Contribution of Supernova Remnants to CRs Secondary to Primary ratios

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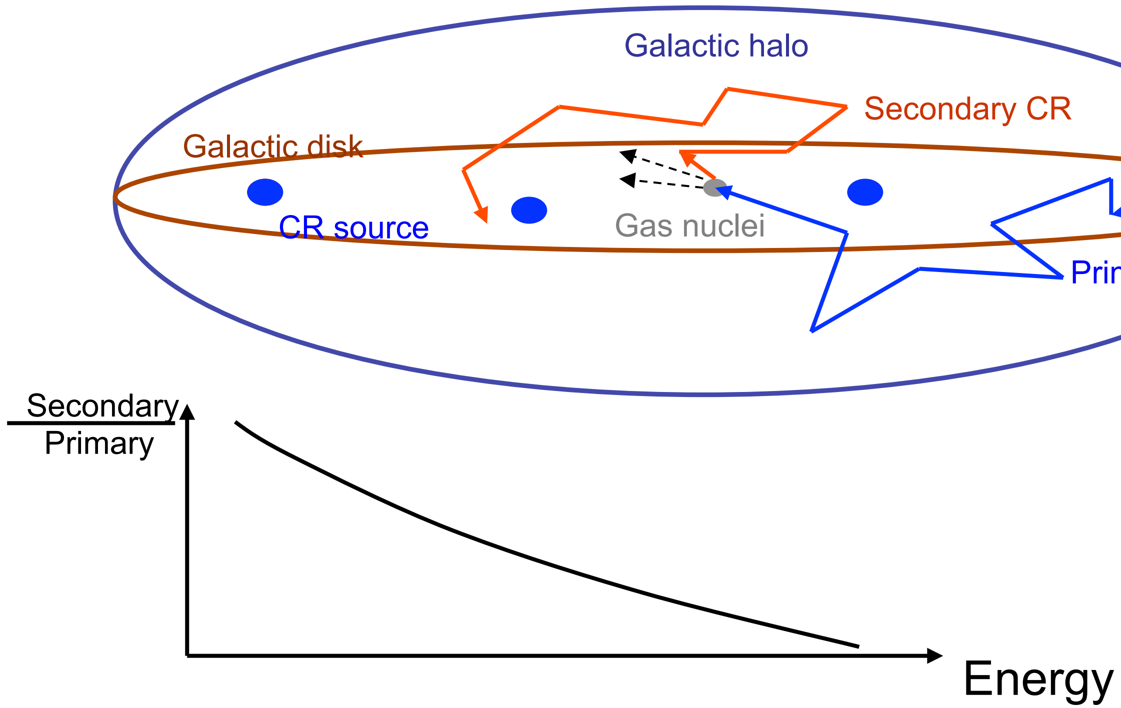
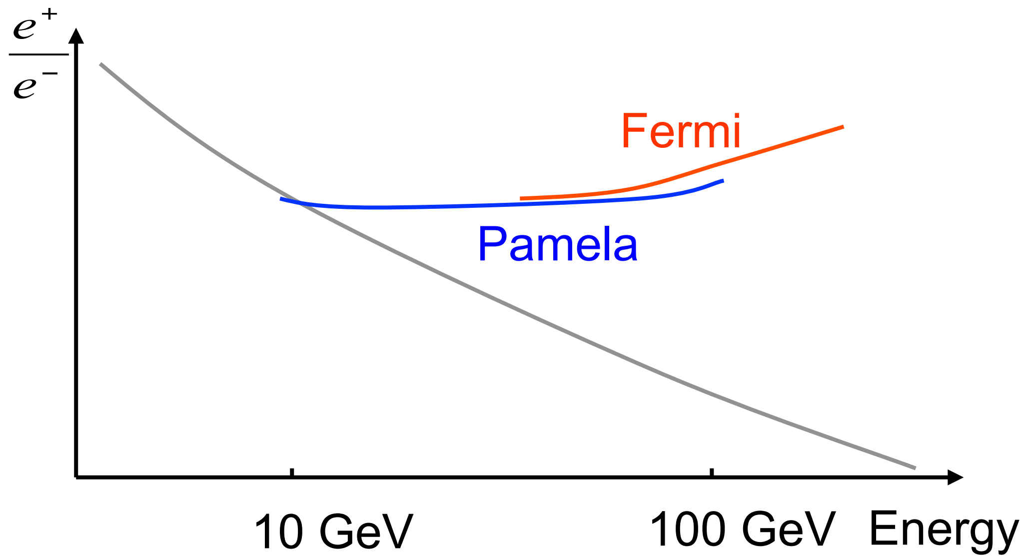
Standard picture for secondary CR generation



