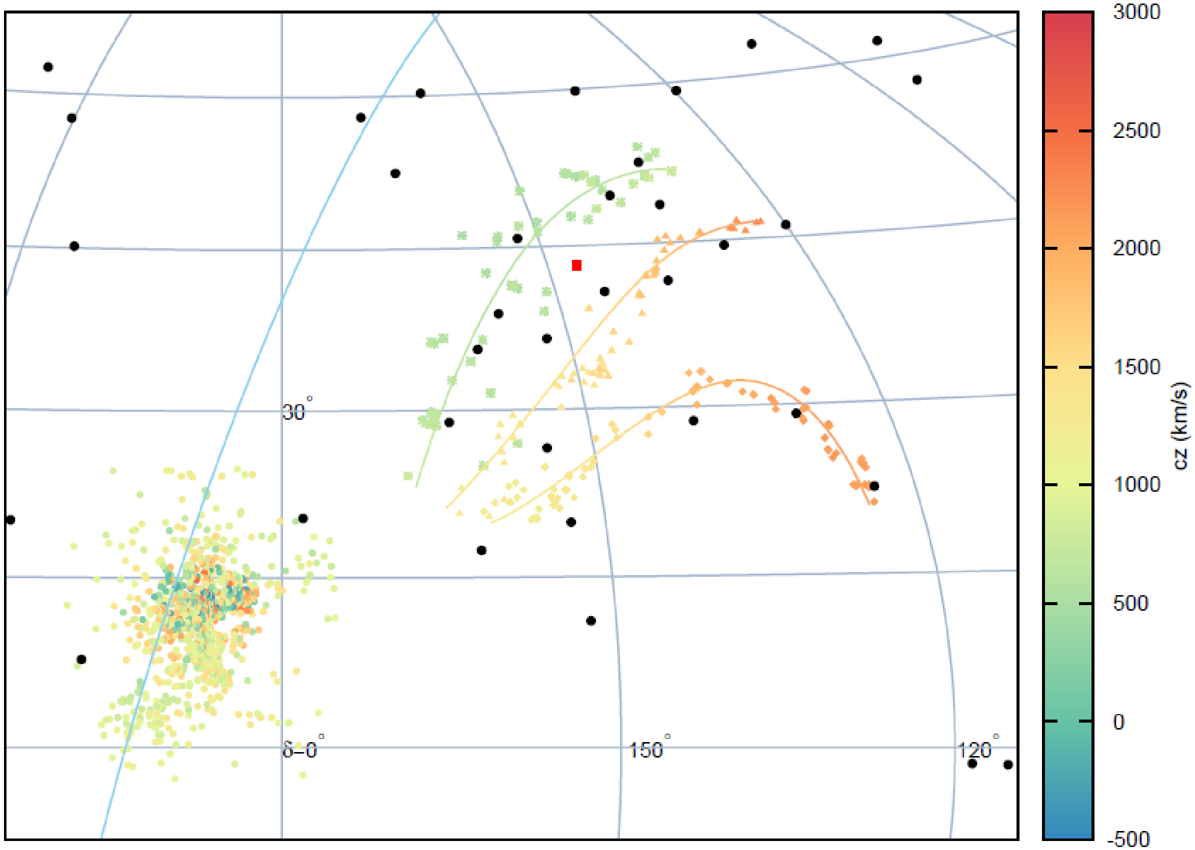
Intergalactic Magnetic Field and Correlation between TA Hotspot Events and Structures of Local Universe



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Issues of UHECRs to be addressed

- energy spectrum ?
- composition ?
- arrival direction ?
  or correlation with astronomical objects ?

(composition and arrival direction → related)

➔ sources of UHECRs ?

“Hotspot” in TA events

(TA 2014)

72 events

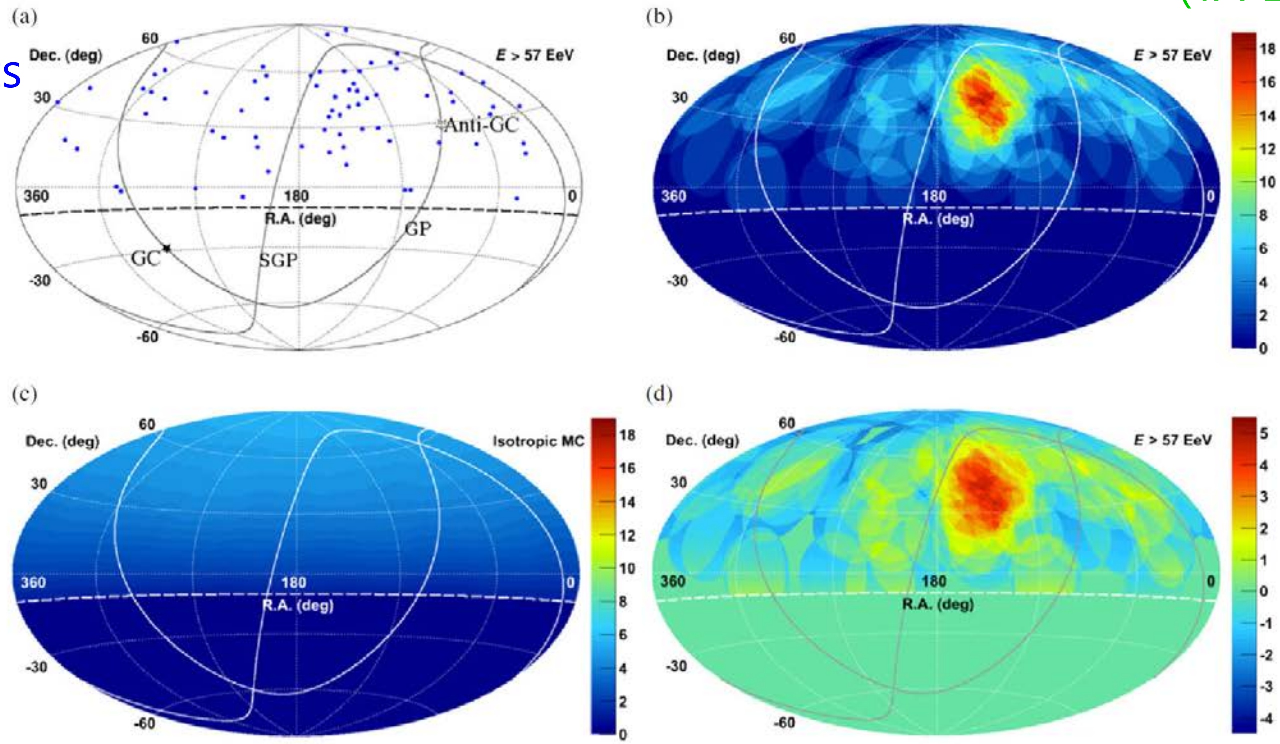


Figure 1. Aitoff projection of the UHECR maps in equatorial coordinates. The solid curves indicate the galactic plane (GP) and supergalactic plane (SGP). Our FoV is defined as the region above the dashed curve at decl. = −10°. (a) The points show the directions of the UHECRs $E > 57$ EeV observed by the TA SD array, and the closed and open stars indicate the Galactic center (GC) and the anti-Galactic center (Anti-GC), respectively; (b) color contours show the number of observed cosmic-ray events summed over a 20° radius circle; (c) number of background events from the geometrical exposure summed over a 20° radius circle (the same color scale as (b) is used for comparison); (d) significance map calculated from (b) and (c) using Equation (1).

“… a cluster of events, hotspot, … using 20° radius circles.”

“The hotspot has a Li-Ma statistical significance of 5.1σ…”

“The probability … by chance in an isotropic cosmic-ray sky, is estimated to be 3.7×10^{-4} (3.4σ).”

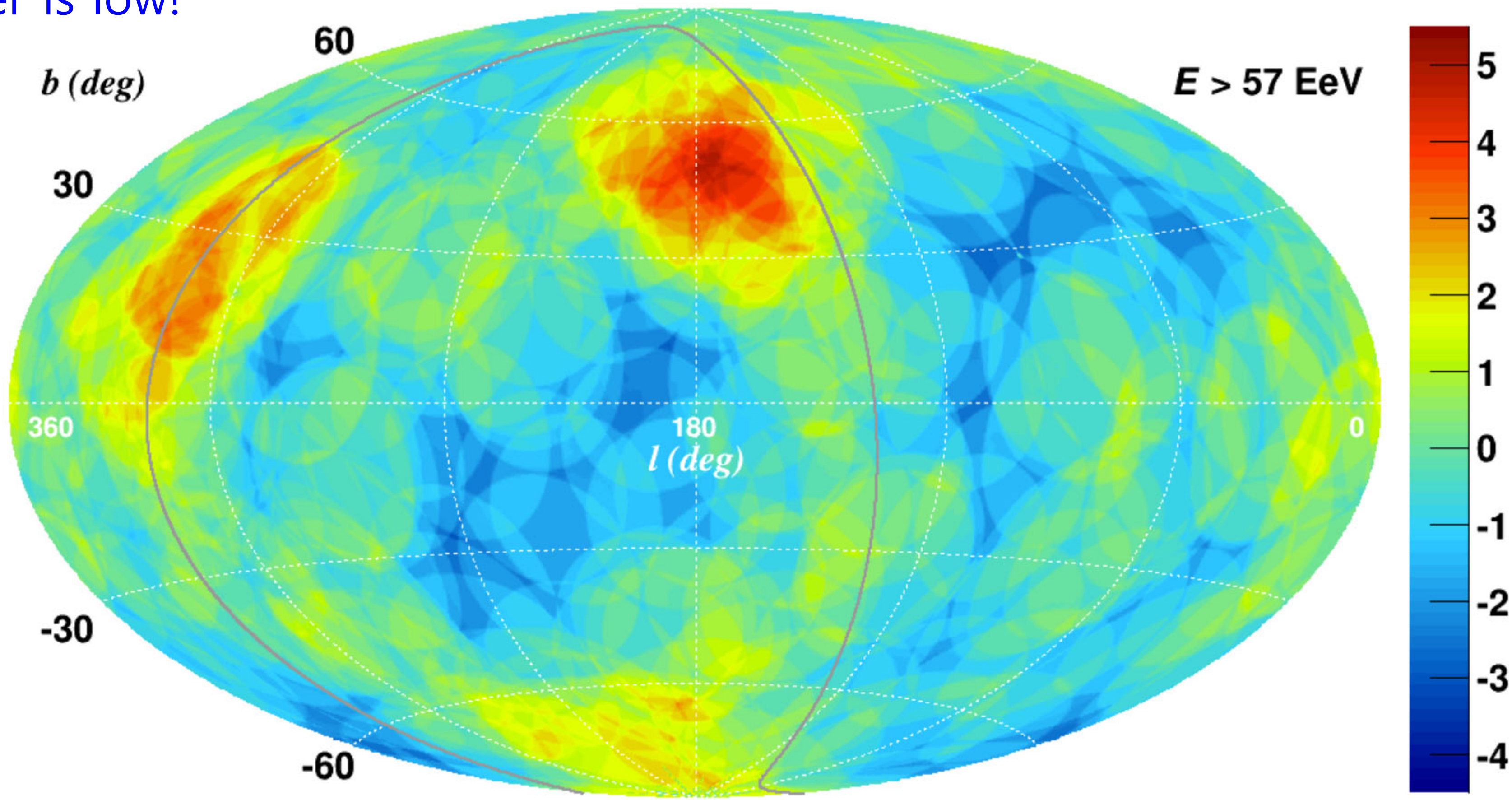
Significance (Galactic Coordinate)

