# Origin of Spectral Hardening of Secondary Cosmic Ray Nuclei

(NK & Lee 2021, ApJ, **917**, 61)


Norita Kawanaka (YITP, Kyoto University)

Shiu-Hang Lee (Department of Astronomy, Kyoto University)


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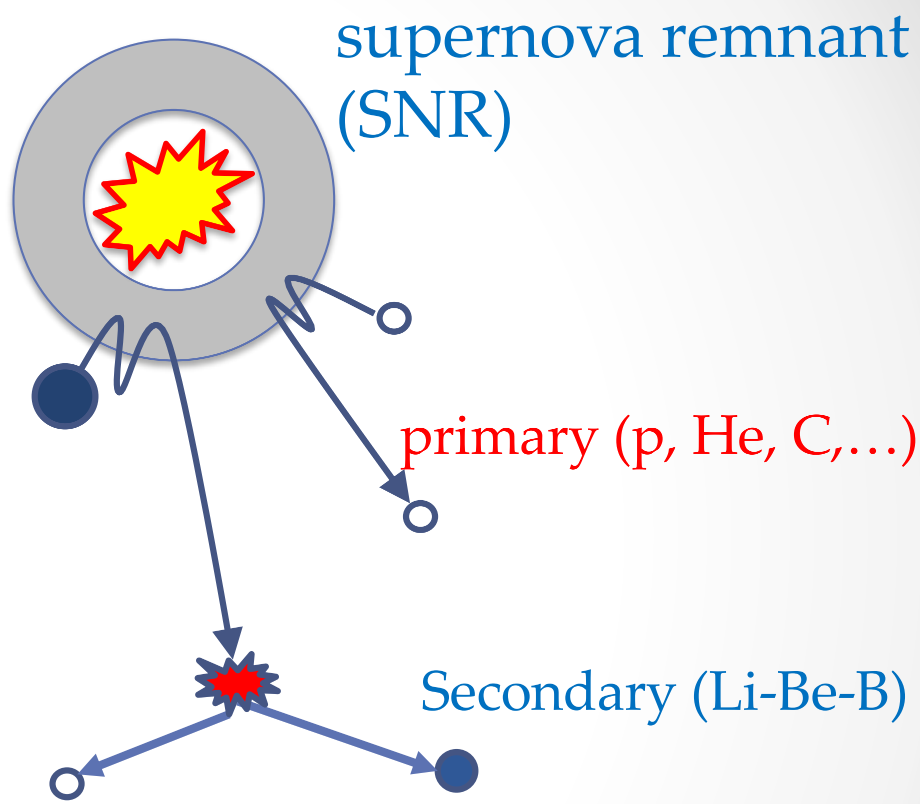
# Galactic Cosmic-rays (p, He, Li-Be-B, C,…)

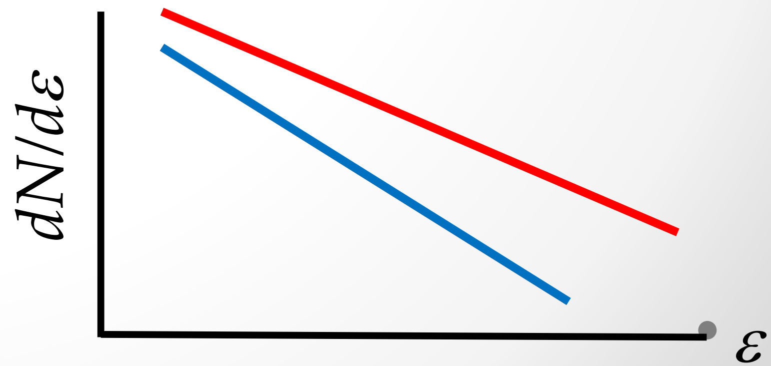
(probably) produced via diffusive shock acceleration at SNRs

**Conventional picture**

<u>proton, He, C, O, etc.</u> : primarily produced at SNRs, power-law spectrum

<u>Li-Be-B</u> : secondarily produced via spallation of heavier nuclei during propagation, having steeper spectrum than primary CRs



# Spectral hardening of CR nuclei

AMS-02:

