Cosmic Ray Propagation in the Interstellar Medium

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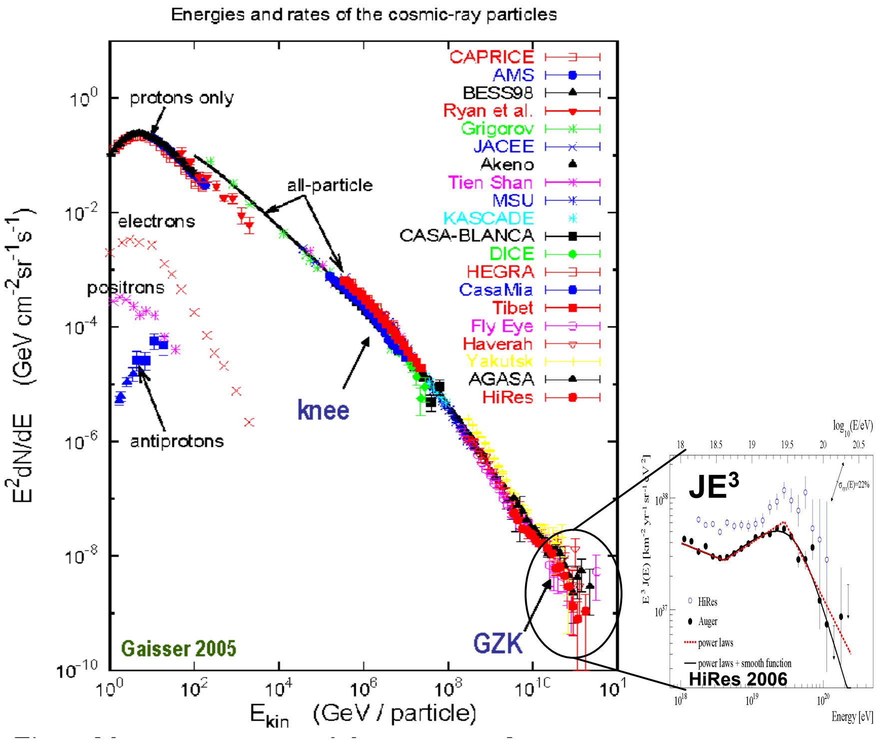
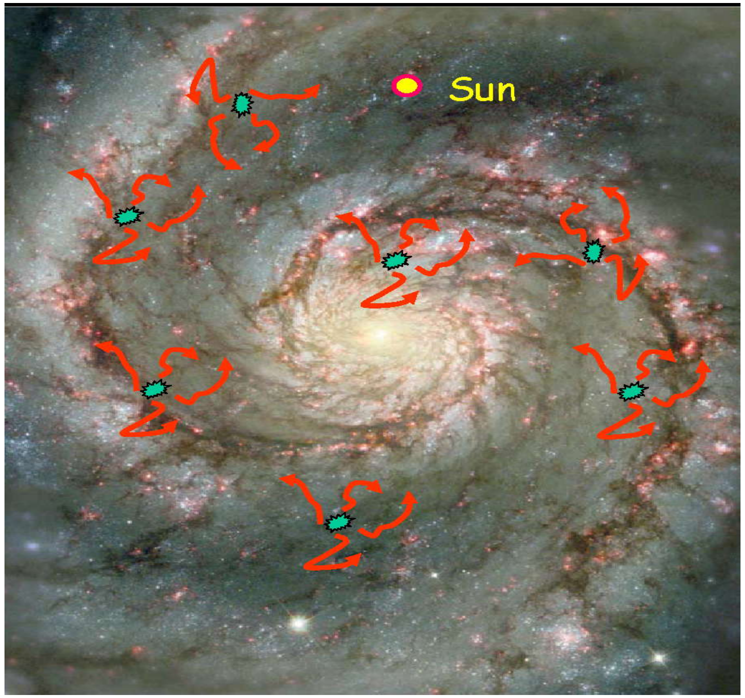
CRISM-2011





energy balance: ~ **15%** of SN kinetic energy go to cosmic rays to maintain observed cosmic ray density Ginzburg & Syrovatskii 1964

steady state:
(without energy losses and fragmentation)

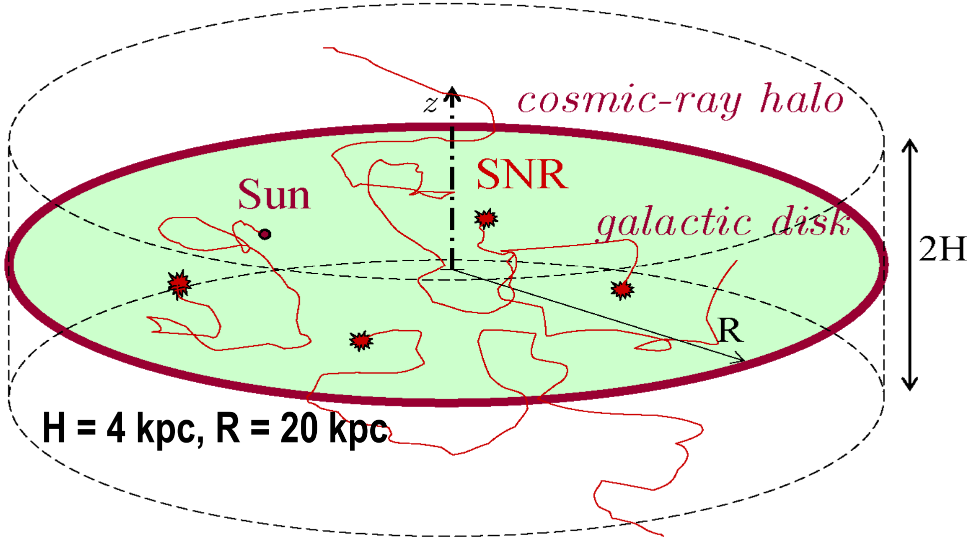
$$J_{cr}(E) = Q_{cr}(E) \times T(E)$$

source

escape time from the Galaxy about 10^8 yr at 1 GeV
(determined from secondary nuclei)

basic empirical diffusion model

Ginzburg & Ptuskin 1976, Berezinskii et al. 1990, Strong & Moskalenko 1998 (GALPROP), Donato et al 2002, Shibata et al 2004, Ptuskin et al. 2006, Strong et al. 2007, Vladimirov et al. 2010, Bernardo et al. 2010, Maurin et al 2010, Putze et al 2010, Trotta et al 2011



