The 'forgotten' neutrons: propagation of high-energy cosmic rays in magnetized astrophysical and cosmological structures

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Background

- Cosmological filaments, galaxy clusters, and galaxies are magnetized reservoirs of cosmic rays (CRs).
- The propagation of CRs in and across these structures is usually modeled assuming that they remain charged.
- At high energies, hadronic interactions can **convert CR protons to neutrons**, which can propagate ballistically over kpc-Mpc distances before decaying back into protons with the aid of relativistic time dilation.

Method

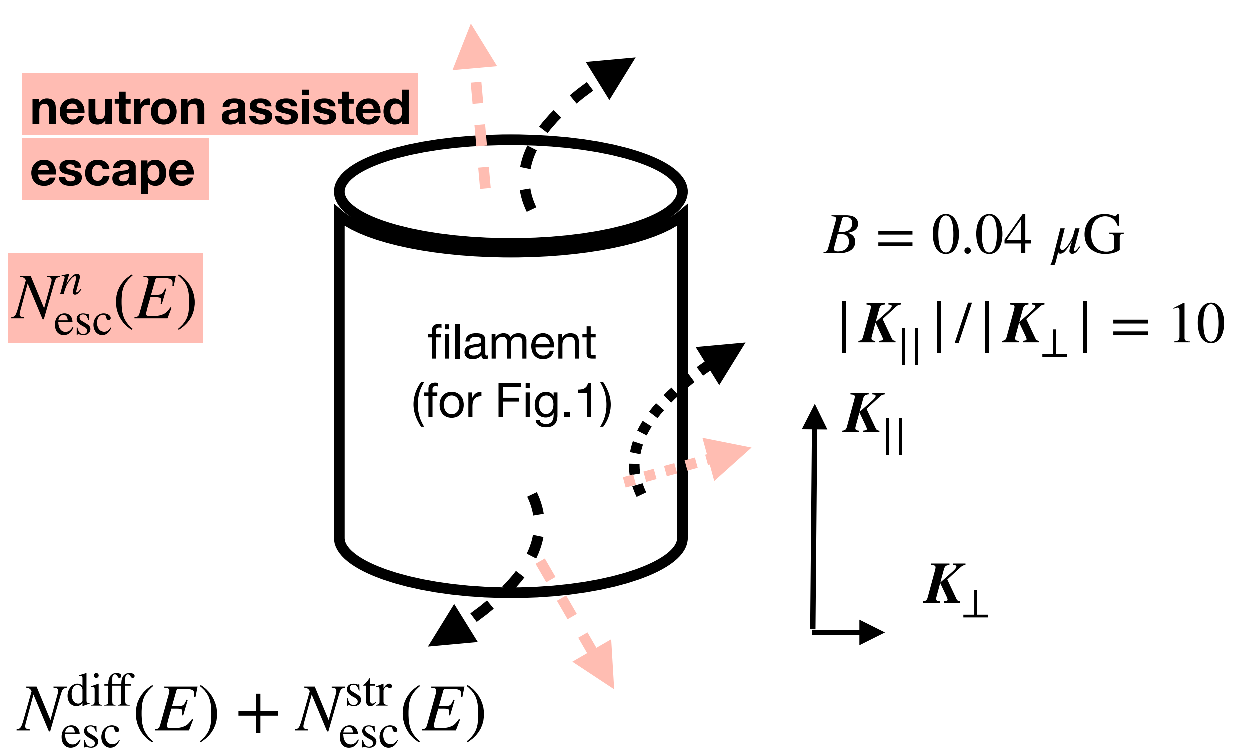
We consider 4 representative environments: (1) Milky-Way-like galaxy, (2) starburst galaxy, (3) galaxy cluster, (4) cosmological filament. CRs are accelerated there and we model their propagation with the transport equation below:

$$\frac{\partial n}{\partial t} = \underbrace{\Big[\overbrace{\nabla\cdot(\boldsymbol{K}\cdot\nabla n)}^{\text{diffusion}} + \overbrace{\boldsymbol{v}_s\cdot\nabla n}^{\text{streaming}} + \overbrace{\frac{\partial}{\partial\gamma}(bn)}^{\text{cooling}} + \overbrace{Q}^{\text{injection}}\Big]}_{\text{deterministic}} + \underbrace{h(\gamma,\boldsymbol{x},t)\frac{\mathrm{d}J_t}{\mathrm{d}t}}_{\text{stochastic}}$$

In addition to the traditional diffusion, streaming, hadronic pp and pγ interactions, we model the **charged (proton)-neutral (neutron) switching** as a stochastic Poisson "jump" process.