**(1) The spectra of p, He, C, O, and Li-Be-B harden above ≳ 200GV**

**(2) Li, Be, and B harden more than He, C and O**

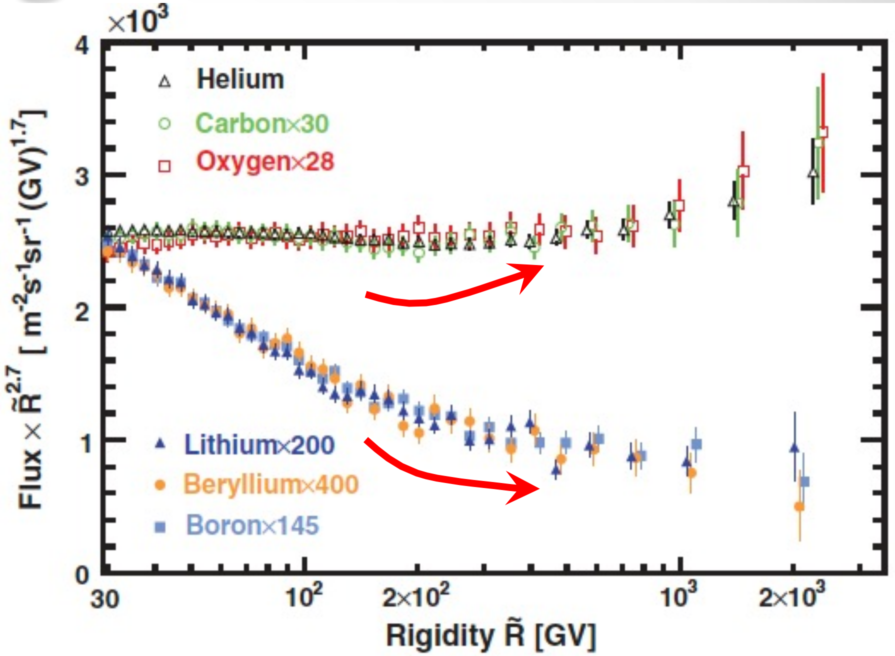
- propagation effect?

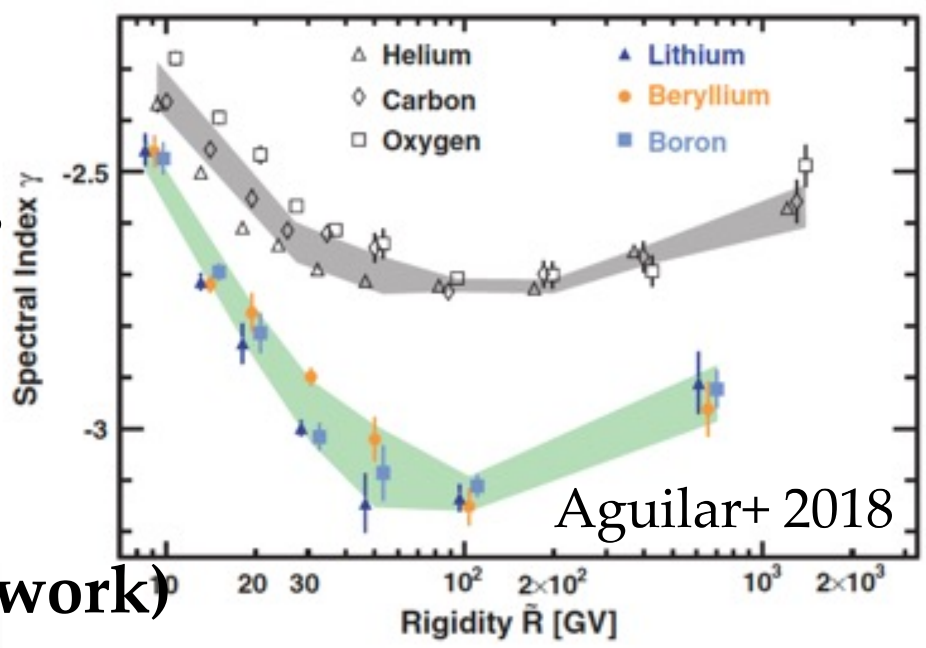
(Thoudam & Horandel 14; Blasi+ 12 etc.)

- reacceleration? (Bresci+ 19 etc.)
- superposition of different kinds of sources? (Niu+ 20 etc.)
- Only Li hardens? primary Li source?

(NK & Yanagita 2018; Boschini+ 2020)

