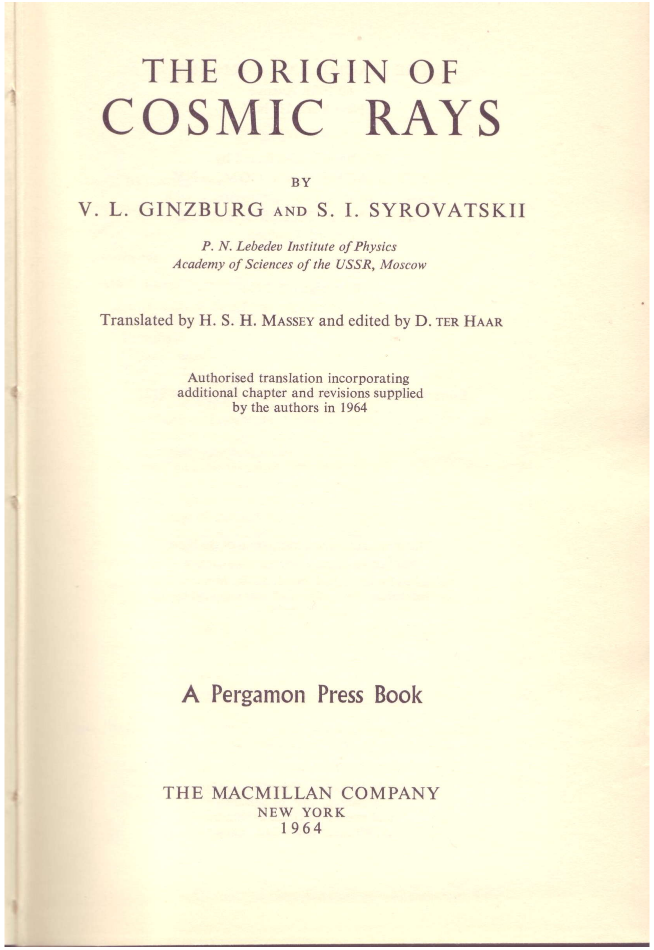

THE ORIGIN OF
COSMIC RAYS

BY
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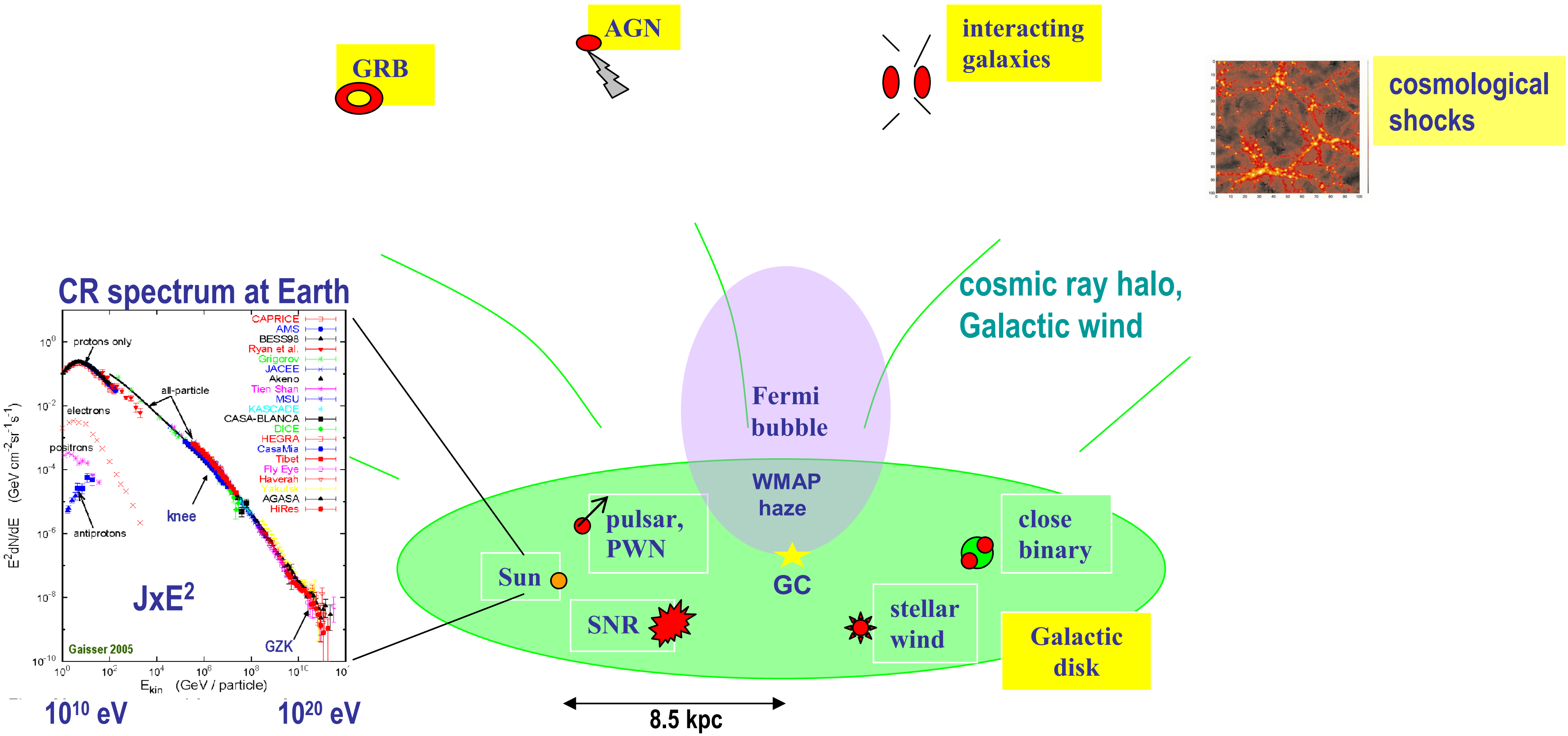
Galactic cosmic rays: acceleration in supernova remnants and transport in interstellar magnetic fields

