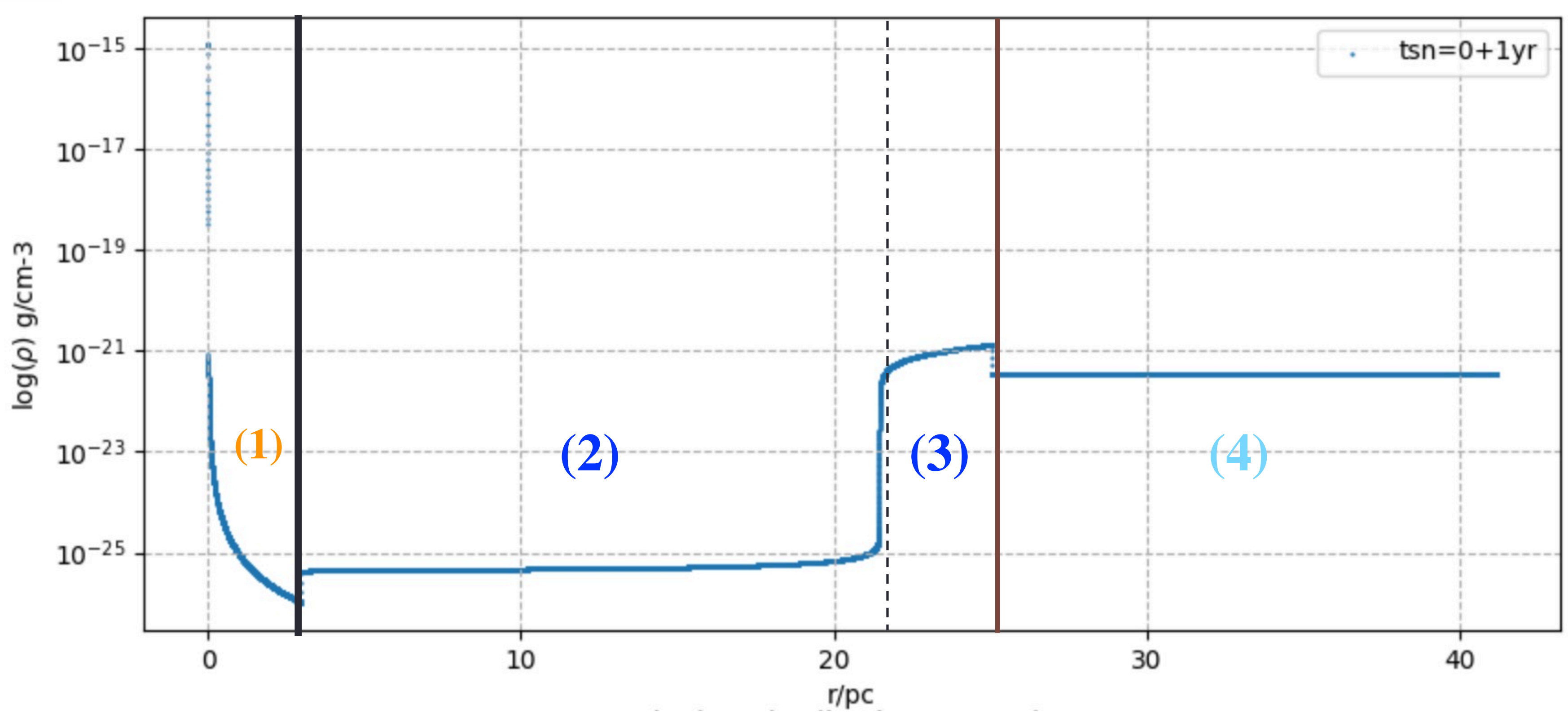
(NGC 7635)

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)



Cross-sections data:

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

Carbon reaction channel:

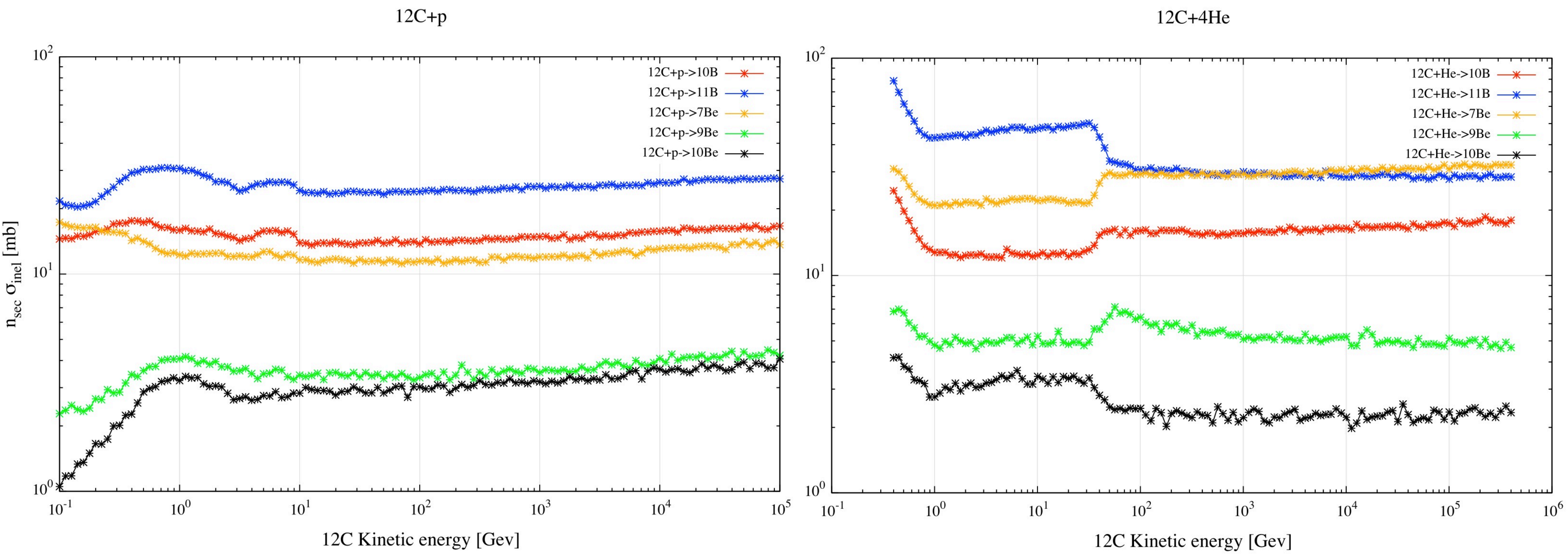


Fig.1. Inclusive cross sections for the production of spallation nuclei in collisions of ***^{12}C* with H and *^{4}He*** nuclei. The plots show the cross sections for the production of ***B (^{10}B , ^{11}B), Be (^{7}Be , ^{9}Be, ^{10}Be)***

Oxygen reaction channel:

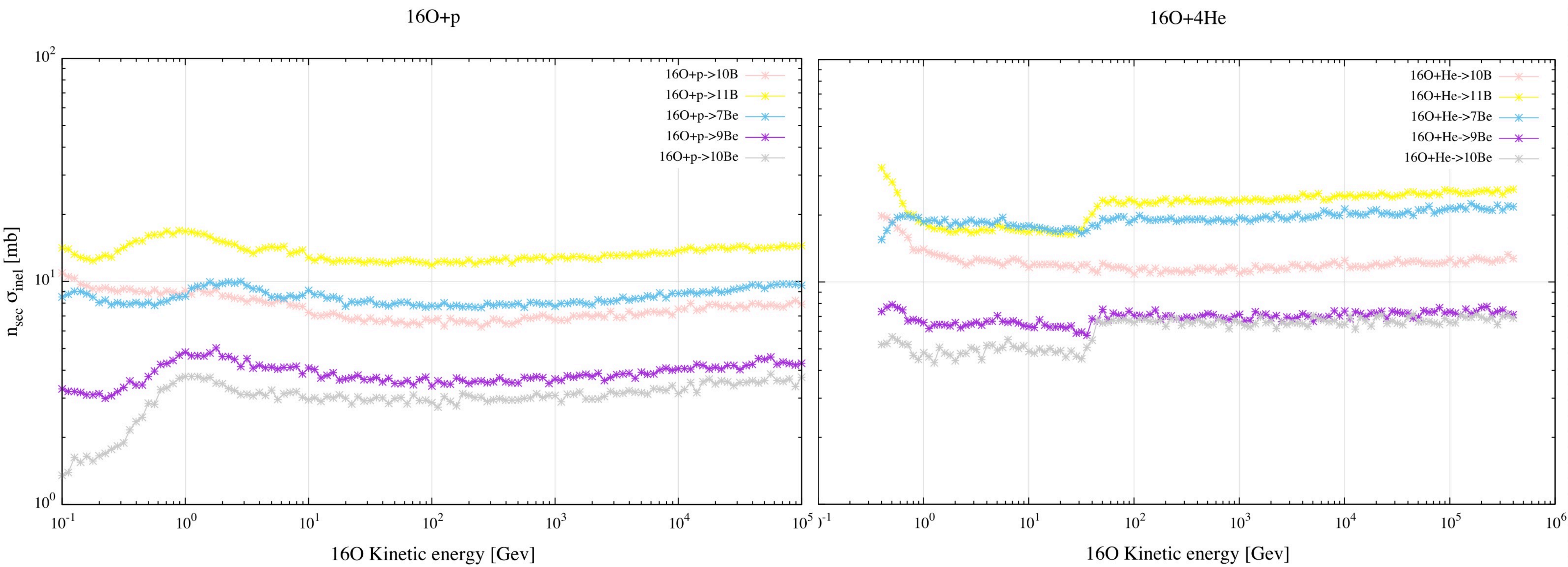
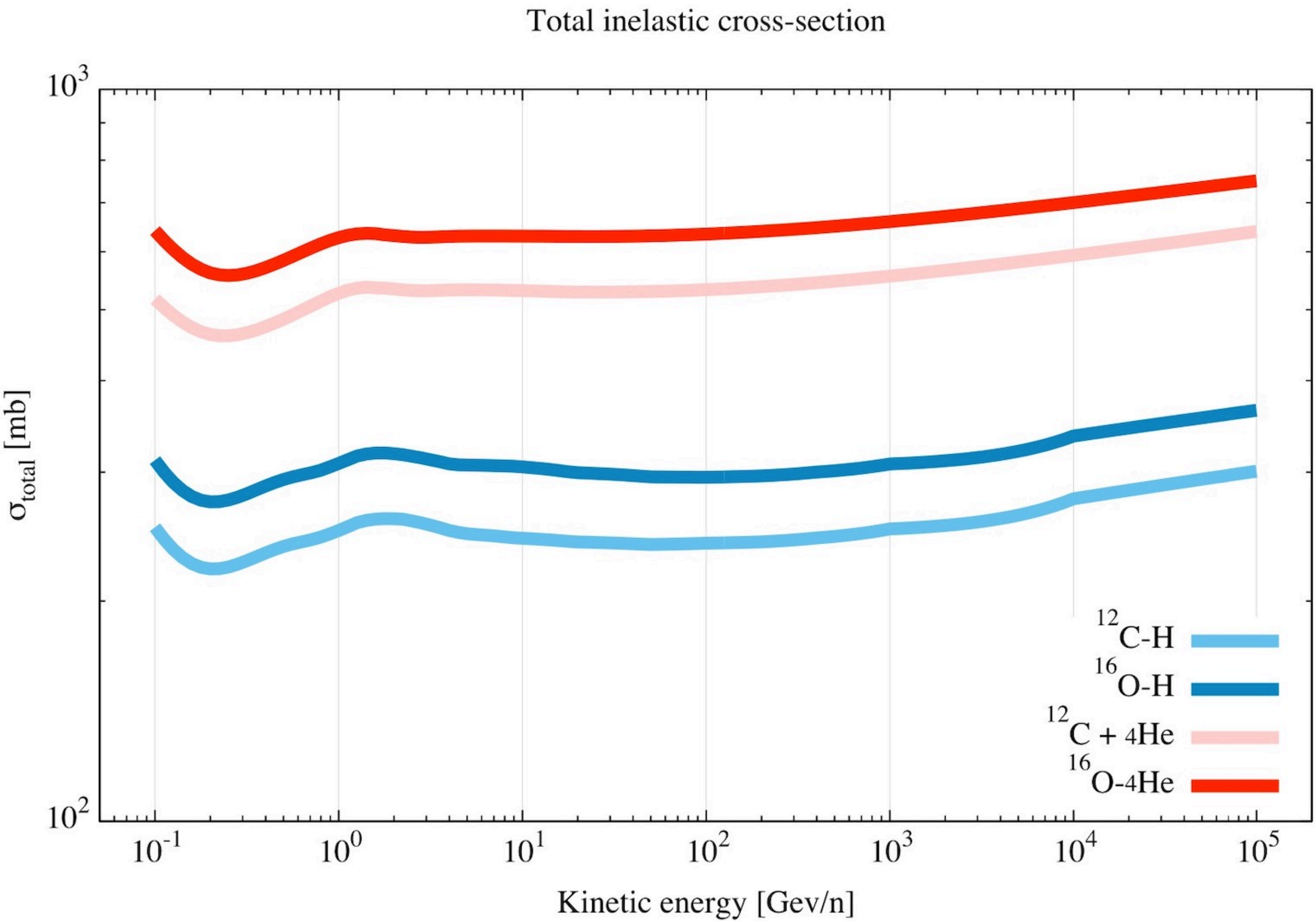