- **Primary Li-Be-B source? (This work)**




Aguilar+ 2018

# Production, Acceleration, and Escape of CRs

NK & Lee 2021

Pri. CRs are accelerated at the SNR

→ interact w/ ambient medium

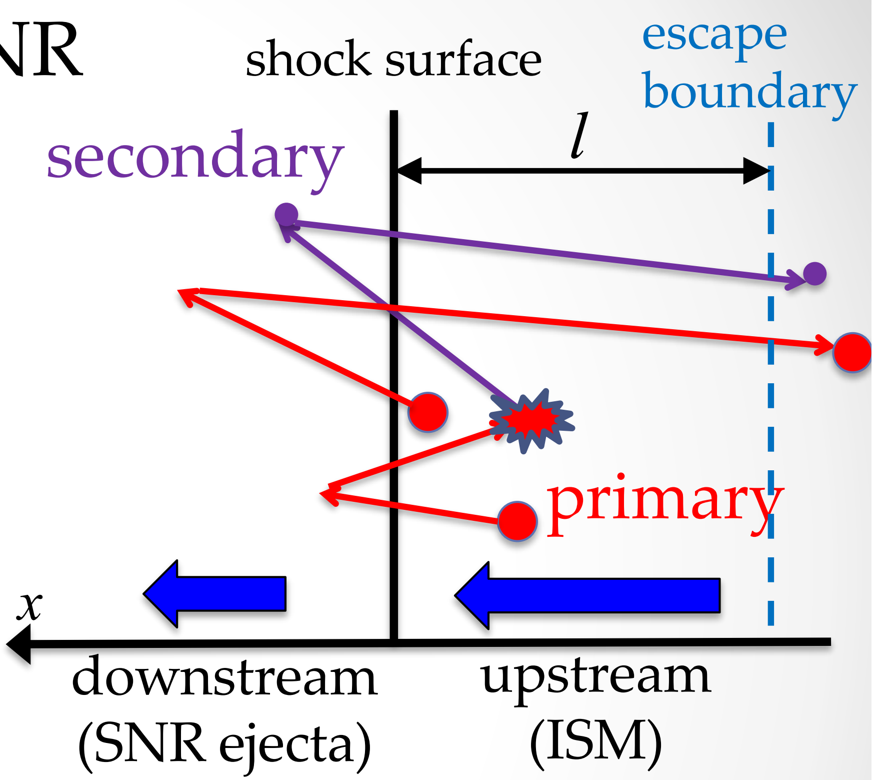
→ sec. CRs production

→ **sec. CRs are also accelerated**

(Mertsch & Sarkar 2009 etc.)

→ **High energy CRs escape the SNR into the ISM earlier**

(Gabici+ 2007, 2009; Ohira+ 2010)




escape condition

$$\frac{D_{SNR}(p)}{u_-} > l \Leftrightarrow p > \frac{u_- l}{D_0} p_0 \equiv p_{esc}(t)$$

diffusion coefficient ($D_{SNR}(p)$)

fluid velocity in the upstream ($u_-$)

distance from the shock to the escape boundary (~size of the SNR) ($l$)

decreases with $t$ ($p_{esc}(t)$)

# CR distribution function $f_i$ at the SNR

NK and Lee 2021

**diffusion-convection equation**

$$u(x)\frac{\partial f_i}{\partial x} = \frac{\partial}{\partial x}\left[D_i(p)\frac{\partial f_i}{\partial x}\right] + \frac{p}{3}\frac{du}{dx}\frac{\partial f_i}{\partial p} - \Gamma_i f_i + q_i + u_- Q_i \delta(x)\delta(p-p_0),$$

