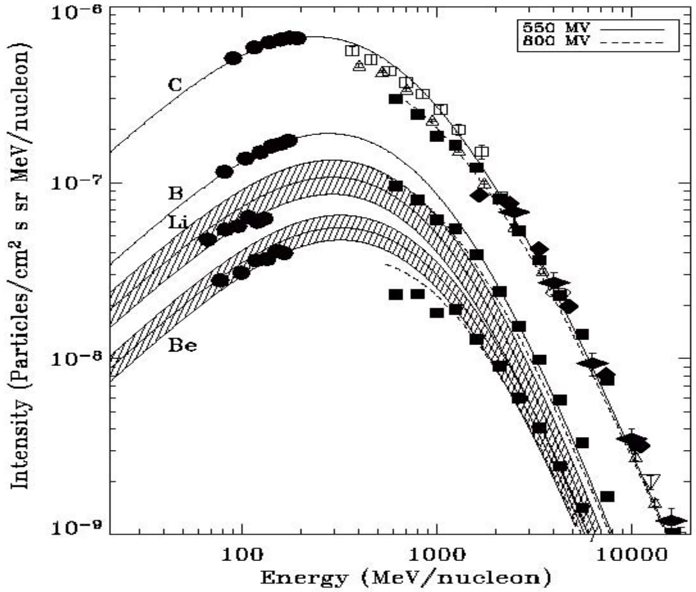
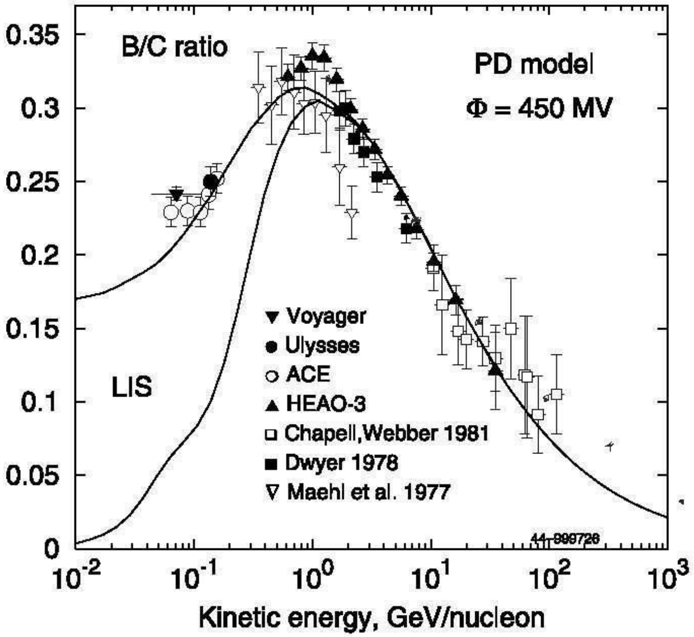
Perspectives theoriques

Vladimir Ptuskin

IZMIRAN

peak in secondary/primary ratio





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

secondary species:

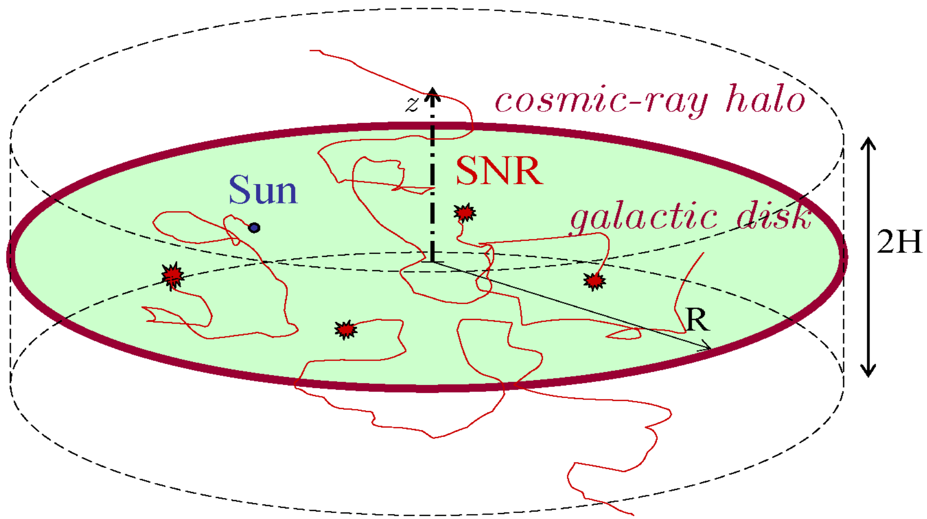
d, 3He, Li, Be, B ... p

$$Q = nv\sigma N$$

escape length:

$$X = \rho v T_e$$

⌊ 10 g/cm^2 at 1 GeV/nucleon



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

escape length

model without galactic wind

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

surface gas density in Galactic disk 2.4 mg/cm^2

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

at 1 GeV/nucleon

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

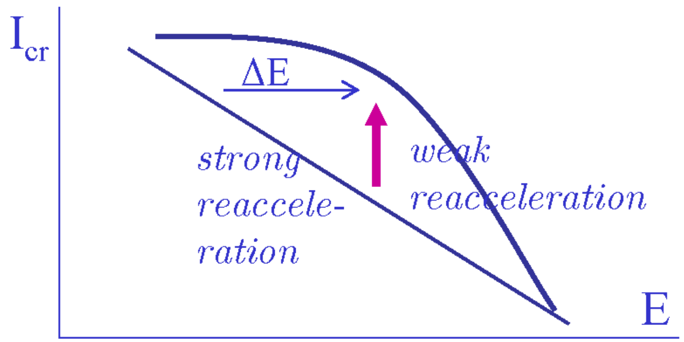
•distributed reacceleration

Simon et al. 1986; Seo & Ptuskin 1994

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

- Kolmogorov spectrum of turbulence

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



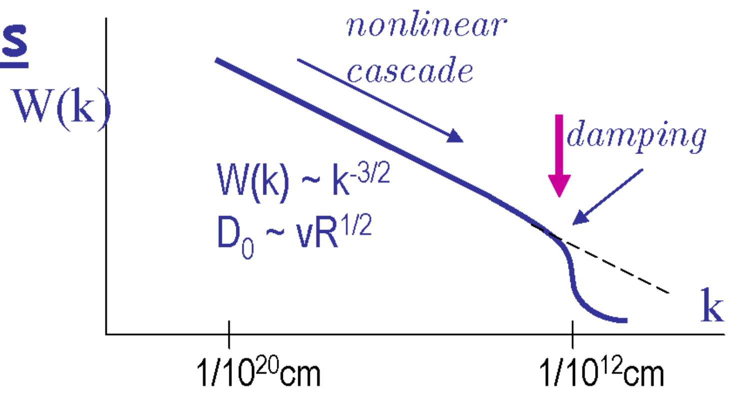
problem:
steep source spectrum

•wave damping on cosmic rays

VSP, Moskalenko et al. 2006

Iroshnikov - Kraichnan cascade
$D_0 \sim vR^{1/2}$

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



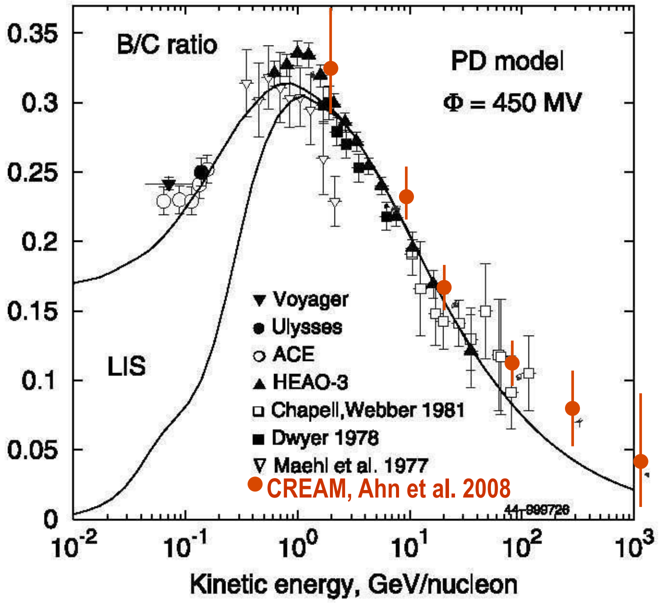
problem:
large anisotropy

B/C ratio in three models of cosmic ray propagation

plain diffusion, “unphysical” break

$D \sim (p/Z)^{0.6}$

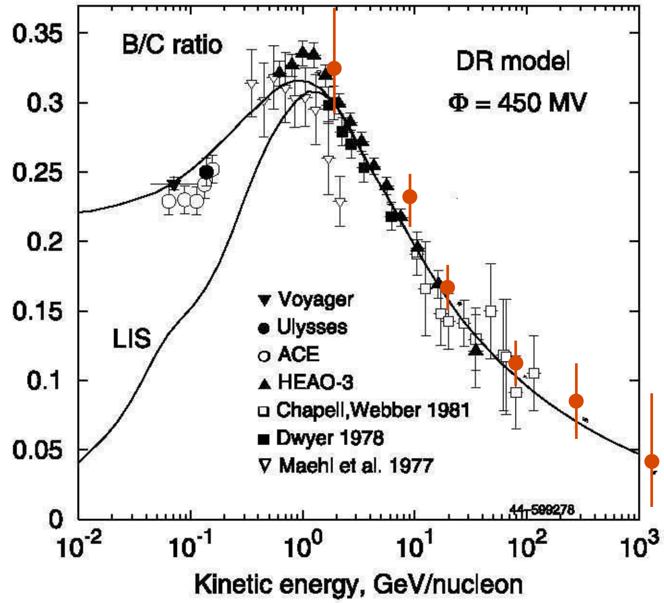
$Q_{cr} \sim (p/Z)^{-2.1}$



diffusion (Kolmogorov) + reacceleration

$D \sim (p/Z)^{0.3}$

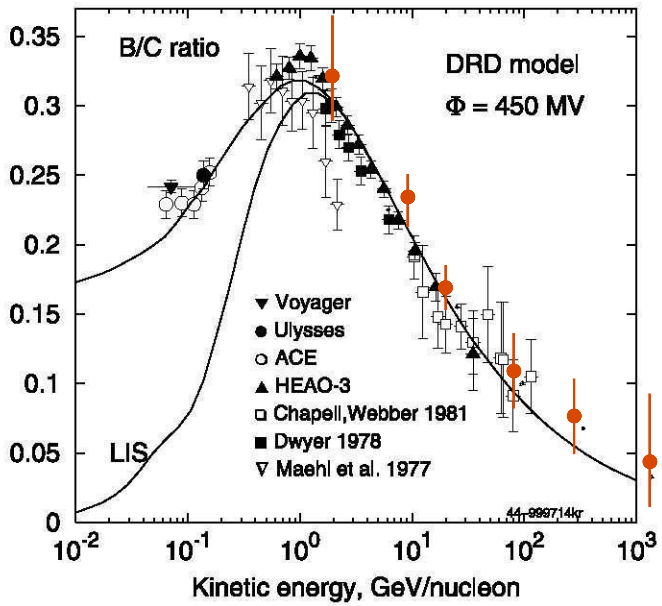
$Q_{cr} \sim (p/Z)^{-2.4}$



diffusion (Kraichnan) + reac. + damping on CR

$D \sim (p/Z)^{0.5}$

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

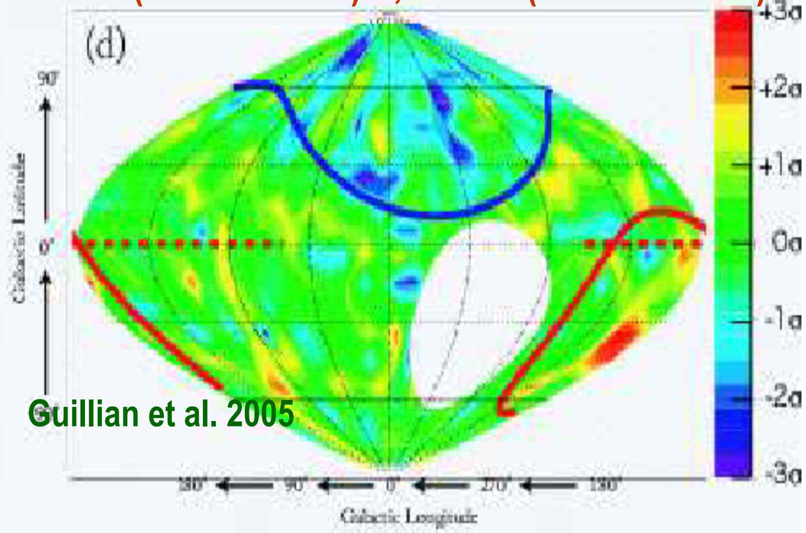


derived exponent of source spectrum at high energies 2.1…2.2 or 2.4

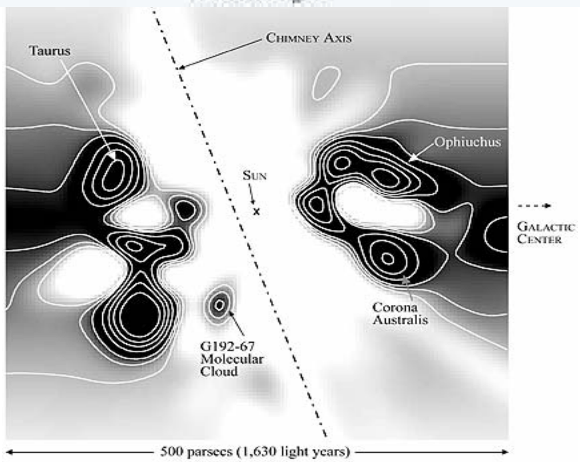
cosmic-ray anisotropy

Super – Kamiokande I, E ~ 10 TeV,

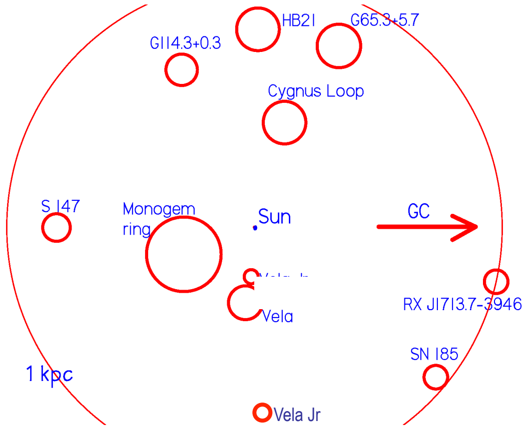
excess (0.104+-0.020)%, deficit (-0.094+-0.014)%



