Propagation of UHECRs in the magnetized cosmic web

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Outline

1. Introduction

   - Motivation: a concentration of UHECR events

2. Magnetized Cosmic Web

   - The Virgo cluster and its filaments of galaxies

   - A plausible model for the origin of TA hotspot

3. Simulation

4. Results

5. Summary

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   - Motivation: a concentration of UHECR events
2. Magnetized Cosmic Web
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Kim et al., Science Advances 5: eaau8227 (2019)

3. Simulation
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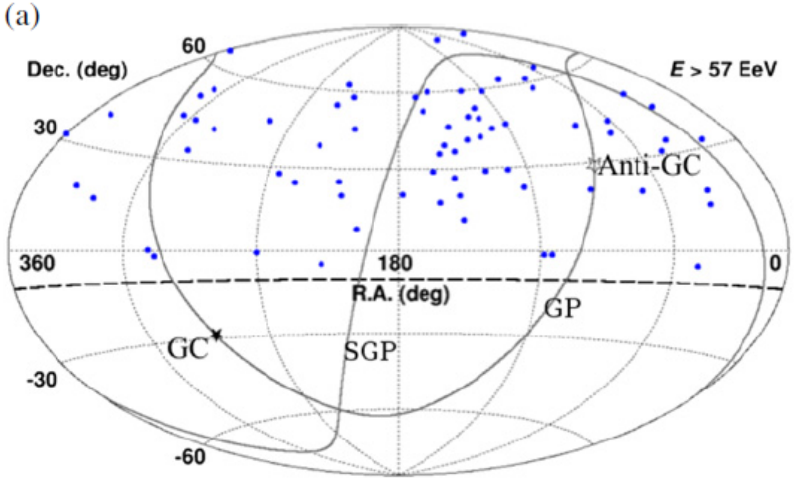
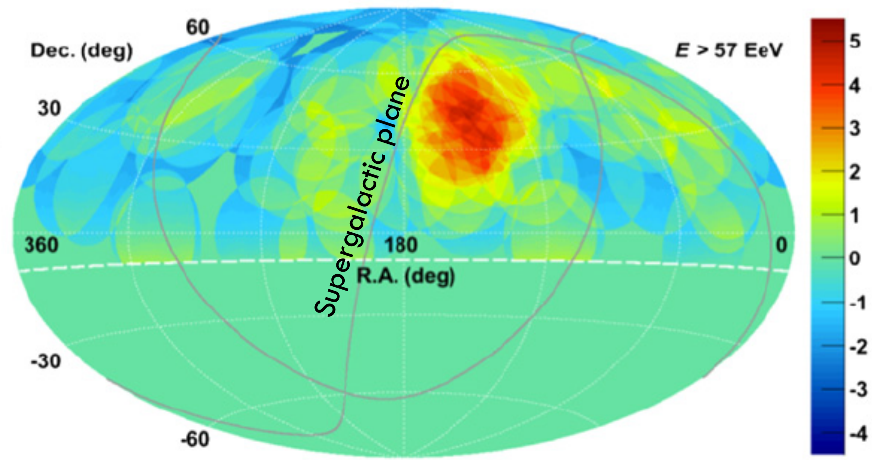
Motivation: A concentration of TA events TA (2014)

TA events with $E > 5.7\times10^{19}$ eV



20° oversampling significance map



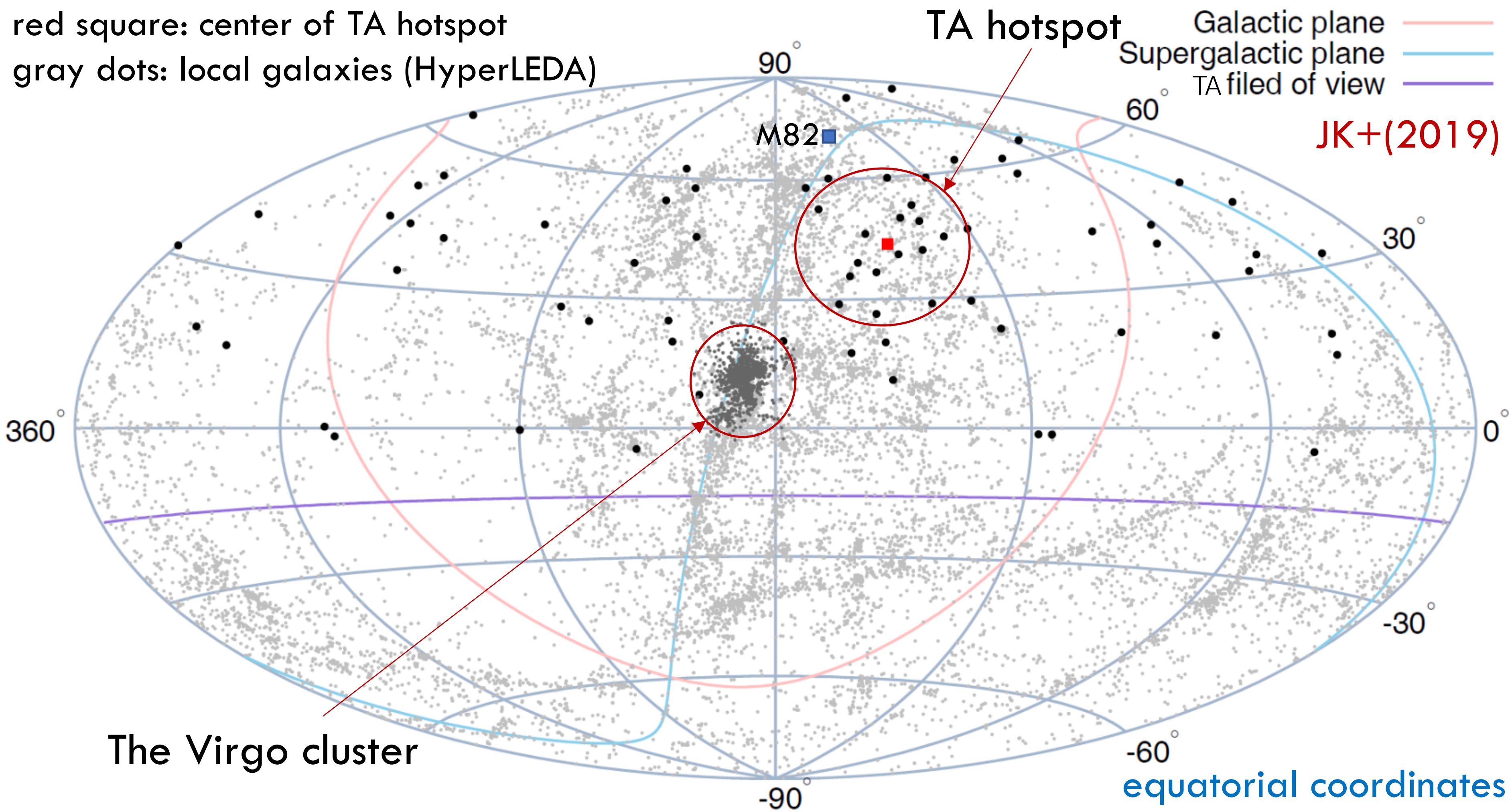
Skymaps in the equatorial coordinates

- 72 events with $E > 5.7\times10^{19}$ eV (5-year TA SD data)
- Maximum local significance: 5.1σ
  - Observed: 19 events
  - Expected from isotropy: 4.5 events

  } ~320% excess to the isotropy
- Post-trial probability: $P(\mathrm{p_{pre}} > 5.1\sigma) = 3.4\sigma$

What is the origin of the TA hotspot?

black dots: TA 5-year data (E > 5.7×10^{19} eV)
red square: center of TA hotspot
gray dots: local galaxies (HyperLEDA)



