Mullard Space Science Laboratory

Propagation and Fate of Cosmic Rays in Cosmological Ecosystem Connected by Filaments

— a phenomenological analysis

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Outline

1. Observed (and unobserved) cosmic ray population

2. *Phenomenological* analysis of cosmic ray propagation in cosmological ecosystem

3. Implications and summary

Credit: TNG simulation

Observed and unobserved populations of cosmic rays (CRs)

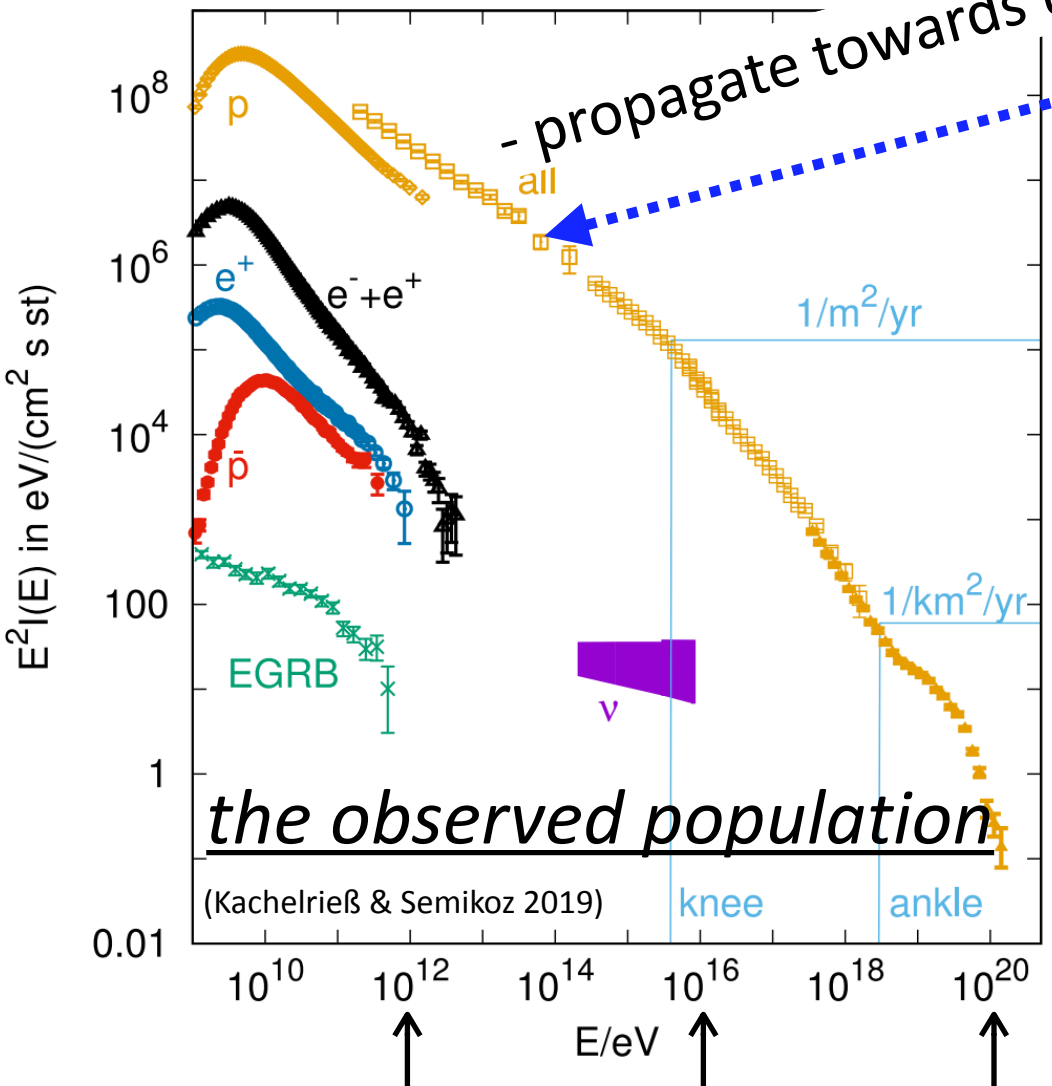
CRs accelerated in astrophysical environment

- propagate towards us

attenuation (pp, p-γ interactions)