H = 4 kpc, R = 20 kpc

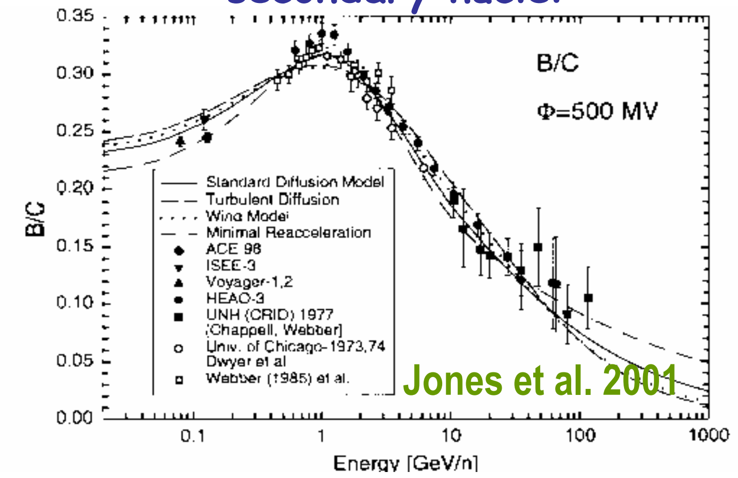
escape length:

$$X \sim 10\ \mathrm{g/cm^2}\ \text{at}\ 1\ \mathrm{GeV/n}$$

surface gas density 2.4 mg/cm²

$$X \approx \frac{v\mu H}{2D}$$

secondary nuclei



Jones et al. 2001

diffusion coefficient:

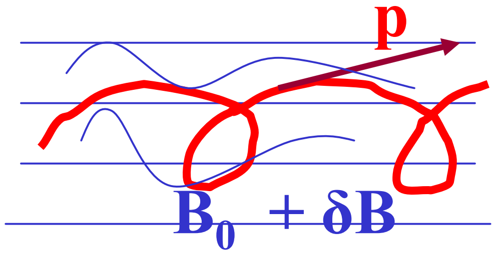
$$D \sim 3\times10^{28}\ \mathrm{cm^2/s}$$

at 1 GeV/n

$l \simeq 1$ pc - diffusion mean free path

“microscopic” theory of cosmic-ray diffusion

$$r_g = 3.3\cdot 10^{12}\left({pc}/{Z} \right)_{\mathrm{GV}} B_{\mu\mathrm{G}}^{-1}\ \mathrm{cm}$$

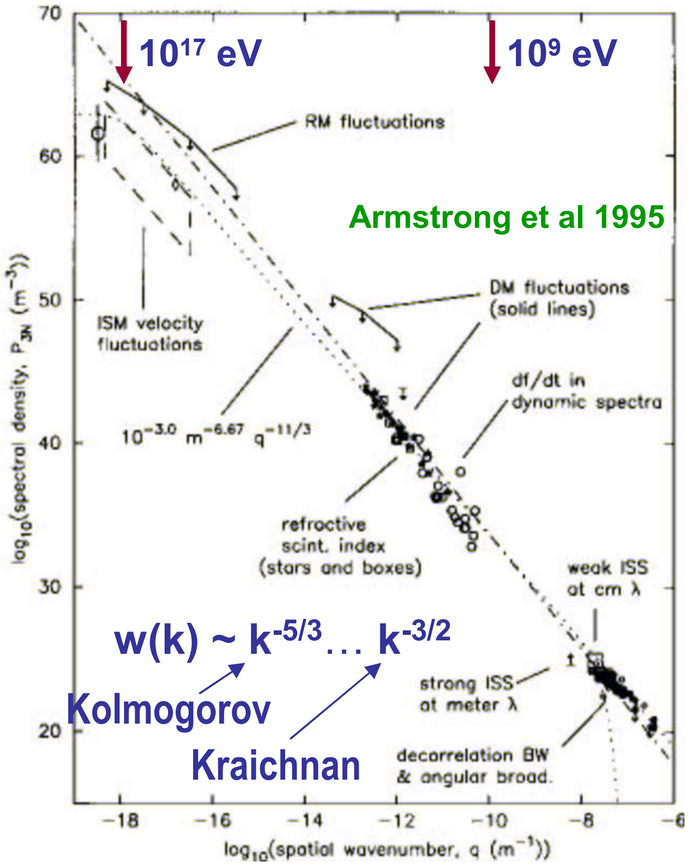


resonant interaction

Larmor radius $\rightarrow$

$$r_g = 1/(k_{\parallel}\cos\theta)$$

$\leftarrow$ resonant wave number



isotropic turbulence:

parallel diffusion

Jokipii 1966

$$D_{\parallel} \approx \frac{v r_g}{3}\frac{B_0^2}{\delta B^2(>k_{\mathrm{res}})}$$

$$\sim v r_g^{1/3} \ldots v r_g^{1/2}$$

anomalous perpendicular diffusion

Jokipii & Parker 1970
Chuvilgin & VP 1993
Giacolone & Jokipii 1999
Casse et al 2001
Shalchi 2011

$$D_{\perp} \sim \frac{\delta B_{\mathrm{tot}}^4}{B_0^4} D_{\parallel} \qquad (\delta B < B_0)$$