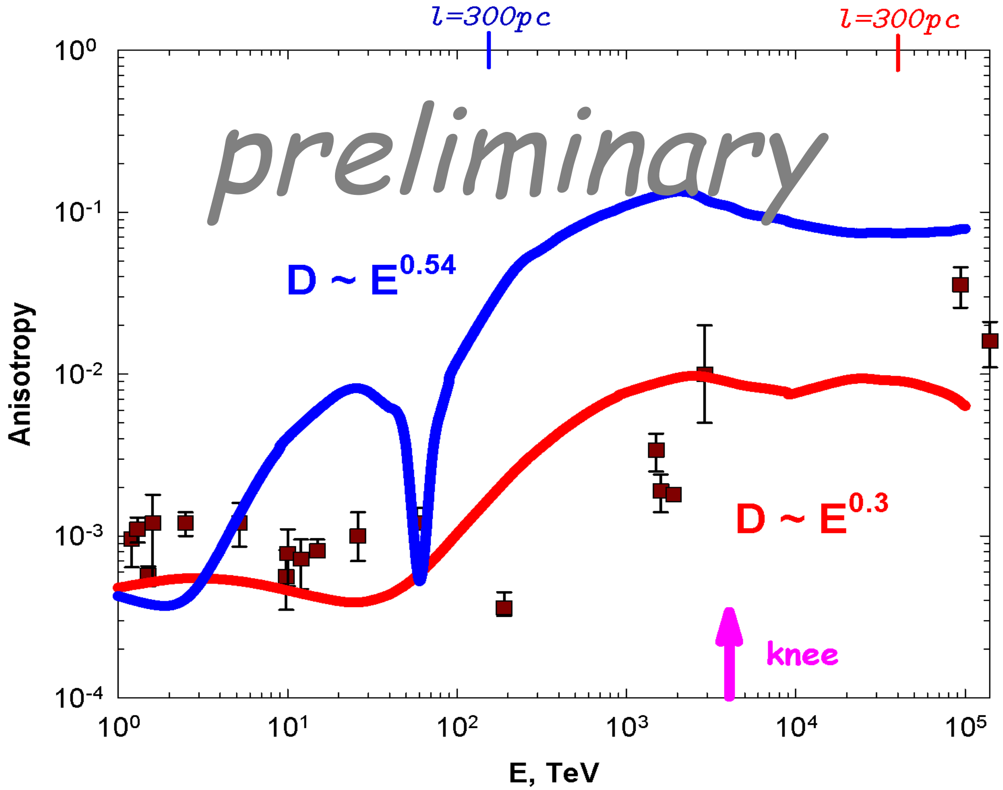
Guillian et al. 2005



Lallerment et al 2003



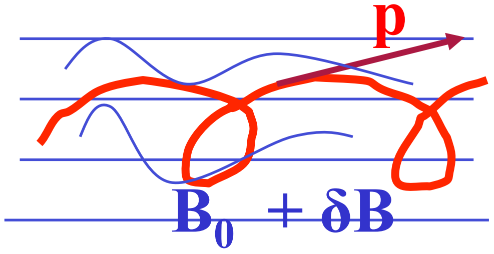
calculated anisotropy in diffusion model,
global leakage + local SNRs: very "unstable"



“microscopic” theory of cosmic-ray diffusion

“microscopic” theory of cosmic-ray diffusion

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



resonant interaction

Larmor radius → $r_g k = 1/(\cos)_{\parallel} \quad N$ ← resonant wave number

isotropic turbulence:

parallel diffusion
Jokipii 1966

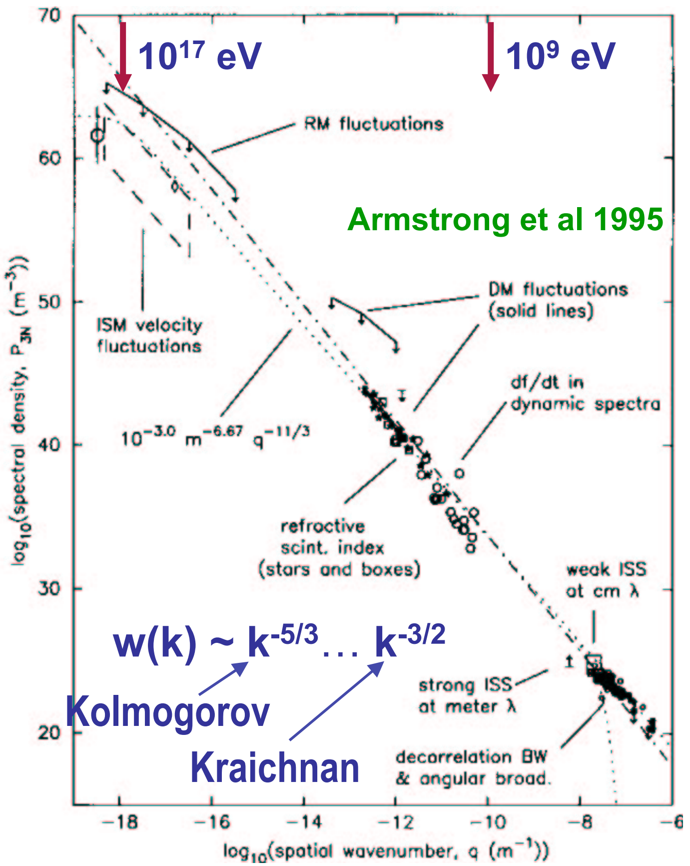
$$D_{\parallel} \approx \frac{v r_g}{3} \frac{B_0^2}{\left(k\, \delta B^2\right)_{res}} \sim v\, r_g^{1/3} \ldots r_g^{1/2}$$

anomalous perpendicular diffusion
Jokipii & Parker 1970
Chuvilgin & VP 1993
Giacolone & Jokipii 1999
Casse et al 2001

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

Hall diffusion

$$D_H \approx \frac{v r_g}{3}$$

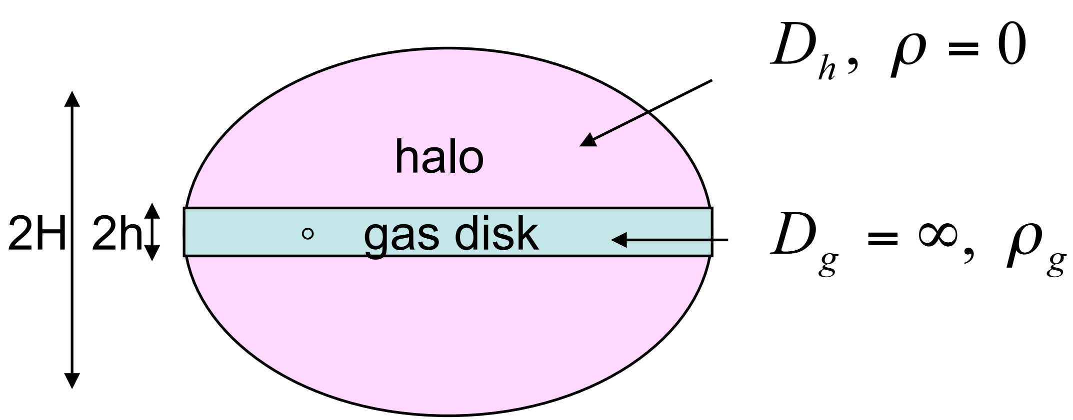


problem: structure of mhd turbulence

- anisotropic Alfvenic ISM turbulence where Alfvenic eddies are stretched along magnetic field, $k_{\|} = k_{\perp}^{2/3} L^{-1/3}$, 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

