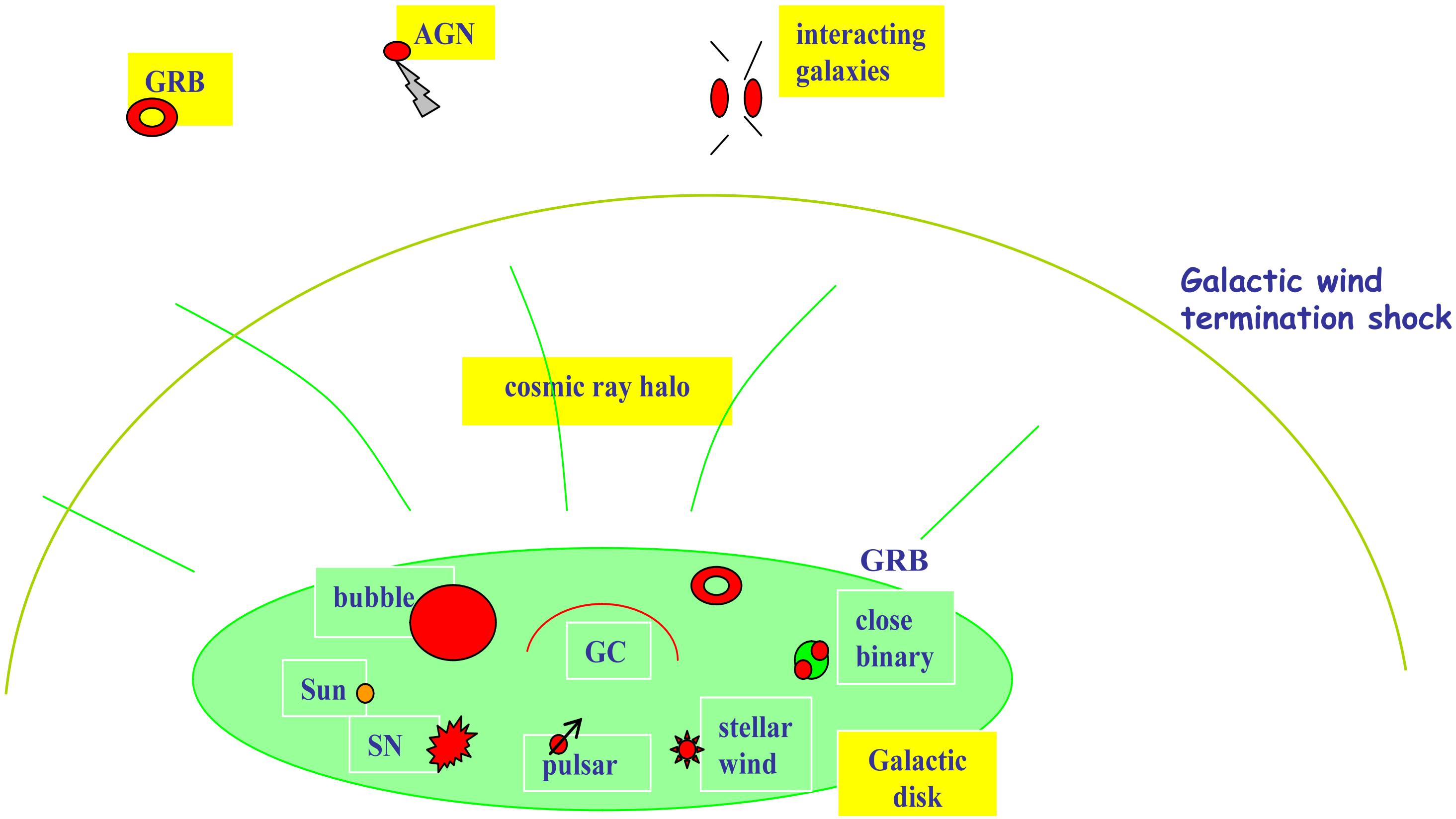
Revue sur le rayonnement cosmique

Vladimir Ptuskin

IZMIRAN

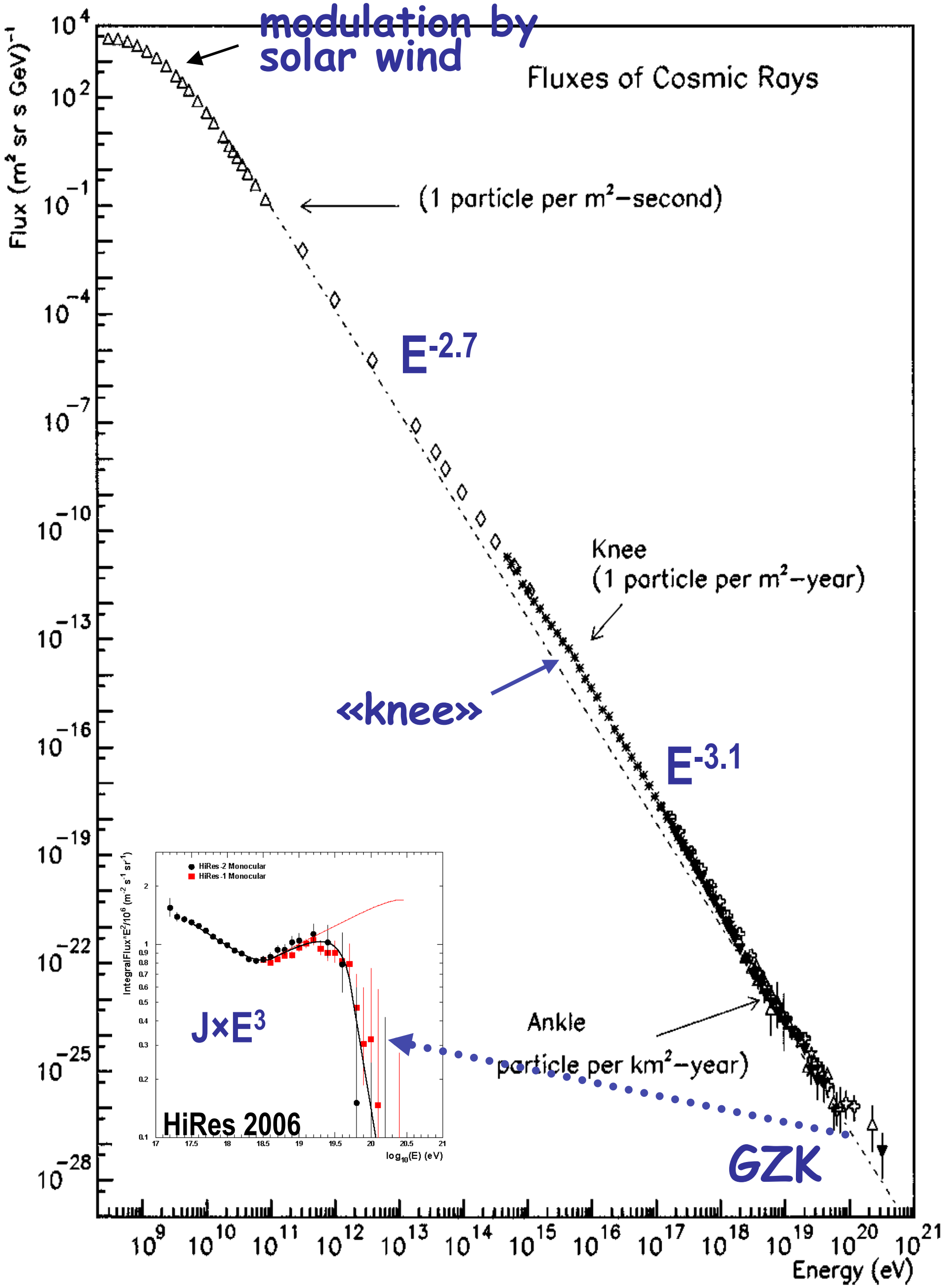


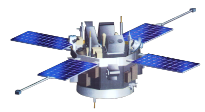
$N_{cr} \sim 10^{-10}$ cm^{-3} - total number density

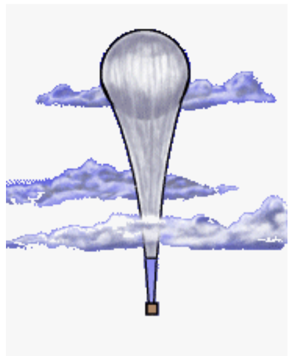
$w_{cr} \sim 1.5$ eV/cm^3 - energy density