V.S.Ptuskin & V.N.Zirakashvili

IZMIRAN, Russia

Ginzburg Conference on Physics, Moscow, May 28 – June 2, 2012



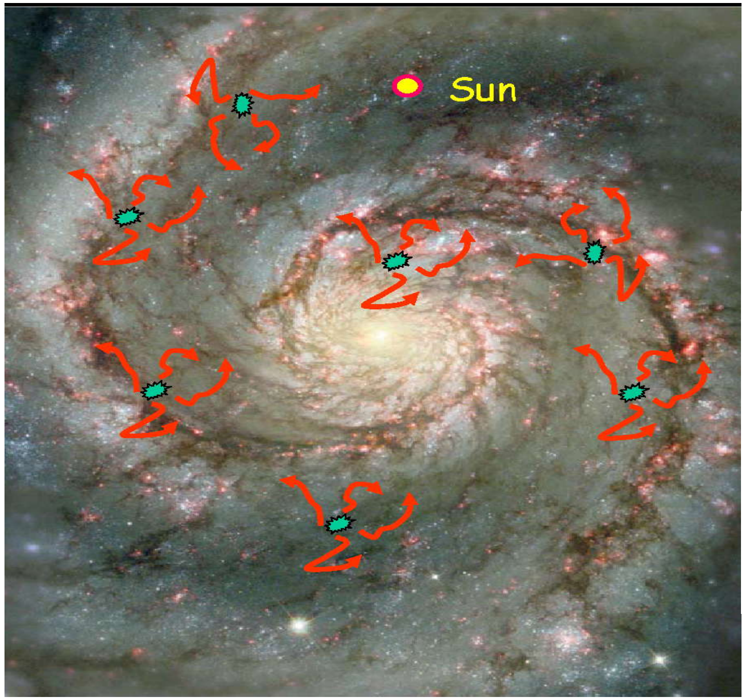
N_{cr} ~ 10^{-10} cm^{-3} - total number density in the Galaxy

w_{cr} ~ 1.5 eV/cm^3 - energy density

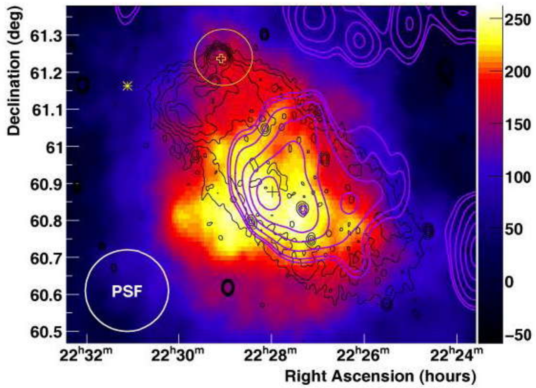
E_{max} ~ 3×10^{20} eV - max. detected energy

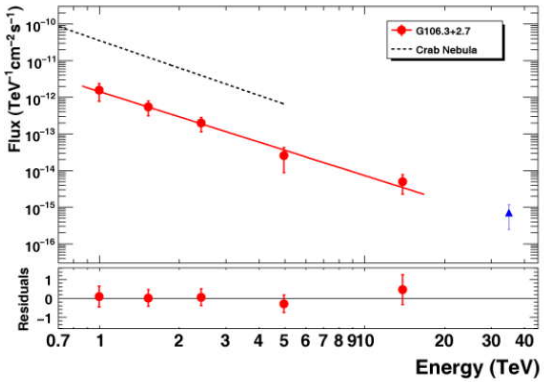
A_1 ~ 10^{-3} – dipole anisotropy at 1 – 100 TeV, slow diffusion

r_g ~ $1 \times E/(Z \times 3 \times 10^{15}$ eV) pc - Larmor radius at $B = 3 \times 10^{-6}$ G