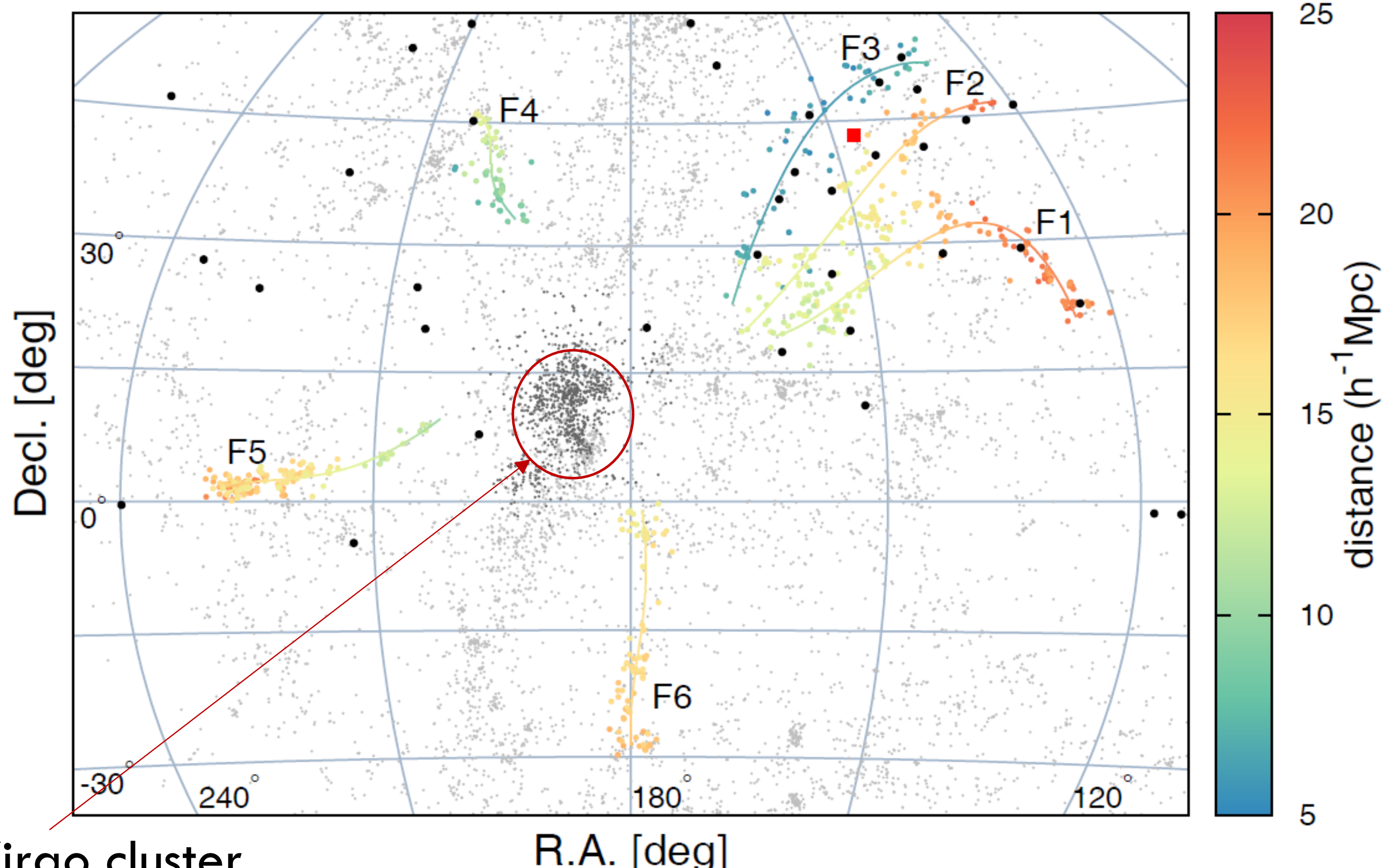
Are TA hotspot events coming from a single source?

No plausible nearby point source behind TA hotspot on the sky!

Six filaments of galaxies connected to the Virgo cluster

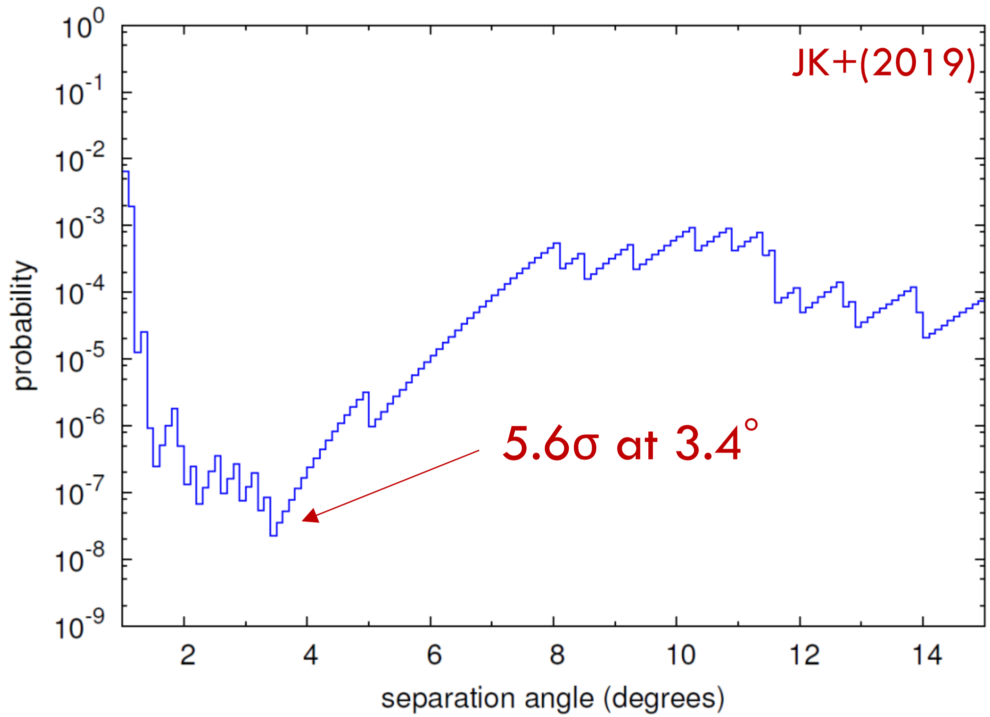
black dots: TA 5-year data TA (2014)
color dots: filaments of galaxies S. Kim+ (2016)
gray dots: local galaxies Makarov+ (2014)

JK+(2019)



The Virgo cluster

Close correlation between TA events and filaments



- 72 events with E > 5.7×10^{19} eV (5-year TA SD data)
- Maximum local significance: 5.6σ

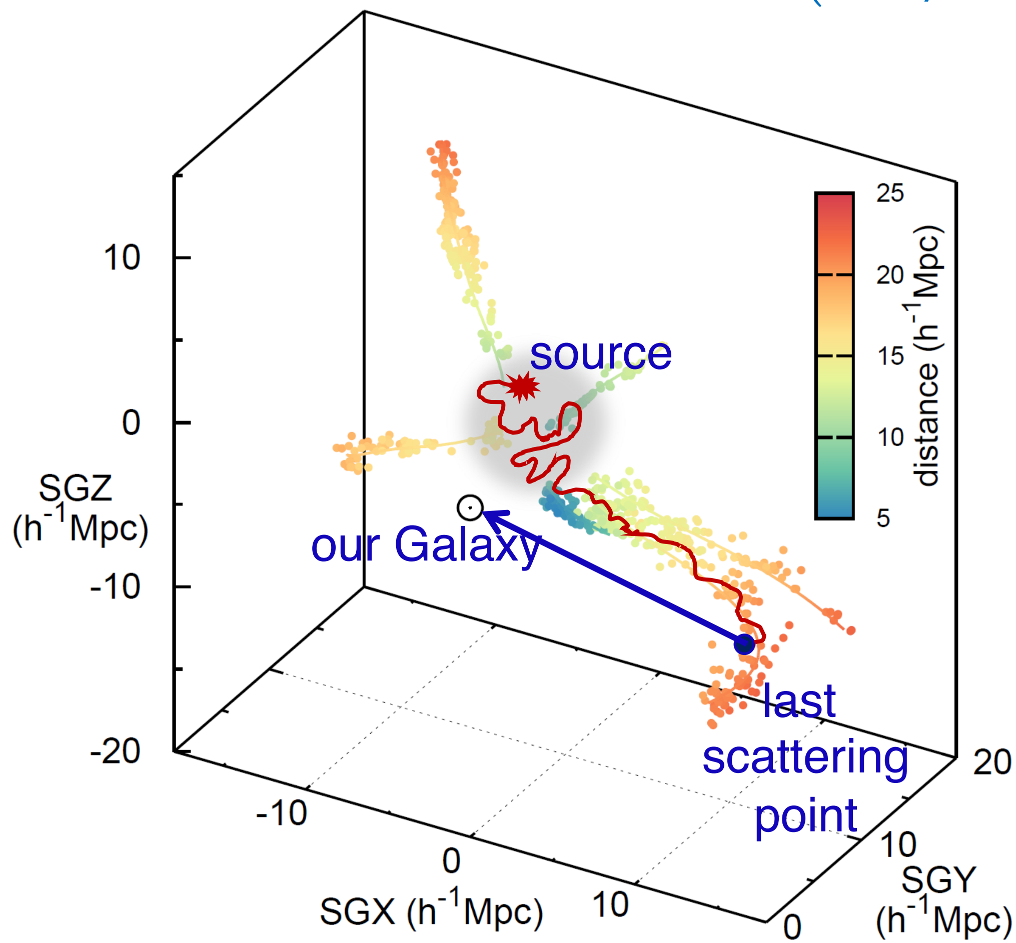
  Observed: 19 events
  Expected from isotropy: 4.2 events
  } ~350% excess to the isotropy

- Post-trial probability: $P(\mathrm{p_{pre}} > 5.6\sigma) = 5.1\sigma$
- The estimated mass composition of UHECRs and strength of galactic magnetic fields are consistent with observations.

A plausible model for the origin of TA hotspot

JK+(2019)

$$\delta \sim f \times \frac{\pi}{2}\left(\frac{5\times10^{19}\ \mathrm{eV}}{E/Z}\right)\left(\frac{L}{25\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{l_c}{1\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{B_{\mathrm{random}}}{20\ \mathrm{nG}}\right)$$



- UHECRs are postulated to be produced at a source (sources) inside the Virgo cluster. They roam around for a while because of cluster magnetic fields. Then, some of them escape through connected filaments.
- This picture requires

  B >~1 μG in clusters

  B > ~20 nG in filaments

  (Size of cluster/filament ~ a few Mpc)

Is it possible for UHECRs to propagate like this way in the cosmic web?

