Acceleration of CRs in SNR shocks: Acid Test

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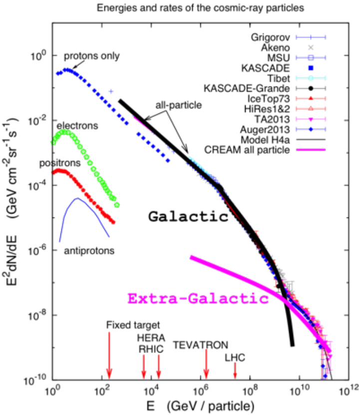
Supported by NASA *Astrophysics Theory Program under* grants NNX14AH36G and 80NSSC17K0255

UCSD CASS

More than 100 years of cosmic ray research...



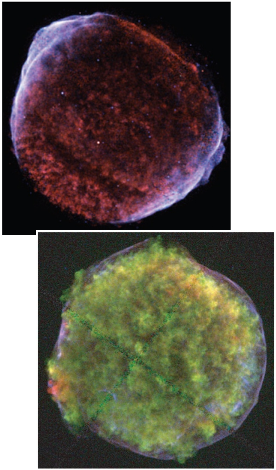
IceCube compilation of CR spectrum

- 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, independent of $\mathrm{sgn}(Z)$
- Any change in power-law index interpreted as change of acceleration regime, source (galactic-extragalactic, etc.)

Outline

1. Preliminary Information
   - The Hypothesis: CR Origin in SNRs via DSA mechanism
   - DSA – The Diffusive Shock Acceleration – Test Particle vs Nonlinear
2. Disagreements with the standard DSA
   - Disagreement #1: Anomalies in positron spectrum
   - EXISTING explanations, issues
3. NEW: Minimal assumptions, single source (SNR) scenario
   - $e^{\pm}$ asymmetry of acceleration: Molecular Clumps
   - Minimum in $e^{+}/(e^{+}+e^{-})$: NL DSA
4. Conclusions: no room (almost) for DM/Pulsars contribution
5. Facing the challenges of Today and Tomorrow
   - Disagreement #2: Violation of Rigidity Law
   - ATIC, Pamela and AMS-02 p/He anomaly

CR acceleration in SNRs



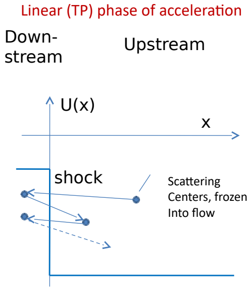
SN 1006 and SN 1572 (Tycho), Reynolds 2008 and Warren et al 2005

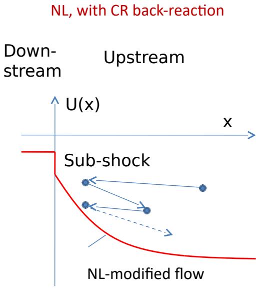
- At least some of the galactic SNR are expected to produce CR up to $10^{15} eV$ (knee energy)
- "Direct" detection is possible only as secondary emission
  - observed from radio to gamma
  - electron acceleration up to $\sim 10^{14} eV$ is considered well established, synchrotron emission in x-ray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

$$pp \to \gamma$$

Fermi-LAT, HESS, Agile,..

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

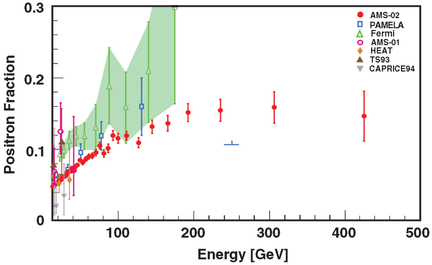


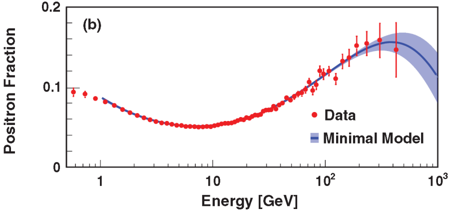


- CR trapped between converging mirrors: $p\Delta x \approx const$
- CR spectrum depends on shock compression, r: $f \sim p^{-q}$, $q = 3r/(r-1)$, $r = q = 4$, Mach $M \to \infty$