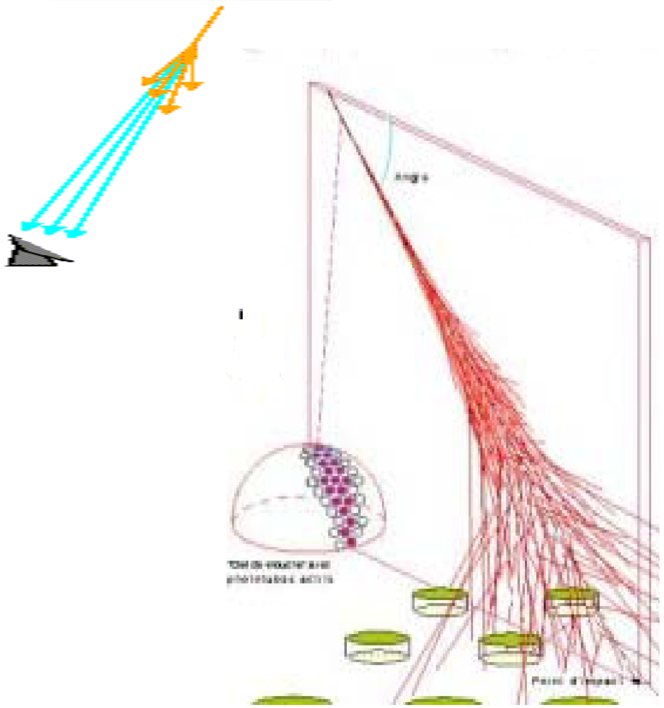
$E_{max} \sim 3 \times 10^{20}$ eV - max. detected energy

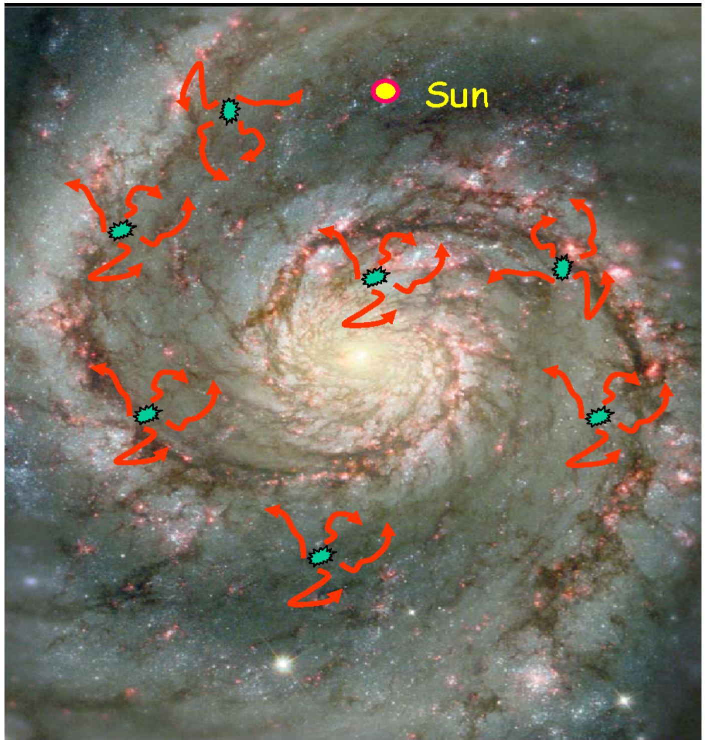
$r_g \sim 1 \times E/(Z \times 3 \times 10^{15}$ eV) pc - Larmor radius


Fluxes of Cosmic Rays
modulation by solar wind
(1 particle per m²–second)
$E^{-2.7}$
Knee
(1 particle per m²–year)
«knee»
$E^{-3.1}$
Ankle
particle per km²–year)
GZK
HiRes-2 Monocular
HiRes-1 Monocular
J×E³
HiRes 2006
Flux (m² sr s GeV)⁻¹
Energy (eV)









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

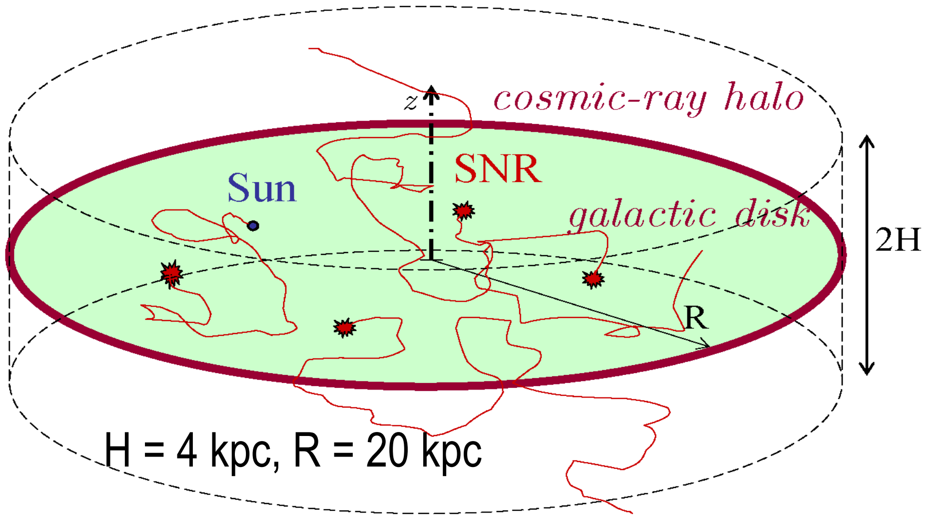
$\nu_{sn} \approx (30\ \mathrm{yr})^{-1}$

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

source

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

basic diffusion model



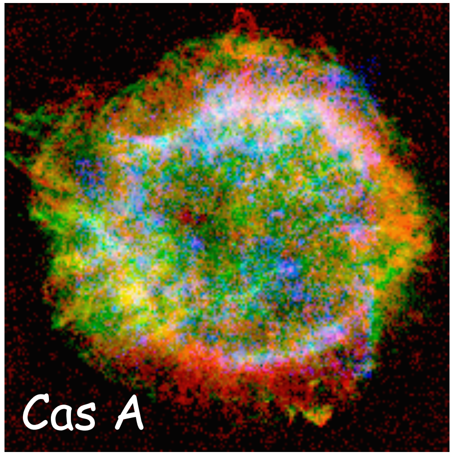
$$T_e \approx \frac{H^2}{2D}$$

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

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

$\Rightarrow \gamma_s = 2.1...2.4$

nonthermal radiation from shell SNRs



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

radio emission

$\nu_{MHz} = 4.6\ B_{\mu G} E_{e,GeV}^2$

$E = 50\ MeV - 30\ GeV$

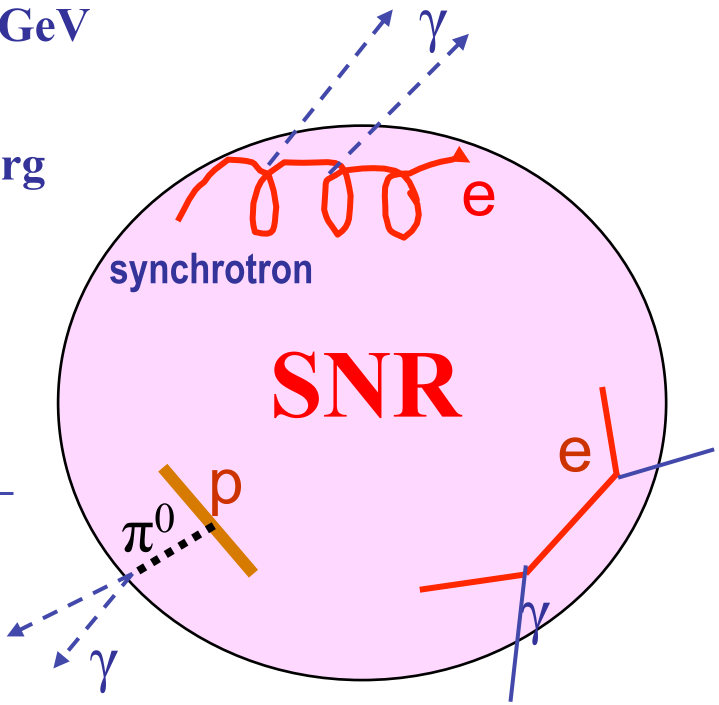
$\gamma = 1.9 - 2.5$

$W_e = 10^{48} - 10^{49}$ erg

γ-rays at E>30 MeV

$E > 30$ MeV

γ Cygni, IC443



inverse Compton

$\varepsilon_\gamma = \varepsilon_0 (E_e/m_e c^2)^2$

X-rays

$\varepsilon_{keV} = 0.069\ B_{mG} E_{e,TeV}^2$

$E_{max} \sim 10$ TeV

SN1006, Cas A, RX J1713-39
RX J0852-46 (“Vela jr”), CTB37B,
Tycho, Kepler, RCW 86 …