- destructed
- propagate away from us

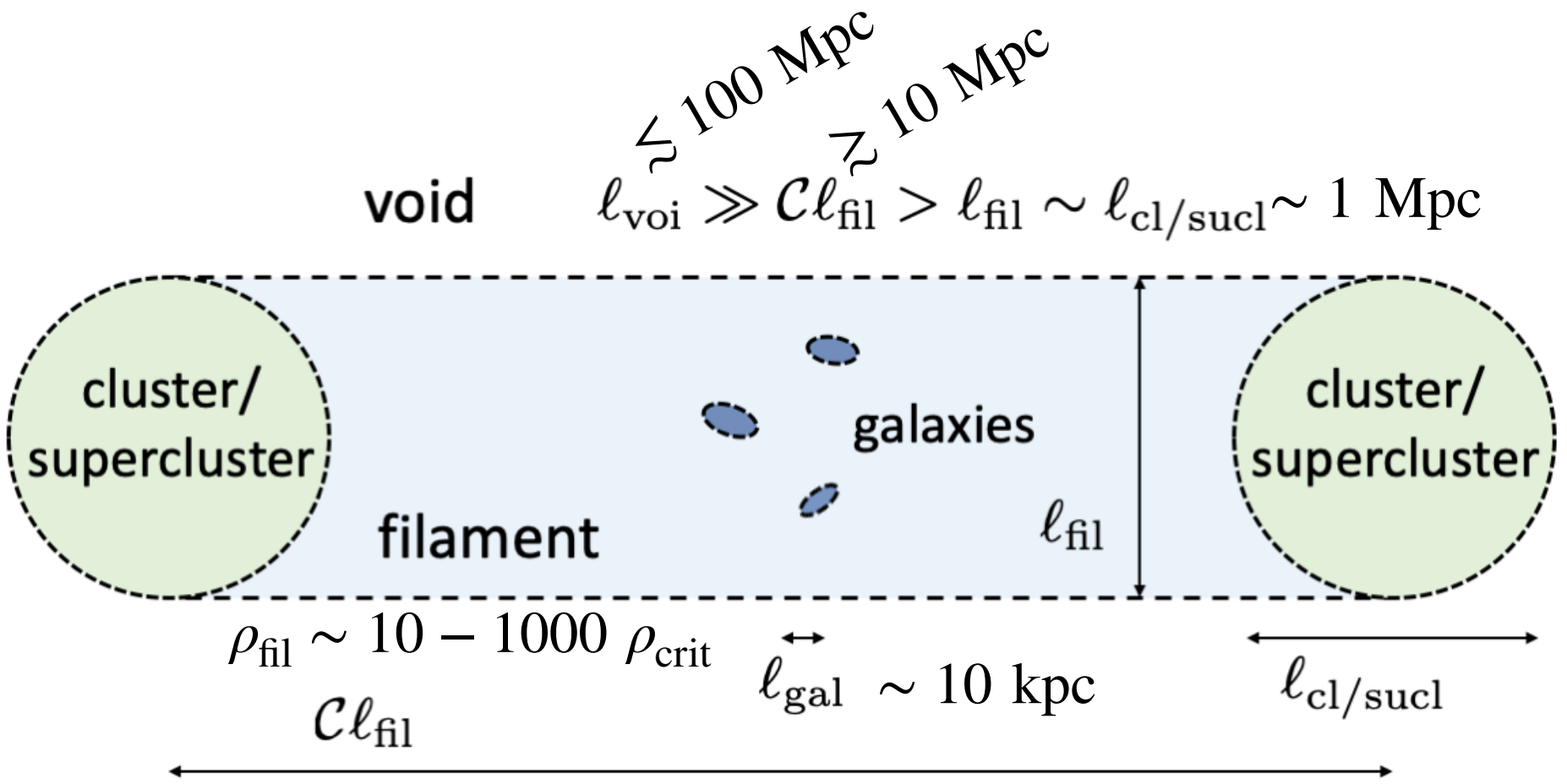
- entrained by magnetised structures



the observed population

the behaviours of a hidden population of cosmic rays

A cosmological ecosystem connected by *filament*



$B_{\rm voi} \ll 10^{-4}$ nG

