Galactic Modulation of Extragalactic Cosmic Rays

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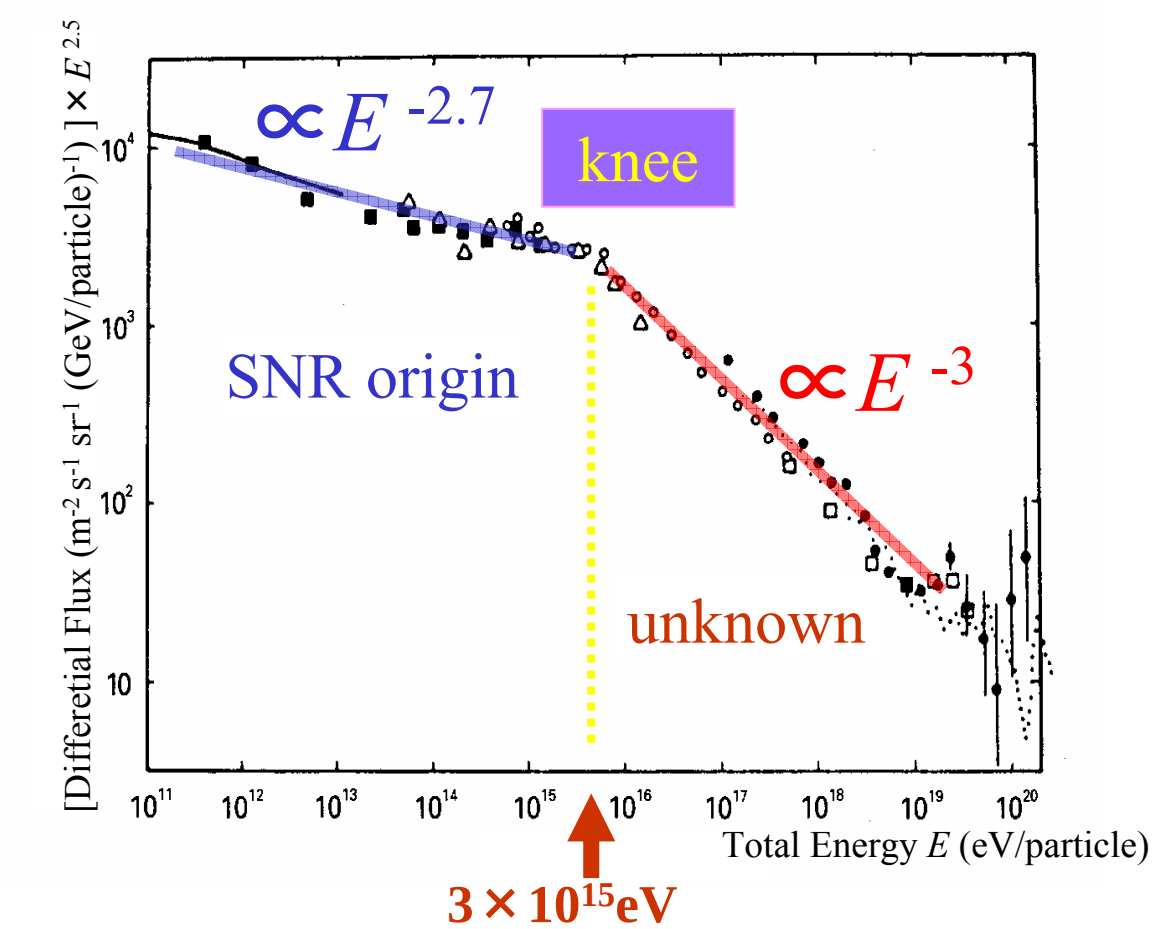
- Contents -

1. Introduction

－CR spectrum, origin of CRs, etc.

CR all particle spectrum



→Power law spectrum

$\sim E^{-2.7}$ ($<3 \times 10^{15}$ eV)

$\sim E^{-3.0}$ ($3 \times 10^{15} - 10^{18}$ eV)

→Spectral break around 10^{15} eV (refered to as the 'knee')

SNR origin of CRs below 10^{15} eV

General arguments

(1) Energetics
(2) Shock acceleration mechanism
(3) Elemental and Isotopic Composition

→ SNRs have the necessary power and the Fermi shock acceleration mechanism provides the observed spectrum.

Direct evidence

(1) GeV CRs

- Synchrotron radio emission from SNRs
- π^0 decay γ-rays from several SNRs by EGRET (Esposito et al. 1996)

(2) TeV CRs

- Synchrotron X-rays from several SNRs (SN1006, RXJ1713,…) (Koyama et al. 1995; Koyama et al. 1997, etc.)
- TeV γ-rays from SNRs **RX J1713.7-3946** have been detected !! (Muraishi et al. 2000; Enomoto et al. 2002; Aharonian et al. 2004)

※CRs above the 'knee' is still unknown !

Possible origin of CRs between 10^{15} and 10^{18} eV

(1) Escape from the galaxy of more energetic particles (Peters 1960)

(2) Z dependence of the maximum energy in shock acceleration (Drury 1983, Lagage & Cesarsky 1983)

(3) Reacceleration of GCRs (Jokipii & Morfill 1985) (Volk & Zirakashvili 2004)

(4) Change of the interaction models in EAS (Erlykin & Wolfendale 2000)

(5) Acceleration by an earlier Galactic GRB (Wick, Dermer & Atoyan 2004)

(6) Necessity of anomalous (extragalactic) CRs ?? (Fitchtel & Linsley 1986)

※ Possibility of the Galactic modulation of extragalactic CRs ?

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2. Galactic modulation of extragalactic CRs

- Motivation
- Simulation method and Results

Motivation

-Possible existence of V.H.E. CRs in IGS -

○ **recent observational results from ICM**

✧EUV and hard X-ray emissions from ICM (Ensslin et al. 1999)

✧Isotropic extragalactic γ-ray background (Loeb & Waxman 2000)

→Existence of L.E. CR electron in IGS

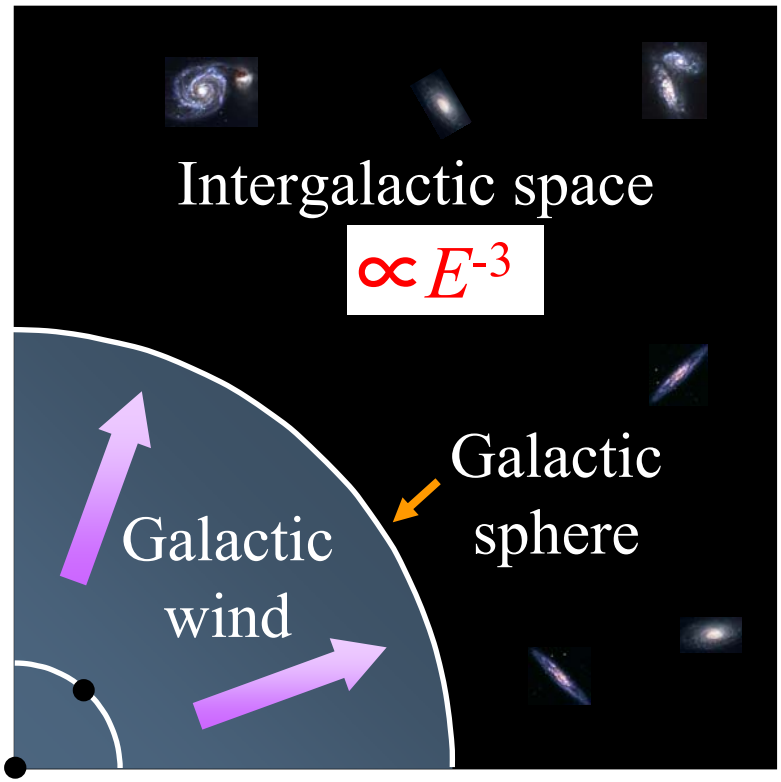
If nuclear components with energy up to 10^{18} eV also exist in the inter-galactic space including around our galaxy,

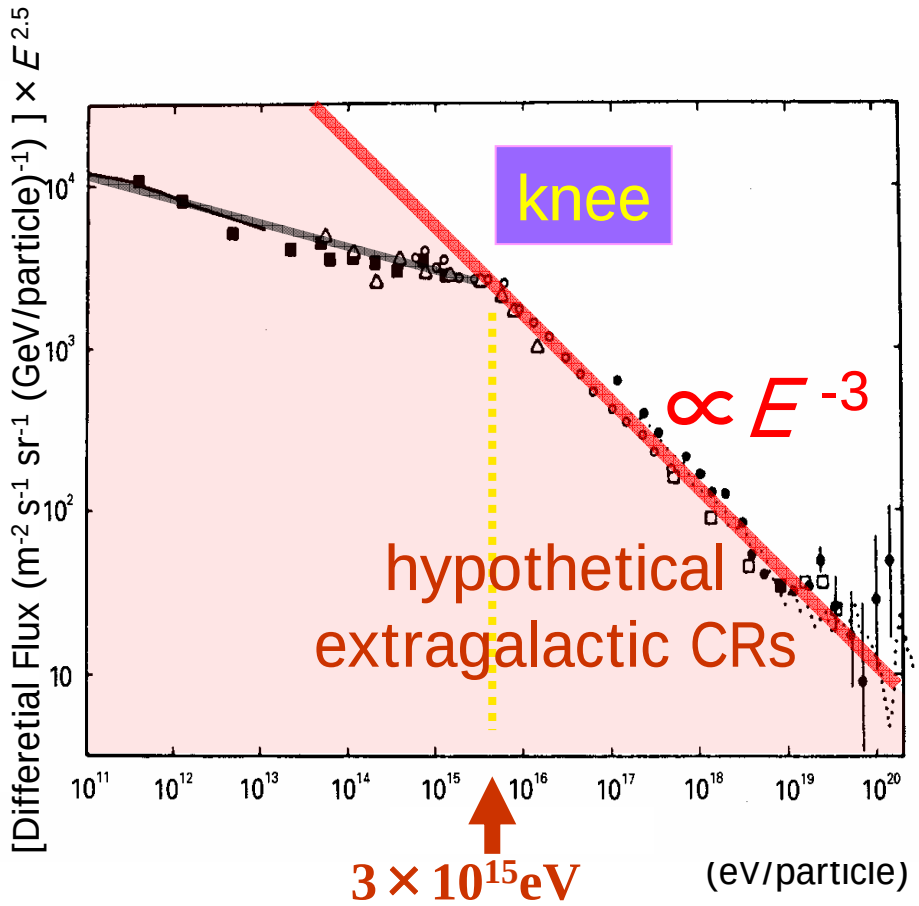
↓ ↓ ↓ ↓ ↓

these components modulated by the galactic wind should be directly observable !!!

