Outstanding Problems in Astroparticle Physics for Plasma Physicists

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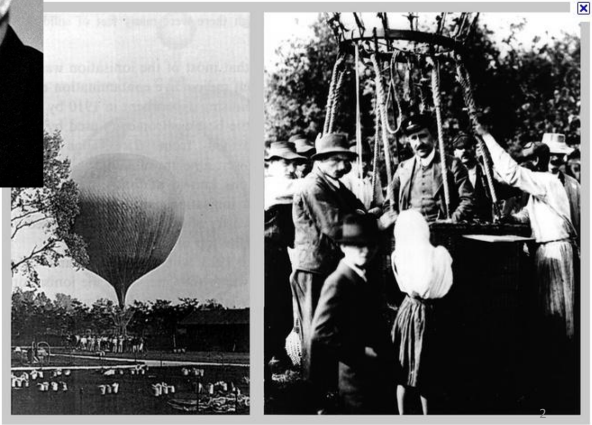
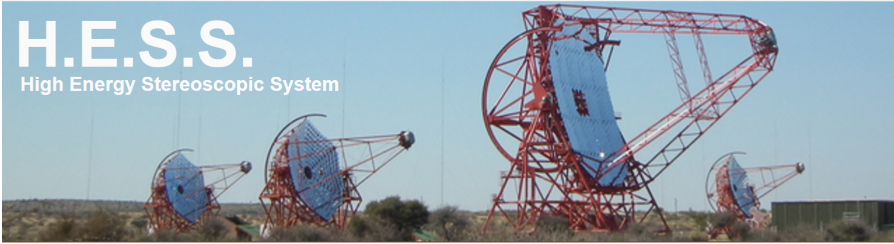
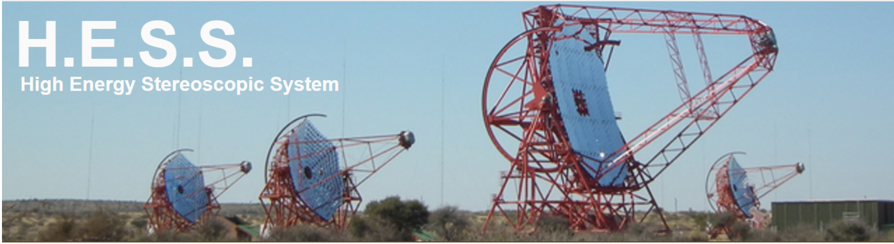
UCSD CASS

