Propagation of Cosmic Rays in the Galaxy

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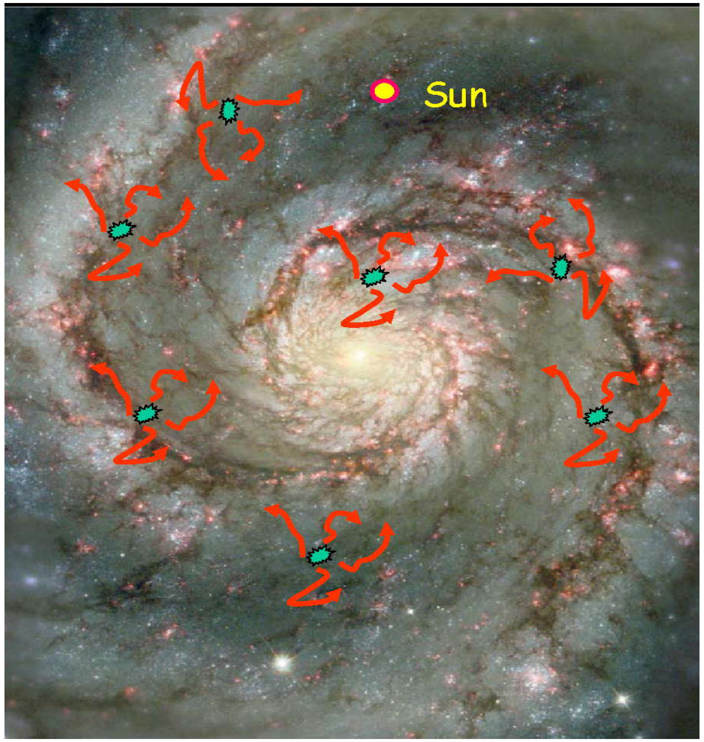
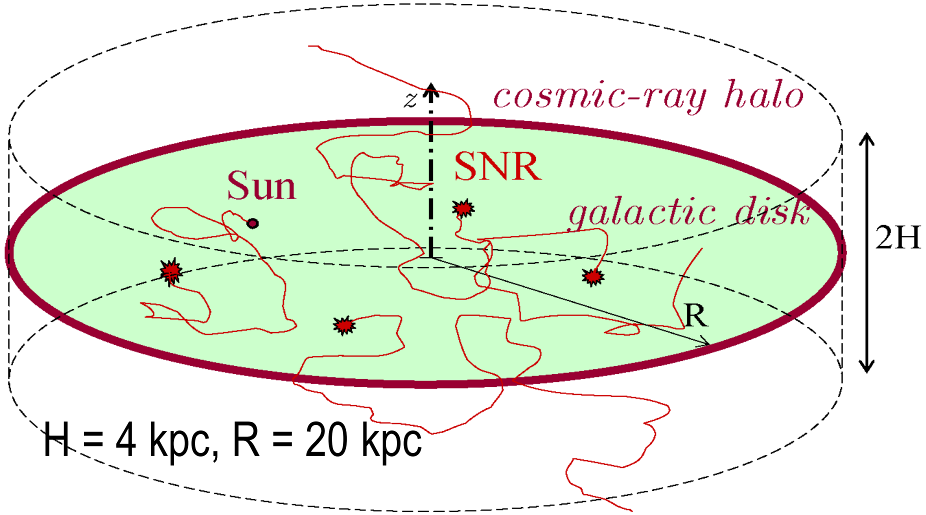


basic diffusion model



Berezinskii et al. 1990, Strong & Moskalenko 1998, Strong et al 2007 (GALPROP code)

~ 15% of SN kinetic energy transfer to cosmic rays,

$$\nu_{sn} = (30\ \mathrm{yr})^{-1}$$

$$J_{cr}(E) = Q_{cr}(E) \times T_e(E)$$

source

confinement time of CR in the Galaxy; ~ 10^8 yr at 1 GeV

$$T_e \approx \frac{H^2}{2D}$$

$$D \approx 3 \times 10^{28}\ \mathrm{cm^2/s\ at\ 1\ GeV}$$

$$D \propto (p/Z)^a, \quad a = 0.3...0.6$$

$$Q_{cr} \propto (p/Z)^{\gamma_s}, \gamma_s = 2.7 - a = 2.1...2.4$$

mechanism of cosmic ray diffusion

$r_g = 1/k$ - resonance condition

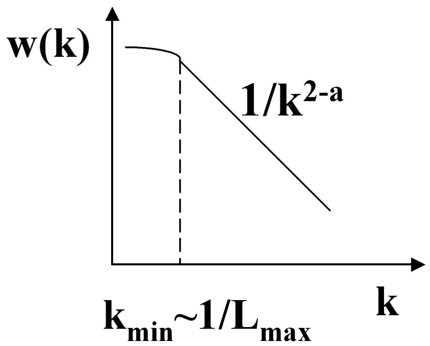
$$D_{\|} \approx \frac{v r_g}{3} \cdot \frac{B_{tot}^2}{B_{res}^2}$$

Jokipii 1966, ...