Numerical simulation of magnetized cosmic web

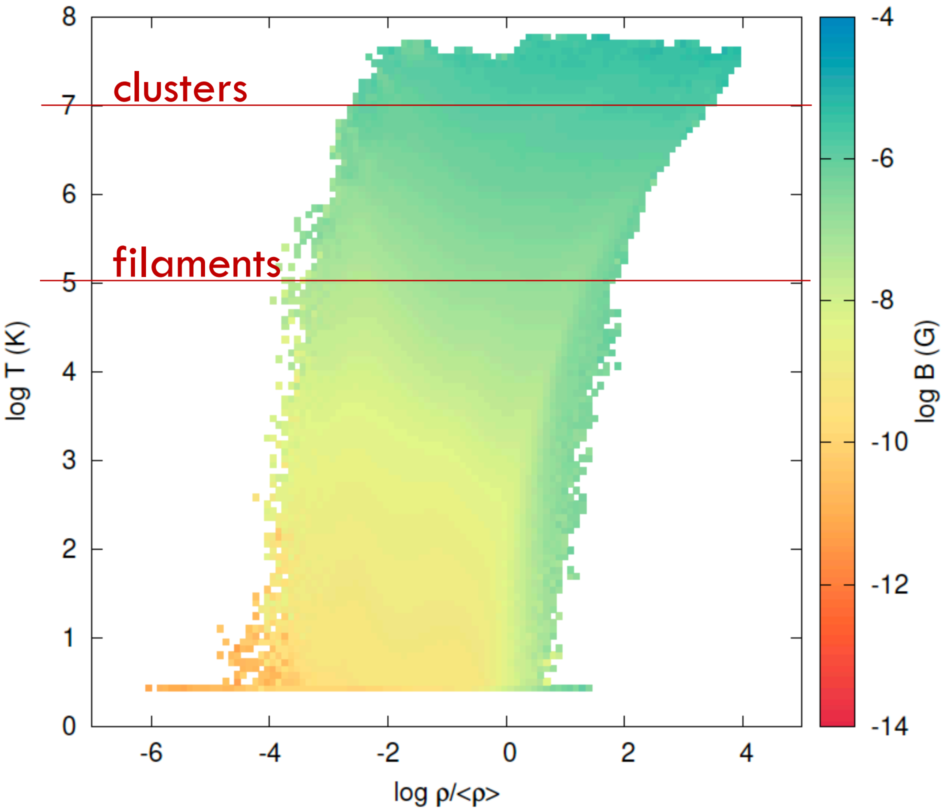
- The model universes are generated through numerical simulations for the LSS formation using a particle-mesh/Eulerian cosmological hydrodynamics code (Ryu+1993).
- Assuming a ΛCDM cosmological model, the following parameters were used:

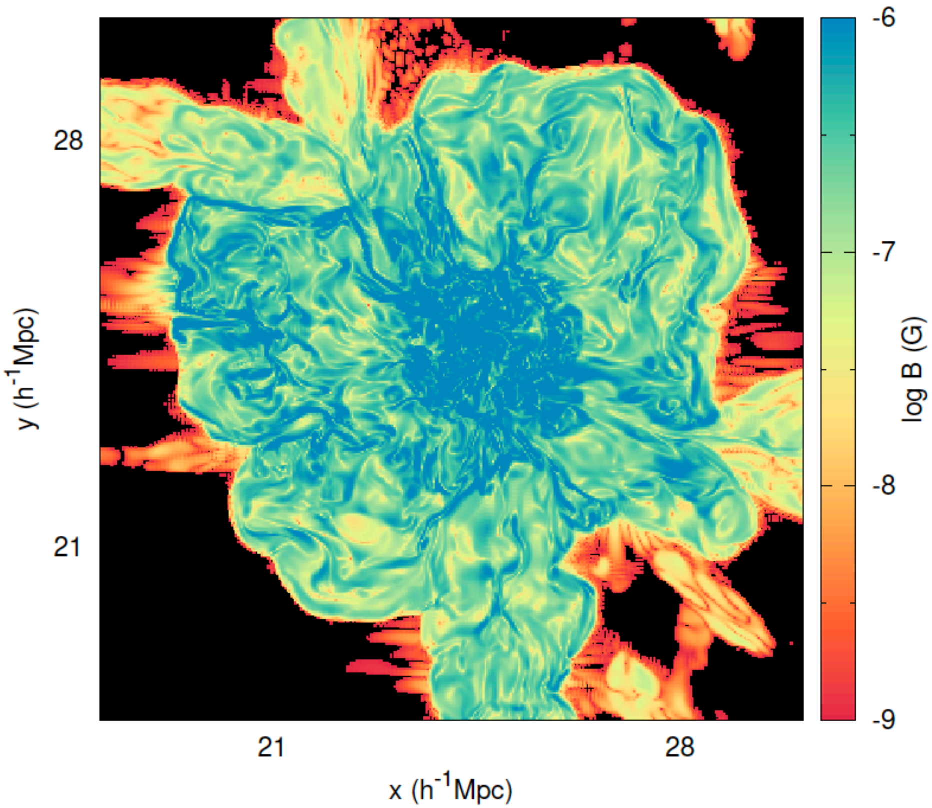
$$\Omega_\Lambda = 0.72,\ \Omega_{DM} = 0.236,\ \text{and}\ \Omega_{BM} = 0.044,$$

$$h = 0.7,\ \sigma_8 = 0.82,\ n = 0.96.$$

- The generation of intergalactic magnetic field is seeded by the Biermann battery mechanism at cosmological shocks (Ryu+1998).
- The overall strength of magnetic field is rescaled to reproduce the observed values of clusters. The core value within 1 h^{-1}Mpc from the X-ray center is rescaled to 2 μG and 3 μG.

Magnetic field strength in LSS of the universe

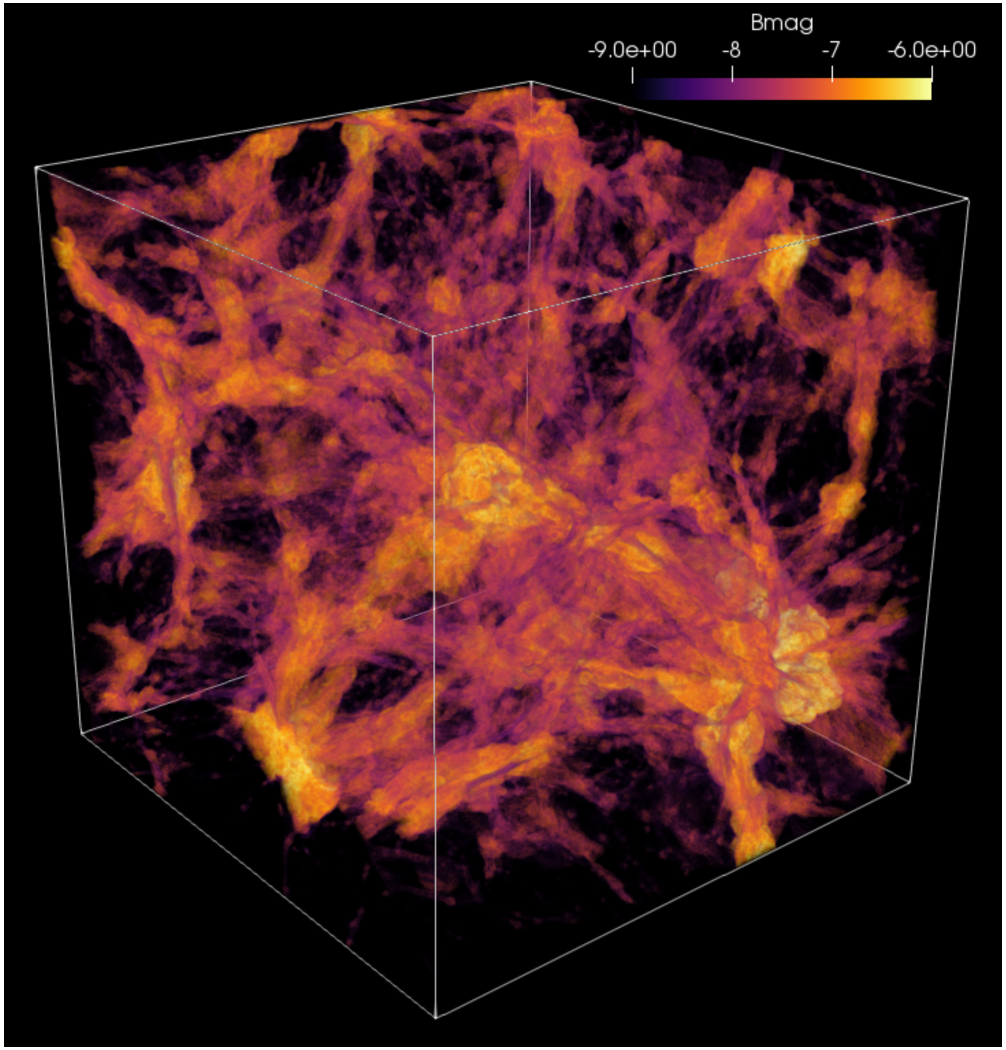




Temp. of intracluster medium: ~10^7 K
Temp. of warm-hot ionized plasma ~10^5–10^7 K