Cosmic rays: discovery

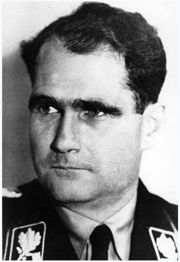
Victor Hess, 1912




H.E.S.S.
High Energy Stereoscopic System



Rudolf Hess
Rudolf Heß



Hess in 1933

Deputy Führer
Stellvertreter des Führers

In office
21 April 1933 – 12 May 1941

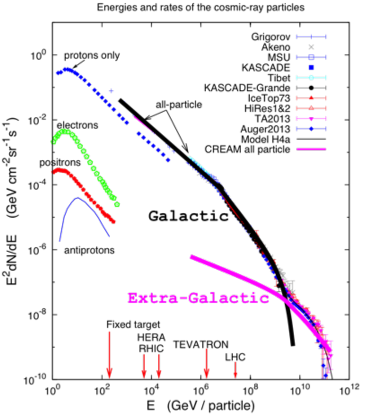
Cosmic rays: role in particle physics

From R. Battiston,

Table 1. Discovery of elementary particles

Particle	Year	Discoverer (Nobel Prize)	Method
e^-	1897	Thomson (1906)	Discharges in gases
p	1919	Rutherford	Natural radioactivity
n	1932	Chadwik (1935)	Natural radioactivity
e^+	1933	Anderson (1936)	Cosmic Rays
$\mu^\pm$	1937	Neddermeyer, Anderson	Cosmic Rays
$\pi^\pm$	1947	Powell (1950) , Occhialini	Cosmic Rays
$K^\pm$	1949	Powell (1950)	Cosmic Rays
π^0	1949	Bjorklund	Accelerator
K^0	1951	Armenteros	Cosmic Rays
Λ^0	1951	Armenteros	Cosmic Rays
Δ	1932	Anderson	Cosmic Rays
Ξ^-	1932	Armenteros	Cosmic Rays
$\Sigma^\pm$	1953	Bonetti	Cosmic Rays
p^-	1955	Chamberlain, Segre' (1959)	Accelerators
anything else	1955 $\Longrightarrow$ today	various groups	Accelerators
$m_\nu \neq 0$	2000	KAMIOKANDE	Cosmic rays

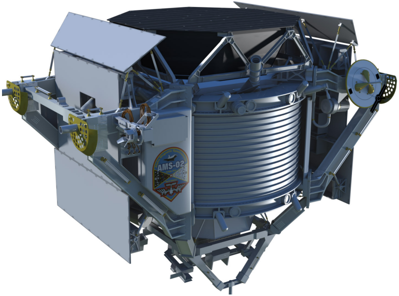
More than 100 years of cosmic ray research...



IceCube compilation of CR spectrum

- CR energy spectrum was long thought to be a featureless power law:
  - a hallmark of the underlying acceleration mechanism:
  - diffusive shock acceleration, DSA
- DSA rigidity (p/Z) spectra should be the same for all CR species
- Any change in power-law index interpreted as change of acceleration regime, source (galactic-extragalactic, etc.)

An incredibly exciting time for this field...



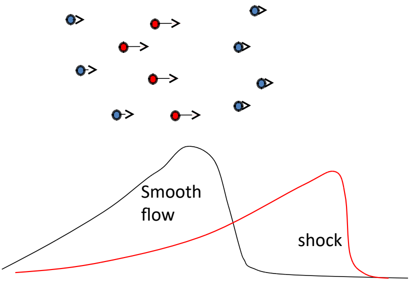
Alpha Magnetic Spectrometer (AMS-02):
Particle detector operating on the International Space Station

- Both energy (rigidity) spectrum and composition aspects of DSA scrutinized using modern instruments and proved not true in some instances
- Either we do not understand how DSA works and/or there are additional, probably exotic CR sources, such as dark matter decay or annihilation

Outline

1. Exciting time for the field, difficult times for DSA
   - DSA: too big to fail?
   - SNRs as main source of galactic CRs (“Standard Model”)
2. Disagreements: anything wrong with DSA?
   - Anomalies in positron spectrum
   - Possible explanations and their weaknesses
3. A new look at positron anomaly
   - Charge-sign dependent CR acceleration: molecular gas ahead of the SNR shock
   - Physics of rising and falling branches of positron fraction: NL DSA
   - Physics of the spectral minimum
4. Conclusions: Room for DM/Pulsars contribution

CR production mechanism: Diffusive Shock Acceleration (DSA)



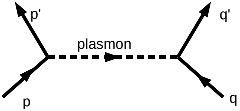
flow velocity

-Most shocks of interest are collisionless

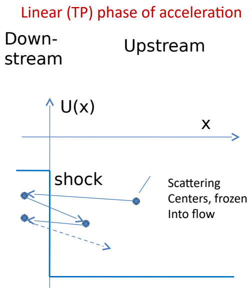
-Big old field in plasma physics

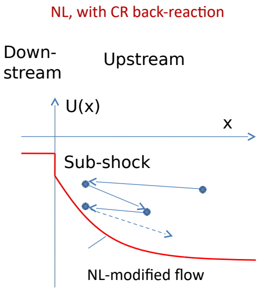
Problems:

- How to transfer momentum and energy from fast to slow gas envelopes if there are no binary collisions?
- waves. . .
- driven by particles whose distribution is almost certainly unstable. . .