→ We numerically examine such a possibility.

Schematic view of our model





→We examine how the spectrum of these CRs should be modulated during this propagation process.

— Fokker-Plank Eq.(spherical symmetric case) —

(Parker 1965)

$$\frac{\partial f}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa \frac{\partial f}{\partial r}\right) - V\frac{\partial f}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 V\right)\frac{p}{3}\frac{\partial f}{\partial p}$$

t : time

r : radial distance

f : distribution function

V : speed of the galactic wind

p : particle momentum

κ : diffusion coefficient for radial propagation

— SDEs equivalent to F-P eq. —

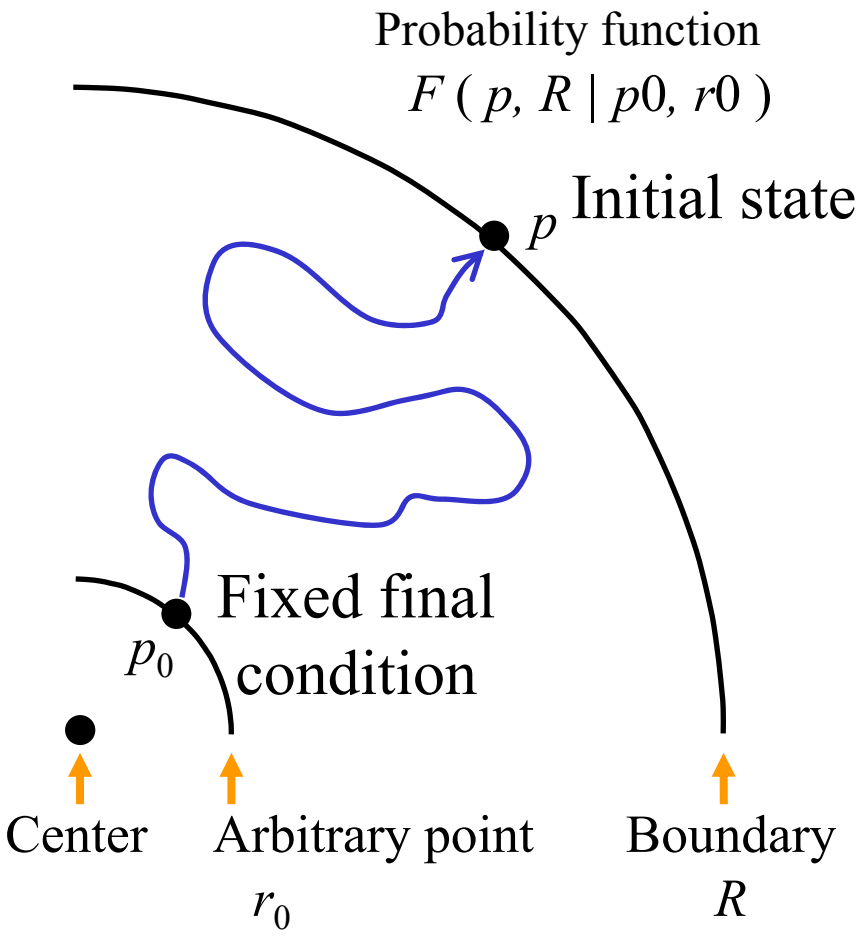
(Jokipii & Owens 1975)

(Yamada, Yanagita & Yoshida 1998)

$$\begin{cases} dr = \left(V + \dfrac{2\kappa}{r} + \dfrac{\partial \kappa}{\partial r}\right)dt + \sqrt{2\kappa}\, dw \\ du = -\dfrac{2V}{3r}dt \qquad \left(u \equiv \ln(p/mc)\right) \end{cases}$$

dw : Wiener process given by a Gaussian distribution

Schematic view of the simulation method with the SDEs "backward in time"



(Yamada, Yanagita & Yoshida 1998)

→We start the simulation from an arbitrary point r_0 for a particle with the observed momentum p_0.

→We trace the particle trajectory backward in time until the particle moves back to the boundary R.

→By repeating this calculation for various p_0 at r_0, we obtain normalized distribution function $F(p, R \mid p_0, r_0)$.

Modulated energy spectrum with the SDEs "backward in time"

$$f_{r_0}(p_0) = \int f_R(p) F(p, R \mid p_0, r_0) dp$$

$f_{r_0}(p_0)$: modulated energy spectrum at an arbitrary point r_0

$f_R(p)$: energy spectrum at boundary R

$F(p, R \mid p_0, r_0)$: normalized distribution function

☆diffusion coefficient

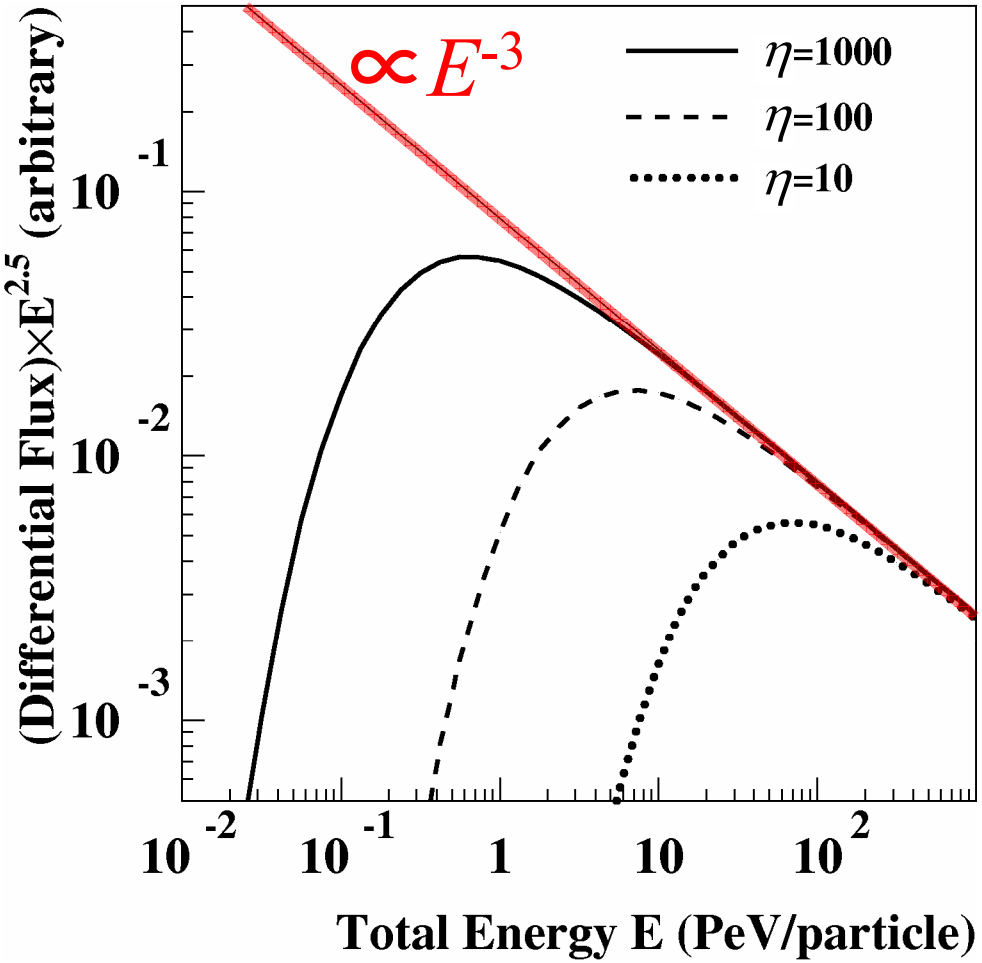
$$\kappa = \eta \kappa_{\text{Bohm}} \approx 3.3\times 10^{28} \eta Z^{-1} \left(\frac{E}{1\text{PeV}}\right)\left(\frac{B}{1\mu\text{G}}\right)^{-1} \text{cm}^2\text{s}^{-1}$$

κ_{Bohm} : Bohm diffusion coefficient

η : the ratio of diffusion mean free path to Larmor radius

B : magnetic field in the galactic halo

Galactic modulated spectra of protons at Earth (r_0 = 8.5 kpc)



- radial distance of the galactic sphere:

$$R = 100\,\mathrm{kpc}$$

(Zirakashvili et al. 1996)

- speed of the galactic wind:

$$V = 300\,\mathrm{km\,s^{-1}}$$

(Zirakashvili et al. 1996)