Temp. of the Virgo cluster: ~3.0×10^7 K
Temp. of sample cluster: ~3.2×10^7 K

Particle propagation in magnetized cosmic web



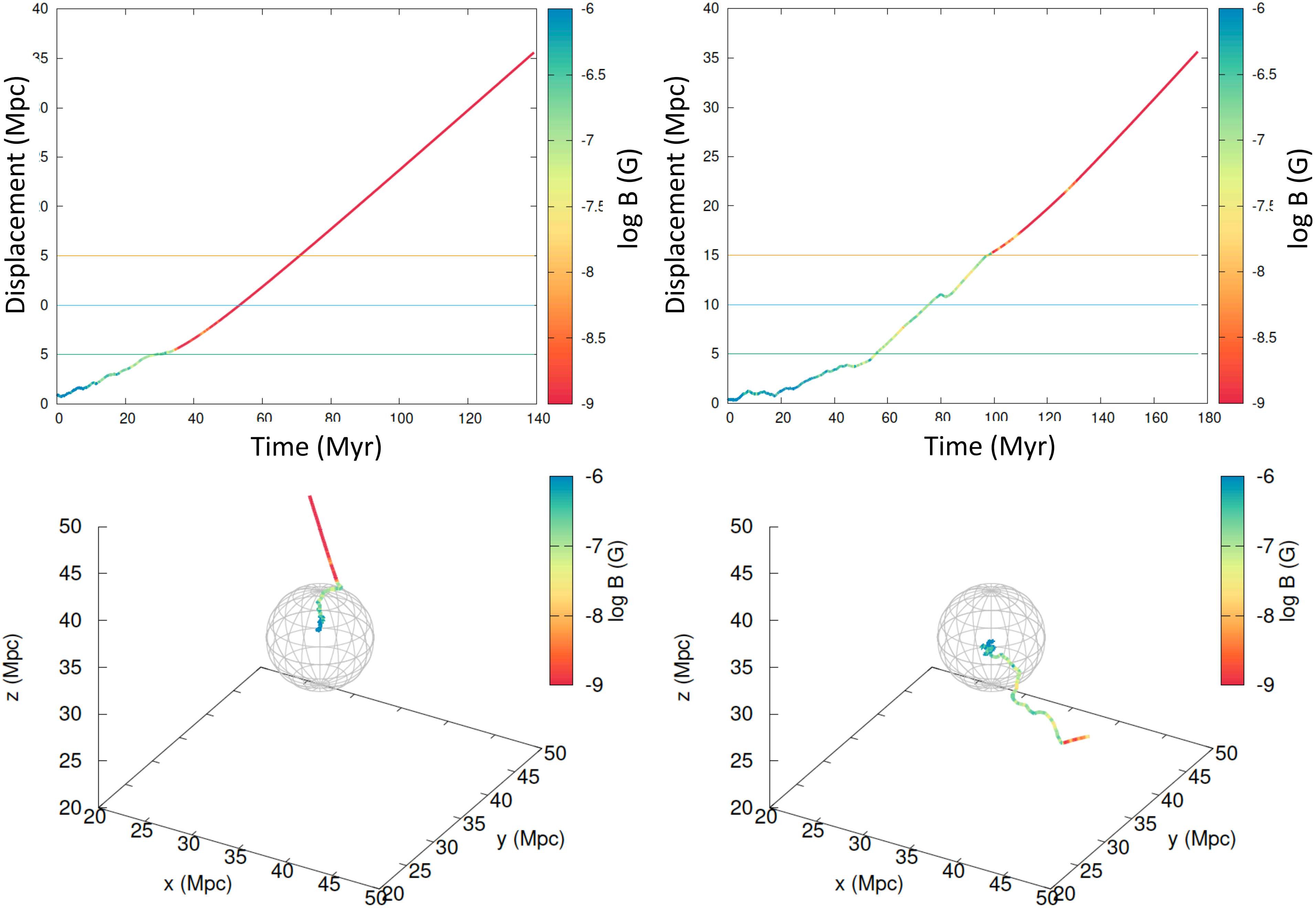
- A cubic box of comoving size of 49 h^{-1}Mpc with periodic boundaries, divided into 1440^3 uniform grid zones.

- The grid resolution is 34.5 h^{-1}kpc, which is smaller than the gyro-radius of UHE protons in most zones.

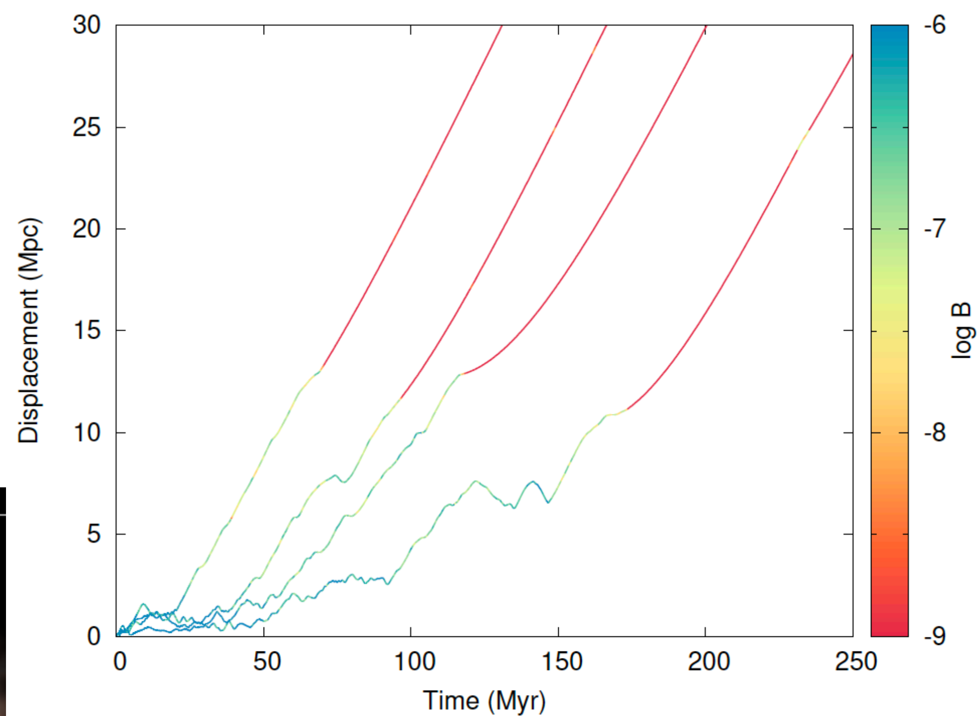
- Inject 10^5 UHE protons with 6×10^{19} eV at random positions within the cluster core toward random directions.

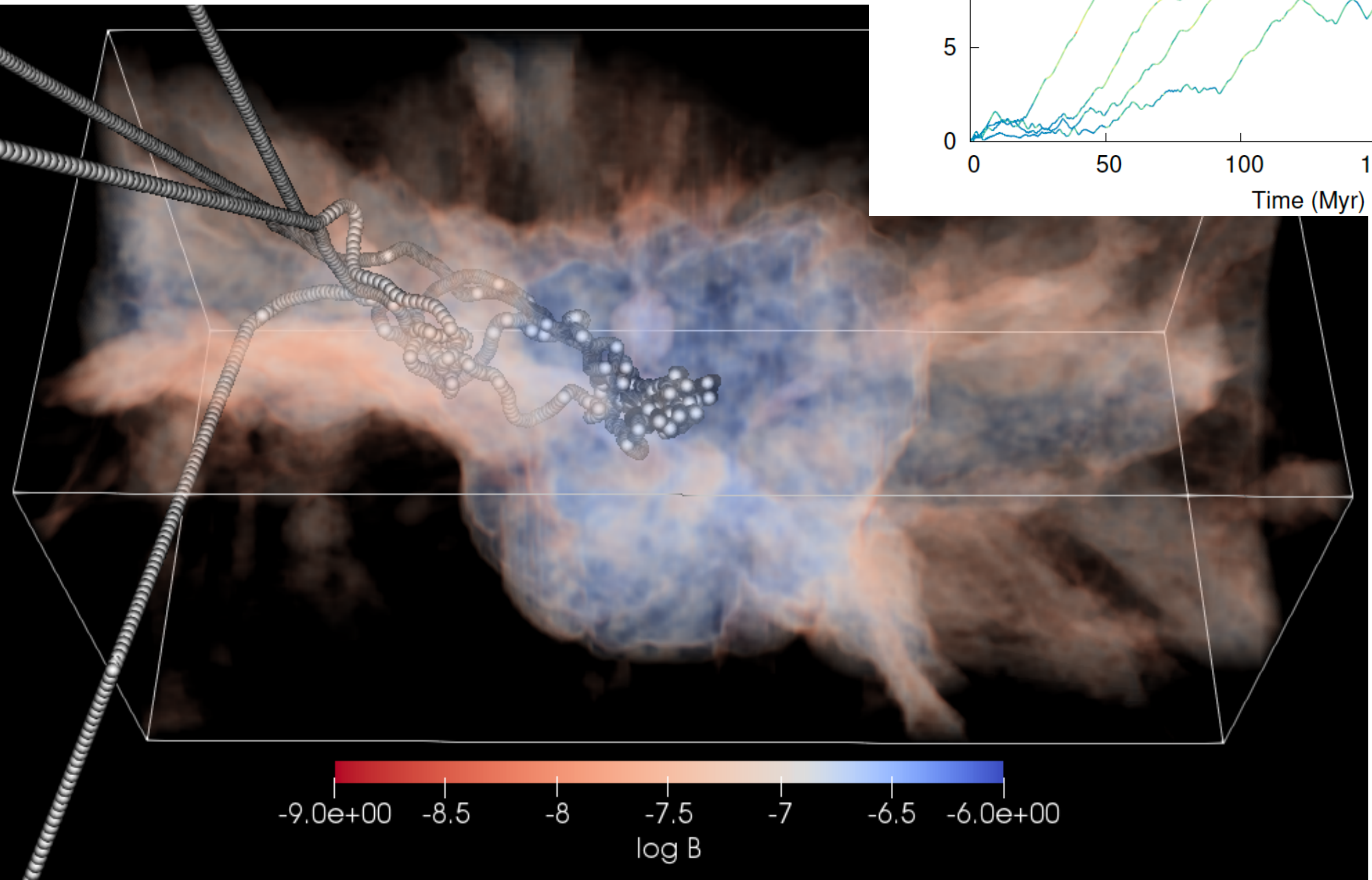
- Trace the trajectories of UHE protons with the relativistic equation of motions.