Essential DSA (aka Fermi-I process, E. Fermi, ~1950s)

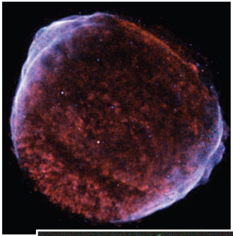


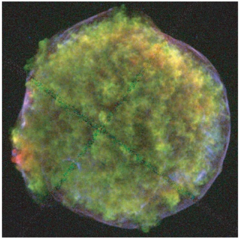


- Particles are trapped between converging mirrors: $p\Delta x \approx const$
- CR spectrum: determined by shock compression, r: $f \sim p^{-q}$, $q = 3r/(r-1)$, $r = q = 4$ for strong shocks $M \to \infty$

- Index q becomes $q(p)$:
  - soft at low p: $q = 3r_s/(r_s - 1)$ $r_s < 4$ $(\sim 2-3)$
  - hard at high p: $q \to 3.5$ (largely independent of $r \gg 1$)

CR acceleration in SNRs





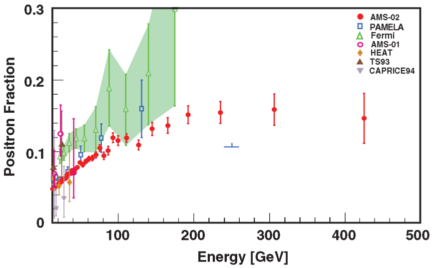
SN 1006 and SN 1572 (Tycho), Reynolds 2008 and Warren et al 2005

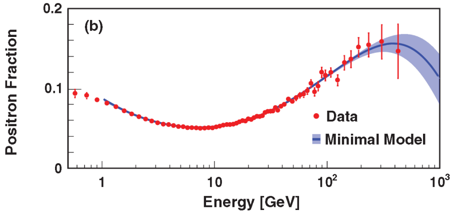
- At least some of the galactic SNR are expected to produce CR up to $10^{15} eV$ (knee energy)
- "Direct" detection is possible only as secondary emission
  - observed from radio to gamma
  - electron acceleration up to $\sim 10^{14} eV$ is considered well established, synchrotron emission in x-ray band (Koyama et al 1995, Bamba et al 2003)
  - tentative evidence of proton acceleration from nearby molecular clouds:

$$pp \rightarrow \gamma$$

Fermi-LAT, HESS, Agile,..

Positron Anomaly (excess)





- Positron excess (Accardo et al 2014)
- Observed by different instruments for several years
- Dramatically improved statistics by AMS-02 (published in 2014)

Things to note:

- Remarkable min at ≈ 8 GeV
- Unprecedented accuracy in the range 1-100 GeV
- Saturation (slight decline?) trend beyond 200 GeV
- Eagerly awaiting next data release!

Suggested explanations of positron excess

- Early explanations focused on the rising branch of positron anomaly
- Most of the SNR related suggestions invoke secondary e^+ produced by galactic CR protons colliding with:
  - ambient dense gas in surroundings of SNR accelerator (Fujita+ 2009)
  - elsewhere in the Galaxy (Blum+2013, Cowsik+ 2014)
  - immediately at shock front (Blasi 2009, Mertsch 2014, Cholis+ 2014)
- Tensions with $\bar{p}$ observations (should show similar trends, as both are secondaries)
- Poor fits to high-precision AMS-02 data or too many *ad hoc* assumptions (e.g. multiple sources with, often, arbitrary power-law indices)

Further explanations

- Pulsars (e.g. Profumo 2012, big review). Possible, but have disadvantage of lacking accurate acceleration models
- Dark matter contribution ??
- Positrons injected into DSA by radioactive elements of SN ejecta

