Cosmic rays in large-scale astrophysical structures

Neutron production and implications for cosmic ray confinement and escape

Ellis R Owen[1,2*], Yoshiyuki Inoue[2,3,4], Tatsuki Fujiwara[2], Qin Han[5] and Kinwah Wu[5,3]

[1] Astrophysical Big Bang Laboratory (ABBL), RIKEN Cluster for Pioneering Research, Wako, Saitama, 351-0198, Japan
[2] Theoretical Astrophysics, Department of Earth and Space Science, The University of Osaka, Osaka 560-0043, Japan
[3] Kavli Institute for the Physics and Mathematics of the Universe (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
[4] Interdisciplinary Theoretical & Mathematical Science Program (iTHEMS), RIKEN, 2-1 Hirosawa, Saitama 351-0198, Japan
[5] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Surrey RH5 6NT, UK

ellis.owen@riken.jp

Energetic cosmic ray neutrons are produced in hadronic interactions. At ultrahigh energies, the decay timescales of these neutrons is dilated, allowing them to traverse distances on the scale of galactic and cosmological structures. Unlike charged cosmic rays, **neutrons are not deflected by magnetic fields**. They propagate ballistically at the speed of light in straight lines. The presence of **a neutral baryonic cosmic ray component** formed in galaxies, groups, clusters, or cosmological filaments **can facilitate the escape and leakage of cosmic rays from magnetic structures** that would otherwise confine them. This mechanism particularly impacts the exchange of ultrahigh-energy particles across magnetic interfaces between galaxy groups, clusters, cosmological filaments and voids.

1. Cosmic ray neutrons

Cosmic rays are energetic, relativistic particles that include hadrons and leptons. They are often considered to be charged, but some cosmic rays are actually neutral. In certain situations, the amount of neutral cosmic-ray baryons can be substantial. For instance, neutrons constitute a large fraction of the baryons in atmospheric cosmic-ray showers (e.g. Schimassek et al. 2024), and most of the cosmic-ray baryons detected at sea level on Earth are neutrons (see Ziegler 1998, Sato 2015).

Free neutrons have a lifetime of 879.6 ± 0.8 s (Particle Data Group, 2020) in their rest frame. At ultrahigh energies, the measured lifetimes of neutrons by the observer can be significantly longer due to relativistic time dilation. High-energy neutrons can therefore propagate ballistically over large distances after they are produced. A 100 PeV neutron can easily cross galaxy-scale structures, and a 10 EeV neutron can traverse a galaxy cluster or super cluster.

2. Neutron production in hadronic interactions

Cosmic rays are accelerated to relativistic energies in violent, magnetized astrophysical environments. Standard acceleration scenarios generally require these particles to be charged (e.g. Fermi 1949, Bell 1978). The fraction of neutral cosmic rays at their sources is therefore typically small. As they propagate away from their sources, cosmic-ray hadrons with energies above a threshold of ~280 MeV can interact with ambient matter (via *pp* interactions), or radiation fields (via *pγ* interactions). These interactions produce secondary particles, with a large fraction being neutrons (see Figures 1 and 2).