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





VERITAS + MILAGRO

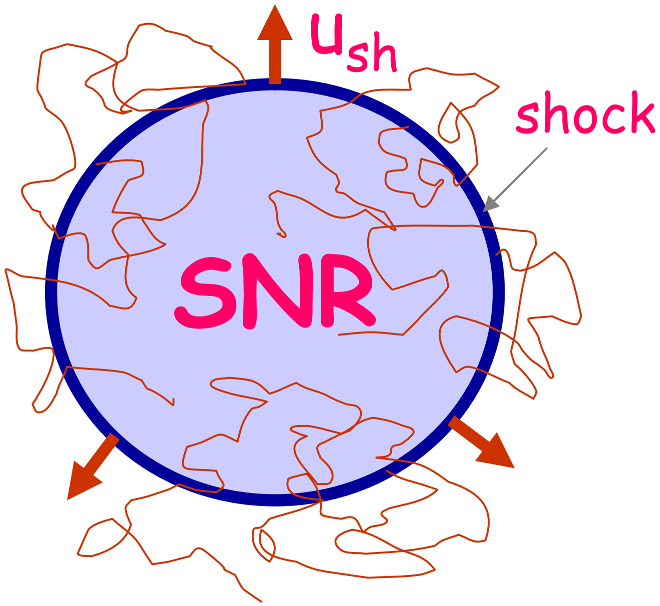
<u>energy balance</u>: ~15% of SN kinetic energy go to cosmic rays to maintain observed cosmic ray density Ginzburg & Syrovatskii 1964

<u>steady state:</u>
(without energy losses)

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

source term, SNR

escape time from the Galaxy, 10^8 yr at 1 GeV, regulated by resonant scattering in random magnetic field $1/k_{res} = r_g$



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

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

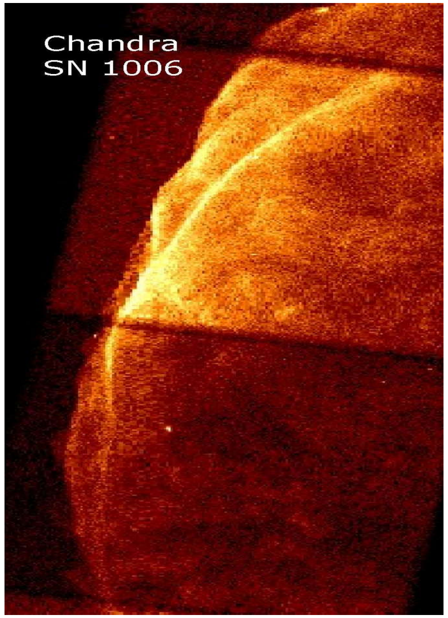
Bell 1978; Lagage & Cesarsky 1983; McKenzie & Vőlk 1982 …

"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

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

abandonment of interstellar Bohm limit hypotheses; $D \not\simeq D_{B,ism}$ anymore



- 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; VZ & 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

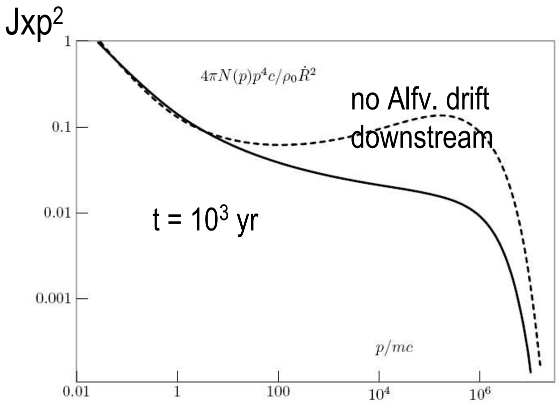
confirmed by X-ray observations of young SNRs