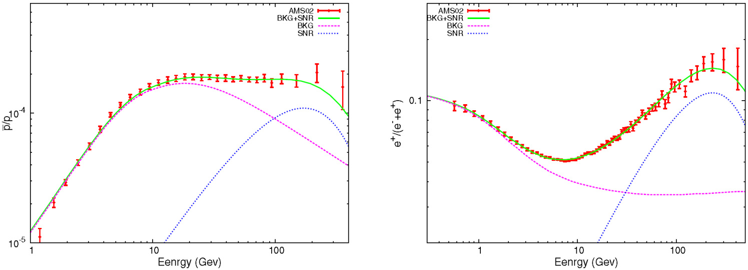
Obvious remarks

- As Pulsars and particularly DM have much weaker predictive capabilities than the DSA-SNR- based models, they should be considered seriously only if (or where) the SNR contribution falls short to account for the positron excess
- SNR contribution to the phenomenon thus constrains possible DM/pulsar contributions

Bottom line:

e^+/e^- explained only by adjusting independent sources

BO-QIANG LU and HONG-SHI ZONG PHYSICAL REVIEW D **93,** 103517 (201



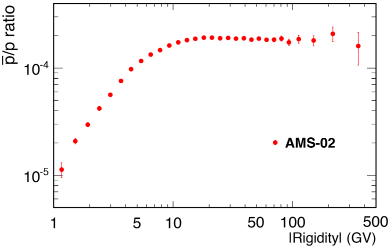
Weaknesses:

- Flatness of $\bar{p}/p$ and position of minimum in e^+/e^- are coincidental
- B/C, $\bar{p}/p$ secondary constraints put a 25% upper bound on SNR contribution to the positron rise (Cholis&Hooper, 2014)

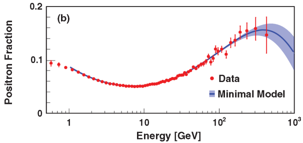
Desirable aspects of the mechanism (Wishlist)

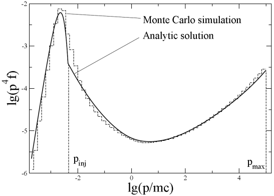
- account for e^+ fraction by a single-source, a nearby SNR
- explain physics of decreasing and increasing branches
- identify physics of the minimum at 8 GeV
- understand $\bar{p}$ flat spectrum as intrinsic, not coincidental: most likely, accelerated just like protons, whenever injected BUT: $\bar{p}/p \neq e^+/e^-$
- $\Longrightarrow$acceleration mechanism ought to be *charge-sign dependent*
- physics of charge-sign selectivity

The Hints



(AMS Days at CERN, Kounine 2015)



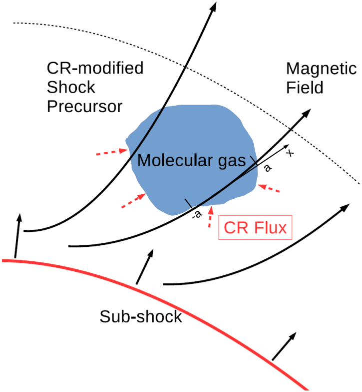


- $\bar{p}$ fraction is flat on the rising e^+ fraction branch $E > 8$ GeV
  - Opposite trends in $e^+/\bar{p}$ spectra at $E < 8$ GeV
  - Both data sets relate to *fractions*, thus eliminating all charge-sign independent aspects of propagation and acceleration
  - Striking similarity with NL DSA solution, assuming most of e^- are accelerated to p^{-4} (standard DSA)

Assumptions of the present model

- A strong SNR propagates in “clumpy” molecular gas, $n_{\mathrm{H}} \gtrsim 30\mathrm{cm}^{-3}$ with filling factor $f_V \sim 0.01$, but mass $\gg$ ambient plasma
- The SNR is not too far away, likely magnetically connected, thus making significant contribution to the local CR spectrum
- Other SNRs of this kind may or may not contribute
- Consider a moderately oblique (shock normal to the ambient magnetic field) portions of SNR shock surface
- High-energy protons are already accelerated to $E \gtrsim 10^{12} eV$ to make a strong impact on the shock structure (CR back reaction, NL shock modification)
- Acceleration process thus transitioned into an efficient regime (in fact, required to, once $E \gtrsim$1 TeV, $M \gtrsim 10 - 15$ and the fraction of accelerated protons $\sim 10^{-4} - 10^{-3}$)

