Cosmic-rays hardening in the light of AMS-02

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Outline

1) Galactic cosmic rays
2) Escape of cosmic rays from supernova remnants
3) The origin of Galactic cosmic rays
4) Summary

Ref. Ohira et al.(2010), Ohira & Ioka (2011), Ohira et al.(2015)

Galactic cosmic ray

SNRs are though to be the origin of the Galactic CR.

What Type? Isolated or in superbubbles?

Observed Galactic CR spectrum

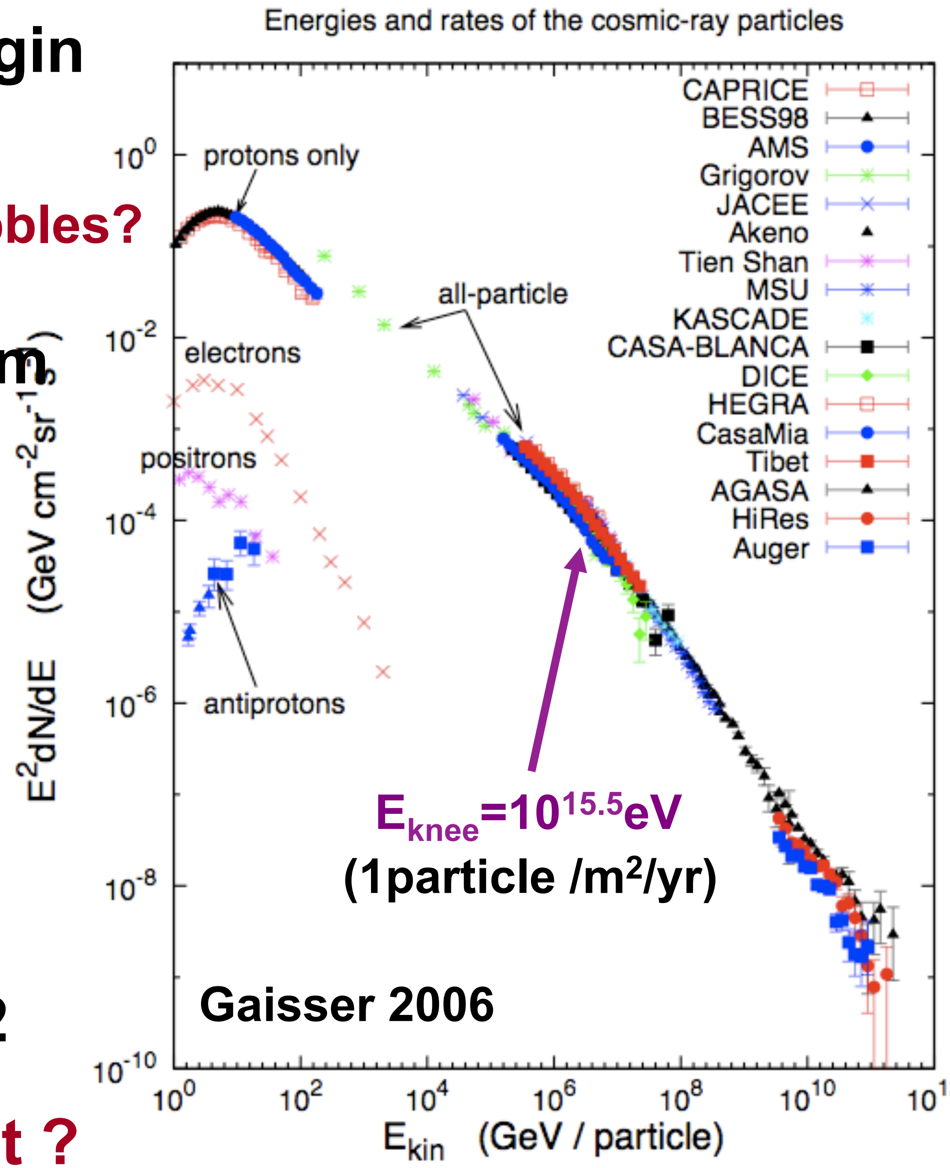
$dN/dE \propto E^{-2.8}$ ($E<10^{12}$eV)