Examples of particle propagation: Direct escape from cluster (left) + Escape to filament (right)



Examples of particles escape to filaments with the magnetic fields

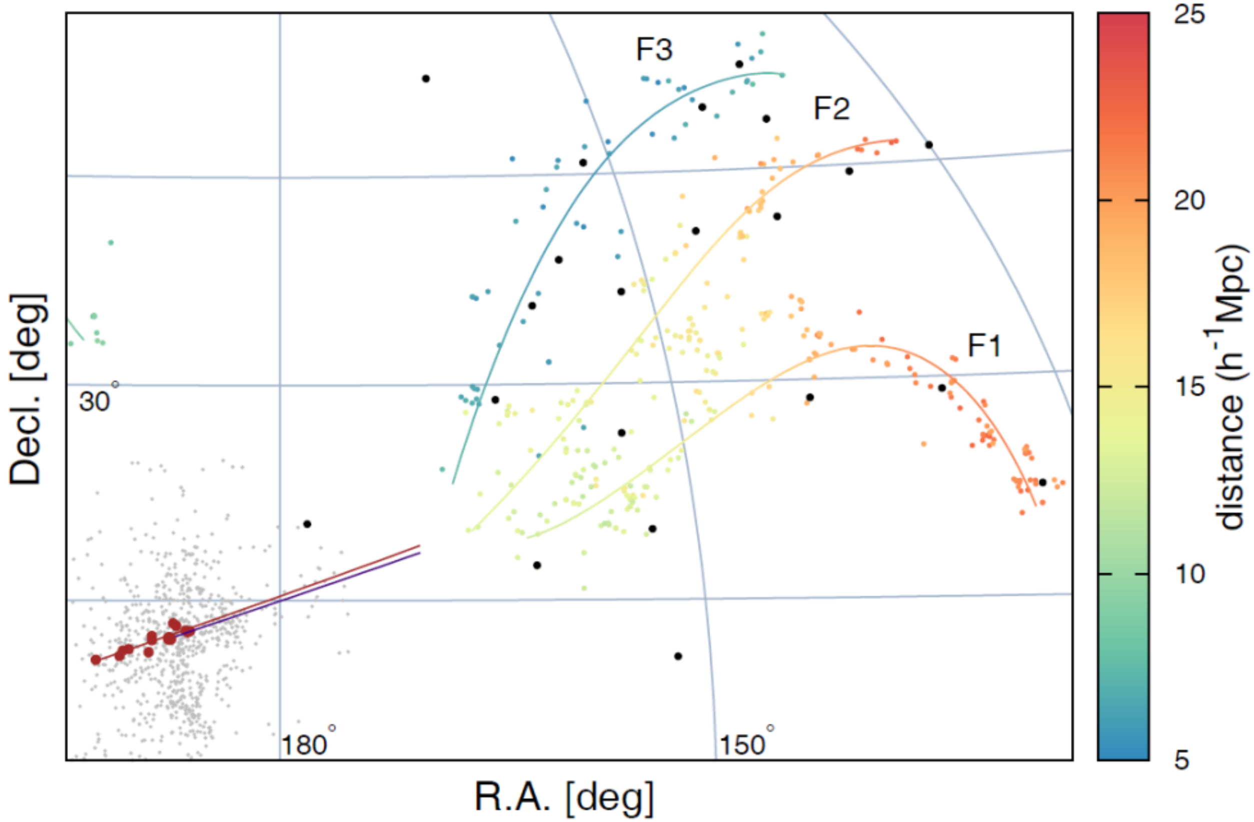




Analysis of 10^5 particles: preliminary

- Core of 2 μG
  - Particles directly escape from the cluster: ~55%
  - Particles escape to the filaments: ~45%
- Core of 3 μG
  - Particles directly escape from the cluster: ~49%
  - Particles escape to the filaments: ~51%
- The results of this study confirm that it is possible for a UHE proton produced from a source in a galaxy cluster to escape through galaxy filaments connected to the cluster.

Intriguing observations in the Virgo cluster



- Brown circles and the brown line plot brightest elliptical galaxies and the extension of the cluster principal axis, respectively, in the Virgo Cluster (West & Blakeslee (2000), S. Kim+ (2018)).
- The extension of M87 jet with the indigo line (Kovalev+ (2007)).

Summary

- The results of this study confirm that it is possible for a UHE proton produced inside the cluster to escape toward and propagate along filaments of galaxies connected to the cluster.

  → Supports the model for the origin of TA hotspot

- The magnetic field distribution in the regions of the Virgo Cluster and the hotspot is required for realistic tests to reproduce the TA hotspot.
- The exploration of IGMF by astronomical projects like SKA can provide better constraints in the near future.
- Under the circumstances, the IGMF model is crucial.

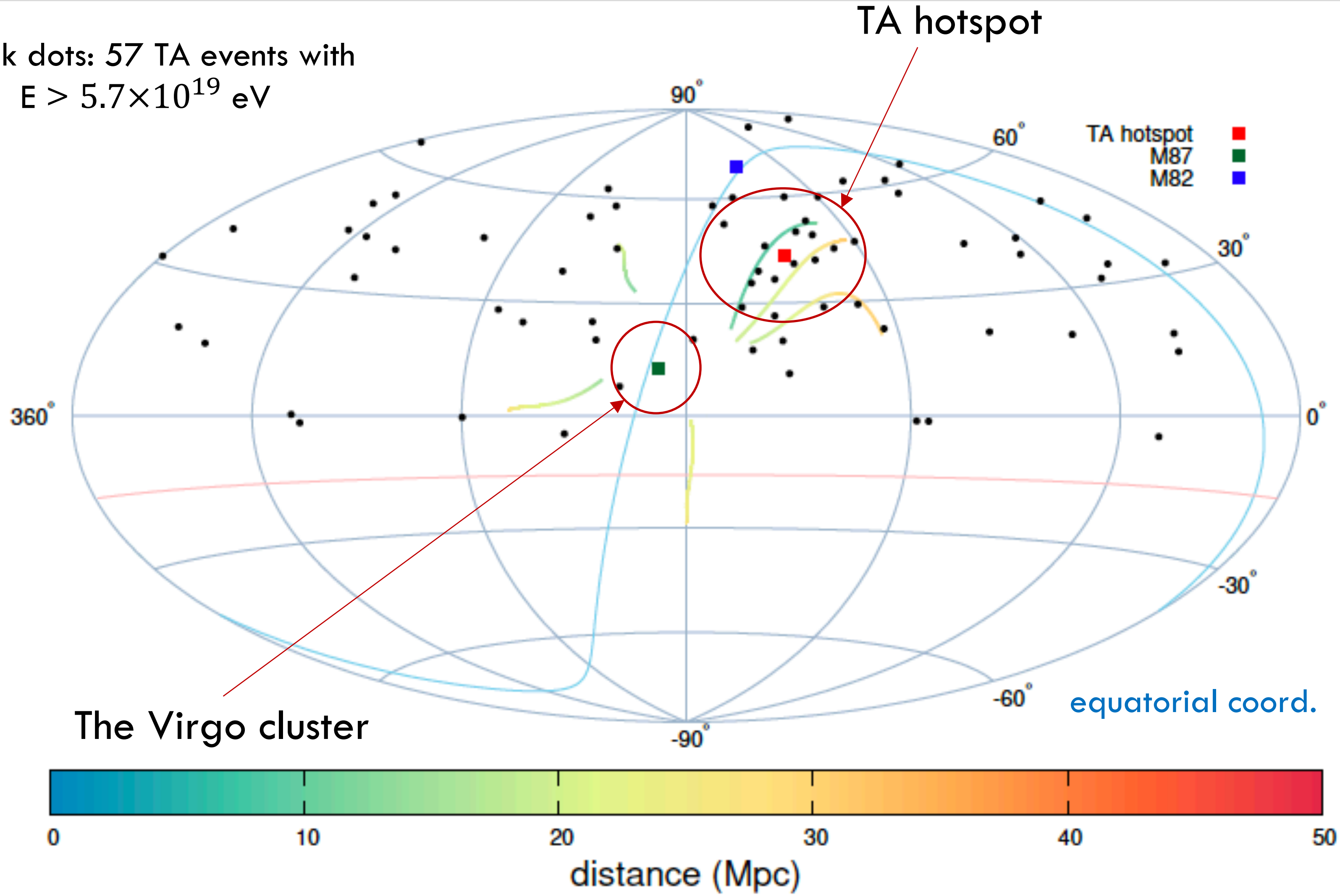
  → More simulations with various IGMF models are in progress.

Thank you!