TeV γ - rays

protons/electrons;

$E_{max} > 100$ TeV

RX J1713, RX J0852-46 (“Vela jr”),
Cas A, RCW 86, CTB37B, SN 1006,
IC 443, W28, W41, G338.3-0.0,
G23.3-0.3, G8.7-0.1…

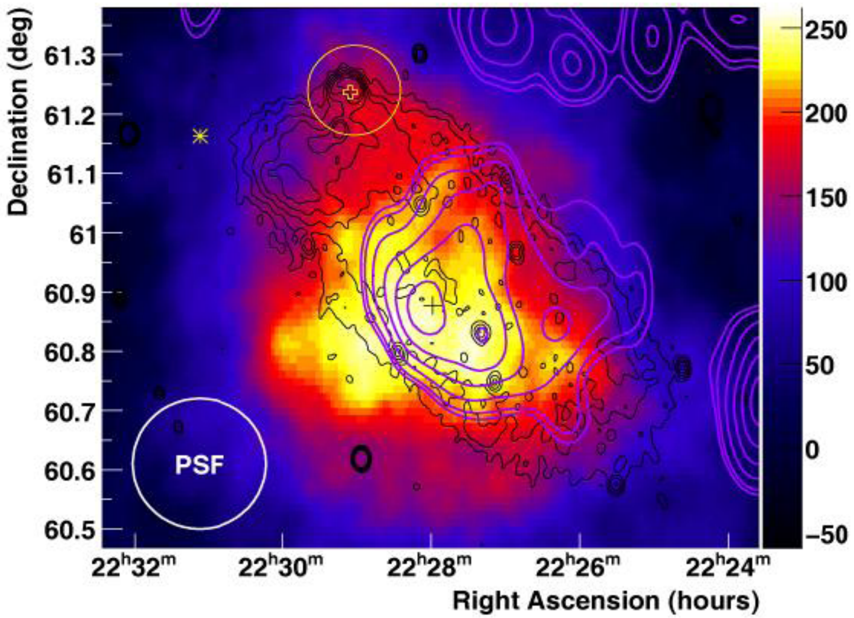
typically:

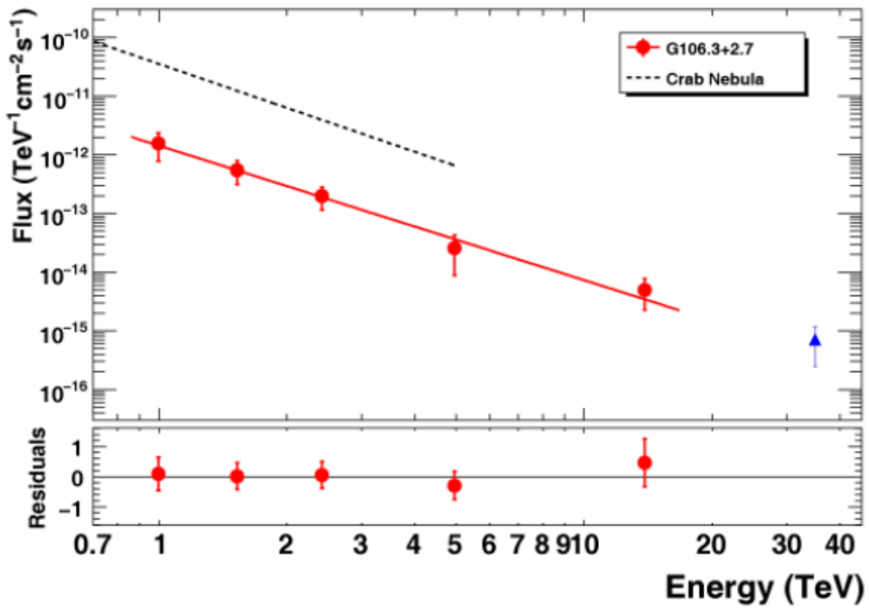
$W_{cr} = 2\times10^{50}$ erg = 0.2 W_{sn}

$N_{cr} \sim E^{-\gamma_s}$, $\gamma_s \sim 2.0$

(with bright phase in TeV γ-rays till ~ 10^4 yr)

SNR G106.3+2.7 / PSR J2229+6114
d = 800 pc, t = 10^4 yr

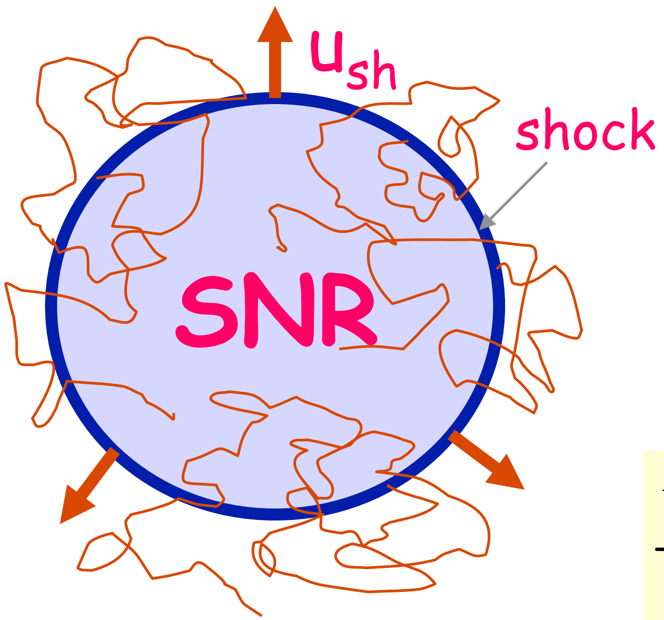




Excess map for the region around SNR G106.3+2.7 / PSR J2229+6114. The black contours indicate the radio shell of the SNR, and the purple contours indicate the density of CO emission. The yellow circle is the Fermi error box, and the open yellow cross indicates the position of the pulsar.
The yellow star is the AGILE source 1AGL J2231+6109.

Right: Photon spectrum for SNR G106.3+2.7 (VERITAS, MILAGRO).

Humensky et al. 2009



diffusive shock acceleration

Fermi 1949, Крымский 1977, Bell 1978, …

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

σ =4 compression ratio

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

-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 in ISM magnetic field $\delta B \sim B_{ism}$

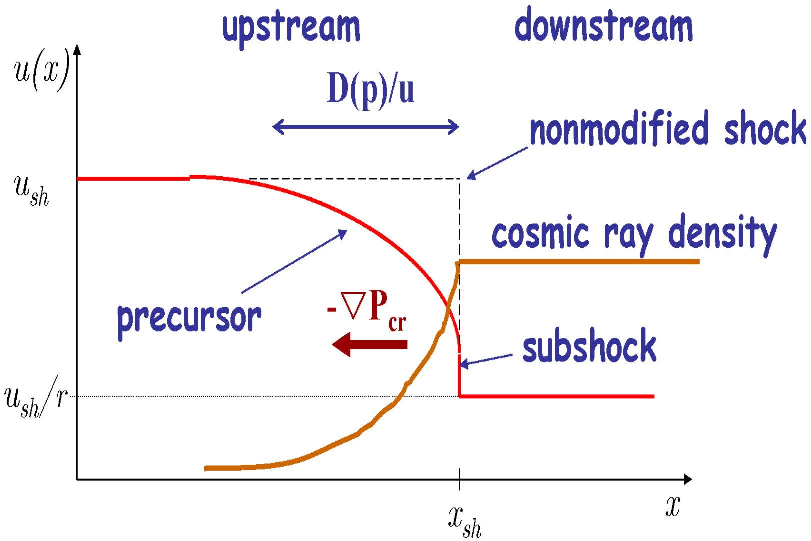
$D_B = vr_g/3$, $E_{max} \approx 10^{13}...10^{14}\, Z$ eV, $E_{max} \sim t^{-1/5}$