- fast magnetosonic waves may not provide required diffusion coefficient in galactic disk because of strong dissipation in warm plasma Barnes & Scargle 1967, … Spanier & Schlickeiser 2005

→ **"sandwich" model**



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

collective effects in cosmic rays

cosmic-ray streaming instability

Ginzburg 1965, Lerche 1967, Wentzel 1969, Kulsrud & Pearce 1969, … Bell 1978 …

motion of cosmic rays through background plasma with bulk velocity $\mathbf{u_{cr}} > \mathbf{V_a}$ generates Alfven waves

CR energy density

growth rate of waves amplitude

$$\frac{w_{cr} u_{cr} V_{a} w_{B}}{c^2 V} \times = \geq \frac{2}{\Pi} \quad 2_{cr} \frac{\int}{a}$$

wave energy density $\delta B^2/4\pi$

resonant scattering

$$\tau \approx \frac{r_g}{\mathrm{v}} \frac{B_0^{\;2}}{\delta B_{res}^2}$$

rate of momentum loss by particles

rate of momentum gain by waves

$$\geq = 2_{crresg} = \sqrt{\frac{4M}{\Xi}} \frac{euN V_{crcra}}{cu} \varphi \tau \phi \varepsilon \; 1 \propto \text{at } 1/_{cr} \quad kr$$

weak turbulence $\delta B << B_0$ and $\Gamma_{cr} << \omega(k) \rightarrow w_{cr}(u_{cr}/c) << B_0^2/4\pi$

$$T = kV_{za}$$

strong instability $w_{cr}(u_{cr}/c) > B_0^2/4\pi$ Bell 2004

almost purely growing non-resonant mode

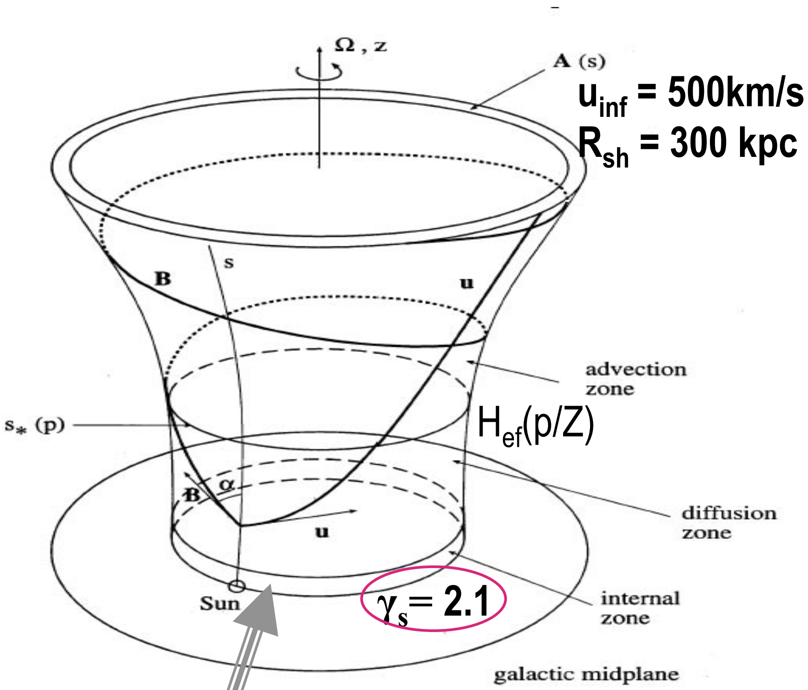
$$\geq_{cr} = \sqrt{\frac{4M}{\Xi}\frac{euN_{crcr}}{c}} \quad \text{at} \quad kkk_{\max} \quad => {}_{resres}\frac{4Muw_{crcr}}{cB_0^2}$$

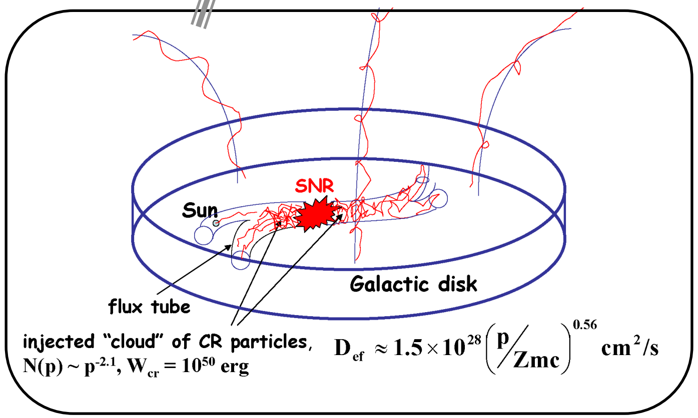
non-linear saturation at $$\frac{B^2}{4M} \lfloor \frac{u_{cr}}{c} w_{cr}$$

(not always reached because of finite shock age/size !)