Backup

Characteristic distribution of TA events

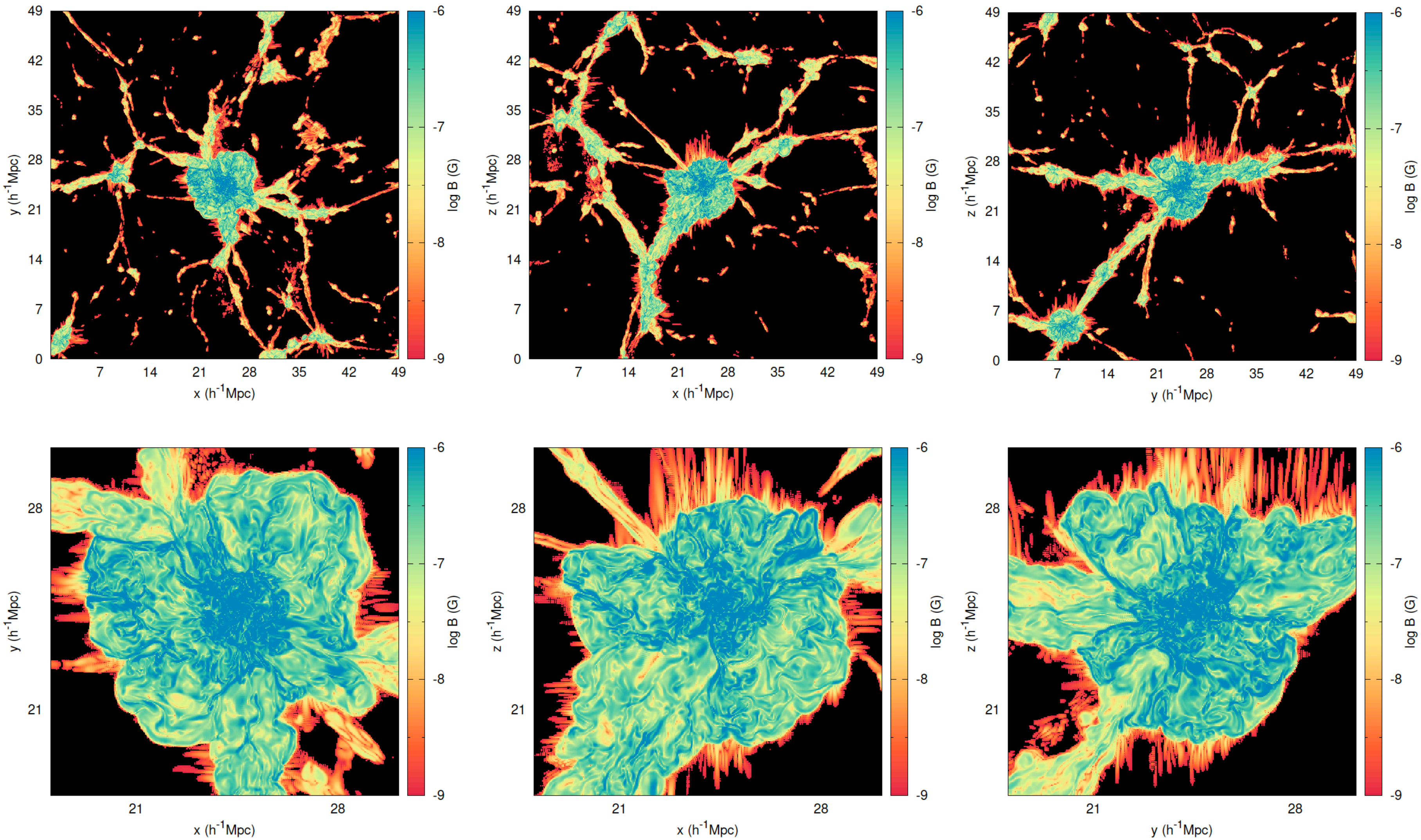
black dots: 57 TA events with $E > 5.7 \times 10^{19}$ eV



→ the nature and origin of TA hotspot?

→ no excess toward the Virgo cluster?

Magnetic field strength in LSS of the universe



Magnetic field is ubiquitous in the Universe!

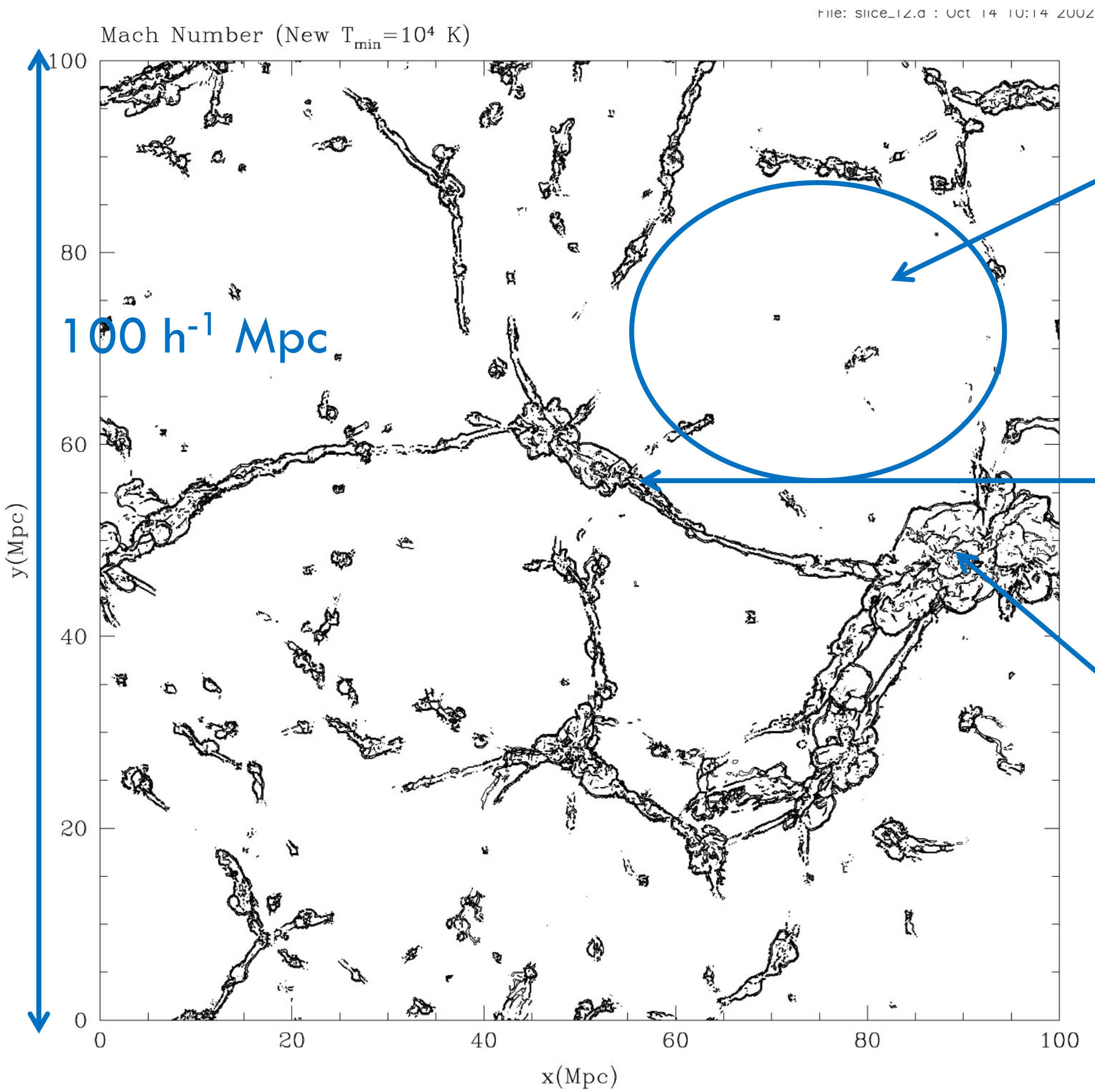
Star	
Magnetar	$\sim 10^{13}$ - 10^{15} G
Neutron star	$\sim 10^{11}$ - 10^{13} G
White dwarf	$\sim 10^{6}$ G
Ap/Bp star	$\sim 10^{3}$ G
Normal star	~ 1 G
Molecular cloud	$\sim 10^{-3}$ G
Interstellar medium	$\sim$ several $\times 10^{-6}$ G
Cluster of galaxies	$\sim$ a few $\times 10^{-6}$ G
Filament of galaxies	$\sim 10^{-8}$ G (?)
Void	$\sim 10^{-19} – 10^{-16}$ G (?)
Early universe	$\sim 10^{-20}$ G (?)

↑ stronger field

↓ larger scale

intergalactic magnetic field (Cluster of galaxies, Filament of galaxies, Void)