$i$ = p, He, Li, Be, B, C, N, O

$\Gamma_i = \Sigma_{i>j}\Gamma_{i\to j}$: spallation rate of nuclei $i$

$Q_i$: injection rate of nuclei $i$

$q_i \sim \Sigma_{i<j}\Gamma_{j\to i} f_j$: injection rate due to the spallation

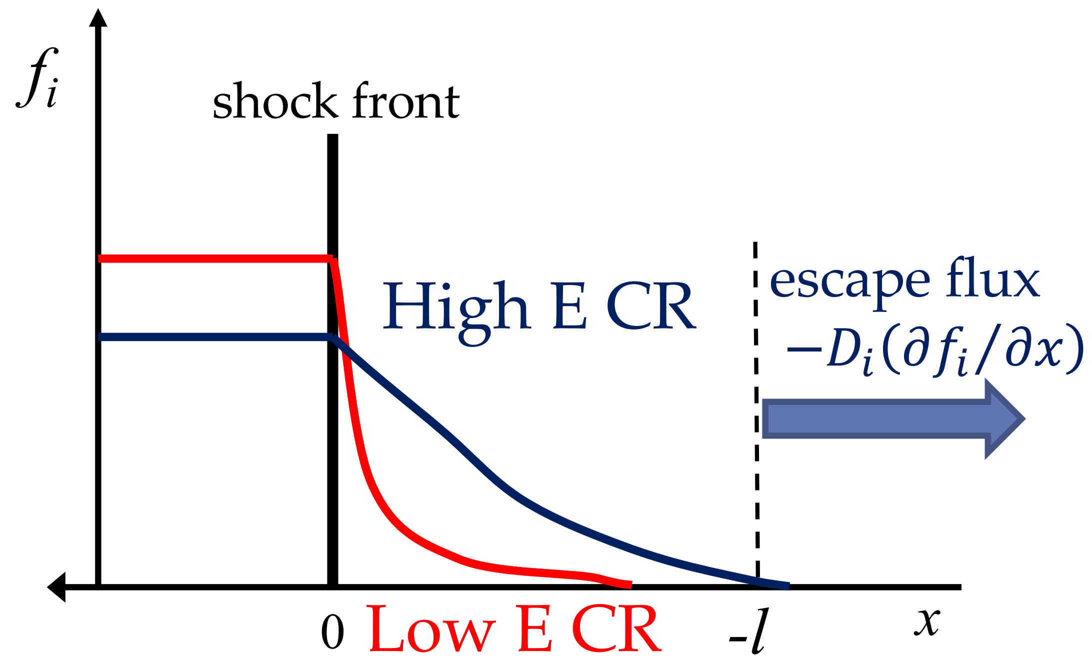
## Boundary conditions

(i) $\lim_{x\to -0} f_i = \lim_{x\to +0} f_i,$

(ii) $\lim_{x\to -l} f_i = 0,$

(iii) $\left|\lim_{x\to +\infty} f_i\right| < \infty,$

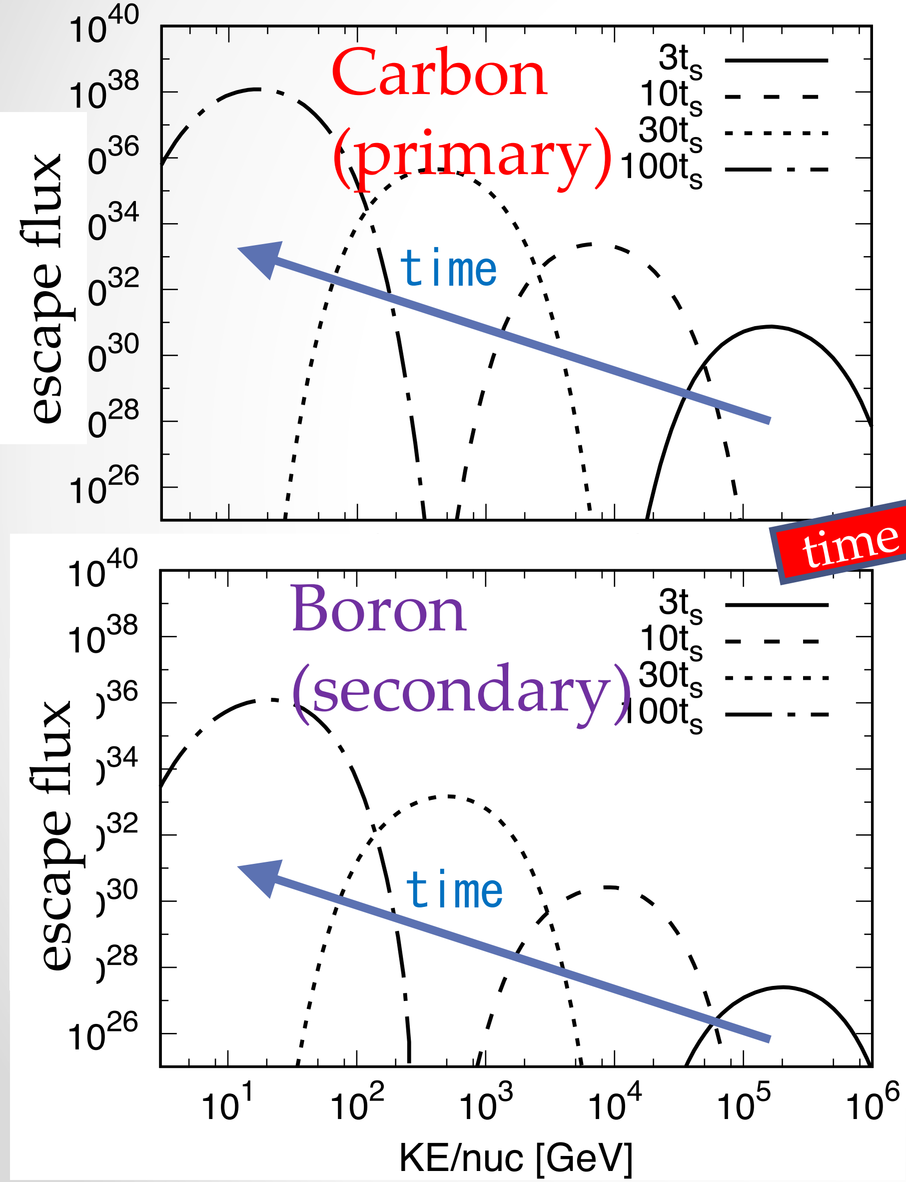
(iv) $\left[D_i(p)\frac{\partial f_i}{\partial x}\right]_{x=+0}^{x=-0} = \frac{1}{3}(u_+ - u_-)p\frac{\partial f_{i,0}}{\partial p} + u_- Q_i \delta(p-p_0),$