galactic wind driven by cosmic rays

Ipavich 1975, Breitschwerdt et al. 1991, 1993





+ cosmic ray streaming instability with nonlinear saturation

Zirakashvili et al. 1996, 2002, VP et al. 1997, 2000, Voelk & Zirakashvili 2004

B_s 211.1

$Ds \sim 10$ $vBp\varphi p \propto \varphi \propto$ $q Z_{crp} mc Zmc$ 272

$BBB(31)_{ss}/22.7,\quad 2.1$

B_s 21 / 2

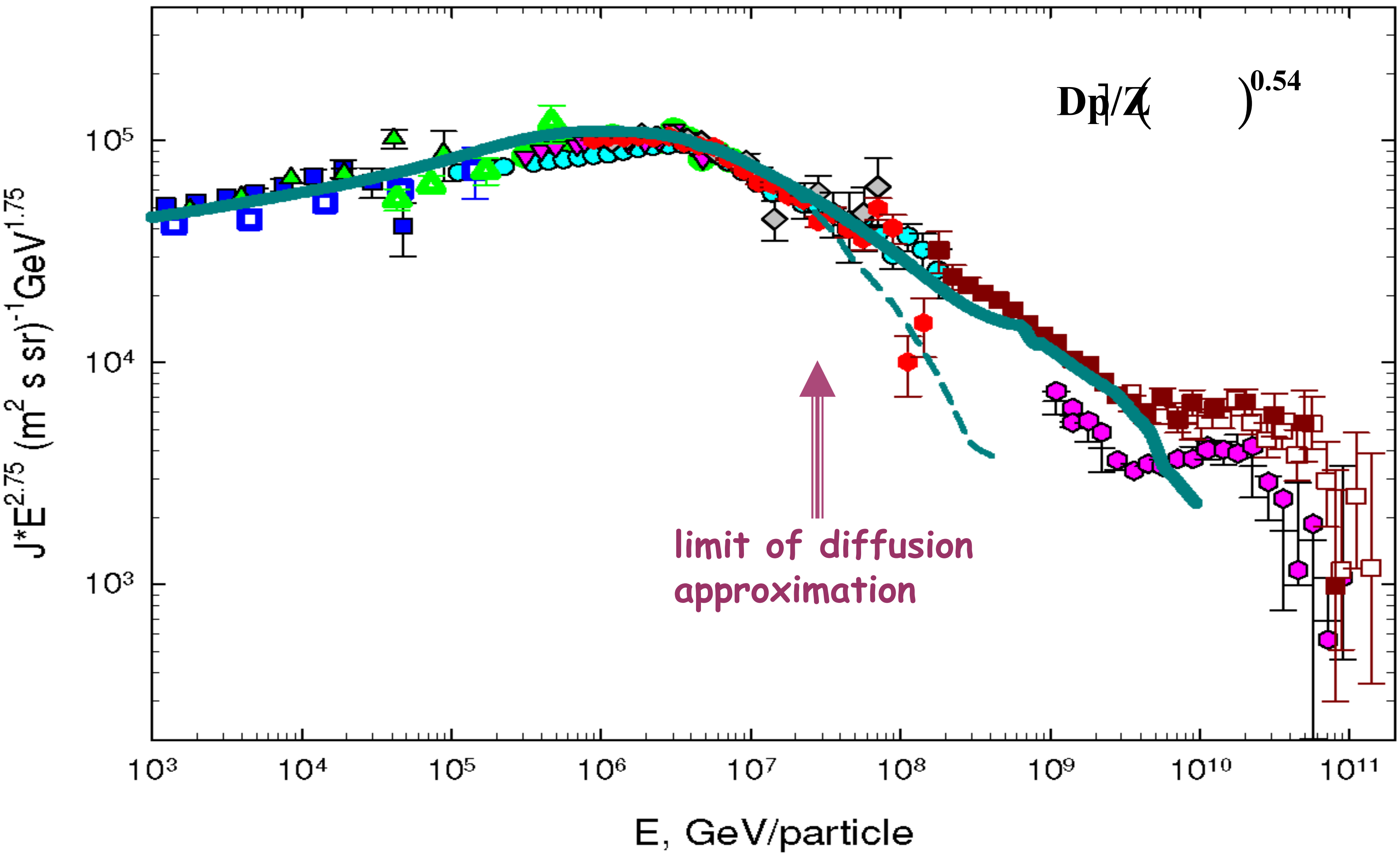
$X \sim\sim \frac{H_{ef}}{DZmcZ}$ $\varphi \propto pp$ p $\varphi \propto$ 20.55

