Cosmic ray $e^{\pm}$ at high energy: A local and recent origin for TeV cosmic-rays?

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joint work with Kfir Blum

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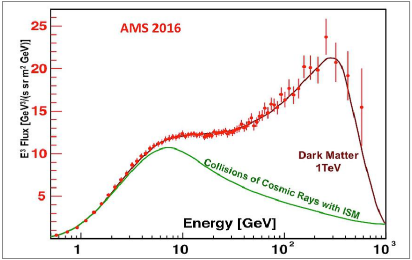
bctp Bethe Center for Theoretical Physics

Why study Cosmic Positrons?

- anomaly? dark matter and pulsar interpretation in tension with observations
- secondary origin?!
- e^+ and e^- sensitive to propagation time → learn about cosmic ray transport



[AMS-02]

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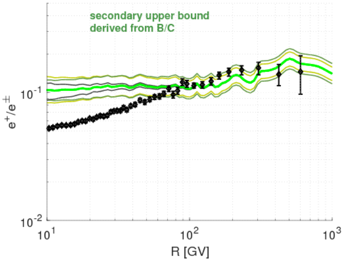
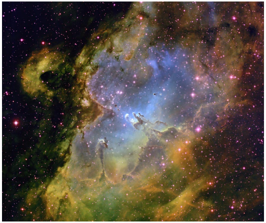


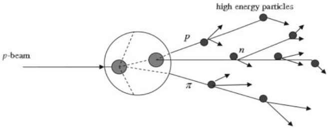
[Blum, Sato, Waxman '17]

Plan

The Origin of Cosmic Rays

- primary sources: SNRs, pulsars (?), dark matter ?, ...
- secondary particles: produced by spallation of cosmic rays
  → can be derived from interstellar fluxes and differential cross sections
  → (presumably) purely secondary particles: B, $\bar{p}$, e^+ ?!
  → tell us about how particles propagate in the galaxy



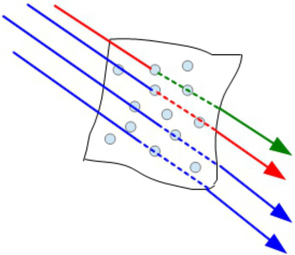


Production of Secondary Cosmic Rays

Secondary Cosmic Rays are produced by the spallation of (mainly primary) Cosmic Rays on the Interstellar Medium

net source term (for heavy nuclei):

$$Q = \sum_P n_P \frac{\sigma_{P \to S}}{m} - n_S \frac{\sigma_S}{m}$$



$n =$ cosmic ray flux
$\sigma =$ spallation cross section
$m =$ average mass of ISM $\approx 1.3 m_\mathrm{p}$

Cosmic Ray Transport

- more or less complex models $\rightarrow$ many assumptions
- model-independent approach: assume simple scaling law

[Ginzburg et al.]

$$\frac{n_a}{n_b} = \frac{Q_a}{Q_b} \quad \Rightarrow \quad n_a = X_{\text{esc}} Q_a$$

with $X_{\text{esc}} = \frac{n_b}{Q_b} =$ 'grammage' [g/cm^2], independent of particle species b, does depend on particle's rigidity $\mathcal{R} = \frac{p}{Z}$

meaning: average column density 'seen' by cosmic rays

For leptons, energy losses can be relevant: $n_{e\pm} = f_e X_{\text{esc}} Q_{e\pm}$

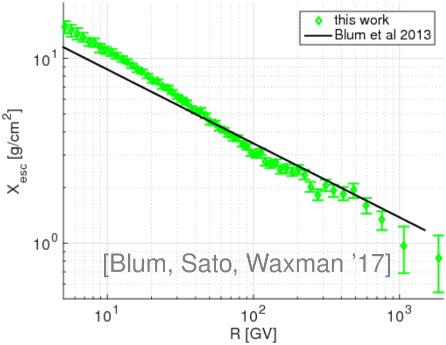
Compute Grammage from Boron/Carbon

$$X_{\rm esc} = \frac{n_B}{Q_B} = \frac{(n_B/n_C)}{\sum_P (n_P/n_C)\frac{\sigma_{P\to S}}{m} - (n_B/n_C)\frac{\sigma_B}{m}}$$