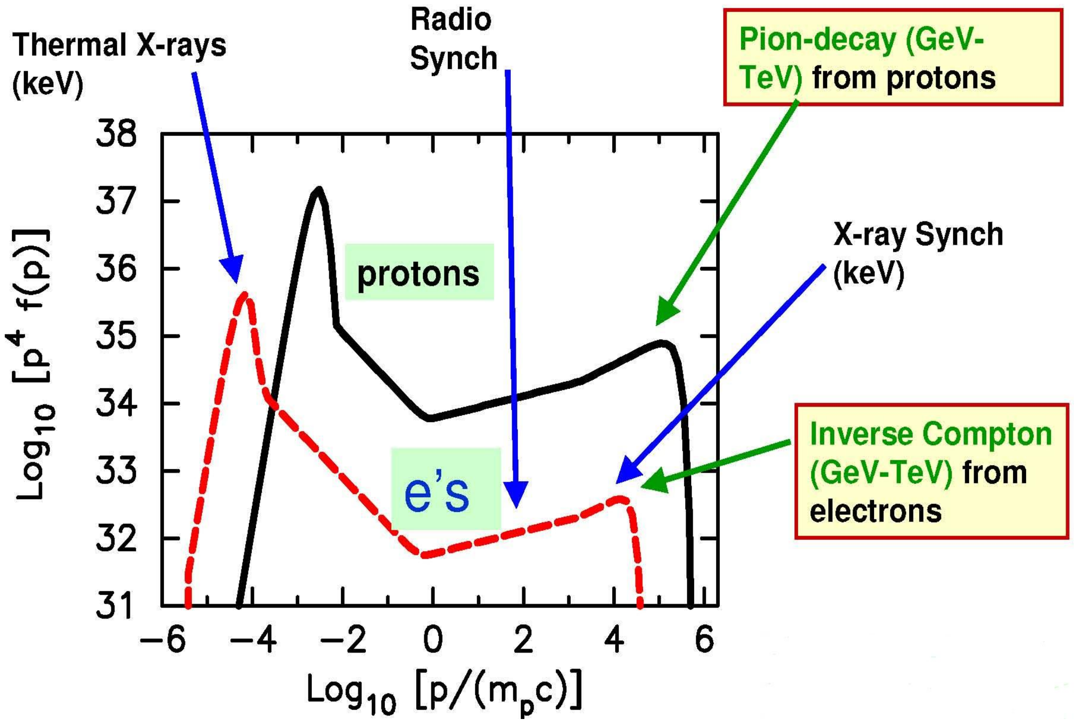
NB: $pc/Z < 0.3(u/c)BR$ – Hillas criterion

- back reaction of cosmic-ray pressure modifies the shock and produces concave particle spectrum

Axford 1977, 1981; Eichler 1984; Berezhko et al. 1996, Malkov et al. 2000; Blasi 2005

$P_{cr} = \xi \rho u_{sh}^2$, $\xi \sim 0.5$



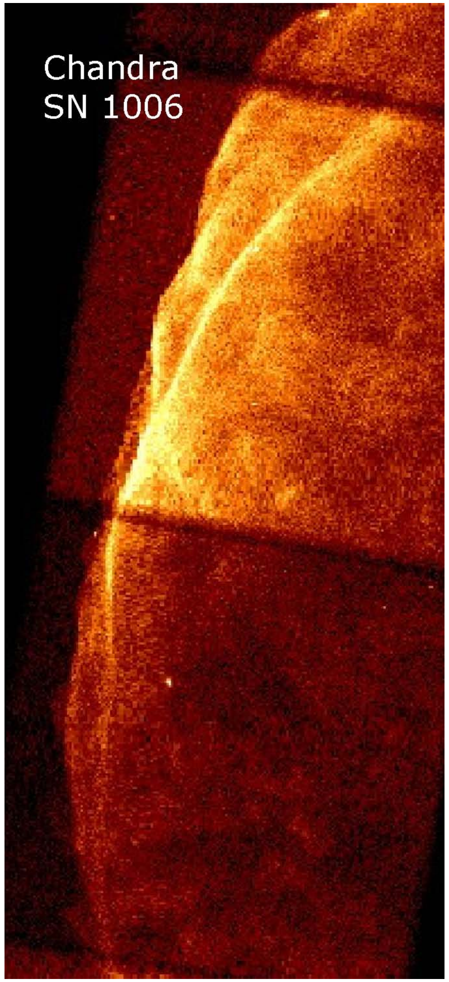


after Ellison

abandonment of interstellar Bohm limit hypotheses;

$D \neq D_{B,ism}$ anymore

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



- linear and non-linear wave dissipation in shock precursor leads to $\delta B(t)$
  VP & Zirakashvili 2003
- finate V_a downstream the shock leads to steeper CR spectrum VZ & VP 2008

under extreme conditions:

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

$E_{max} \sim 10^{17} Z\,(u_{sh}/3\times10^4 км/с)^2\, M_{ej}^{1/3} n^{1/6}$ эВ

$\delta B_{max} \sim 10^3\,(u_{sh}/3\times10^4\ км/с) n^{1/2}$ мкГ

confirmed by X-ray observations of young SNRs
Cas A, SN 1006, Tycho, RCW 86, Kepler, RX J1713.7-3946 (?), Vela Jr.

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

numerical simulation of cosmic-ray acceleration in SNR

Zirakashvili & VP 2008, 2009
VP et al 2009

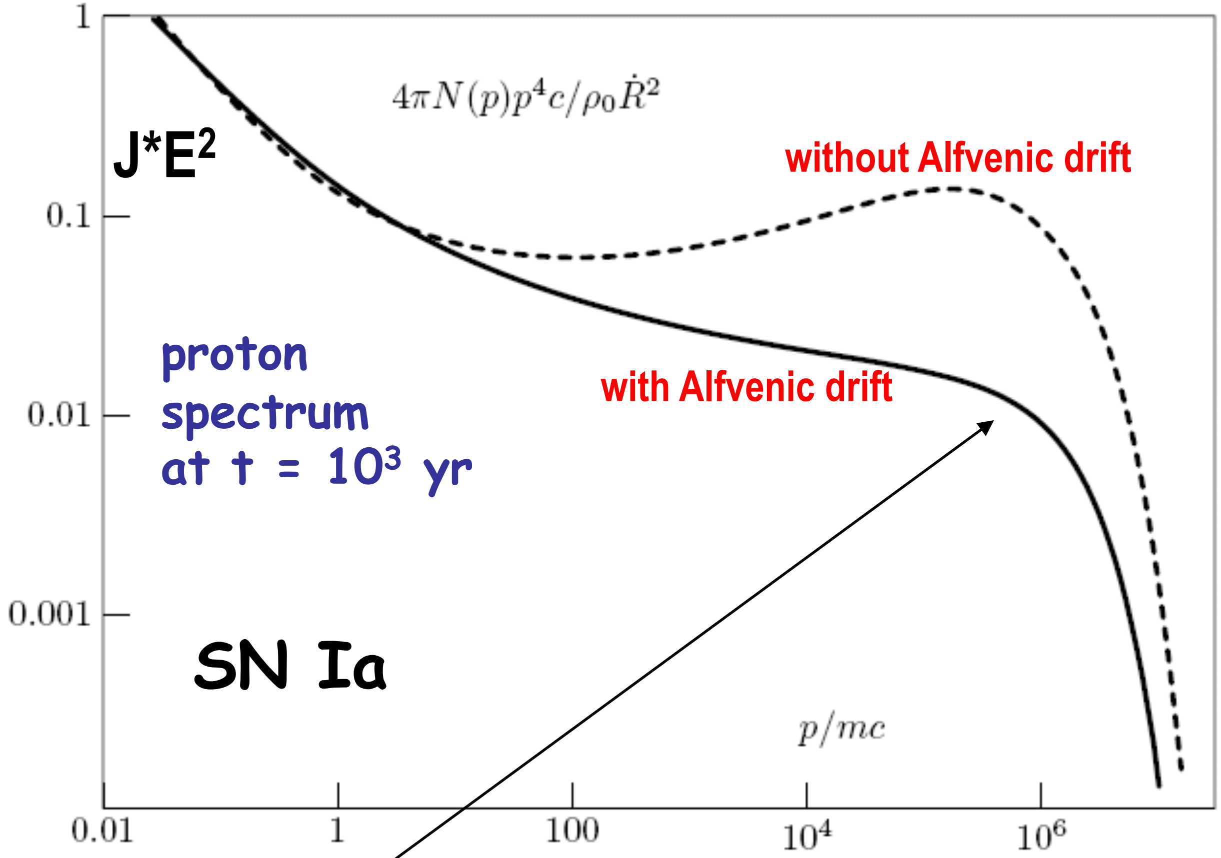
- spherically symmetric hydrodynamic eqs. including **CR pressure** + diffusion-convectior eq. for cosmic ray distribution function (compare to Berezhko et al. 1996, Berezhko & Voelk 2000; Kang & Jones 2006)