$B_{\rm fil} \sim 10$ nG

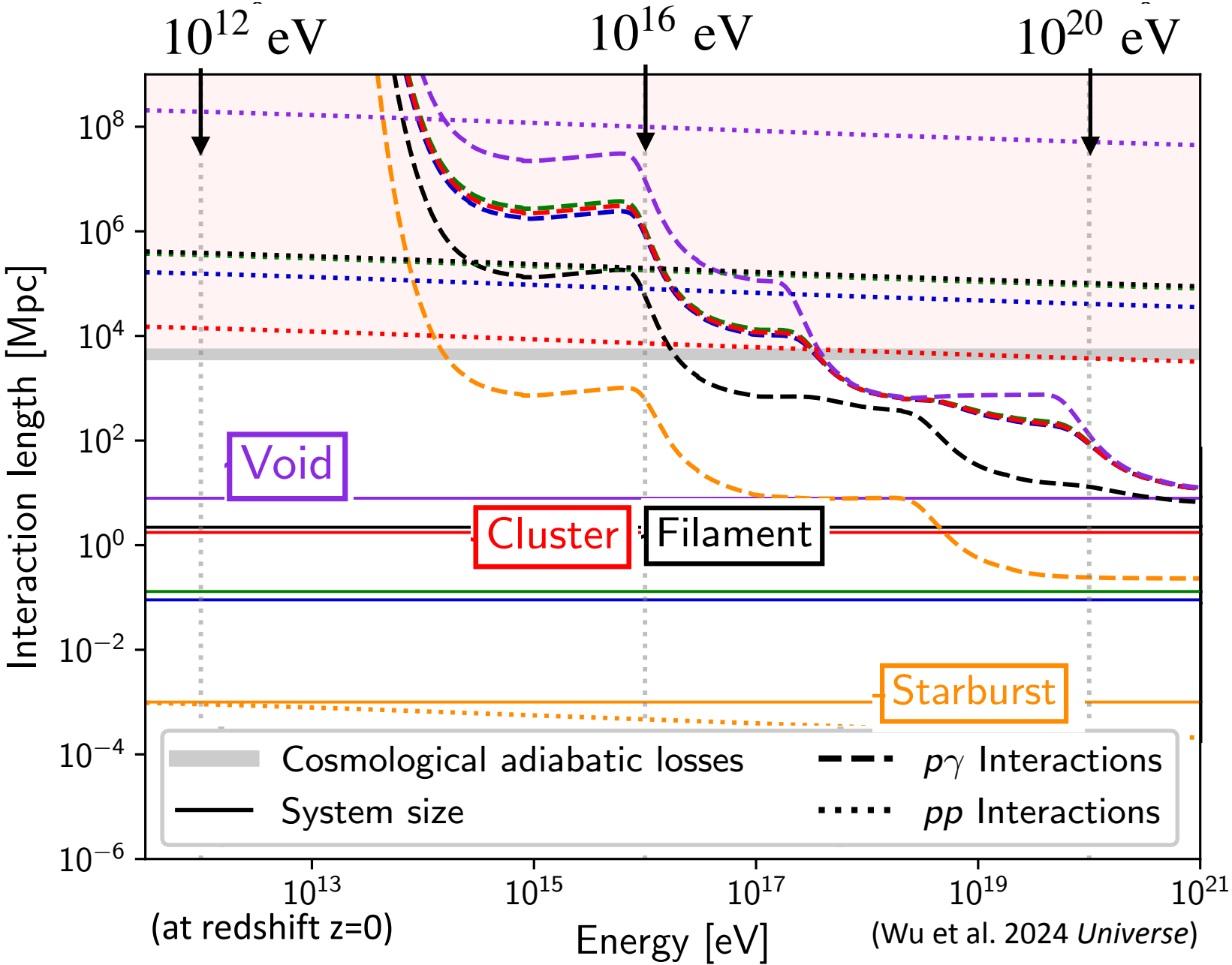
$B_{\rm cl/sucl} \sim 10\ \mu$G

(Wu et al. 2024 *Universe*)

CR proton $E = 10^{12},\ 10^{16},\ 10^{20}$ eV

gyro-radius $R \sim 0.1$ pc, 1 kpc, 10 Mpc $\cdot \left(\frac{B}{10\text{nG}}\right)^{-1}$

