Origin of Spectral Hardening of Secondary Cosmic Ray Nuclei

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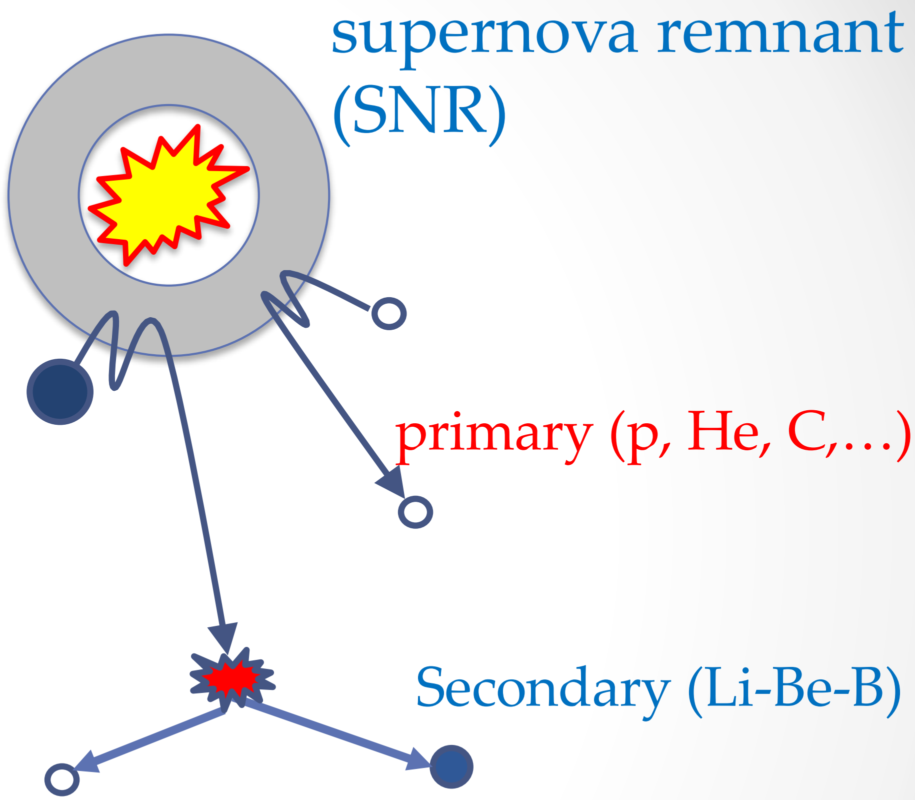
Connecting high-energy astroparticle physics for
origins of cosmic rays and future perspectives
YITP, Kyoto 8/12/2020

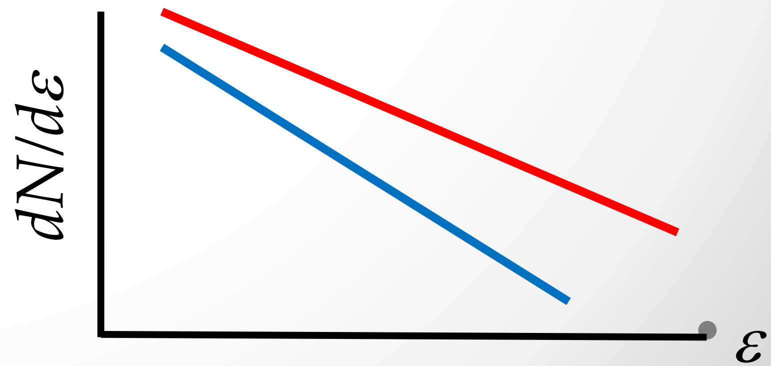
Galactic Cosmic-rays (p, He, Li-Be-B, C,…)

(probably) produced via diffusive shock acceleration at SNRs

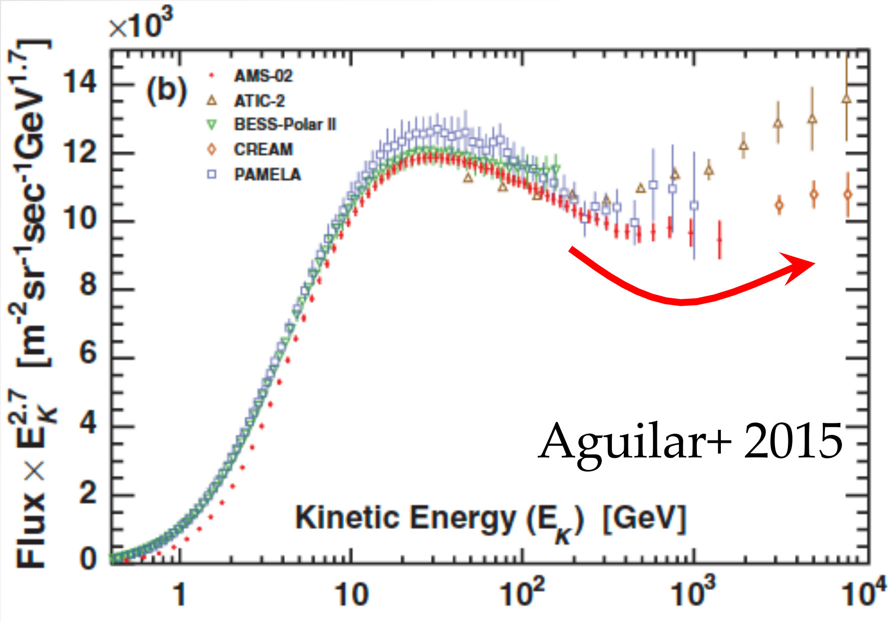
<u>proton, He, C, O, etc.</u> : primarily produced at SNRs, power-law spectrum