cosmic ray particles are strongly magnetized but the large-scale random magnetic field (with L_{max} ~ 100 pc) makes diffusion close to isotropic

spectrum of turbulence: $w(k)dk \sim k^{-2+a}dk$, $D_{\|} \sim v r_g^{\,a}$

$$B_{res}^2 = \int_{k_{res}} w(k)\,dk$$



$a = 1/3$ Kolmogorov spectrum

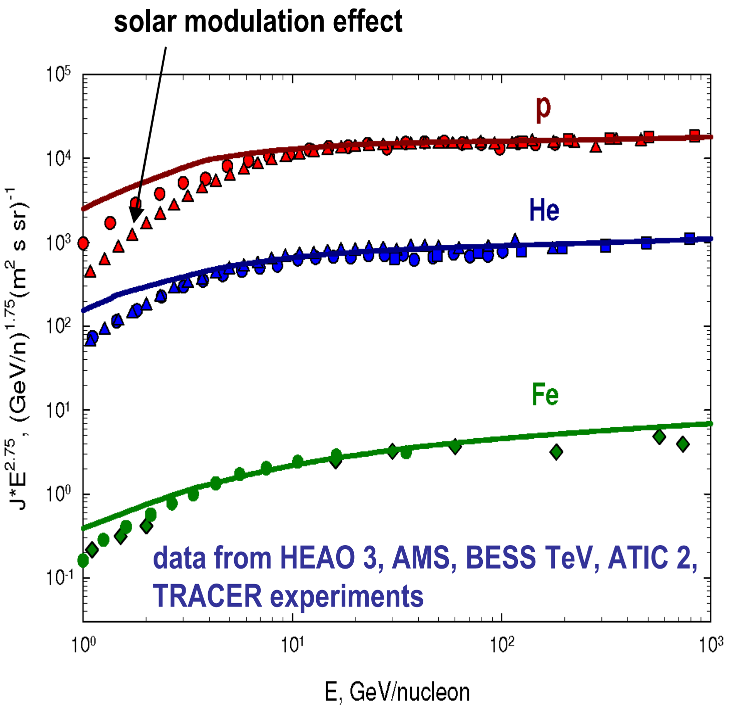
$a = 1/2$ Kraichnan spectrum

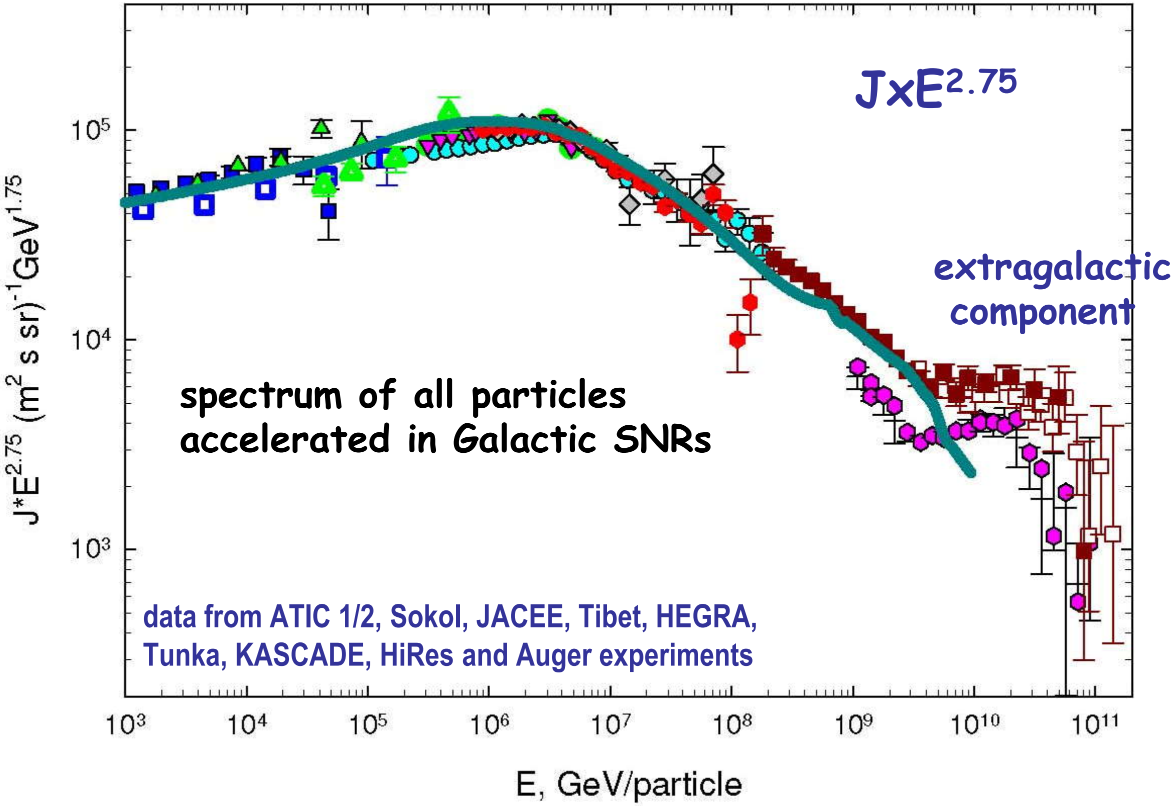
$a = 0$ random discontinuities

$a = 1$ white noise (leads to Bohm diffusion scaling $D_B = v r_g/3$)

calculated interstellar spectra produced by diffusive shack acceleration in SNRs Ia, IIP, Ib/c, IIb, normalized at 10^3 GeV

VP, Zirakashvili, Seo 2010





diffusion in the Galaxy:

$$D \propto \left(pc/Z \right)^{0.54}$$

Jones et al 2001

«knee» is formed at the beginning of Sedov stage

$$p_{knee}c/Z = 1.1 \times 10^{15} E_{sn,51} n^{1/6} M_{ej}^{-2/3} \text{ eV}$$

numerical simulation of cosmic-ray acceleration in SNRs

VP et al 2010, 2013, Zirakashvili & VP 2012

$$\frac{\partial \rho}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r} r^2 u \rho, \qquad (1)$$