Recent observations of B/C ratio show

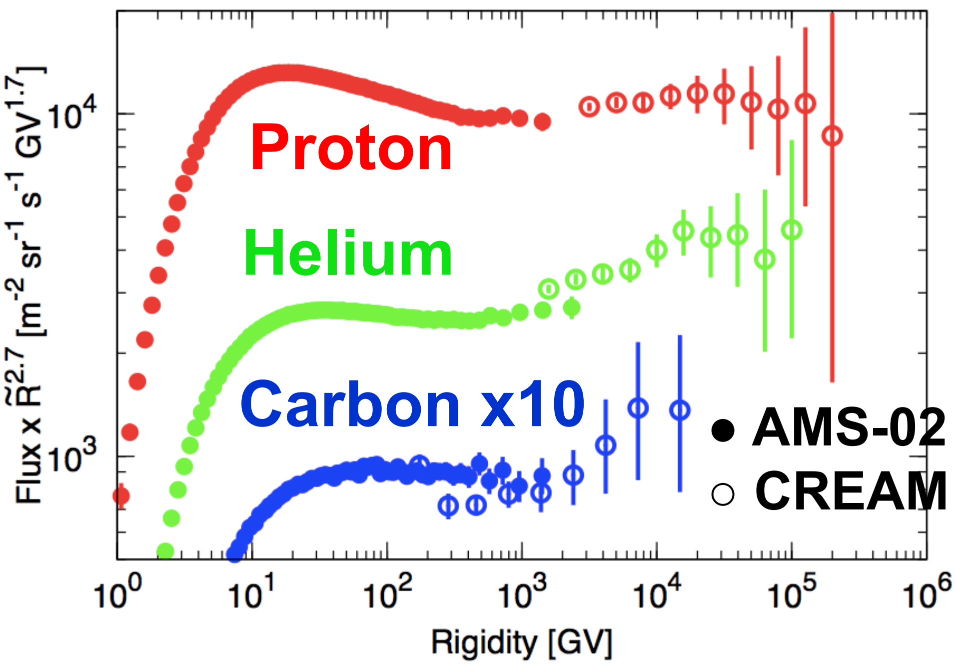
$Q_{sour} \propto E^{-2.4}$

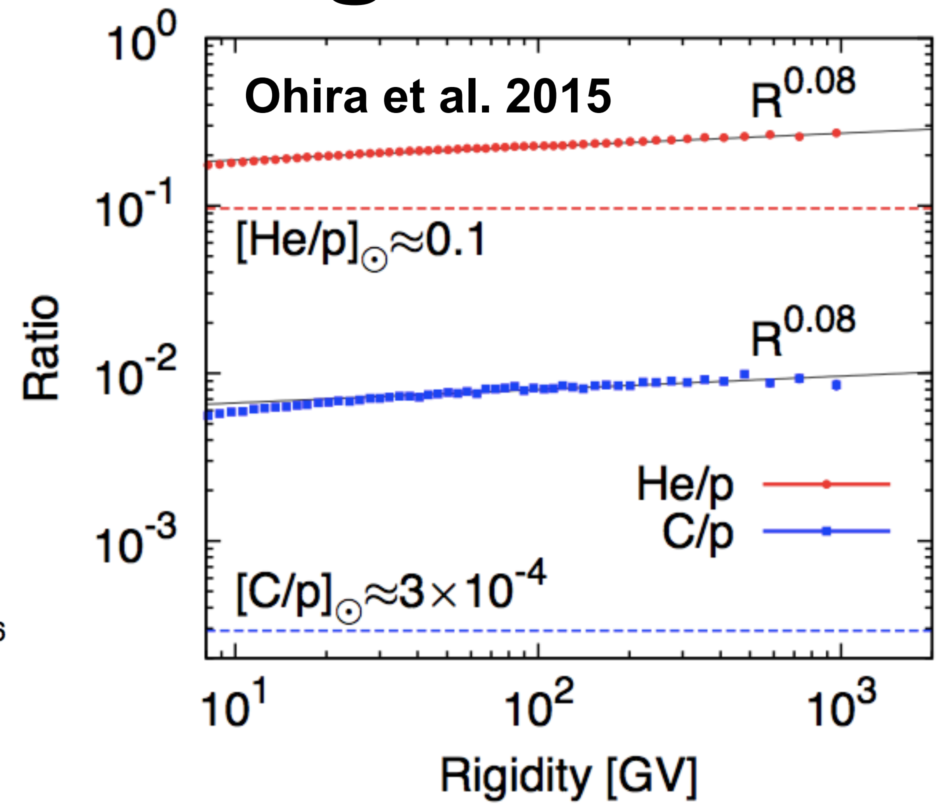
DSA model $Q \propto E^{-2}$

Inconsistent ?