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





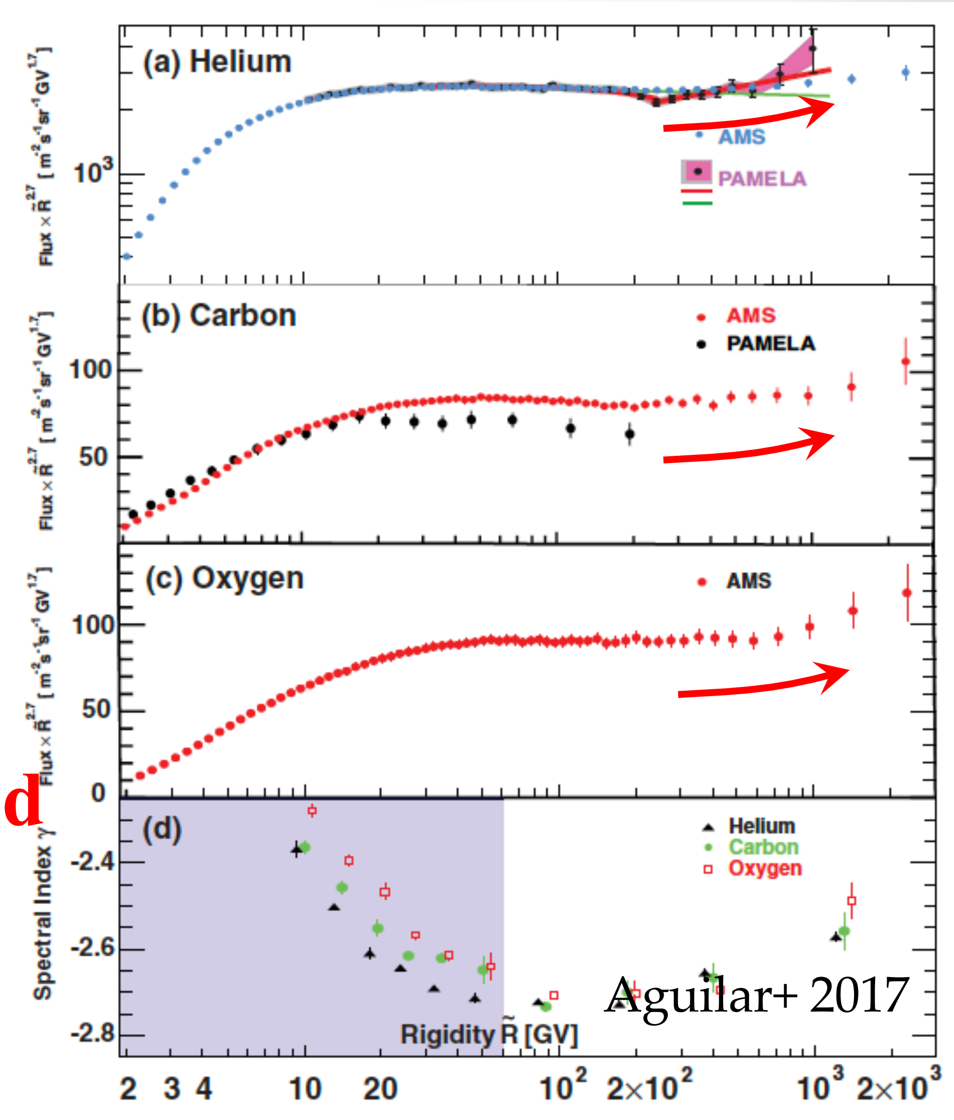
Spectral hardening of primary CR nuclei



Direct measurements of CRs by PAMELA / AMS-02 / CALET etc.

→ The spectra of *p*, He, C, and O harden above ≳200 GV

acceleration physics?
propagation effect?
local source?



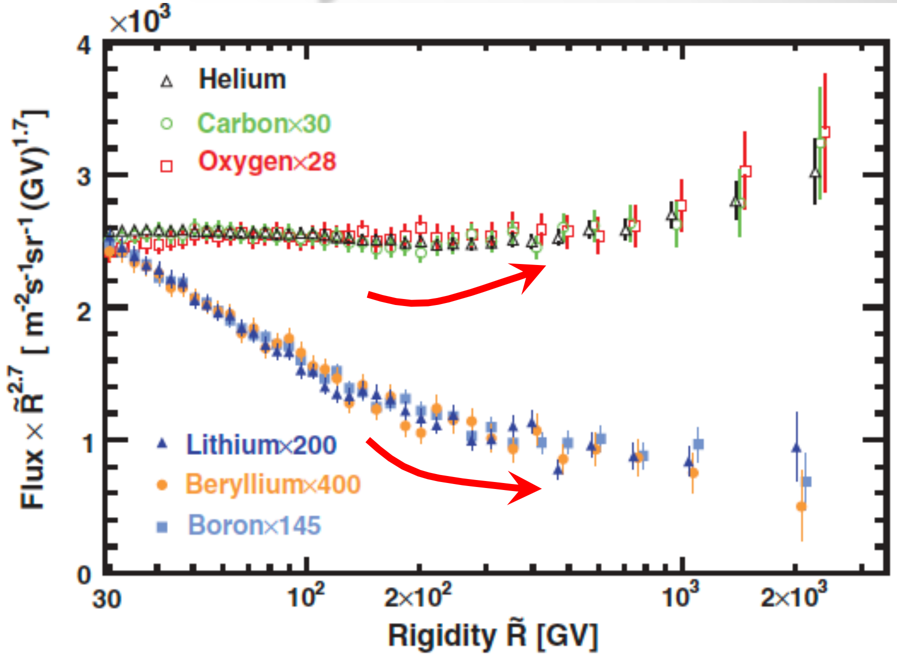
Ne, Mg, and Si also harden (Aguilar+ 2020)

Spectral hardening of "secondary" CR nuclei

AMS-02:

(1) The spectra of Li, Be, and B harden above ≳ 200GV

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



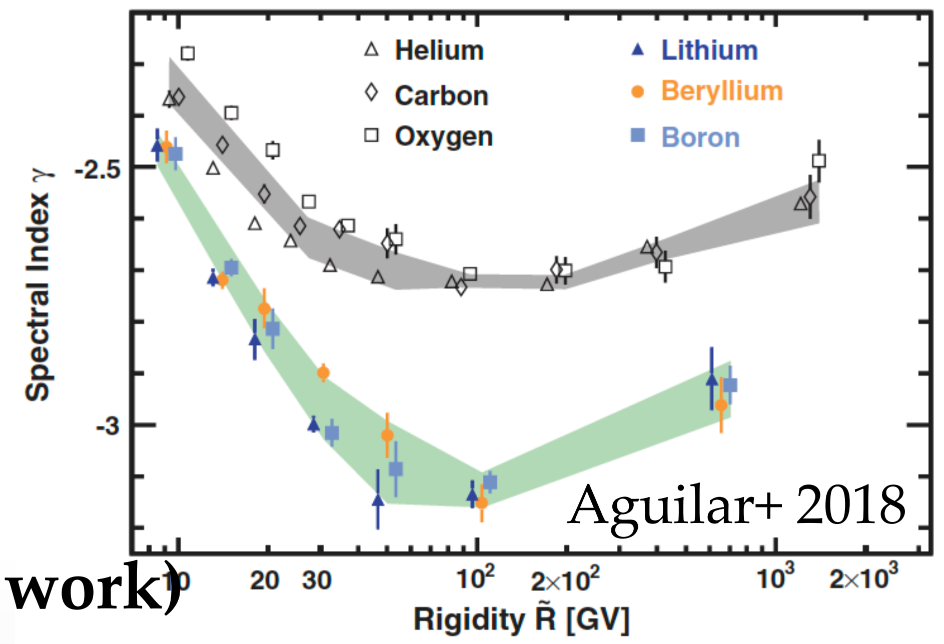
- propagation effect?

(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)

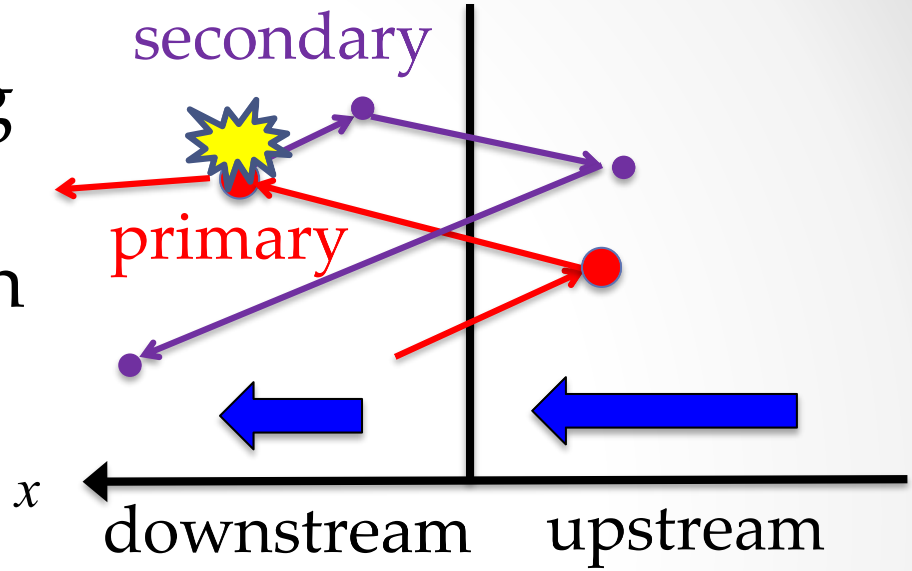
- **Primary Li-Be-B source? (This work)**

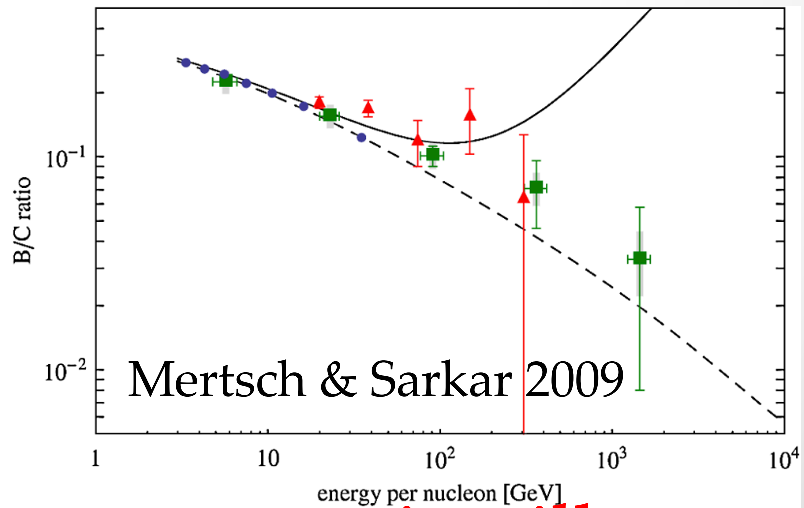


Production and Acceleration of secondary CRs

Mertsch & Sarkar 2009 etc.