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

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

VP & VZ 2003



- finate V_a downstream the shock leads to steeper CR spectrum   VZ & VP 2008

numerical simulation of cosmic-ray acceleration in SNR

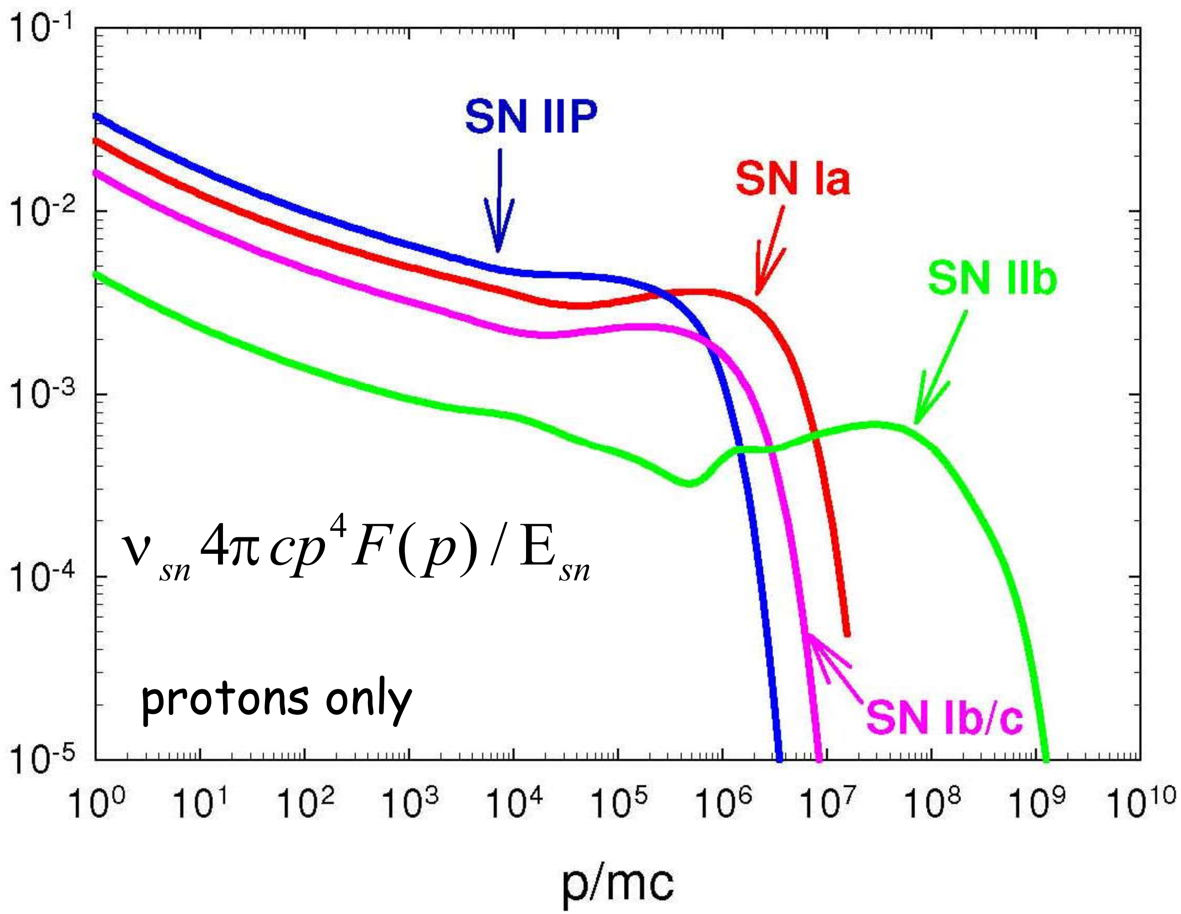
VP, VZ & Seo 2010

- 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

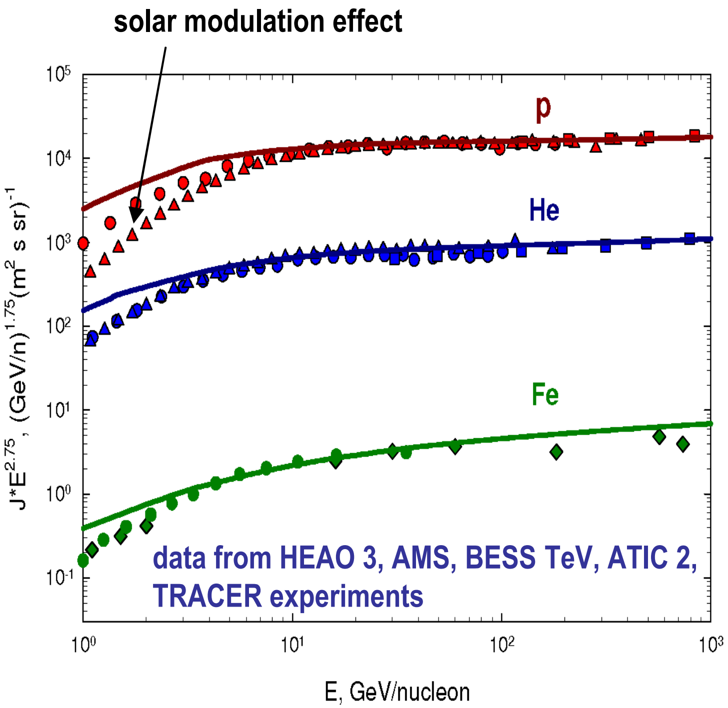


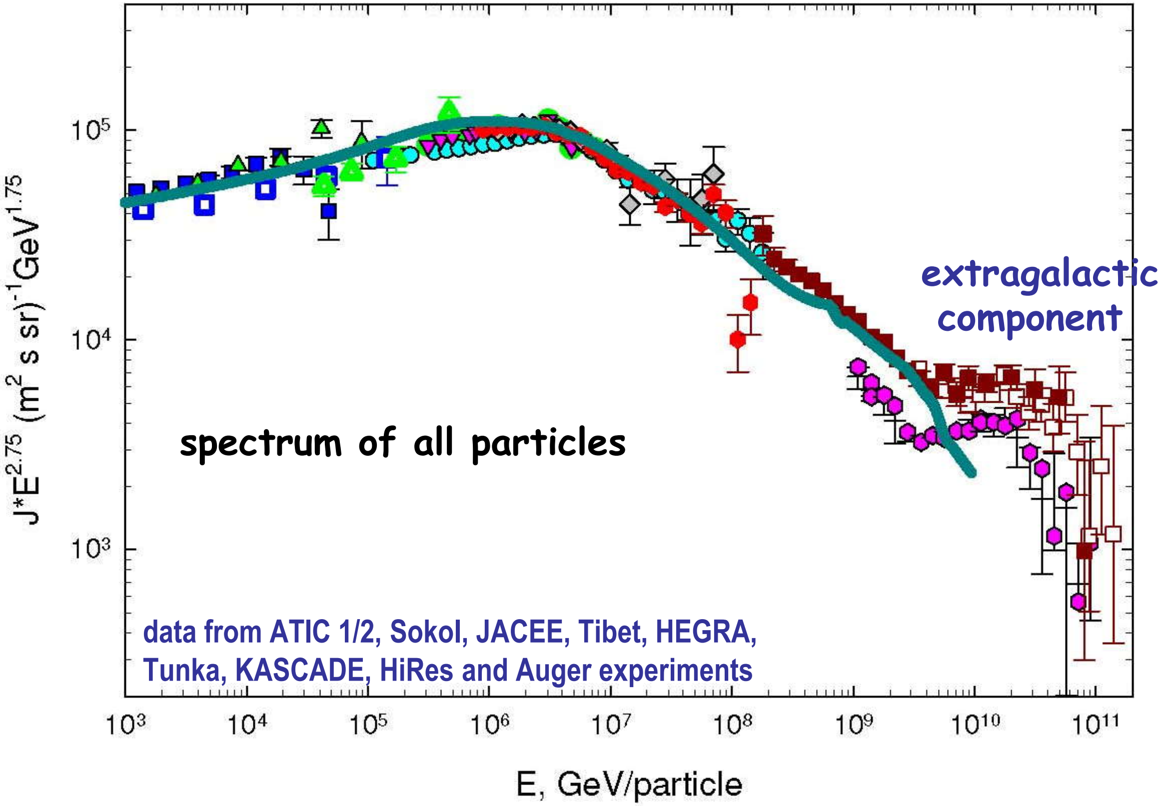
«knee» is formed at the beginning of Sedov stage