- Ind $q \to q(p)$: soft at low p:
  - $q = 3r_s/(r_s - 1) \sim 5$
- hard at high p : $q \to 3.5$
- for $M > 10$, $E_{max} \gtrsim 1$ TeV (MM'97) acceleration must go nonlinear (confirmed by, e.g., Amato, Blasi, Caprioli, Reville, ...analyses and numerics in 2000s)

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

- focus on the rising branch of $e^+/(e^+ + e^-)$
- invoke secondary e^+ from CR pp with thermal gas

Problems:

- Tensions with $\bar{p}$: secondaries with differing spectra
- Poor fits, free parameters, no physics of 8 GeV upturn...

Alternative suggestions:

- Pulsars (lacking accurate acceleration models)
- Dark matter contribution ??

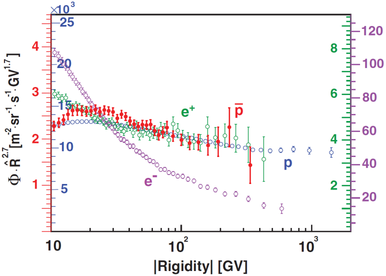
Stating the Obvious ....

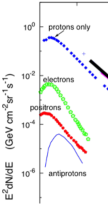
- DSA@SNR' predictive capability $\gg$ Pulsar or DM models
- $\rightarrow$ DM/P– only if the DSA@SNR fails

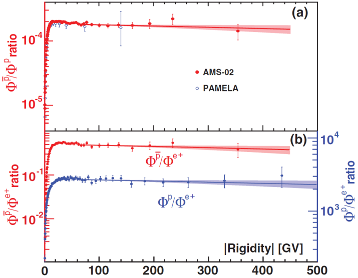
Upshot

- SNR contribution constrains DM/Pulsar contributions

Possible hints from p and $\bar{p}$







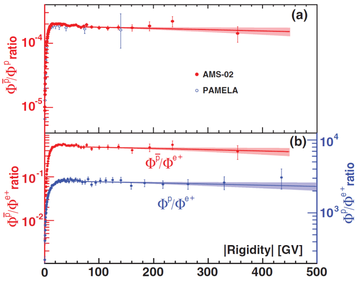
AMS-02:Aguilar+ 2016

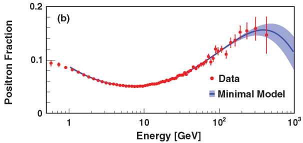
particle\property	charge	mass	secondary?	pulsar?
p	$+$	M	no	no
$\bar{p}$	-	M	yes	no
e^+	$+$	m	both	yes
e^-	-	m	no	both

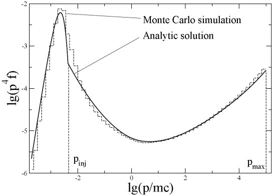
The Wishlist

- account for e^+ fraction by a single-source, a nearby SNR (contribution from similar sources not excluded)
- explain physics of decreasing and increasing branches, 8 GeV min
  - $\rightarrow$ lends credence to high energy predictions
- understand $\bar{p}/p$ and e^+/p flat spectra as intrinsic, not coincidental:
  - most likely $\bar{p}$ and e^+accelerated similarly to protons, whenever injected BUT:
  - $\bar{p}/p = e^+/p \neq e^+/e^-$ - Why so?
- plausible answer: acceleration/injection is *charge-sign and mass/charge ratio dependent*
- understand the physics of charge-sign and m/e selectivity