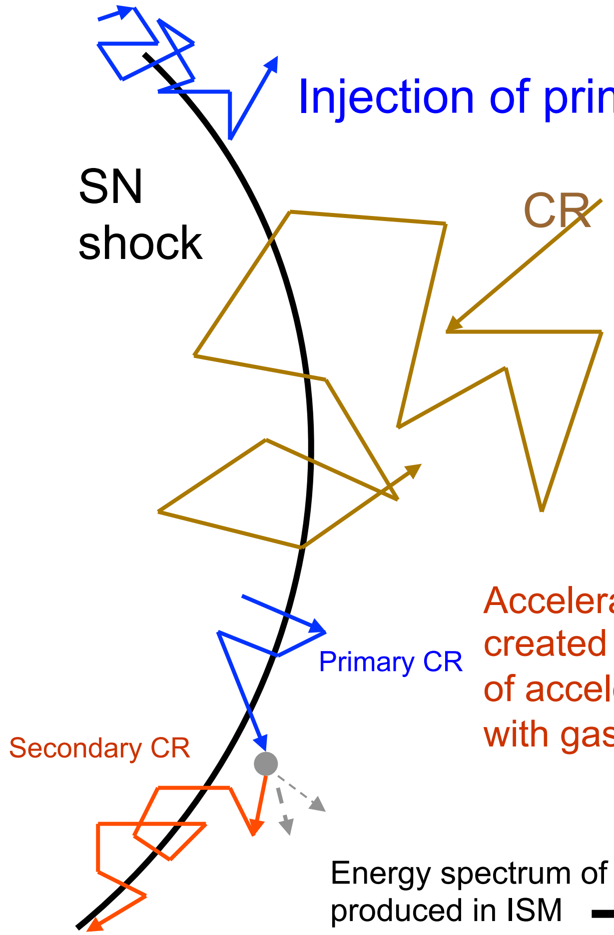
Positron/electron ratio



- Pulsar
- Dark matter
- Local source
- SNRs
- …

Production of primary and secondary (Li, Be, B, e^+, $\bar{p}$, …) CRs in SNRs

Berezhko, Ksenofontov, Ptuskin, Völk, Zirakashvili (2003)



Injection of primaries from thermal pool

Reacceleration of primary and secondary CRs

Effect is proportional to the volume sweep up by SN shock
Efficient in the case of diluted ISM

Acceleration of secondaries, created in nuclear collisions of accelerating primary CRs with gas atoms

Effect is proportional to the number of collisions
Efficient in the dense ISM

Energy spectrum of secondary CRs produced in SNR is harder then produced in ISM → s/p ratio flattens with energy

The model: basic equations

Berezhko, E.G., Yelshin, V.K., Ksenofontov, L.T. (1994), Berezhko, E.G., Völk, H.J. (1997)

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{w}) = 0,$$

$$\rho \frac{\partial \mathbf{w}}{\partial t} + \rho(\mathbf{w}\nabla)\mathbf{w} = -\nabla(P_c + P_g),$$

$$\frac{\partial P_g}{\partial t} + (\mathbf{w}\nabla)P_g + \gamma_g(\nabla \mathbf{w})P_g = \alpha_a(1-\gamma_g)c_a \nabla P_c,$$