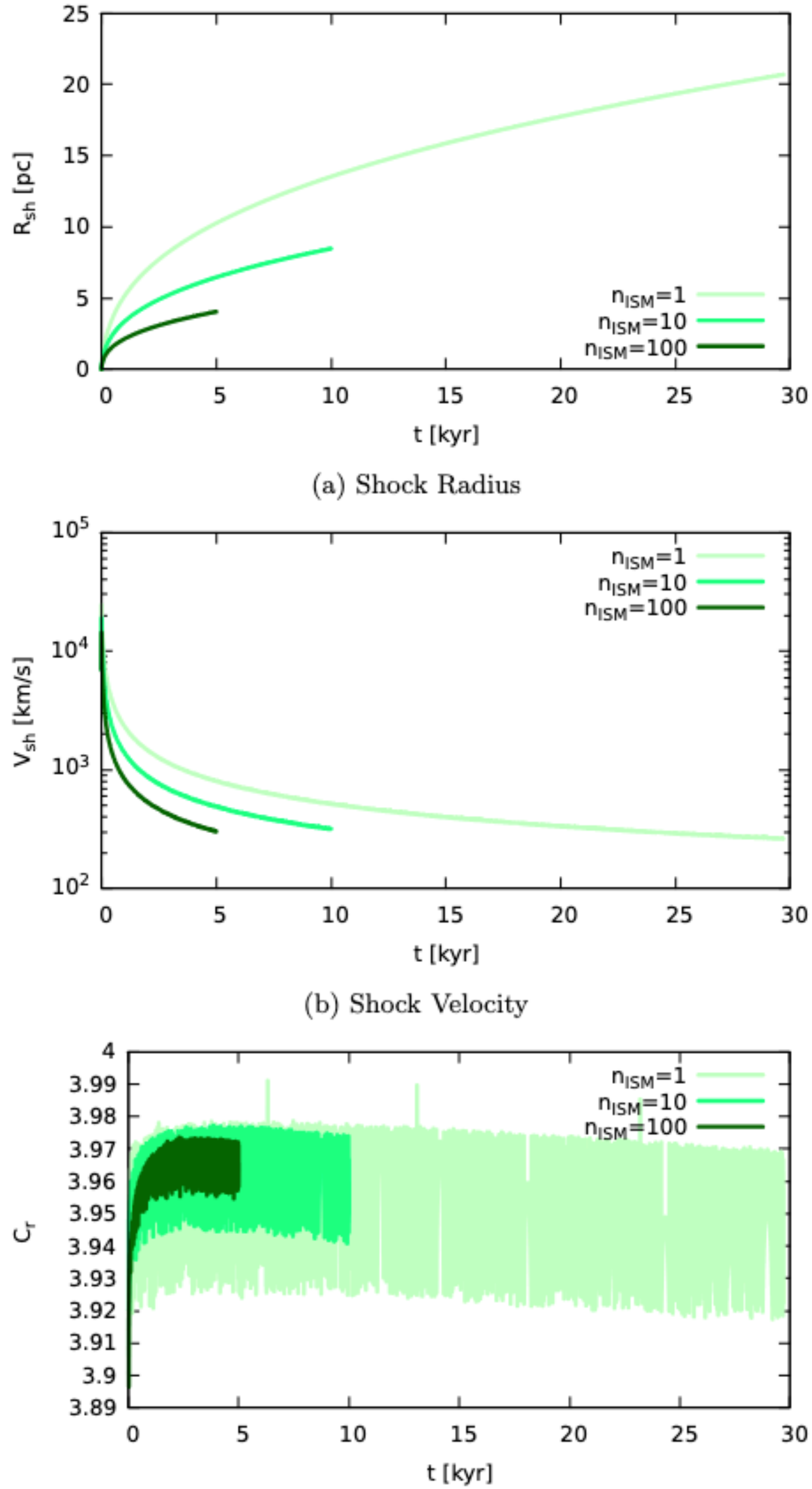
Fig.2. Inclusive cross sections for the production of spallation nuclei in collisions of ***^{16}O* with p and *^{4}He*** nuclei.

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
10^3
10^2
σ_{total} [mb]
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