The Hints







MC-Don Ellison

Analytic sol. MM'97

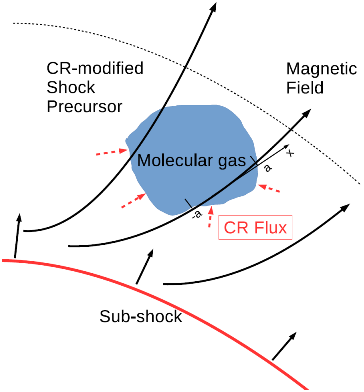
- $\bar{p}$ fraction is flat on the rising e^+ fraction branch $E > 8$ GeV
  - Opposite trends in e^+/e^- and $\bar{p}/p$ spectra at $E < 8$ GeV
  - Both are *fractions*, thus eliminating charge-sign independent aspects of propagation and acceleration (still, HS effects?)
  - Striking similarity with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

The Assumptions

- SNR shock propagates in “clumpy” molecular gas ($n_{\mathrm{H}} \gtrsim 30\mathrm{cm}^{-3}$, filling factor $f_V \sim 0.01$)
- High-energy protons are already accelerated to (at least) $E \sim 10^{12} eV$ 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 $\gtrsim 10^{-4} - 10^{-3}$)

- The SNR is not too far away, possibly magnetically connected, thus making significant contribution to the local CR spectrum
- Other SNRs of this kind may or may not contribute

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



- Shock-acc'd CRs form a precursor : κ - CR diff. coeff.,

$$L_p \sim \kappa / u_{sh}$$

- With some help from plasma textbooks...
- Maximum electric field due to $e - i$ collisions

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

- maximum ES potential inside

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

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

$$F = e^2 N^2 / r^2 \sim 10^{16} \mathrm{lb} \quad (\propto n^2 r^4)$$

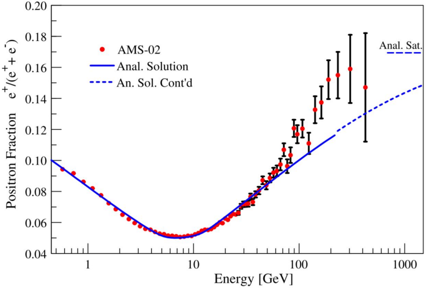
As $N \sim 10^{19}$, $I = 13.6$ eV, ionization energy only~ 100 Jouls

- 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

E in MC: Injection/acceleration of e^+ and $\bar{p}$ into DSA

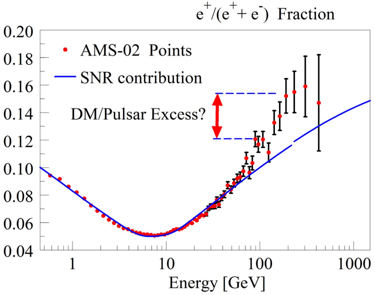
- electric field traps e^- and some $\bar{p}$ inside MC
- ejects secondary e^+ →charge-sign asymmetry

PHYSICAL REVIEW D **94,** 063006 (2016)



- $e^+$are pre-accelerated in **E** to $\lesssim 1$ GeV and readily injected into DSA
- at $E_e \lesssim$ few GeV, e^+ spectrum is dominated by the subshock compression ratio, r_s
  - spectral index $q = q_s \equiv 3r_s/\left(r_s - 1\right)$ and the spectrum $f_{e^+} \propto p^{-q_s}$.
- at higher energies, particles perceive higher flow compression
  - PL-index inside the source $q \to 3.5$

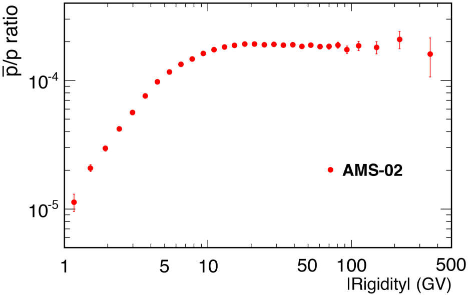
e^{+}spectra, compared and contrasted to e^{-}



- e^{-} are from the TP phase with p^{-4} source spectra (and other TP-SNRs)
- $\Longrightarrow$ $e^{+}/\left(e^{-}+e^{+}\right)$-spectrum $= p$–spectrum in $p^{4}f\left(p\right)$ customary normalization

