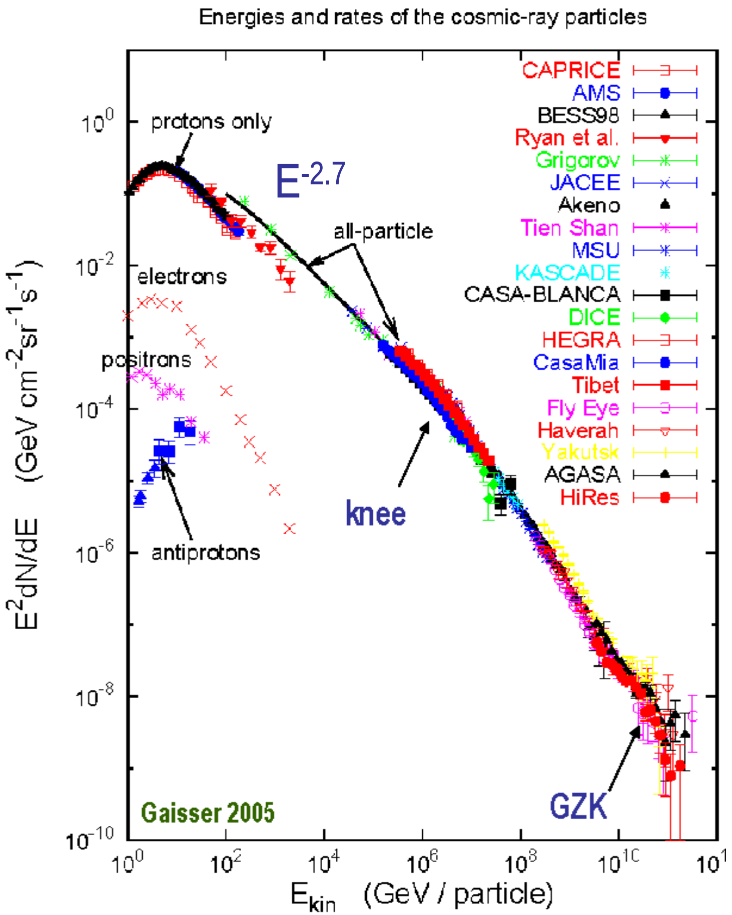


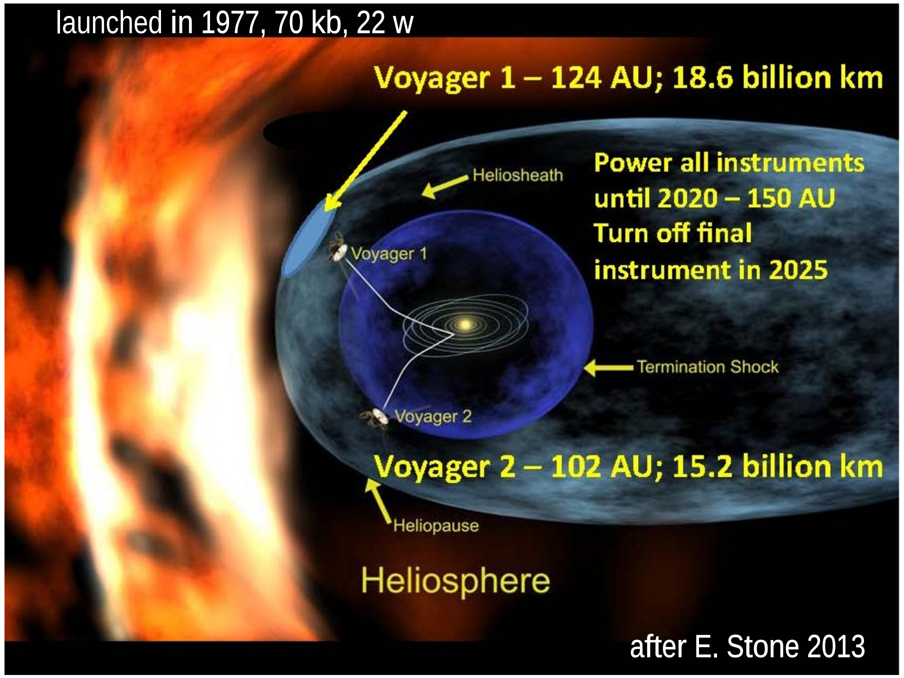
Cosmic ray acceleration and transport from MeV energies to the knee

Vladimir Ptuskin

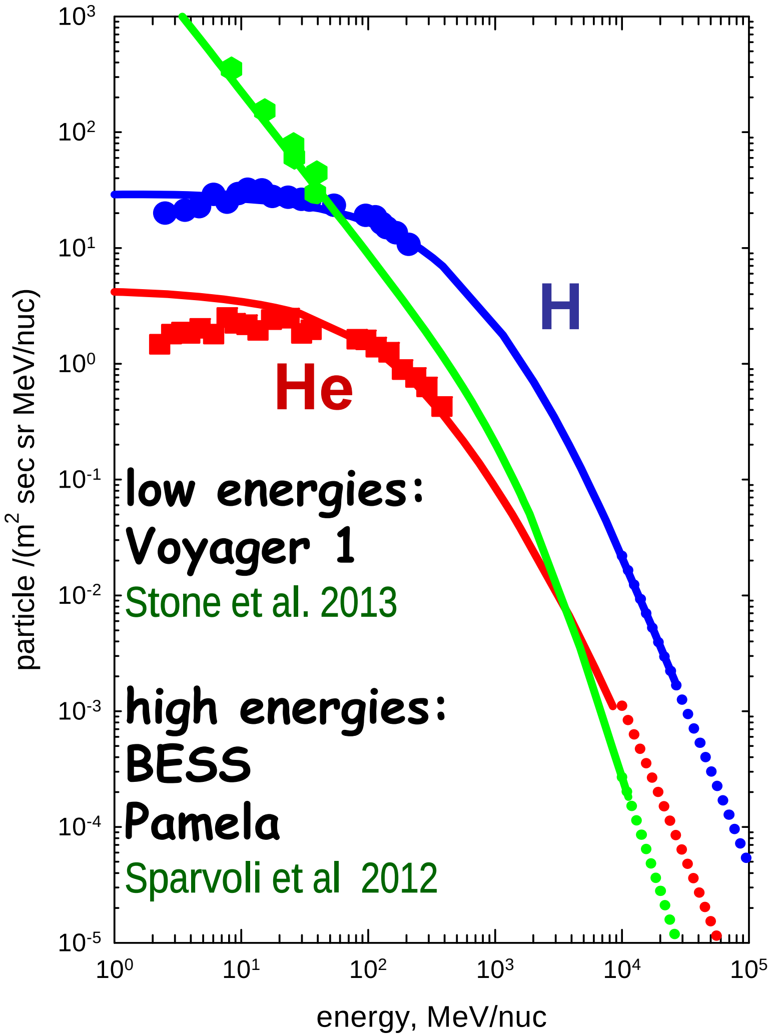
IZMIRAN, Russia
University of Maryland, USA

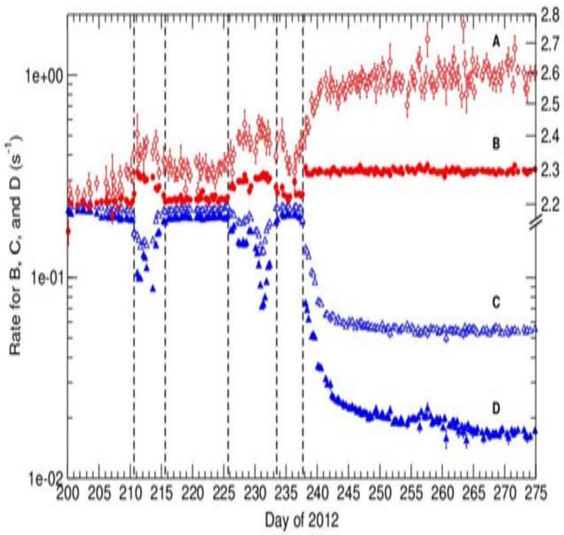
Paris, November 13 – 14, 2014

Voyager 1 at the edge of interstellar space



direct measurements of interstellar
CR spectra at low energies





From outside:

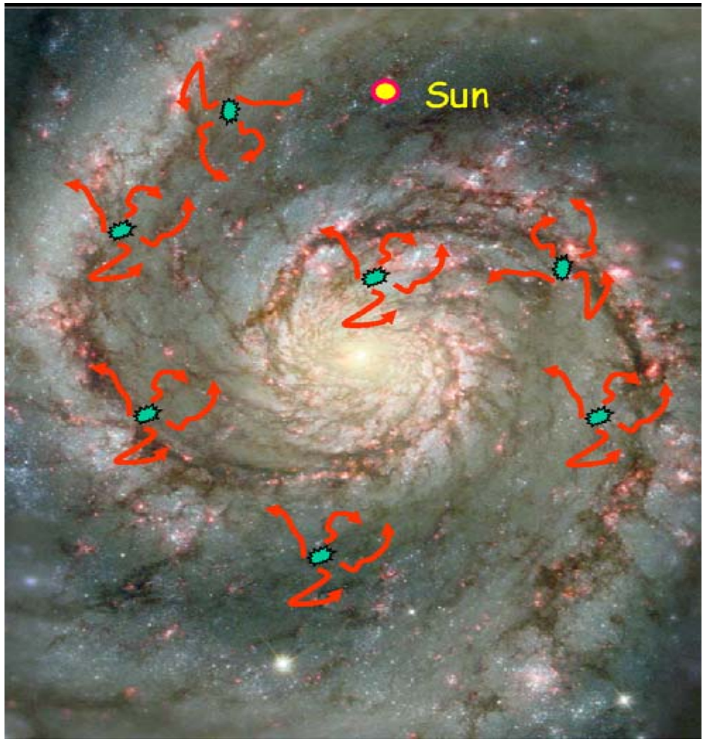
GCR protons
>70 MeV

GCR electrons
7 to ~100 MeV

From inside:

ACR protons
7 to 60 MeV

TSPs
0.5 to 30 MeV



~ 15% of SN kinetic energy transfer to cosmic rays

Ginzburg & Syrovatsky 1964

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

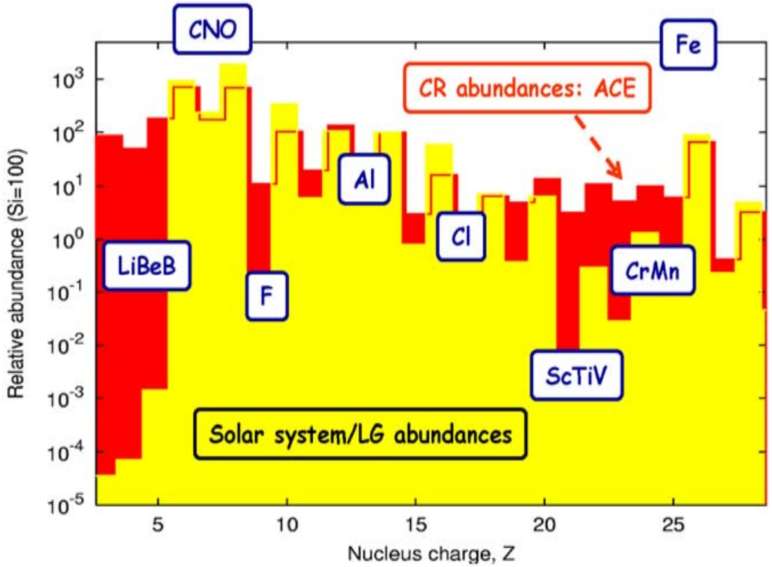
cosmic ray intensity

$E^{-2.7}$ $E^{-2.2}$ $E^{-0.5}$

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

source power

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

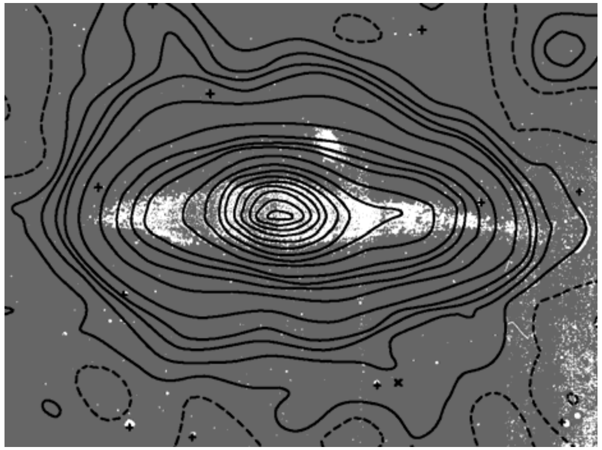


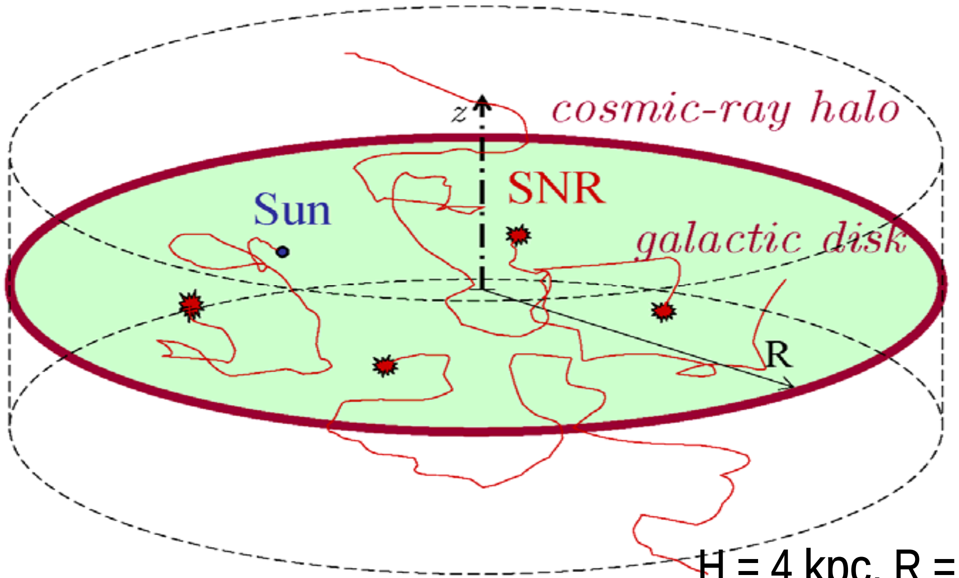
traversed matter thickness ~ 12 g/cm^2 at 1 GeV/nuc
(surface gas density of galactic disk ~ 2.5 10^{-3} g/cm^2)

basic empirical diffusion model

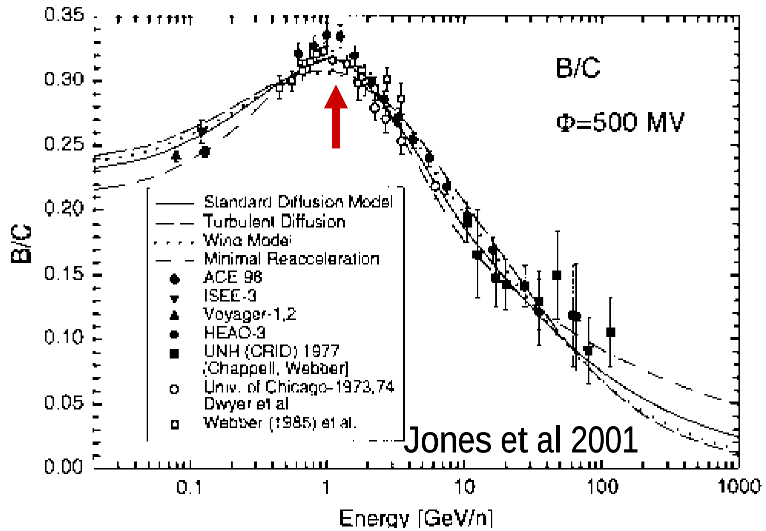
Ginzburg & Ptuskin 1976, Berezinskii et al. 1990, Strong & Moskalenko 1998 (GALPROP), Donato et al 2002, Ptuskin et al. 2006, Strong et al. 2007, Vladimirov et al. 2010, Bernardo et al. 2010, Maurin et al 2010, Putze et al 2010, Trotta et al 2011