Hydrodynamic equations

$\rho(\boldsymbol{r}, t)$ – gas density

$\mathbf{w}(\boldsymbol{r}, t)$ – gas velocity

$P_g(\boldsymbol{r}, t)$ – gas pressure

$f(p, \boldsymbol{r}, t)$ – CR distribution function

$$\frac{\partial f_A}{\partial t} = \nabla(\kappa_A \nabla f_A) - \mathbf{w}_c \nabla f_A + \frac{\nabla \mathbf{w}_c}{3} p \frac{\partial f_A}{\partial p} + Q_A$$

$$\frac{\partial f_e}{\partial t} = \nabla \kappa \nabla f_e - \mathbf{w}\nabla f_e + \frac{\nabla \mathbf{w}}{3} p \frac{\partial f_e}{\partial p} - \frac{1}{p^2}\frac{\partial}{\partial p}\left(\frac{p^3}{\tau_1} f_e\right)$$

CR transport equations for ions, antiprotons and electrons

$$P_c = \frac{4\pi c}{3}\int_0^\infty dp \frac{p^4 f}{\sqrt{p^2 + m^2 c^2}}$$

CR pressure

$$Q = \eta \frac{\rho_1 u_1}{4\pi m p_{inj}^2} \delta(p - p_{inj})\delta(r - R_s)$$

Injection term

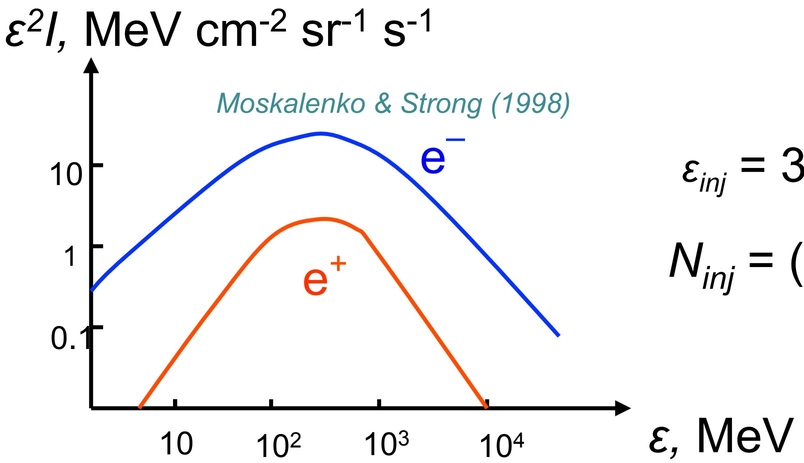
$$\kappa(p) = \kappa_B(p) = \frac{pc}{3eB}$$

CR diffusion coefficient

$$\tau_1 = \frac{9 m_e^2 c^2}{4 r_0^2 B^2 p}$$

Synchrotron loss time

The model: parameters



ε_{inj} = 300 MeV — effective energy of injected CR electrons and positrons

$N_{inj} = (4\pi/c)\, I(\varepsilon > \varepsilon_{inj})$ — number density of injected particles

$B_0 = B_{ISM} = 5\ \mu G$ — upstream (unamplified) magnetic field

$E_{SN} = 10^{51}$ erg
$M_{ej} = 1.4\ M_{Sun}$ — supernova explosion parameters

$N_H = 1.5$ cm^{-3} — ISM density

$$n_s = n_s' + n_s''$$

n_s' secondaries produced in nuclear collisions of primary CRs within the Galactic disk