- ratio $e^{+}/\left(e^{-}+e^{+}\right)$ is de-propagated and probes directly into the positron accelerator!
- before DM/pulsars are declared responsible for the excess above the SNR (blue curve), the following (prosaic) aspects may be considered:
  1. e^{+} release from MC farther upstream (additional spectrum hardening)
  2. synchrotron pile-up near the cut-off energy
  3. electrostatic breakdown of MC with enhanced e^{+} generation

Antiprotons



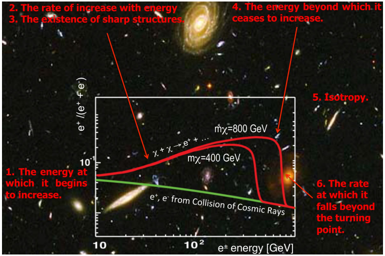
- If most of $\bar{p}$ and p come from the same source as e^+ ($\bar{p}$ generated in MCs ahead of SNR shock), the $\bar{p}$ and e^+ spectra should be the same as p at $E \gtrsim 10$ GeV
- Similarly, $\bar{p}/p$ should be flat if $\bar{p}$ are co-injected (albeit as secondaries) into any SNR-DSA process
- Decline of $\bar{p}$ at lower energies is consistent with electrostatic retention in MC
- Solar modulation may also contribute to $p - \bar{p}$ difference at lower energies
- Flat $\bar{p}/p$ should continue up to $p \sim p_{\mathrm{max}}$ and decline at $p \gtrsim p_{\mathrm{max}}$ (secondaries with no acceleration)

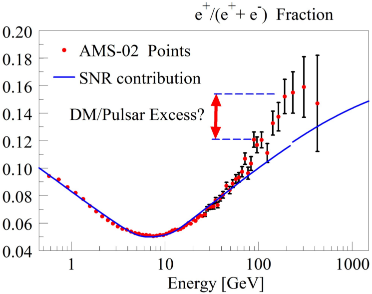
Conclusions

- secondary positrons from pp collisions in MCs ahead of SNR, expelled into shock precursor are seeded for DSA
- shock-accelerated positrons develop a concave spectrum, characteristic for the NL DSA.
- most of the negatively charged light secondaries (e^-), and to some extent, $\bar{p}$, remain inside MCs making less ($\bar{p}$), or almost no contribution (e^-) to the overall spectrum, compared to e^+
- 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 is not fully accounted for only in the range $\sim 200 - 400$GeV, BUT:
- physical phenomena to be included in the next-step model (e^+/e^- run-away breakdown, Syn. pile-up, etc.) are may suffice for a conventional explanation of the residual excess

Message to the Observers

Not every bump in the data is from DM





Rigidity Law of Shock Acceleration and Propagation

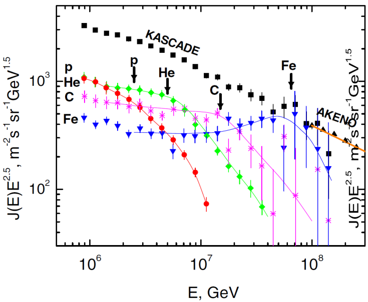
- Equations of motion, written for particle rigidity $\boldsymbol{\mathcal{R}} = \mathbf{p}c/eZ$ instead of momentum:

$$\frac{1}{c}\frac{d\boldsymbol{\mathcal{R}}}{dt} = \mathbf{E}(\mathbf{r},t) + \frac{\boldsymbol{\mathcal{R}} \times \mathbf{B}(\mathbf{r},t)}{\sqrt{\mathcal{R}_0^2 + \mathcal{R}^2}},$$

$$\frac{1}{c}\frac{d\mathbf{r}}{dt} = \frac{\boldsymbol{\mathcal{R}}}{\sqrt{\mathcal{R}_0^2 + \mathcal{R}^2}}.$$