CR hardening





Spectra of CR p and He (and C) break at R~300GV.

Spectra of CR He and C are harder than that of CR p.

The standard model predicts that all primary CRs have the same spectral index.

→ The standard model needs other physics.

Escape of Cosmic rays from SNRs

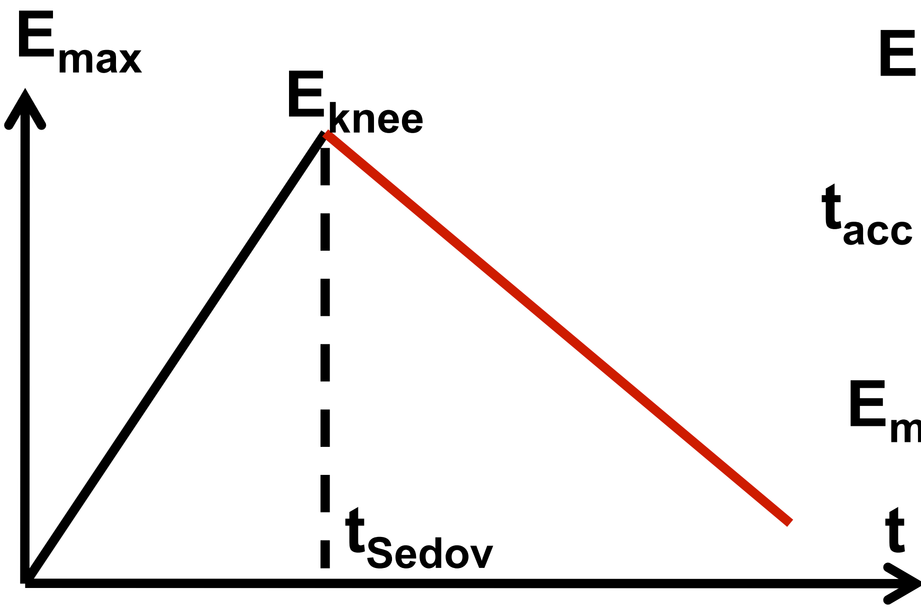
$$R_{sh} = R_{Sedov} \times \begin{cases} (t_{age} / t_{Sedov}) & (t_{age} < t_{Sedov}) \\ (t_{age} / t_{Sedov})^{2/5} & (t_{age} > t_{Sedov}) \end{cases}$$

$$R_{diff} \propto (D t_{age})^{1/2}$$

Free expansion phase (t < 200yr): age limited

$$E_{max} = E_{knee} \, (t / t_{Sedov}) \qquad \text{(B should be amplified)}$$

Sedov phase (t < 10^5 yr) : escape limited



$E_{m,esc}$ is obtained from $t_{esc} = t_{acc}$

$$t_{acc} \sim \frac{D}{u_{sh}^2} \;, \; t_{esc} \sim \frac{R_{sh}^2}{D} \;, \; D = \eta_g \frac{cE}{3eB}$$

$$E_{max} \propto \frac{B(t) t^{-1/5}}{\eta_g(t)} = E_{knee} \, (t / t_{Sedov})^{-\alpha}$$