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

1/3 of SN kinetic energy goes to cosmic rays

calculated interstellar spectra $J x E^{2.75}$ produced by SNR Type Ia, IIP, Ib/c, IIb, normalized at 10^3 GeV



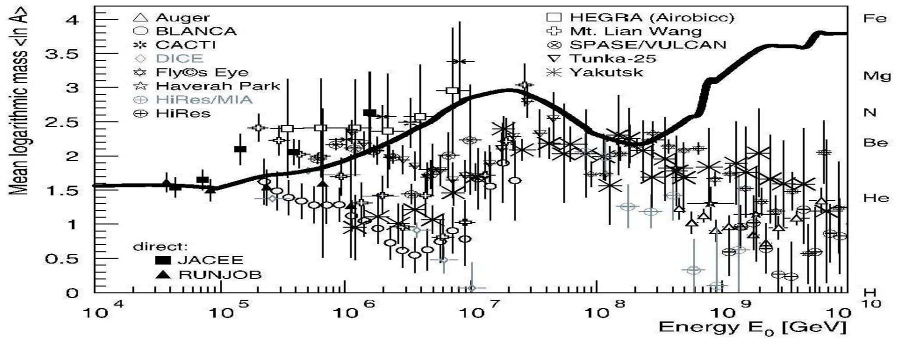


diffusion in the Galaxy:

$$D \propto \left({}^{pc}\!/_{Ze} \right)^{0.54}$$

Jones et al 2001

plain diffusion model works up to < $3x10^{16}Z$ eV !?