HD-EVO
Type-Ia

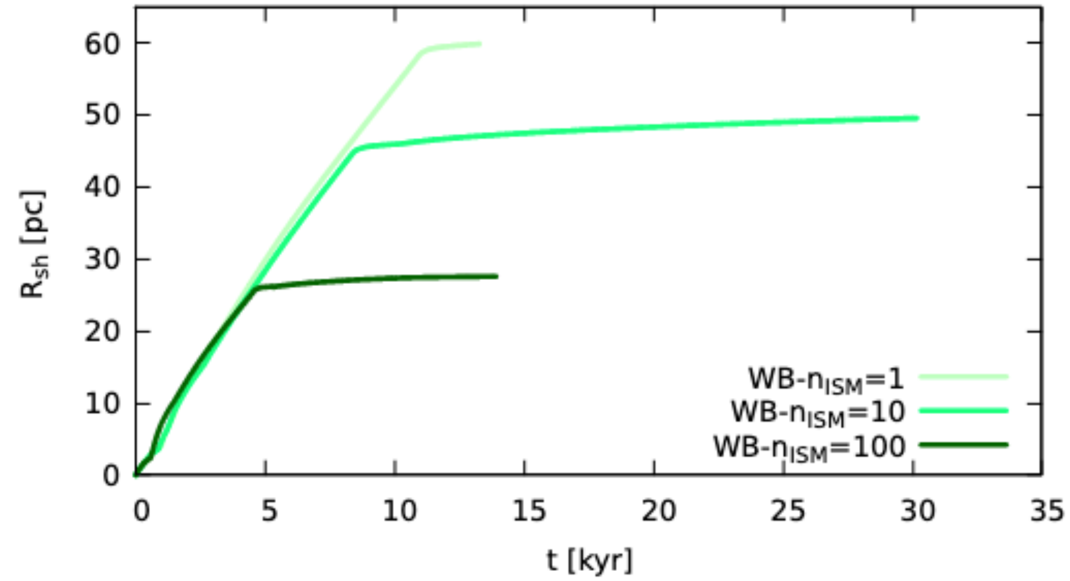


(a) Shock Radius

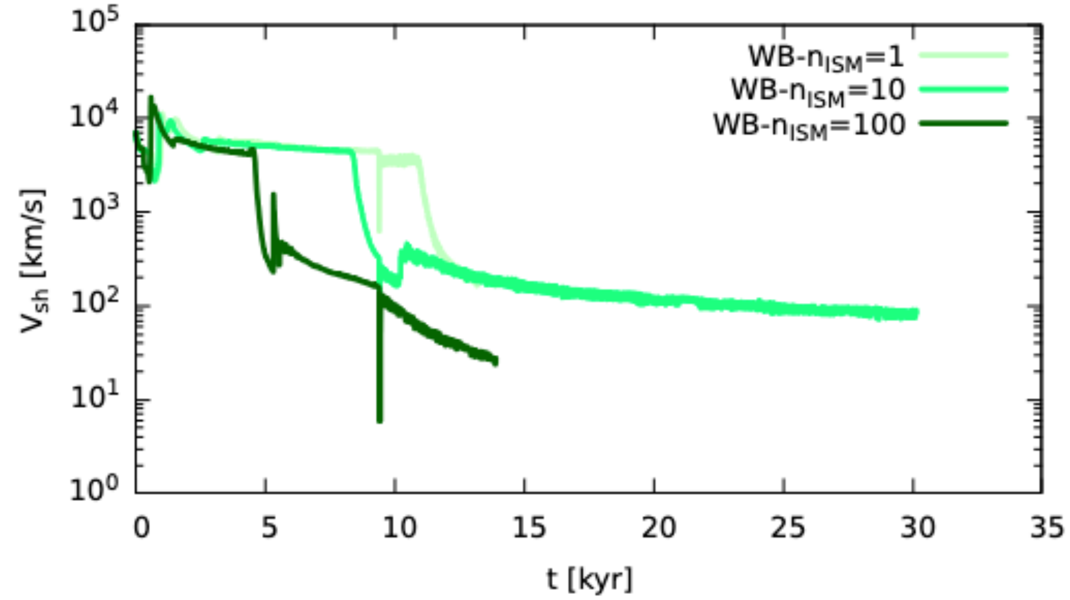
(b) Shock Velocity

(c) Compression ratio

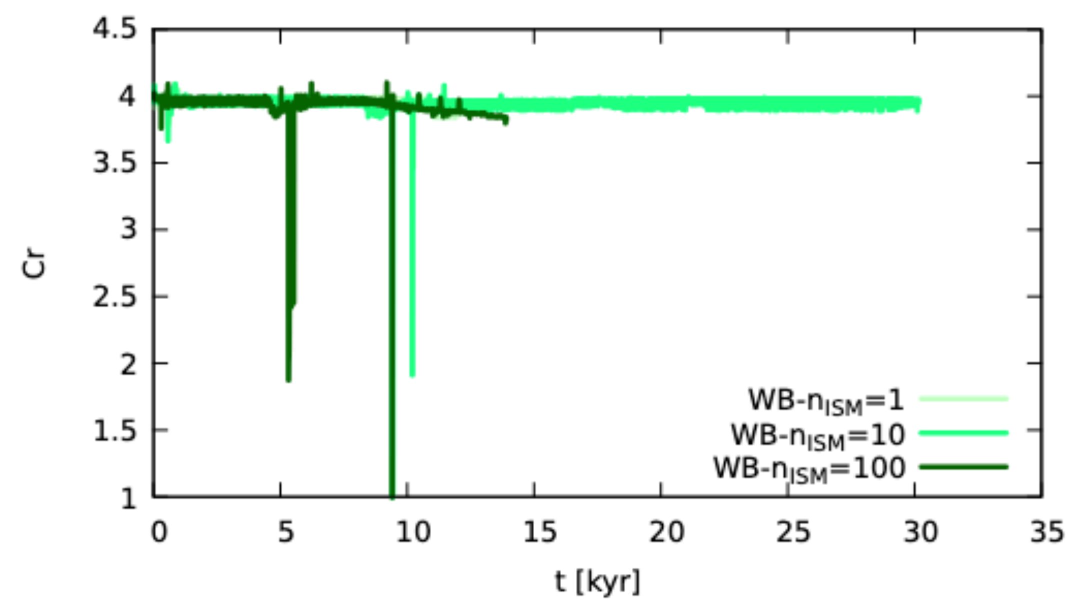