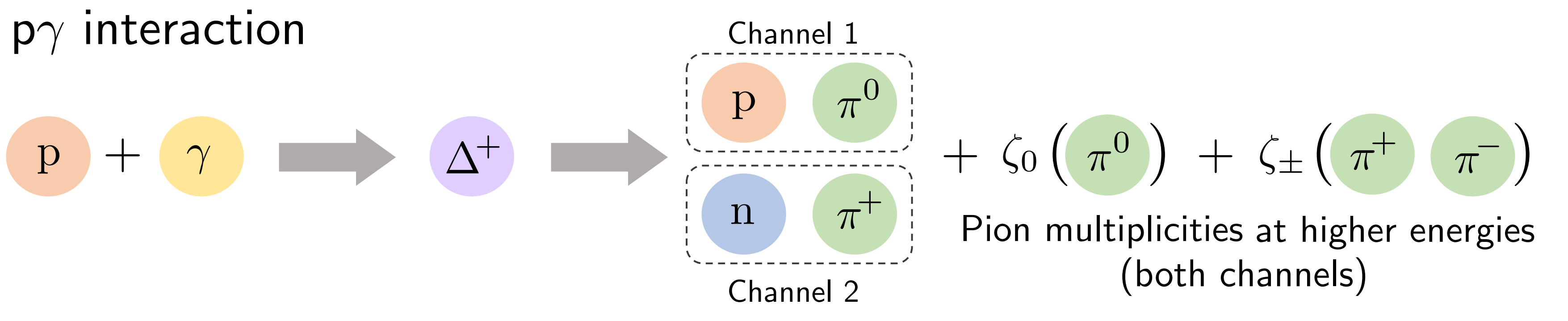
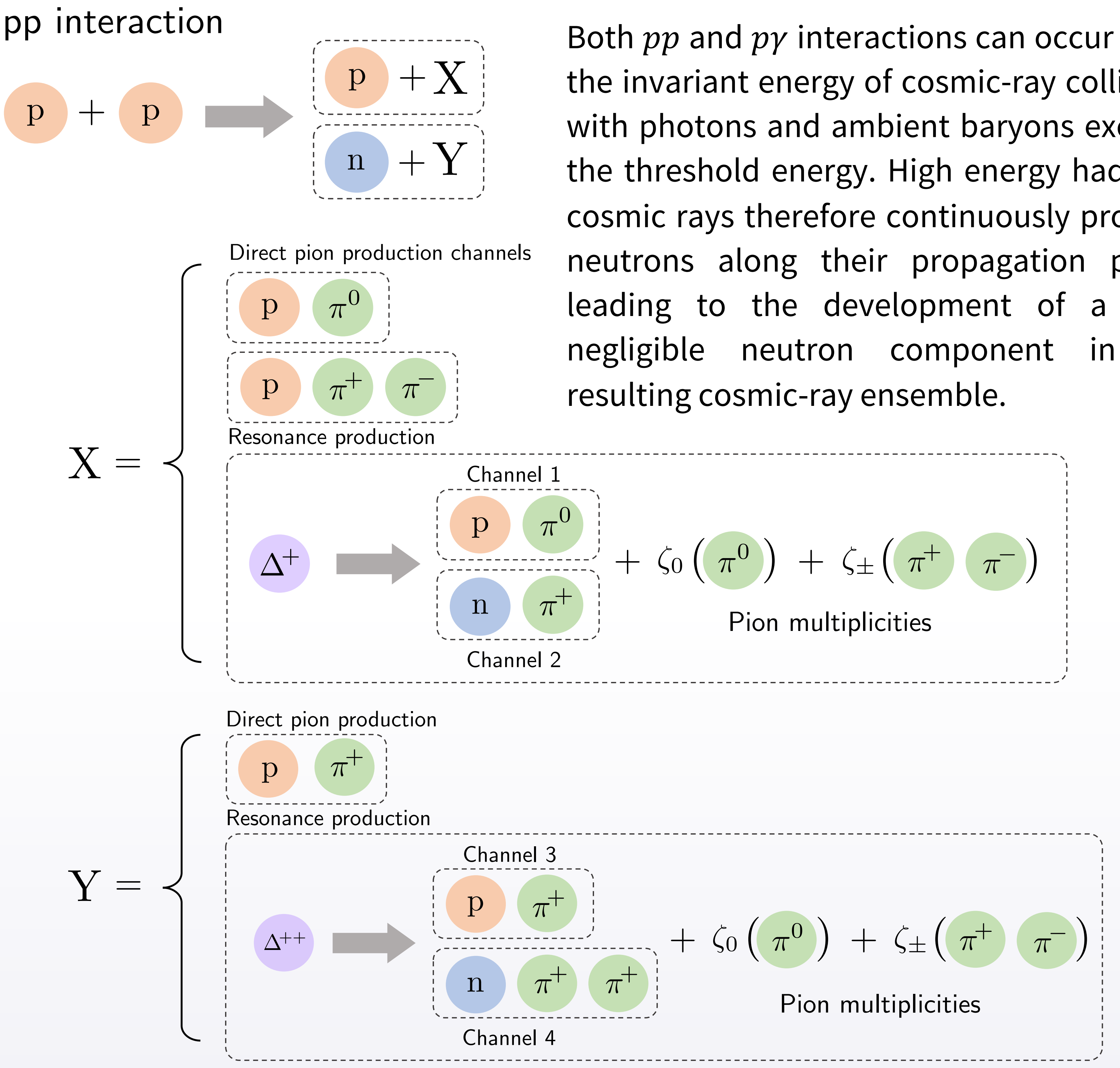