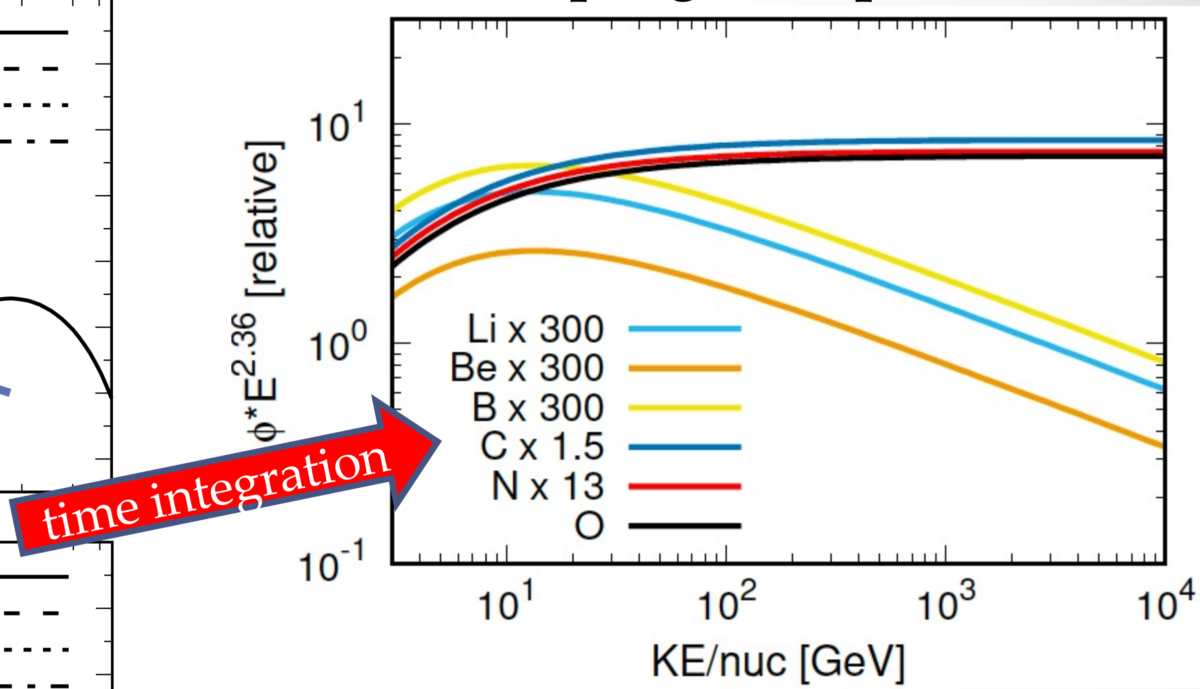
# Case 1: uniform ISM ($n_{amb}$ = const.)