Primary CRs are accelerated
→ interact with surrounding medium
→ secondary CRs production
→ **secondary CRs are also shock-accelerated**
→ HE primary CRs can produce more secondaries
→ The spectrum of secondary CRs would be harder than that of primary CRs





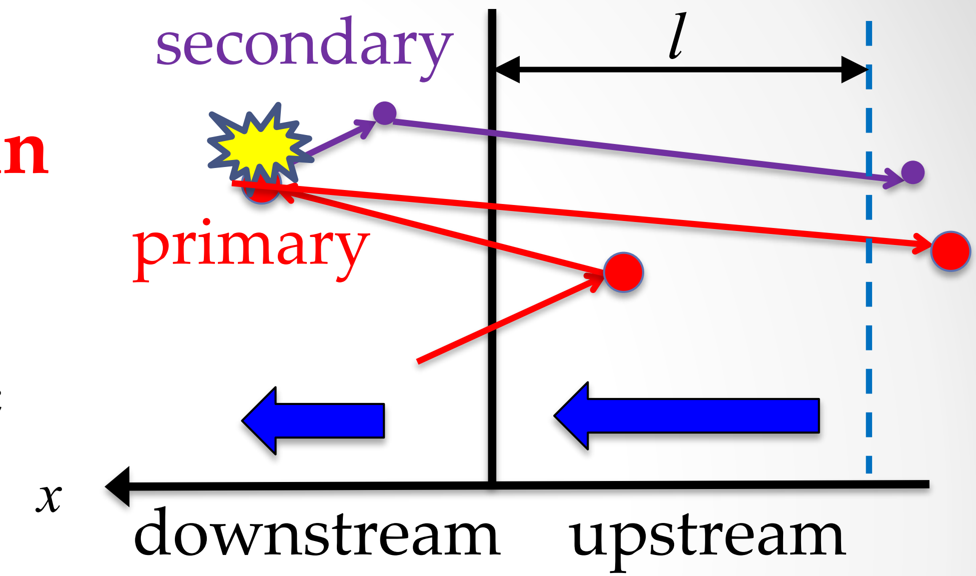
⚠ The escape of CRs into the upstream is still not taken into account in this model.

Escape-limited CR acceleration

Gabici+ 2007, 2009; Ohira+ 2010

CRs with higher energy escape the SNRs earlier than those with lower energy

supported by γ-ray observations (Aharonian & Atoyan 1996; Gabici+ 09; Ohira+ 11; see also Oka-san's poster)



escape condition for a particle

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

diffusion length

decreases with t

$u_- = u_{sh}$: expansion velocity of the SNR

$l \sim R_{sh}$: escape boundary ~ size of the SNR

$D_{SNR} = D_0(p/p_0)$: diffusion coefficient $\propto B^{-1}$

CR distribution function f_i at the SNR

NK and Lee in prep.

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 = 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