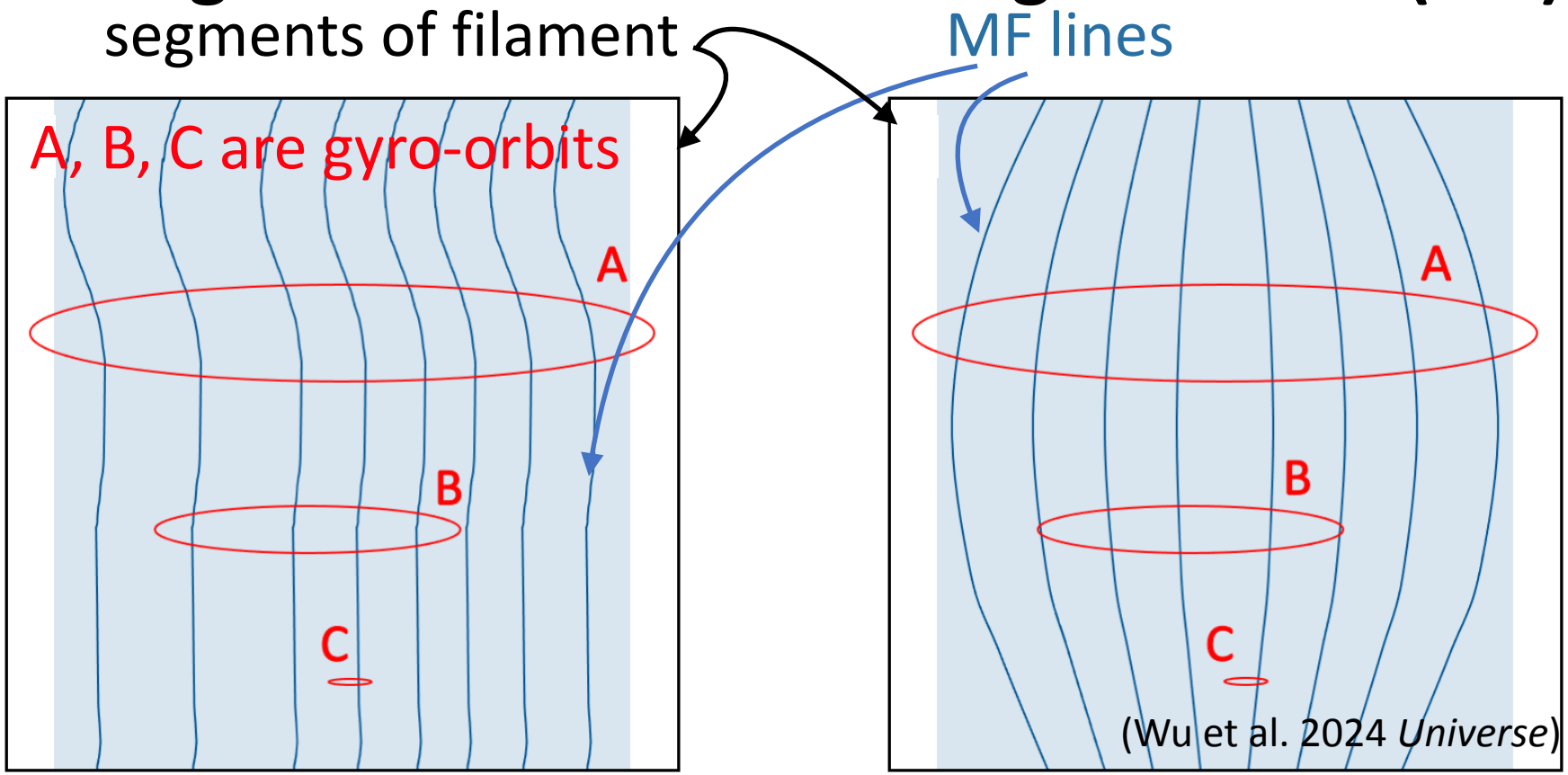
Cooling and destruction of CRs during propagation



CRs with $E \sim 10^{12} - 10^{16}$ eV do not suffer much attenuation

CRs with $E \sim 10^{16} - 10^{20}$ eV suffer from attenuation

Some generic scenarios for magnetic field (MF) configuration



- MF are ordered on the scale of the filament segment
- no significant small scale disordered MF