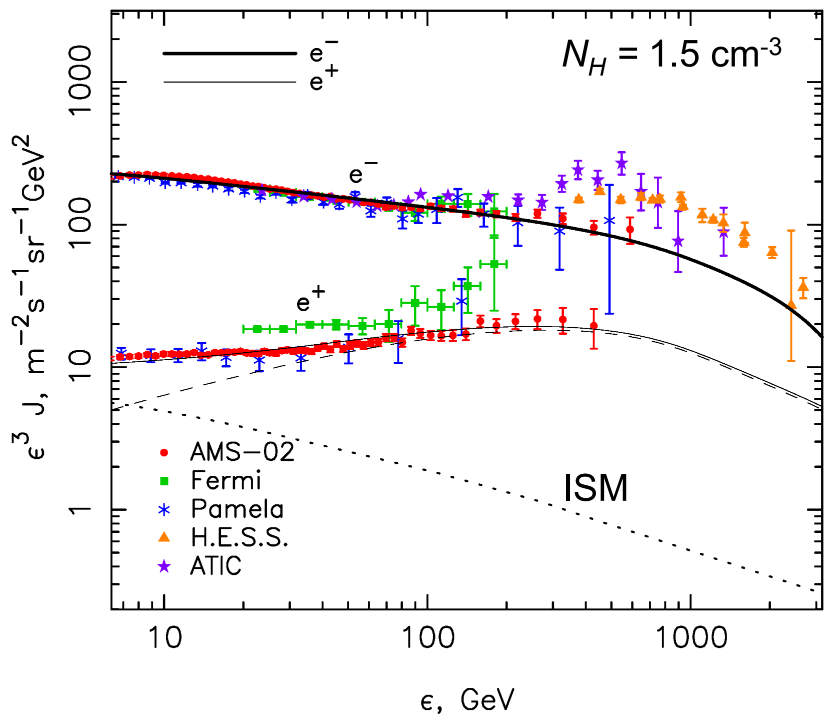
n_s'' secondaries in the Galactic disk volume produced in SNRs and modified due to their propagation effect.

$$n_s''(\epsilon) = k_e \frac{\tau_{\rm loss}(\epsilon)}{\epsilon} \int_{\epsilon}^{\infty} d\epsilon' N_s(\epsilon'),$$

k_e is the normalization factor

τ_{loss} loss time determined by inverse Compton scattering and synchrotron emission. (Stawarz et al. 2010)

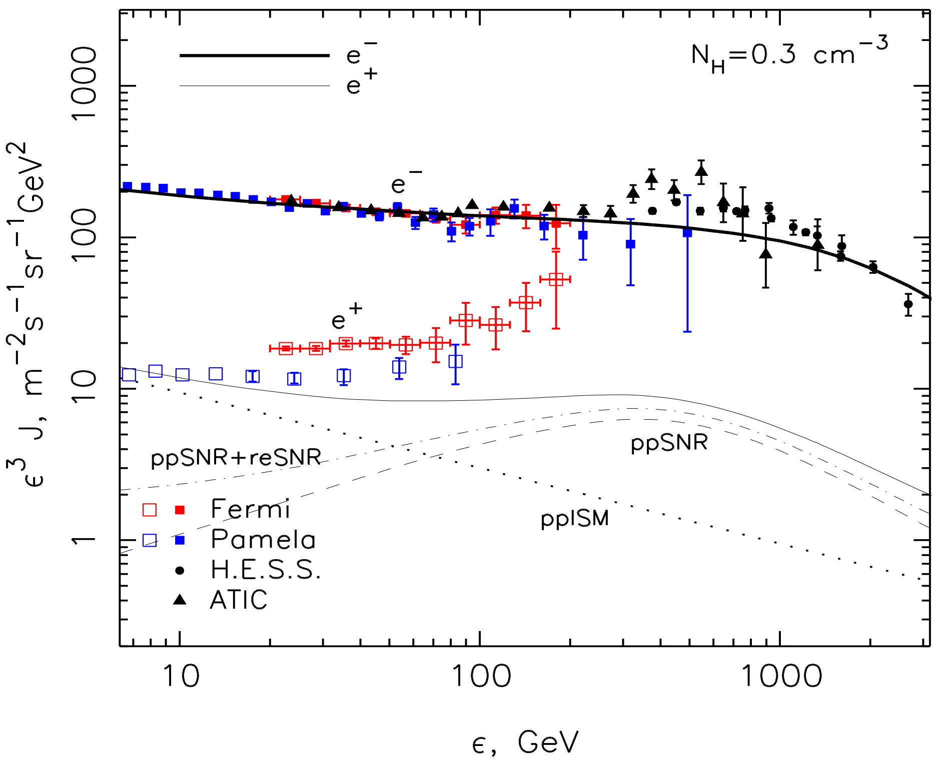
Energy spectra of electrons and positrons, produced in SNRs



At ε > 10 GeV positron spectrum is dominated by component created in p-p collisions