HD-EVO
CCSN



(a) Shock Radius



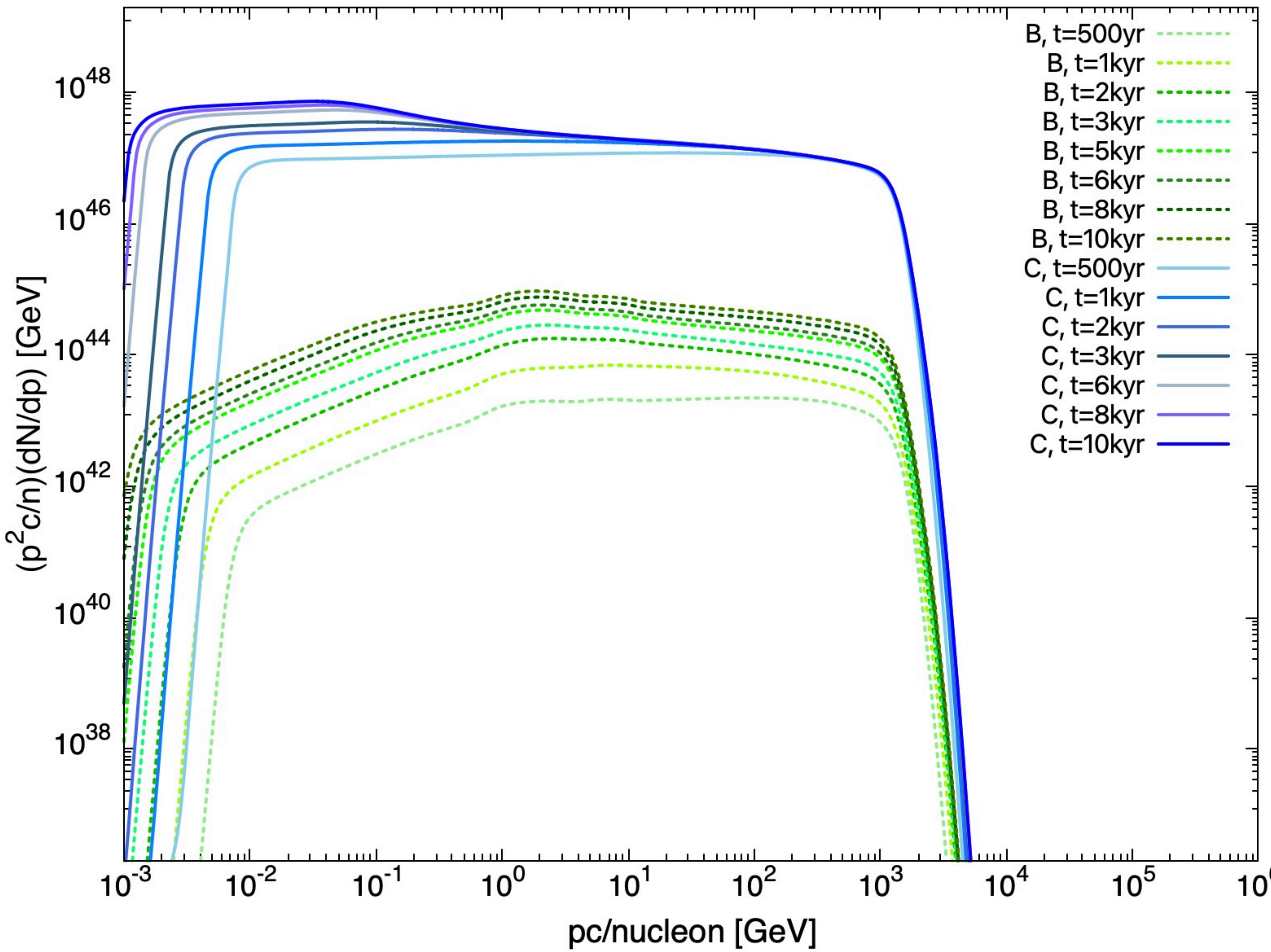
(b) Shock Velocity



(c) Compression ratio

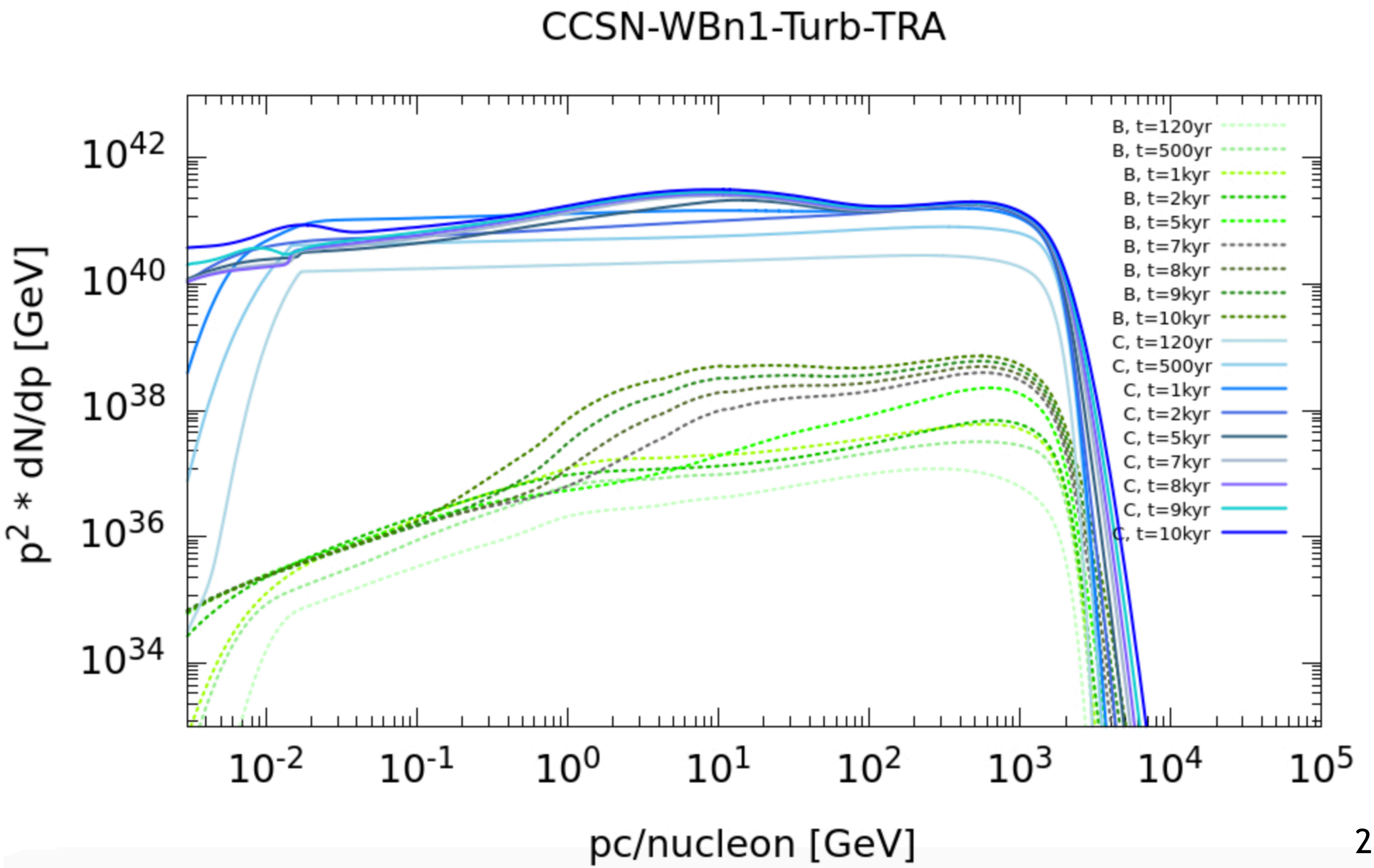
Total Momentum Spectrum

(Type-Ia)