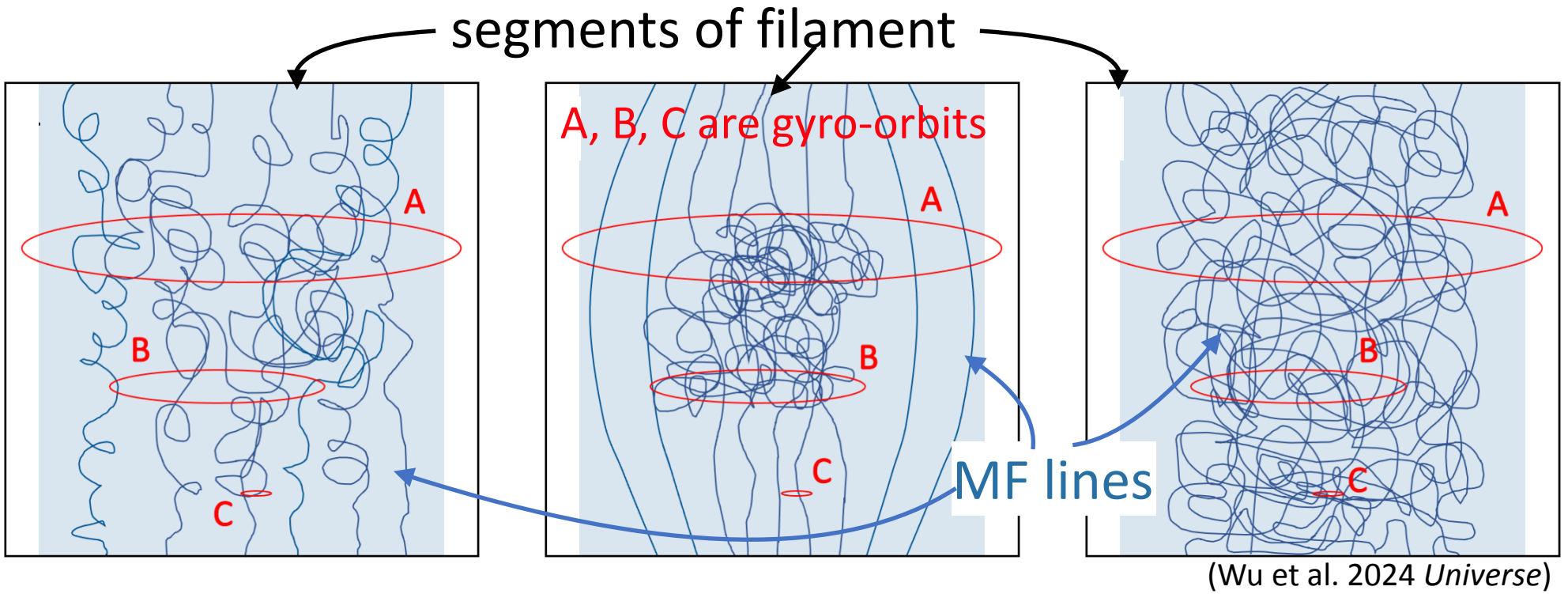
$$|B_s|/|B_g| \ll 1$$

Type A: not confined by MF

Type B: confined with diffusion (across different MF components)

Type C: confined with drifting (along MF)

When there are small scale disordered magnetic fields (MF)



(Wu et al. 2024 *Universe*)

$|B_s|/|B_g|$ increases and the small scale disordered MF dominates

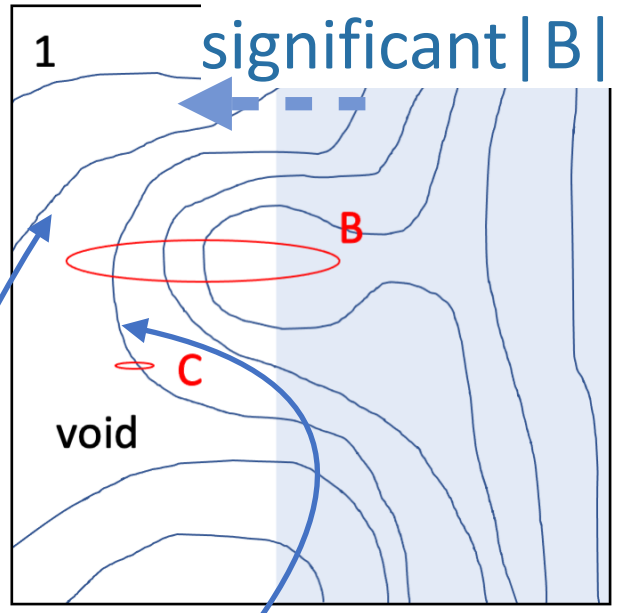
Type A: not confined

Type B: confined with (significant) diffusion

Type C: confined (guided by small scale MF)

More specific scenarios of magnetic field (MF) configuration

filament-void interface

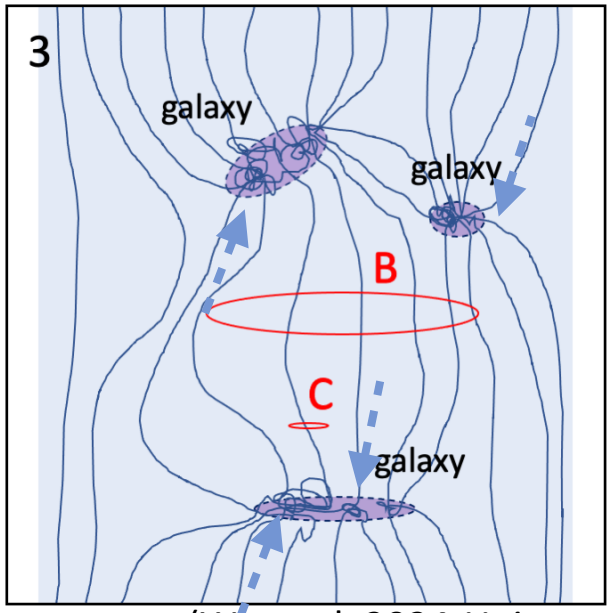


significant|B| decrease

closed MF lines

open MF lines

filament-galaxy interface



(Wu et al. 2024 *Universe*)