Filament example below: cylindrical shape + characteristic B field + radiation + gas

CR particles may escape from the curved surface (side) or the top/bottom (end).

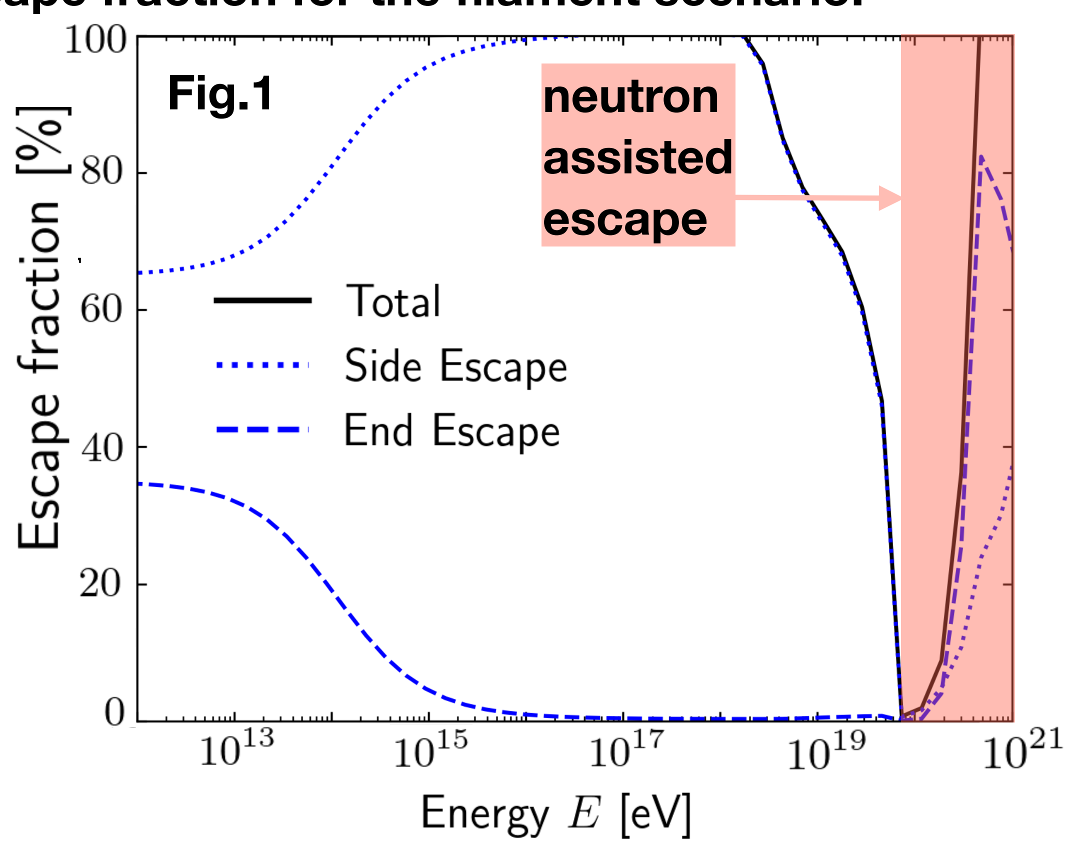


Key Results

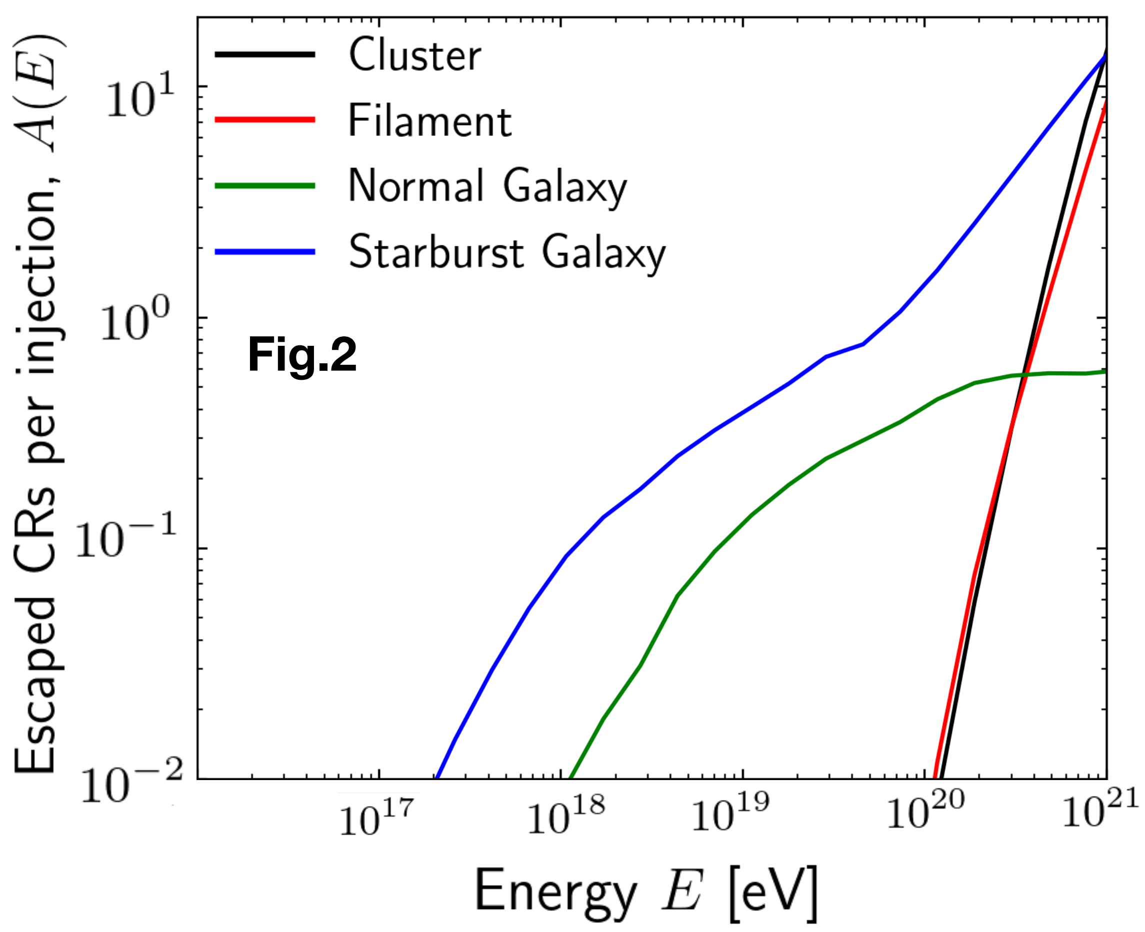
We define escape fraction as:

$$f_{\rm esc}(E) = \frac{N^{\rm diff}_{\rm esc}(E) + N^{\rm str}_{\rm esc}(E) + N^{n}_{\rm esc}(E)}{N_{\rm inj}(E)} \qquad A(E) = \frac{N^{n}_{\rm esc}(E)}{N_{\rm inj}(E)}$$

Escape fraction for the filament scenario:



Escape per injection for all 4 scenarios:



Conclusion and Outlook

- **Neutron-mediated steps yield CR escape** at energies where charged-particle transport alone would predict strong confinement (Fig.1).
- More than one escaping nucleon per injected CR primary is found in the 4 scenarios **at ultra-high energies** (Fig.2).
- Neutron formation can alter the geometry of the emergent CR flux escaping from structures, **suggesting a qualitative shift in how ultra-high-energy CRs are transferred from embedded sources into cosmic large scale structures**, when intermediate neutron propagation is considered.

We will CR composition-dependent treatment of these effects for more parameterised astrophysical structures in future work.

References:

1. This work (Owen et al. 2026) is under review for *Universe*
2. Construction and numerical methods for the stochastic differential equation (transport equation) can be found in e.g. Mathematical Biology Series: Stochastic Age-Structured Population Systems; Science Press, 2013 by Sun, C.L.
3. pp & $p\gamma$ events drawn from Aafrag 2.01, QGSJET-II-04m, and SOPHIA