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial r} - \frac{1}{\rho}\left(\frac{\partial P_g}{\partial r} + \frac{\partial P_c}{\partial r}\right), \qquad (2)$$

$$\frac{\partial P_g}{\partial t} = -u\frac{\partial P_g}{\partial r} - \frac{\gamma_g P_g}{r^2}\frac{\partial r^2 u}{\partial r} - (\gamma_g - 1)(w - u)\frac{\partial P_c}{\partial r}, \qquad (3)$$

$$\frac{\partial N}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r} r^2 D(p,r,t)\frac{\partial N}{\partial r} - w\frac{\partial N}{\partial r} + \frac{\partial N}{\partial p}\frac{p}{3r^2}\frac{\partial r^2 w}{\partial r}$$
$$+ \frac{\eta^f \delta(p - p_f)}{4\pi p_f^2 m}\rho(R_f + 0, t)(\dot{R}_f - u(R_f + 0, t))\delta(r - R_f(t))$$
$$+ \frac{\eta^b \delta(p - p_b)}{4\pi p_b^2 m}\rho(R_b - 0, t)(u(R_b - 0, t) - \dot{R}_b)\delta(r - R_b(t)).$$
$$(4)$$

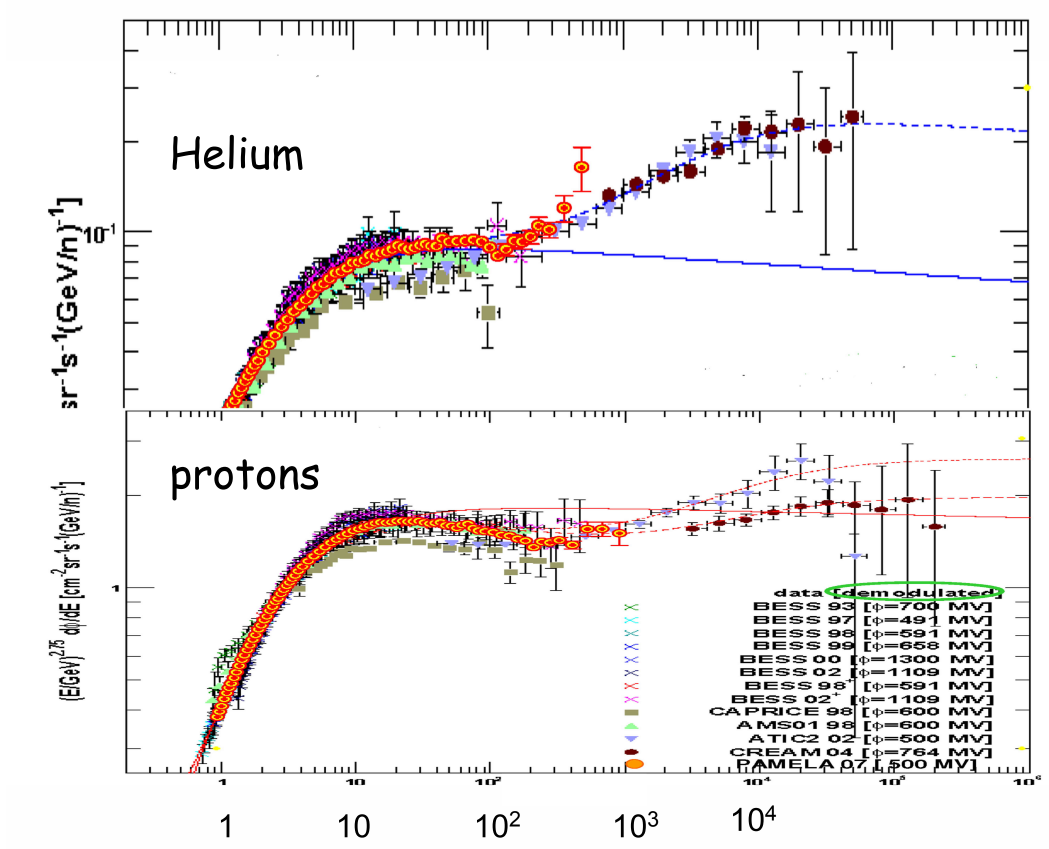
- spherically symmetric hydrodynamic eqs. including **CR pressure** + diffusion-convection eq. for cosmic ray distribution function (compare to Berezhko et al. 1996, Berezhko & Voelk 2000; Kang & Jones 2006)

- Bohm diffusion in **amplified magnetic field** $B^2/8\pi = 0.035\ \rho u^2/2$ (Voelk et al. 2005 empirical; Bell 2004, Zirakashvili & VP 2008 theoretical)

- account for **Alfvenic drift $w = u + V_a$** upstream and downstream

- relative SNR rates: **SN Ia : IIP : Ib/c : IIb = 0.32 : 0.44 : 0.22 : 0.02** Chevalier 2004, Leaman 2008, Smart et al 2009

demodulated spectra $J \times E^{2.75}$ ATIC, CREAM, PAMELA etc.
(after Lavalle 2011)



details to explain:

hardening above 200 GeV/nucleon

concave source spectrum

new source
Zatsepin & Sokolskaya 2006

reacceleration in local bubble
Erlykin & Wolfendale 2011

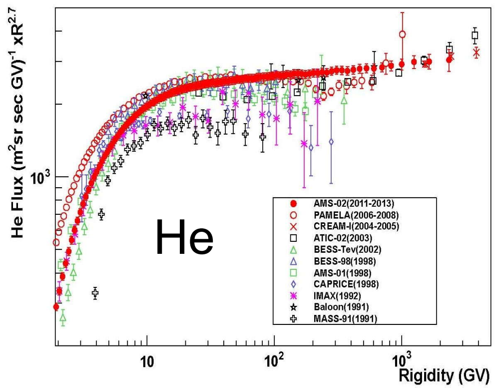
streeming instability at low energies Blasi et al. 2012