NGC4631





H = 4 kpc, R = 20 kpc



empirical diffusion coefficient

$$D \sim 3\times10^{28}\ \mathrm{cm}^2/\mathrm{s} \quad \text{at } 1\ \mathrm{GeV/n}$$

diffusion mean free path

$$l \sim 1\ \mathrm{pc}$$

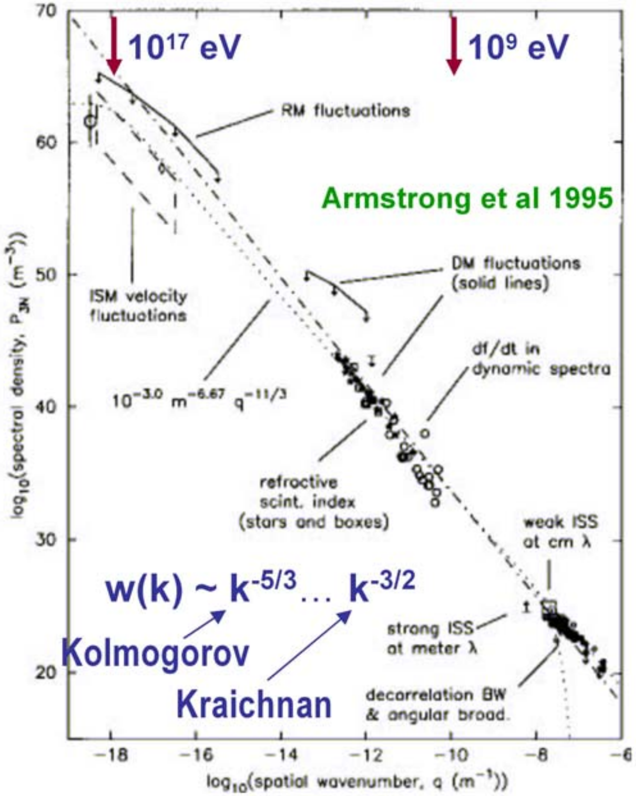
mechanism of cosmic ray diffusion

r_g = 1/k - resonance condition

$$D_{\parallel} \approx \frac{vr_g}{3} \cdot \frac{B_{tot}^2}{B_{res}^2}$$

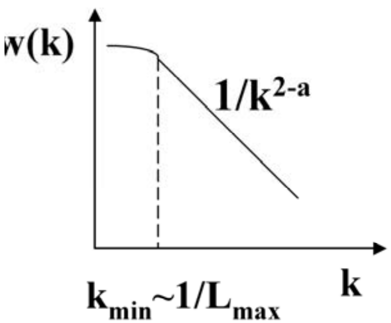
Jokipii 1966, ...

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



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

$w(k)dk \sim k^{-2+a}dk$, $D_{\parallel} \sim vr_g^{\,a}$



$a = 1/3$ Kolmogorov spectrum

$a = 1/2$ Kraichnan spectrum

$a = 0$ random discontinuities

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

regimes of cosmic ray diffusion

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

- may be valid up to $10^{17}Z$ eV
- source spectrum $R^{-2.4}$ – too soft to be produced in SNRs

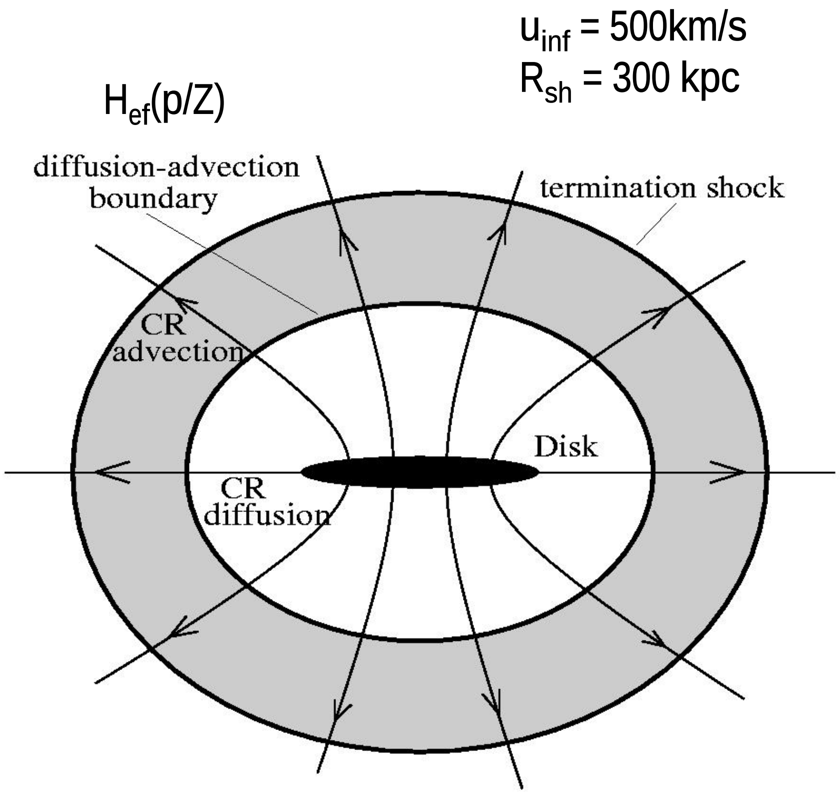
  (but dispersion of SNR parameters may help)
- anisotropy – acceptable
- peak of B/C ratio at 1 GeV/n – explained by distributed reacceleration
- underpredicts antiproton flux below few GeV
- in contradiction with theory of MHD turbulence (wave distribution in k-space)
- contradiction to radio-astronomical data ? (too many secondary leptons)

Kraichnan spectrum: $D \sim vR^{1/2}$ +wave damping

- 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
- B/C ratio at V1 energies is too high
- not in contradiction with theory of MHD turbulence –

diffusion-convection model: galactic wind driven by CR

Ipavich 1975, Breitschwerdt et al. 1991, 1993, Everett et al.2008, 2010



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,

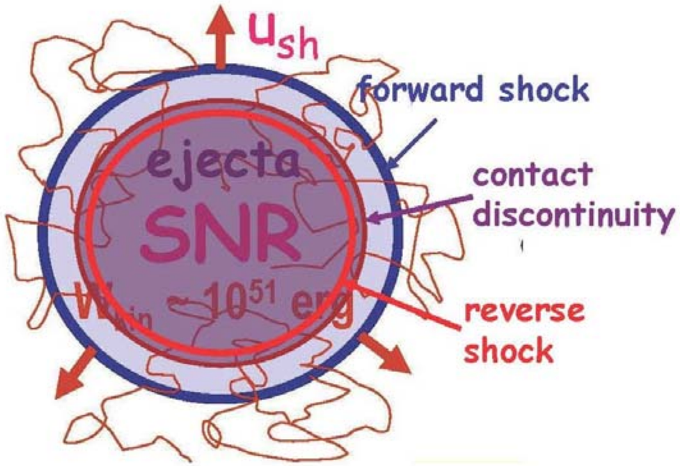
$$D \sim \frac{\mathrm{v}B}{q_{cr}}\left(\frac{p}{Zm_p c}\right)^{\gamma_s - 1} \approx 10^{27}\beta\left(\frac{p}{Zm_p c}\right)^{1.1}\ \mathrm{cm}^2/s,$$