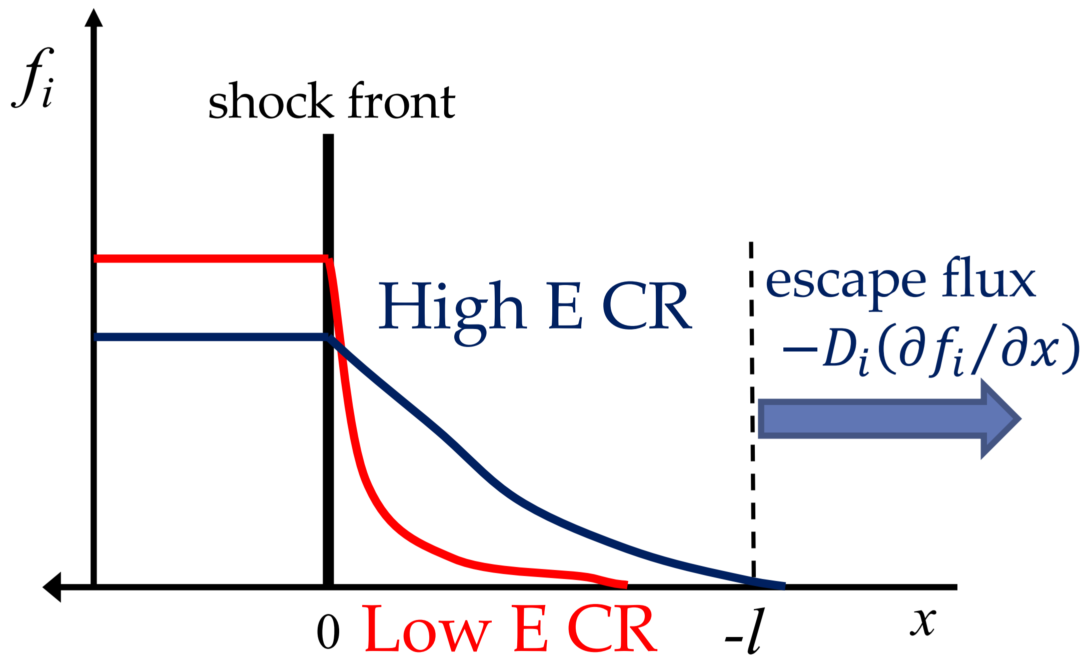
Boundary conditions

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

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

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

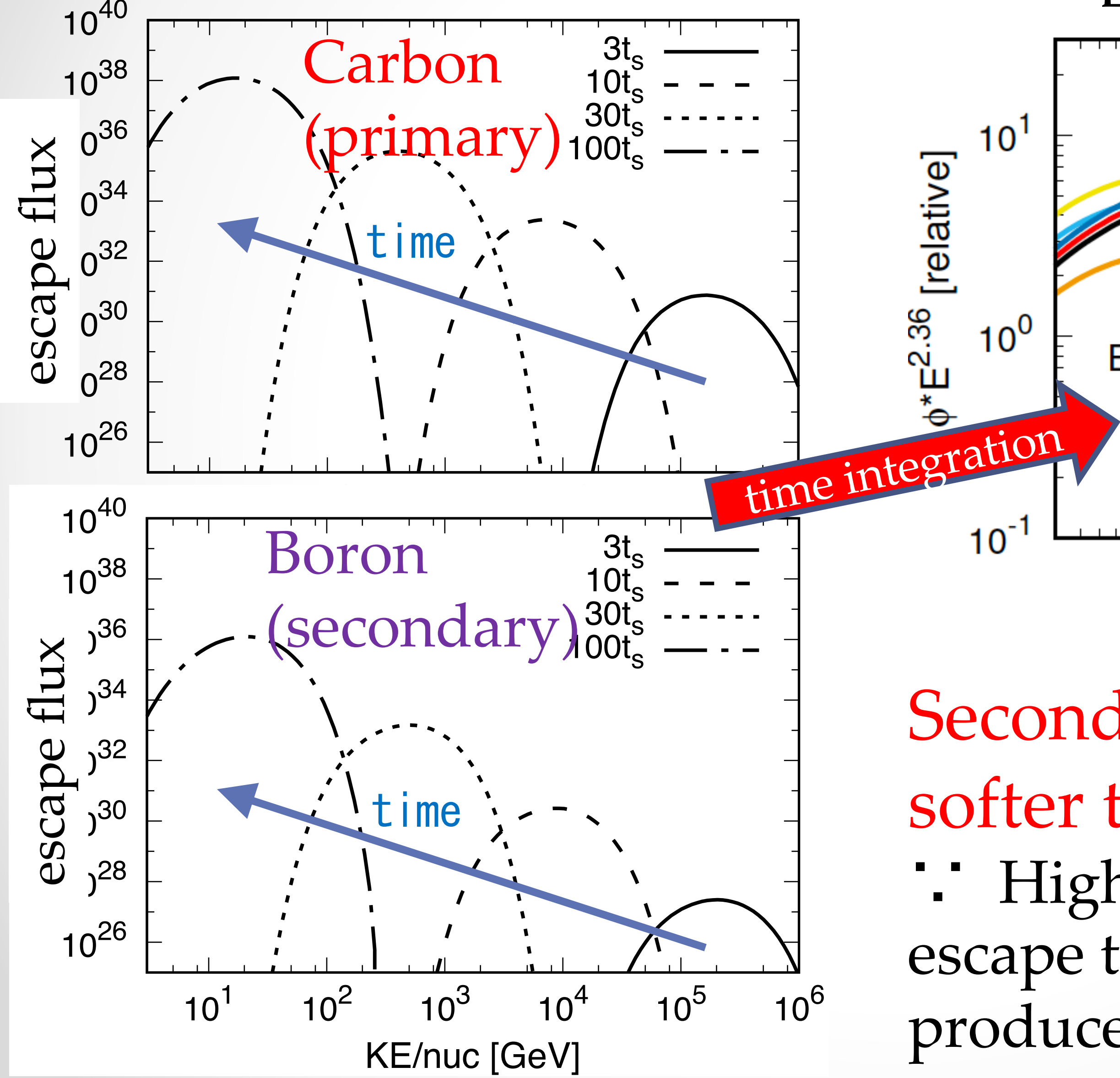
(iv) $\left[D_i(p)\frac{\partial f_i}{\partial x}\right]_{x=+0}^{x=-0} = \frac{1}{3}(u_+ - u_-)p\frac{\partial f_{i,0}}{\partial p} + u_- Q_i\delta(p-p_0)$,



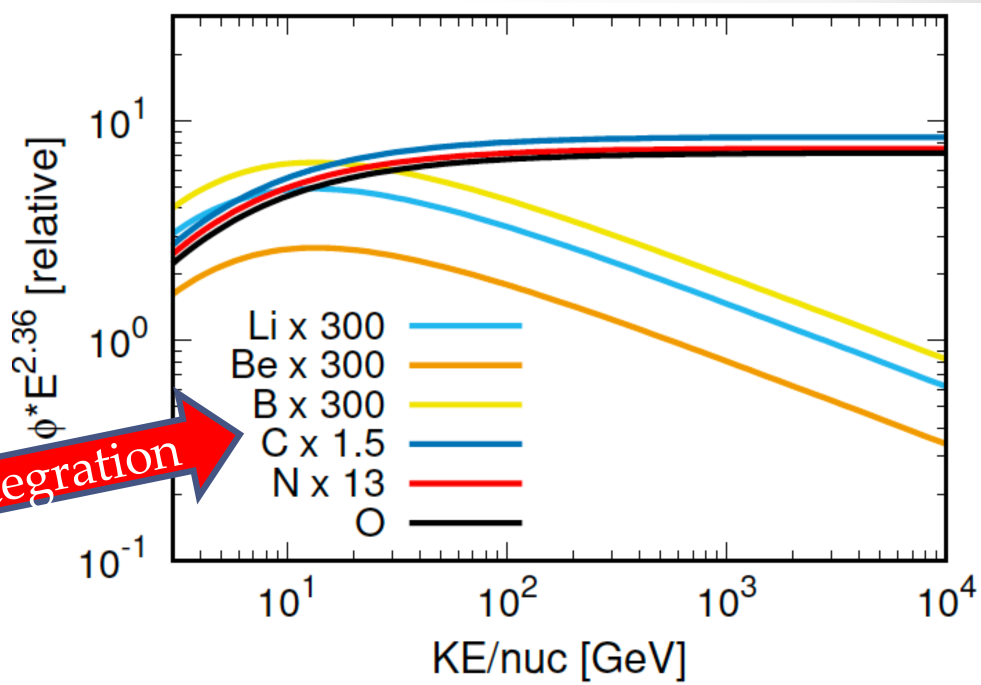
Case 1: uniform ISM (n_{amb} = const.)

NK and Lee in prep.