$E_{m,esc}$ decreases with time

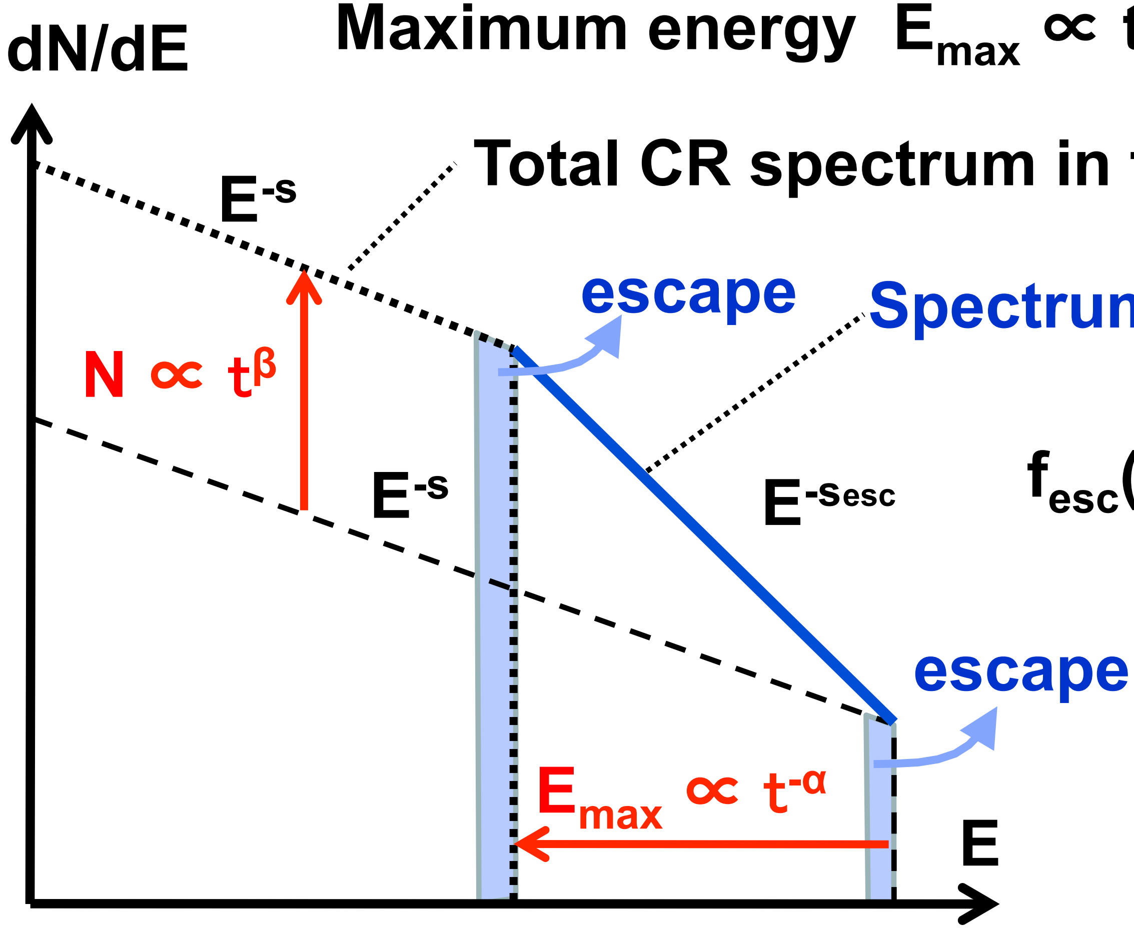
Spectrum of escaping CRs

CR number $N(E=mc^2) \propto t^{\beta}$, $\beta > 0$

Maximum energy $E_{max} \propto t^{-\alpha}$, $\alpha > 0$

Total CR spectrum in the SNR $f_{SNR} \propto t^{\beta} E^{-s}$

Spectrum of escaping CRs $f_{esc}(E)$



$$f_{esc}(E)\, dE = f_{SNR} \frac{dE_{max}}{dt} dt$$

$$f_{esc} \propto E^{-s_{esc}}$$

$$s_{esc} = s + \frac{\beta}{\alpha} \qquad s \neq s_{esc}$$

Y. Ohira, K. Murase, R. Yamazaki, 2010, A&A, 513, A17

(Ptuskin&Zirakashvili(2005), Ohira&Ioka(2011), Caprioli et al.(2010), Drury(2011))

Application to the CR He and C hardenings

$\Delta s = 0.08$ means that He/p at 10^{15}eV is about 3 times larger than that at 10^{9}eV.

The acceleration region of high-energy CRs is different from that of low-energy CRs in our escape model.