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

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

diffusive shock acceleration

Fermi 1949, Krymsky 1977, Bell 1978, ...



$$J \sim p^{-\gamma_s}, \quad \gamma_s = \frac{\sigma + 2}{\sigma - 1} = 2$$

for test particles !

compression ratio = 4

$$\frac{u_{sh} R_{sh}}{D(p)} > 10$$

-condition of CR acceleration and confinement

- D(p) should be anomalously small both upstream and downstream; CR streaming creates turbulence in shock precursor

Bell 1978; Lagage & Cesarsky 1983; McKenzie & Vőlk 1982 ...

"Bohm" limit $D_B = vr_g/3$: $E_{max} \approx 0.3 \cdot Ze \cdot \frac{u_{sh}}{c} \cdot B \cdot R_{sh}$

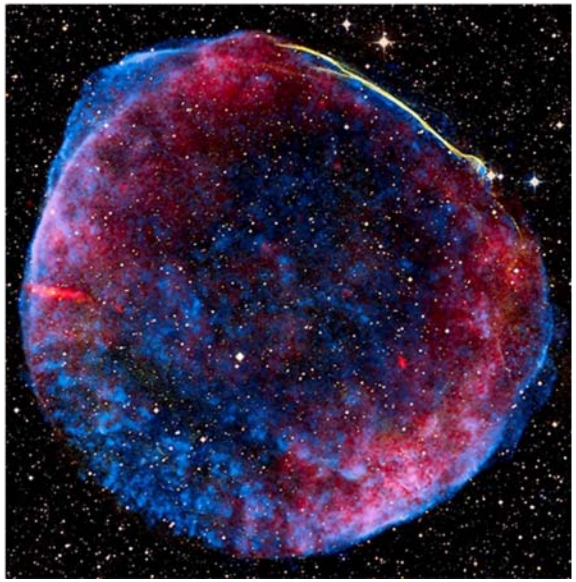
$E_{max,ism} = 10^{13} \ldots 10^{14}\, Z\, eV$ for $B_{ism} = 5\ 10^{-6}$ G

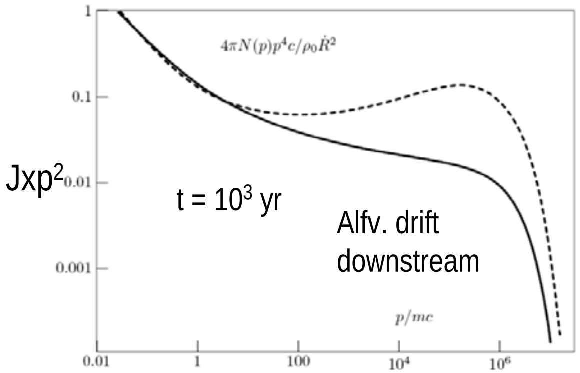
$\sim B_{sh} t^{-1/5}$ at Sedov stage

abandonment of interstellar Bohm limit hypotheses;

$D \neq D_{B,ism}$

SN 1006





- strong cosmic-ray streaming instability gives $\delta B >> B_{ism}$ in young SNR Bell & Lucek 2000, Bell 2004

Pelletier et al 2006; Amato & Blasi 2006; Zirkashvili & VP 2008; Vladimirov et al 2009; Gargate & Spitkovsky 2011

under extreme conditions (SN Ib/c, e.g. SN1998 bw)

$E_{max} \sim 10^{17} Z\,(u_{sh}/3\times10^4\text{ km/s})^2\, M_{ej}^{1/3} n^{1/6}$ eV

$B_{max} \sim 10^{-3}\,(u_{sh}/3\times10^4\text{ km/s}) n^{1/2}$ G

confirmed by X-ray observations of young SNRs

SN 1006, Cas A, Tycho, RCW 86, Kepler, RX J1713.7-3946, Vela Jr., G1.9+0.3

$B^2/8\pi = 0.035\,\rho u^2/2$ Voelk et al. 2005

- wave dissipation in shock precursor leads to rapid decrease of δB and E_{max} with time

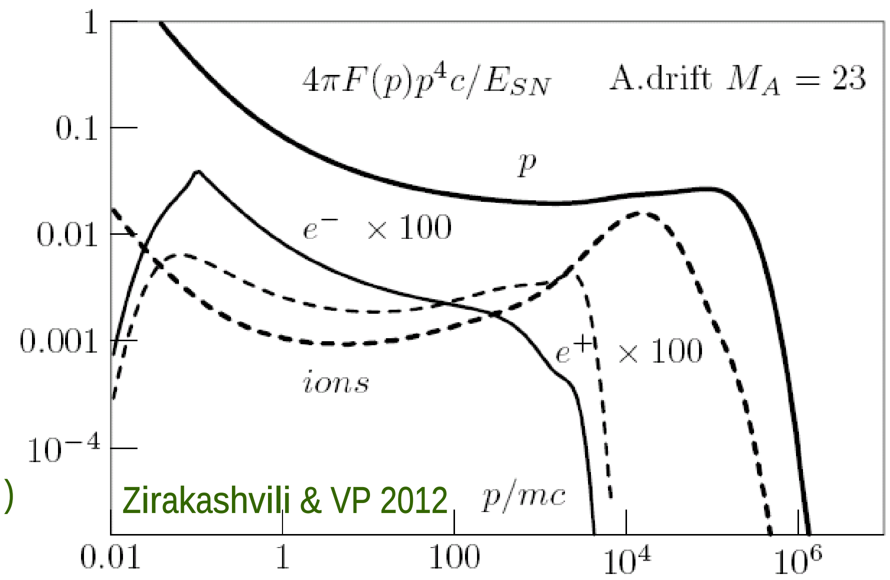
VP & Zirakashvili 2003

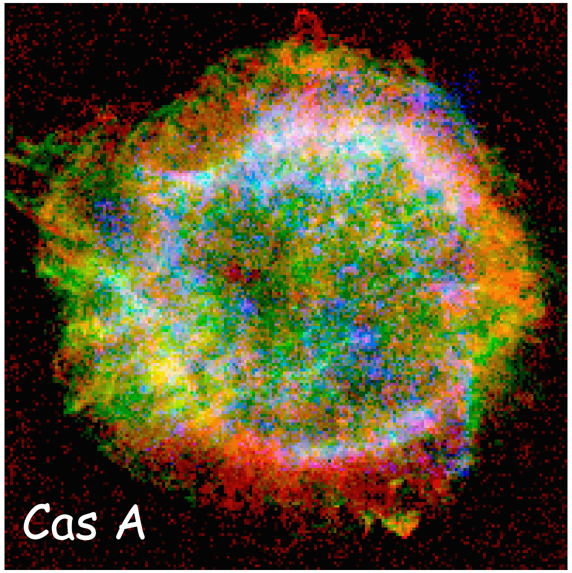
- finate V_a leads to steeper CR spectrum

$$\sigma = \frac{u_1 - V_{a,1}}{u_2 + V_{a,2}}$$

numerical simulations of particle acceleration and radiation in SNR

Berezhko et al. 1994-2006, Kang & Jones 2006
Zirakashvili & VP 2012,
semianalytic models Blasi et al.(2005), Ellison et al. (2010))





radio polarization in red (VLA),
X-rays in green (CHANDRA),
optical in blue (HST)