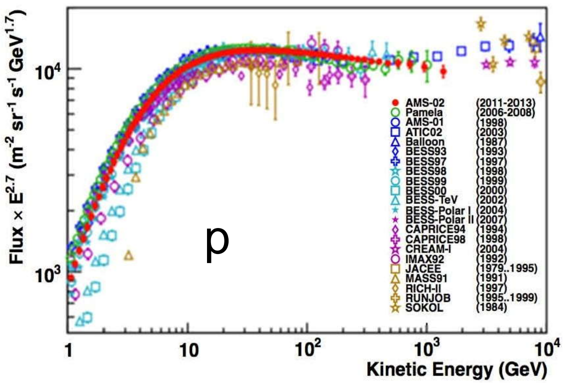
spectra of p and He are different

strong shock goes through material enriched in He:
- helium wind VP et al. 2010,
- bubble Ohira & Ioka 2011

effect of injection
Malkov et al 2011

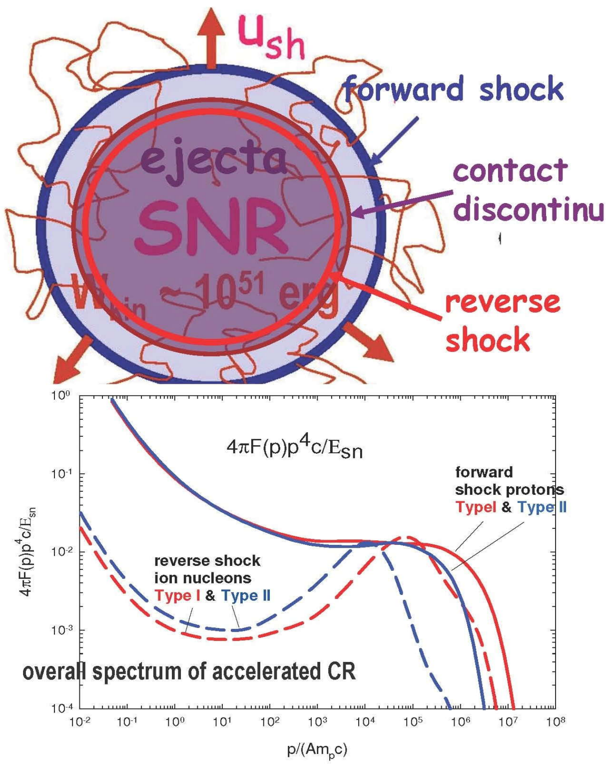
AMS02 2013

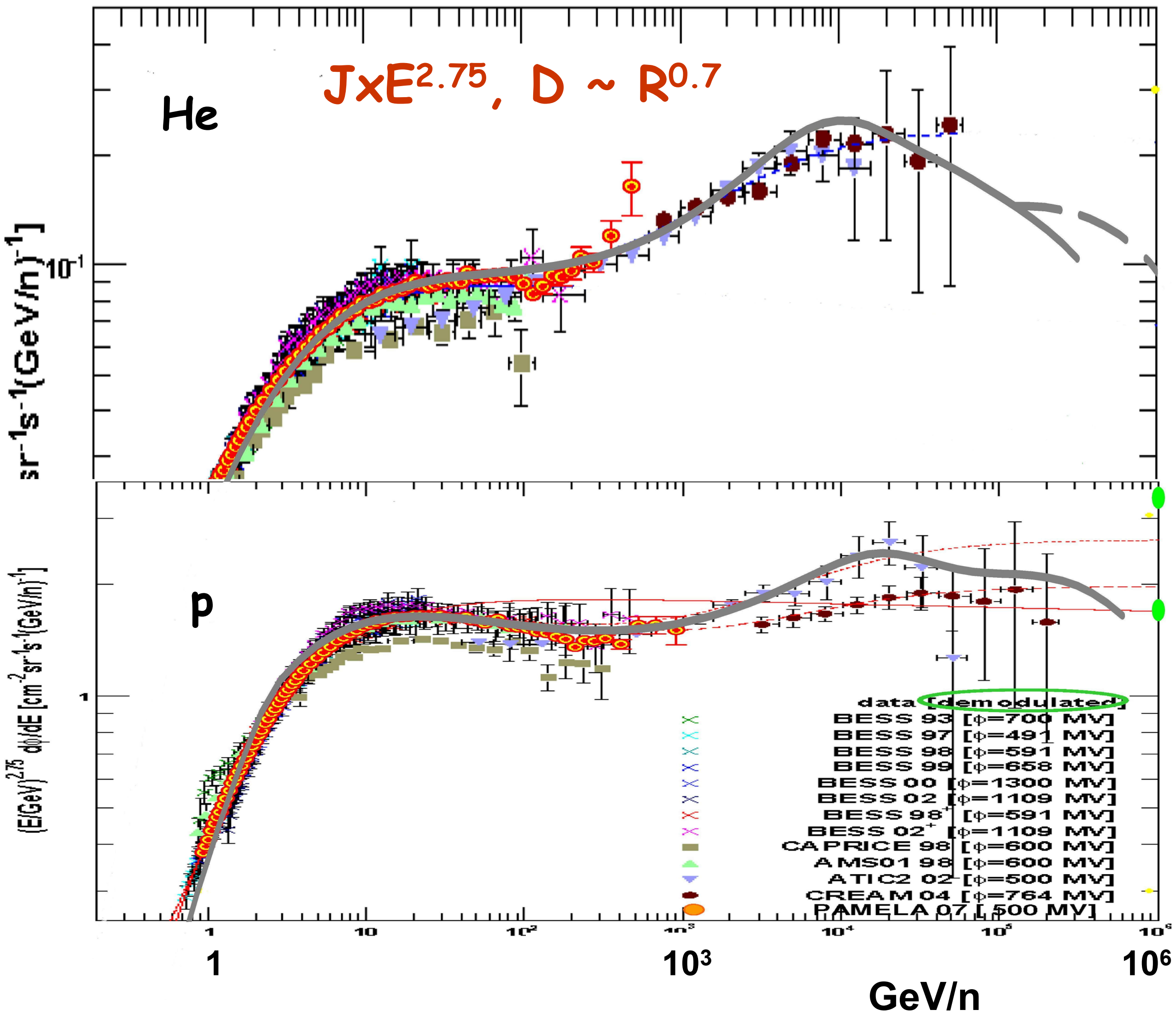


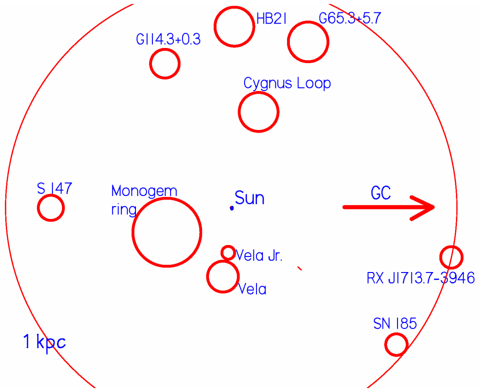


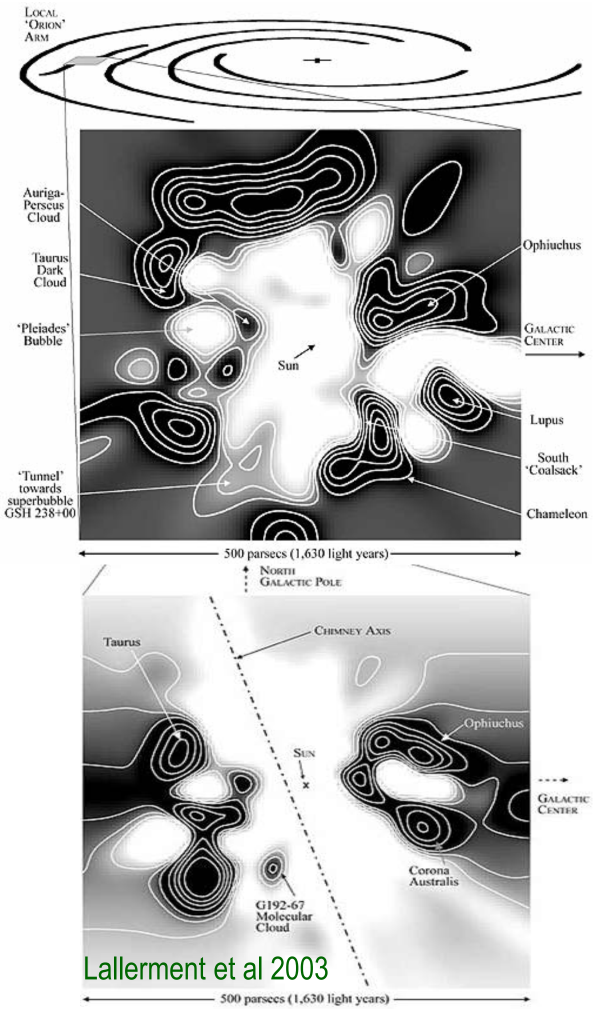
acceleration by forward and reverse shocks