The level of significance for a hotspot in Auger is low!

TA: S_{MAX} = 5.19σ, (l, b) = (174.8°, 50.6°)

PAO: S_{MAX} = 3.57σ, (l, b) = (315.2°, 12.9°)

(From Kawata's presentation)



Source of TA hotspot events?

Magnetic field is ubiquitous in the Universe!

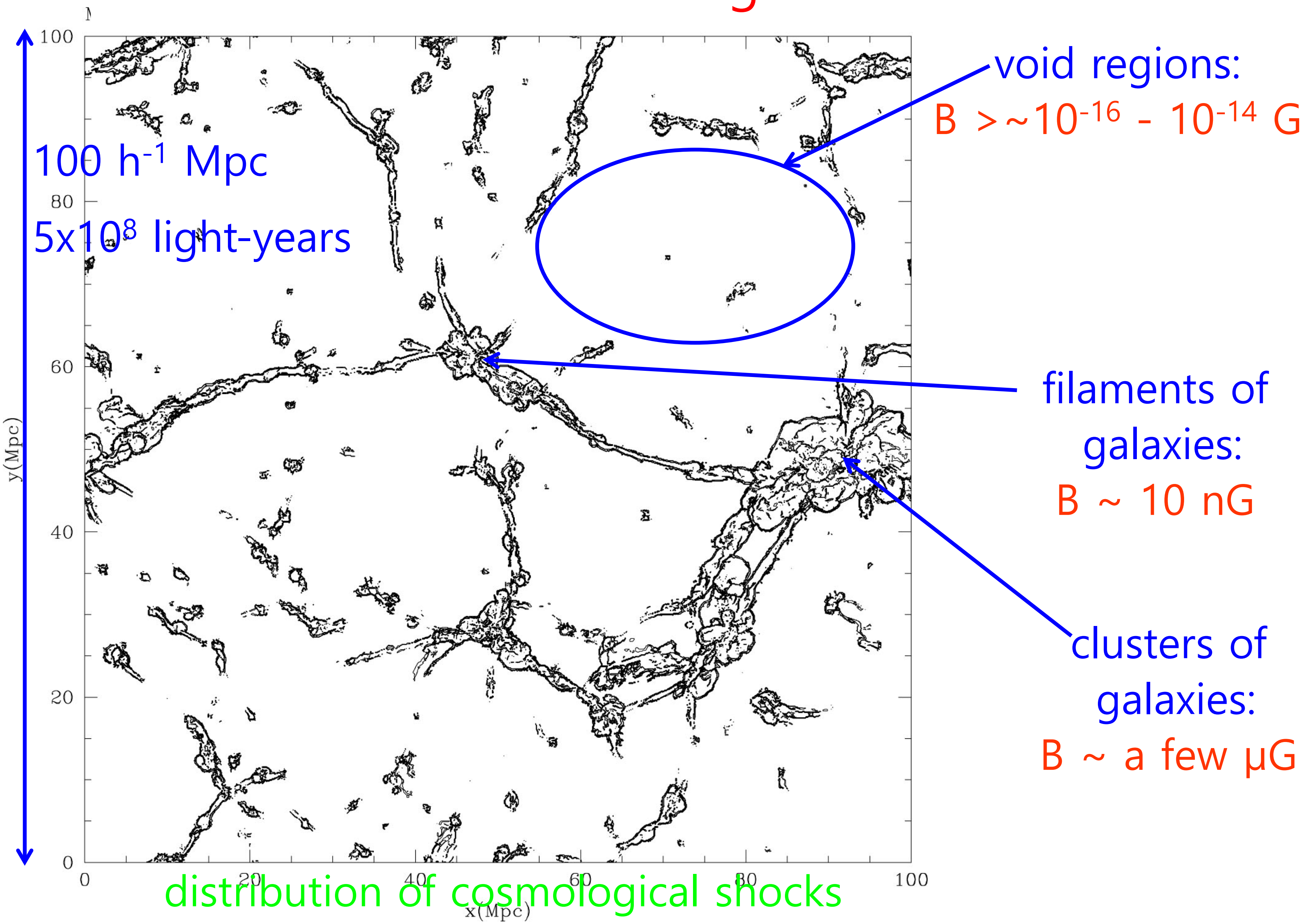
Star	
Magnetar	~ 10^{13} - 10^{15} G
Neutron star	~ 10^{11} - 10^{13} G
White dwarf	~ 10^{6} G
Ap/Bp star	~ 10^{3} G
Normal star	~ 1 G
Molecular cloud	~ 10^{-3} G
Interstellar medium	~ several x10^{-6} G
Cluster of galaxies	~ a few x 10^{-6} G
Filament of galaxies	~ 10^{-10} G (?)
Void	~ 10^{-16} – 10^{-14} G (?)
Early universe	~ 10^{-20} G (?)
Planck mass monopole	~ 10^{55} G

stronger field ↑

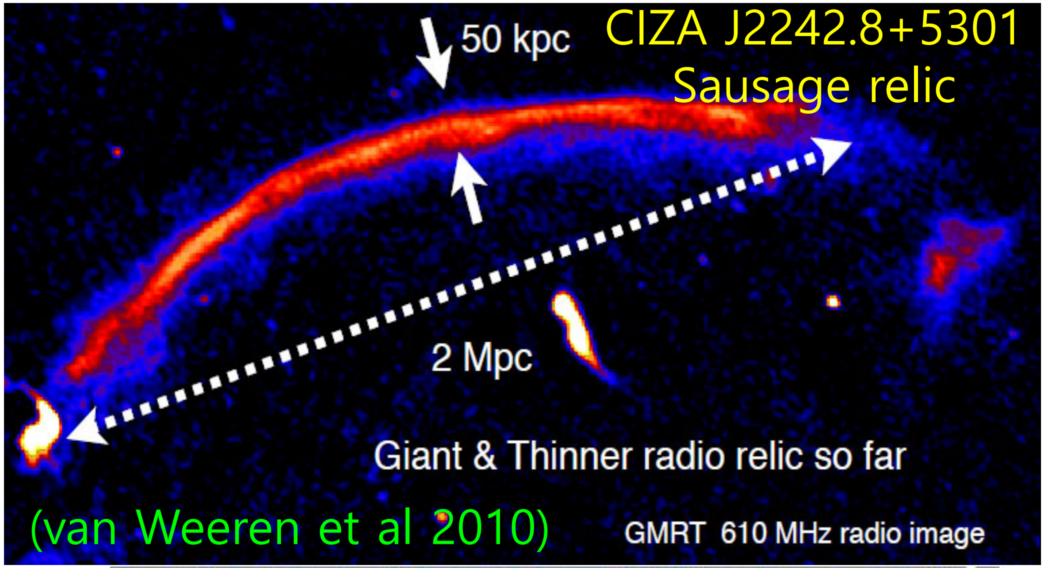
larger scale ↓

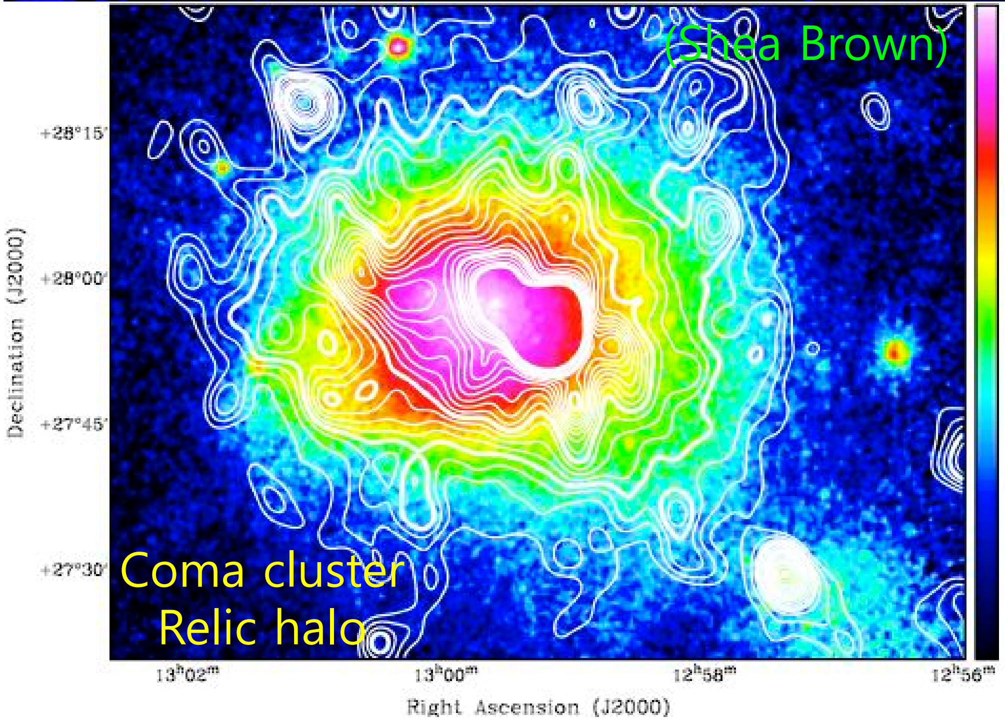
Cluster of galaxies, Filament of galaxies, Void → intergalactic magnetic field