- 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)

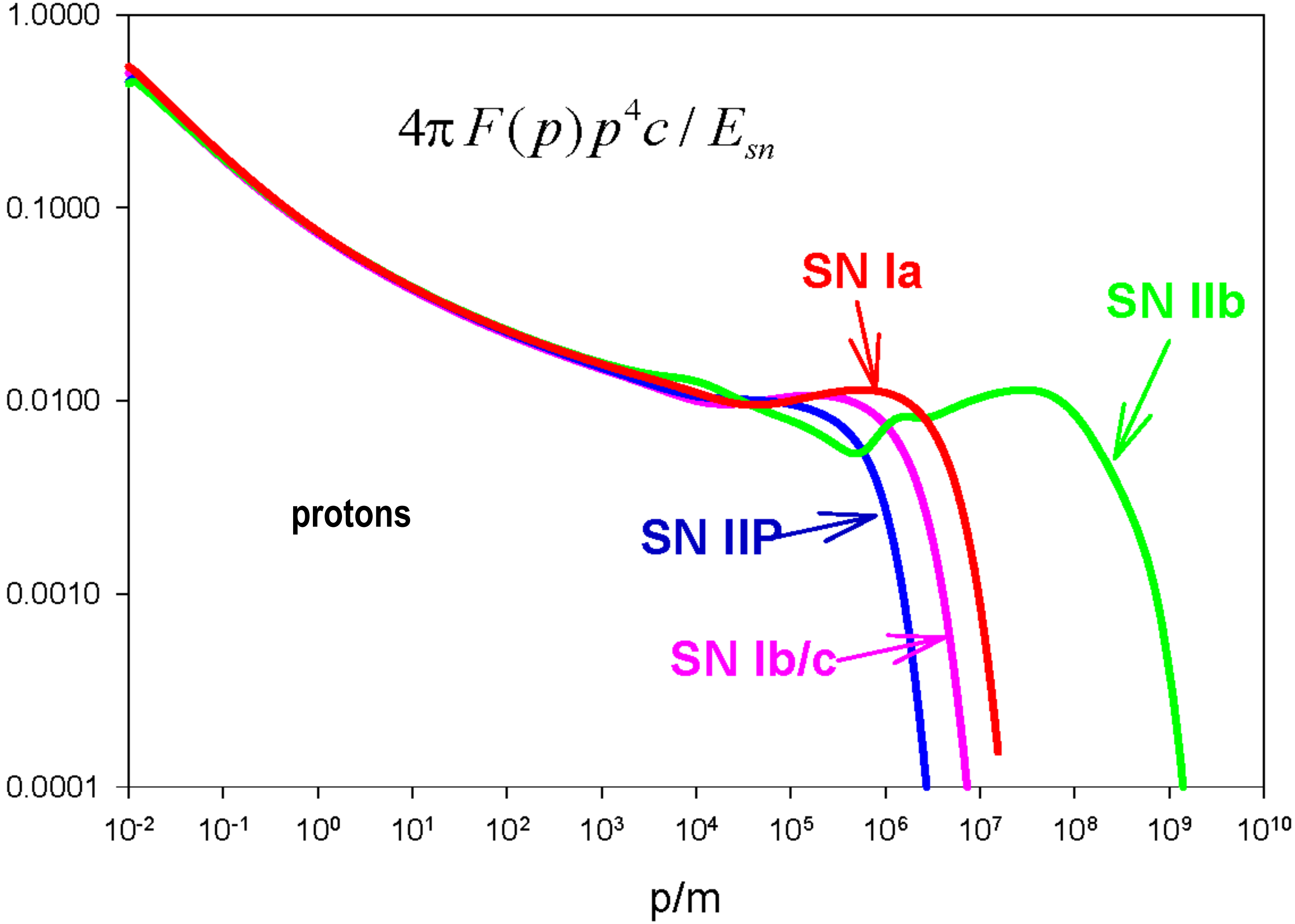
- account for **Alfvenic drift w = u + V_a** upstream and downstream

- injection efficiency $\eta = 0.1 u_{sh}/c$ Zirakashvili 2007

- 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



$p_{max,3}cZuRe \approx 2.410$ eV 13 $(\ _{shsh})^2$ $\sqrt{\ }$

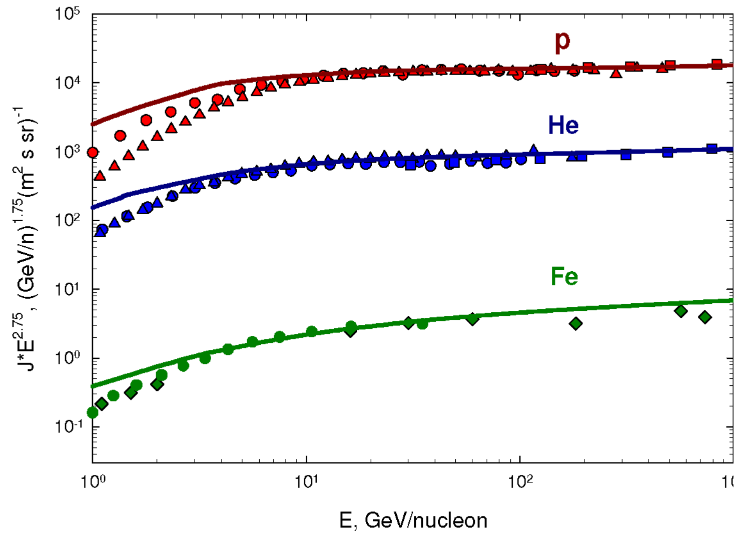


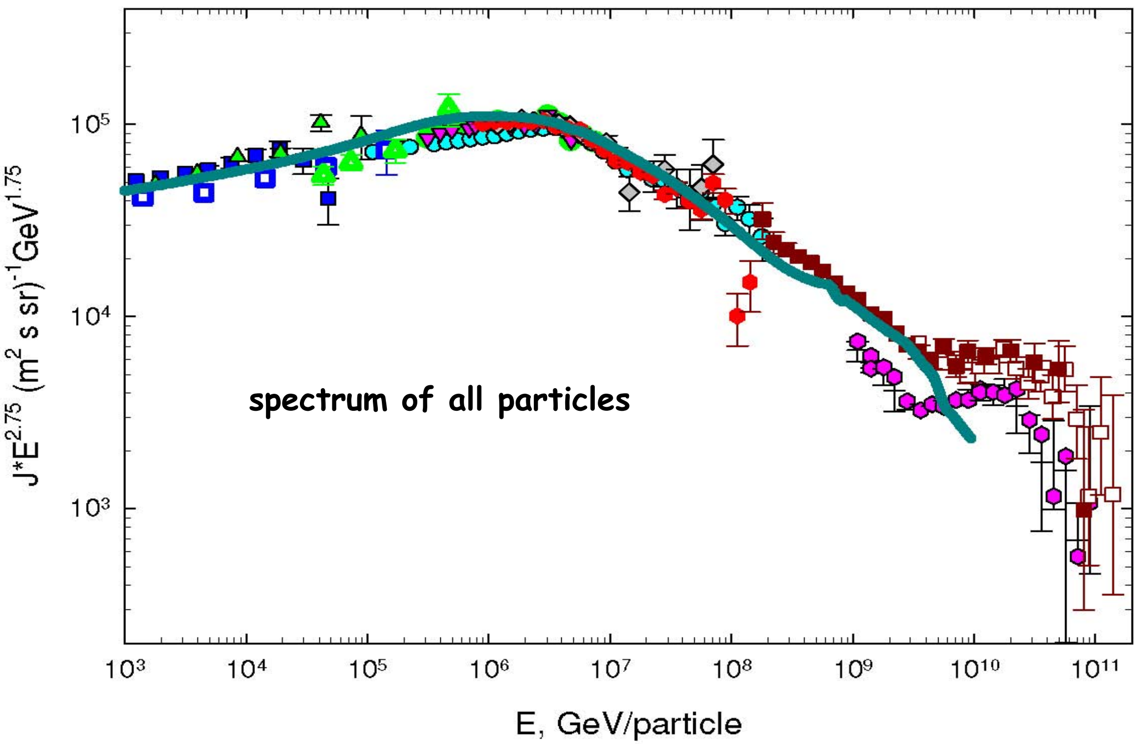
«knee» position: pcZnMpeZ4410 eV, 8.410 eV. kneesnejkneesnwej 151/62/3151 ,51,515,6 22