VP, Seo, Zirakashvili 2013



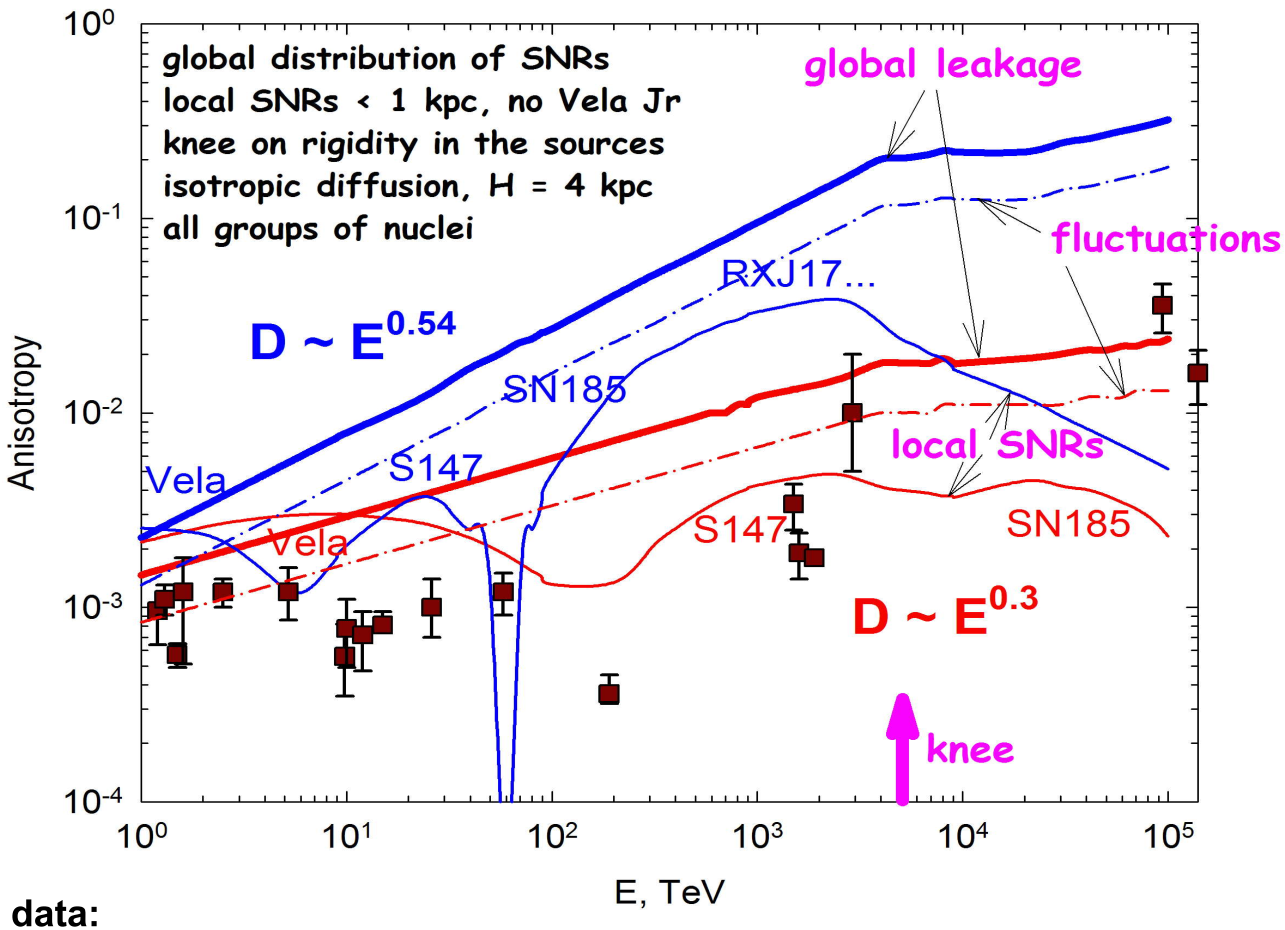






Lallerment et al 2003

large-scale anisotropy

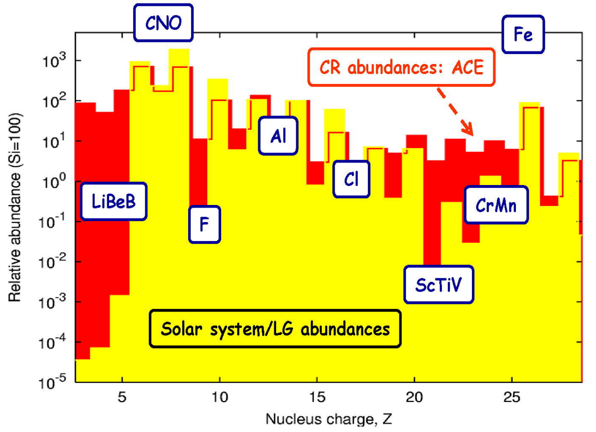


data:

Gomboshi et al. 1975, Linsley & Watson 1977, Lloyd-Evans 1982, Kifune et al. 1986, Lee & Ng 1987, Bird et al. 1989, Nagashima et al. 1989, Andreev et al. 1991, Cutler & Groom 1991, Fenton et al. 1995, Mori et al. 1995, Aglietta et al. 1996, Efimov et al. 1997, Munakata et al. 1999, Ambrosio et al. 2003

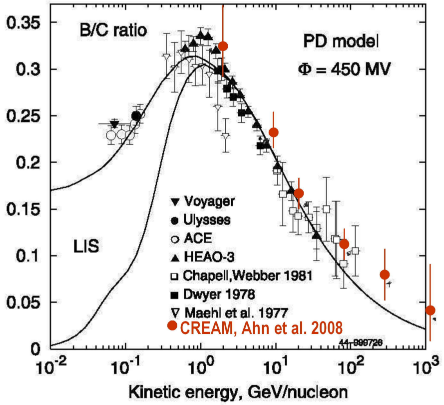
dependence of diffusion on energy

secondary nuclei



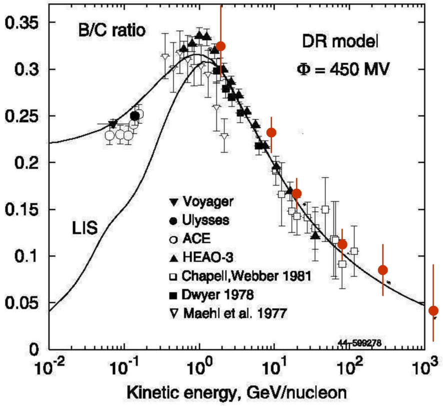
B/C ratio in three models of cosmic ray propagation

plain diffusion, "unphysical" break



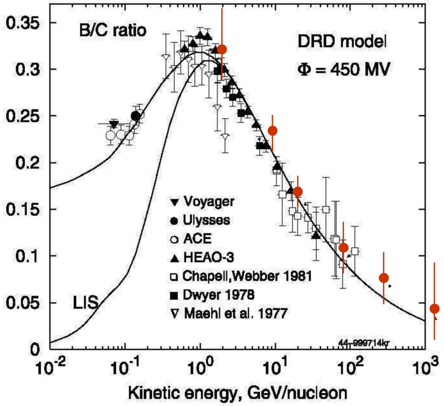
$D \sim (p/Z)^{0.6}$
$Q_{cr} \sim (p/Z)^{-2.1}$

diffusion (Kolmogorov) + reacceleration



$D \sim (p/Z)^{0.3}$
$Q_{cr} \sim (p/Z)^{-2.4}$

diffusion (Kraichnan) + reac. + damping on CR



$D \sim (p/Z)^{0.5}$
$Q_{cr} \sim (p/Z)^{-2.2}$

derived exponent of source spectrum at high energies 2.1…2.2 or 2.4

escape length, ~ 12 g/cm^2 at 1 GeV/nuc

$$X \approx \mu v H / 2D$$

surface gas density of galactic disk, ~ 2.5 g/cm^2

size of cosmic ray halo, ~ 4 kpc

regimes of cosmic ray diffusion

Kolmogorov turbulence spectrum: $D \sim vR^{1/3}$

may be valid up to $10^{17}Z$ eV

source spectrum $R^{-2.4}$ – too soft to be produced in SNRs (but dispersion of SNR parameters may help)

anisotropy – acceptable

peak of B/C ratio at 1 GeV/n – explained by distributed reacceleration (although the predicted antiproton flux is too low ?)