- EM-fields $\mathbf{E}(\mathbf{r},t)$ and $\mathbf{B}(\mathbf{r},t)$ are arbitrary
- $\rightarrow$ all species with $\mathcal{R} \gg \mathcal{R}_0 = Am_pc^2/Ze$ (A is the atomic number and m_p- proton mass, so $\mathcal{R}_0 \sim A/Z$ GV), have identical orbits in the phase space $(\mathbf{r}, \boldsymbol{\mathcal{R}})$.
- species with different A/Z should develop the same rigidity spectra at $\mathcal{R} \gg \mathcal{R}_0$, if they enter acceleration at a constant ratio

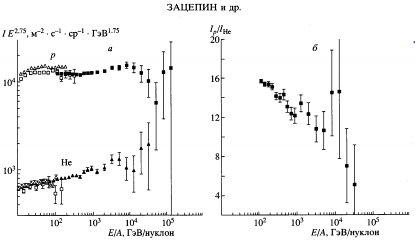
Some support for Rigidity Law



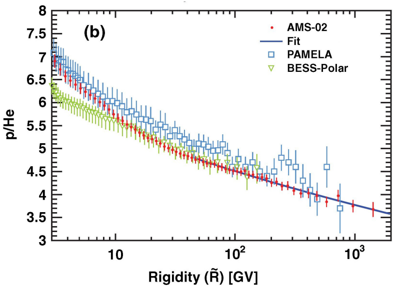
CR spectra of different elements in the knee area (from Berezinsky Review)

- cut-offs of different elements are organized by rigidity rule for acceleration and propagation
- if p's and He^{2+} start acceleration at $\mathcal{R} \gg \mathcal{R}_0$ in a ratio N_p/N_{He}
- this ratio is maintained in course of acceleration and the rigidity spectra must be identical
- if both species propagate to observer without collisions, they should maintain the same N_p/N_{He}
- DSA predicts distribution $\propto \mathcal{R}^{-q}$ where, q depends on Mach number as $q = 4/\left(1 - M^{-2}\right)$

Violation of Rigidity Law



Zatsepin et al. 2004 (ATIC)



AMS-02 (2015) results along with earlier data

<u>Key Distinction:</u>

- Several instruments revealed deviation (≈ 0.1 in spectral index) between He and p's, claimed inconsistent with DSA (e.g., Adriani et al 2011)
- DSA predicts a flat spectrum for the He/p ratio
- similar result obtained recently by AMS-02 for C/p ratio
- points to initial phase of acceleration where elemental similarity (rigidity dependence only) does not apply
- A/Z is the same for He and C

Some explanations of He spectral hardening

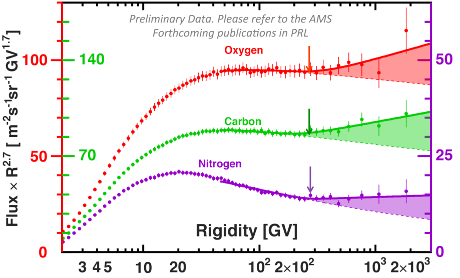
- three different types of SNRs contribute Zatsepin & Sokolskaya (2006)
- outward-decreasing He abundance in certain SNR, such as super-bubbles, result in harder He spectra, as generated in stronger shocks Ohira & Ioka (2011)
- He is neutral when processed by weak shocks. It is ionized when the SNR shocks are young and strong, Drury, 2011
- p/He --Forward/reverse SNR shock, Ptuskin & Zirakashvili, 2012

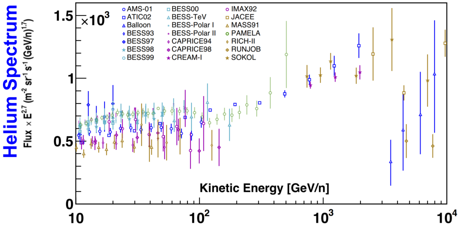
Issues:

- most suggestions are hard to reconcile with Occam's razor principle
- tension with the He-C-O striking similarity
- spallation scenarios overproduce CR secondaries