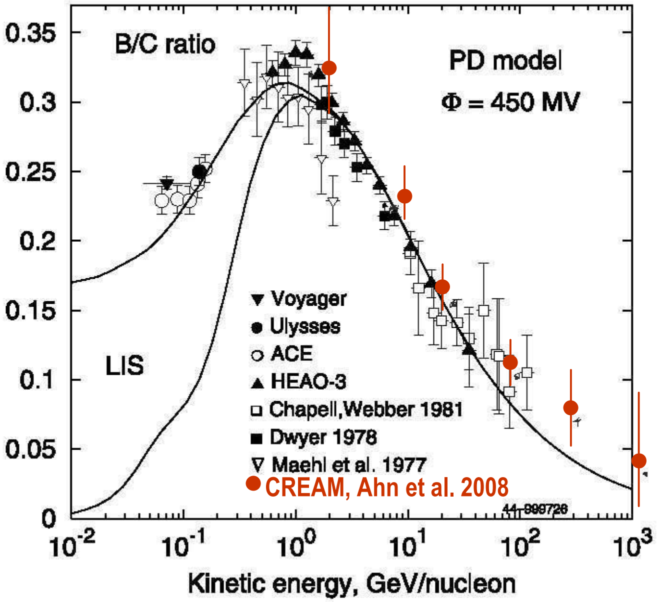
Hall diffusion

$$D_{\mathrm{H}} \approx \frac{v r_g}{3}$$

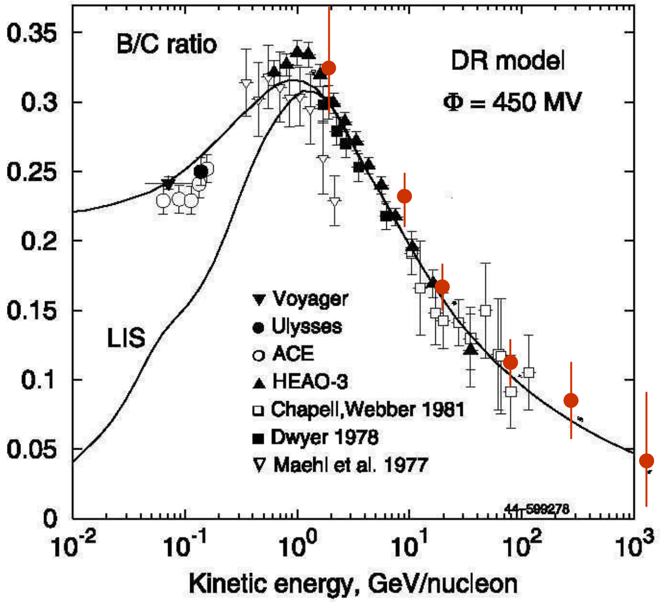
B/C ratio in three models of cosmic ray propagation

plain diffusion, “unphysical” break

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



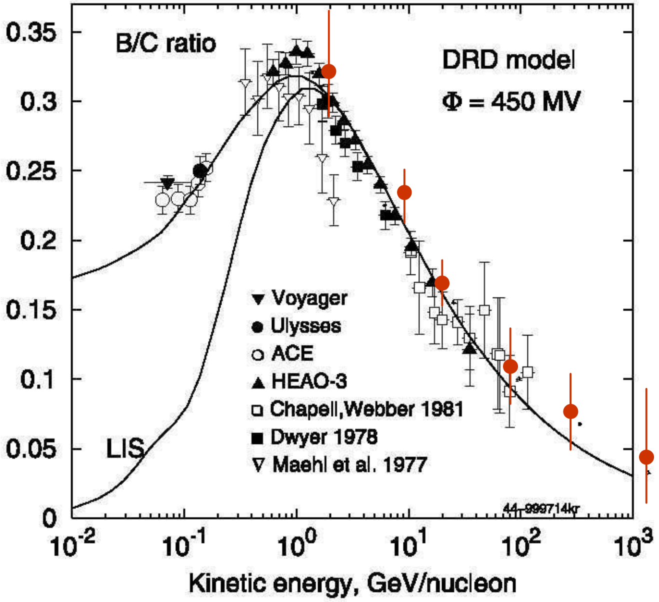
diffusion (Kolmogorov) + reacceleration



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

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

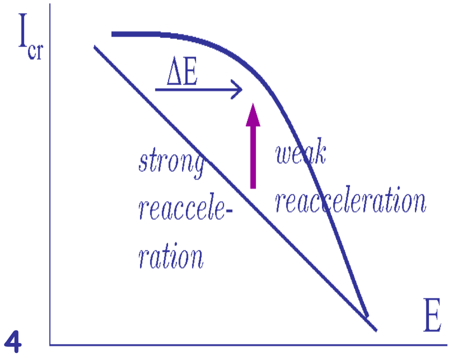
physical explanations of peak in sec./prim. ratio:

•distributed reacceleration

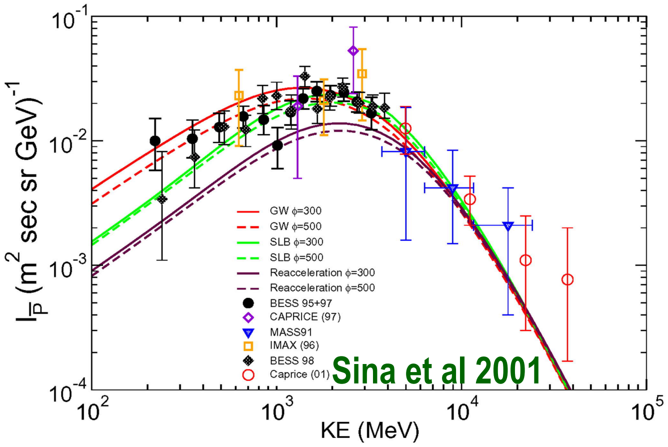
Simon et al. 1986; Seo & Ptuskin 1994

$D_{pp} \sim p^2 V_a^2/D$, $D \sim vR^{1/3}$

- Kolmogorov spectrum of turbulence



problem:
low flux of
secondary
antiprotons



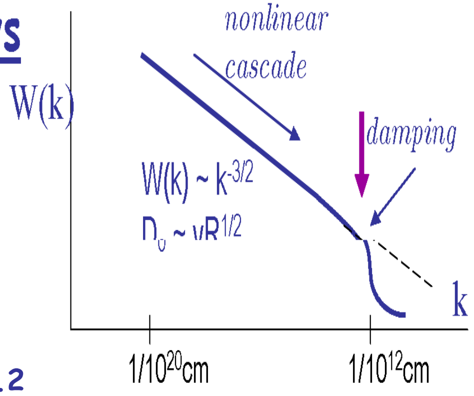
sources spectrum $q \sim R^{-2.4}$
($R^{-2.4}$ at $R < 3$ GV) ??