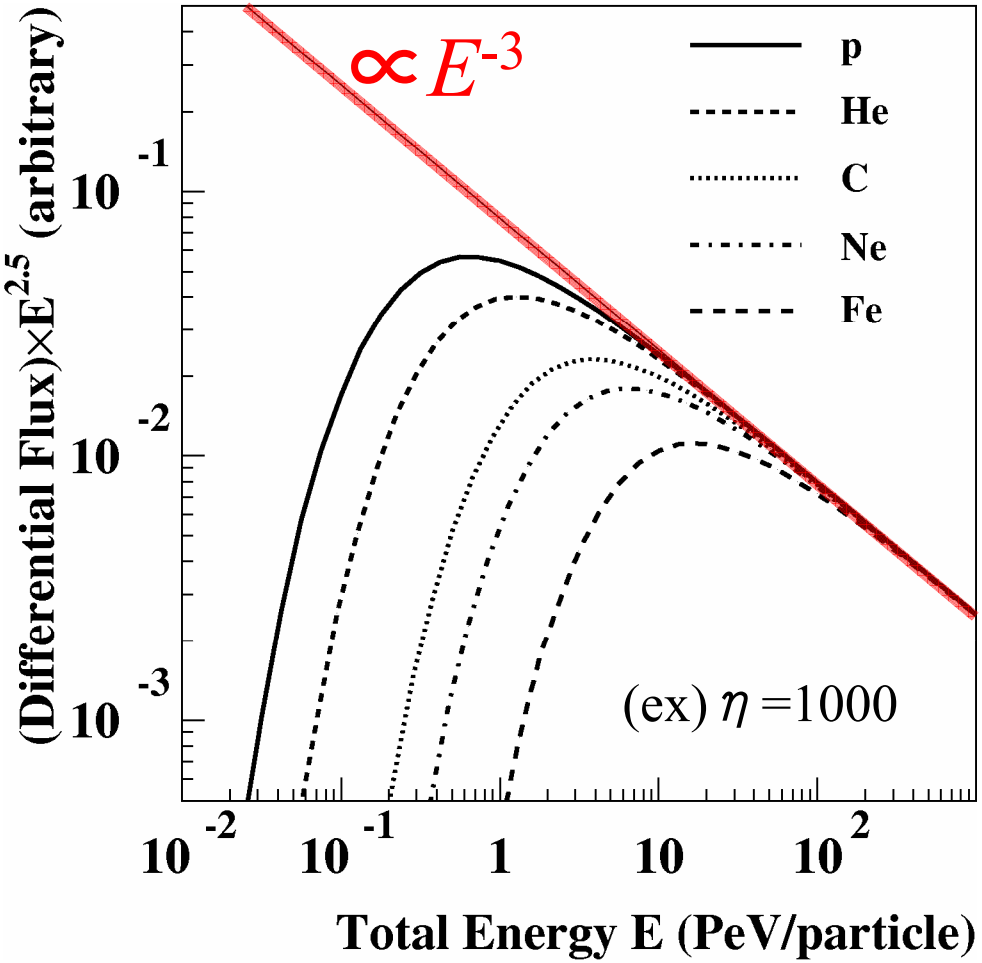
- magnetic field:

$$B = 1\,\mu\mathrm{G}$$

→ The spectrum breaks around the knee energy.

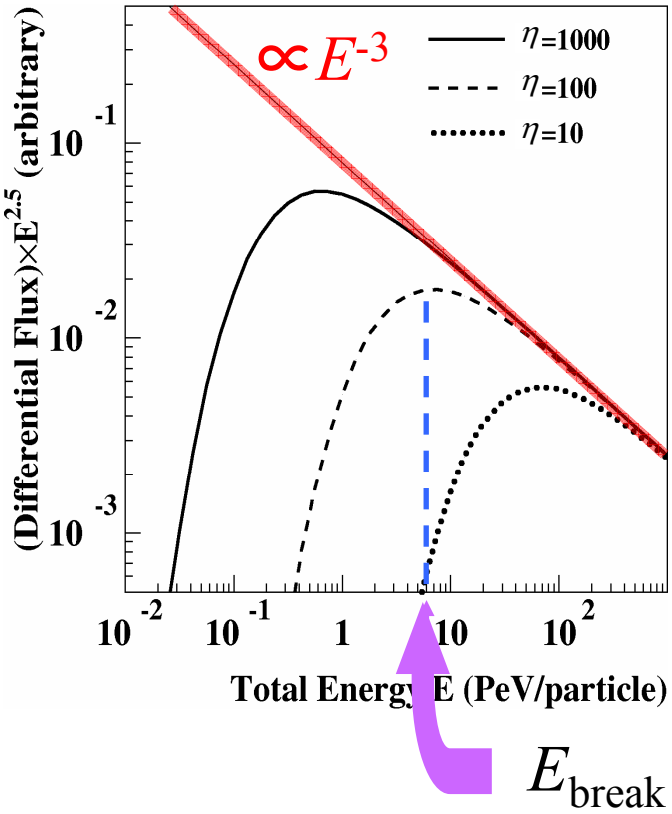
→ If η increased by some factor, the break point is shifted to lower energy by the same factor.

Modulated spectra of various nuclear components



→ **The break point of the nuclear components is shifted to higher energy by a factor of Z compared with that for protons.**

Break point in the modulated spectrum of the hypothetical extragalactic CRs



→The resultant modulated spectrum depends on five parameters, η , Z, R, V, and B.

→If we difine the breaking energy E_{break} as the energy at which the modulated spectrum becomes maximal, then…

$$E_{break}(\eta,B,R,V,Z) \approx 6\times10^{15}\, Z \left(\frac{\eta}{100}\right)^{-1}\left(\frac{B}{1\mu\mathrm{G}}\right)\left(\frac{R}{100\mathrm{kpc}}\right)\left(\frac{V}{300\,\mathrm{kms}^{-1}}\right)\mathrm{eV}$$

3. A model of the all-particle spectrum near the knee region

— A model of the all-particle spectrum

$$F_{\mathrm{Total}}(E) = F_{\mathrm{Modul}}(E) + F_{\mathrm{SNR}}(E)$$

F_{Total} : expected all-particle spectrum

F_{Modul} : modulated extragalactic component (←using our result!)

F_{SNR} : component originating in SNRs in our galaxy

$$F_{\mathrm{SNR}}(E) = \sum_{Z} f_{\mathrm{SNR}}^{Z}(E)$$

$$f_{\mathrm{SNR}}^{z}(E) \propto E^{-\alpha_z} \exp\left(-E/\left(Z E_{\mathrm{max}}\right)\right)$$

Z : atomic number

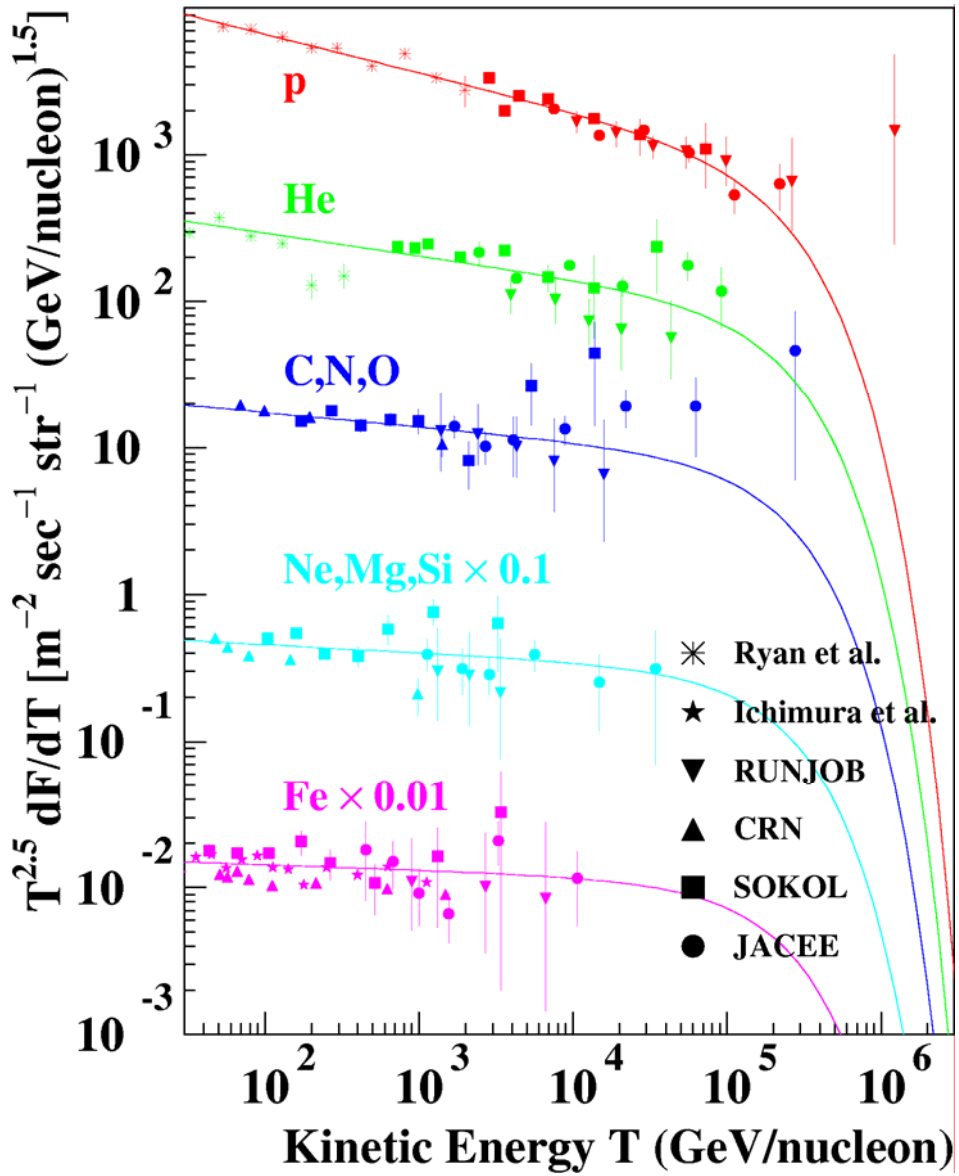
f_{SNR}^{Z} : each nuclear components

E_{max} maximum energy attained by proton accelerated in SNRs

α_z : spectral index of each nuclear components

→We fit f_{SNR}^{Z} with the results of various direct observation in TeV energy region.