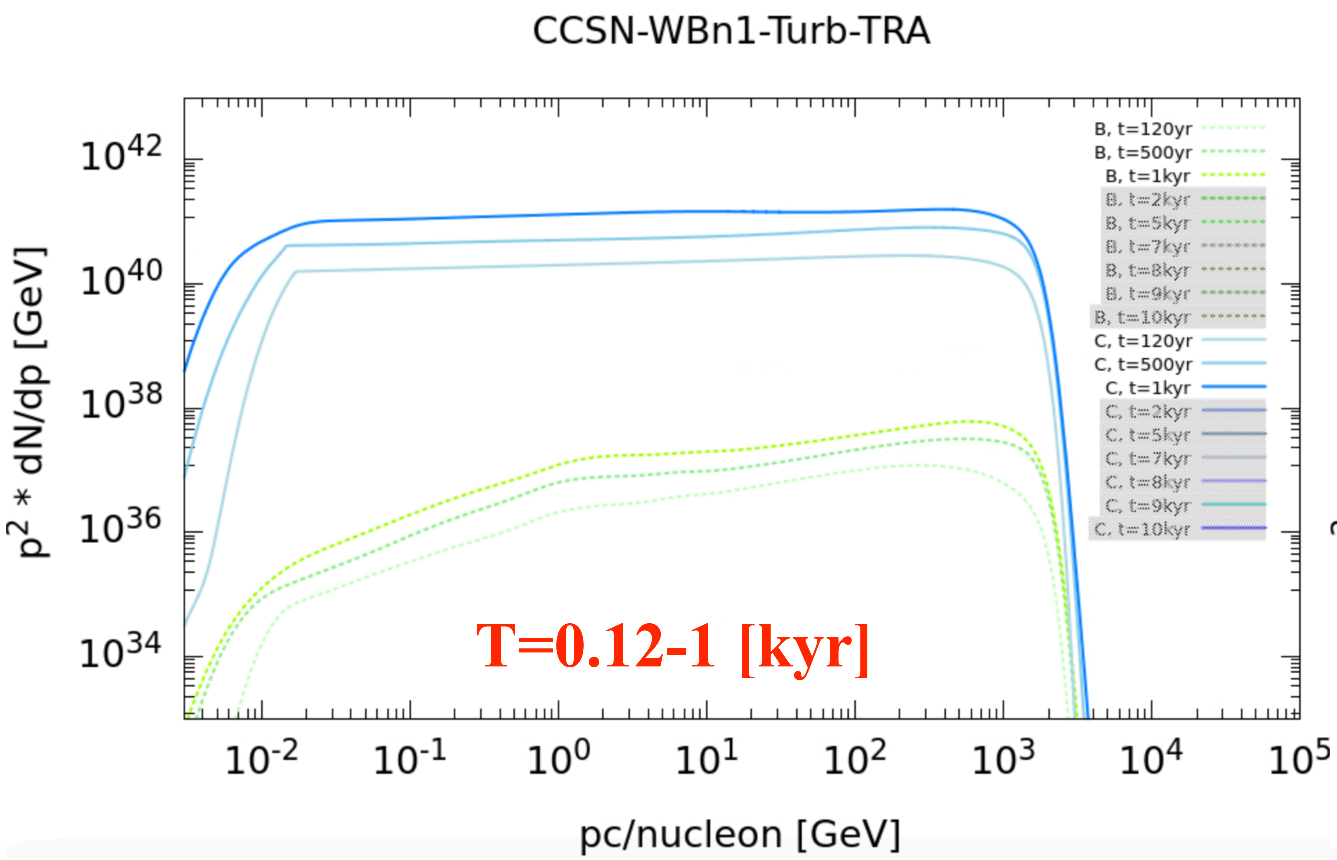


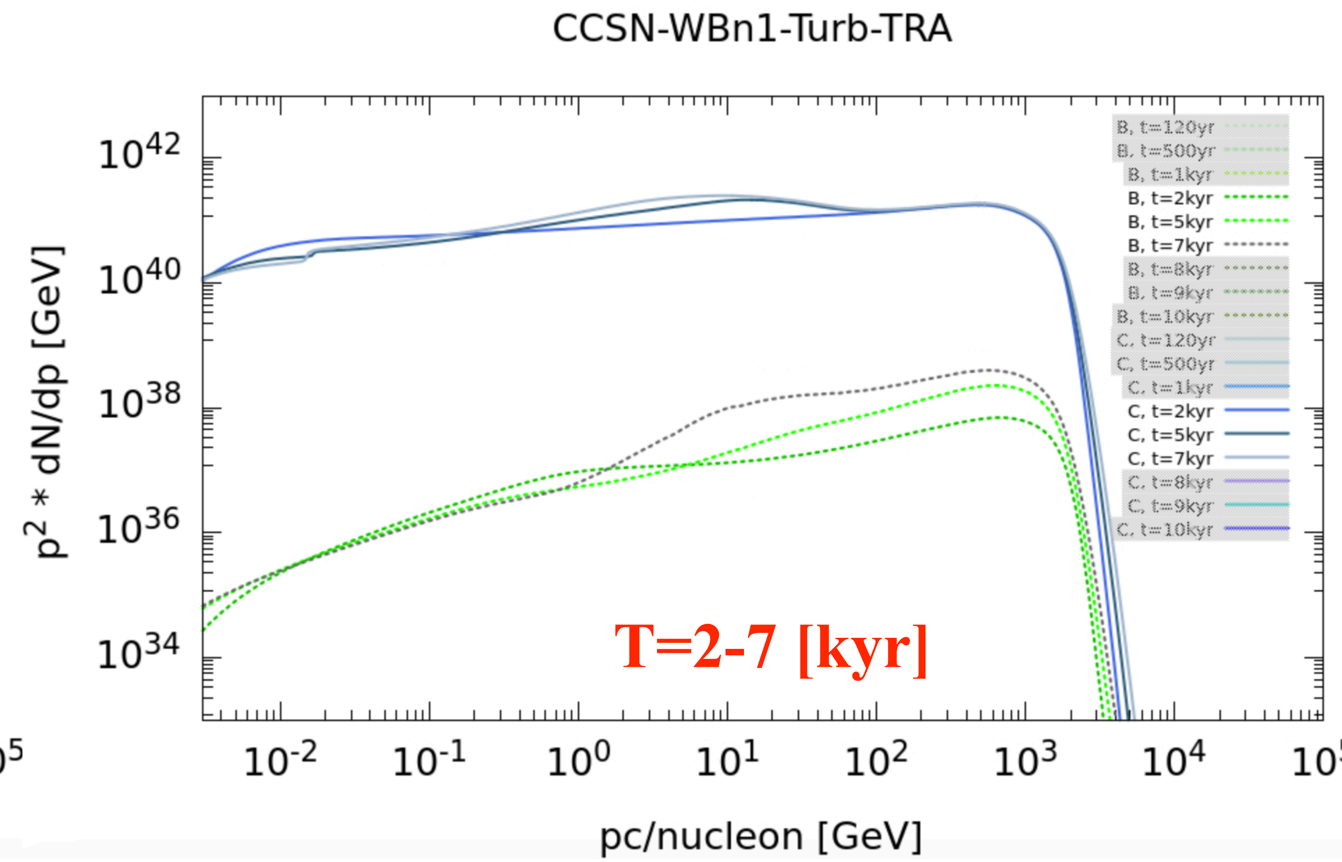
Total Momentum Spectrum

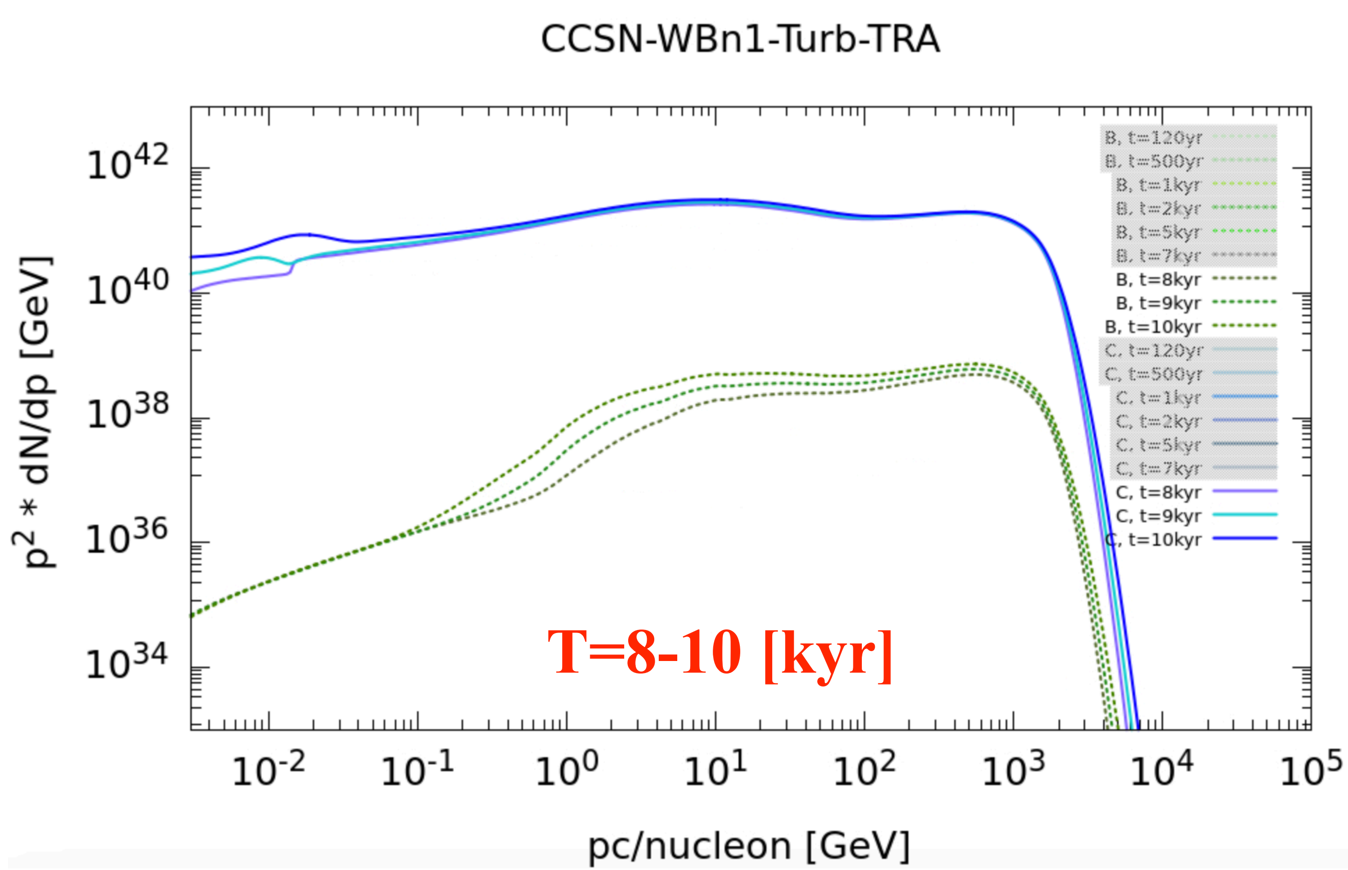
(Core-collapse)