non-linear evolution of cosmic ray cloud injected from SNR

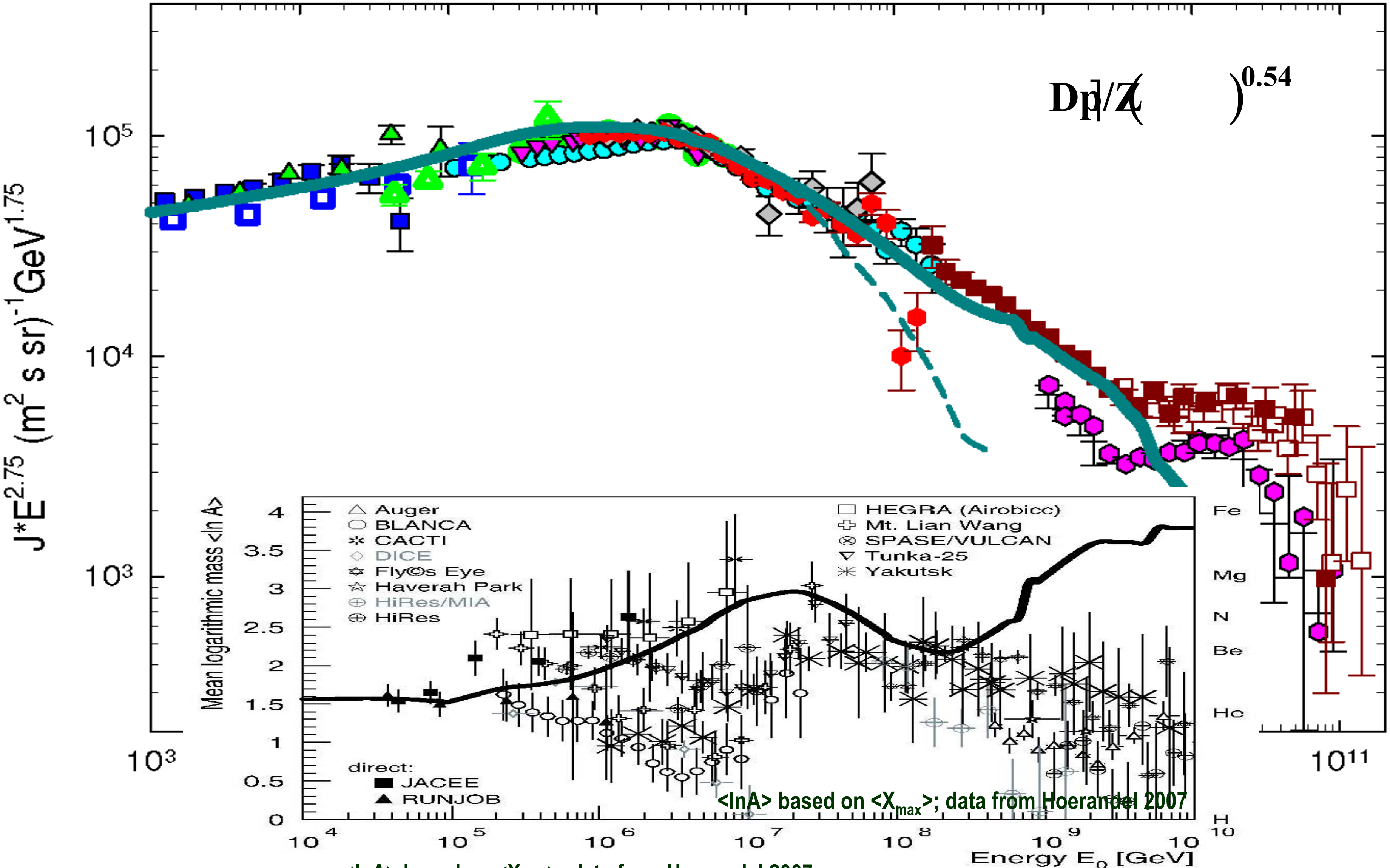
VP et al. 2007

above the knee
limit on galactic sources

all-particle spectrum produced by SNRs



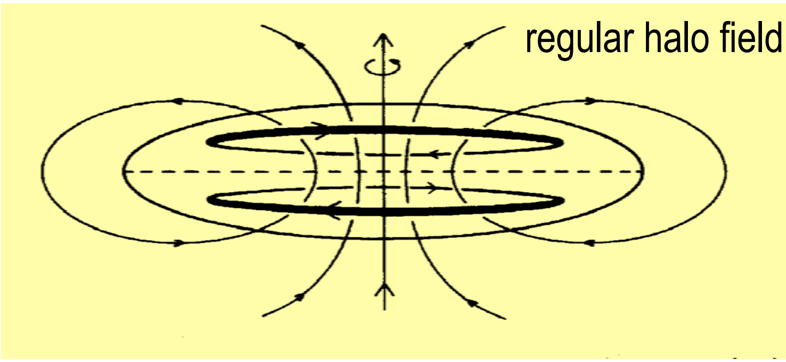
all-particle spectrum produced by SNRs

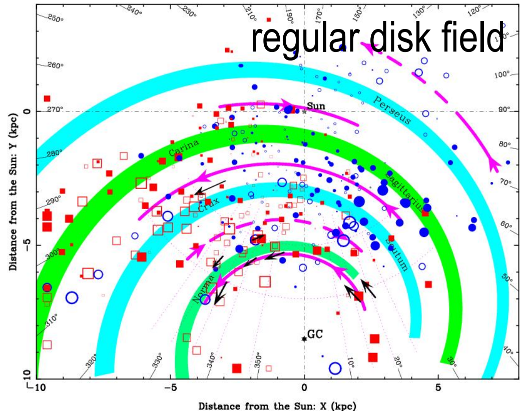


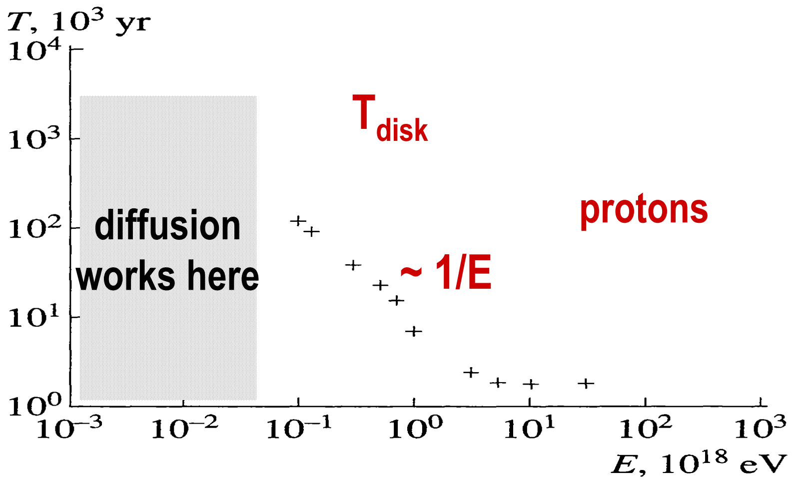
<lnA> based on <Xmax>; data from Hoerandel 2007

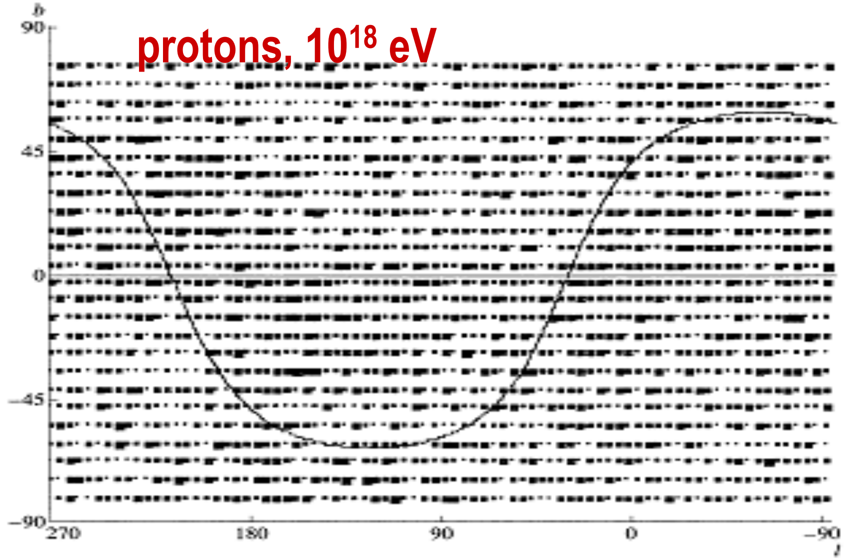
extension of propagation model till 10^{19} eV: trajectory calculations

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



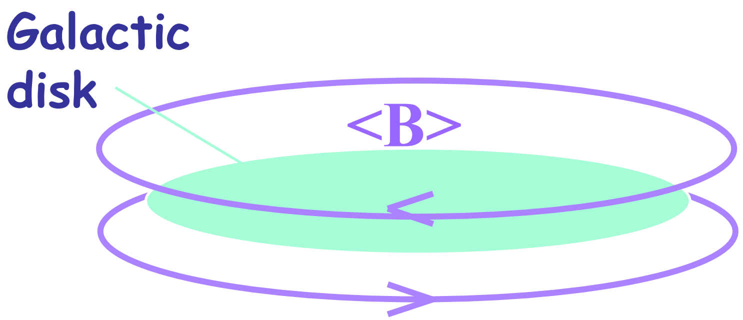






knee as a result of cosmic ray propagation

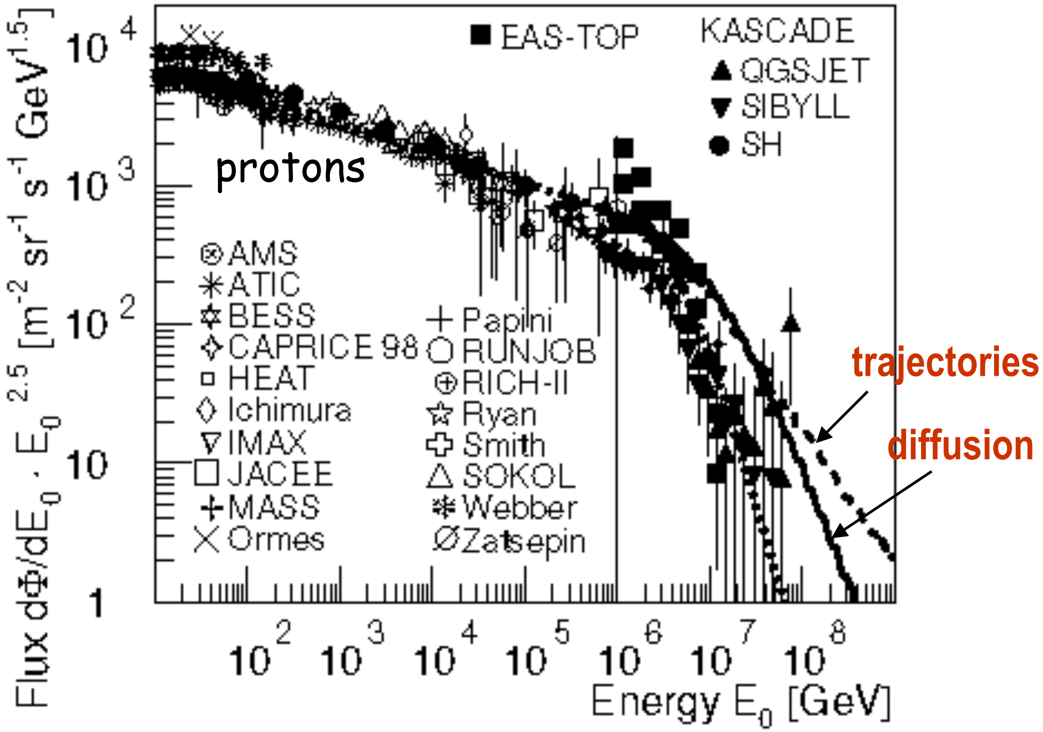
effect of Hall diffusion



Syrovatsky 1971, Ptuskin et al.1993 Kalmykov & Pavlov 1999, Candia et al. 2003, Hörandel et al. 2005