calculated interstellar spectrum

intensity and compasition are normalized to observations at 1000 GeV

Dβ|(þ/4.9Z GV)Dβ$^{0.54}$ at > 4.9 GV;at < 4.9 GV





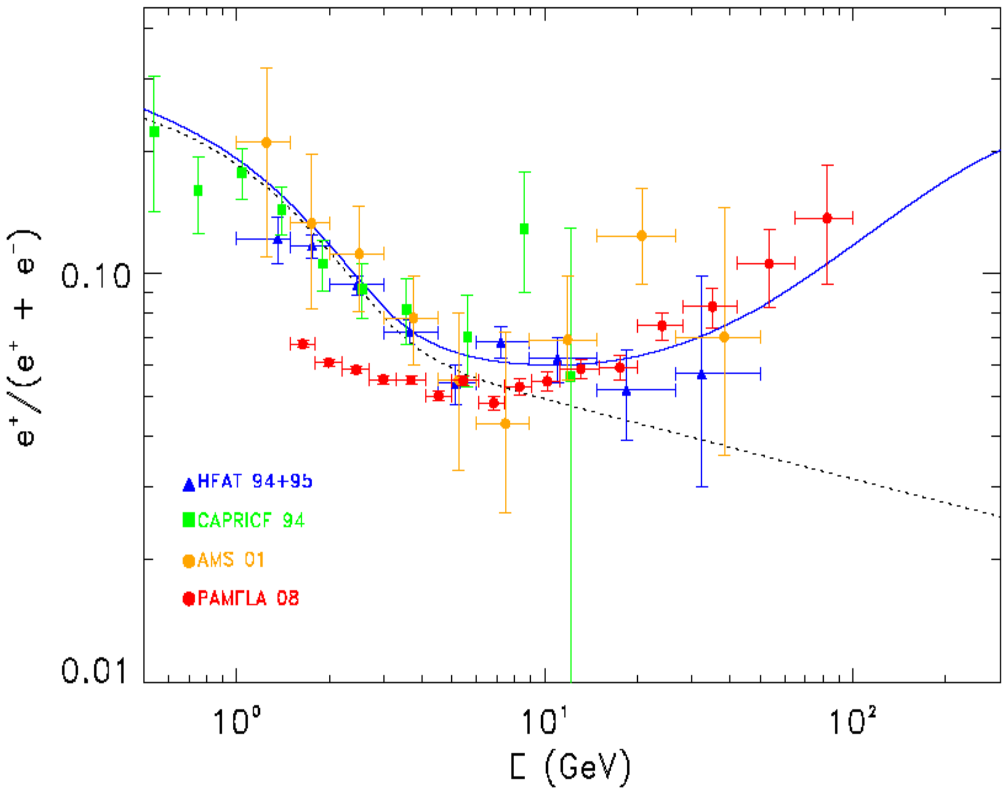
data from HEAO 3, AMS, BESS TeV, ATIC 2, TRACER experiments

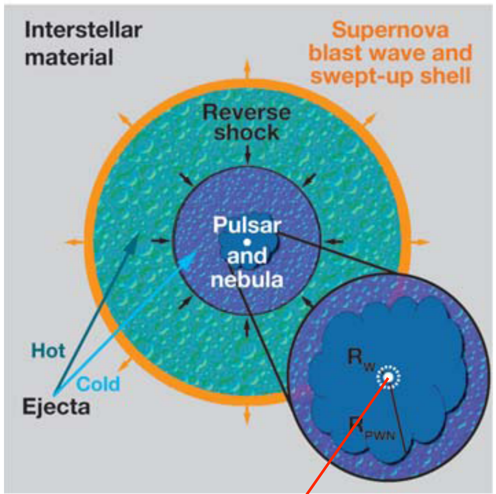
data from ATIC 1/2, Sokol, JACEE, Tibet, HEGRA, Tunka, KASCADE, HiRes and Auger experiments

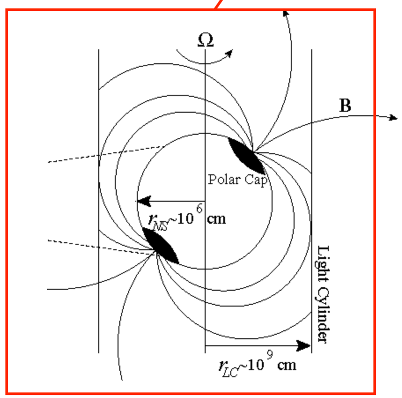
VP, Zirakashvili, Seo 2009

«primary» positrons in cosmic rays; pulsars, dark matter, ... ?