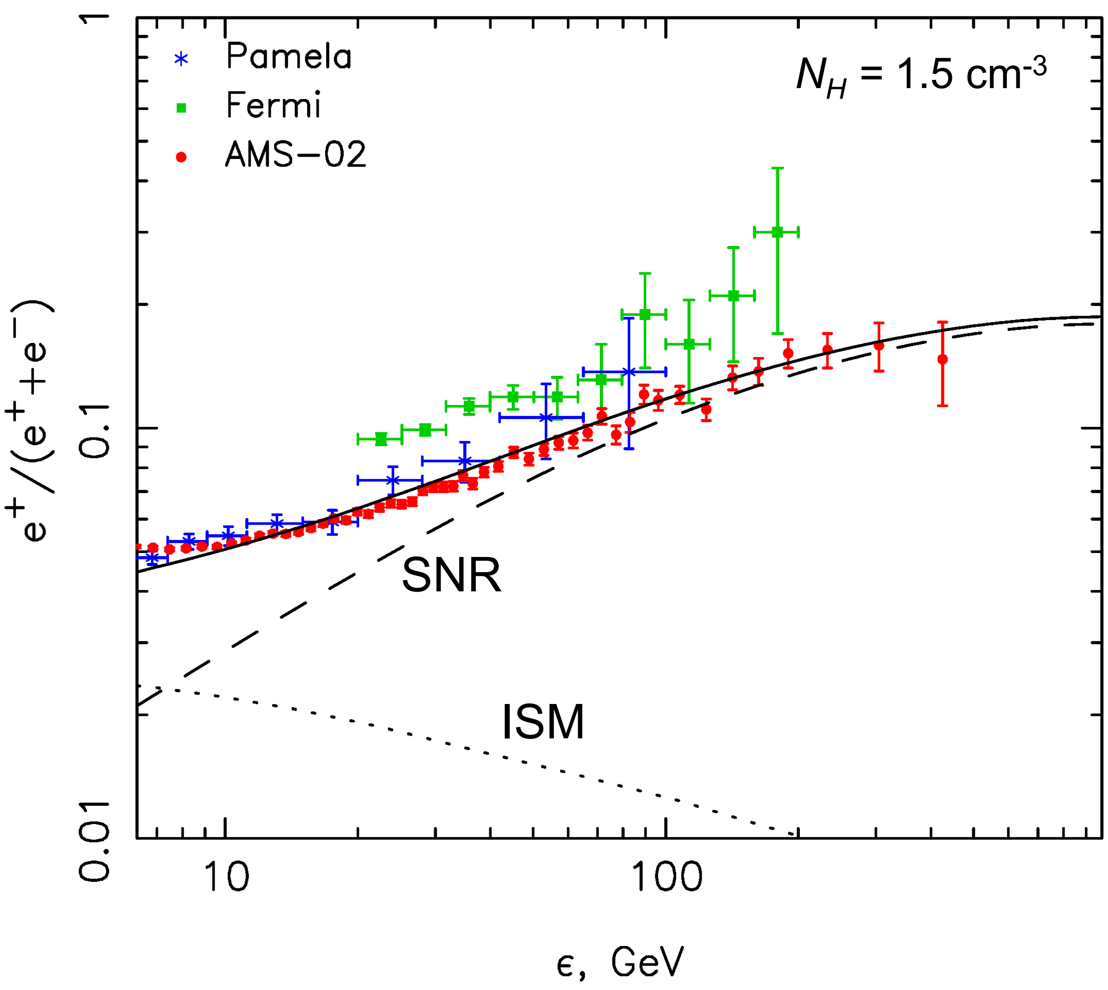
(roughly consistent with previous estimate (Blasi 2009))