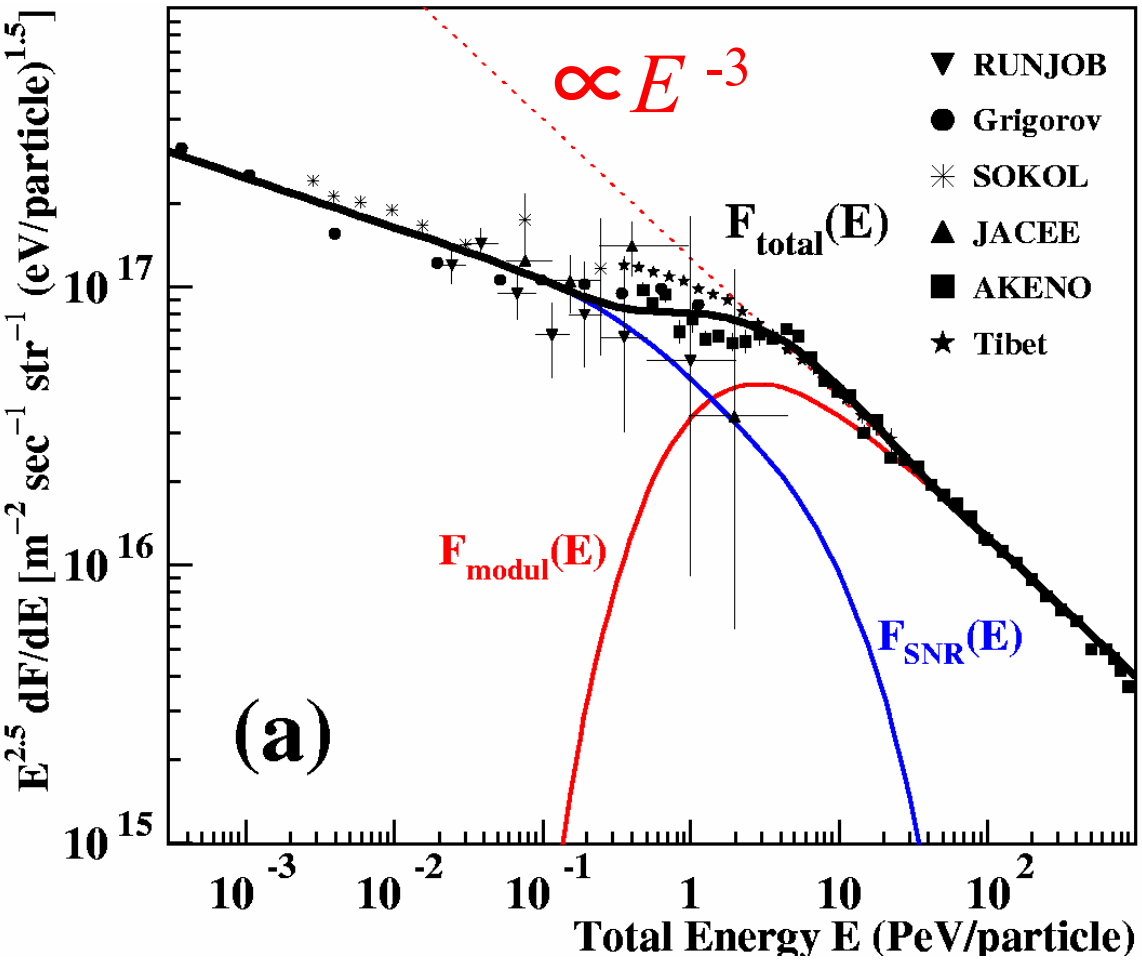
Energy spectra obtained using direct measurements and the fitted curves



(ex) E_{max}=500TeV

→ **We define the sum of these components as the SNR component, F_{SNR} .**

Single-component model for $F_{\mathrm{modul}}(E)$



(ex1) $F_{\mathrm{Modul}}(E) = f^{\mathrm{proton}}_{\mathrm{Modul}}(E)$

$R = 100\,\mathrm{kpc}$ $\eta = 250$

$B = 1\,\mu\mathrm{G}$ $Z = 1\,(\mathrm{proton})$

$V = 300\,\mathrm{km\,s^{-1}}$

→ We can replace $f^{\mathrm{proton}}_{\mathrm{Modul}}$ with another nuclear component, f^{Z}_{Modul}.

(ex2) $F_{\mathrm{Modul}}(E) = f^{\mathrm{Fe}}_{\mathrm{Modul}}(E)$

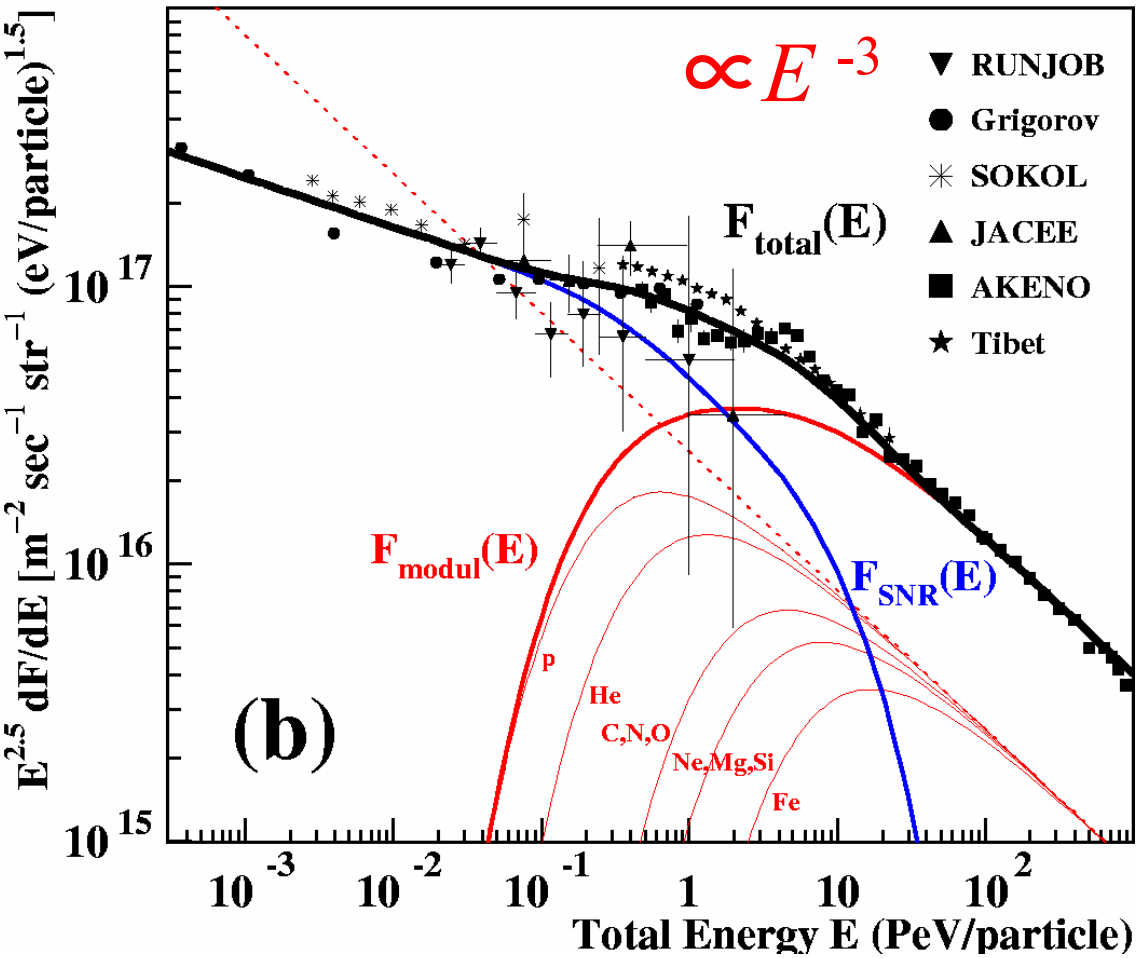
$R = 100\,\mathrm{kpc}$ $\eta = 500$

$B = 0.077\,\mu\mathrm{G}$ $Z = 26\,(\mathrm{Fe})$

$V = 300\,\mathrm{km\,s^{-1}}$

→Our model can reproduces the observed spectrum around the knee fairly well !