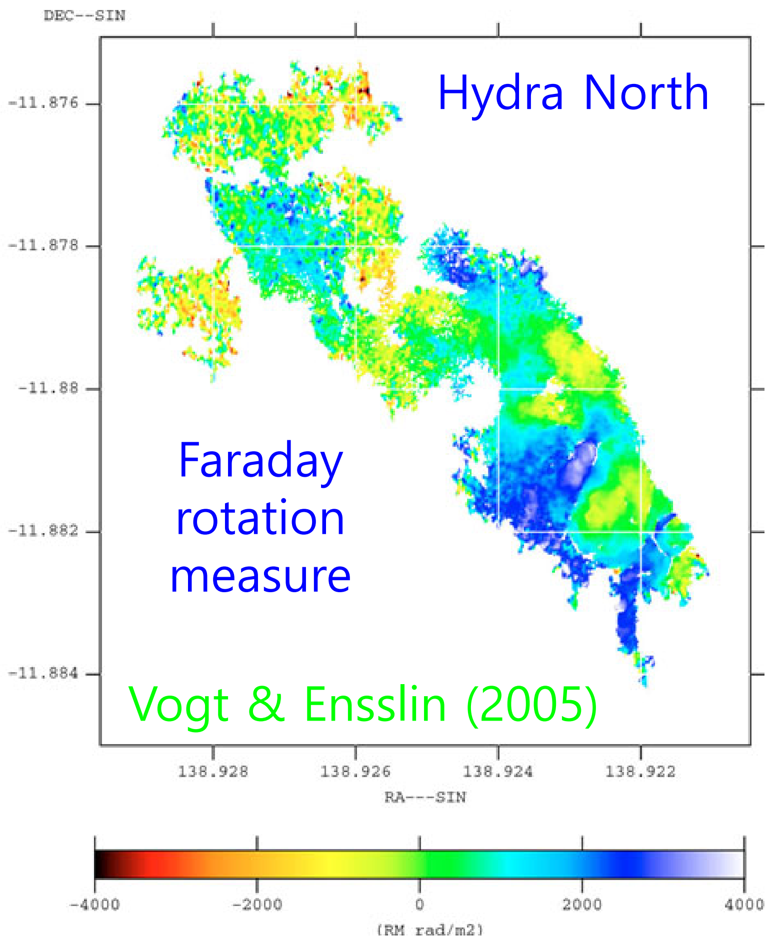
The universe is magnetized!



Magnetic fields in galaxy clusters appears in observations







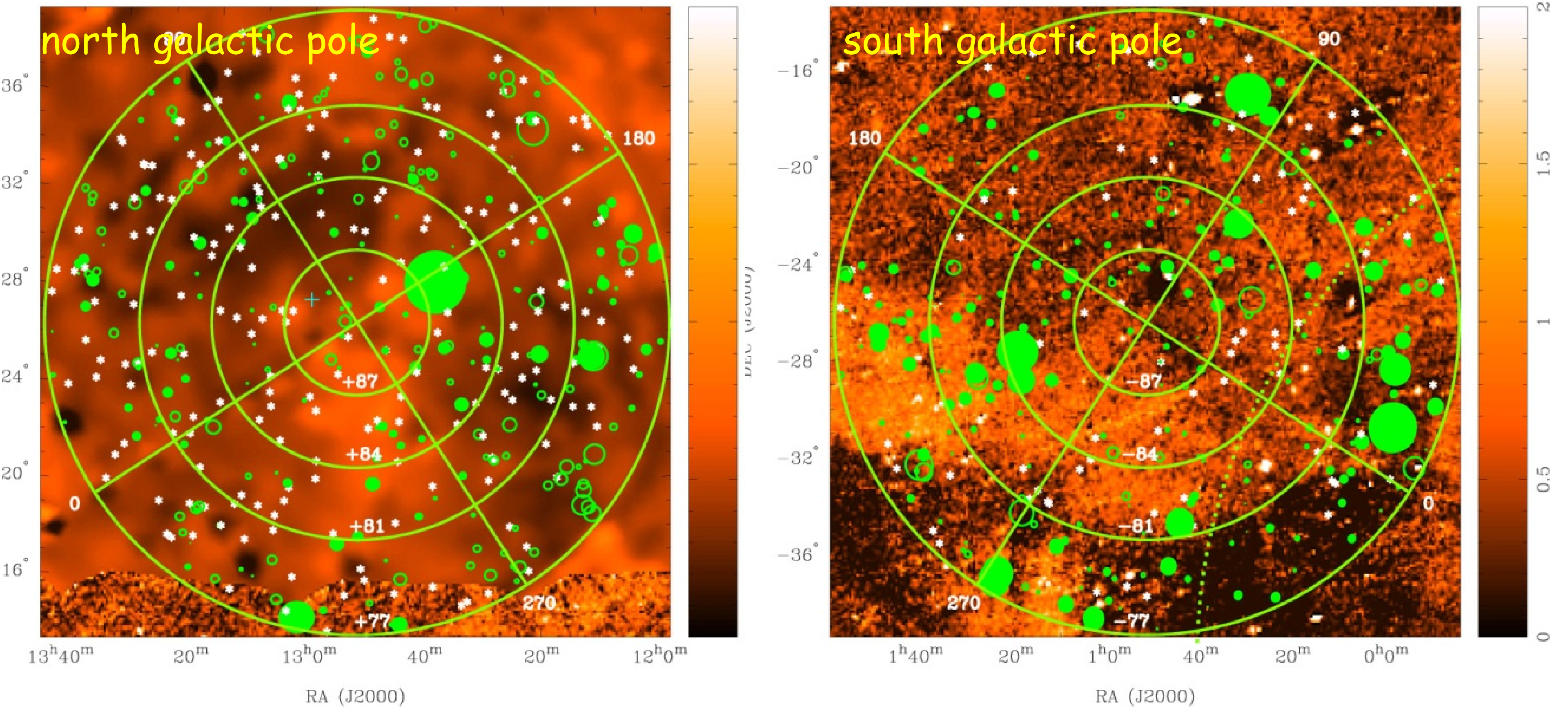
Clusters of galaxies – numbers and energetics

density of baryonic matter	$n \sim 10^{-2}\,\mathrm{cm}^{-3}$
flow velocity	$\upsilon \sim \mathrm{several} \times 10^{2}\ \mathrm{km/s}$
gas temperature	$T \sim 10^{8}\,\mathrm{K}$
magnetic fields	$B \sim \mathrm{a\ few}\ \mu\mathrm{G}$
gas kinetic energy	$E_{\mathrm{kinetic}} \sim 10^{-11}\,\mathrm{erg/cm}^{3}$
gas thermal energy	$E_{\mathrm{thermal}} \sim 10^{-10}\,\mathrm{erg/cm}^{3}$
magnetic energy	$E_{\mathrm{magnetic}} \sim 10^{-12}\,\mathrm{erg/cm}^{3}$

Magnetic fields in filaments of galaxies

faraday rotation measure

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



→ extragalactic contribution of ~6 rad/m^2

Schnitzeler et al (2010)

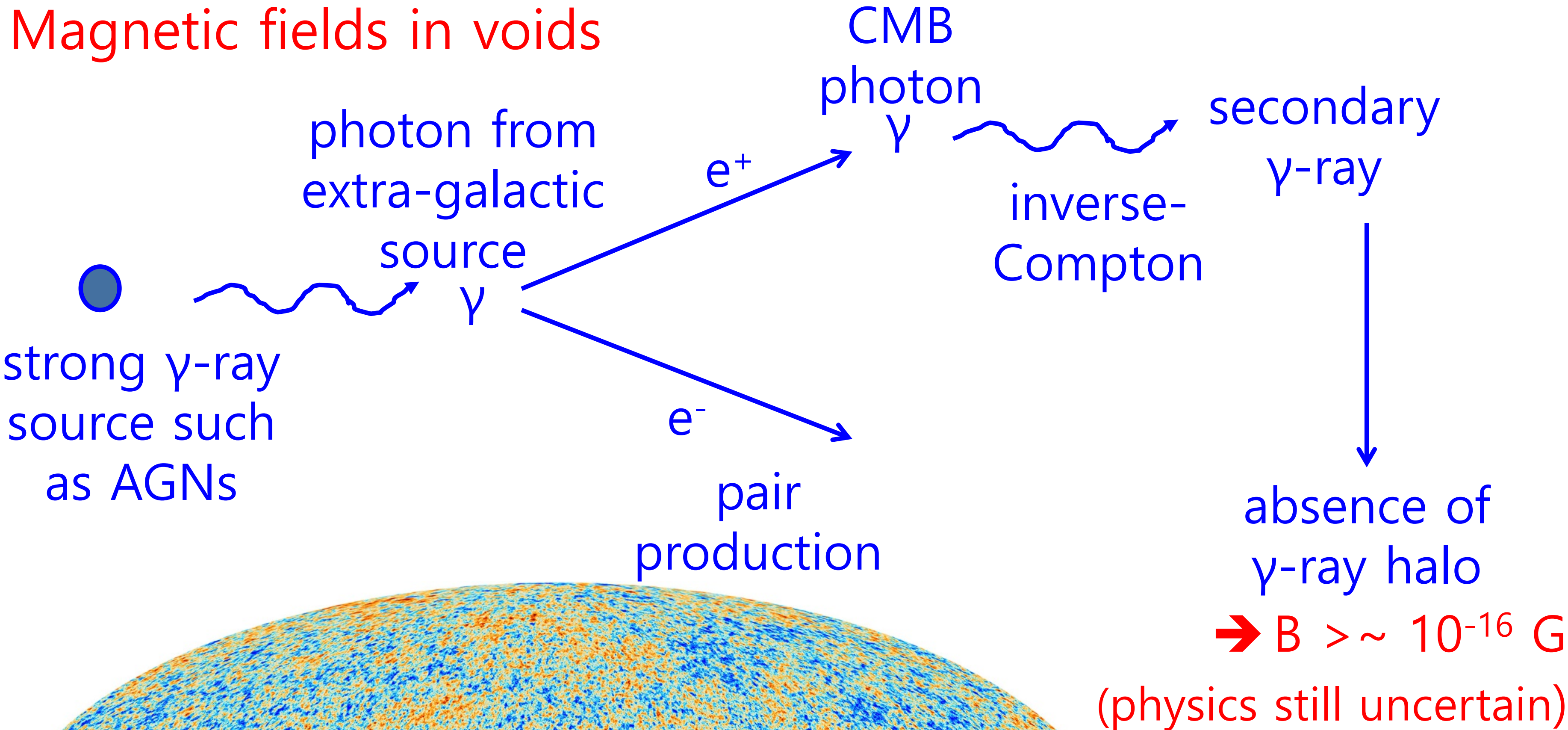
mostly due to magnetic fields in filaments of galaxies