Aharonian et al 1995, Zhang & Cheng 2001, Hooper et al 2009 …

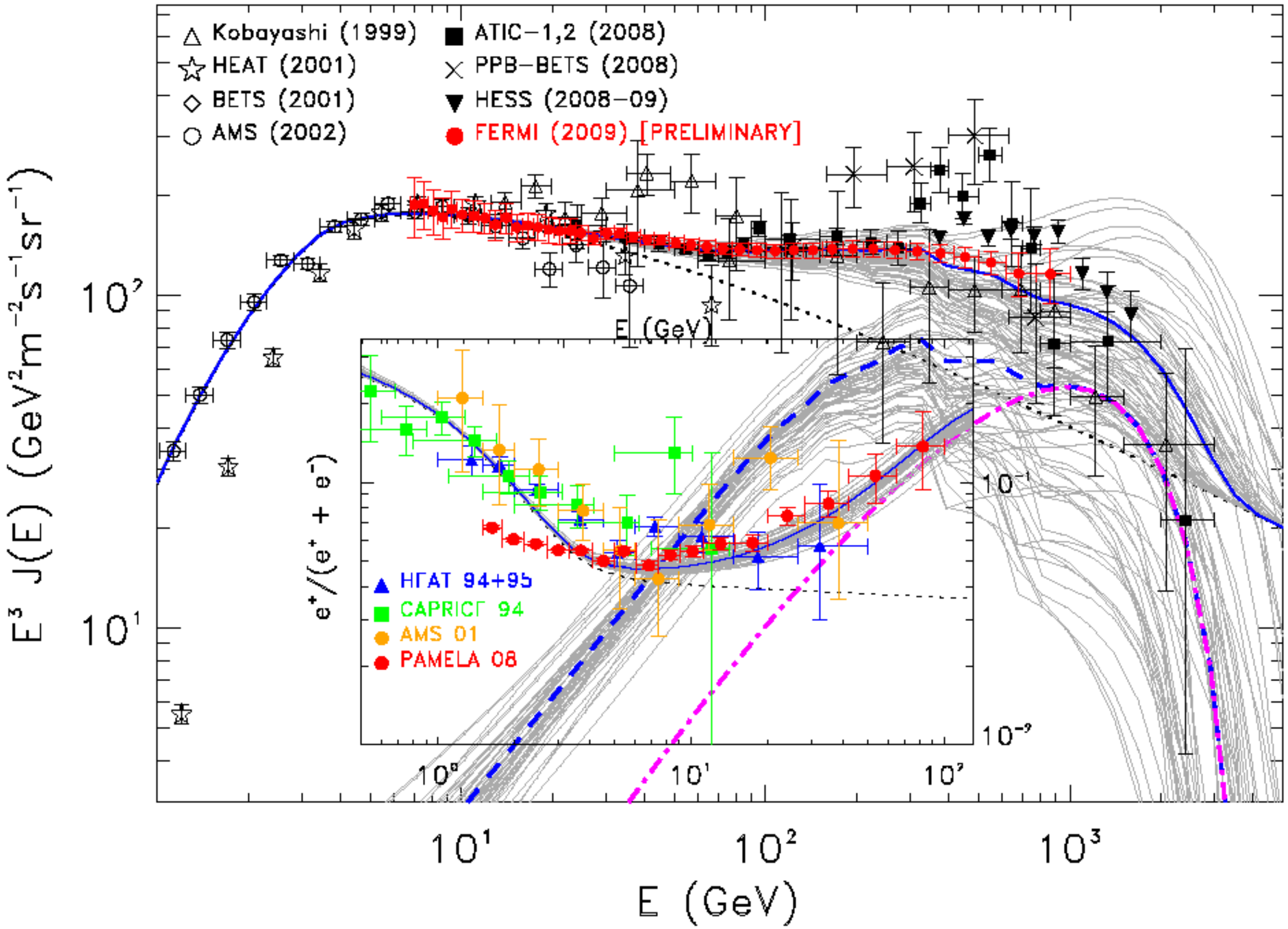




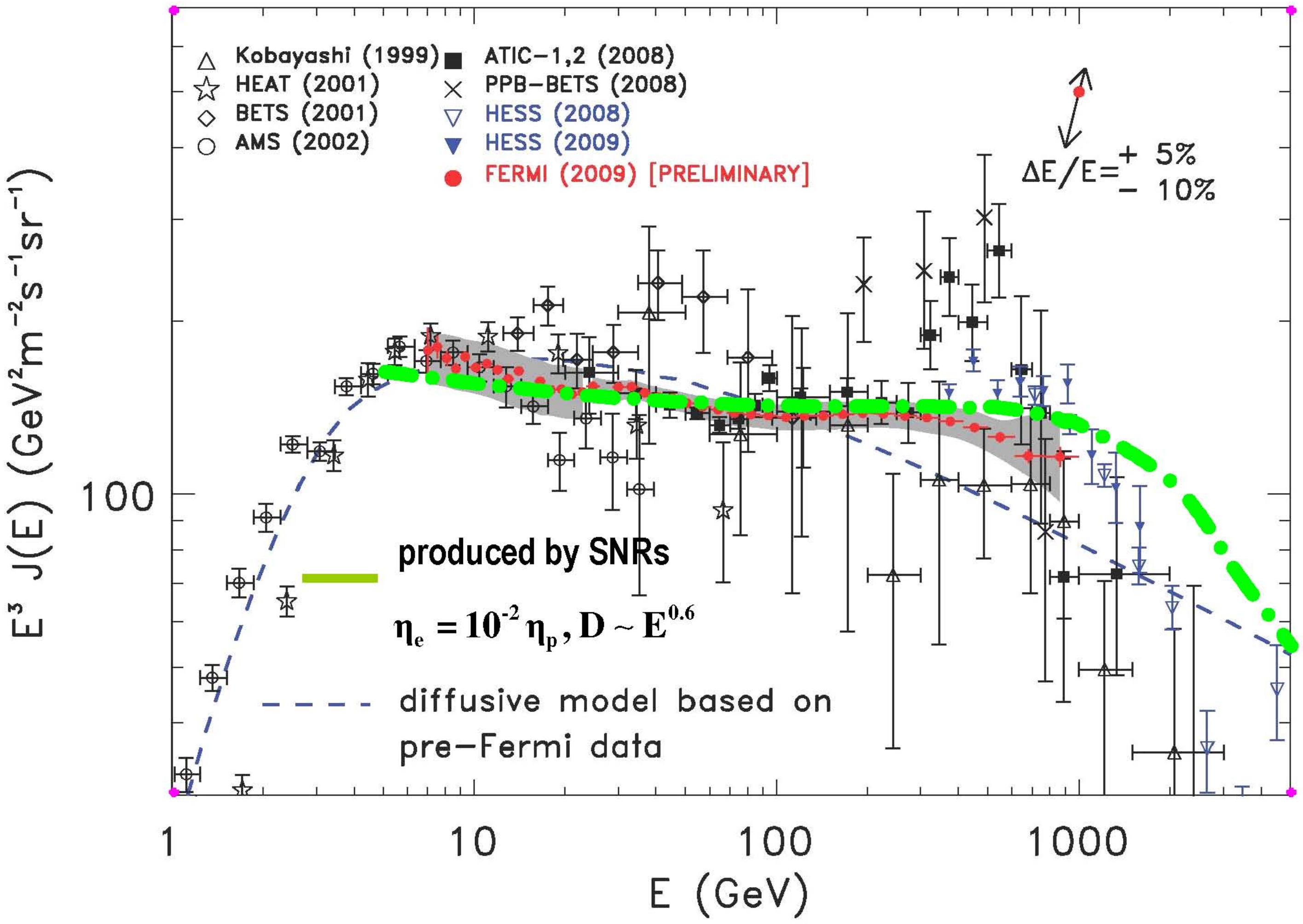


Gaensler & Slane 2006
Arons 2007

Bernardo et al. 2009

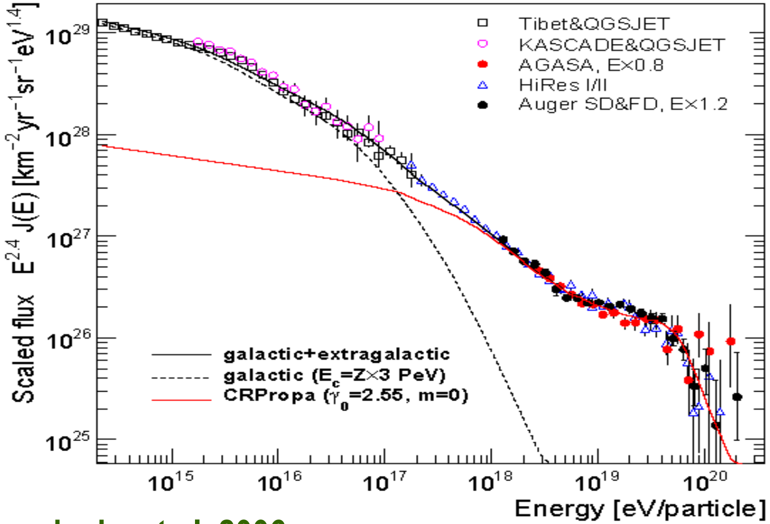


e- + e+



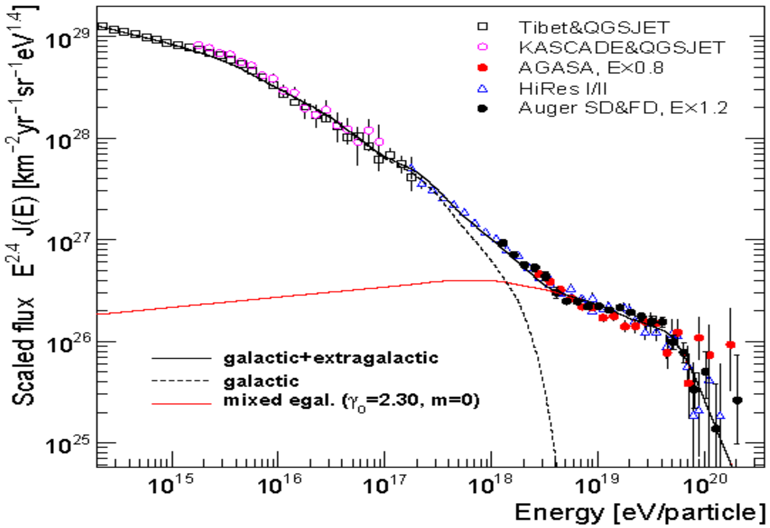
Kobayashi (1999)
HEAT (2001)
BETS (2001)
AMS (2002)
ATIC-1,2 (2008)
PPB-BETS (2008)
HESS (2008)
HESS (2009)
FERMI (2009) [PRELIMINARY]
ΔE/E= + 5% − 10%
produced by SNRs
$\eta_e = 10^{-2}\eta_p, D \sim E^{0.6}$
diffusive model based on pre-Fermi data
$E^3 J(E)$ ($GeV^2 m^{-2} s^{-1} sr^{-1}$)
100
1
10
100
1000
E (GeV)