Composite model for $F_{\mathrm{modul}}(E)$



(ex3)

$$F_{\mathrm{Modul}} = f_{\mathrm{Modul}}^{\mathrm{proton}} + f_{\mathrm{Modul}}^{\mathrm{He}} + f_{\mathrm{Modul}}^{\mathrm{CNO}} + f_{\mathrm{Modul}}^{\mathrm{NeMgSi}} + f_{\mathrm{Modul}}^{\mathrm{Fe}}$$

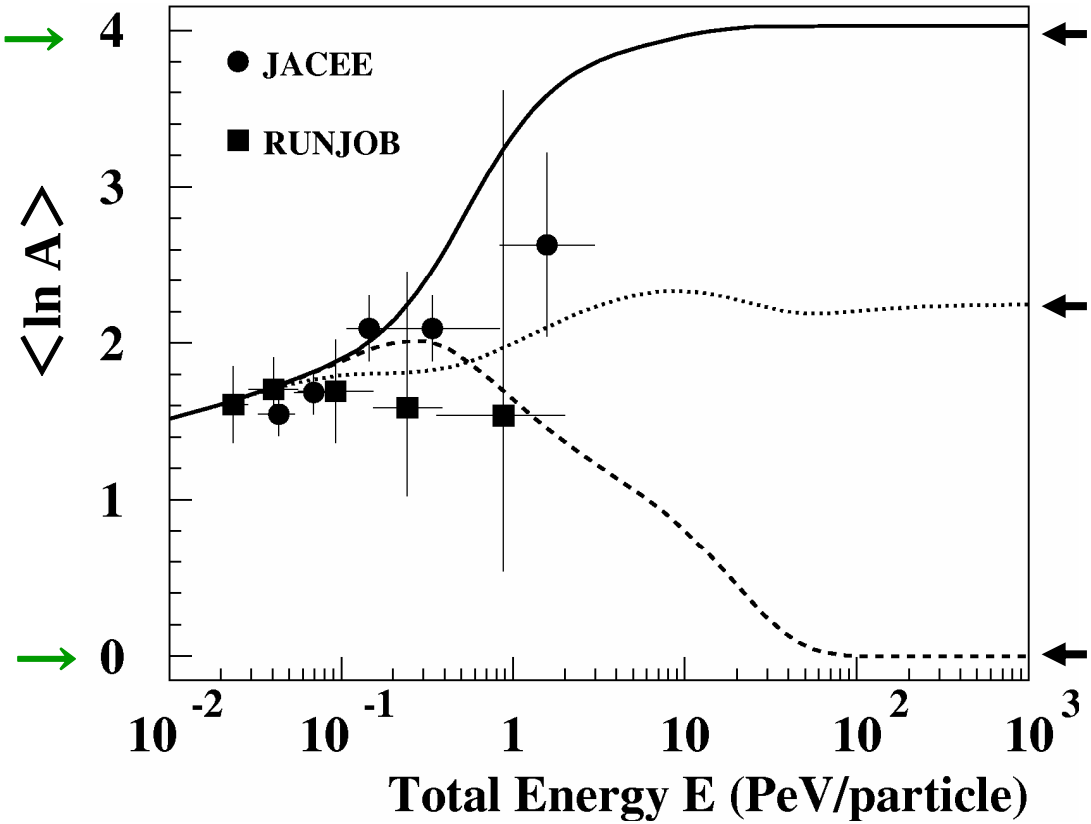
$R = 100\,\mathrm{kpc} \quad \eta = 250$

$B = 1\,\mu\mathrm{G} \quad V = 300\,\mathrm{km\,s^{-1}}$

$Z = 1(\mathrm{proton}),\ 2(\mathrm{He}),\ 7(\mathrm{CNO}),\ 12(\mathrm{NeMgSi}),\ 26(\mathrm{Fe})$

→We can also reproduce the spectrum using the model with a composite hypothetical CRs

Expected mean mass of CRs around the knee region



all Fe →

All proton →

(ex2) Single-component model for $F_{\mathrm{modul}} = f_{\mathrm{Modul}}^{\mathrm{Fe}}$

(ex3) Composite model for $F_{\mathrm{Modul}} = f_{\mathrm{Modul}}^{\mathrm{proton}} + f_{\mathrm{Modul}}^{\mathrm{He}} + f_{\mathrm{Modul}}^{\mathrm{CNO}} + f_{\mathrm{Modul}}^{\mathrm{Fe}} + f_{\mathrm{Modul}}^{\mathrm{NeMgSi}}$

(ex1) Single-component model for $F_{\mathrm{modul}} = f_{\mathrm{Modul}}^{\mathrm{proton}}$

→ Our model should be tested by future experiments in an energy range much higher than the knee.

4. Discussion

- Energetics of hypothetical extragalactic CRs
- Possible origin

★Energetics of the hypothetical CRs

- If the hypothetical CR spectrum extends down to their rest mass energy
  ($F_{CR}(E) \approx 4.3\times10^{20} E^{-3}\ \mathrm{cm^{-2}s^{-1}sr^{-1}eV^{-1}}$),

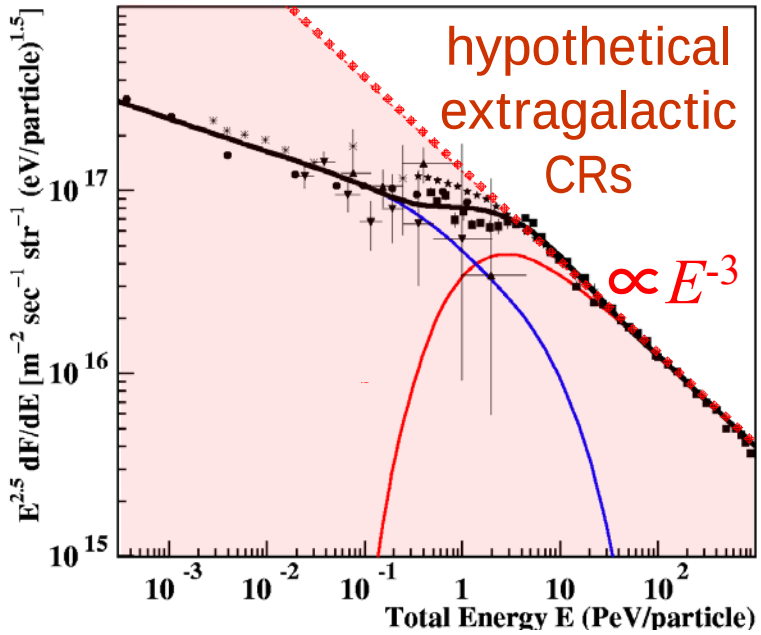
$$\longrightarrow \quad \rho_{CR} = \int_{E_m}^{\infty} \frac{4\pi}{v} F_{CR}(E)\, E\, dE$$

$$\approx \underline{294\ \mathrm{eV\,cm^{-3}}}$$

- Also if the hypothetical CRs pervade the intergalactic space uniformly, corresponding density parameter…

$$\Omega_{CR}\, h_{70}^2 \approx \underline{0.057} \quad (\sim \quad \Omega_B h_{70}^2 \approx \underline{0.020}\ )$$

(Burles et al. 2001)



→The hypothetical CRs may contribute to Dark Matter ??

→The spectrum becomes harder in the energy lower than the knee (low-energy cutoff) ?

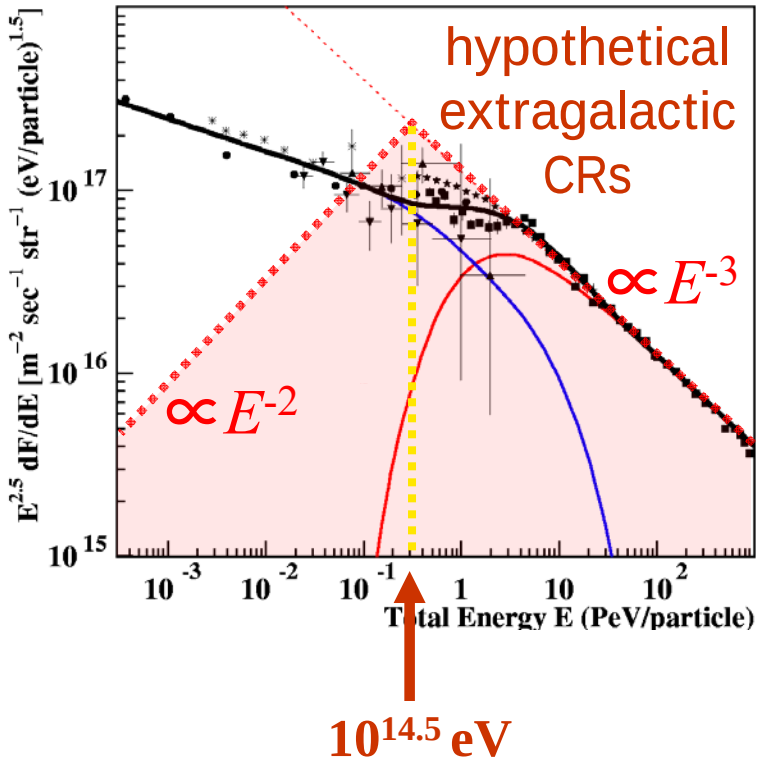
→CRs are confined in local regions?

- If the hypothetical CR spectrum becomes harder with the index of 2 in the energy range lower than 10^14.5 eV, …

$$F_{\mathrm{CR}}(E) \approx \begin{cases} 4.3\times10^{20}\,E^{-3}\ \mathrm{cm^{-2}s^{-1}sr^{-1}eV^{-1}} & (\geq 10^{14.5}\,\mathrm{eV}) \\ 1.3\times10^{6}\,E^{-2}\ \mathrm{cm^{-2}s^{-1}sr^{-1}eV^{-1}} & (\leq 10^{14.5}\,\mathrm{eV}) \end{cases}$$

$$\longrightarrow \rho_{\mathrm{CR}} = \int_{E_{\mathrm{m}}}^{\infty} \frac{4\pi}{v} F_{\mathrm{CR}}(E)\,E\,dE$$

$$\approx \underline{0.0078\ \mathrm{eV\,cm^{-3}}}$$



→much small !