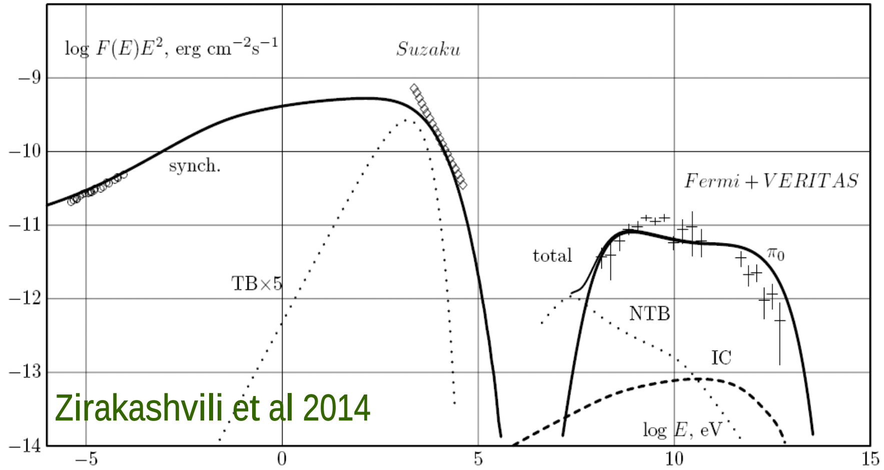


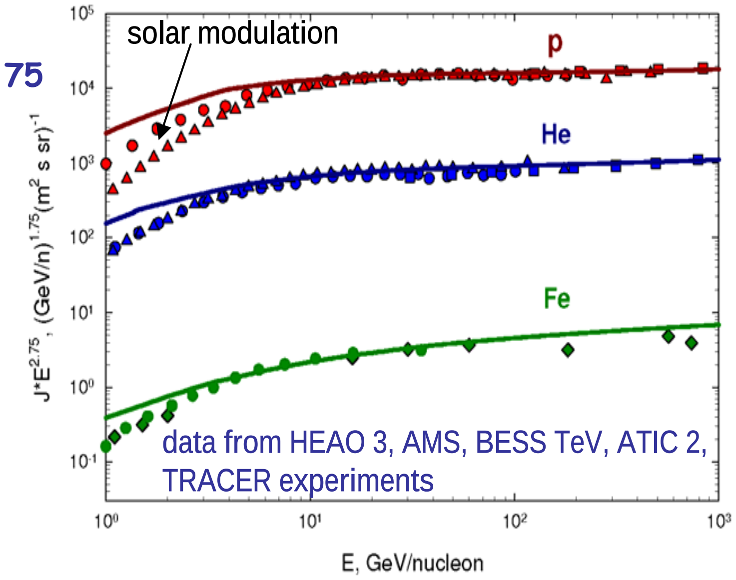
Fig. 6.— The broad-band spectral energy distribution of nonthermal radiation of Cas A calculated within the hadronic model H1. The following radiation processes are taken into account: synchrotron radiation of accelerated electrons (solid curve on the left), IC emission (dashed line), gamma-ray emission from pion decay (solid line on the right), thermal bremsstrahlung (dotted line on the left), nonthermal bremsstrahlung (dotted line on the right). Experimental data in gamma-ray (Fermi LAT, present work); VERITAS, Acciari et al. 2010, data with error-bars) and radio-bands (Baars 1977, circles), as well as the power-law approximation of Suzaku X-ray data (Maeda et al. 2009, diamonds) from the whole remnant are also shown.

calculated spectrum of Galactic cosmic rays:

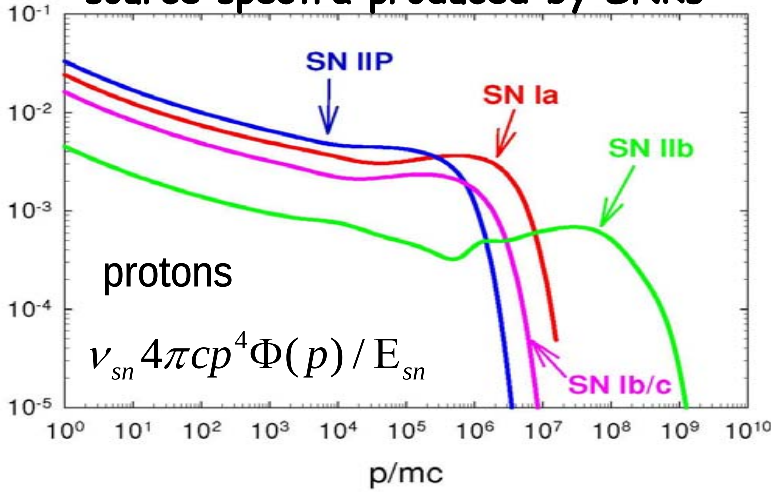
acceleration in SNRs, transport in interstellar magnetic fields, $D \sim R^{0.54}$