<lnA> based on <X_{max}>; data from Hoerandel 2007

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

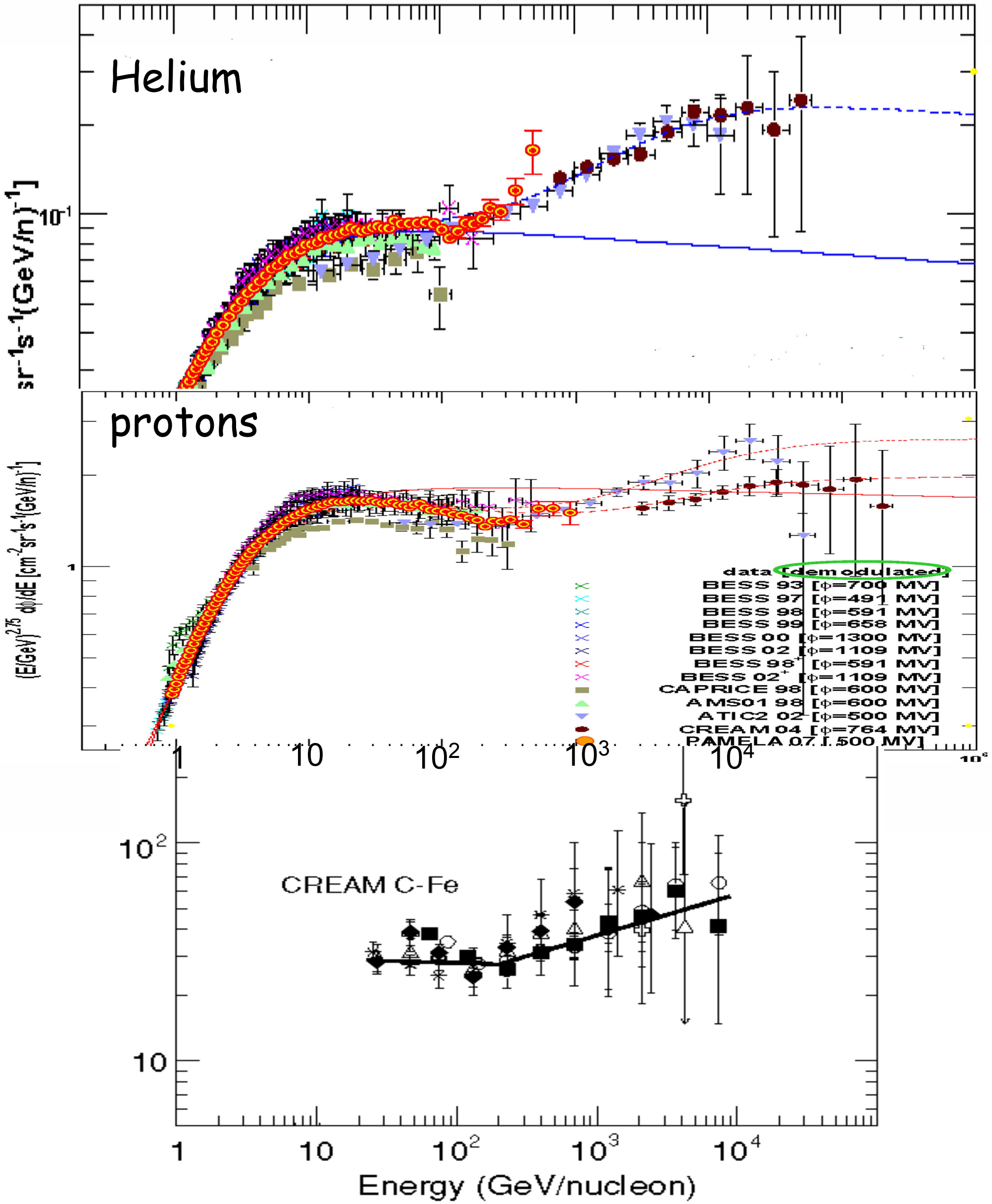
new source
Zatsepin & Sokolskaya 2006

reacceleration in local bubble
Erlykin & Wolfendale 2011

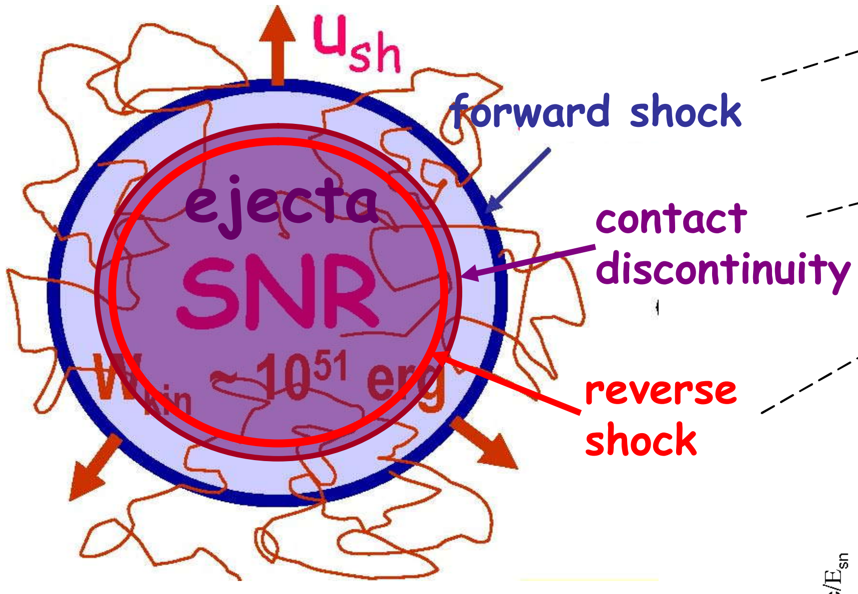
spectra of p and He are different

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



more sophisticated code for CR acceleration in SNR, two shocks are included VZ & VP 2011