NK & Lee 2021

$n_{amb}$ = 0.1 $cm^{-3}$




Escaping CR spectra



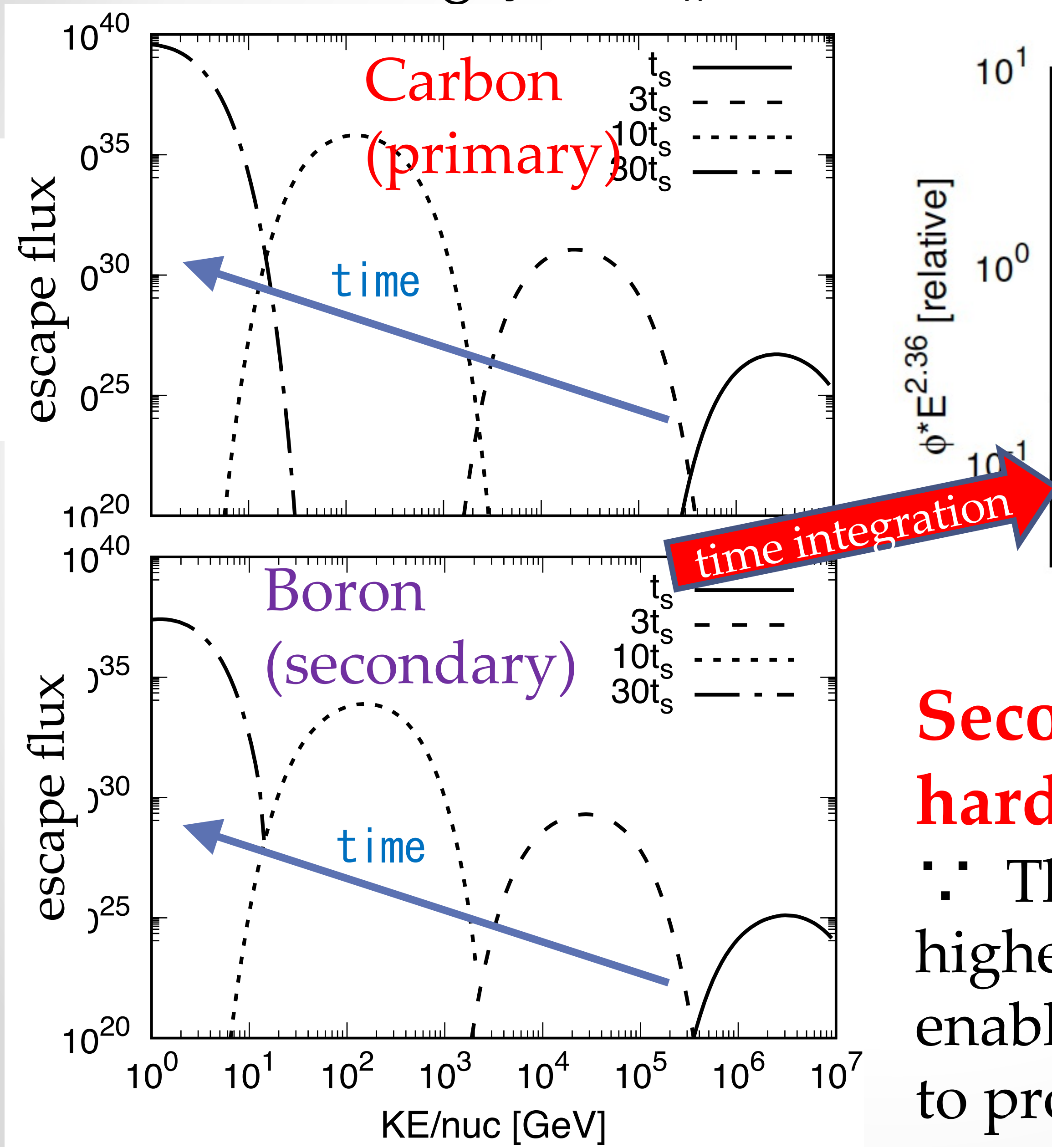

Secondaries are always softer than primaries ☹

∵ High energy primaries escape the SNR earlier and produce less secondaries.

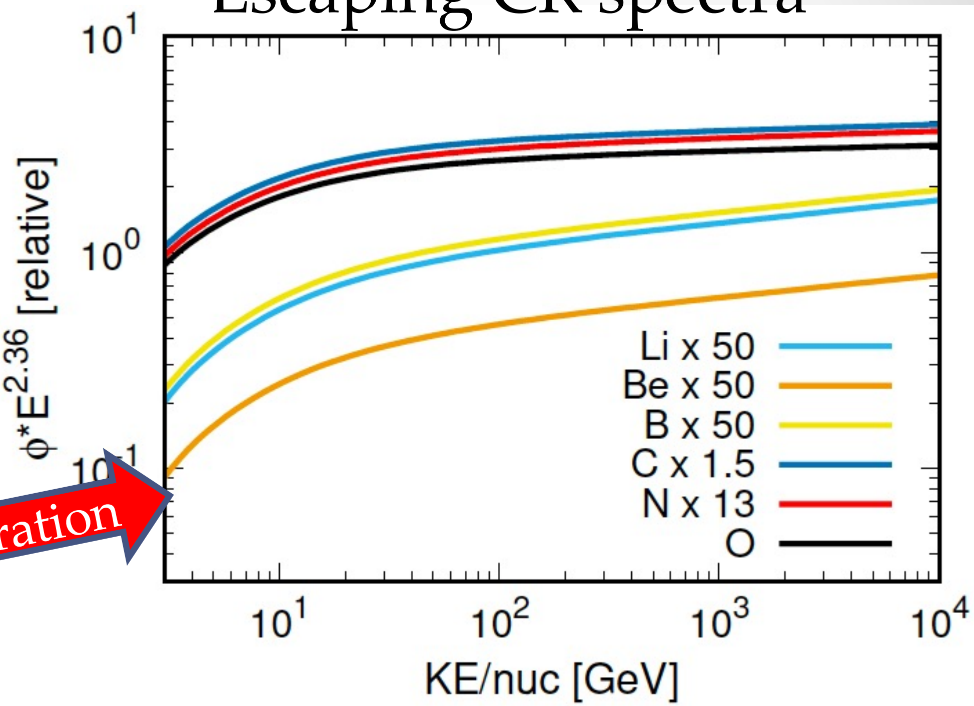
# Case 2: SN with dense CSM ($n_{amb} \propto r^{-2}$)

$\dot{M} = 1\times10^{-3} M_{\odot}\ \mathrm{yr}^{-1}$, $v_w = 100\ \mathrm{km\ s}^{-1}$

NK and Lee 2021




Escaping CR spectra




**Secondaries are always harder than primaries ☺**

∵ The ambient density is higher in the early phase, which enables high energy primaries to produce more secondaries.