Interaction of shock-acc'd CRs with gas clumps (MC)



- Shock-acc'd CRs form a precursor $L_p \sim \kappa/u_1$: κ - CR diff. coeff., u_1 shock velocity $\kappa = \kappa_B \simeq c r_g(p)/3$, r_g -gyro-radius

- CR number density increases towards subshock

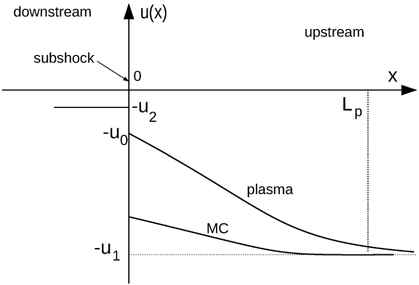
$$n_{CR}(x) = \frac{x_0 n_{CR}^0}{x_0 + x_{MC}}$$

- CR charge the MC at a relative rate (charge/discharge)

$$\eta = \frac{\dot{n}_{\rm CR} L_{\rm MC}}{V_{Te} n_0 + V_i n_i}$$

$$\sim \frac{L_{\rm MC}}{L_{\rm CR}} \cdot \frac{u_1 n_{\rm CR}}{V_{Te} n_0 + V_i n_i}$$

Electrodynamics of CR-MC interaction



- MC move faster (in the shock frame) than the upstream flow (bow-shocks form)
- CR number density in MC increases explosively:

$$n_{CR}(t) = n_{CR}^{0} x_0 / (x_0 - u_1 t)$$

- Reaction from the MC:
- buildup of electric field of a *positive* electrostatic potential
- minus-charge particles are attracted and stay inside MC during the subsequent shock crossing $\rightarrow$ evade acceleration
- plus-charge particles are expelled and injected into DSA
- charge-sign asimmetry of injection/acceleration

Short digression into elementary plasma physics

- plasmas enforce almost "zero-tolerance" policy in regard to violation of their charge neutrality

Example

take 1cm^3 of air
ionize and separate p and e to distance r =0.5 cm
the resulting force

$$F = e^2 N^2 / r^2 \sim 10^{16} \text{ lb}$$

As $N \sim 10^{19}$, $I = 13.6$ eV
ionization energy only~ 100 Jouls

- similarly, injection of an external charge into plasma must lead to enormous electrostatic forces
- key words here are "separate" and "inject"
- need a powerful mechanism
- energetic CRs can do that

Electrodynamics inside MC

- Two-fluid equations:

$$\begin{aligned}\frac{dV_i}{dt} &= \frac{e}{m_i}E(x,t) - \nu_{in}V_i \\ \frac{dV_e}{dt} &= -\frac{e}{m_e}E - \nu_{ei}(V_e - V_i) \\ \frac{\partial n_{e,i}}{\partial t} &= -\frac{\partial}{\partial x}n_{e,i}V_{e,i} \\ n_e &= n_i + n_{CR}\end{aligned}$$

- Electric field is related to CR charging rate and ion outflow:

$$E(x,t) = \frac{m_e}{e}\nu_{ei}\frac{n_{CR}}{n_{CR}+n_i}\left(\frac{\dot{n}_{CR}}{n_{CR}}x + V_i\right)$$