flux ratios: measured cosmic ray data

cross sections: measured in various experiments

roughly 20% uncertainty, mainly from cross sections

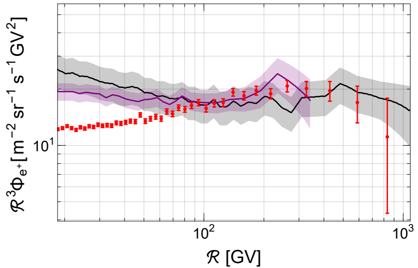


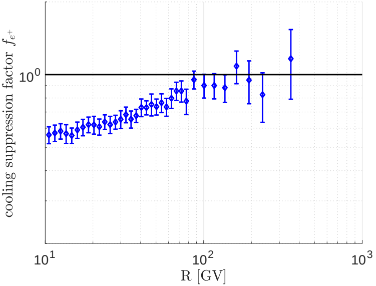
Upper Bound on the Secondary Positron Contribution

Setting $f_e = 1$ results in an upper bound on the sec. positron flux:

[Katz, Blum, Waxman '09]

$n_{e\pm} = X_{\rm esc} Q_{e\pm}$ $\qquad$ $n_{e\pm} = \frac{n_{\bar{p}}}{Q_{\bar{p}}} Q_{e\pm}$

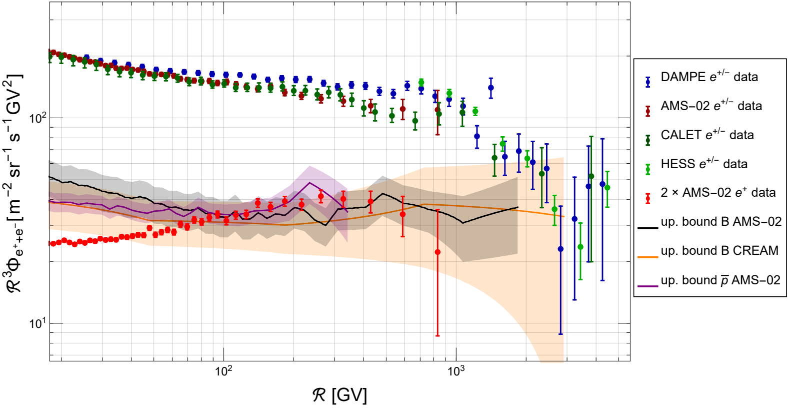




The measured loss suppression factor is ≤ 1 (!!)

Secondary Part in the measured $e^+ + e^-$ Spectrum

here: secondary positrons ≈ secondary electrons



The upper bound on the secondary contribution saturates with the measured spectrum above a few TV.

Secondary origin of high energy $e^{\pm}$?

Comparison of $e^{+}(+e^{-})$ data with the sec. upper bound reveals:

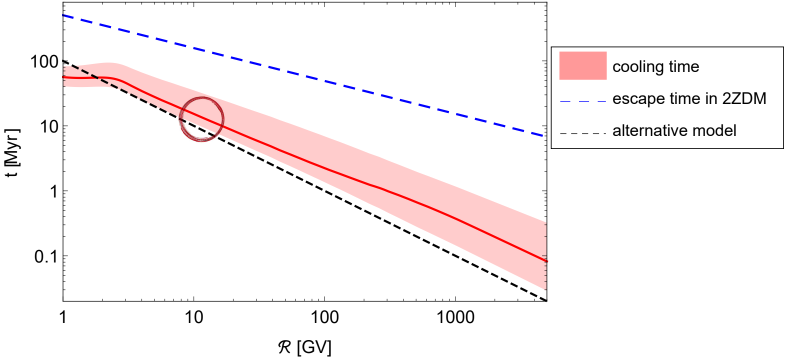
- the measured positrons can be secondary!
- the measured $e^{-} + e^{+}$ above the cooling break, i.e. around few TV, can be secondary!

If so, it implies that energy losses are not relevant up to these energies, i.e. the cooling time must be small.

Is that possible?!

(Ir)relevance of Energy Losses

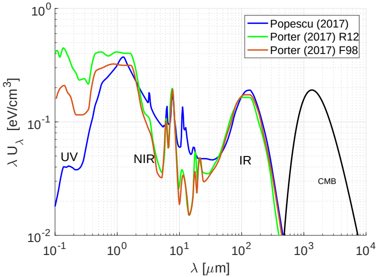
For leptons, energy losses play an important role $\underline{\text{if } t_{\text{cool}} < t_{\text{esc}}}$.