•wave damping on cosmic rays

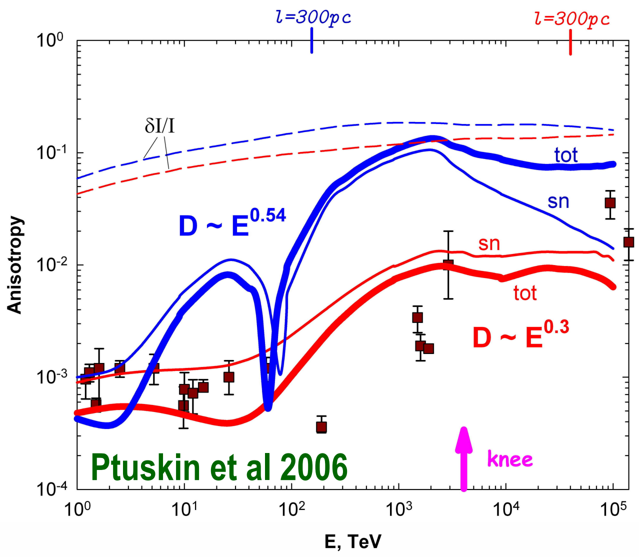
VSP, Moskalenko et al. 2006

Iroshnikov - Kraichnan cascade

$D_0 \sim vR^{1/2}$



problem:
large
anisotropy



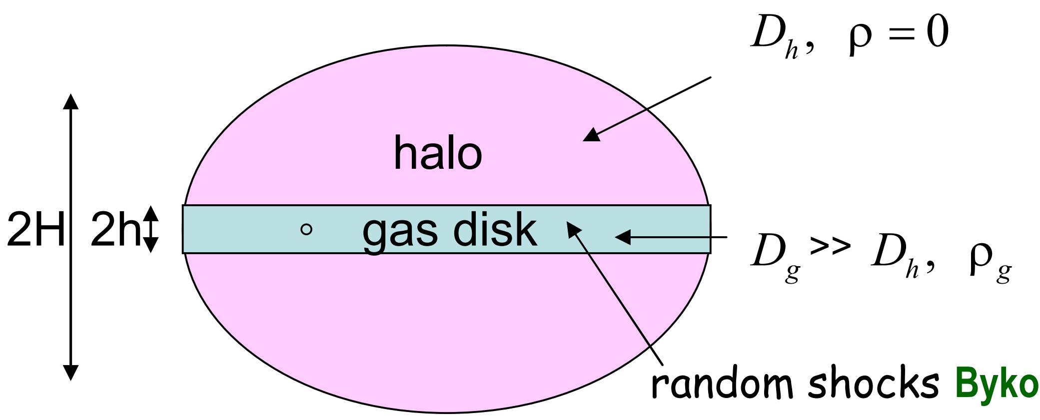
sources spectrum $q \sim R^{-2.2}$
(more steep at $R < 40$ GV) !!

problem: structure of mhd turbulence

- anisotropic Alfvenic ISM turbulence where Alfvenic eddies are stretched along magnetic field, $k_{\parallel} = k_{\perp}^{2/3} L^{-1/3}$, can not provide empirical diffusion coefficient
  Shebalin et al. 1983, Higdon 1984, Bieber et al. 1994, Montgomery & Matthaeus 1995, Goldreich & Shridhar 1995, Chandran 2000, Yan & Lazarian et al. 2002, Bereznyak et al 2010, Forman et al. 2011

- fast magnetosonic waves can be isotropic (via independent acoustic-type cascade Cho & Lazarian 2003) but they may not provide needed diffusion coefficient in galactic disk because of strong dissipation in warm plasma Barnes & Scargle 1967, … Spanier & Schlickeiser 2005

→ **"sandwich" model**

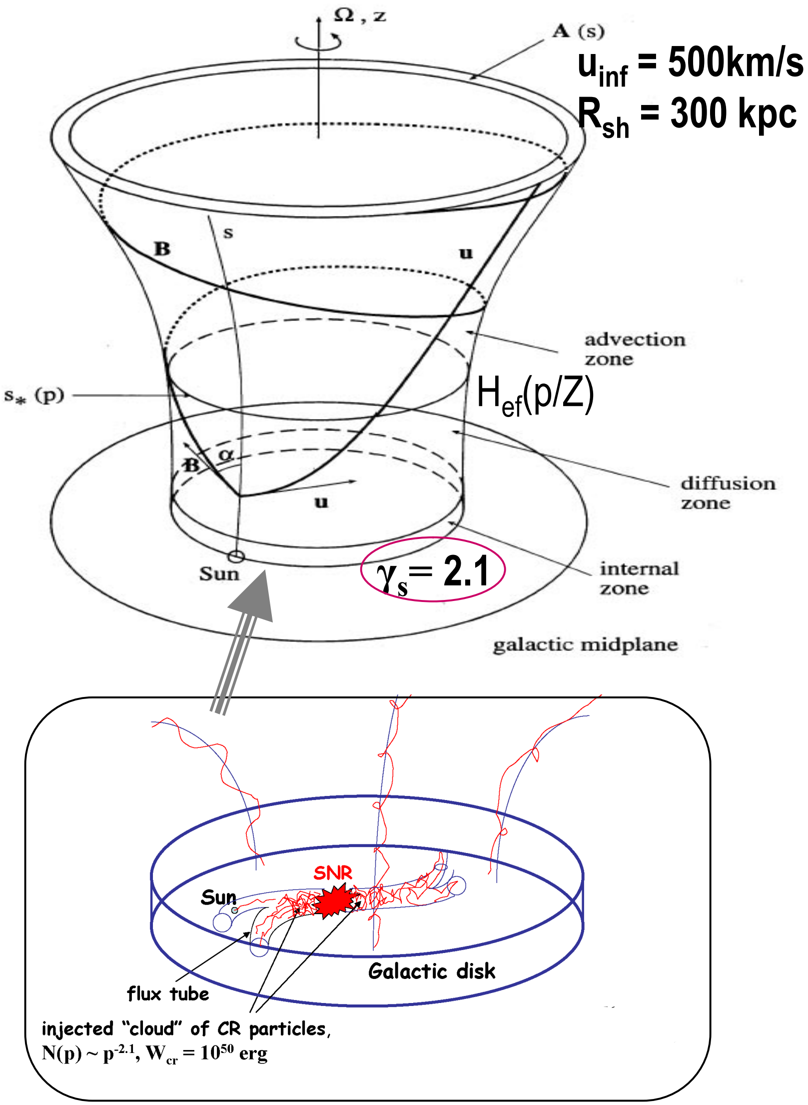


random shocks Bykov & Toptygin 1987

$$X = \frac{v \mu H}{2 D_h}$$

plasma effects of cosmic rays in interstellar medium

Ginzburg 1965, Lerche 1971, Wentzel 1969, Kulsrud & Pearce 1969, Kulsrud & Csarsky 1971, Skilling 1971, Farmer & Goldreich 2004