Figure 1: Photo-pion production occurs when hadrons (e.g. protons) collide with the photons of a radiation field. The dominant interactions in photo-pion production are resonant single-pion production, direct single-pion production, and multiple-pion production. Resonant single-pion production occurs through the formation of Δ+ particles. These decay through two major channels that produce charged and neutral pions, secondary protons and neutrons. Adapted from Owen (2023).



Both *pp* and *pγ* interactions can occur while the invariant energy of cosmic-ray collisions with photons and ambient baryons exceeds the threshold energy. High energy hadronic cosmic rays therefore continuously produce neutrons along their propagation paths, leading to the development of a non-negligible neutron component in the resulting cosmic-ray ensemble.

Figure 2: These are the dominant pion production channels in the pp interaction. Here, ξ_0 and $\xi_\pm$ are the multiplicities for neutral and charged pions, respectively. The Δ^+ and Δ^{++} baryons are the resonances. This interaction operates above a threshold energy of ~280 MeV, which is the proton energy required for the production of a neutral pion through the channel $pp \rightarrow pp\pi^0$. Cosmic ray neutrons are produced directly as secondary baryons, and through resonance decays. Figure from Owen (2023).

3. Cosmic rays in magnetized structures

Relativistic cosmic-ray particles propagate ballistically in free space, travelling close to the speed of light. Charged cosmic rays are deflected by magnetic fields. In regions with tangled magnetic fields (e.g. within a galaxy), deflections are continuous and randomized, making charged cosmic ray propagation effectively diffusive. Magnetic fields have structure on distinct scales, quantified by a coherence length - the scale over which a magnetic field has a coherent structure. A charged cosmic ray can be confined within a domain of coherent magnetic structure depending on its energy and the characteristic field strength and structure. This creates an energy-dependent sieve mechanism, where charged cosmic rays are magnetically confined by astrophysical and large-scale structures (see Figure 3).