★Possible origin of hypothetical extragalactic CRs

- Reacceleration of GCRs ? (Jokipii & Morfill 1985) (Volk & Zirakashvili 2004)
- Early starburst in galaxy clusters? (Voelk & Atoyan 2000)
- Cluster merger ? (Blasi 2001)
- Shock acceleration in large-scale structure formation ? (Miniati et al. 2000)

More energetic !

In the future

- **TeV γ-ray observation from cluster merger**
  - **→existence of shock accelerated extragalactic CRs**
  - **→relation between extragalactic CRs and CRs above the knee**

5. Conclusion

- All-particle spectrum of CRs around “the knee” region is reproduced well by a superposition of the two components,

  GCRs of SNR origion and,

  the extragalactic CRs modulated by the galactic wind.

- The position of “the knee” may give us ideas on the structure of the galactic sphere (its size, the speed of the galactic wind, and etc.・・・・etc.) .

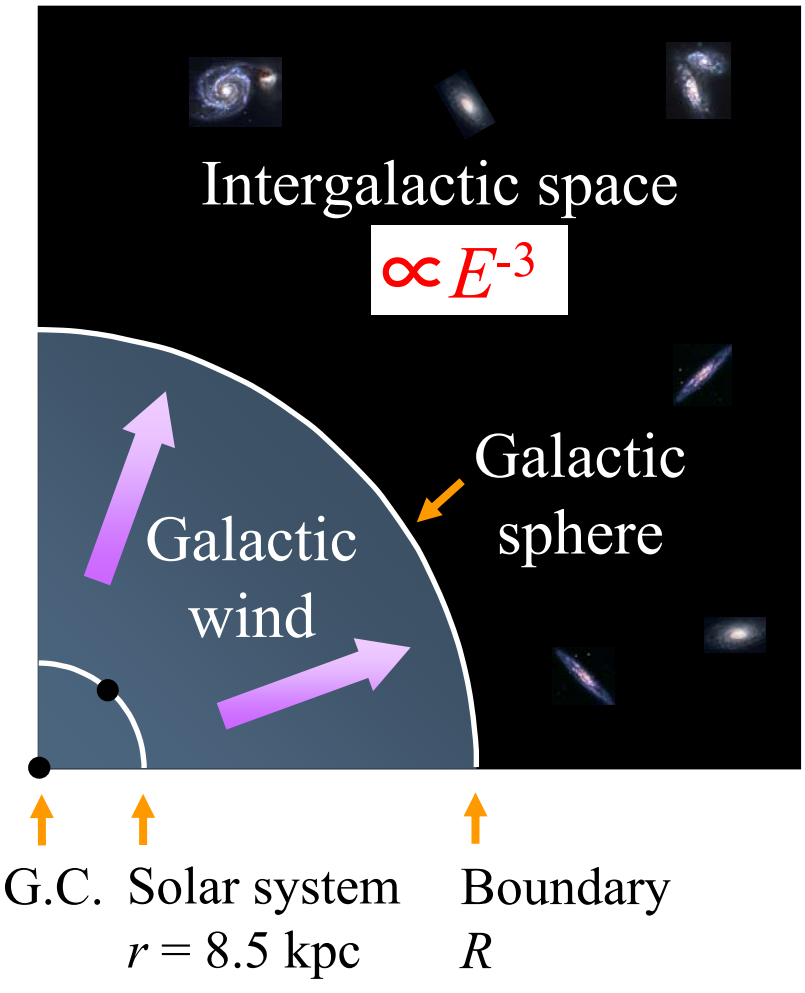
- Future observations of CRs above the knee region will tell us the chemical composition of the extragalactic CRs.

- Simulation experiments in more realistic setting for galactic structure are needed.