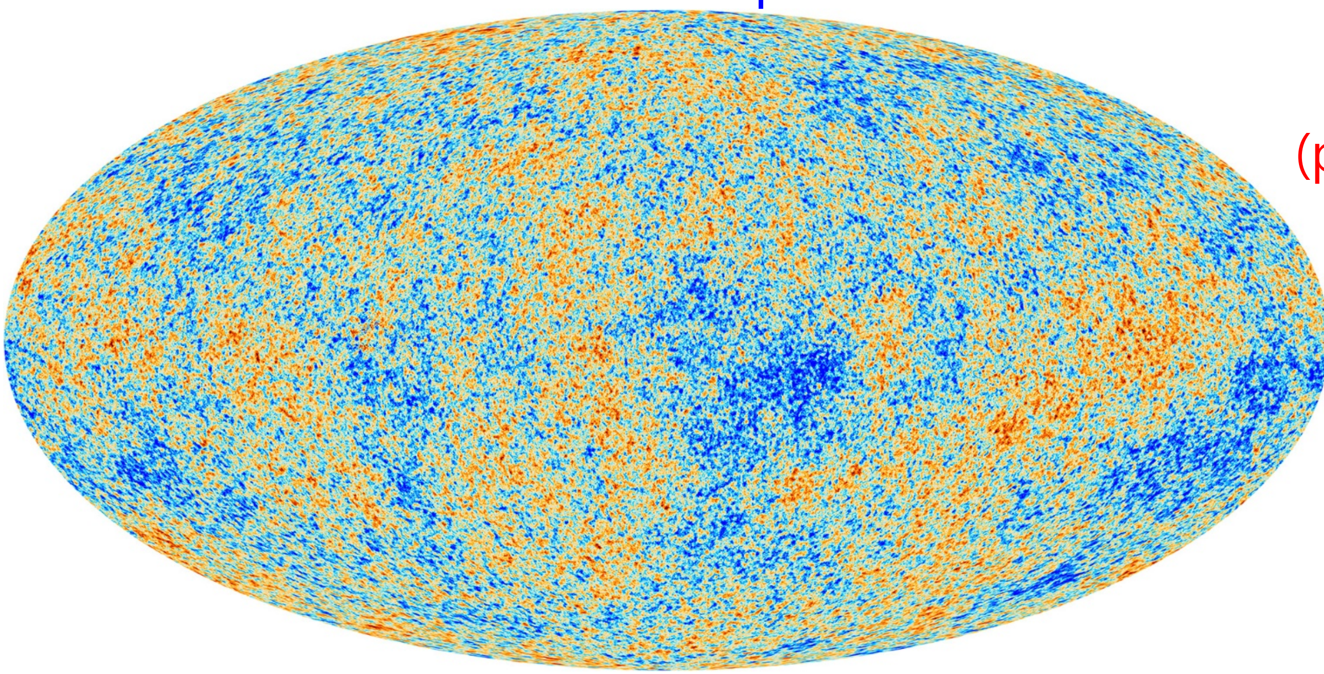
→ B ~ 10 nG (needs to be further confirmed)

Filaments of galaxies – numbers and energetics

density of baryonic matter	$n \sim 10^{-5}\,\mathrm{cm}^{-3}$
flow velocity	$\upsilon \sim \text{a few } \times 10^{2}\ \mathrm{km/s}$
gas temperature	$T \sim 10^{6}\,\mathrm{K}$
magnetic fields	$B \sim 10\ \mathrm{nG}$
gas kinetic energy	$E_{\mathrm{kinetic}} \sim 10^{-14}\,\mathrm{erg/cm^{3}}$
gas thermal energy	$E_{\mathrm{thermal}} \sim 10^{-15}\,\mathrm{erg/cm^{3}}$
magnetic energy	$E_{\mathrm{magnetic}} \sim 10^{-17}\,\mathrm{erg/cm^{3}}$

Magnetic fields in voids





limits from CMB

➔ B <~ 10^{-9} G

Void regions – numbers and energetics

density of baryonic matter	$n \sim 10^{-7}\,\mathrm{cm}^{-3}$
flow velocity	$\upsilon \sim 10^{2}\ \mathrm{km/s}$
gas temperature	$T \sim 10^{4}\,\mathrm{K}$
magnetic fields	$B >\sim 10^{-16} - 10^{-14}\ \mathrm{G}$

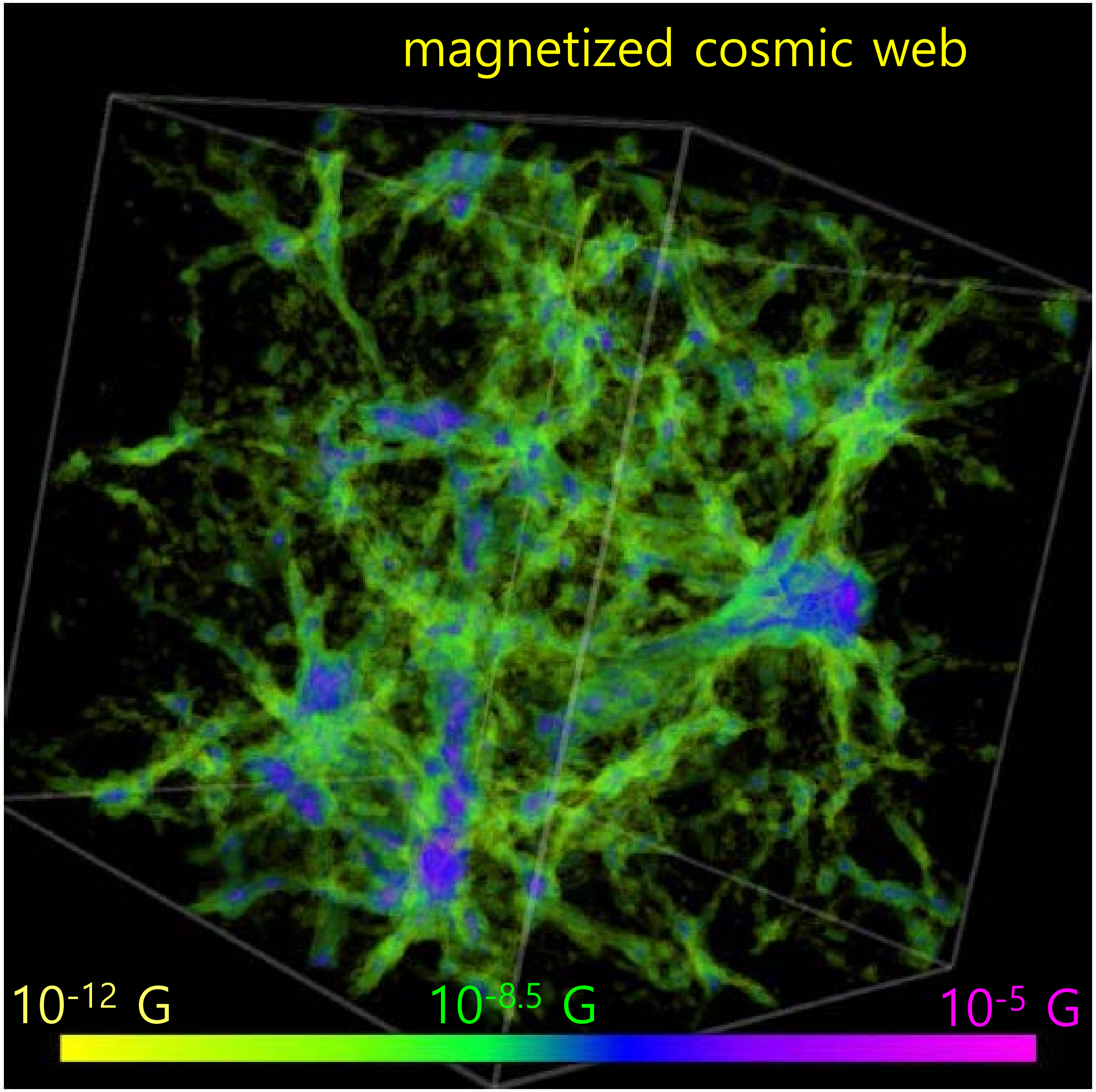
gas kinetic energy	$E_{\mathrm{kinetic}} \sim 10^{-17}\,\mathrm{erg/cm}^{3}$
gas thermal energy	$E_{\mathrm{thermal}} \sim 10^{-19}\,\mathrm{erg/cm}^{3}$
magnetic energy	$E_{\mathrm{magnetic}} \sim 10^{-33} - 10^{-29}\ \mathrm{erg/cm}^{3}$

A model for the origin magnetic fields in clusters and filaments: turbulence dynamo (small-scale dynamo)

- seed fields ← primordial or astrophysical ?
- turbulence ← shock waves, jet, and etc
- amplification of seed fields by turbulent flow motions

The mechanism for the origin of magnetic fields in voids: still controversial?