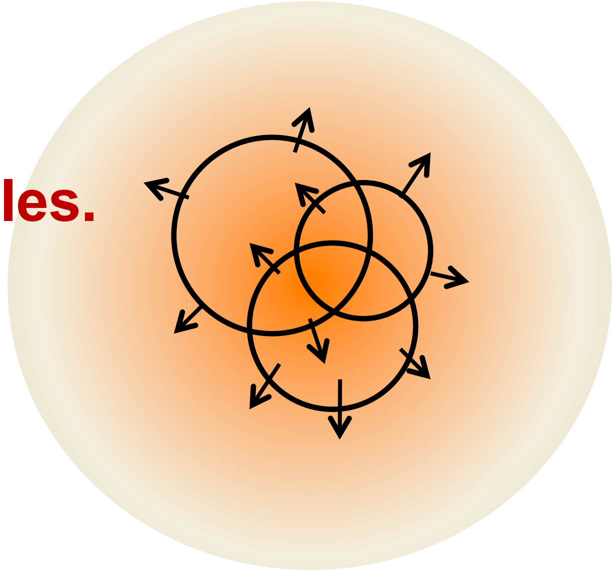
We should consider the inhomogeneous abundance region.

Superbubbles

Massive stars mainly explode in superbubbles.

Stellar ejecta dominates around the center of superbubles. (Higdon et al.1998)

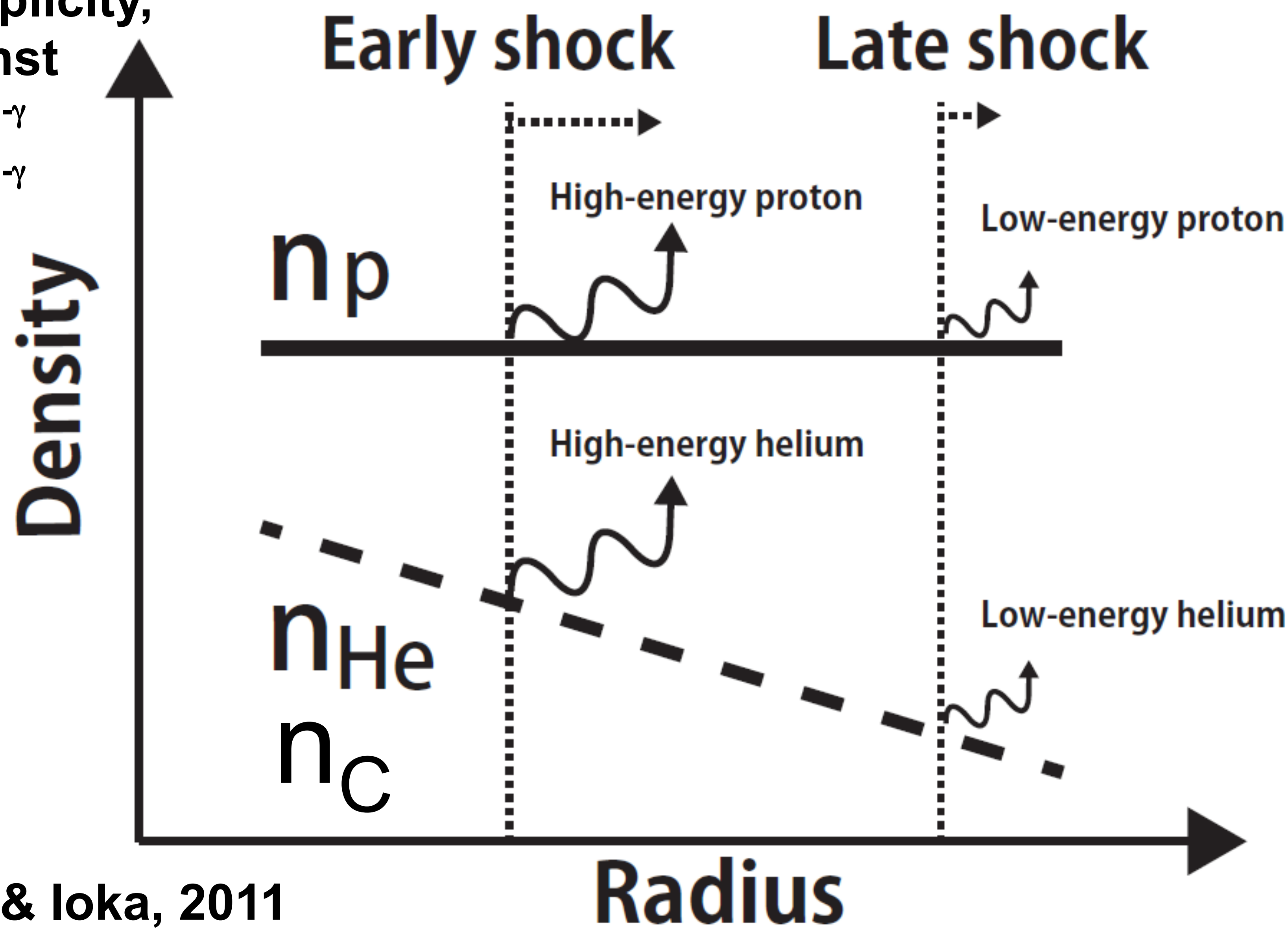
He/p and C/p in the center of SB are larger than those in outer region of SB.