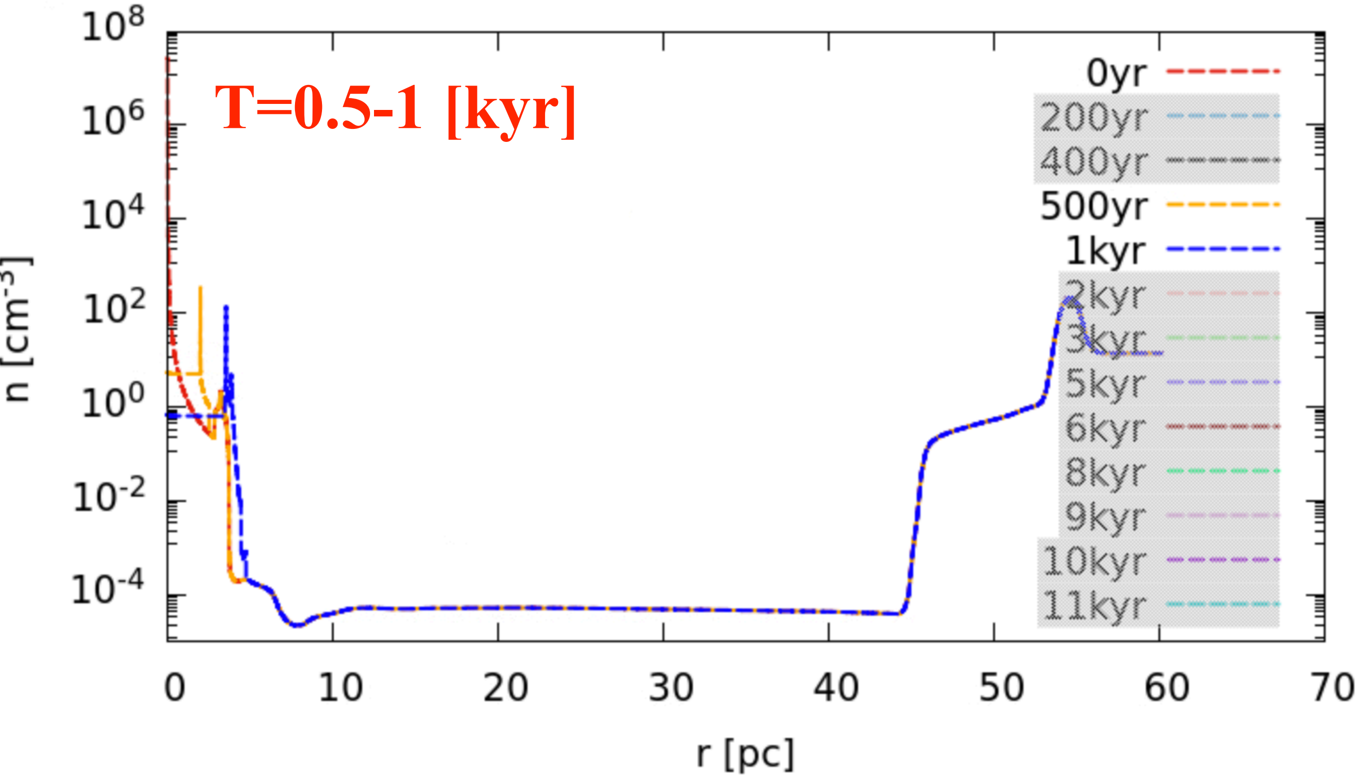
Spe-Evo


CCSN-WBn1-Turb-TRA
p^2 * dN/dp [GeV]
pc/nucleon [GeV]
T=0.12-1 [kyr]
B, t=120yr
B, t=500yr
B, t=1kyr
B, t=2kyr
B, t=5kyr
B, t=7kyr
B, t=8kyr
B, t=9kyr
B, t=10kyr
C, t=120yr
C, t=500yr
C, t=1kyr
C, t=2kyr
C, t=5kyr
C, t=7kyr
C, t=8kyr
C, t=9kyr
C, t=10kyr