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



Escaping CR spectrum



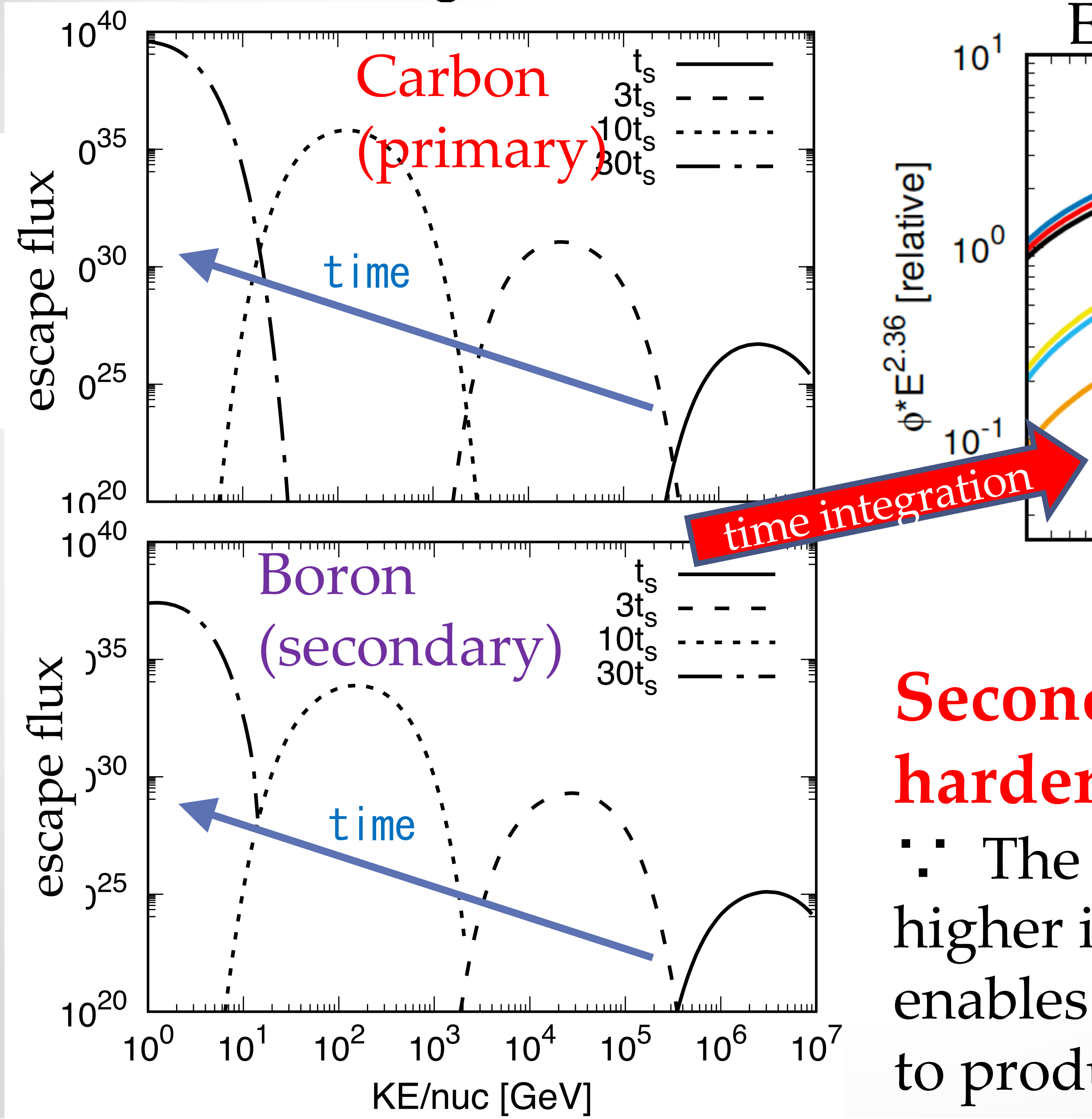
Secondaries are always softer than primaries ☹

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

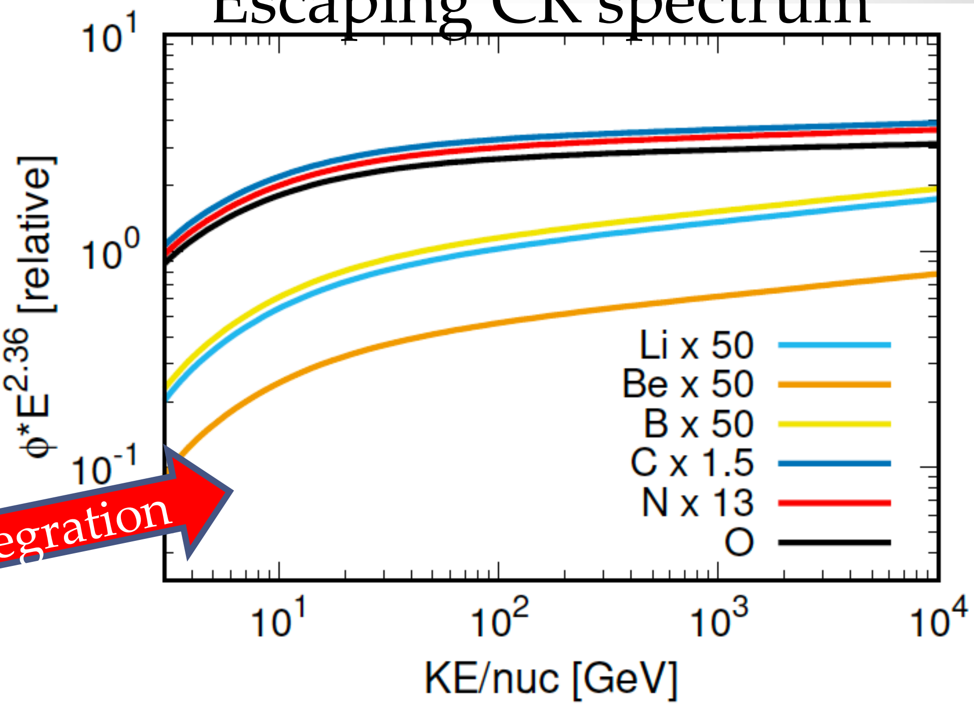
Case 2: SN with dense CSM ($n_{amb} \propto r^{-2}$)

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

NK and Lee in prep.