Ohira & Ioka, 2011

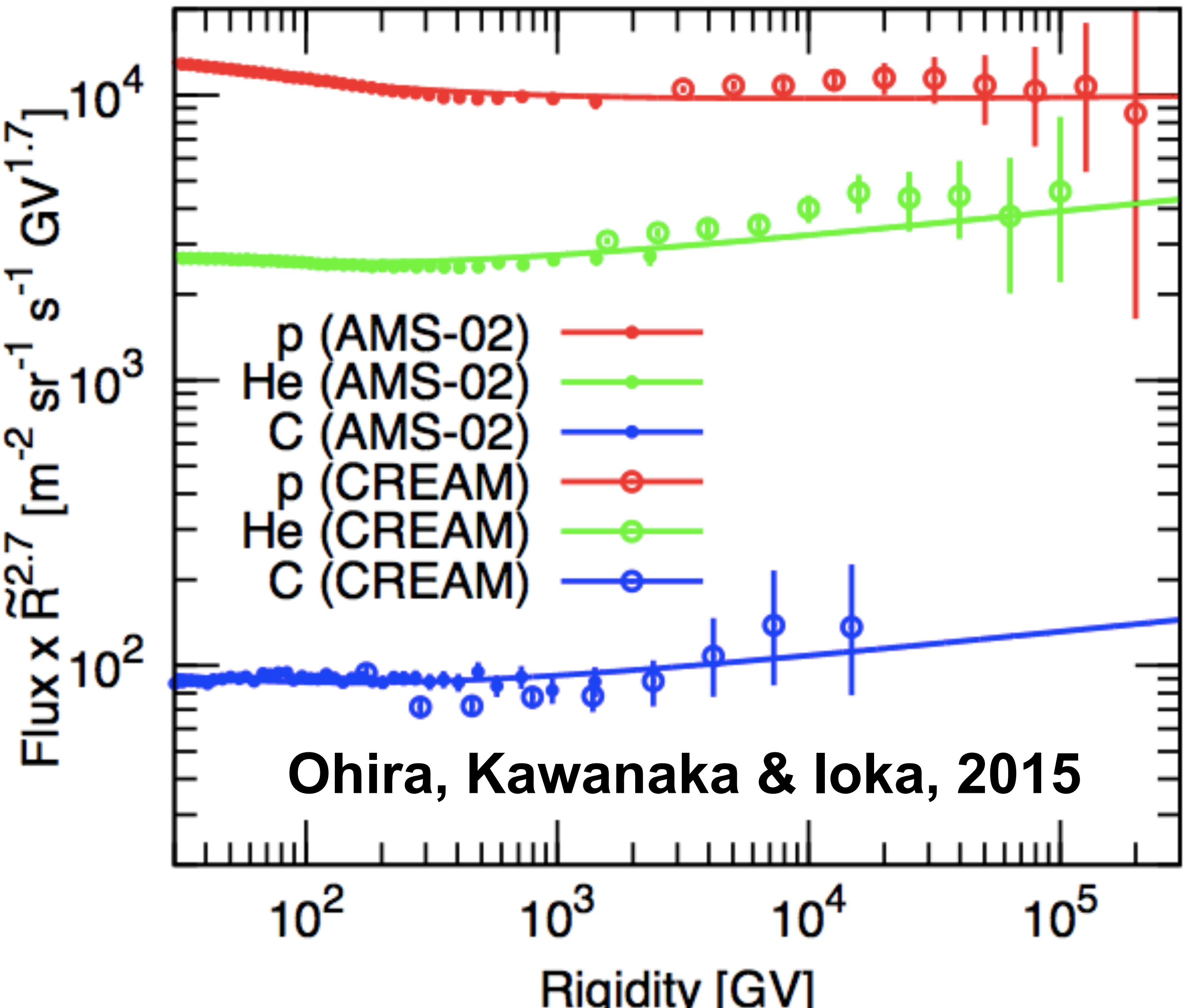
Schismatic picture

For simplicity,
n_p = const
$n_{He} \propto r^{-\gamma}$
$n_C \propto r^{-\gamma}$



Ohira & Ioka, 2011

Comparison of our model and CR obs.



n_p = const.

$n_{He,C} \propto r^{-0.52}$

$N_{CR,i} \propto n_i$

$E_{max} \propto Z R_{sh}^{-6.5}$

$T = 10^6$ K

$D \propto R^{0.44}$

$T = 10^6$K

Superbubble!

CR Carbon hardeing

AMS-02 shows C/p $\propto R^{0.08}$ and C/He $\propto R^{0}$.

To produce the helium rich region, stellar ejecta dominate over ISM around the center of superbubbles.

The C/He of stellar ejecta is about 10 times larger than that of ISM.

To keep C/He constant, the stellar ejecta must dominate over ISM in the whole CR production region.

→ The origin of GCRs is supernova ejecta and stellar winds in superbubbles.

Ohira, Kawanaka, Ioka, 2015

Summary

Recently, AMS-02 show that

the spectrum of CR He and C are harder than that of CR p, and CR spectra of p and He (and C) break at R~300 GV.