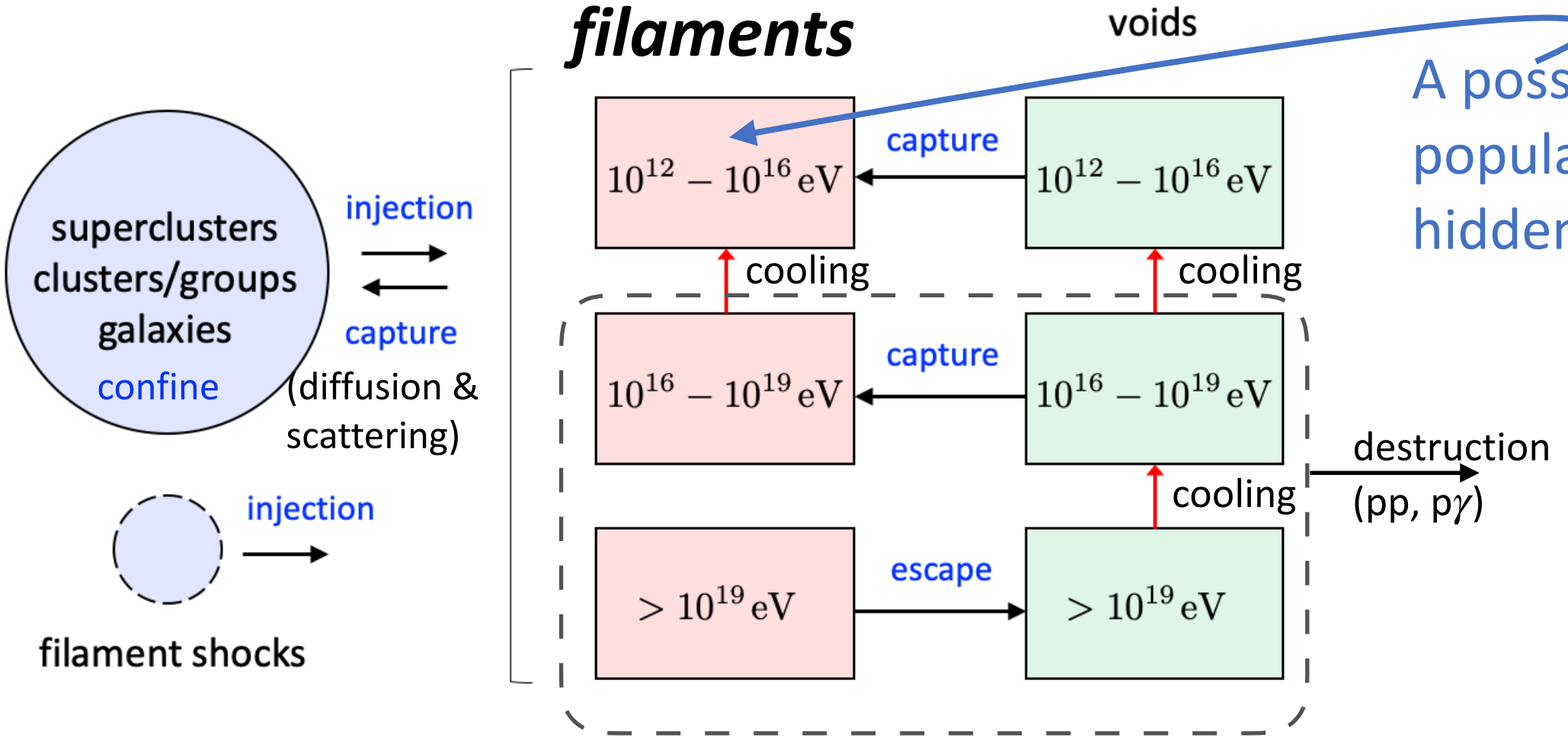
significant|B| increase at the interfaces to galaxies

MF configuration

energy of CRs —> gyro orbit —> transport and fate of CRs

The role of the key component — *filament*

$B_{\rm cl/sucl} \sim 10\ \mu$G $\quad B_{\rm fil} \sim 10$ nG $\quad B_{\rm voi} \ll 10^{-4}$ nG



A possible fossil population of CRs hidden in filaments

(Wu et al. 2024 *Universe*)

Summary & outlook

(1) Cosmic **filament** connect galaxy (groups, clusters, superclusters) and **act as interfaces for CR transport** between them as well as the void. The **magnetic field configuration of the filament ecosystem is important for CR transport**.

(2) **CRs** accelerated in galaxies embedded in the filament ecosystem may be **entrained by filaments** and never reach us. Their energies are $\sim 10^{12} - 10^{16}$ eV and **form a fossil record of the power generation**.