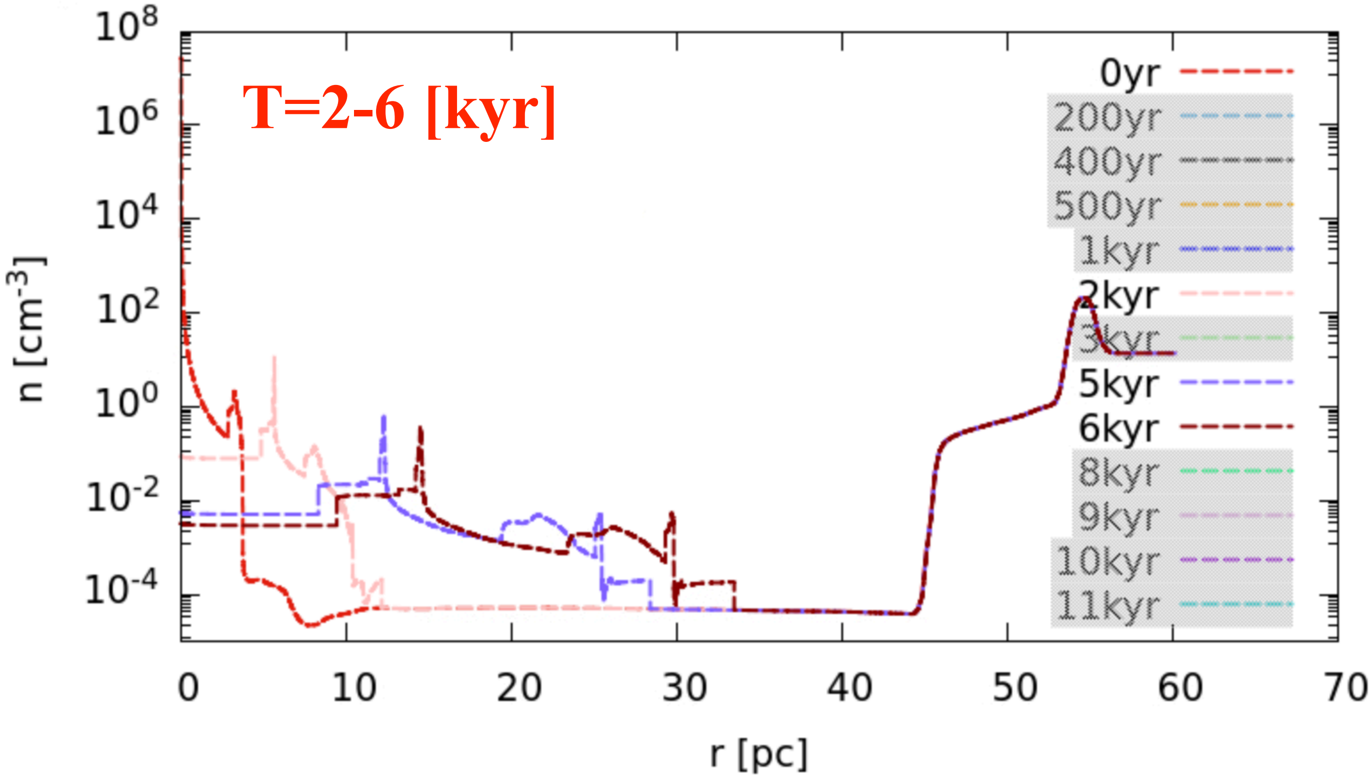

CCSN-WBn1-Turb-TRA
p^2 * dN/dp [GeV]
pc/nucleon [GeV]
T=2-7 [kyr]
B, t=120yr
B, t=500yr
B, t=1kyr
B, t=2kyr
B, t=5kyr
B, t=7kyr
B, t=8kyr
B, t=9kyr
B, t=10kyr
C, t=120yr
C, t=500yr
C, t=1kyr
C, t=2kyr
C, t=5kyr
C, t=7kyr
C, t=8kyr
C, t=9kyr
C, t=10kyr


CCSN-WBn1-Turb-TRA
p^2 * dN/dp [GeV]
pc/nucleon [GeV]
T=8-10 [kyr]
B, t=120yr
B, t=500yr
B, t=1kyr
B, t=2kyr
B, t=5kyr
B, t=7kyr
B, t=8kyr
B, t=9kyr
B, t=10kyr
C, t=120yr
C, t=500yr
C, t=1kyr
C, t=2kyr
C, t=5kyr
C, t=7kyr
C, t=8kyr
C, t=9kyr
C, t=10kyr

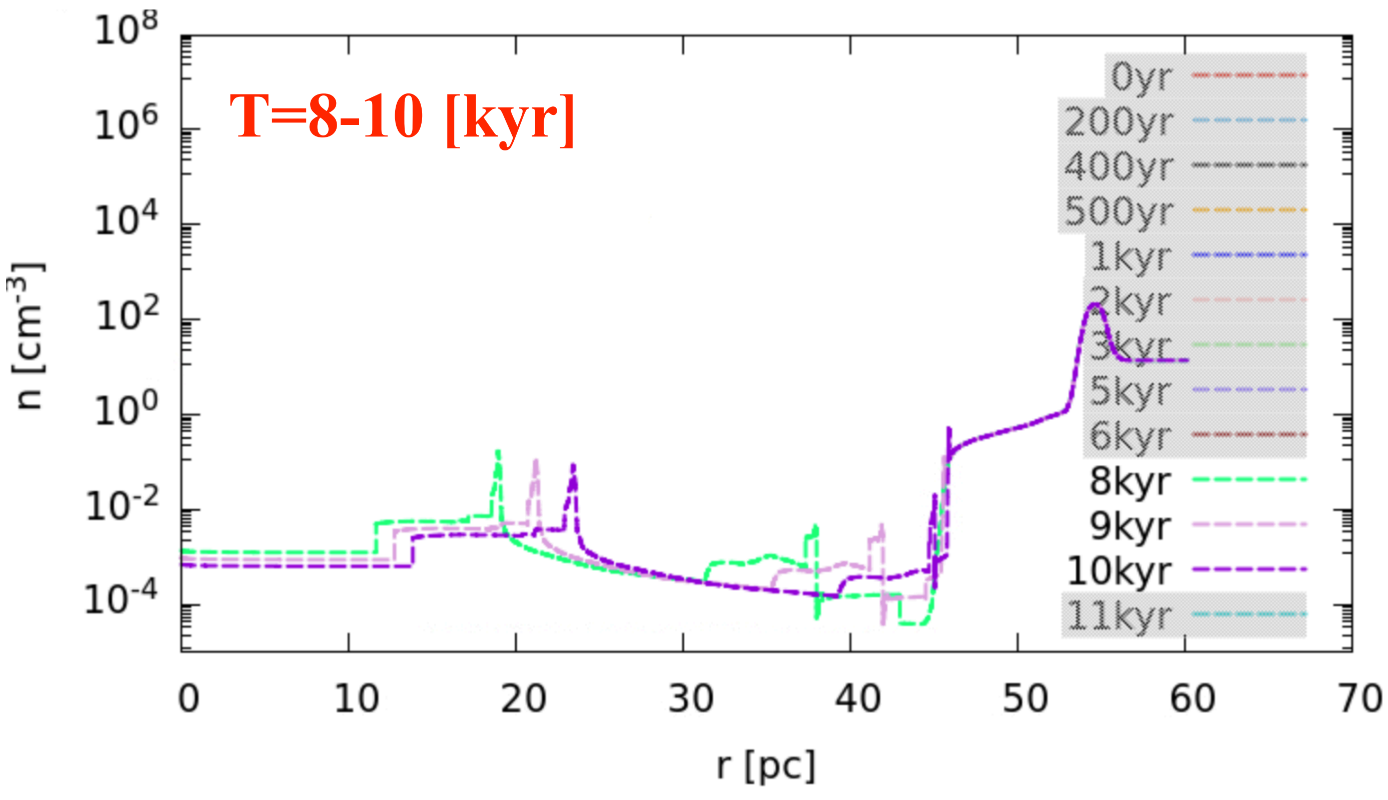
HD-Evo



T=0.5-1 [kyr]
0yr
200yr
400yr
500yr
1kyr
2kyr
3kyr
5kyr
6kyr
8kyr
9kyr
10kyr
11kyr
n [cm⁻³]
r [pc]



T=2-6 [kyr]
0yr
200yr
400yr
500yr
1kyr
2kyr
3kyr
5kyr
6kyr
8kyr
9kyr
10kyr
11kyr
n [cm⁻³]
r [pc]



T=8-10 [kyr]
0yr
200yr
400yr
500yr
1kyr
2kyr
3kyr
5kyr
6kyr
8kyr
9kyr
10kyr
11kyr
n [cm⁻³]
r [pc]