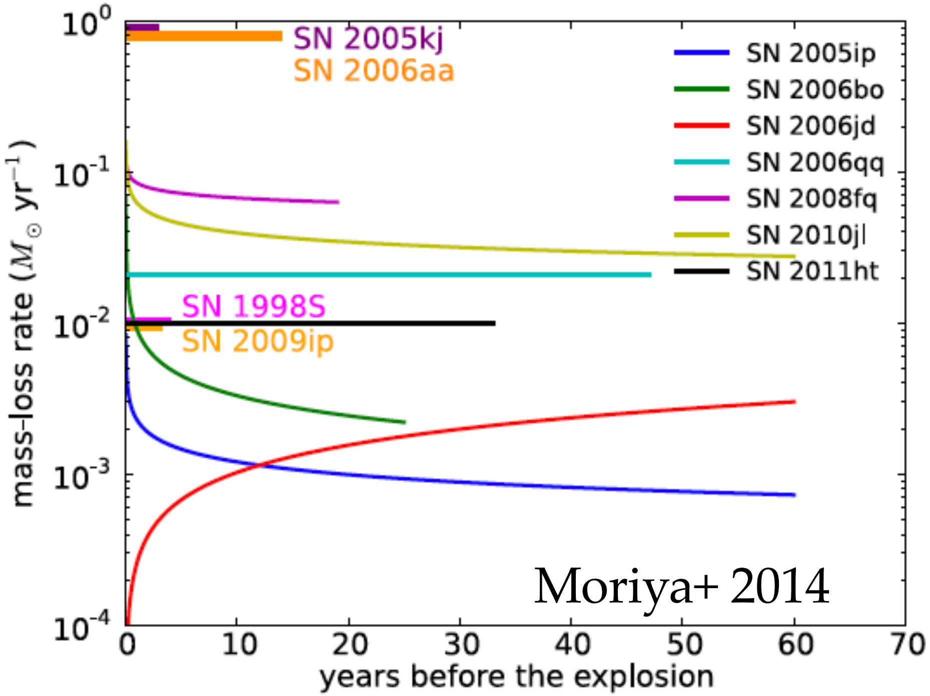
Escaping CR spectrum



Secondaries are always harder than primaries ☺

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

SN with CSM as a secondary CR accelerator



- e.g., Type IIn SNe:

mass loss rate before the explosion $\gtrsim 10^{-3} M_\odot \, \mathrm{yr}^{-1}$ ($v = 100$ km s^{-1})

- total mass of CSM

$\gtrsim 0.1 - 1 M_\odot \sim$ SN ejecta mass

- typical size of CSM $\gtrsim 0.01$ pc

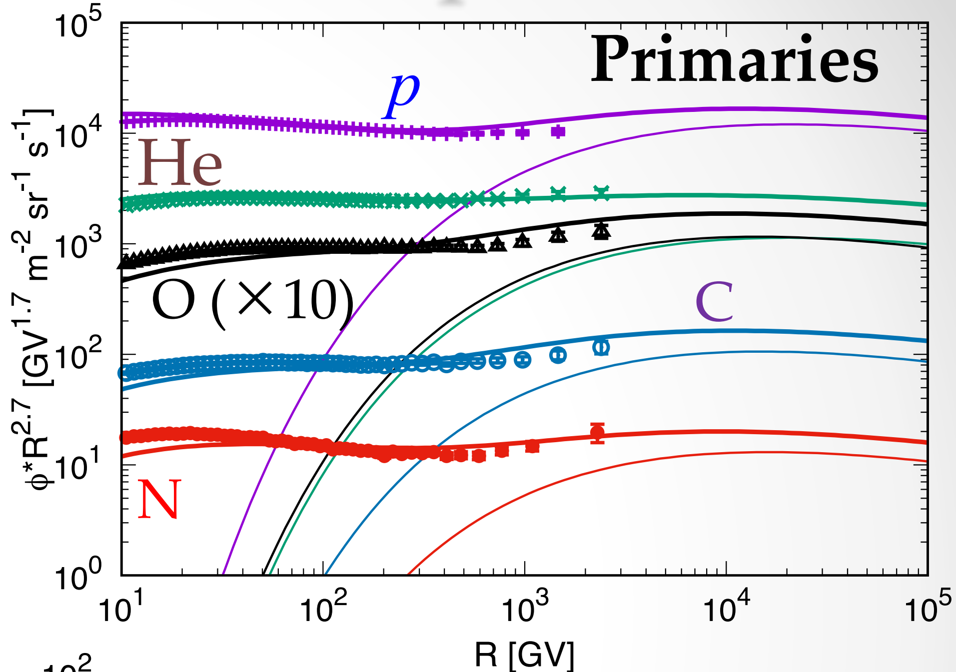
Hypothesis : CR Li-Be-B nuclei (and their primary nuclei) are produced and accelerated at a local SNR in the dense CSM.