Magnetic fields in the large-scale structure from simulation



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

→ reproduce magnetic fields in clusters (~ a few μG) and filaments (~ 10 nG)

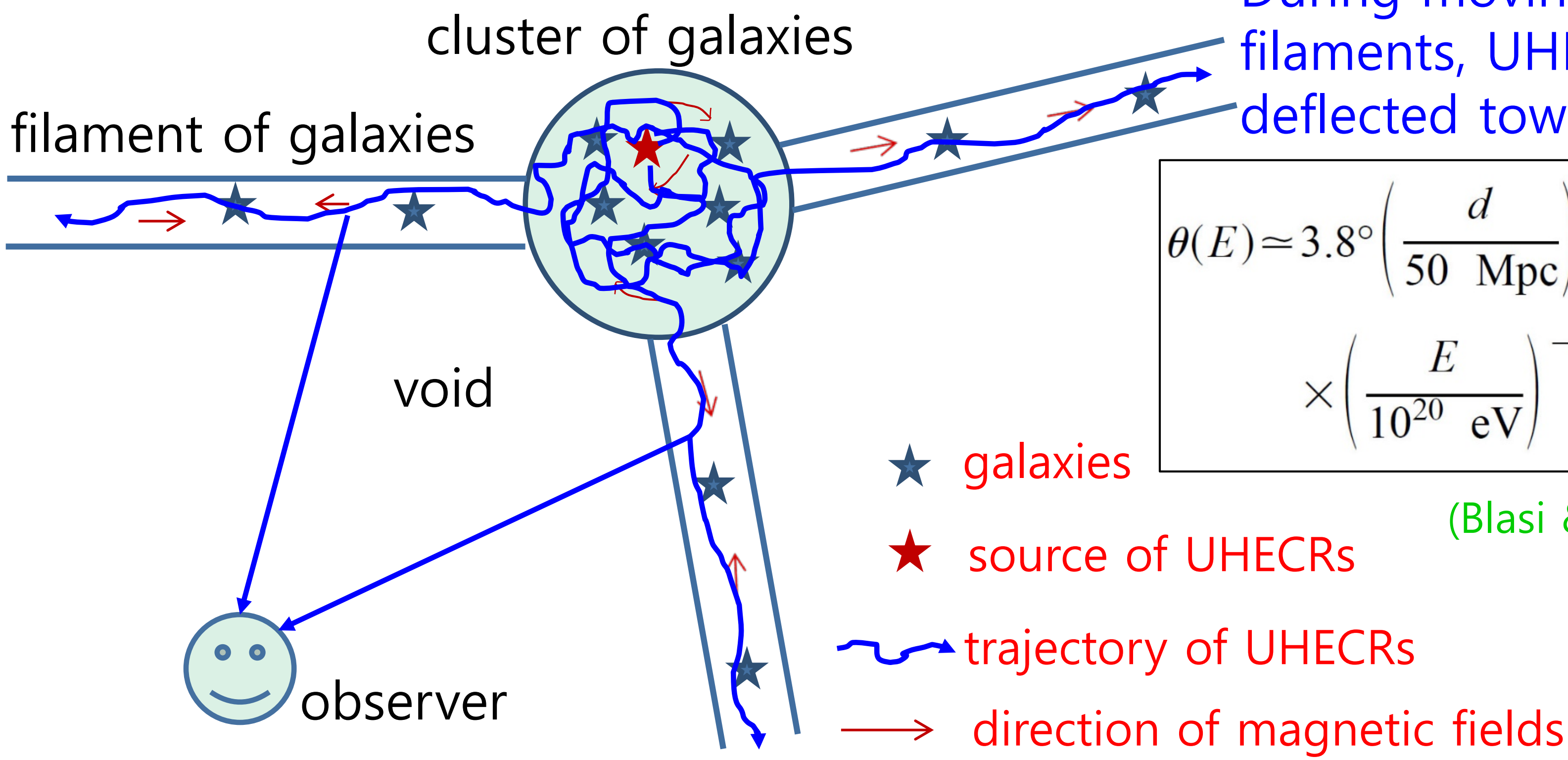
(Ryu, Kang, Cho & Das 2008)

Trajectories of UHECRs through the IGMF

UHECRs, if produced inside clusters, are confined in them, and then escape toward open field, possibly to filaments.

Larmor radius:

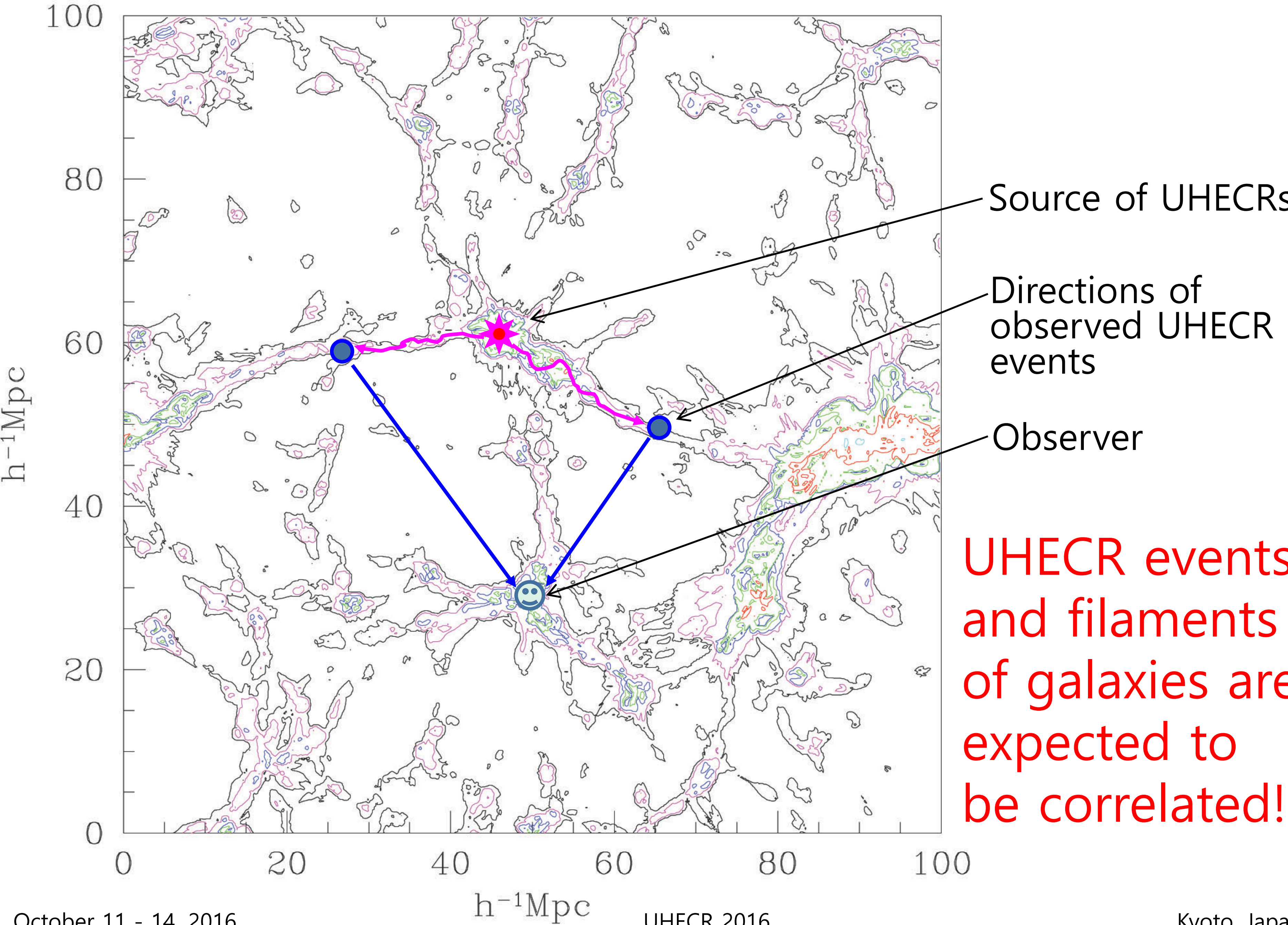
$$r_L \approx \frac{100\ \text{kpc}}{Z}\left(\frac{E}{10^{20}\ \text{eV}}\right)\left(\frac{B}{1\ \mu\text{G}}\right)^{-1}$$



During moving along filaments, UHECRS can be deflected towards us!