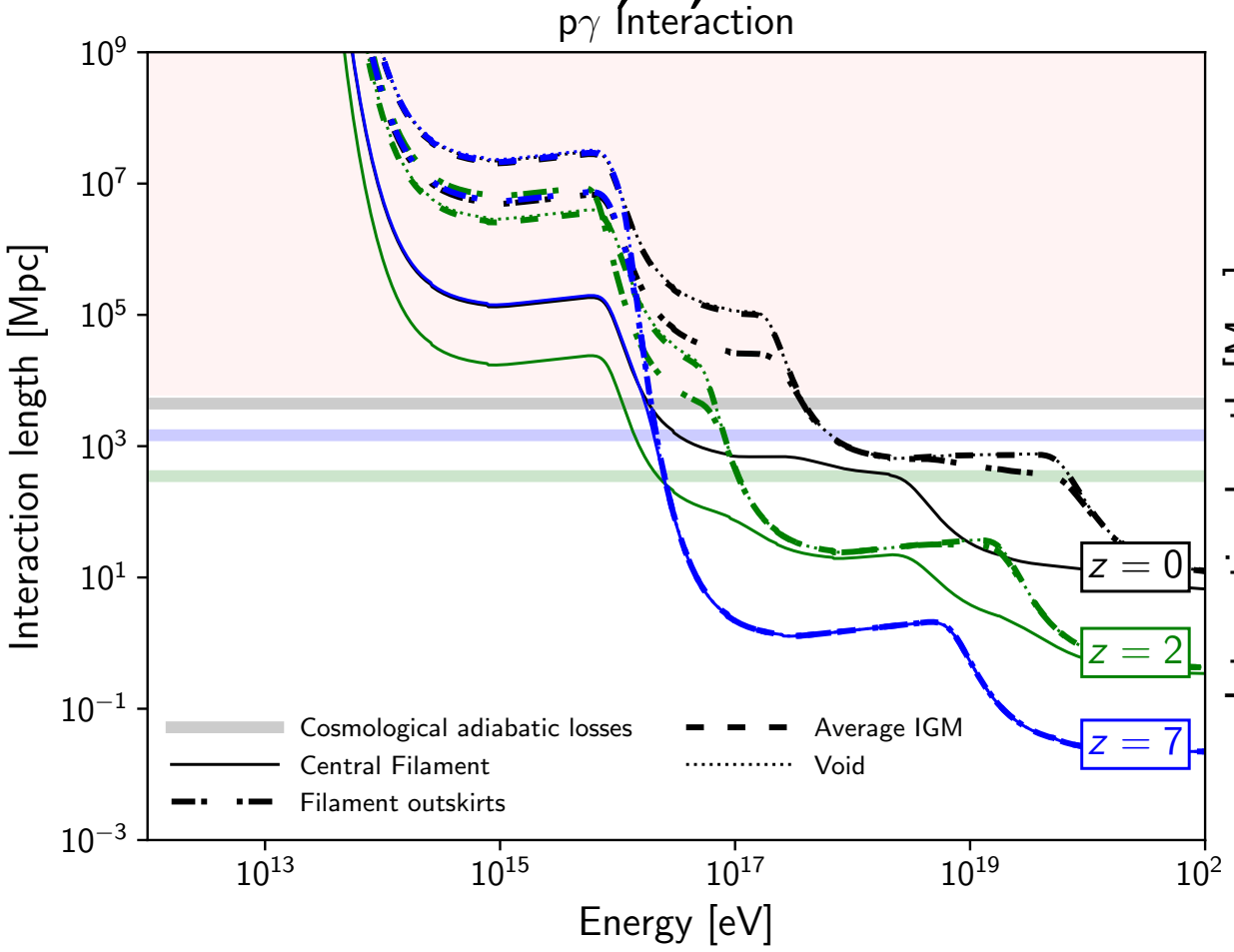
(3) We plan to model the propagation and evolution of the CR population in filaments over cosmic time, and investigate whether the hidden population can be probed indirectly.