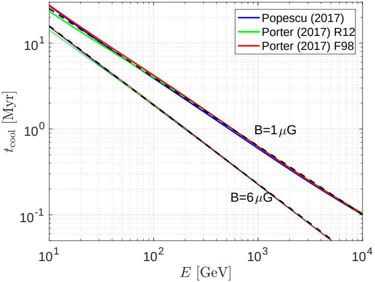


Direct measurement of escape time through radioactive nuclei point towards $t_{\text{esc}} \sim 10$ Myr at 10 GV. [see e.g. Blum et al. ’17]

Cooling Time

The main uncertainties on the cooling time come from the galactic magnetic field.





Secondary $e^{\pm}$ at $E \gtrsim 3$ TeV require short propagation time.

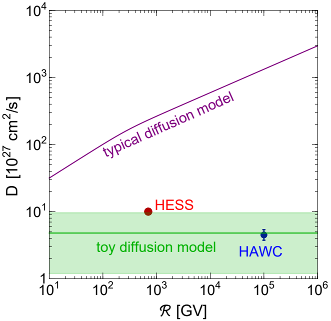
Observational Constraints

Secondary $e^{\pm}$ beyond 1 TV require $t_{\mathrm{esc}} \lesssim 0.1$ Myr at this rigidity.
Does any observation constrain this requirement?

- radioactive nuclei → $t_{\mathrm{esc}} \sim 10$ Myr at 10 GV → consistent
- anisotropic GMF and simulations [see e.g. Giacinti, Kachelriess, Semikoz]
  → transport away from the disc → support short escape time
- $\langle n_{\mathrm{ISM}} \rangle = \frac{X_{\mathrm{esc}}}{1.3\, m_p\, c\, t_{\mathrm{esc}}} \approx (3.5 \pm 1.5)\ \mathrm{cm}^{-3}$ at $\mathcal{R} = 3$ TV
  → conflict with Local Bubble and slow diffusion?

Size and Density of the Diffusion Region

- diffusion coefficient measured by HAWC and HESS (no hint for rigidity dependent diffusion)
- within 0.1 Myr, TV cosmic rays travel $\mathcal{O}(100)$ pc
- Local Bubble: underdense region of radius $\sim$ 100 pc, possibly overdense regions at the boundary



Is it possible that $\langle n_{\rm ISM} \rangle \approx$ few $\rm cm^{-3}$ in the propagation region?

$\rightarrow$ work in progress

Explicit Models

motivation: anisotropic GMF → escape height depends on rigidity

Toy Model 1: **Diffusion Model** w/ rigidity dependent boundary L

$$X_{\rm esc} \propto \frac{L}{D}\,, \qquad t_{\rm esc} \propto \frac{L^2}{D}$$

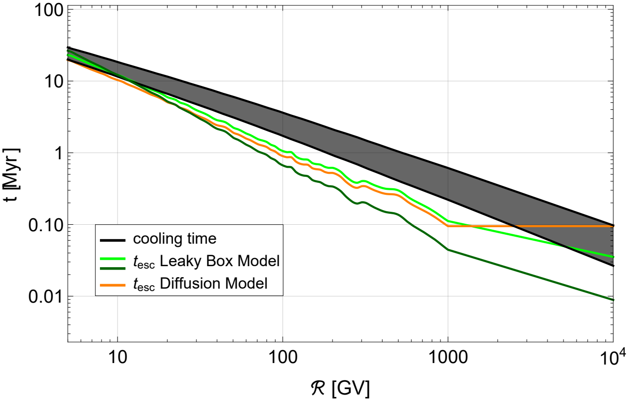
- $L \propto X_{\rm esc} \sim \mathcal{R}^{-0.5}$ and $D =$const. reproduces nuclei
- $t_{\rm esc} \propto \mathcal{R}^{-1}$ falls faster than $t_{\rm cool} \propto \mathcal{R}^{0.8-1}$

Toy Model 2: **Leaky Box Model** w/ rigidity dependent volume V

$$X_{\rm esc} \propto \frac{N}{V} t_{\rm esc}$$

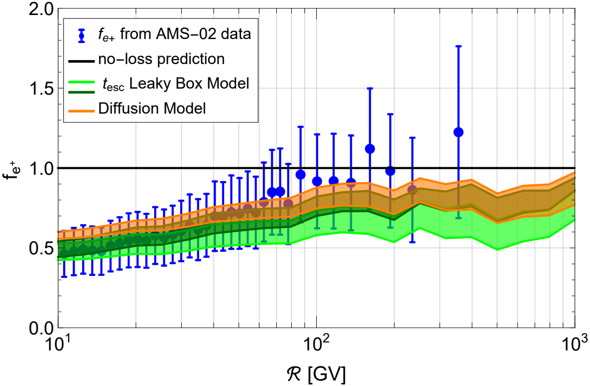
- if N/V increases sufficiently fast with $\mathcal{R}$, $t_{\rm esc}$ can be smaller than $t_{\rm cool}$