A ~ 10^{19} eV **B** ~ 10^{16} eV **C** ~ 10^{12} eV

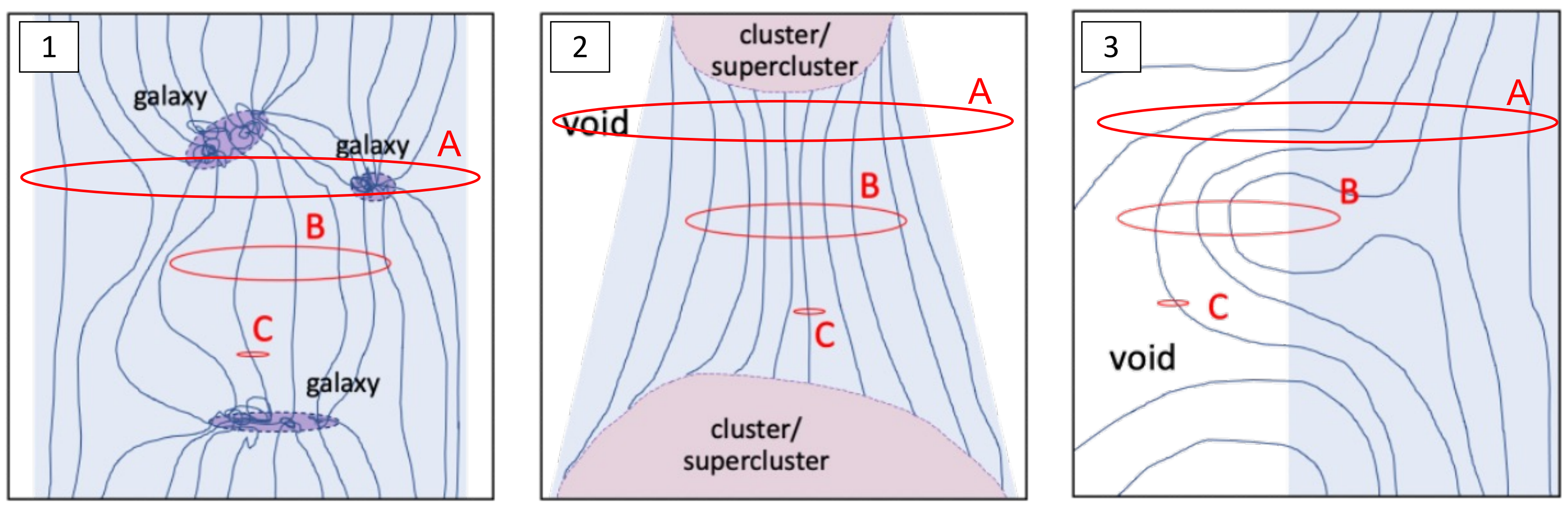


Figure 3: Schematic example of three specific situations for the confinement and propagation of energetic particles in cosmic filament environments. Panel 1 shows the interweaving structure of magnetic field lines connected between a group of galaxies embedded in a filament. Panel 2 shows the filament connecting two clusters/superclusters, where the filament magnetic field lines have a concave configuration. Panel 3 shows the closed and open magnetic field lines in the interfacing regions of a cosmic filament and a void. The gyration of the charged particles in the magnetic fields may be classified into three regimes represented by the red ellipses, not to scale, marked with A (cases where particles are not confined), B (particles are weakly confined) and C (particles are strongly confined). Adapted from Wu et al. (2024).

The escape of cosmic rays from their host magnetized structures depends on their ability to:

- Exceed the confinement energy through energization/acceleration (e.g., from gyration radius B to A in Figure 3).
- Break magnetic confinement via cross-field particle diffusion or fast tracking.
- Escape via folded fields or magnetic topologies that allow for confinement breaking (Figure 3, panel 3).
- Be directly removed by advection in magnetized flows.

The temporary conversion of charged cosmic rays to neutrons via hadronic interactions provides another escape mechanism, as neutrons are not confined by magnetic fields.

4. Neutron escape channel

Secondary neutrons produced in hadronic interactions are not affected by magnetic fields. Unless they undergo a further hadronic interaction, they propagate ballistically until they decay (survival distances are shown in Figure 4). Neutrons formed within galaxies typically experience a hadronic interaction before they escape. In larger-scale structures, ultrahigh-energy neutrons can propagate up to a few 10s of Mpc. This is sufficient to break magnetic confinement or traverse boundaries between structures (e.g. connecting filaments/galaxy clusters).