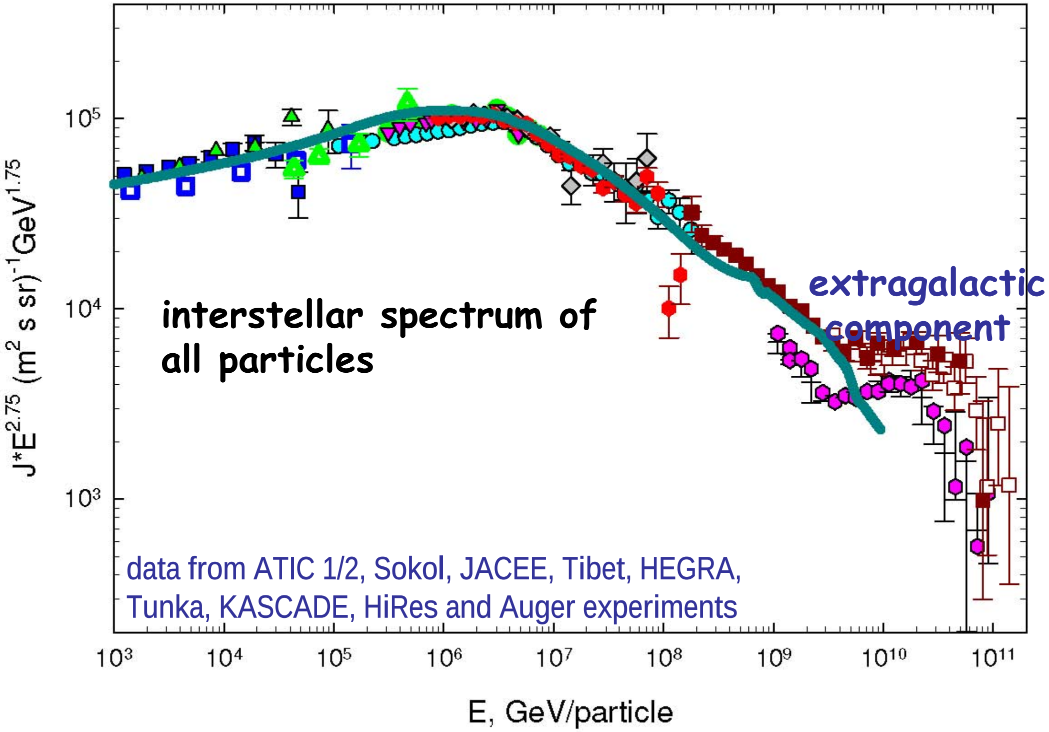
VP, Zirakashvili, Seo 2010

$J \times E^{2.75}$



source spectra produced by SNRs





«knee» is formed at the beginning of Sedov stage

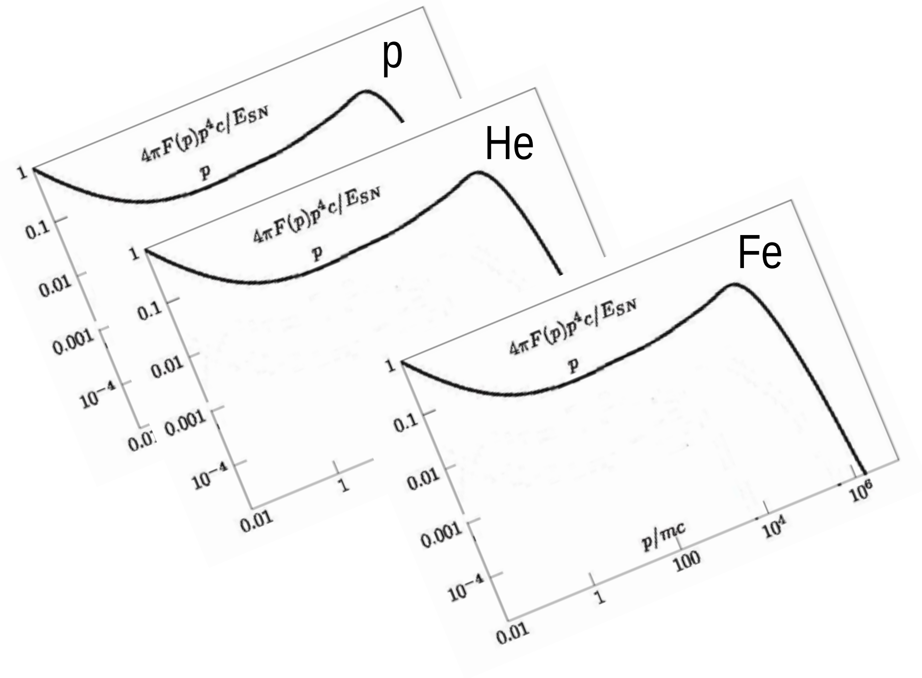
$$E_{knee}/Z = 1.1\times10^{15}\, W_{sn,51}\, n^{1/6} M_{ej}^{-2/3}\ \mathrm{eV},$$

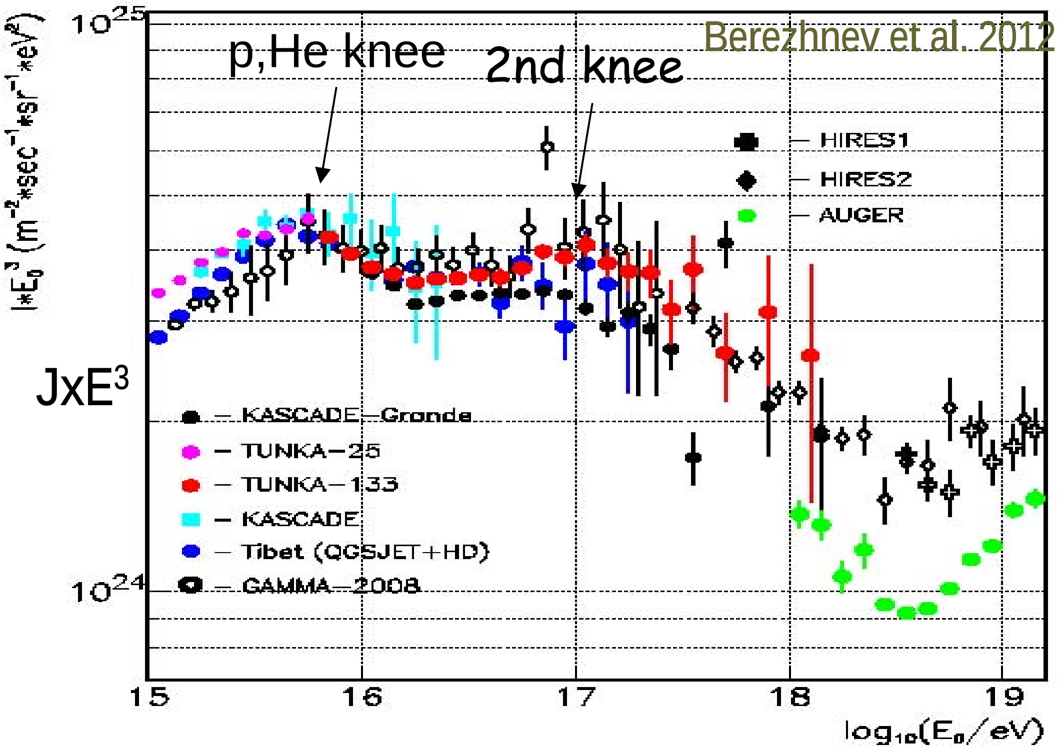
$$E_{knee} c/Z = 8.4\times10^{15}\, W_{sn,51} \sqrt{\dot{M}_{-5}/u_{w,6}}\, M_{ej}^{-1}\ \mathrm{eV}$$

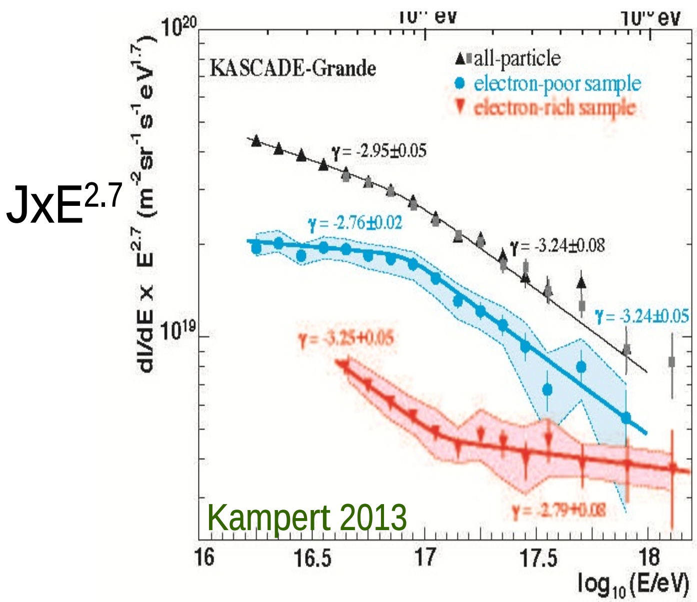
knee and beyond

structure above the knee

different types of nuclei, E_{knee} ~ Z
different types of SN
transition to extragalactic component







features to explain:

hardening above 200 GeV/nucleon

concave source spectrum

superposition of sources

new source Zatsepin & Sokolskaya 2006

reacceleration in local bubble Erlykin & Wolfendale 2011

streeming instability below 200 GV Blasi et al. 2012

spectra of p and He are different

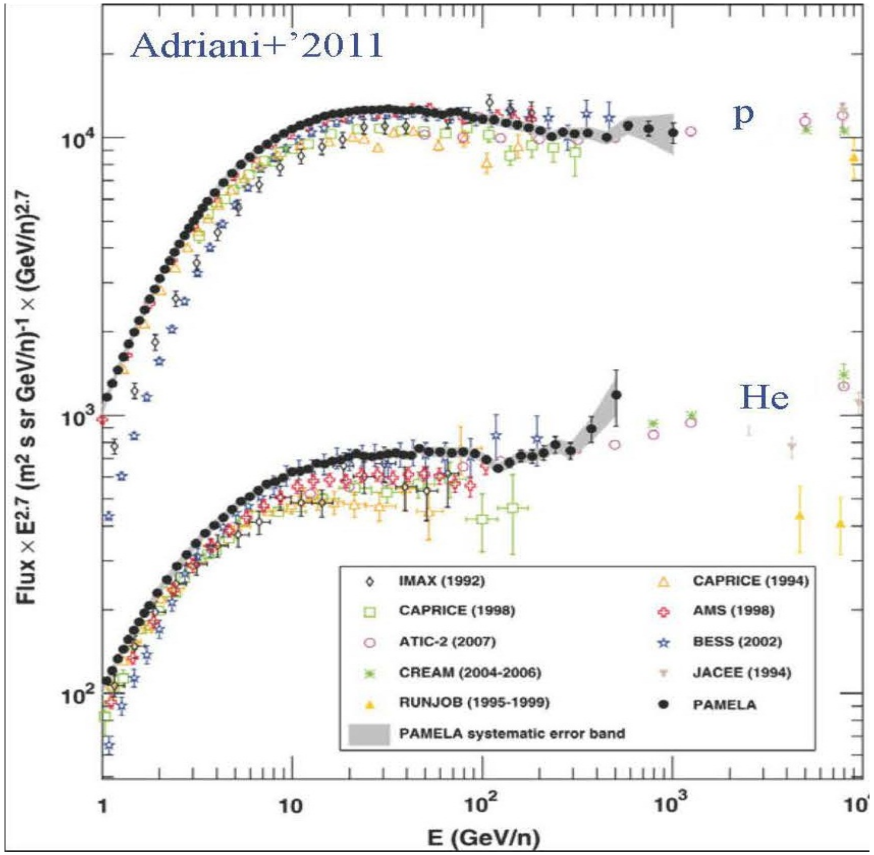
shock goes through material enriched in He:

- helium wind VP et al. 2010,
- bubble Ohira & Ioka 2011

effect of injection Malkov et al 2011

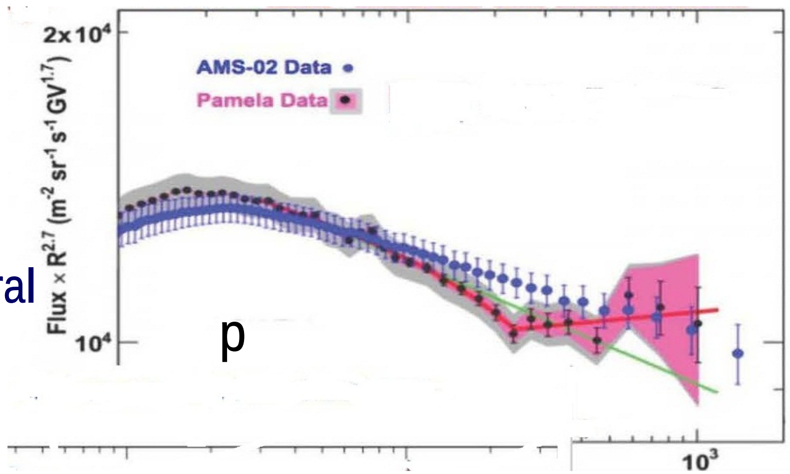
both features

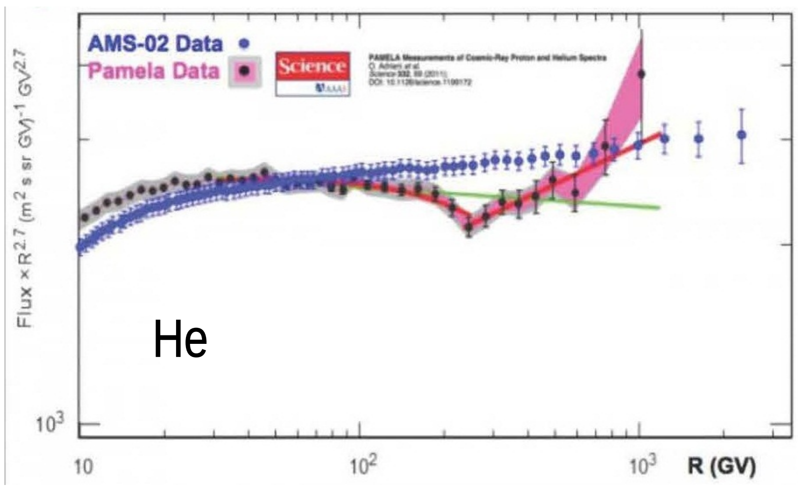
contribution of reversed SNR shock VP et al 2013



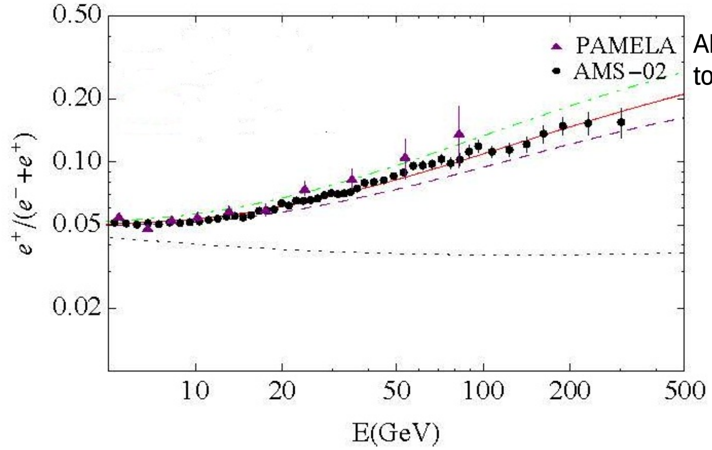
BUT !