Relevant Timescales of the Toy Models



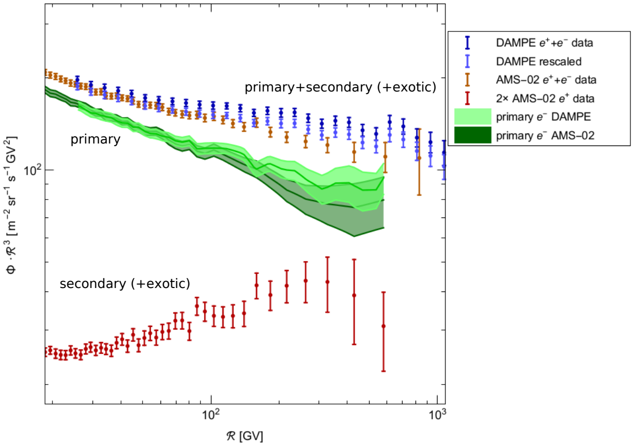
When the cooling time becomes smaller than the escape time, energy losses are relevant.

Loss Suppression Factor in the Toy Models



The observed positron loss suppression factor is reproduced.

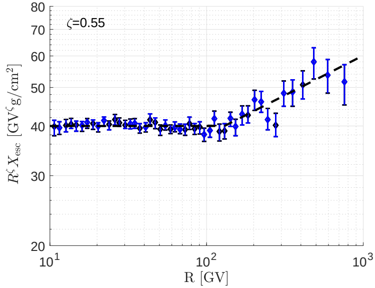
Disentangle the Electron Component

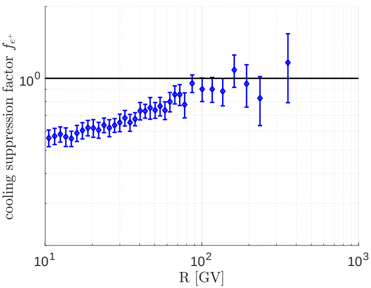


$$\underbrace{e^+ + e^-}_{\textit{primary+secondary}} \quad - \quad \underbrace{2 \cdot e^+}_{\textit{''secondary''}} \quad = \quad \underbrace{e^-}_{\textit{primary}}$$

Coincident Trends in Nuclei and Positrons

Spectral hardening of CR grammage and saturation of loss suppression factor f_{e^+} at same rigidity:





Summary

Secondary interpretation of positrons and $e^- + e^+$ at high rigidity after all – possible.

★

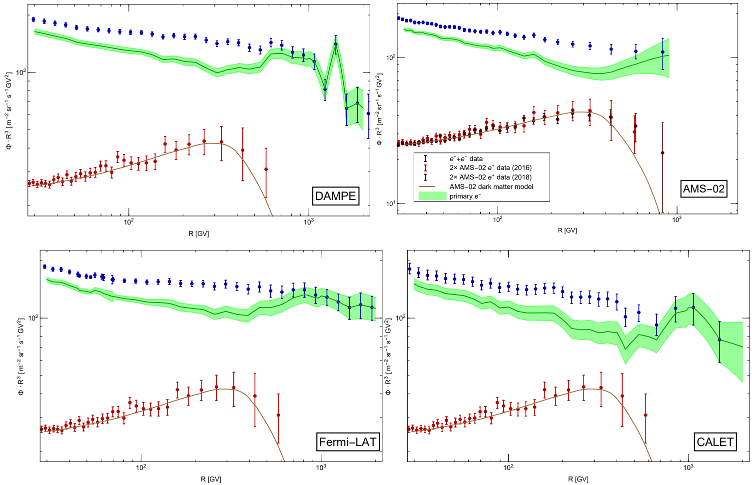
Secondary $e^- + e^+$ at a few TV require short propagation time $t_{esc} \leq 0.1$ Myr which implies $\langle n_{ISM} \rangle \approx$ few cm^{-3} in the propagation region.

★

Crucial implications on the propagation volume and thus on indirect dark matter limits!

If the e^+ came from dark matter...

...or a pulsar or any source with a sharp cutoff, the primary electron flux would look like this:



A double kink in the primary electron spectrum → unphysical!