Self-similar solution

- Ions leave the MC symmetrically: $V_i(x,t) = xV(t)$, $E \propto V_i$, assuming $x = 0$ being a midpoint of the field line threading the MC, $|x| \leq a$
- All other solutions converge to this form
- Electric field $(-\infty < t < 0)$:

$$E(x,t) \simeq \frac{m_i}{e} a\nu_{in}^2 \frac{x\alpha}{(t_0 - t)^2}\left[1 + \frac{\alpha}{t_0 - t}\right]$$

with dimensionless parameter that characterizes ion depletion

$$\frac{\alpha}{t_0} \sim \left(\frac{1eV}{T_e}\right)^2 \frac{n_{CR}^0}{n_n}\sqrt{\frac{m_n}{m_i}\left(\frac{m_n}{m_i}+1\right)\frac{m_e}{m_i}} \sim \Delta n_i/n_i \ll 1$$

(t measured in $i - e$ collision times)

Solution for electric field in MC, cont'd

- Maximum electric field (at MC edge)

$$E_{\max} \simeq \frac{m_e}{e} u_1 \nu_{ei} \frac{n_{CR}^0}{n_i}$$

- electrostatic potential with a maximum in the middle of the MC ($x = 0$) screens the MC interior from penetrating CR

$$\frac{e\phi_{\max}}{m_p c^2} \sim \frac{a}{1pc} \frac{u_1}{c} \frac{n_{CR}}{1cm^{-3}} \left(\frac{1eV}{T_e} \right)^{3/2}$$

- A 1-parcec MC (r_g of a PeV proton) is acceptable as it occupies only a $u_1/c \ll 1$- fraction of CR precursor
- electric field is strong enough to keep low-energy CRs away from the MC interior
- keeps secondary e^- (and $\bar{p}$, to much lesser extent) inside, ejects secondary e^+
- charge sign asymmetry of injection into DSA established

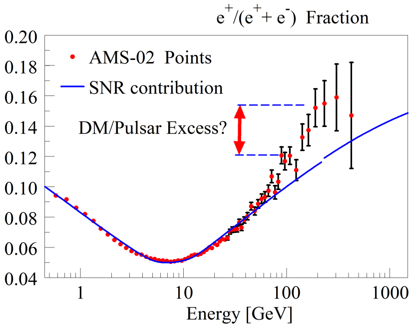
Positron Injection into DSA

- secondary e^+ are largely produced deep inside MC, preaccelrated in E and easily injected into DSA
- injection from many MCs occasionally crossing the shock occurs with a time-averaged rate $Q(p, x)$
- Q decays sharply with x, the distance from the subshock
- it has a broad maximum at $p \sim e\phi_{\max}/c$
- near subshock, CR number density sharply increases on account of GeV particles. They generate secondary $e^{\pm}$ and $\bar{p}$, on the periphery of MC. The edge electric field then expels positively charged secondaries (e^+) and sucks in negatively charged ones, such as e^- and, to some extent, $\bar{p}$
- typical energy of expelled positrons $< 1 - 2$ GeV

Shock Acceleration of Positrons

- As the shock is modified, acceleration starts in its precursor since $\partial u/\partial x \neq 0$
- However, most of the positrons are released from the MC near the subshock
- at lower energies, their spectrum is dominated by the subshock compression ratio, $r_s = u_0/u_2$
- spectral index $q = q_s \equiv 3r_s/(r_s - 1)$ and the spectrum $f_{e^+} \propto p^{-q_s}$.
- at higher energies, positrons feel progressively higher flow compression (diffuse farther ahead of the subshock)
- their spectrum tends to a universal form with $q \to 3.5$

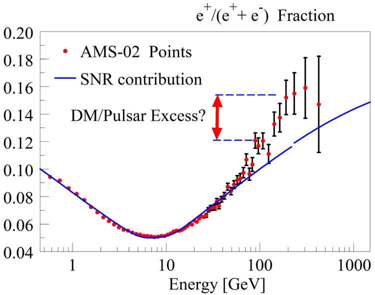
Positron spectra



- Shock structure is self-consistently adjusted to the pressure of accelerated protons