preliminary AMS-02 data do not show spectral features

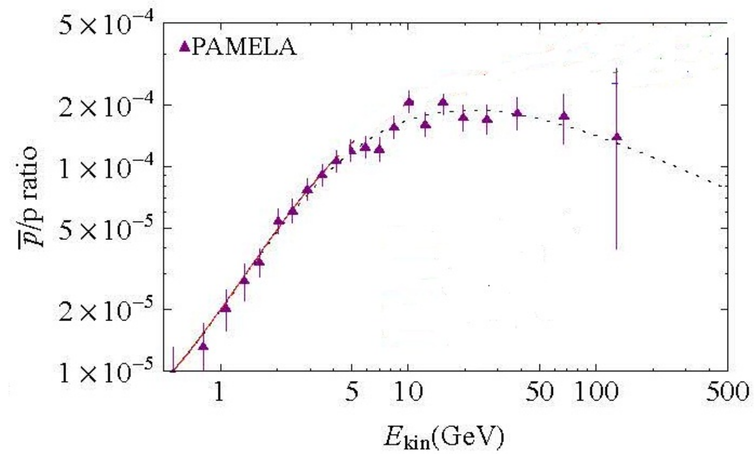


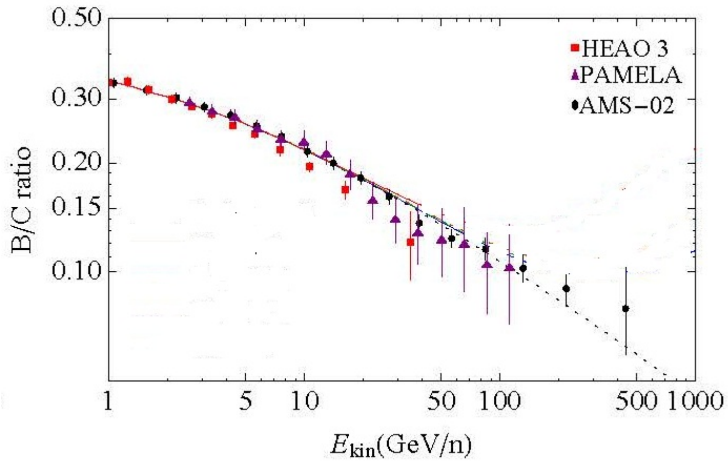


positrons in cosmic rays



AMS-02 up to 500 GeV now





GALPROP calculations Cholis, Hooper 2014

H = 4 kpc

D = 2.95 10^{28}v(R/3 GV)$^{0.43}$ cm^2/s

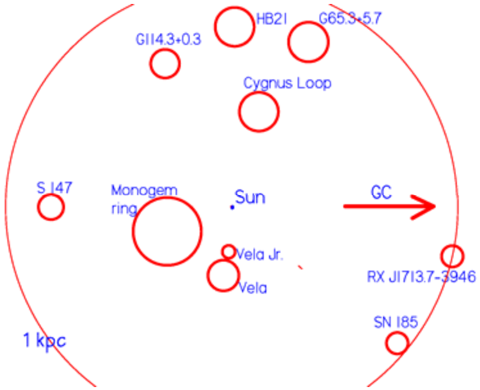
V_a = 10 km/s

pulasar origin Harding, Ramaty 1987, Aharonian et al. 1995, Hooper et al. 2008, Malyshev et al. 2009

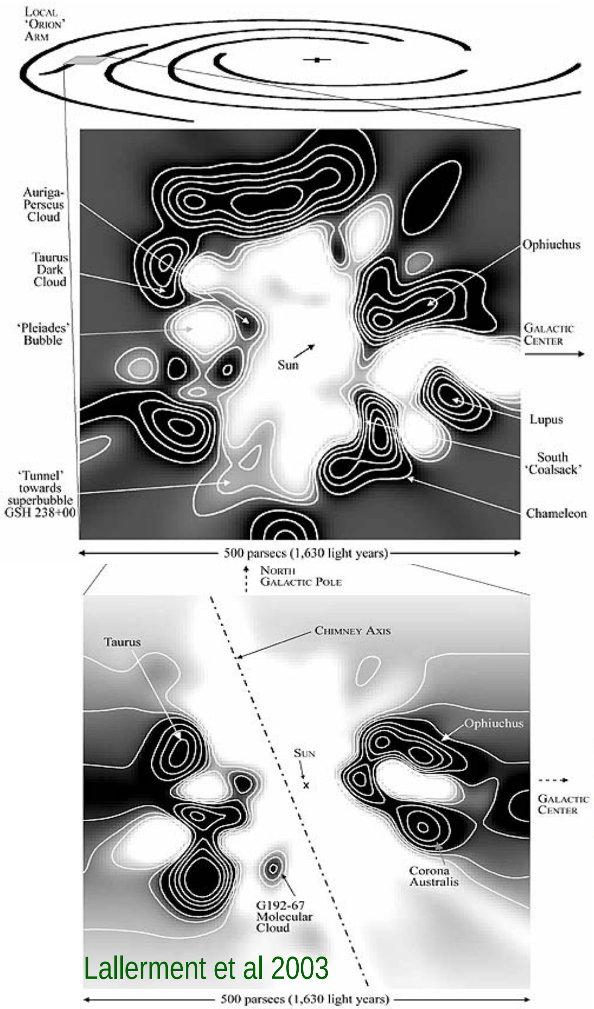
e+ production and acceleration in shell SNRs Blasi 2009, Berezhko, Ksenofontov 2013

reverse shock in radioactive ejecta Ellison et al 1990, Zirakashvili, Aharonian 2011

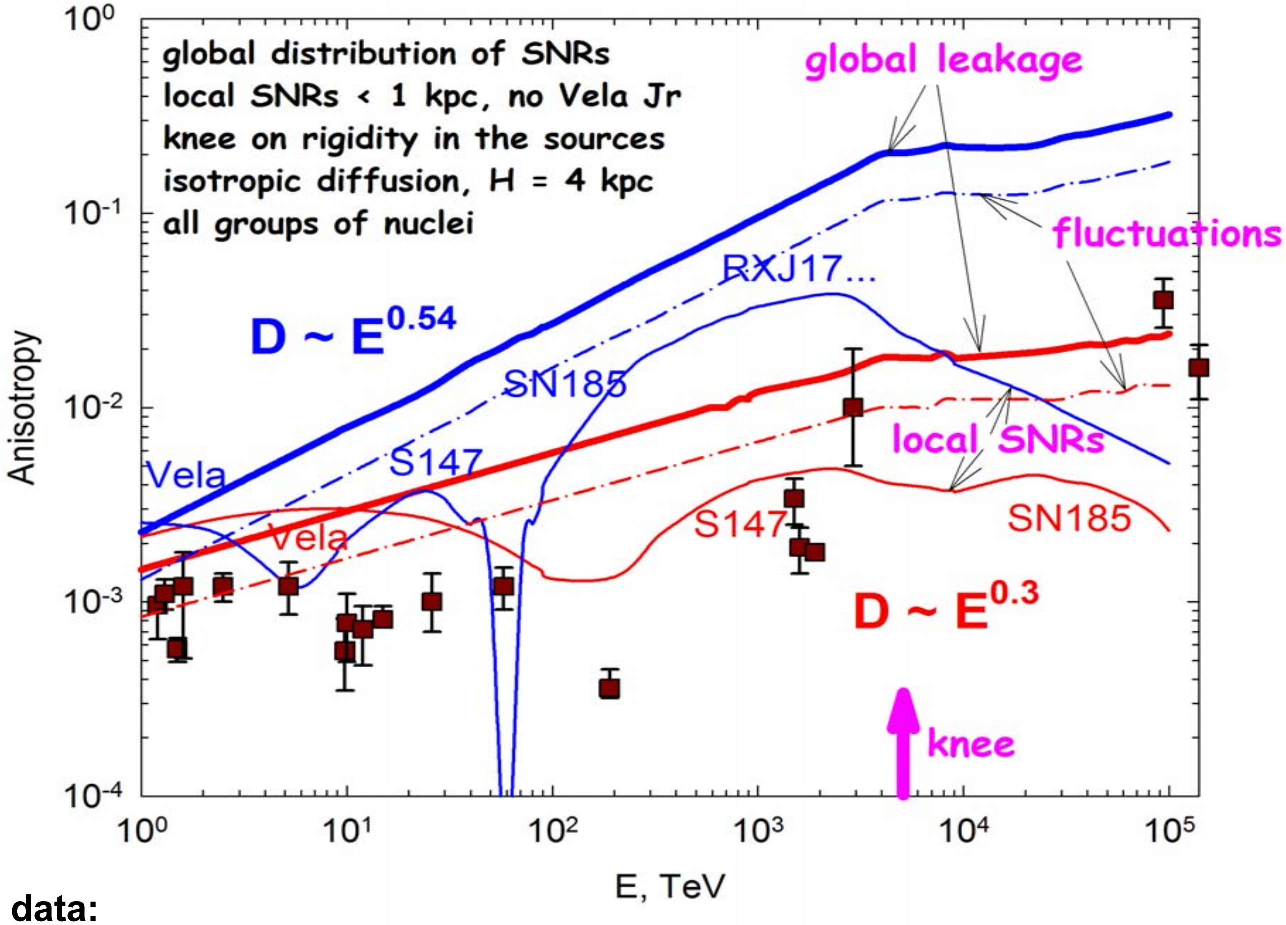
annihilation and decay of dark matter Tylka 1989, Fan et al 2011



large-scale anisotropy



Lallerment et al 2003



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

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.

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 included in GALPROP code). Energy dependence of diffusion is still uncertain.

High-accuracy measurements indicate deviations of cosmic ray spectra from plain power laws below the knee. If confirmed, it requires refining models of cosmic ray acceleration and propagation.