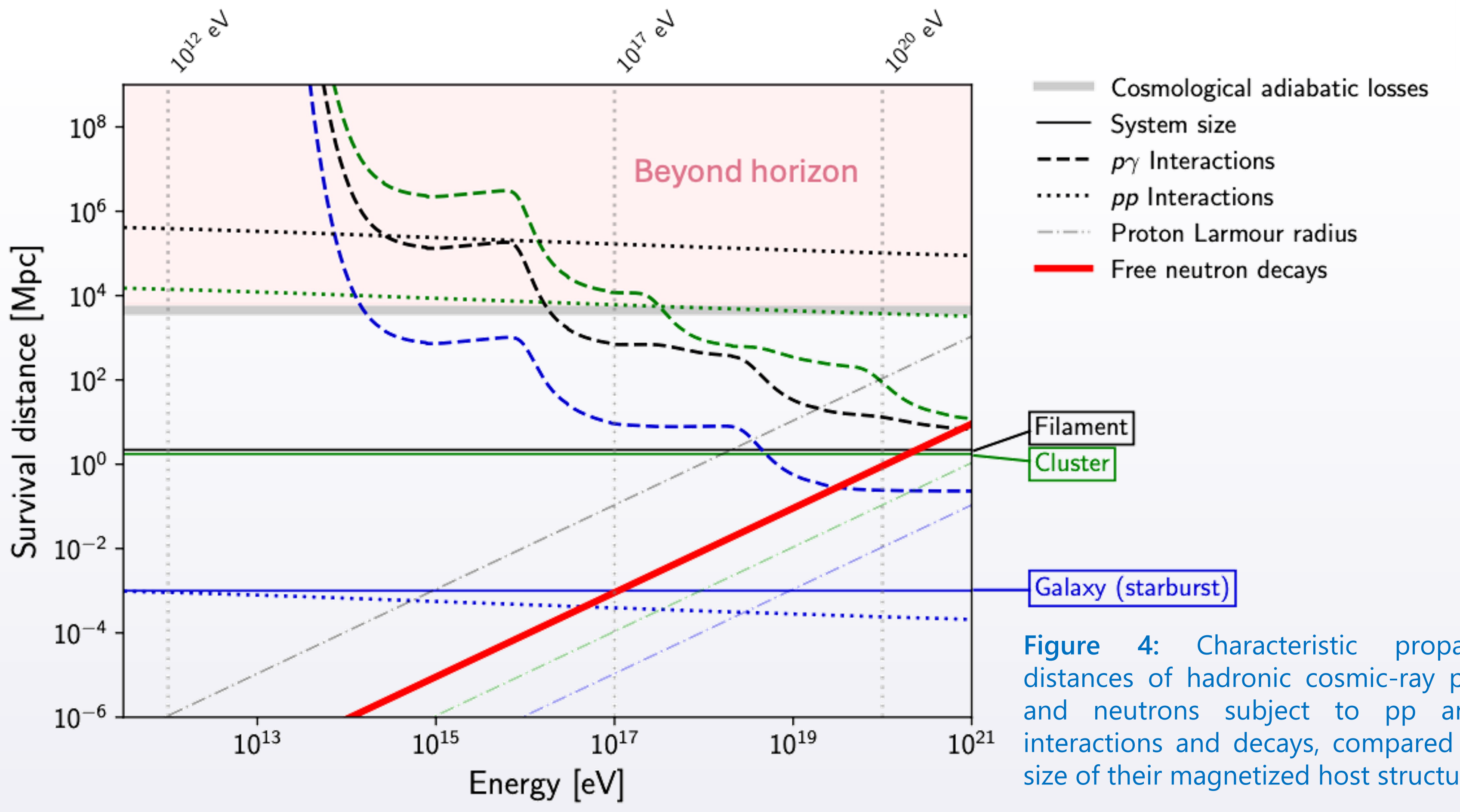


Figure 4: Characteristic propagation distances of hadronic cosmic-ray protons and neutrons subject to pp and pγ interactions and decays, compared to the size of their magnetized host structures.

References: Bell (1978), *MNRAS* 182(2): 147; Fermi (1949), *Phys. Rev.* 75: 1169; Owen (2023), *A&G* 64(1): 29; Particle Data Group (2020), *Review of Particle Physics*. Berkeley, CA: Lawrence Berkeley Laboratory; Sato (2015), *PLoS ONE* 10(12): e0144679; Schimassek et al. (2024), *Phys. Rev. D* (submitted, arXiv: 2406.11702); Ziegler (1998), *IBM J. Res. Dev.* 41(1); Wu et al. (2024), *Universe*, 10(7), 287

Acknowledgements: E.R.O. is a Special Postdoctoral Researcher, supported by the RIKEN Special Postdoctoral Researcher Program for junior scientists, and also acknowledges a Postdoctoral Fellowship of the Japan Society for the Promotion of Science (JSPS KAKENHI Grant Number JP22F22327). K.W. and Q.H. acknowledge support from the UCL Cosmoparticle Initiative. Q.H. is supported by a UCL Overseas Research Scholarship and a UK Science and Technology Facilities Council Research Studentship. Y.I. is supported by an NAOJ ALMA Scientific Research Grant Number 2021-17A, JSPS KAKENHI Grant Numbers JP18H05458, JP19K14772, and JP22K18277, and the World Premier International Research Center Initiative (WPI), MEXT, Japan.