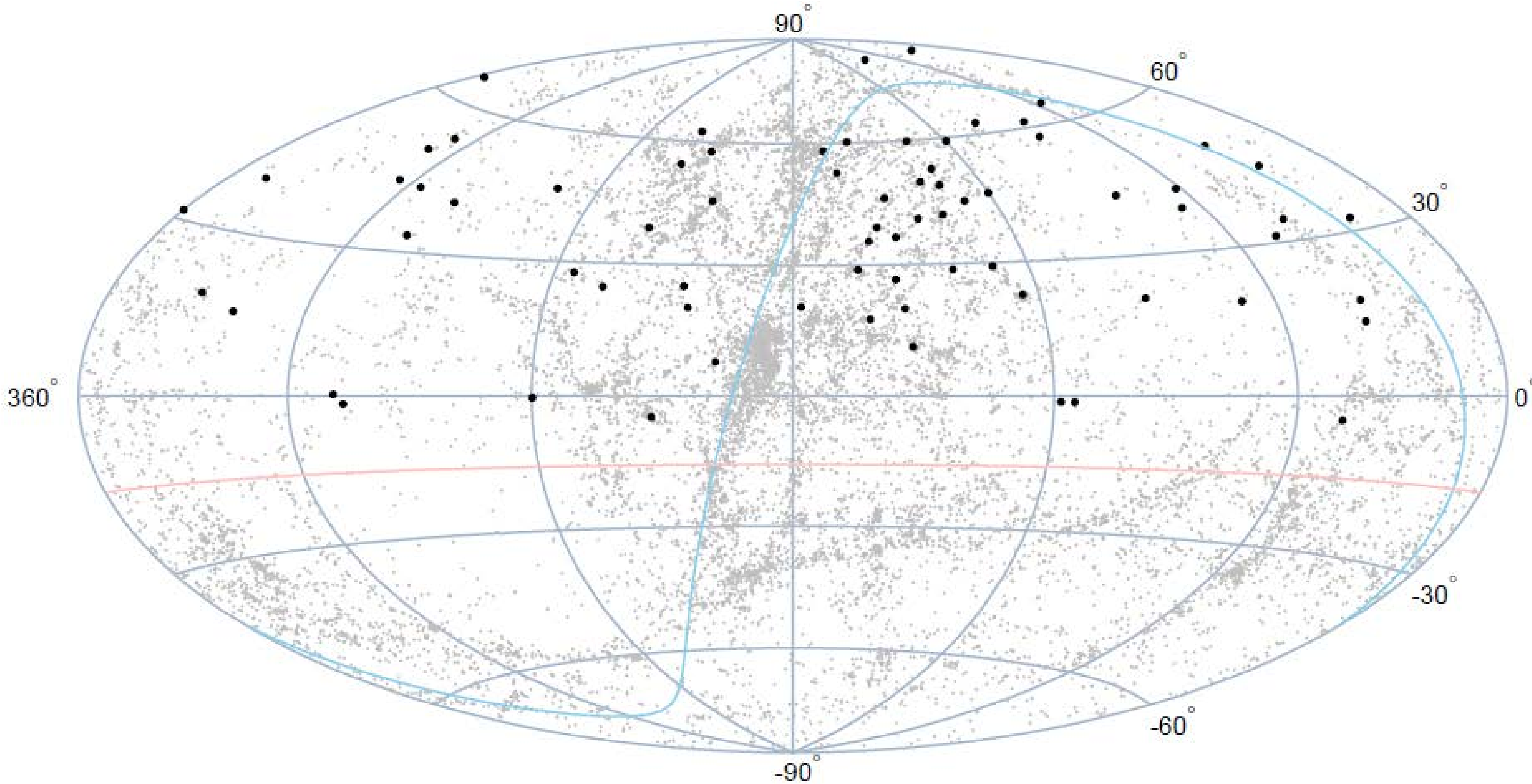
$$\theta(E) \simeq 3.8^\circ \left(\frac{d}{50\ \text{Mpc}}\right)^{1/2}\left(\frac{l_{coh}}{1\ \text{Mpc}}\right)^{1/2} \times \left(\frac{E}{10^{20}\ \text{eV}}\right)^{-1}\left(\frac{B}{10^{-9}\ \text{G}}\right).$$

(Blasi & Olinto 1990)



UHECR events and filaments of galaxies are expected to be correlated!

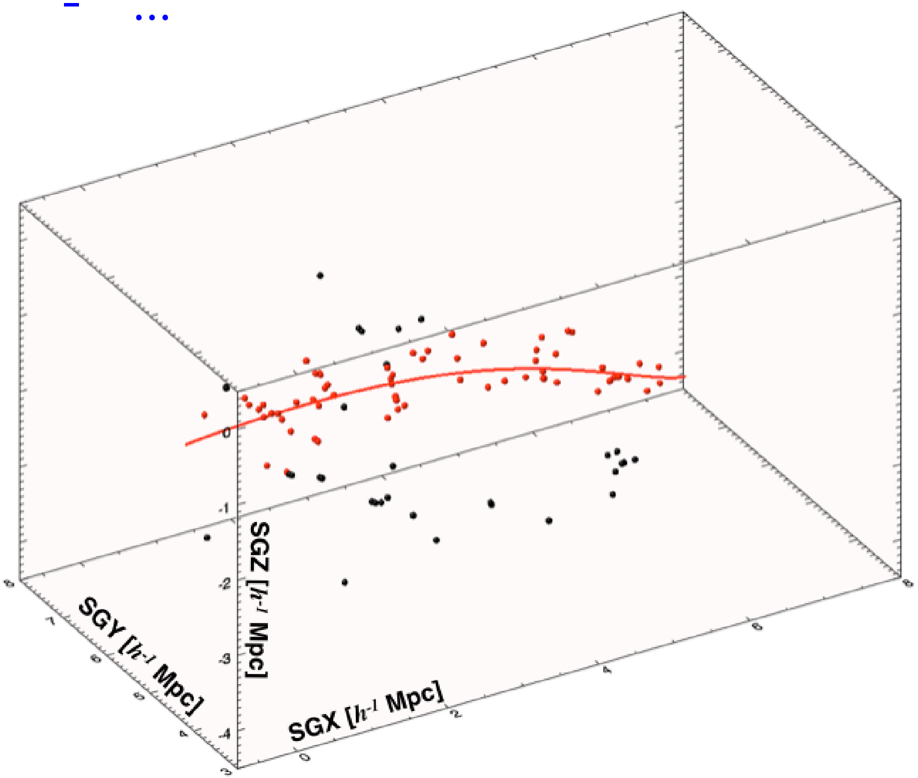
72 TA events with ≥ 57 EeV and galaxies with v ≤ 3500 km/s (or d ≤ 35 h-1 Mpc) from HyperLEDA in equatorial coordinates

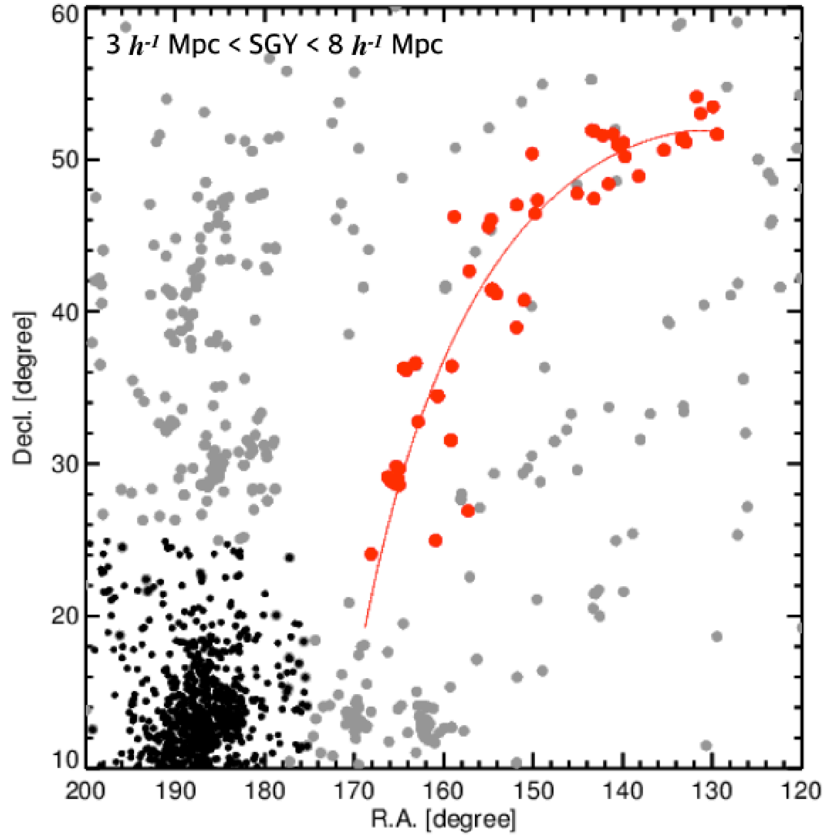


Are there filaments around the area of hotspot events and are they correlated to hot spot events ?

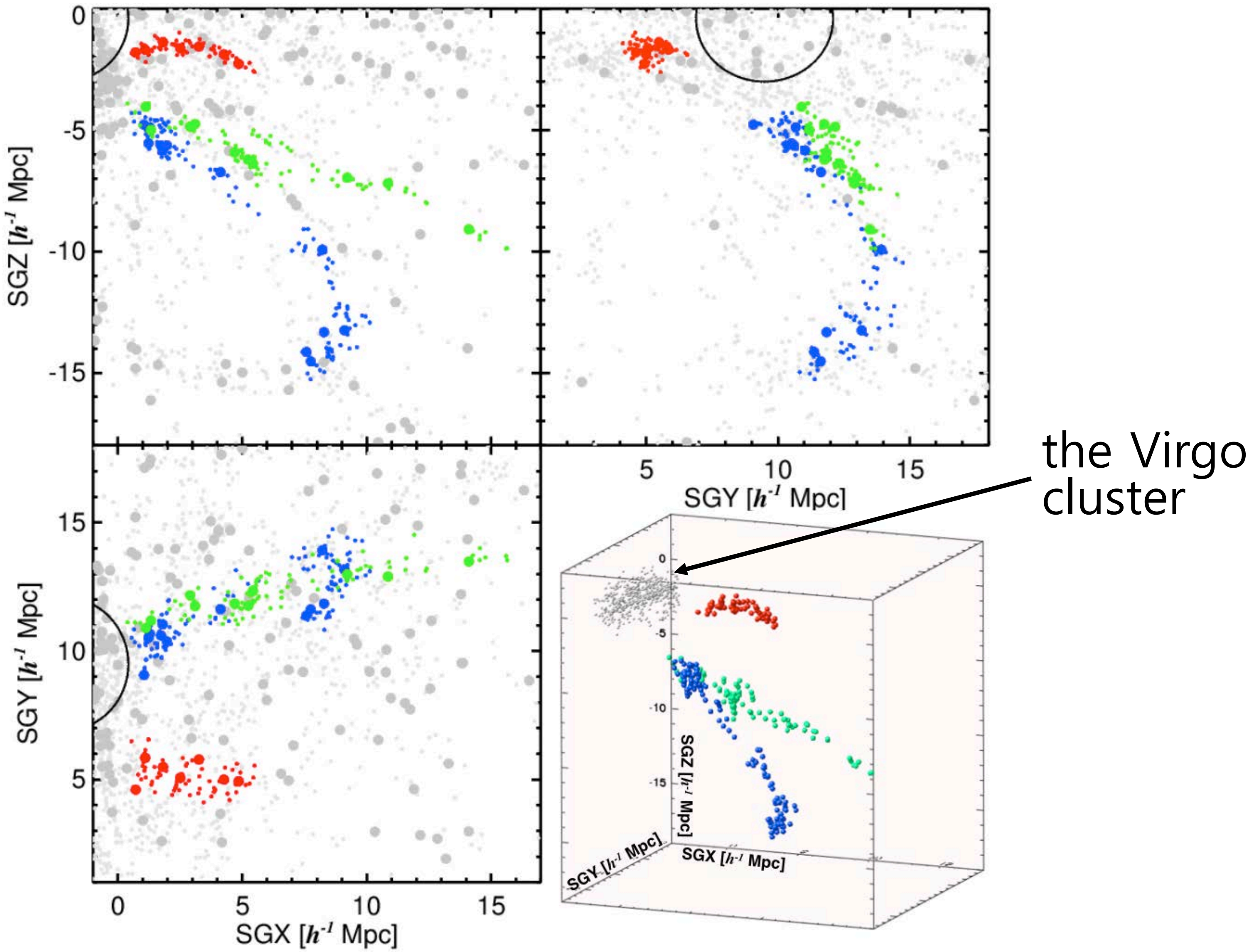
Finding filaments around the region of TA hotspot