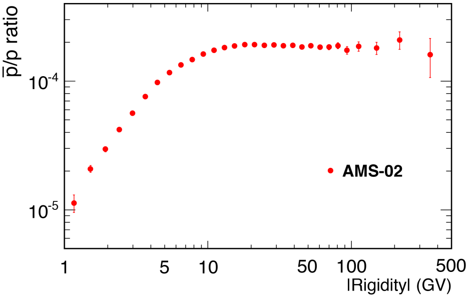
- e^+ and other secondaries produced in *pp* collisions of shock accelerated CRs with MC gas, as well as e^- can be treated as test particles in a given shock structure
- positively charged particles are enhanced while negatively charged suppressed because of charge-asymmetric injection from MC
- plausible assumption: e^+/e^- *injection rate* $\gg 1$.

Positron spectra cont'd



- In calculating $e^+/(e^- + e^+)$, e^- are assumed to be from conventional shocks with p^{-4} source spectra
- $\Longrightarrow$ $e^+/(e^- + e^+)$ spectrum = proton spectrum in $p^4 f(p)$ customary normalization
- background e^- (with p^{-4} spectrum) propagate distance similar to that of e^+
- $\Longrightarrow$ratio $e^+/(e^- + e^+)$ is de-propagated and probes directly into the positron accelerator!
- excess above the blue curve is not SNR – e.g., DM or pulsars
- as SNR contrib. is rising with E, constraints on DM signal in 200-400 GeV range are weaker compared to secondary e^+(decaying) without acceleration

Antiprotons



- If most of $\bar{p}$ and p come from the same source as e^+ ($\bar{p}$ generated in MCs ahead of SNR shock), the $\bar{p}$ spectrum should be the same as p at $E \gtrsim 10$ GeV
- Similarly, $\bar{p}/p$ should be flat if $\bar{p}$ are injected as secondaries into any SNR-DSA process
- Decline of $\bar{p}$ towards lower energies is consistent with electrostatic retention in MC
- This effect has not been quantified for $\bar{p}$
- Solar modulation may also contribute to $p - \bar{p}$ difference at low energy
- Flat $\bar{p}/p$ should continue up to $p \sim p_{\max}$; should decline at $p \gtrsim p_{\max}$ (secondaries with no acceleration)

Conclusions

1. A weakly ionized dense molecular gas (MC) in SNR shock environment, illuminated by shock accelerated protons results in the following phenomena:
   - an MC of size L_{MC} is charged (positively) by penetrating protons to$\sim (L_{\mathrm{MC}}/pc)\,(V_{sh}/c)\,(1eV/T_e)^{3/2}\,(n_{CR}/cm^{-3})$GV
   - secondary positrons produced in pp collisions inside the MC are pre-accelerated by the MC electric potential and expelled from the MC to become a seed population for the DSA (get "injected")
   - most of the negatively charged light secondaries (e^-), and to some extent, $\bar{p}$, along with the primary electrons, remain locked inside the MC
2. Assuming that the shock Mach number, proton injection rate, and cut-off momentum all exceed the thresholds of NL acceleration, the spectrum of injected positrons has concave form, which physically corresponds to a steepening due to the subshock reduction, and flattening resulting from acceleration in the smooth part of the shock

Conclusions cont'd

- the crossover energy is related to the change in proton transport (diff. coeff. changes from $\kappa \propto p^2$ to $\kappa \propto p$) and respective contribution to the CR partial pressure in a mildly-relativistic regime. The crossover pinpoints the 8 GeV minimum in the $e^+/(e^+ + e^-)$ fraction measured by AMS-02
- due to the NL subshock reduction, the MC remains unshocked so that secondary $\bar{p}$ and, in part, heavier nuclei accumulated in its interior largely evade shock acceleration
- The AMS-02 positron excess in the range $\sim 200 - 400$GeV is not accounted for by the SNR positron spectrum and is available for alternative interpretations (DM, Pulsars, ???)
- However, an e^+/e^- run-away break down in MC with $e^\pm$ production may alter the last conclusion