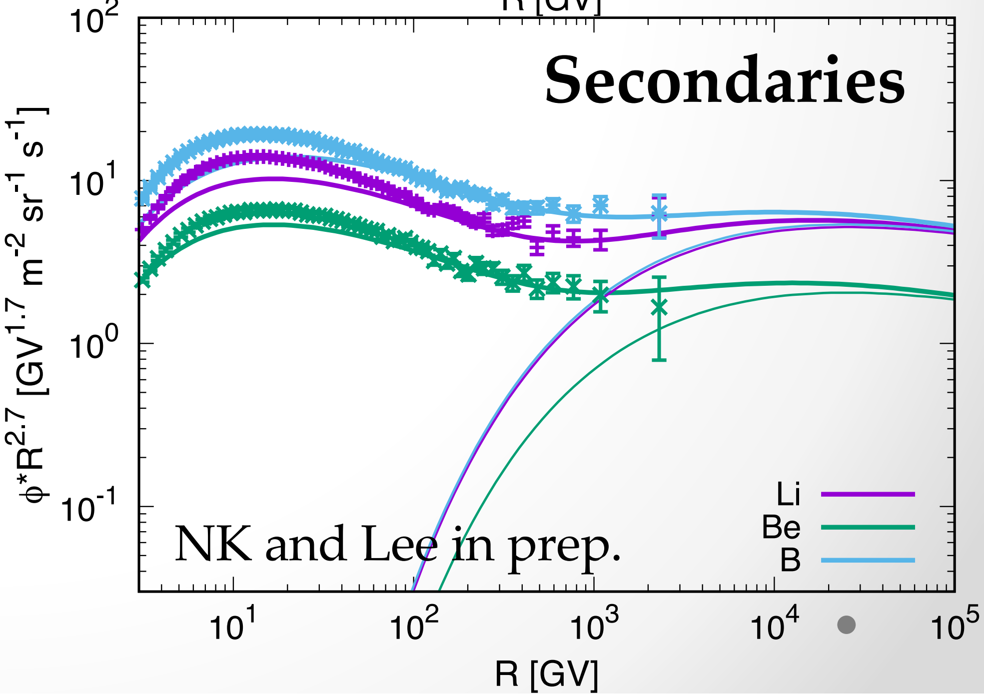
Fitting to the observed CR spectra

a local SNR with CSM:
(thin lines)

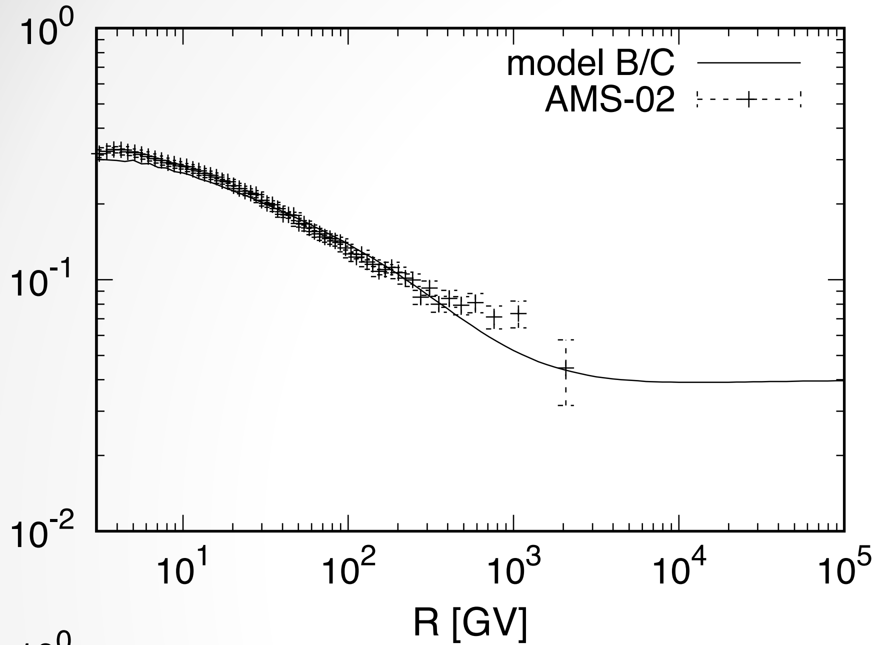
$$\left\{\begin{array}{l}\dot{M} = 1\times10^{-3} M_\odot\ \mathrm{yr}^{-1},\\ v_w = 100\ \mathrm{km\ s}^{-1},\\ E_{SN} = 10^{51}\mathrm{erg}, \eta_{CR} = 0.1\\ \text{age: } 1.5\times10^5\ \mathrm{yr}\\ \text{distance: } 1.5\ \mathrm{kpc}\end{array}\right.$$

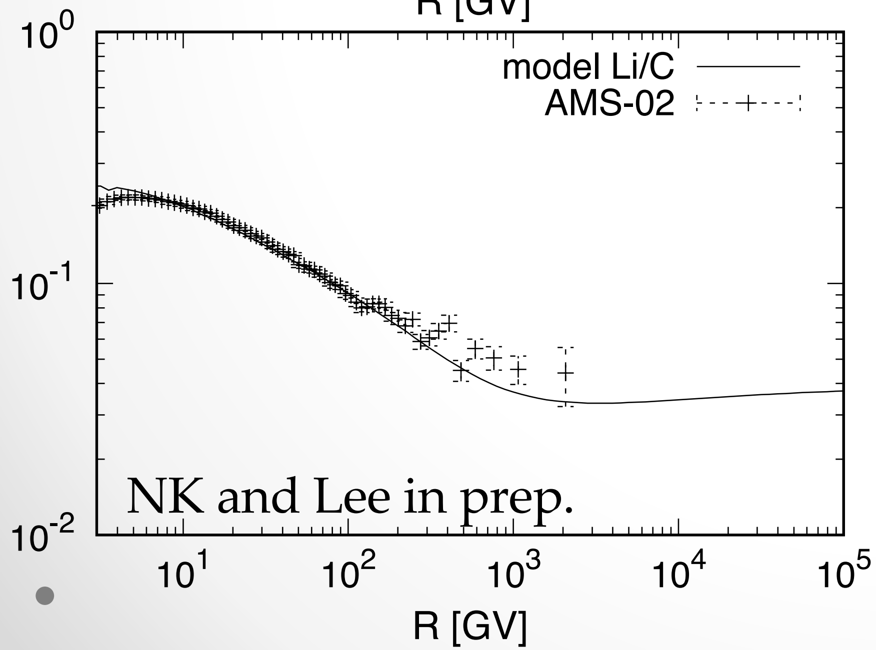
Spectral hardenings of primary and secondary nuclei are reproduced simultaneously!





Prediction





background ($\lesssim$ 200 GV):
Secondaries are softer than primaries.

a local SNR contribution ($\gtrsim$ 200 GeV):
Secondaries are harder 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 etc.