Recent AMS-02 hint on the origin of p/He Anomaly

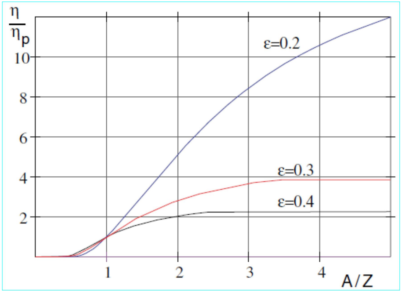
Kounine, AMS-02 (2017) ICRC 2017





- flat C/He ratio eliminates most scenarios
- points to initial phase of acceleration, *injection*, where elemental similarity (rigidity dependence only) does not apply
- A/Z is the same for He and C
- $\mathcal{R}_0 = Am_pc^2/Ze$ that determines the injection from thermal plasma also the same

Occam's approach to p/He acceleration by DSA@SNR



Injection efficiency (normalized to proton, MM'98)

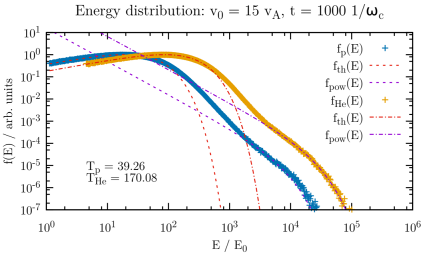
Assumptions:

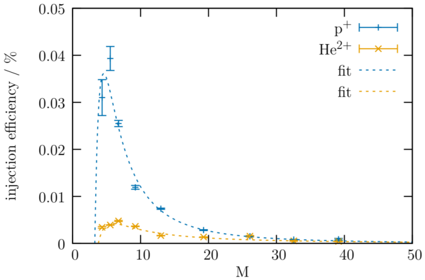
- single source (SNR)
  - shock propagates into ionized homogeneous plasma
- shock radius $R(t)$ and Mach (t) from Sedov-Taylor solution

Main ideas:

- preferential injection of He into DSA for higher Mach numbers
- injection dependence on A/Z and on ϵ, inverse wave amplitude $\epsilon \sim B_0/\delta B \propto M^{-1}$
- $\eta_{\rm inj}$ saturates with A/Z (cf $(A/Z)^2$ -? Caprioli's talk on Monday). Physically, should even $\to 0$ for $A/Z \to \infty$
- injection bias is due to Alfven wavesf driven by protons, thus retaining protons downstream more efficiently than He, C and other high A/Z species

Validating Physical ideas by hybrid Simulations

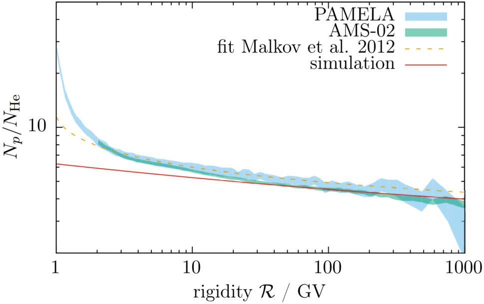




- 1D in configuration space, full velocity space simulations
  - shock propagates into ionized homogeneous plasma
- p and He are thermalized downstream according to Rankine-Hugoniot relations
- preferential injection of He into DSA for higher Mach numbers is evident
- injection dependence on Mach is close to theoretically predicted $\eta \sim M^{-1} \ln M$ (MM'98)

plots from A. Hanusch, T. Liseykina, MM, 2017

p/He ratio integrated over SNR life



p/He from A. Hanusch, T. Liseykina, MM, 2017

- p/He result automatically predicts the p/C ratio since the rest rigidity (A/Z) is the same for C and He

Some Conclusions

- the p/He ratio at $\mathcal{R} \gg 1$, is not affected by CR propagation, regardless the individual spectra
- telltale signs, intrinsic to the particle acceleration mechanism
- reproducible theoretically with no free parameters
- PIC and hybrid simulations confirm p and He injection scalings with Mach number Hanusch et al, ICRC 2017