theory of MHD turbulence – contradiction to wave distribution in k-space

Kraichnan turbulence spectrum: $D \sim vR^{1/2}$

may be valid up to $10^{16}Z$ eV only

source spectrum $R^{-2.2}$ – consistent with shock acceleration in SNRs

anisotropy – too high

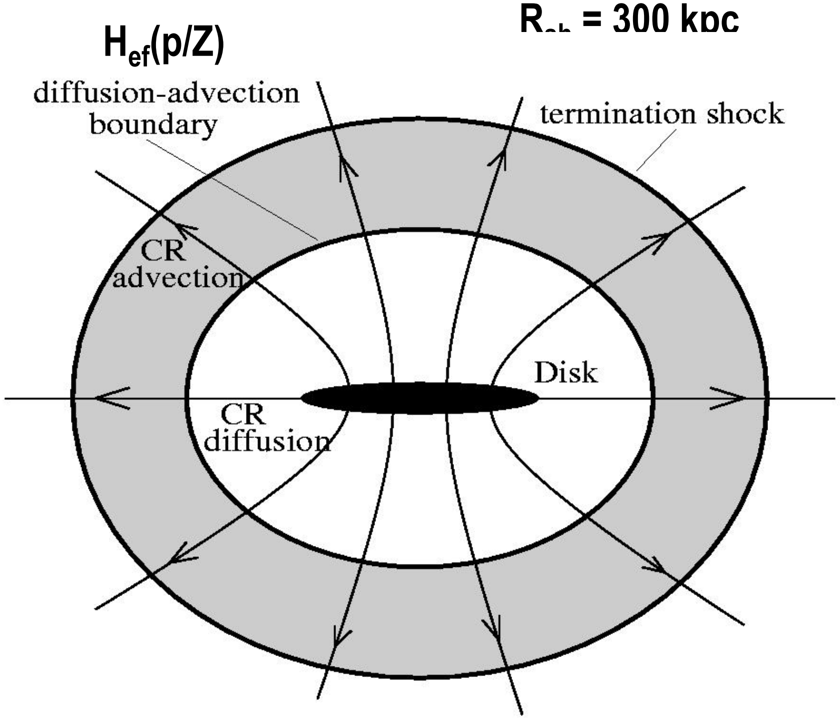
peak of B/C ratio at 1 GeV/n – explained by turbulence dissipation on CR

theory of MHD turbulence – not in contradiction (although wave dissipation is too strong ?)

diffusion-convection model: galactic wind driven by CR

Ipavich 1975, Breitschwerdt et al. 1991, 1993

u_{inf} = 500km/s
R_{sh} = 300 kpc



CR scale height is larger then the scale height of thermal gas. CR pressure gradient drives the wind.

+ **cosmic ray streaming instability with nonlinear saturation**

Zirakashvili et al. 1996, 2002, 2005, VP et al. 1997, 2000,

$$D \sim \frac{vB}{q_{cr}}\left(\frac{p}{Zm_p c}\right)^{\gamma_s - 1} \approx 10^{27}\beta\left(\frac{p}{Zm_p c}\right)^{1.1} \mathrm{cm}^2/s,$$

$$\gamma = (3\gamma_s - 1)/2 \approx 2.7, \quad \text{at} \quad \gamma_s \approx 2.1$$

$$X \sim \frac{H_{ef}}{D} \sim \left(\frac{p}{Zm_p c}\right)^{\frac{\gamma_s - 1}{2}} \sim \left(\frac{p}{Z}\right)^{-0.55}$$

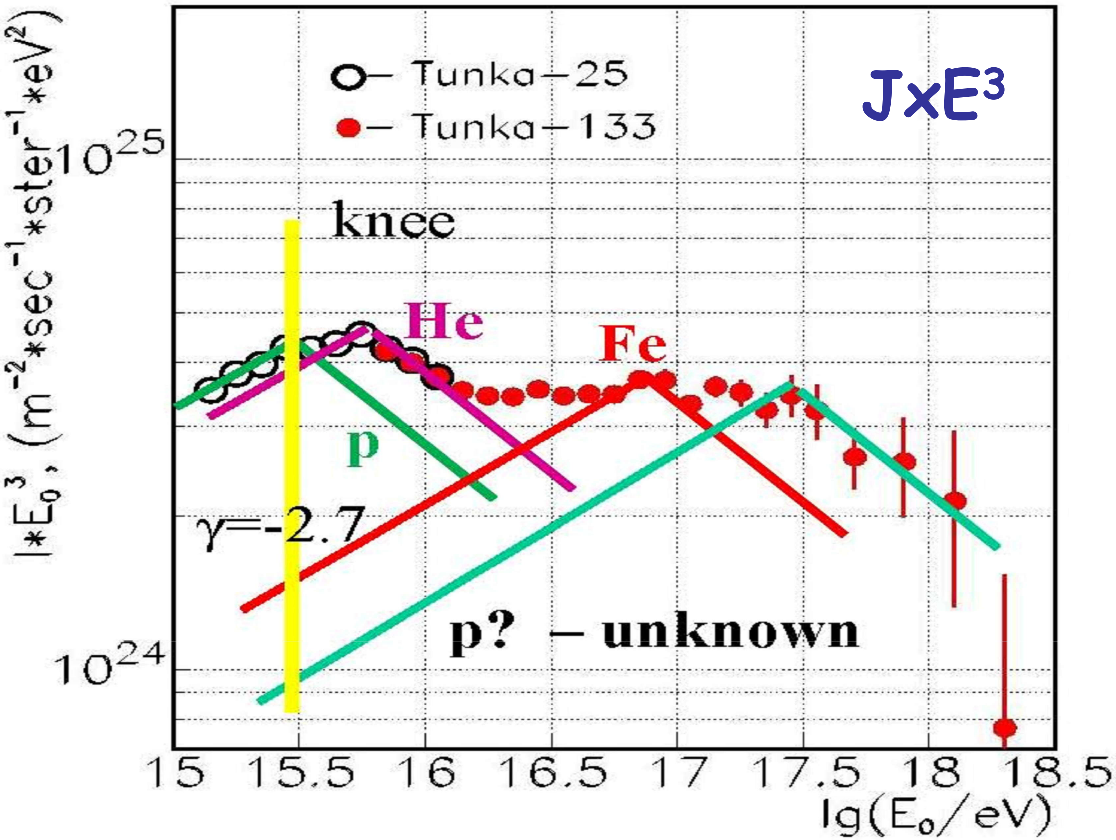
knee and above

different types of nuclei,
$E_{knee} \sim Z$;
different types of SNRs;
transition to extragalactic CR