Magnetized cosmic web

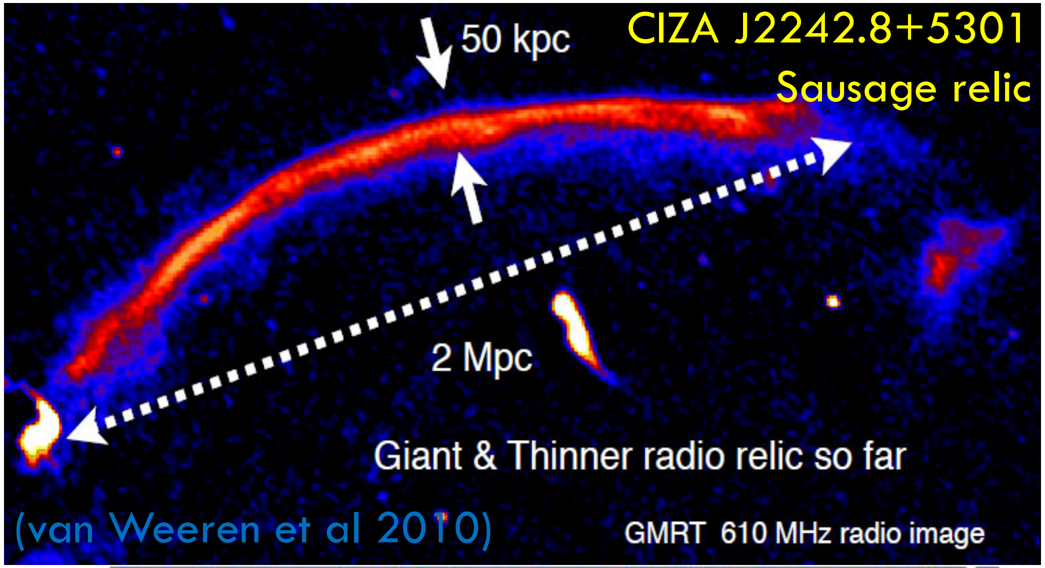


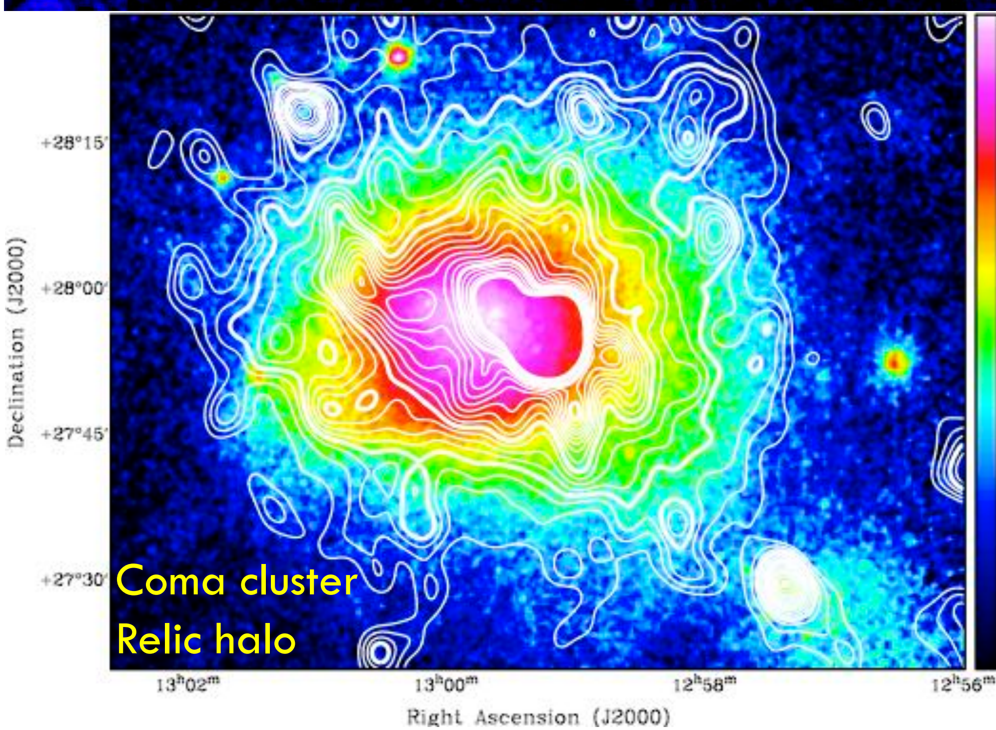
void regions:
$\sim 10^{-19} < B < \sim 10^{-16}$ G