injected "cloud" of CR particles, $N(p) \sim p^{-2.1}$, $W_{cr} = 10^{50}$ erg

galactic wind driven by cosmic rays

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

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

$$\gamma = (3\gamma_s - 1)/2 \approx 2.7, \qquad \gamma_s \approx \boxed{2.1}$$

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

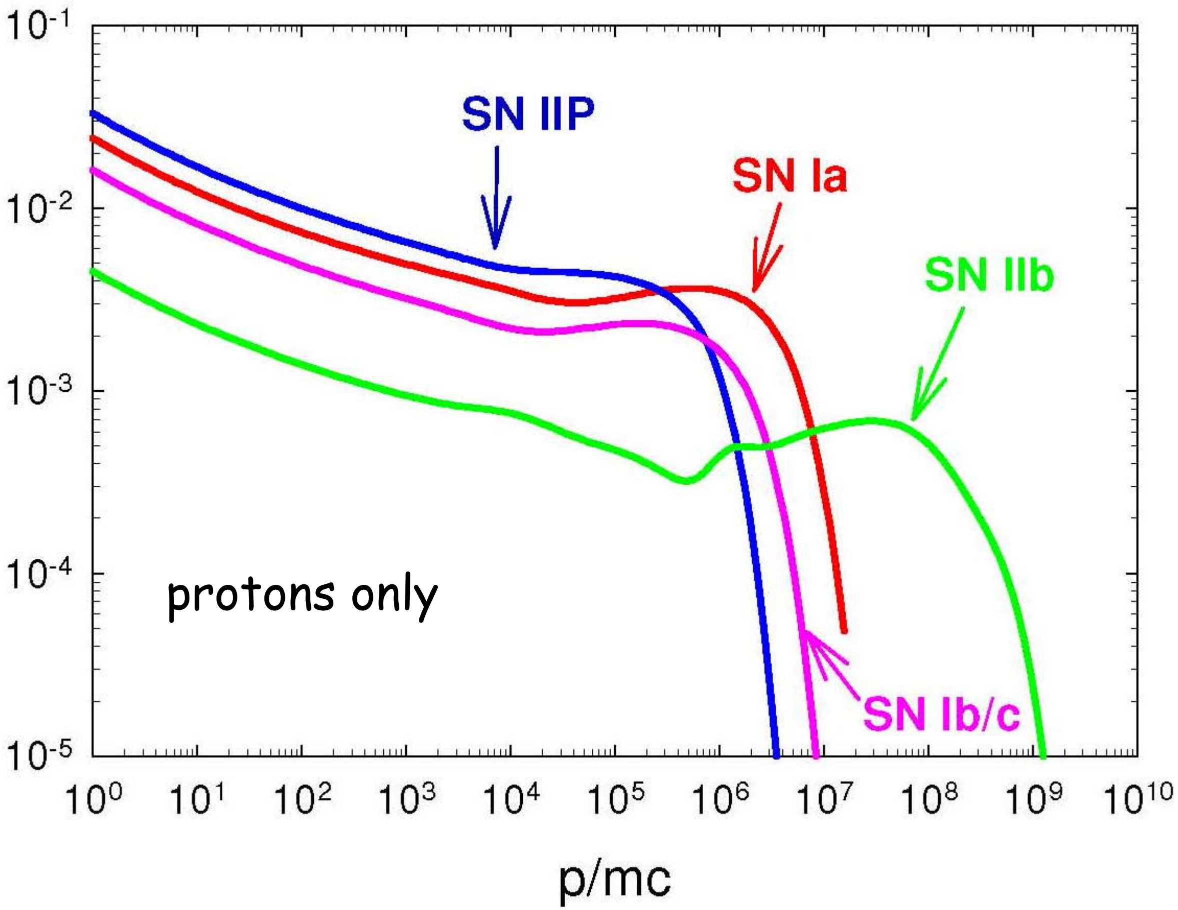
non-linear evolution of cosmic ray distribution after exit from SNR

Ptuskin et al. 2007, Fujita et al. 2011

numerical simulation of cosmic-ray acceleration in SNR

Ptuskin, Zirakashvili & Seo 2010

- 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



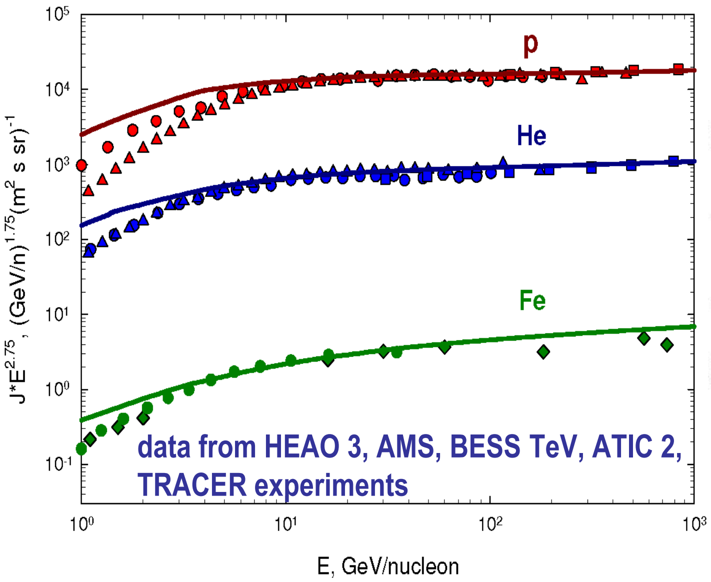
«knee» is formed at the beginning of Sedov stage

$$p_{knee}c/Z = 1.1\times10^{15}\,E_{sn,51}\,n^{1/6}M_{ej}^{-2/3}\ \mathrm{eV},$$