transition to extragalactic component



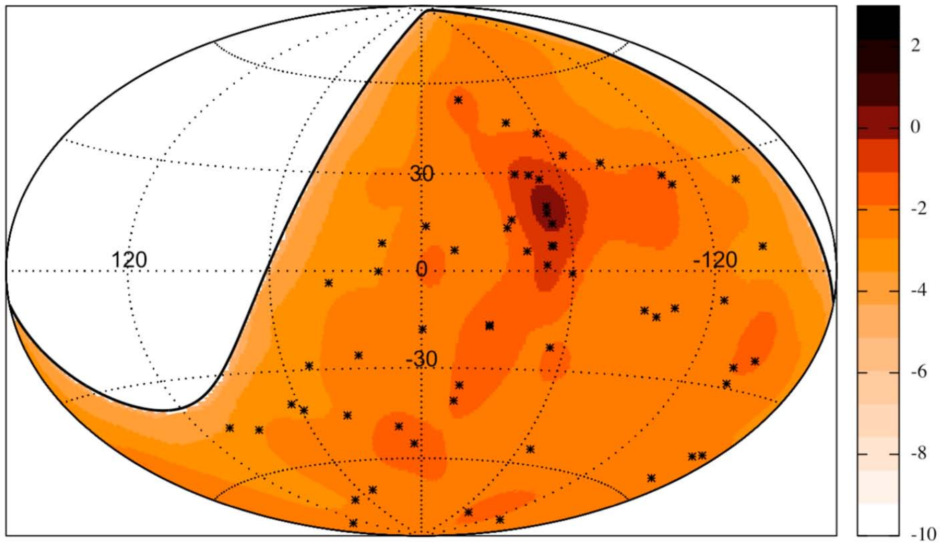
Berezinsky et al. 2006
Allard et al 2005

(a) Extragalactic protons



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

Anisotropy of ultra-high energy cosmic rays



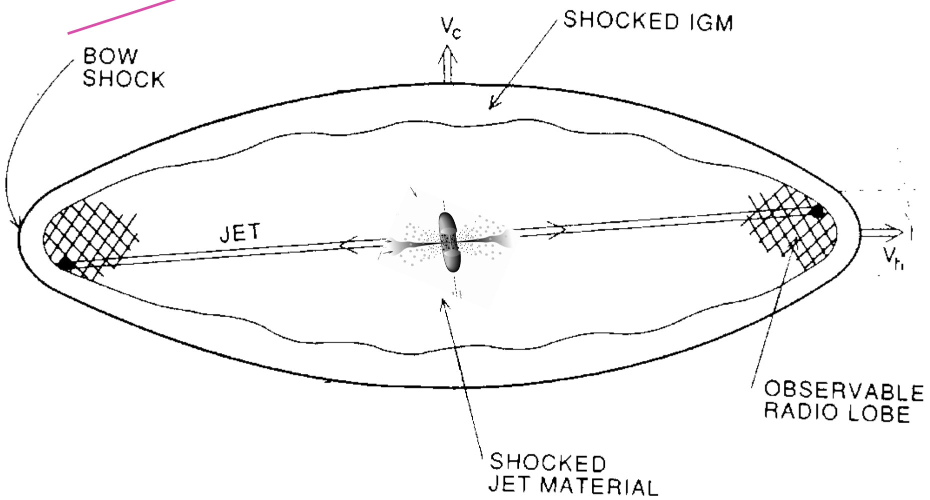
58 events now (with Swift-BAT AGN density map)

J.Aublin – Auger Coll., ICRC09

extragalactic sources

energy release in units 10^{40} erg/(s Mpc^3)

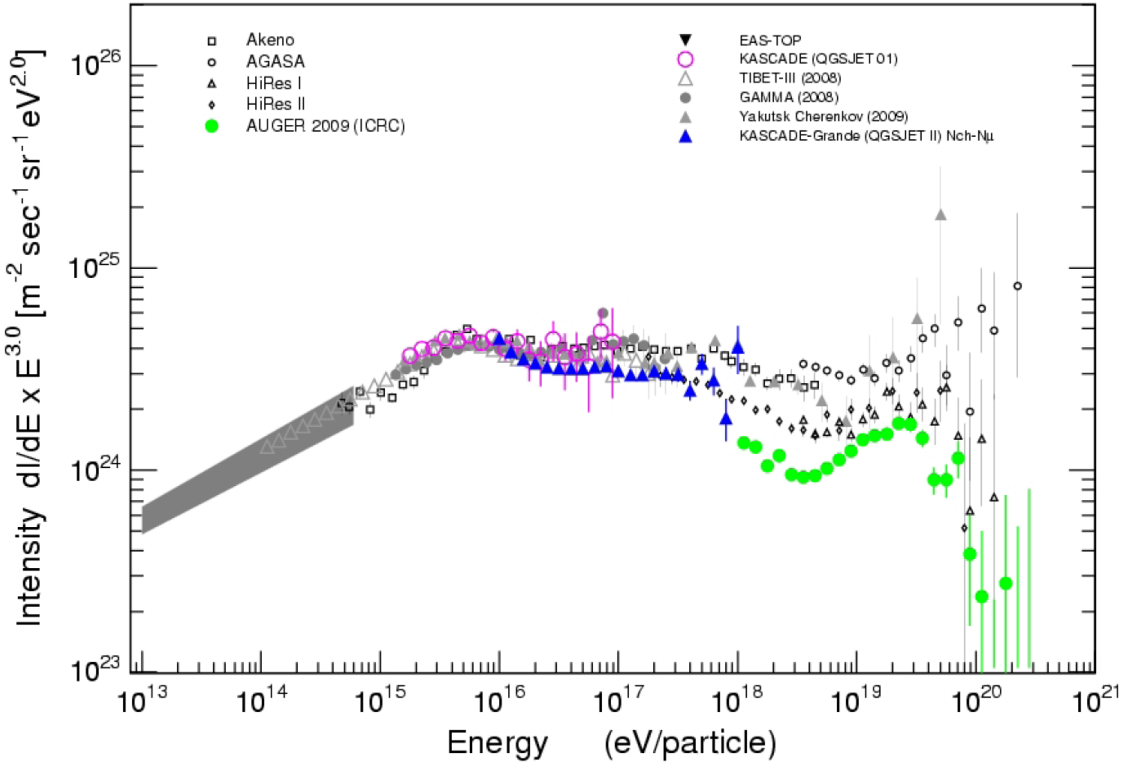
cosmic rays $E > 10^{19.5}$ эВ	supernovae	AGN jets	GRB progenitors	accretion on galaxy clusters
$3\ 10^{-4}$ (Auger)	0.3	3 0.01 for jets with $L_{kin} > 10^{44}$ erg/s	$3\ 10^{-4}$ X/gamma	10



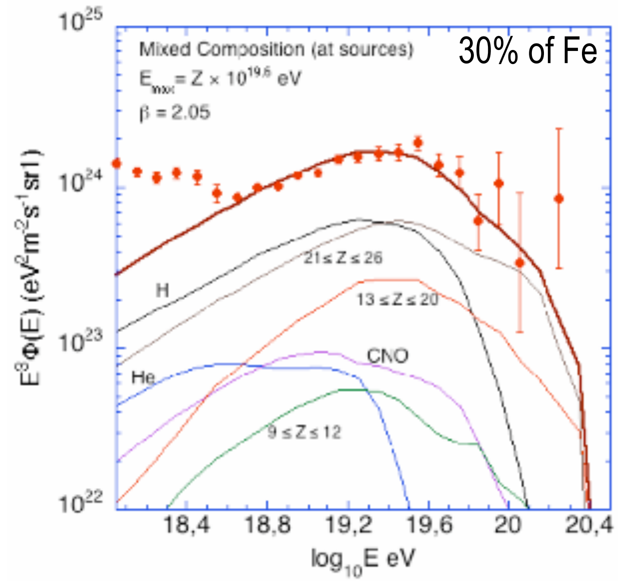
Schematic diagram of overpressured cocoons around jets (Begelman & Cioffi 1989).

$$E_{max} \approx 10^{20} Z\, L_{jet,45}^{1/2}$$

Lovelace 1976, Biermann & Strittmatter1987,
Blandford 1993, Norman et al 1995,
Farrar & Gruzinov 2009



Allard et al. 2008



Conclusions

The theoretical study of diffusive shock acceleration mechanism, the observations of TeV gamma ray and nonthermal X-ray radiation from a number of SNRs provided detailed physical picture of particle acceleration by supernova blast waves. Essential part of this picture is the significant magnetic field amplification in young SNRs due to the development of cosmic-ray streaming instability in the shock precursor.

The "excessive" positron flux in cosmic rays probably requires changes to the standard model of cosmic ray origin.

Cosmic rays in the energy range 10^{17} to 10^{19} eV, where the transition from Galactic to extragalactic component occurs, remains poorly studied both experimentally and theoretically.