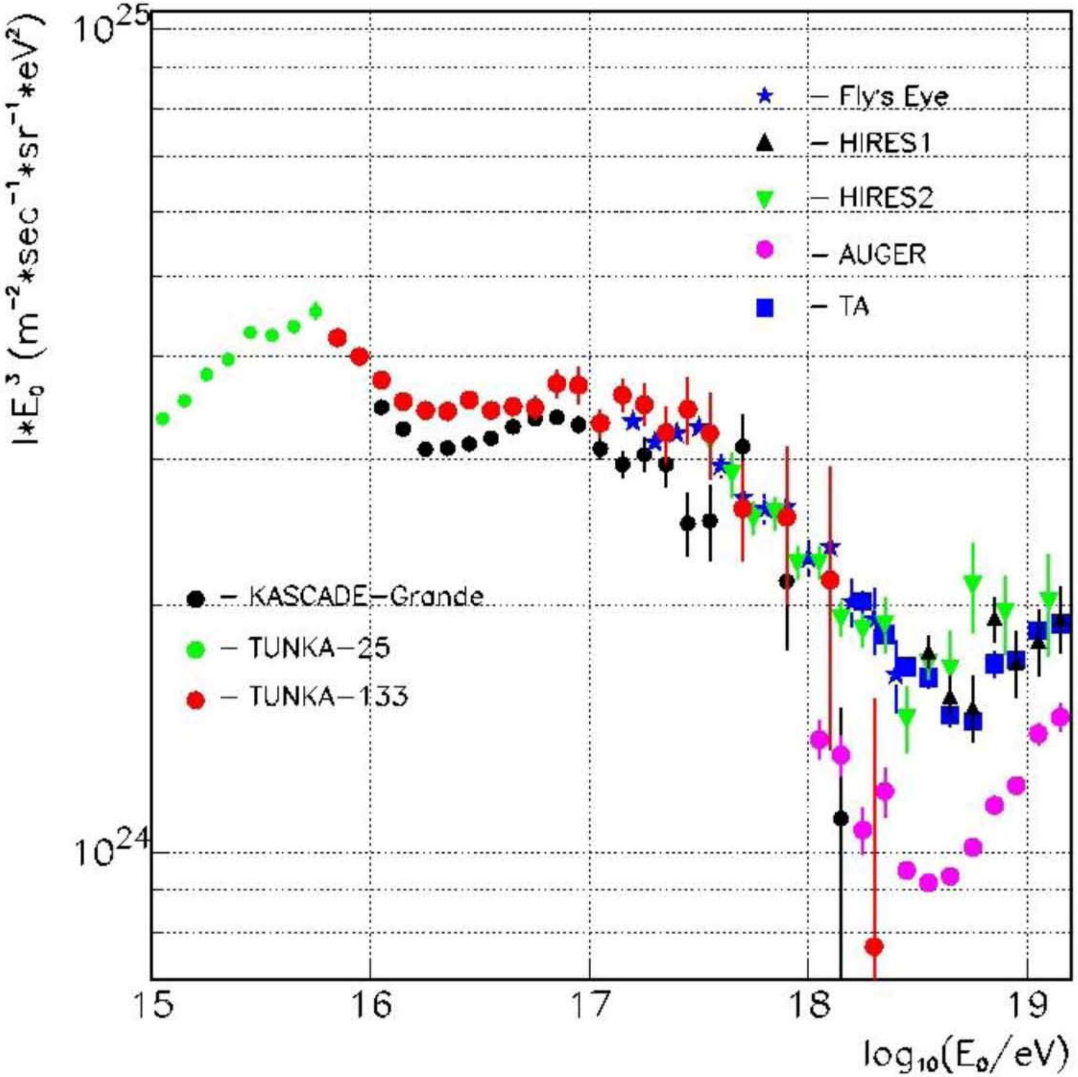
knee at 3-4 PeV
hardening at 20-30 PeV,
2nd knee at 200-300 PeV;
contribution of
extragalactic (?)
protons ~50% at ~ 200 PeV

Sveshnikova et al 2013
33rd ICRC, paper 0304;
J Phys Conf Ser 409, 2062;
Astropart Phys (in press)

Prosin et al. (Tunka collaboration) 2013



Combined spectrum: comparison with some other works



1. Agreement with KASCADE-Grande
2. Agreement with old Fly's Eye, HiRes and TA spectra.

ICRC 2013

Conclusions

Cosmic ray origin scenario where supernova remnants serve as principle accelerators of cosmic rays in the Galaxy is strongly confirmed by recent numerical simulations. SNRs can provide cosmic ray acceleration up to 5×10^{18} eV.

Problem: Light observed cosmic-ray composition above 3×10^{17} eV.

Diffusion model provides reasonably good description of cosmic ray propagation in the Galaxy even under simplified assumptions on cosmic ray transport coefficients and geometry of propagation region (e.g. included in GALPROP code).

Problem: Energy dependence of diffusion is still uncertain.

High-accuracy measurements reveal deviations of cosmic ray spectra from plain power laws both below and above the knee. It requires refining models of cosmic ray acceleration and propagation.