Energy spectra of electrons and positrons, produced in SNRs

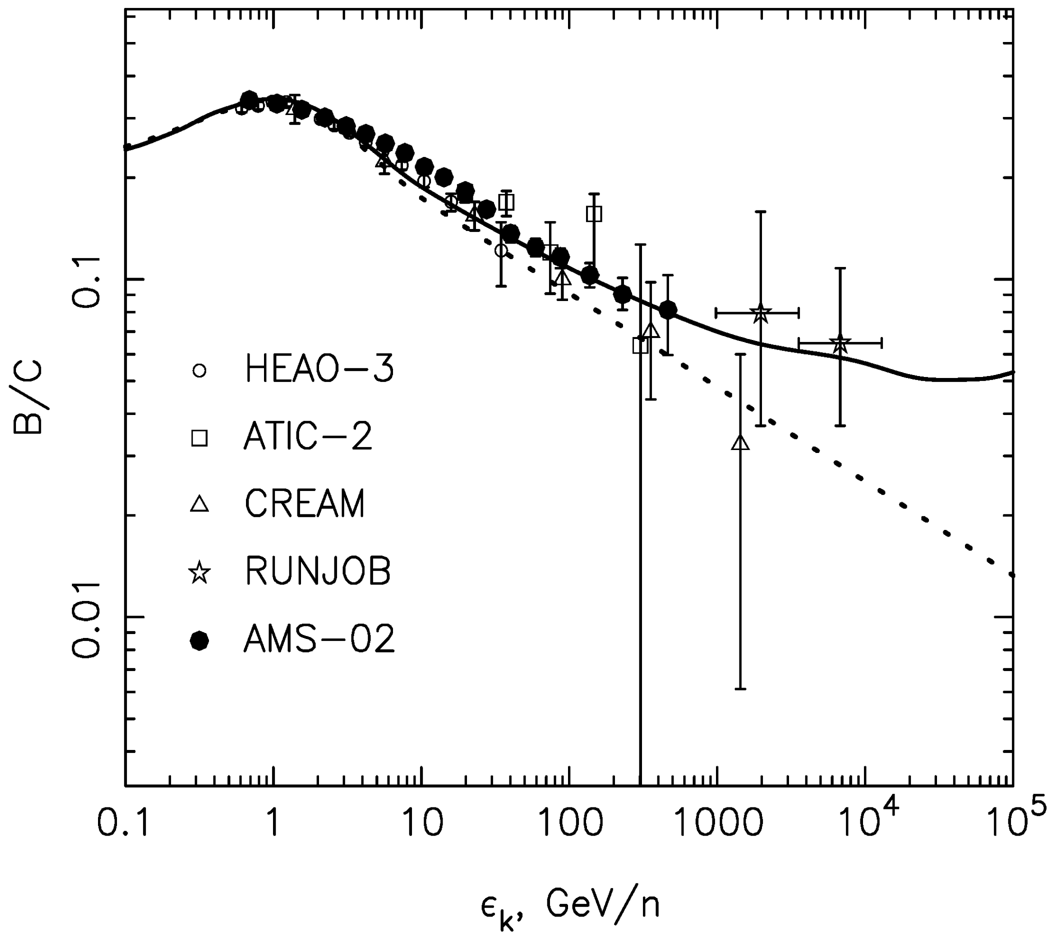


At lower ISM density reaccelerated positron component (reSNR) becomes more relevant