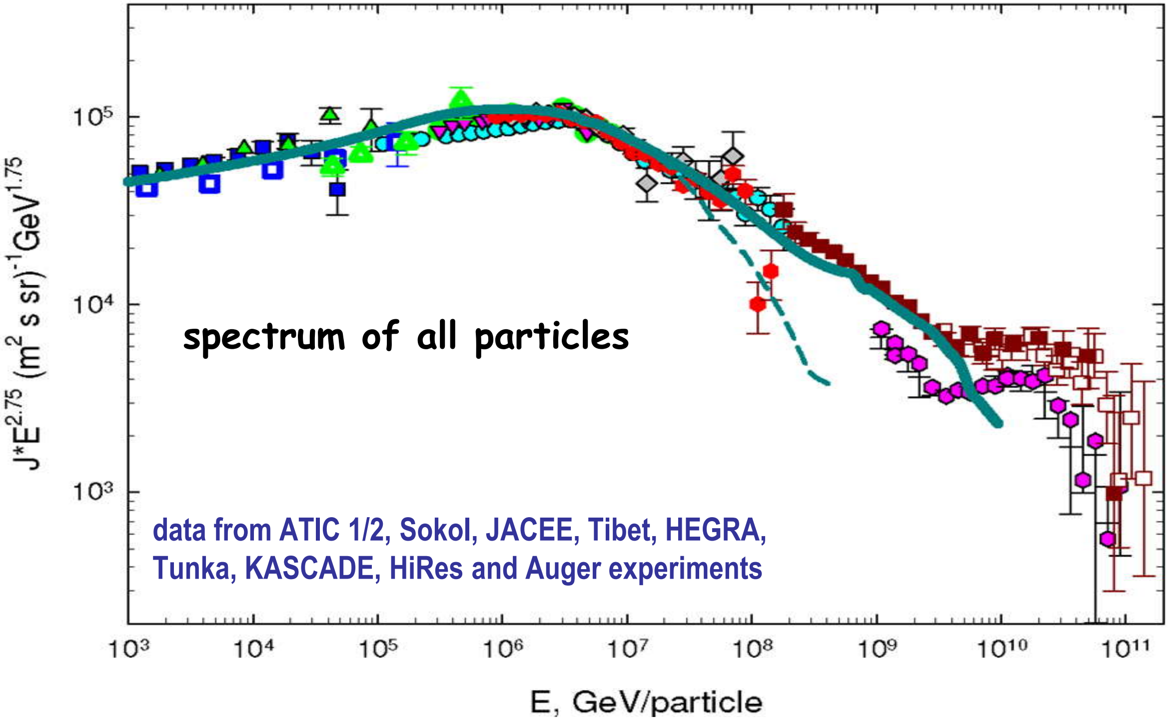
$$p_{knee}c/Z = 8.4\times10^{15}\,E_{sn,51}\sqrt{\dot{M}_{-5}/u_{w,6}}\,M_{ej}^{-1}\ \mathrm{eV}$$

calculated interstellar spectra normalized at 10^3 GeV

assuming $D \propto \left({}^{pc}\!/_{Ze} \right)^{0.54}$ - Jones et al 2001

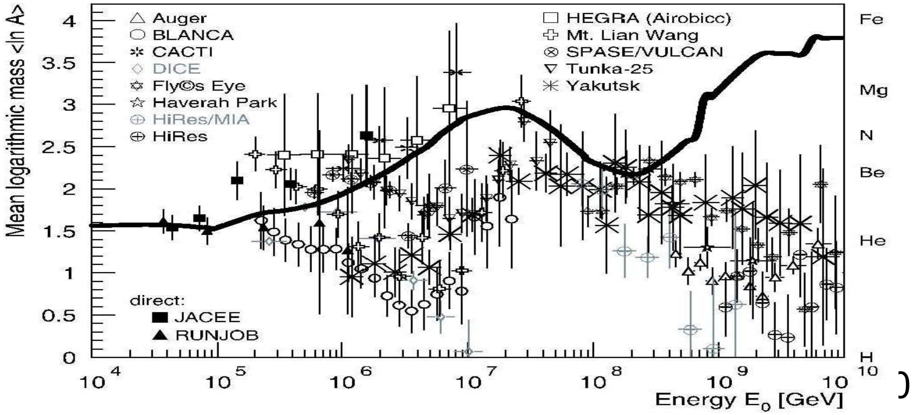


data from HEAO 3, AMS, BESS TeV, ATIC 2, TRACER experiments



data from ATIC 1/2, Sokol, JACEE, Tibet, HEGRA, Tunka, KASCADE, HiRes and Auger experiments

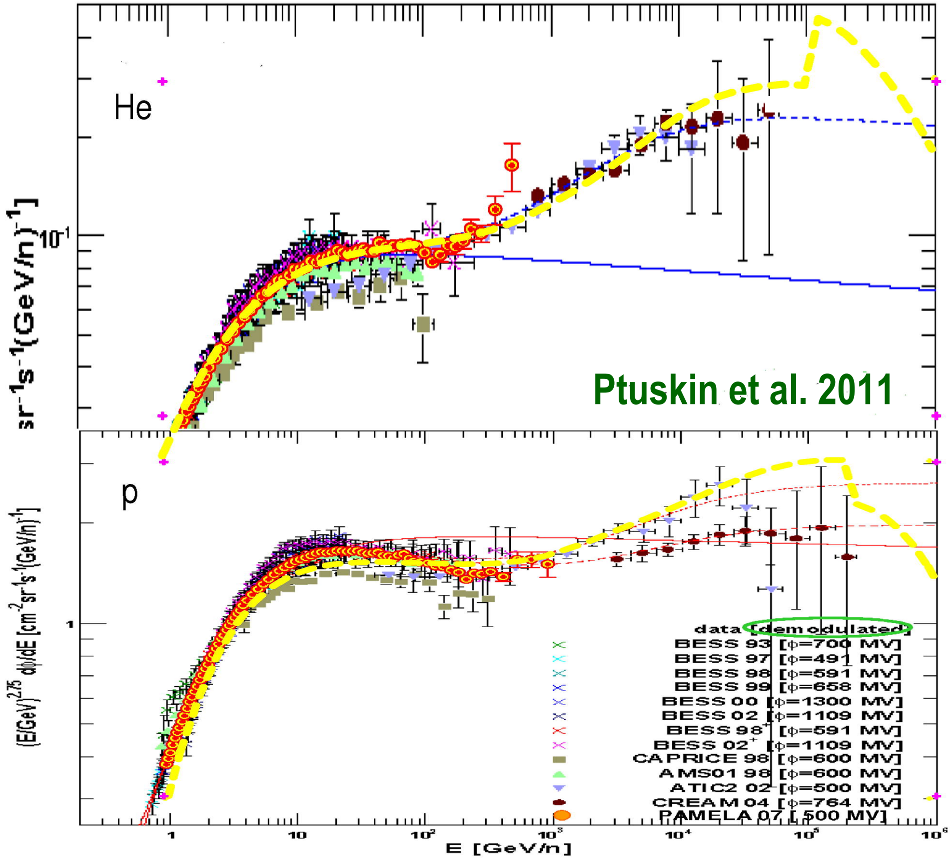
composition



<lnA> based on $\langle X_{max} \rangle$; data from Hoerandel 2007

more details:

hardening above 200 GeV/nucleon; spectra of p and He are different

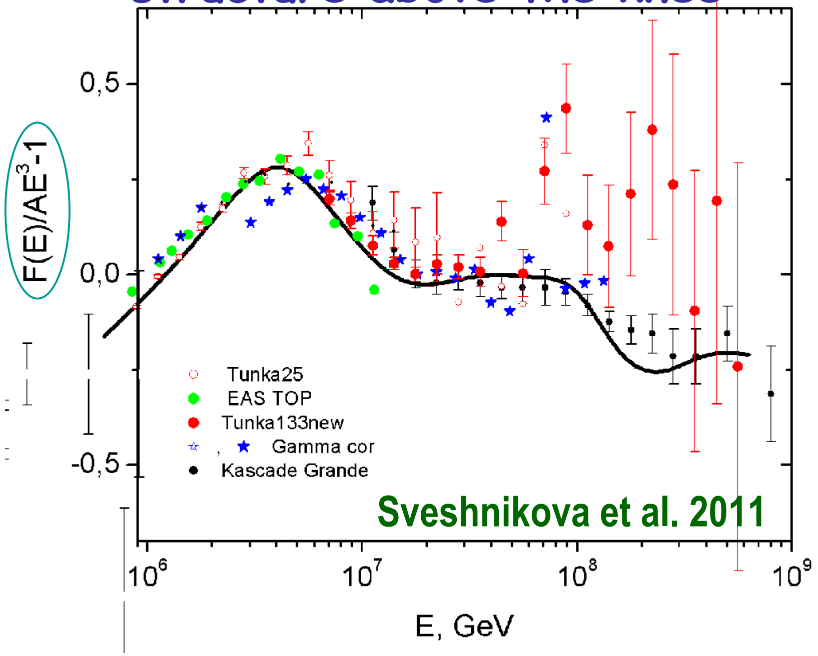


Ptuskin et al. 2011

new source; concave source spectrum; shock goes through material enriched in He, etc…

Zatsepin & Sokolskaya 2006, Ohira & Ioka 2011

structure above the knee



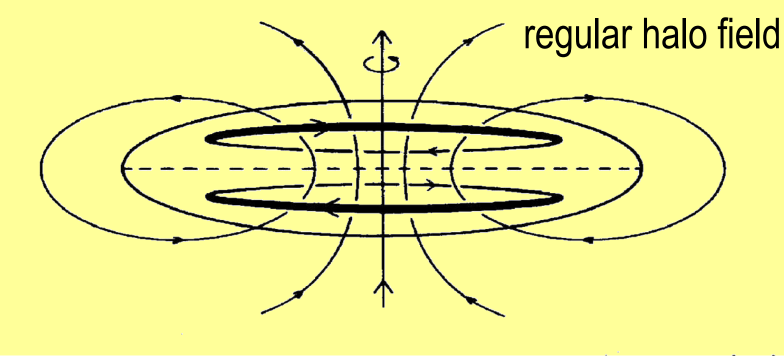
Sveshnikova et al. 2011

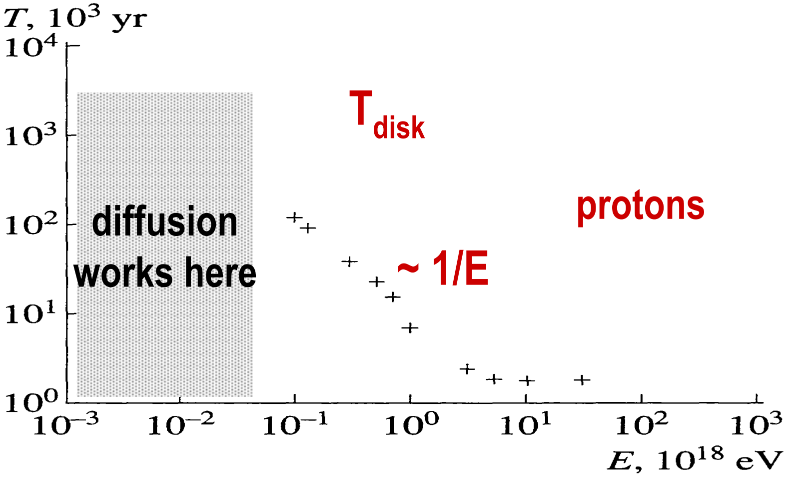
different types of nuclei;
different types of SN;
"single source" model of the knee

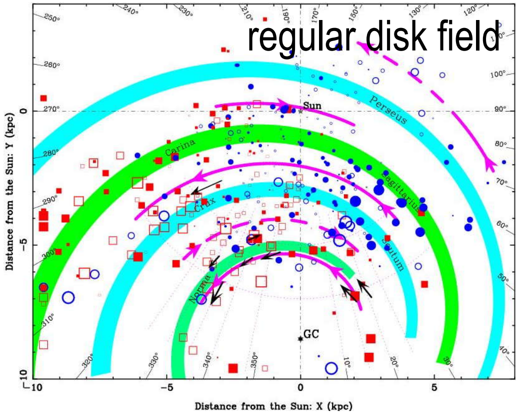
Erlykin & Wolfendale 1997, 2011
Donato et al. 2009