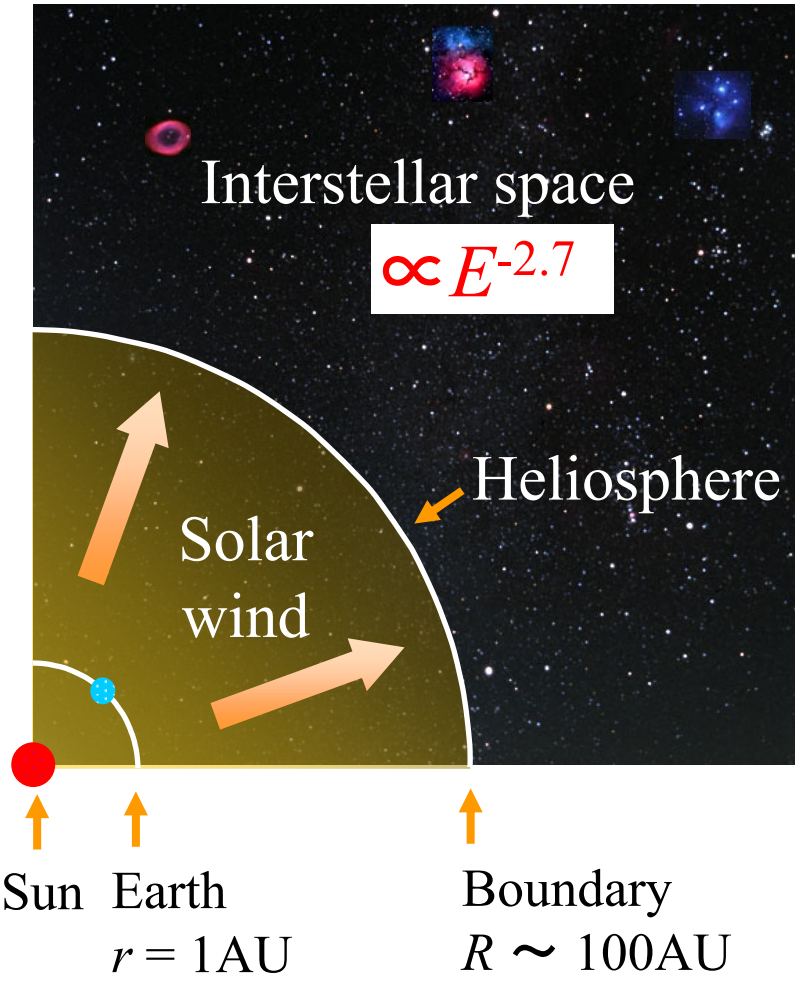
-The END-

Supplement

Schematic view of our model

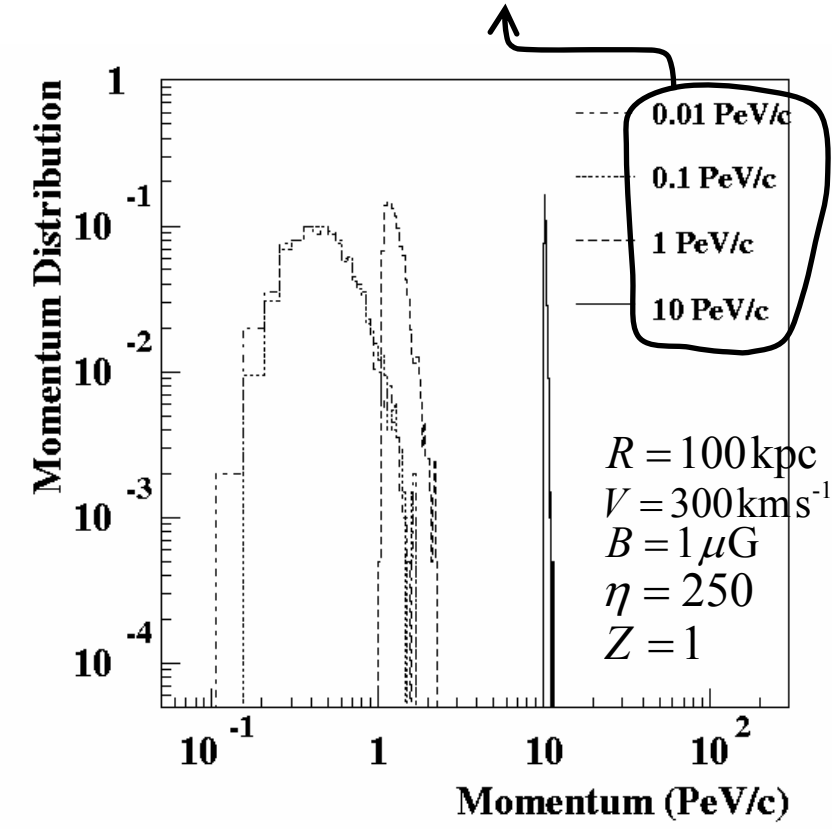


Solar modulation



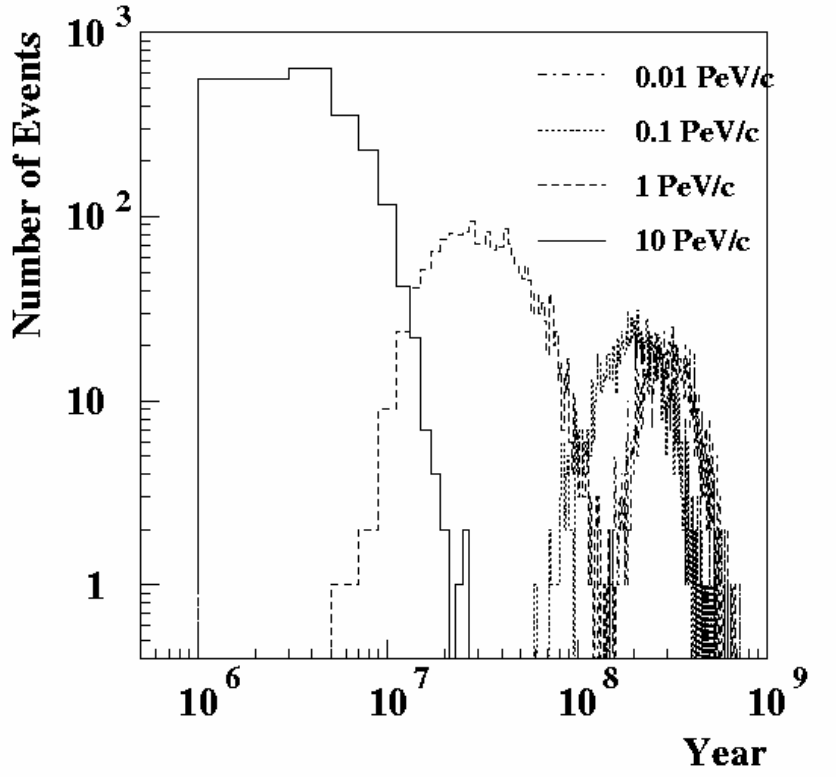
Nomalized distribution function

$F(p, 100\,\mathrm{kpc} \mid p_0, 8.5\mathrm{kpc})$



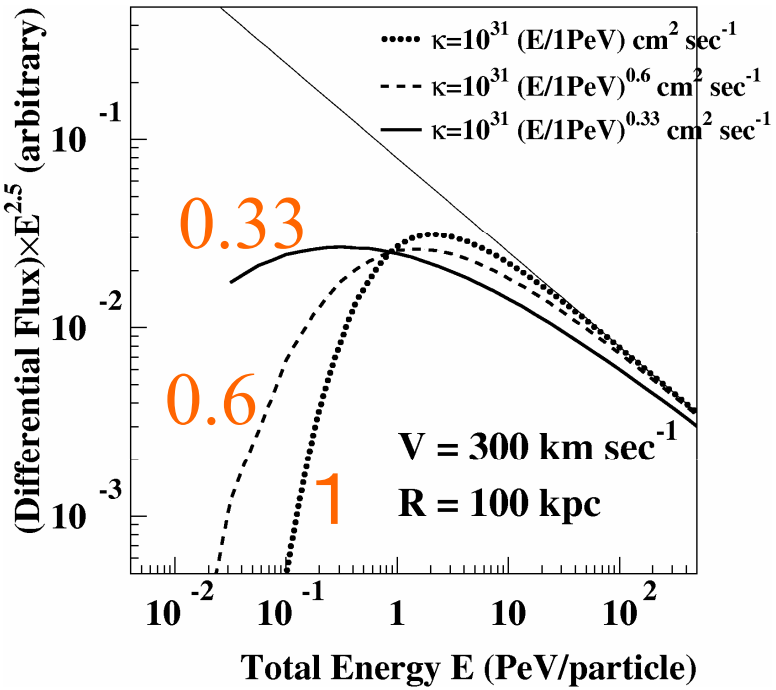
→CR protons below 0.01PeV/c at the boundary could not almost arrive on Earth.

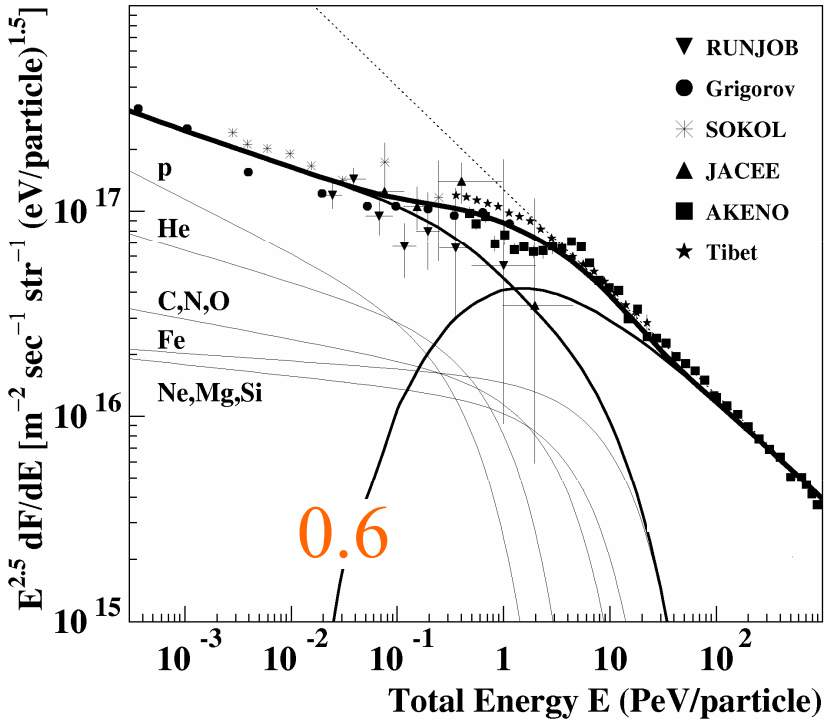
Distribution function of arrival time



→The arrival time is shorter than 10^9 yr even for particle with 0.01PeV/c which could barely reach Earth.

Dependence of modulated spectra on the diffusion coefficient





✧ Hypothetical CRs in SMC

Measurements employing the EGRET telescope show that the density of CRs inside the SMC is several times less than in our galaxy. This fact indicates simply that GeV CRs may originate in each galaxy, possibly in SNRs. This result seems to be incompatible with the existence of the hypothetical extragalactic CRs that we introduced here.

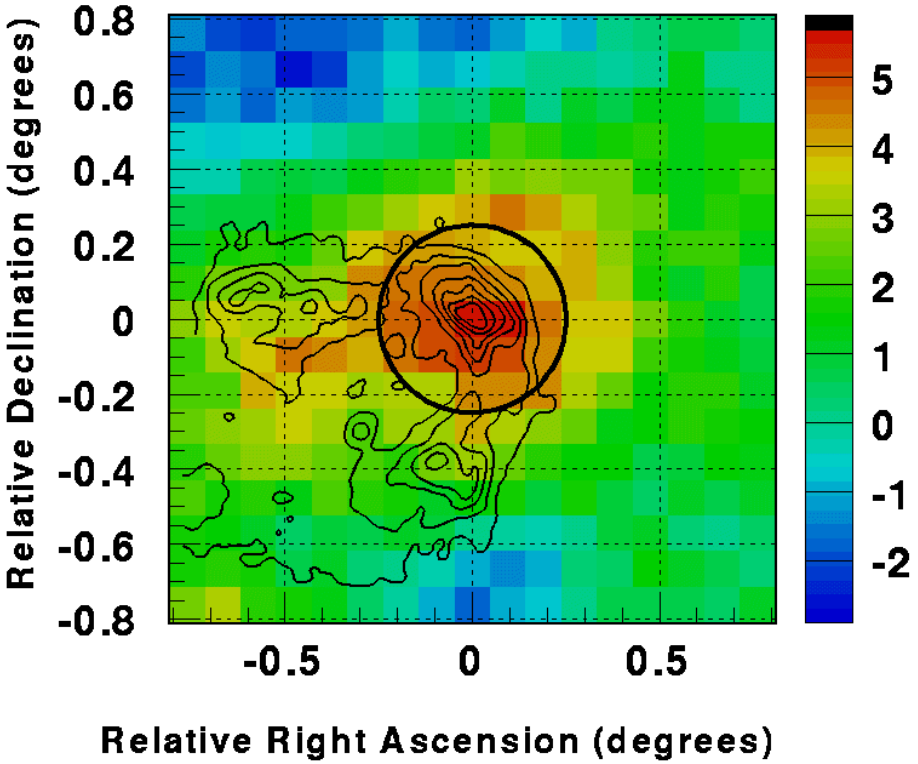
However, if SMC has a galactic wind, like our galaxy, the intensity of hypothetical CRs in the GeV region inside the SMC should be suppressed, due to the modulation effect of the SMC itself.

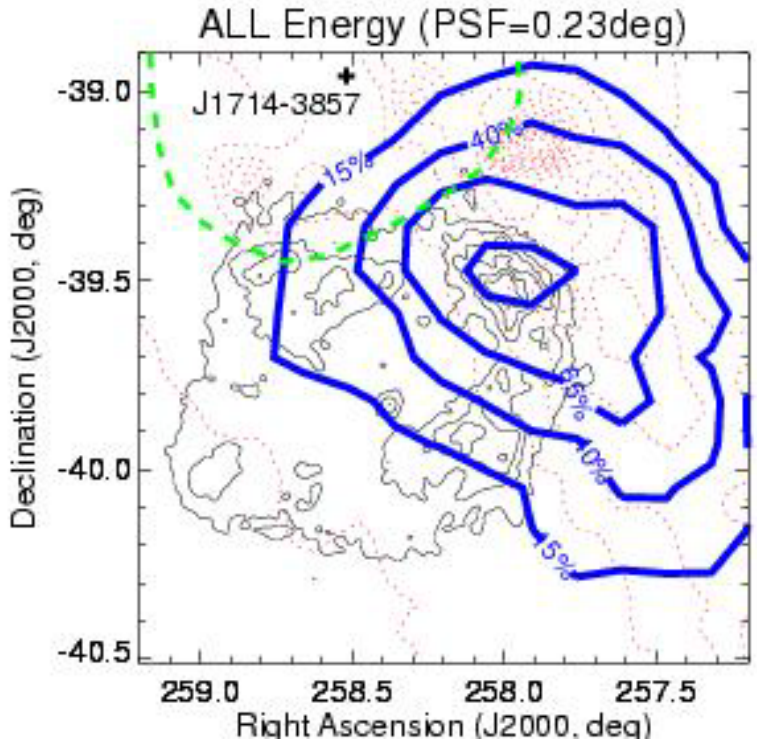
✧ Plausible value for V and R

In our model, the extragalactic CRs spend long times in the outer region of the galactic sphere (>20kpc) rather than the inner region like around the galactic disk (<20kpc).