- used galaxies in HyperLEAD and EVCC catalogs
- worked in the supergalactic coordinates
- picked neighboring galaxies using Voronoi tessellation
- constructed filamentary structures
- found three new filaments around the hotspot area
- ...

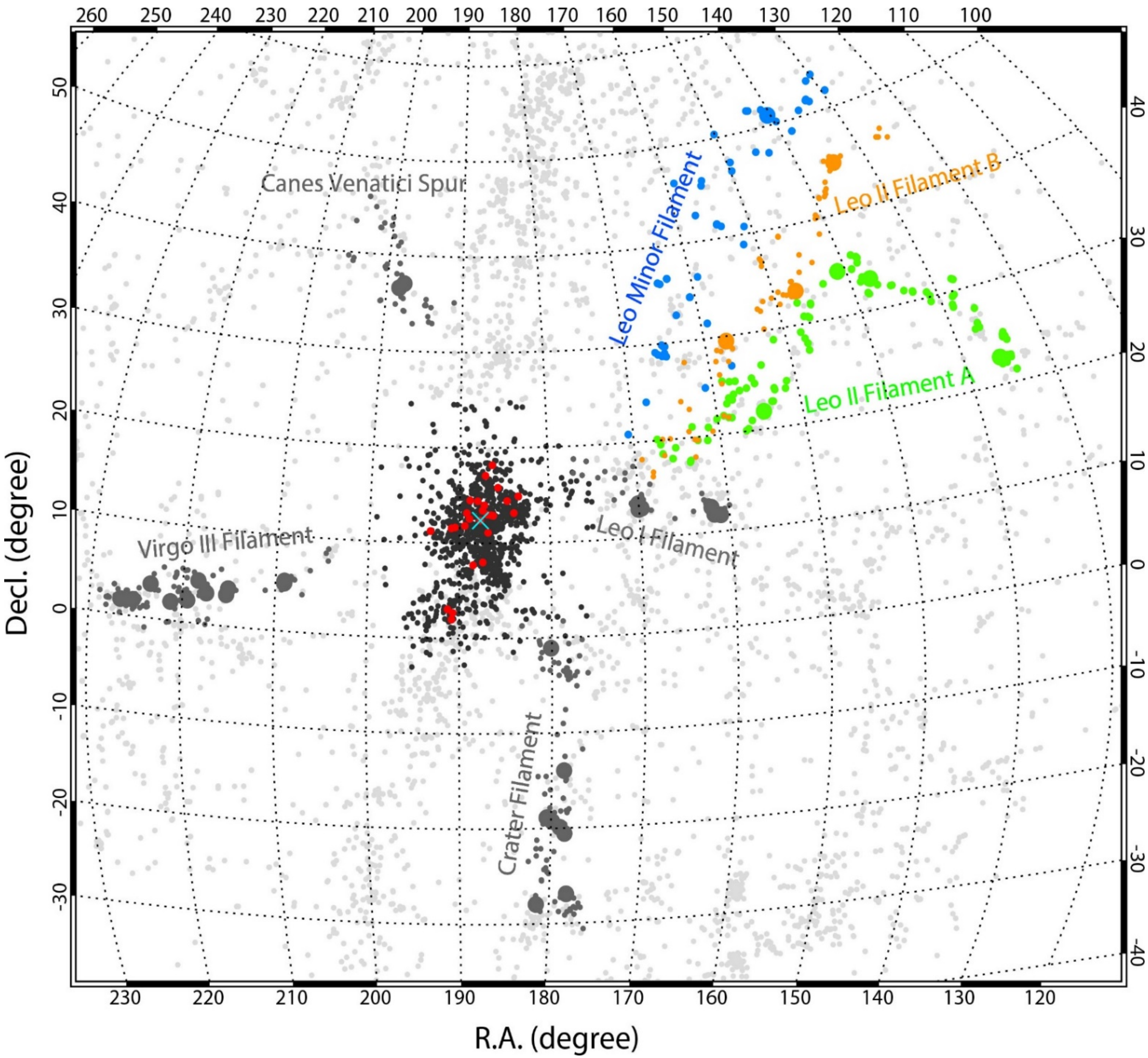




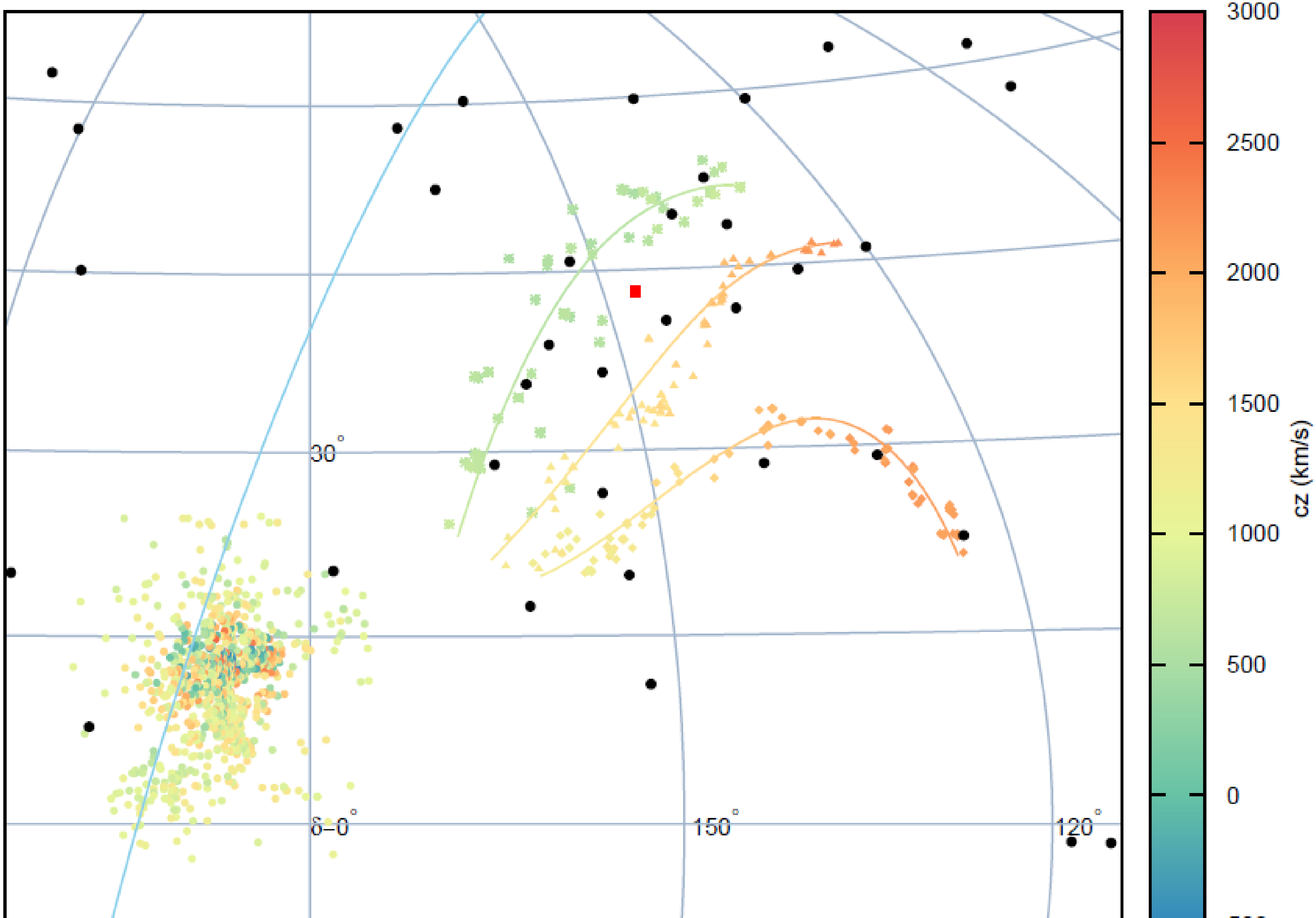
Three filaments around the hotspot area, which seem to be connected to the Virgo cluster, in the supergalactic coordinates