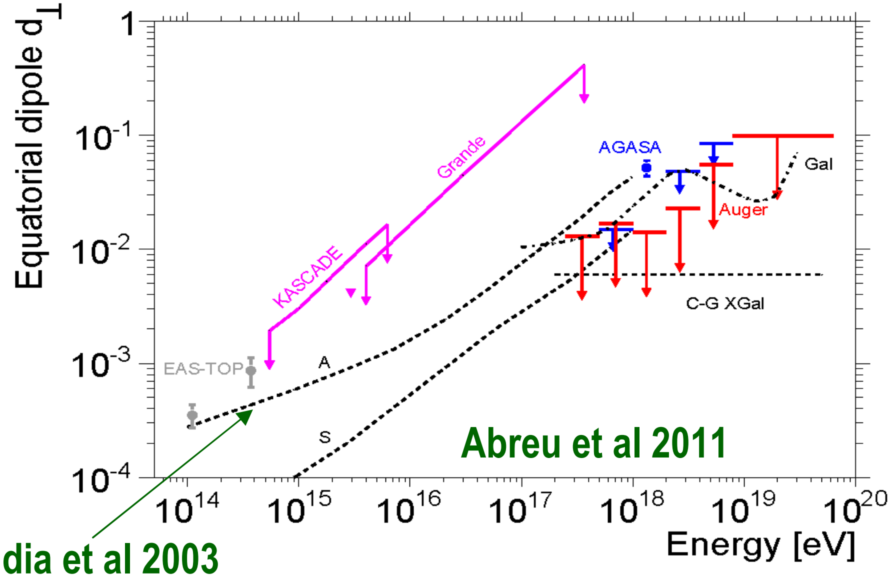
extension of propagation model up to 10^{19} eV: trajectory calculations

Syrovatsky 1971, Berezinsky et al. 1991, Gorchakov et al 1991, VP et al 1993, Lampard et al 1997, Zirakashvili et al 1998, Hörandel et al. 2005









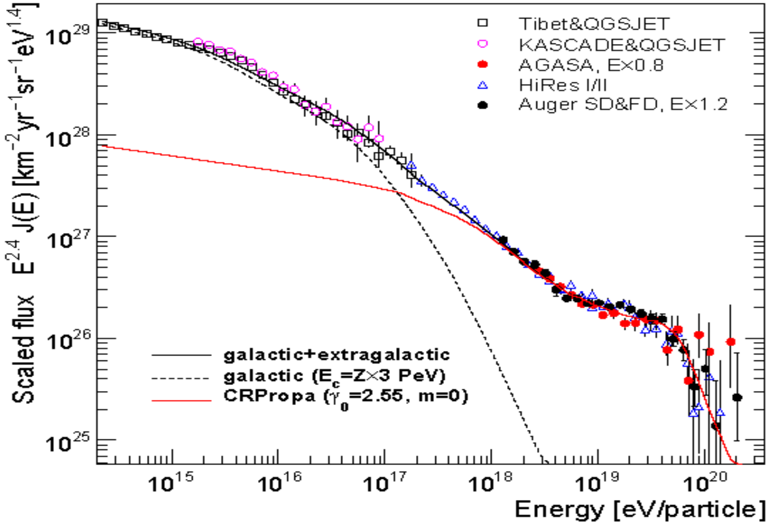
Abreu et al 2011

Candia et al 2003

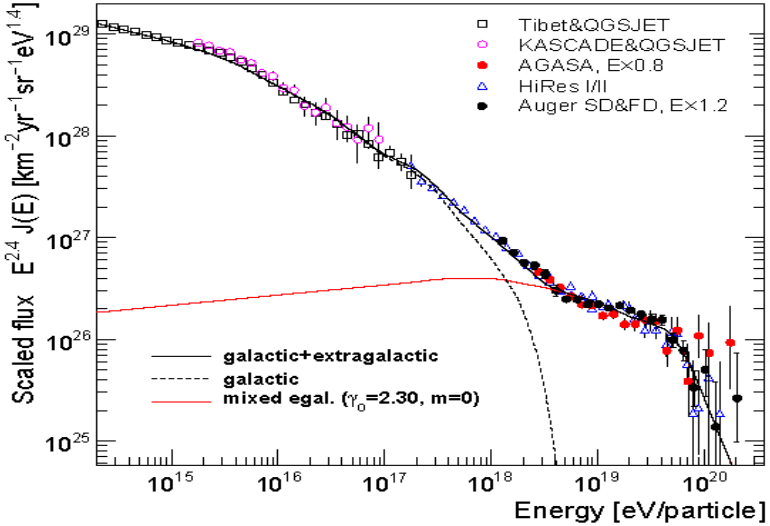
$$r_g = 1 \times \frac{E_{EeV}}{Z \times B_{\mu G}}\ \text{Kpc}$$

transition to extragalactic cosmic-ray component

Allard et al 2005
Berezinsky et al. 2006



(a) Extragalactic protons



(b) Mixed Composition (adopted from [49])

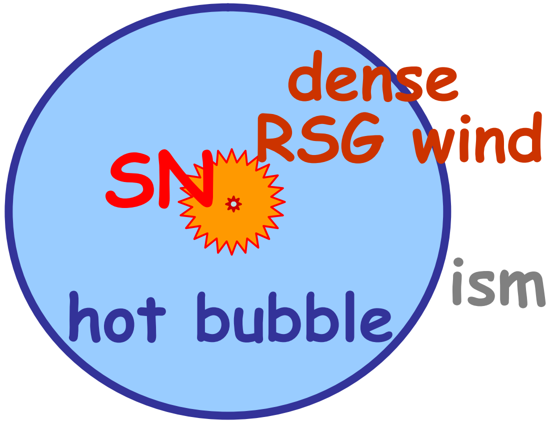
Conclusions

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 5x10^{18} 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. as in GALPROP code).

Collective effects of cosmic rays may selfconsistently provide the global structure of Galactic wind flow and the MHD turbulence needed for diffusion of energetic particles.

High-accuracy measurements reveal deviations of cosmic ray spectra from plain power laws both below and above the knee that requires theory refinement.



types of SN included in calculations

Chevalier 2004 (r_{sn} -relative SN rate Leaman 2008, Smart et al 2009)

SN Ia: E_{sn} = 10^{51} erg, n = 0.1 cm^{-3}, M_{ej} = 1.4 M_s, r_{sn}= 0.32

SN IIP: E_{sn} = 10^{51} erg, n = 0.1 cm^{-3}, M_{ej} = 8 M_s, r_{sn}= 0.44

SN Ib/c: E_{sn} = 10^{51} erg, n = 0.01 cm^{-3} (bubble), M_{ej} = 2 M_s,
(fast H-poor W-R wind sweeps up RSG wind), r_{sn}= 0.22

SN IIb: E_{sn} = 3.10^{51} erg, dM/dt = 10^{-4} M_s/yr (RSG wind),
n = 0.01 cm^{-3} (bubble), M_{ej} = 1 M_s, r_{sn}= 0.02