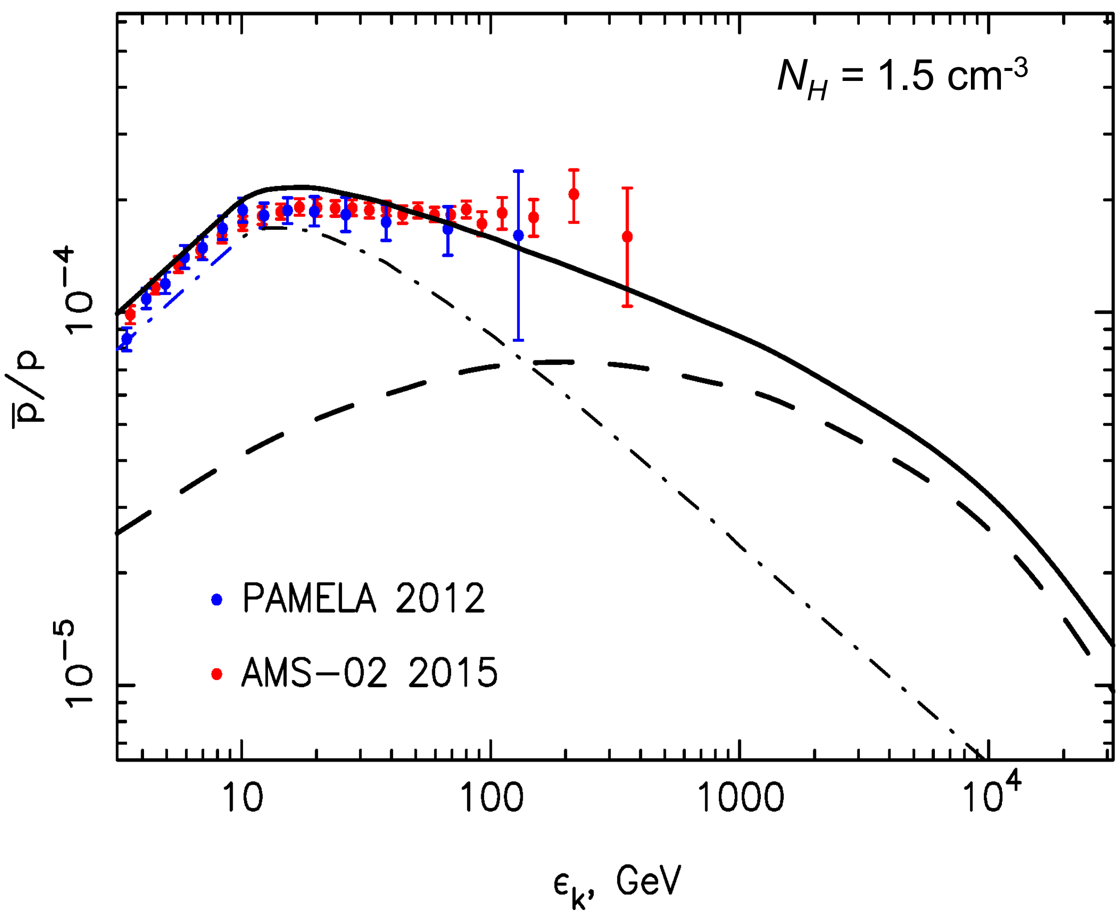
Positron to electron ratio

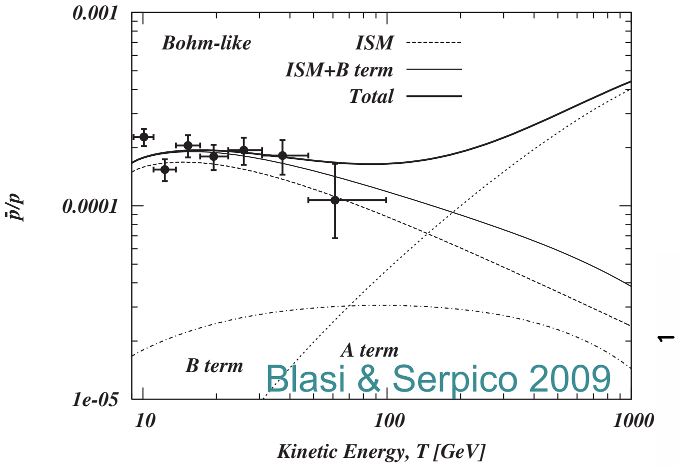


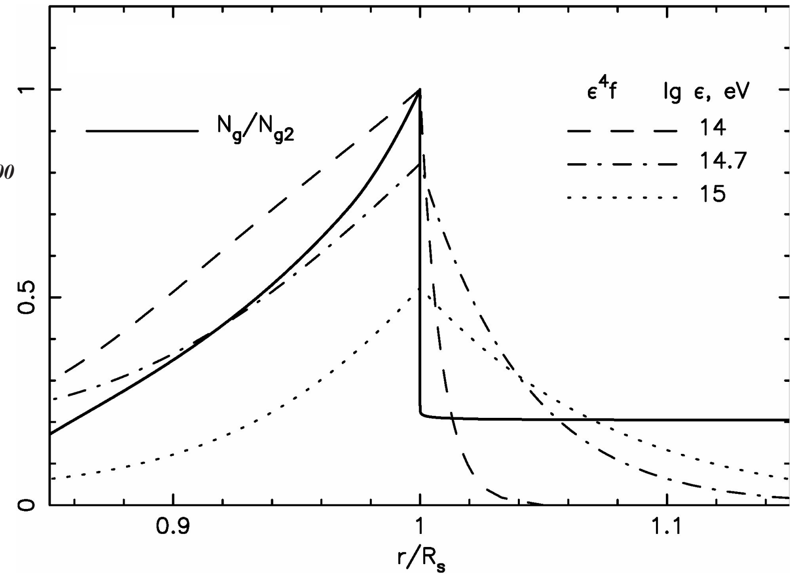
Boron to carbon ratio



Antiproton to proton ratio



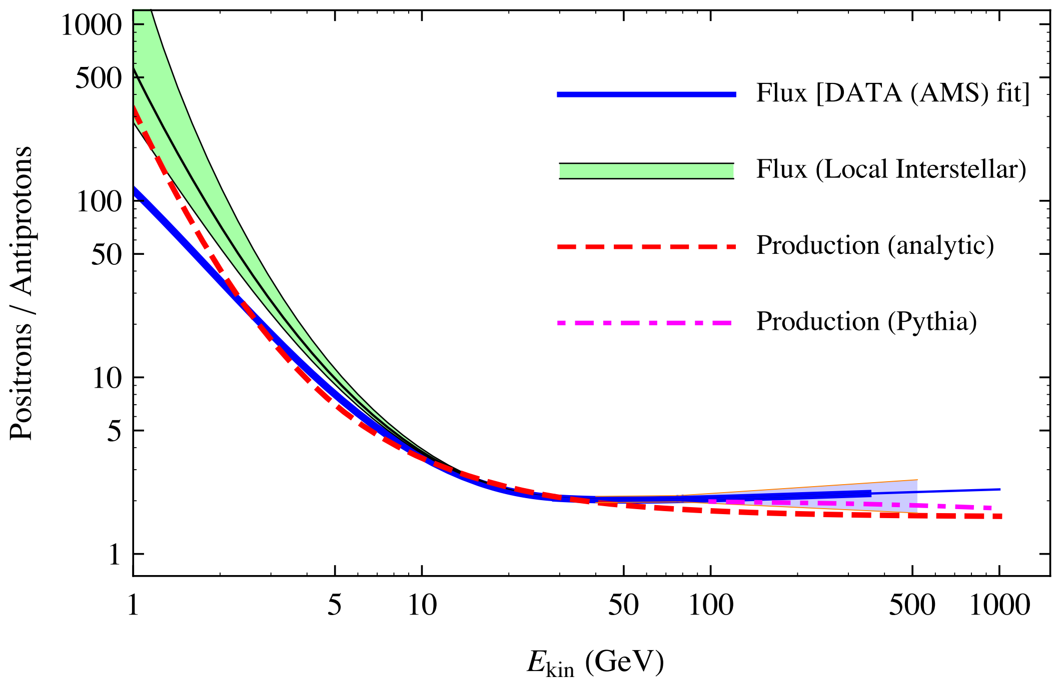




The overlap between the radial profile of protons *f*(*r*, *p*) with the gas density profile progressively decreases with the increase of energy at high energies, because the radial profile of protons becomes progressively broader.

Positrons to antiprotons ratio

Lipari, arXiv:1608.02018



"These results strongly suggest that cosmic ray positrons and antiprotons have a common origin as secondaries in hadronic interactions."

Conclusions

- Production of secondary CRs in SNRs produces considerable effect in their resultant energy spectrum making it essentially flatter above 10 GeV.

- Calculated energy spectra of antiprotons, positrons and secondary nuclei Li, Be, B with reasonable set of parameters are consistent with experimental data obtained in recent experiments PAMELA, Fermi and AMS-02.

- If majority of GCRs are accelerated in SNRs expanding in moderately dense ISM, than the observed flattening of CRs secondary to primary ratio can be explained by SNRs contributions only.

- Contribution of SNRs in production of secondary CRs should be taken into account in any scenario of their origin.