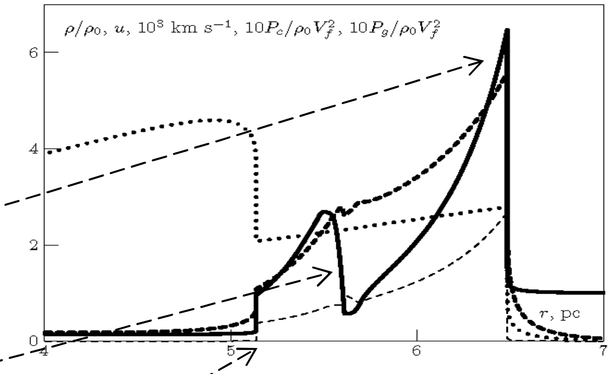
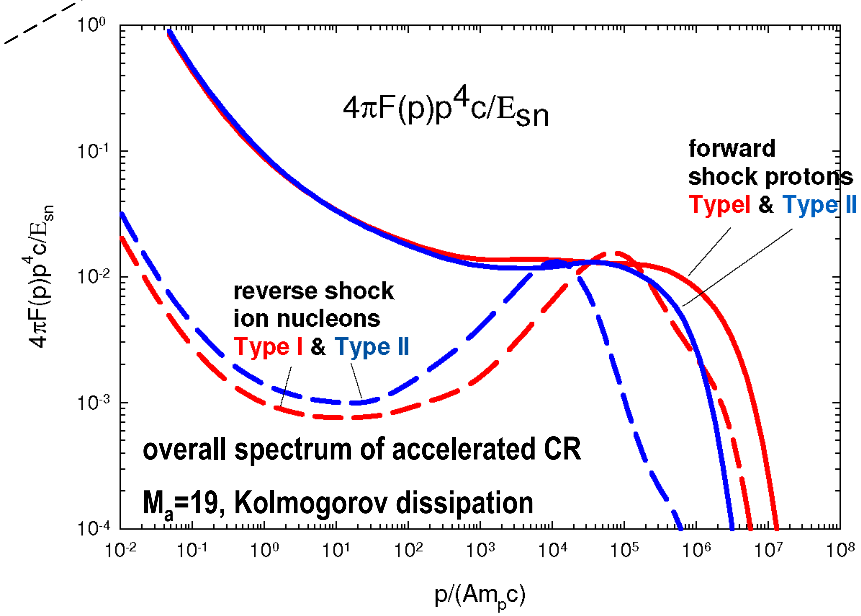
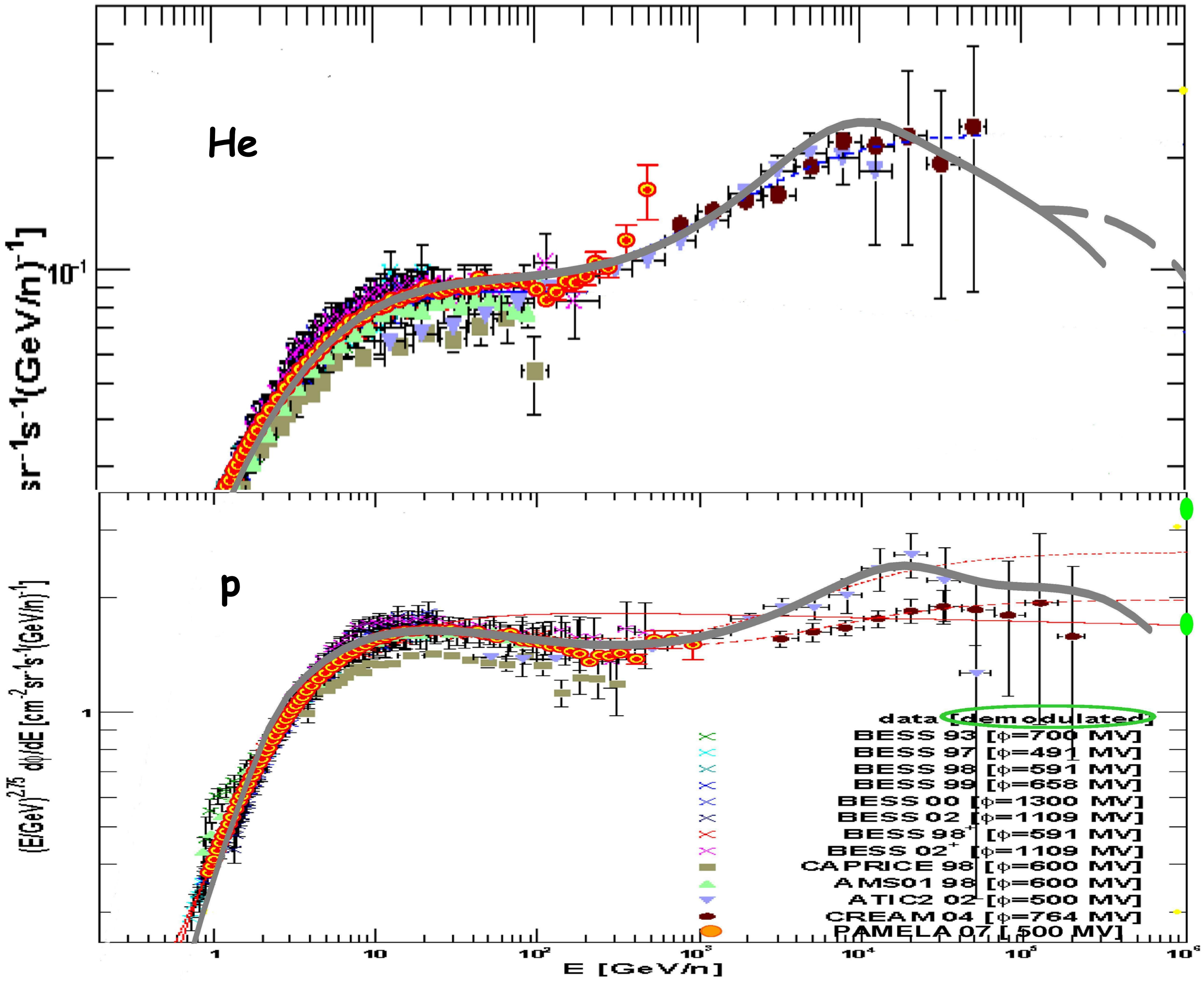