# Fitting to the AMS-02 data

NK & Lee 2021

**a local SNR with CSM:**

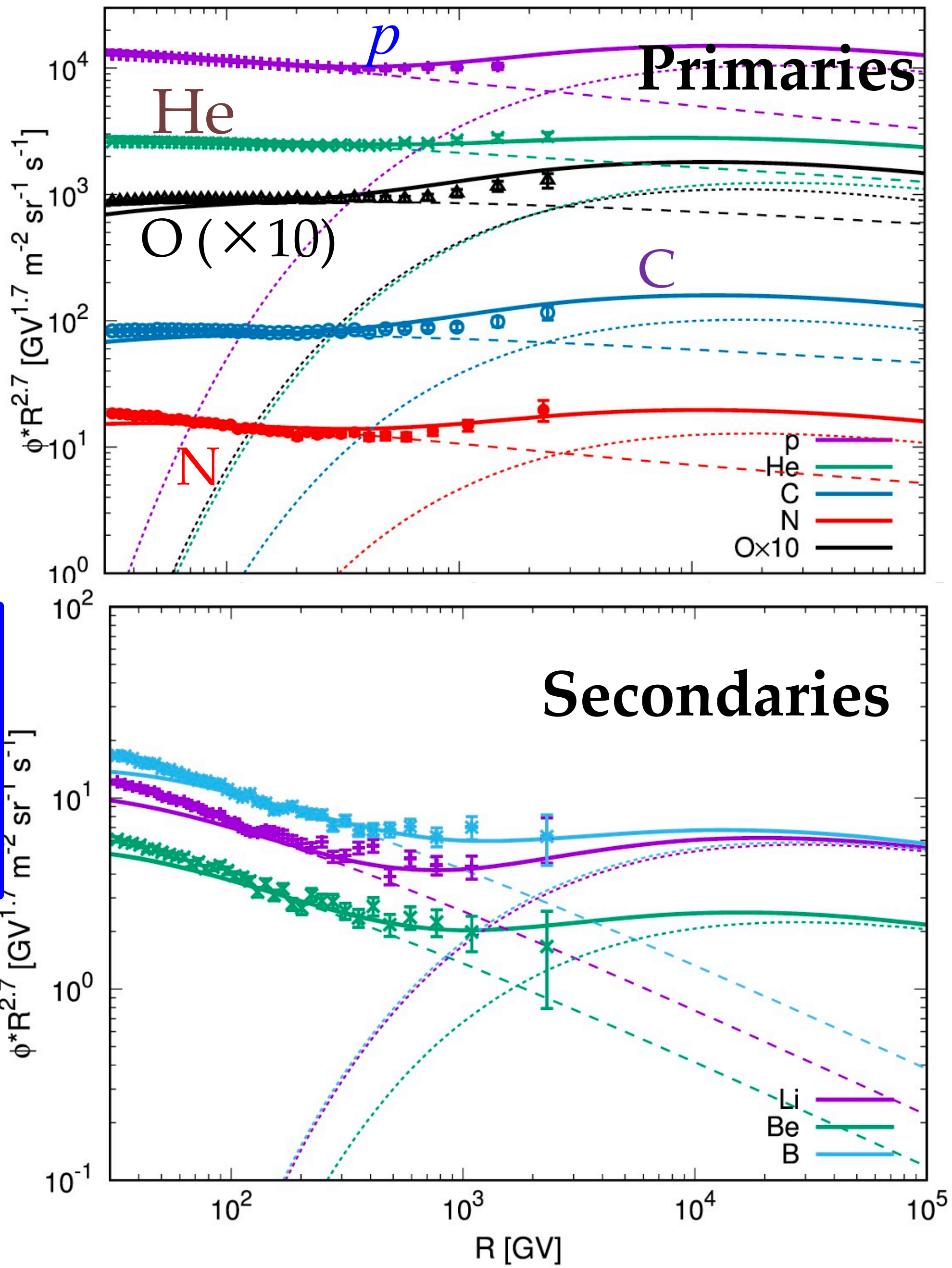
(dotted lines)

$$\begin{cases} \dot{M} = 2.5\times10^{-3} M_\odot \ \mathrm{yr}^{-1}, \\ v_w = 100 \ \mathrm{km\ s}^{-1}, \\ E_{\rm SN} = 10^{51} \mathrm{erg}, \eta_{\rm CR} = 0.1 \\ \text{age: } 1.6 \times 10^5 \ \mathrm{yr} \\ \text{distance: } 1.6 \ \mathrm{kpc} \end{cases}$$