$D_{\perp} \sim R^{0.2}, \; D_A \sim R$

Hörandel et al. 2005

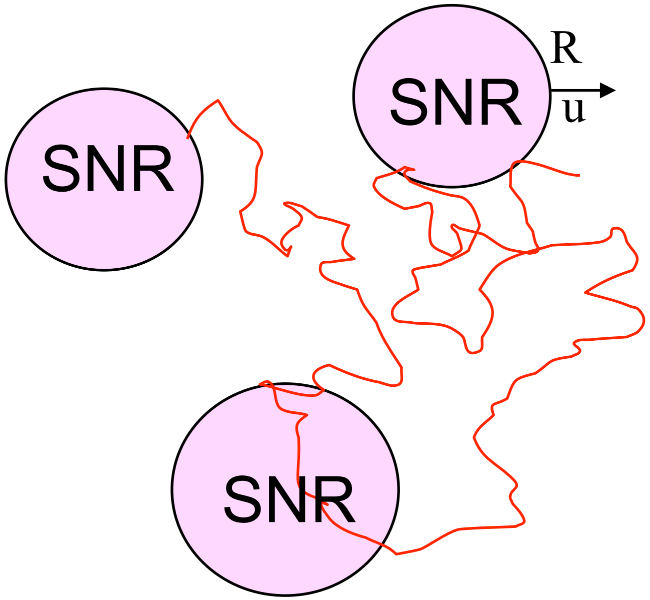


additional change of source spectrum is needed

additional resources for cosmic ray acceleration to ultra high energies

- Reacceleration by multiple shocks

OB star association: $u=3\times10^3$ km/s, $B=10^{-5}$ G, R=30 pc



$f \sim 1/p^3$

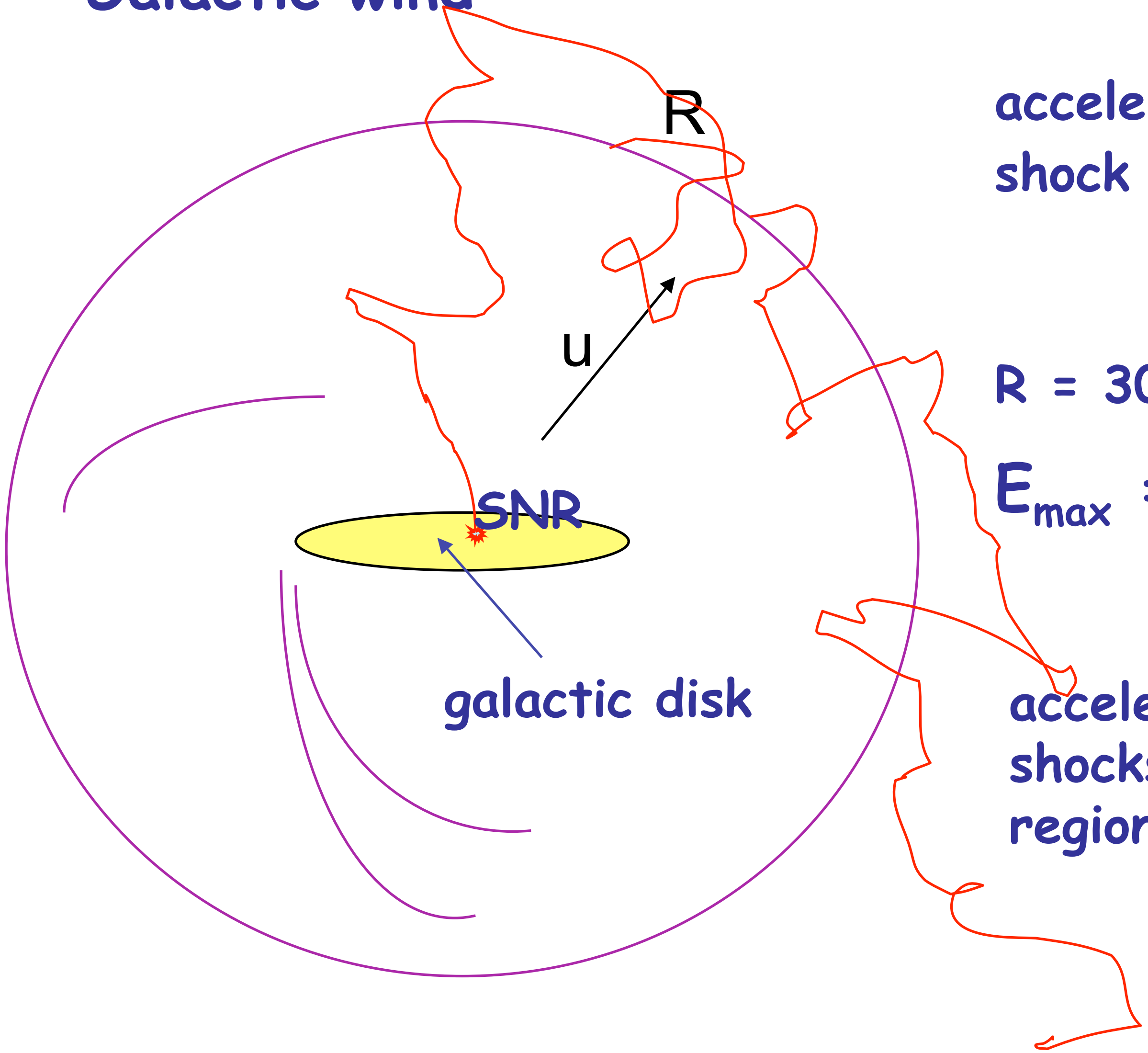
$t_a \sim R/(F_{sh}u)$ at $D_i < uR$

$\sim D/(F_{sh}u^2)$ at $D_i > uR$

$E_{max} \sim 10^{17}\, Z$ eV

Axford & Ip 1991, Bykov & Toptygin 1990, 2001
Klepach et al. 2000, Parizot et al.2004