Figure 2: Radial dependencies of the gas density (thick solid line), the gas velocity (dotted line), CR pressure (thick dashed line) and the gas pressure (dashed line) at $t = 10^3$ yr. At this moment of time the forward shock velocity is 3300 km s^{-1}, its radius is 6.5 pc, the reverse shock velocity is 1600 km s^{-1}, its radius is 5.1 pc, the magnetic field strength downstream of the forward shock is 160 μG while the magnetic field downstream the reverse shock is 56 μG.



interstellar spectra $J \times E^{2.75}$ (plain diffusion in ISM, $D \sim R^{0.6}$)

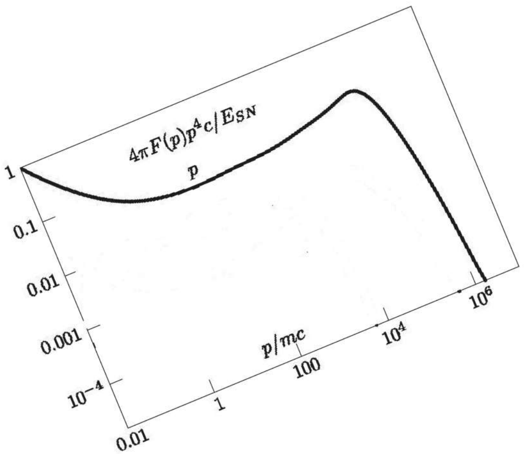


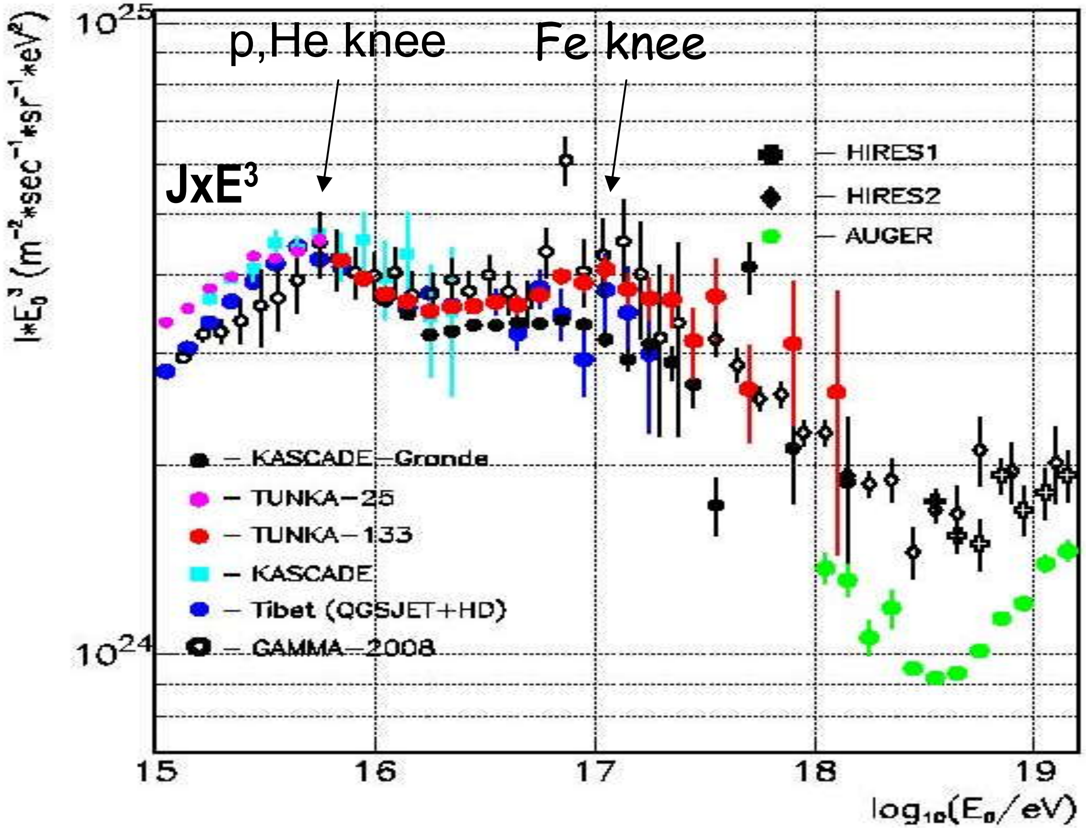
more features to explain:

Berezhnev et al. 2012

structure above the knee

different types of nuclei, $E_{knee} \sim Z$
different types of SN
transition to extragalactic component





or single source model of the knee
Erlykin & Wolfendale 1997 Erlykin et al. 2011

Conclusion

Cosmic ray origin scenario where SNRs serve as principle accelerators of cosmic rays in the Galaxy is strongly confirmed. SNRs are able to provide the needed cosmic ray source spectrum up to ~ 5×10^{18} eV.

The nonlinear shock modification that produces the concave source spectrum of accelerated particles can contribute/explain the hardening of cosmic ray spectra at ~ 200 GV. The difference in the observed spectra of protons and helium can be explained by CR acceleration at the reverse shock moving through the depleted in hydrogen material of supernova ejecta.

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

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), $r_{sn} = 0.22$