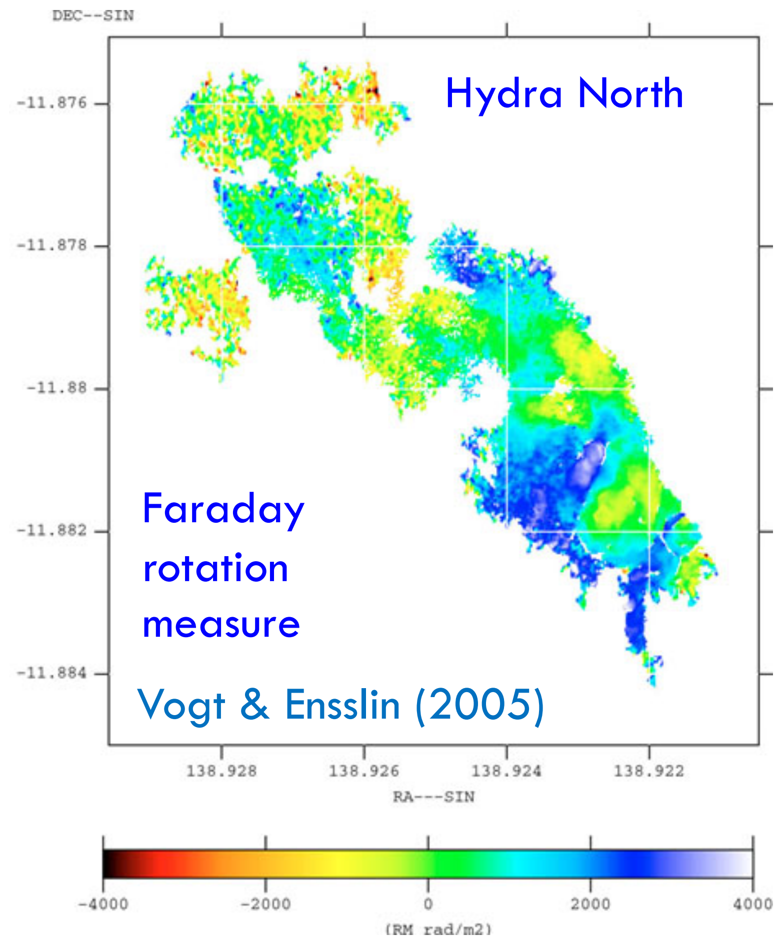
filaments of galaxies:
B ~ 10 nG

clusters of galaxies:
B ~ a few μG

Magnetic fields in clusters of galaxies

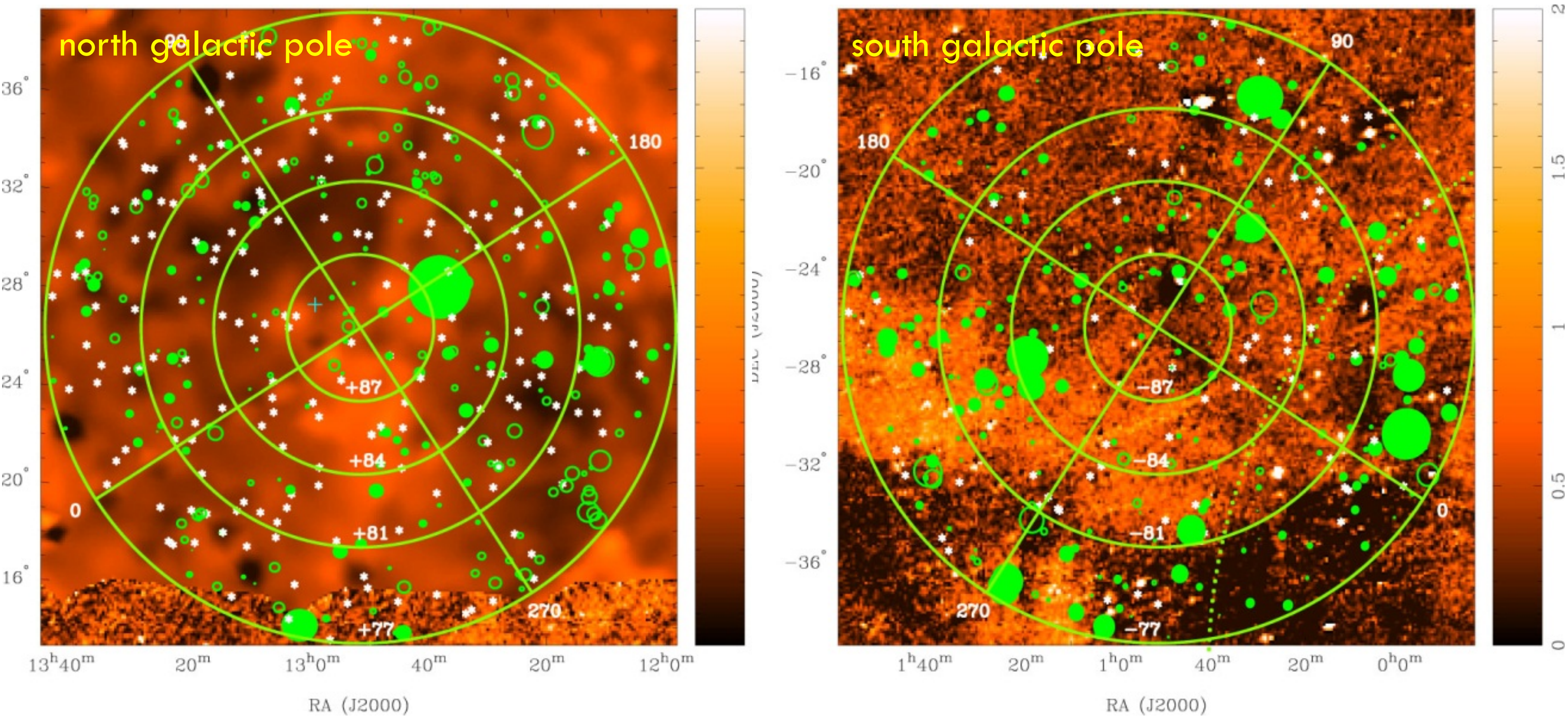






Magnetic fields in filaments of galaxies

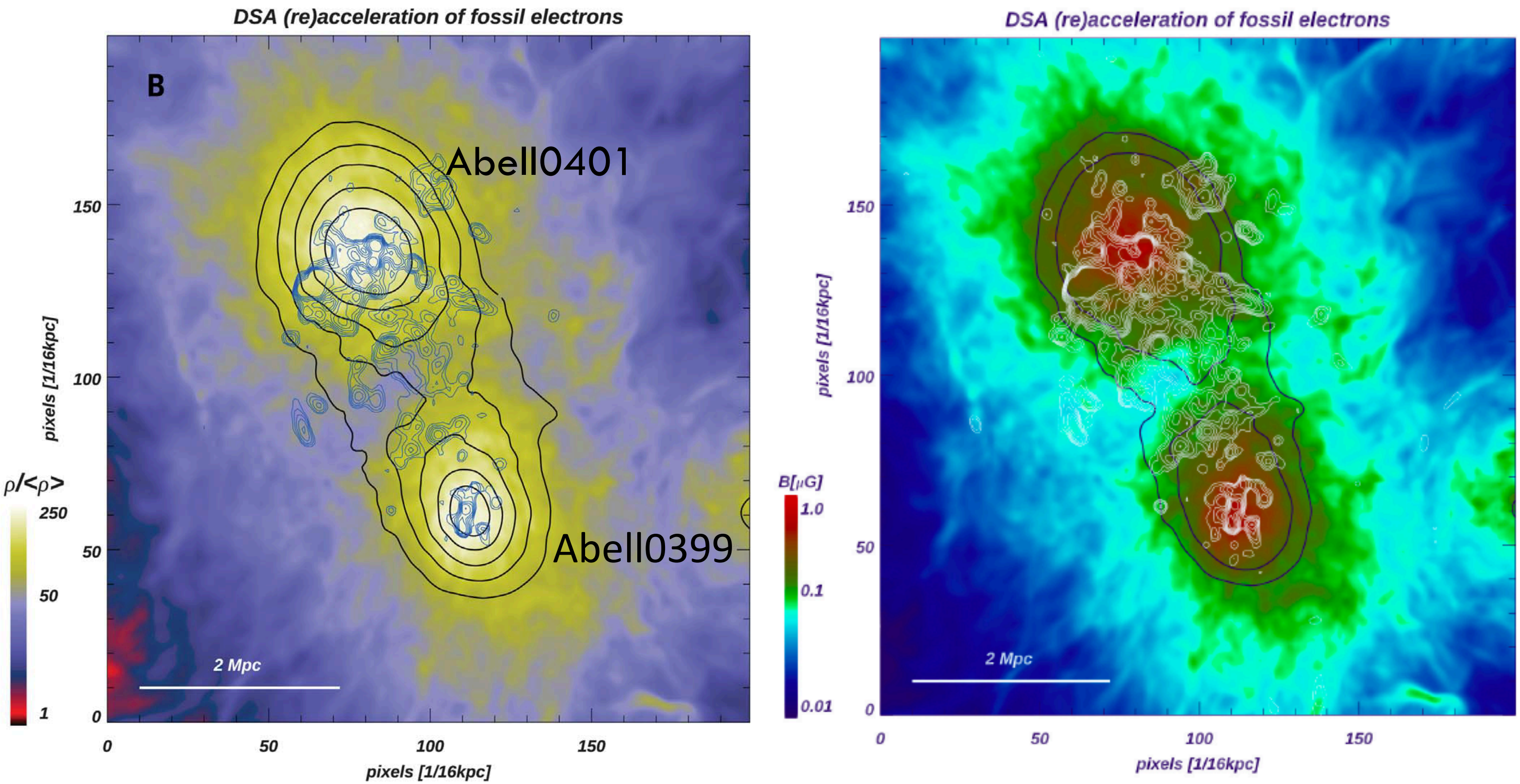
Mao et al (2010), Stil et al (2011)



Faraday rotation measure

→ B ~ 10 nG (needs to be further confirmed)

Magnetic fields in filaments of galaxies



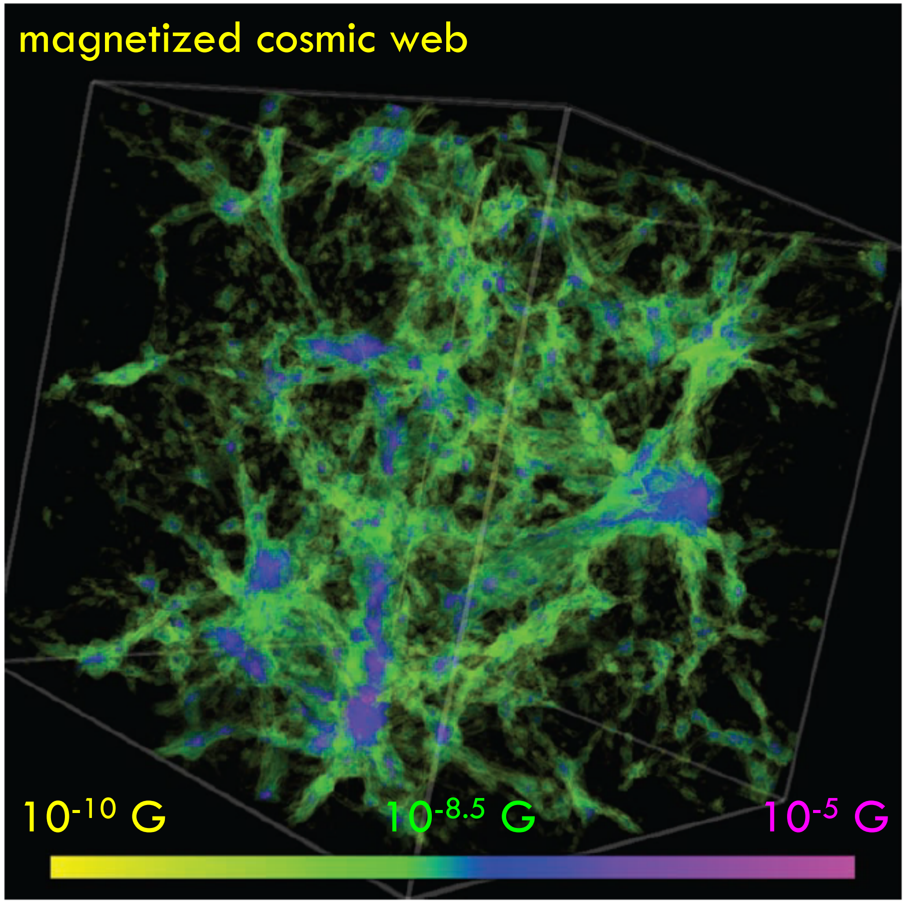
Govoni et al. (2019)

Observed a ridge of radio emission connecting the merging galaxy clusters.

→ B < 1 μG

Magnetic fields in the large-scale structure from simulation

Magnetic fields in the LSS



Ryu et al. (2008)

- A simulated distribution of the intergalactic magnetic fields in a box of $(100\ h^{-1}\mathrm{Mpc})^3$

- Based on a turbulence dynamo model, the average strength of magnetic field would be

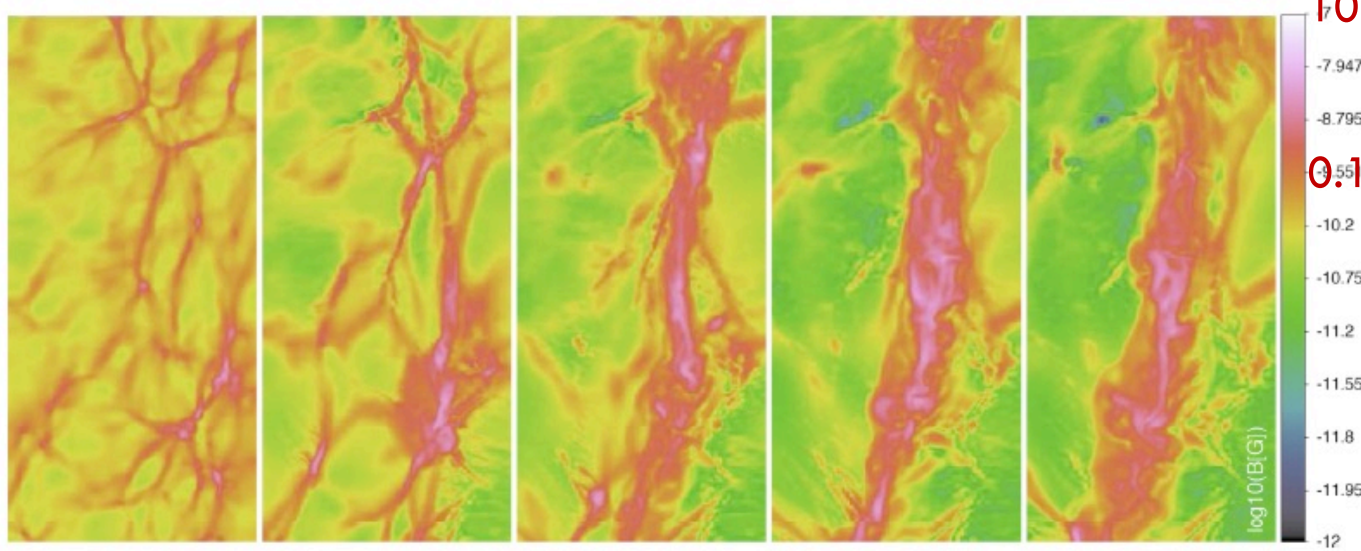
B in clusters: ~ a few μG

B in filaments: ~10 nG

→ Consistent with the required strength of magnetic fields by our picture

Magnetic fields in the large-scale structure from simulation

Magnetic fields in filaments of galaxies



Vazza et al. (2014)

An evolution of magnetic fields in filaments from a simulation shown with 9 Mpc×18 Mpc image

→ Consistent with the required strength of magnetic fields by our picture