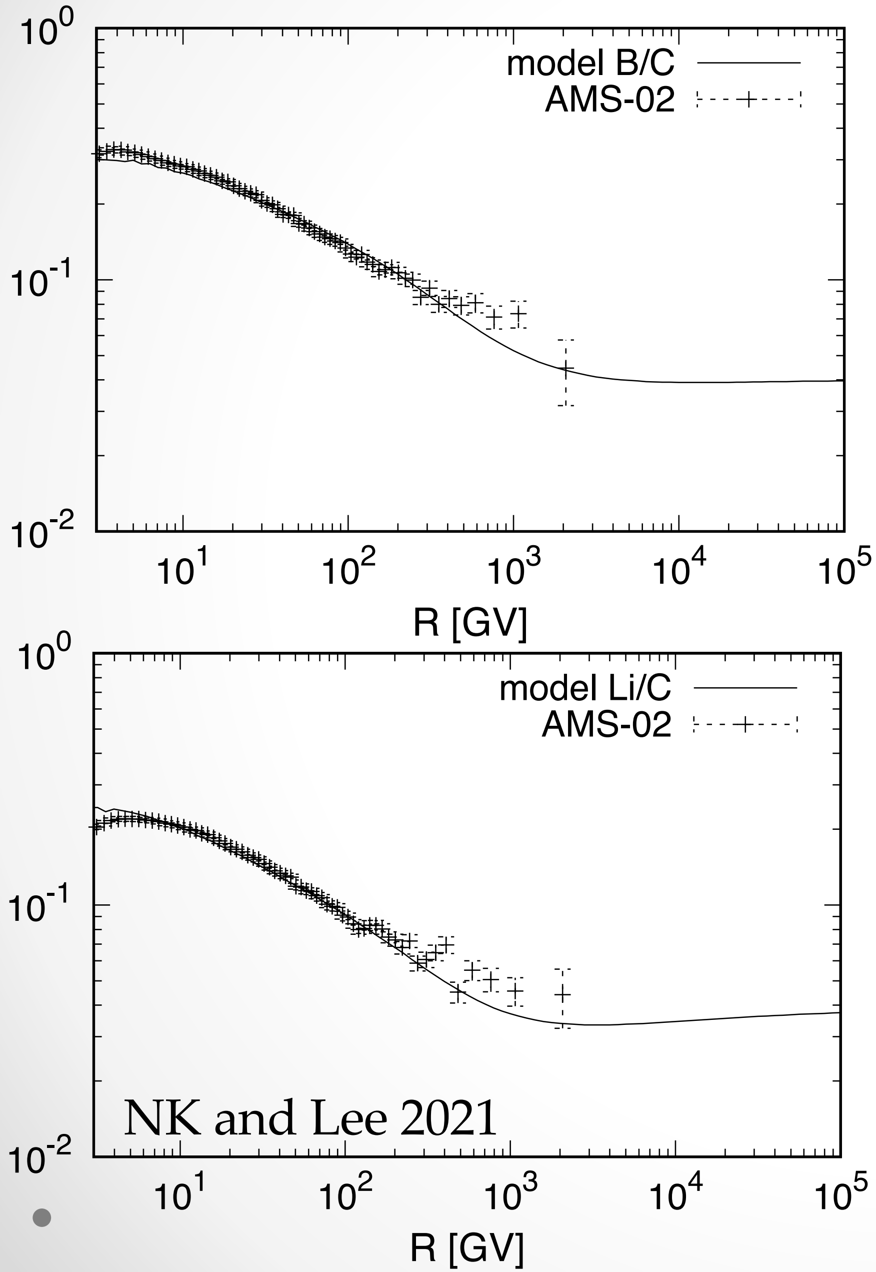
**Hardening of both pri. and sec. CRs are reproduced simultaneously!**

… if abundances of CNO in the CSM enhanced by a factor ~3 (metal-rich CSM)

… stripped-envelope SN (Ib/c)?



# Prediction




<u>background</u> (≲ 200 GV):
Secondaries are <u>softer</u> than primaries.

<u>a local SNR contribution</u> (≳ 200 GeV):
Secondaries are <u>harder</u> than primaries

Energy dependence of **secondary-to-primary ratios** would flatten at higher energies
# It may rise with energy!

# Summary

- We propose a local supernova with dense circumstellar medium as the birth place of the hard CR Li-Be-B component appearing $\gtrsim$ 200 GV.
- We calculate the production and acceleration of secondary CR nuclei in the SNR, as well as their escape into the ISM in a consistent way.
- The energy spectra of p, He, Li, Be, B, C, N, and O predicted from our model are consistent with the observations of AMS-02.
- Our scenario may be tested by secondary-to-primary ratios (e.g., B/C, Li/C, etc.) in $\gtrsim$ TeV range.
- AMS-02, CALET, DAMPE, AMS-100 etc.