- Galactic wind

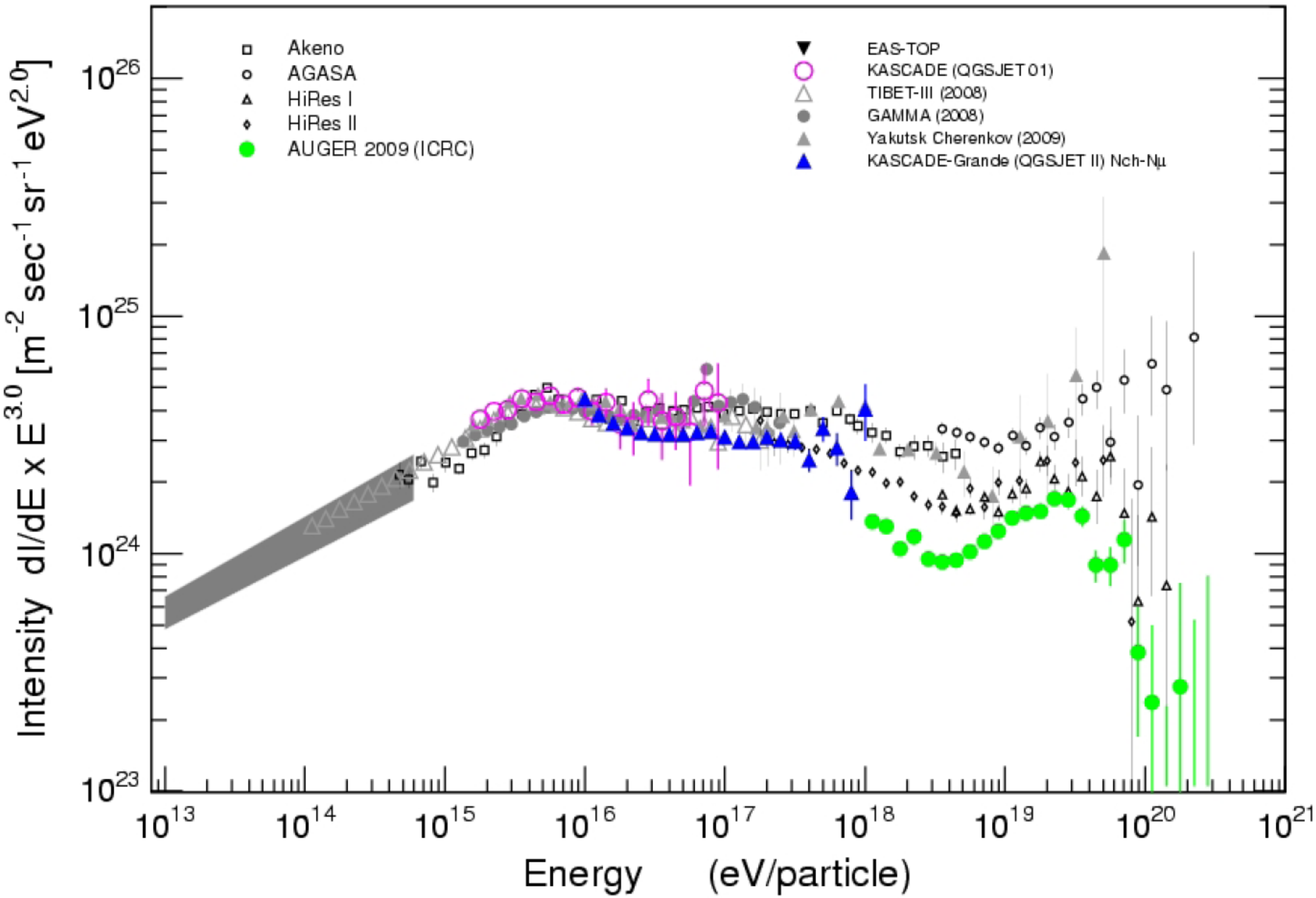


acceleration at termination shock Jokipii & Morfill 1985, 1991
Zirakashvili et al 2005

R = 300 kpc, u = 400 km/s

$E_{max} = 10^{18}\,Z\ \mathrm{eV}$

acceleration by traveling shocks and interaction regions Völk & Zirakashvili 2004


Akeno
AGASA
HiRes I
HiRes II
AUGER 2009 (ICRC)
EAS-TOP
KASCADE (QGSJET 01)
TIBET-III (2008)
GAMMA (2008)
Yakutsk Cherenkov (2009)
KASCADE-Grande (QGSJET II) Nch-Nμ
Intensity dI/dE x E^3.0 [m^-2 sec^-1 sr^-1 eV^2.0]
Energy (eV/particle)
10^23
10^24
10^25
10^26
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21

Conclusion

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).

Critical issues:

- structure of interstellar mhd turbulence
- importance of collective (plasma) effects in cosmic ray transport
- confinement of ultra-high energy cosmic rays in large-scale galactic magnetic field; transition to extragalactic component

flat component of secondary nuclei produced by strong SNR shocks

Wandel et al. 1987, Berezhko et al. 2003

production by primaries inside SNRs

grammage gained in SNR

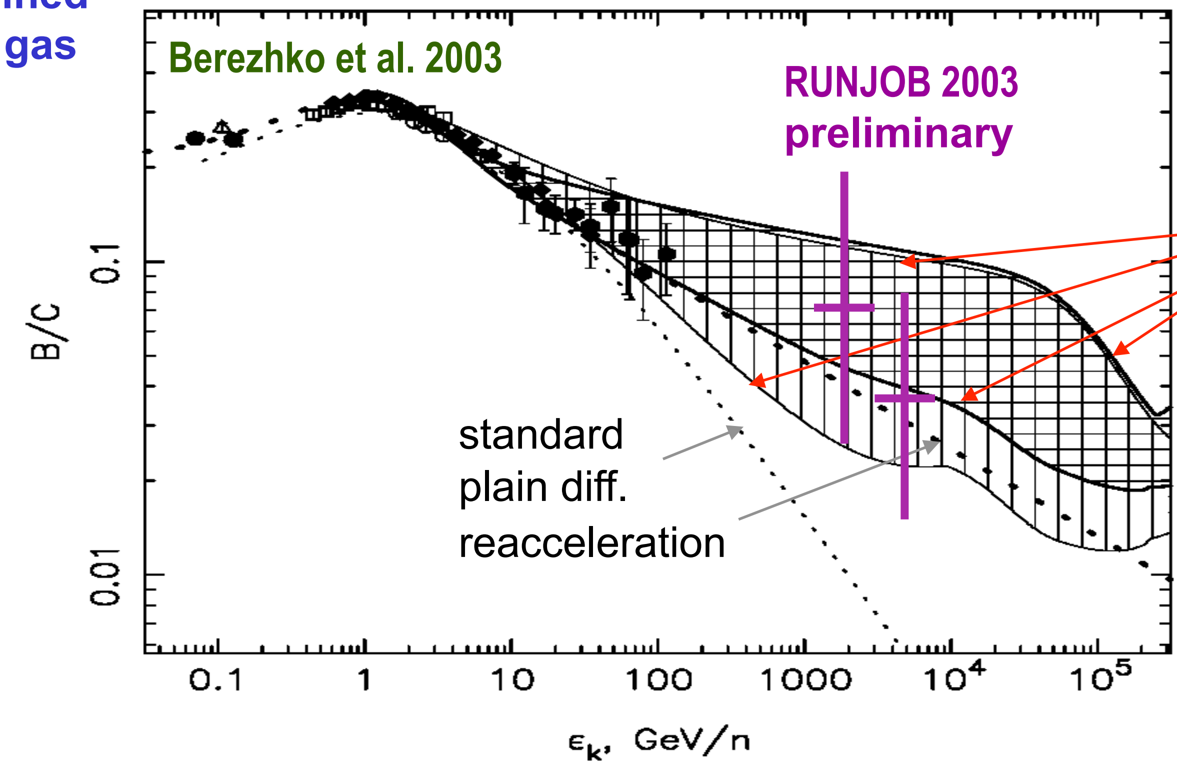
$$\frac{N_{2,\mathrm{flat}}}{N_{2,\mathrm{stand}}} \sim \frac{X_{\mathrm{SNR}}}{X_{\mathrm{ISM}}} \sim 0.02$$

grammage gained in interstellar gas

reacceleration in ISM by strong shocks

$$\frac{N_{2,\mathrm{flat}}}{N_{2,\mathrm{stand}}} \sim \frac{X_{\mathrm{ISM}}}{X_{\mathrm{SNR}}} f_{\mathrm{SNR}} \sim 0.2$$

volume filling factor of SNRs



plain diff.
reacceleration
n_{ism} = 0.003...1 cm^{-3}
Bohm diffusion
$T_{SNR} = 10^5$ yr