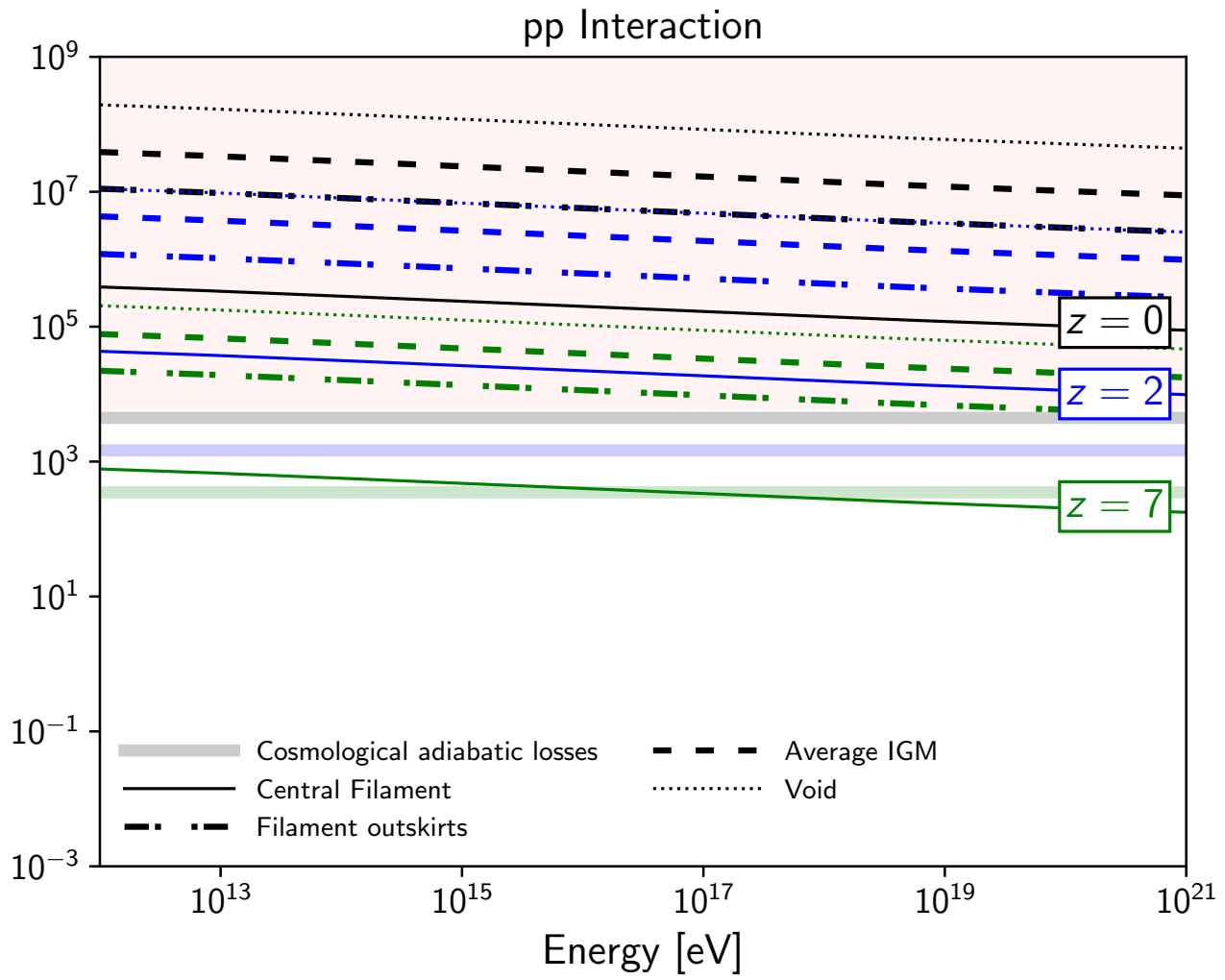
Backup slides

Parameters used in computing the path lengths.

Environment	Redshift	Radiation Energy Density [eV cm^{-3}] Starlight	Dust	Gas Density [g cm^{-3}]	Size [h] [Mpc]
Central filament [a]	0	3.7	5.2	4.0×10^{-29}	0.30
	2	28	42	3.6×10^{-28}	0.20
	7	3.4	4.7	2.0×10^{-26}	<0.050
Filament outskirts [a]	0	0.10	0.14	1.4×10^{-30}	2.0
	2	0.076	1.1	1.3×10^{-29}	2.5
	7	0.091	0.13	7.0×10^{-28}	>2.8
Void [b]	0	0.022	0.032	8.0×10^{-32}	7.9
	2	0.17	0.25	1.4×10^{-30}	6.7
	7	0.021	0.028	7.6×10^{-29}	6.0
Average IGM [c]	0	0.024	0.035	4.0×10^{-31}	–
	2	0.19	0.29	3.6×10^{-30}	–
	7	0.023	0.031	2.0×10^{-28}	–
Starburst galaxy [d]	0	670	310	1.7×10^{-20}	0.0010
CGM [e]	0	0.24	0.34	1.0×10^{-28}	0.10
Intra-group medium [f]	0	0.22	0.31	4.4×10^{-28}	0.12
Intra-cluster medium [g]	0	0.21	0.28	1.1×10^{-27}	1.9

The interaction lengths of protons undergoing pp interaction processes (left panel) and pγ processes (right panel) for photo-pair and photo-pion production in cosmic filaments and voids, at redshifts of z = 0, 2, and 7.





the prospects of particles with given gyration orbits to transfer between filaments and voids, filaments and clusters/superclusters, and filaments and embedded galaxies. '?' denotes that transfer through the described pathway is subject to the efficiency of diffusion across the magnetic field, in competition with other relevant processes, e.g., the survival of particles in the presence of pp or pγ interactions.

Interface Type	A	B	C
Void to filament	✗	✓	✓
Filament to void	✓	?	✗
Cluster/supercluster to filament	✗	?	?
Filament to cluster/supercluster	✗	✓	?
Galaxy to filament	✗	✓	?
Filament to galaxy	✗	??	?

'??' denotes that there could be complications in the transfer of particles through the described pathway caused by other factors, such as the presence of a magnetic barrier in the filament–cluster/–supercluster interface, and/or the diffusion of particles through the magnetic field internal to the systems.