The reason why we adopt the speed of the galactic wind to be 300 km s^-1 is based on the results of MHD simulations (Zirakashvili et al.1996). In this model, the resultant velocity profile reveal that it increases almost linearly with distance up to z=20 kpc and then becomes a constant with about a few hundred km s^-1 up to 100 kpc.

Significance map around RXJ1713 (CANGAROO observation)



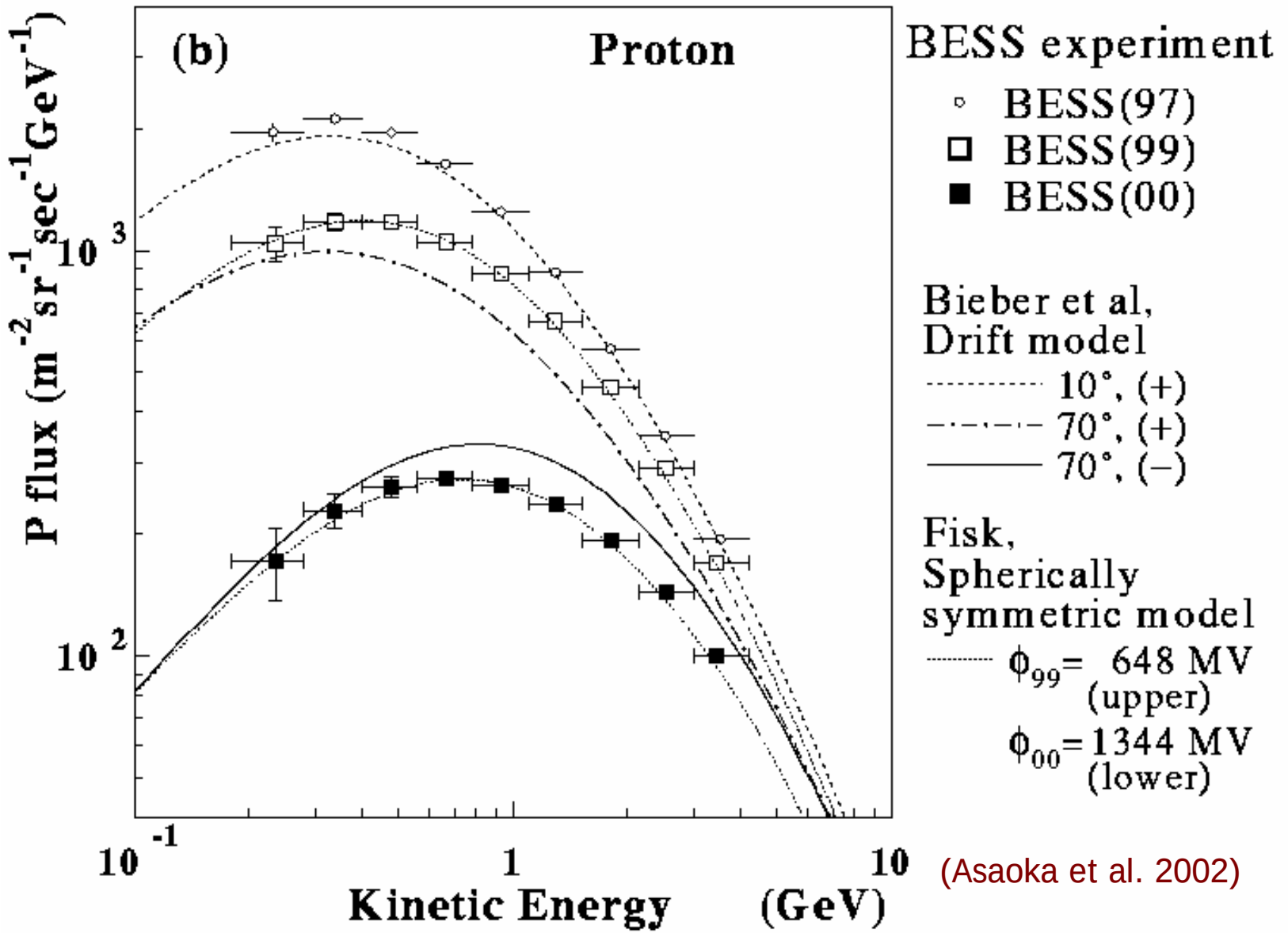


3.8m telescope

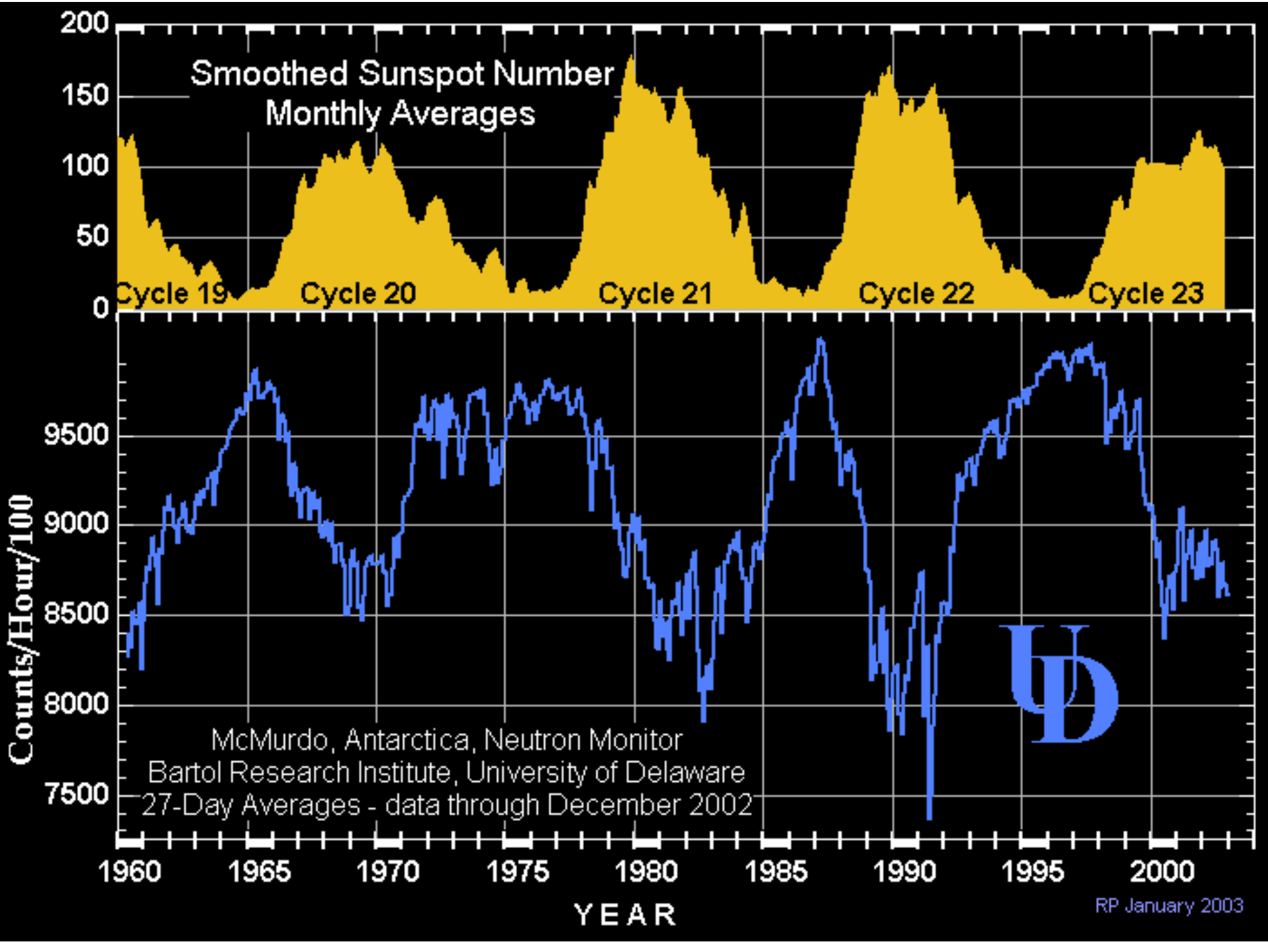
Muraishi et al., A&A 357, L57 (2000)

10m telescope

Enomoto et al., Nature 416, 823 (2002)



(Asaoka et al. 2002)


Smoothed Sunspot Number
Monthly Averages
200
150
100
50
0
Cycle 19
Cycle 20
Cycle 21
Cycle 22
Cycle 23
Counts/Hour/100
9500
9000
8500
8000
7500
McMurdo, Antarctica, Neutron Monitor
Bartol Research Institute, University of Delaware
27-Day Averages - data through December 2002
1960
1965
1970
1975
1980
1985
1990
1995
2000
YEAR
RP January 2003