The runaway CR spectrum is different from that in the accelerator.

$$f_{SNR} \propto t^{\beta} E^{-s},\ E_{max} \propto t^{-\alpha} \longrightarrow f_{esc} \propto E^{-s_{esc}} \qquad s_{esc} = s + \frac{\beta}{\alpha}$$

Considering the inhomogeneous abundance region, spectra of runway CR He and C become harder than that of CR protons.

($\beta_{He}, \beta_{He} < \beta_p$)

Considering the Mach-number evolution with 10^6 K, runaway CR spectra of all CRs break at R~300 GV.

CR Observations suggest the CR origin is SNRs in superbubbles.

Spectral break at R~300 GV

Recent AMS-02 and CREAM observations show that spectra of CR p, He and C break at R~300 GV.

Spectral index $s_{obs} = s + \frac{\beta}{\alpha} + \delta$

If one of s, α, and β has a time dependence or δ has an energy dependence, all CR spectra break at the same rigidity.

Here, we consider the time (energy) dependence of s

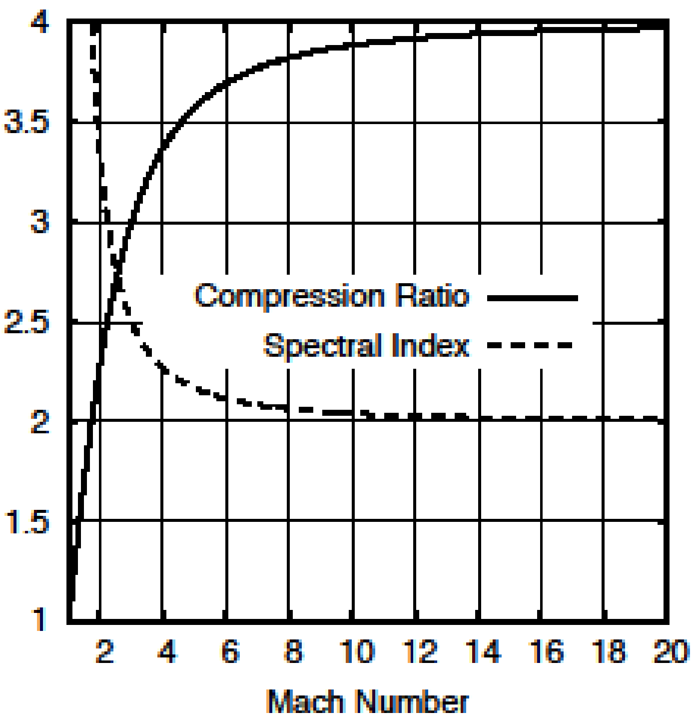
$$s = \frac{u_1 + 2u_2}{u_1 - u_2} = 2\,\frac{1 + M^{-2}}{1 - M^{-2}}$$

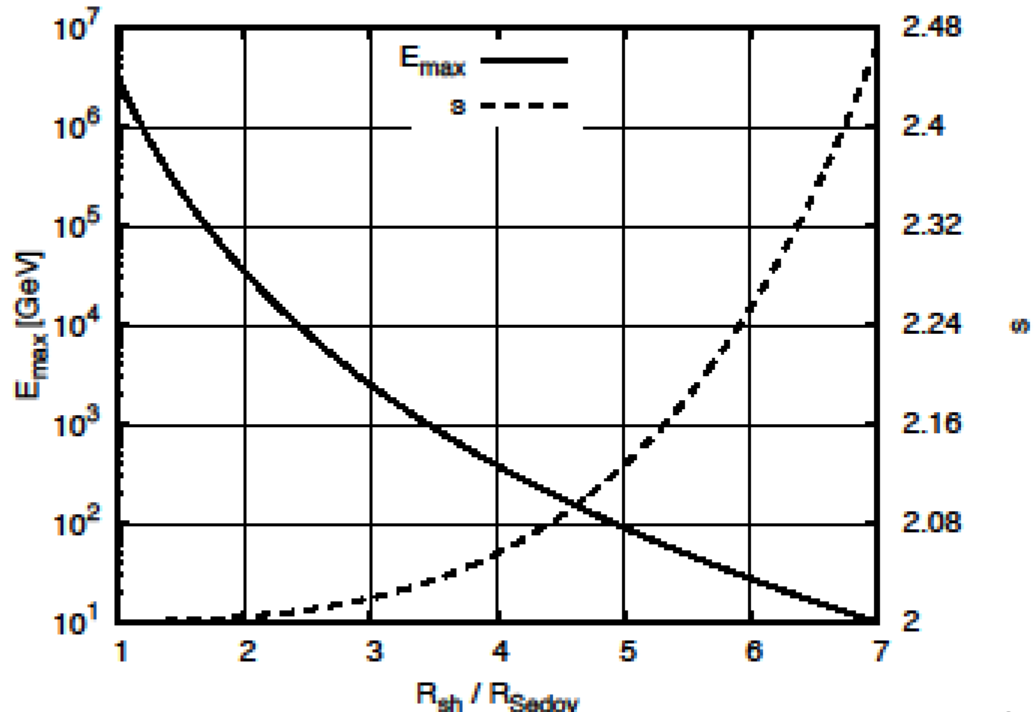
Sedov solution

$\rho_{tot}(R_{sh}) = m_p(n_p(R_{sh}) + 4n_{He}(R_{sh}))$

$$M \approx 10^3 \left(\frac{\rho_{\rm tot}(R_{\rm sh})}{\rho_{\rm tot}(R_{\rm Sedov})}\right)^{-\frac{1}{2}} \left(\frac{T}{10^4\ {\rm K}}\right)^{-\frac{1}{2}} \left(\frac{R_{\rm sh}}{R_{\rm Sedov}}\right)^{-\frac{3}{2}}$$

Mach number





T = 10⁶K

$$s = \frac{u_1 + 2u_2}{u_1 - u_2} = 2\,\frac{1 + M^{-2}}{1 - M^{-2}}$$

$$M \approx 10^3 \left(\frac{\rho_{\rm tot}(R_{\rm sh})}{\rho_{\rm tot}(R_{\rm Sedov})}\right)^{-\frac{1}{2}} \left(\frac{T}{10^4\ {\rm K}}\right)^{-\frac{1}{2}} \left(\frac{R_{\rm sh}}{R_{\rm Sedov}}\right)^{-\frac{3}{2}}$$