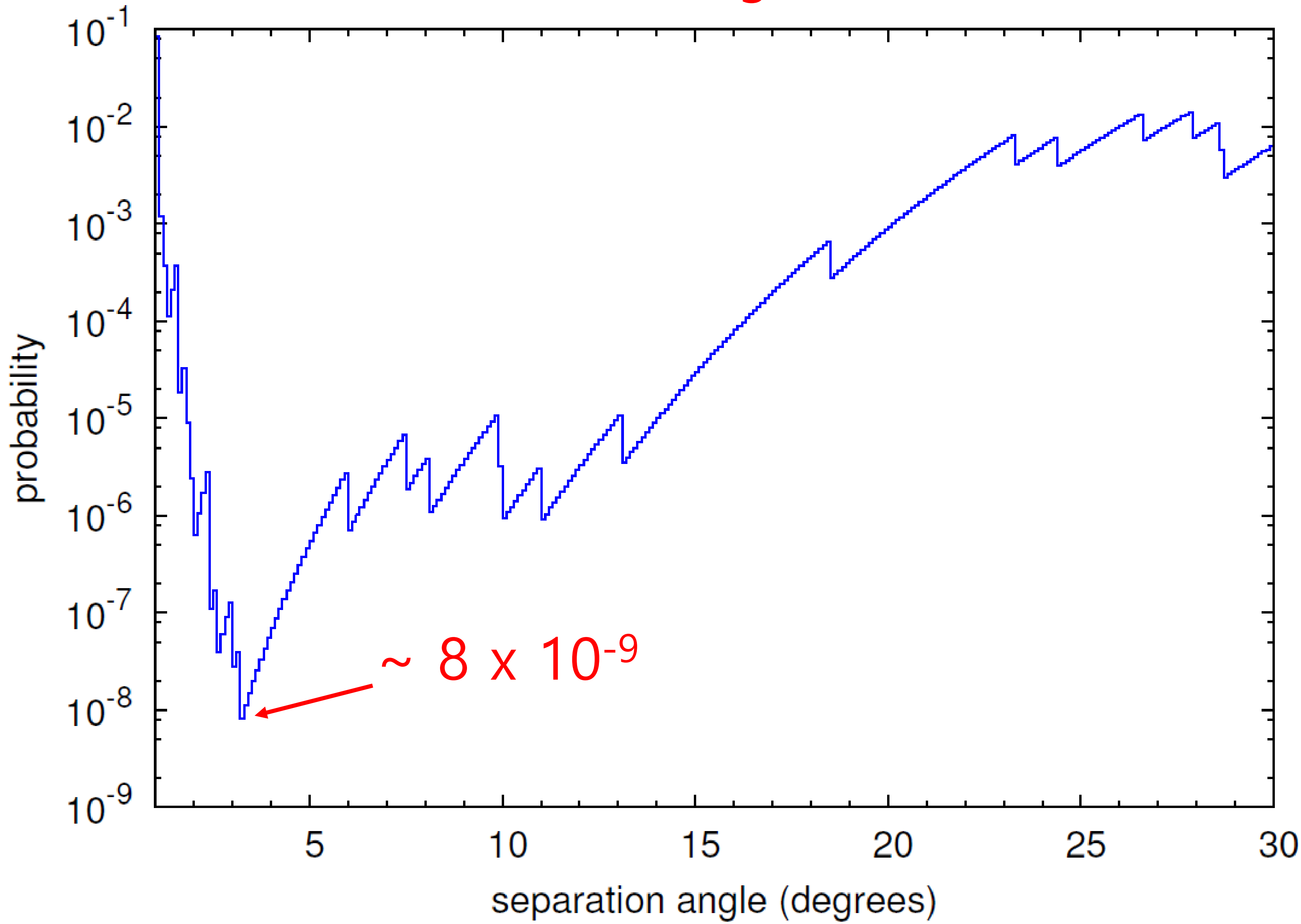
Three filaments in the equatorial coordinates



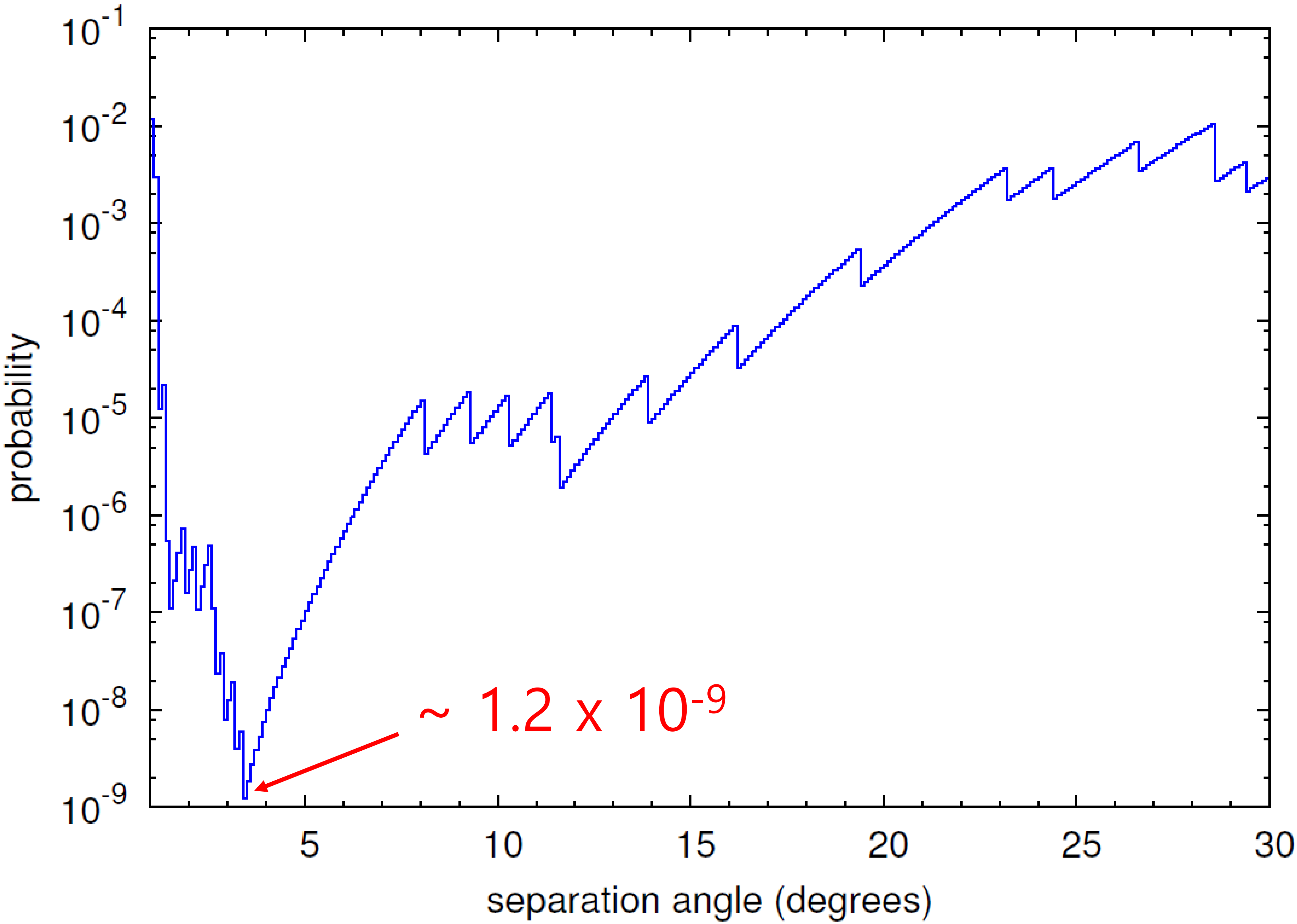
Zoom-up around the hotspot region: correlation between TA events and filaments?



Binomial probability of the excess of TA events with ≥ 57 EeV around filament-member galaxies inside ≤ θ



Binomial probability of the excess of TA events with ≥ 57 EeV around the spines of three filaments inside ≤ θ



Summary of statistical analysis

reference	angle	cr_num	sim_num	p_sim	iso_num	bino_prob	bino_sig
galaxies	3.2	18	48865	4.89E-02	3.52	8.17×10^{-9}	5.76
spines	3.4	18	43274	4.33E-02	3.12	1.23×10^{-9}	6.08

- We found that 18 (18) out of 72 events correlated at 3.2° (3.4°) , while 3.53 (3.12) events were expected to correlate by chance for an isotropic expectation. The binomial probability of observing by chance in an isotropic expectation an equal, or larger, number of events than that found in the data

$$P(X \geq 18) = 8.17 \times 10^{-9} \rightarrow 5.76\sigma$$
$$P(X \geq 18) = 1.23 \times 10^{-9} \rightarrow 6.08\sigma$$

- We simulated 10^9 sets of isotropic arrival directions containing the same number of events as the data set. For the filament spine, we found the post trial probability is

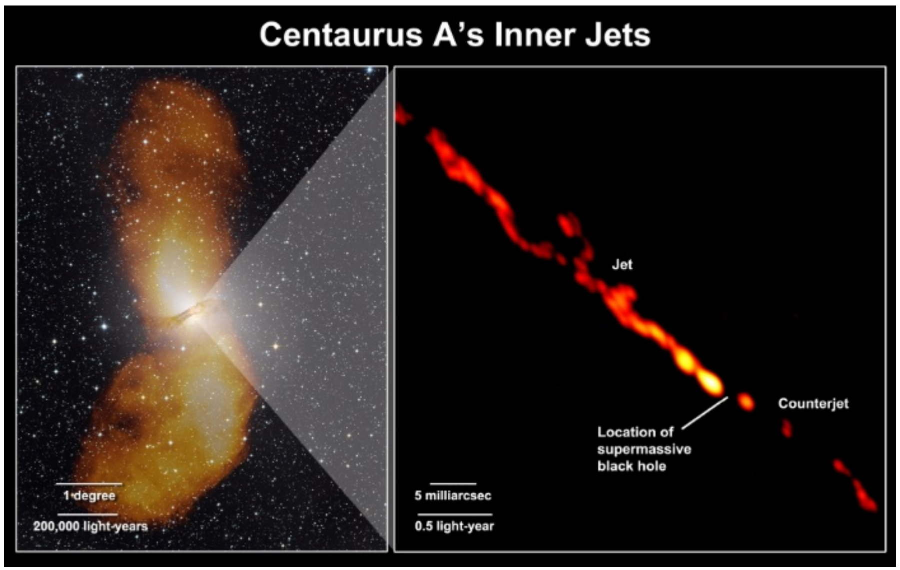
$$P = 2.0 \times 10^{-8}$$

(Kim, Ryu, etal to be submitted)

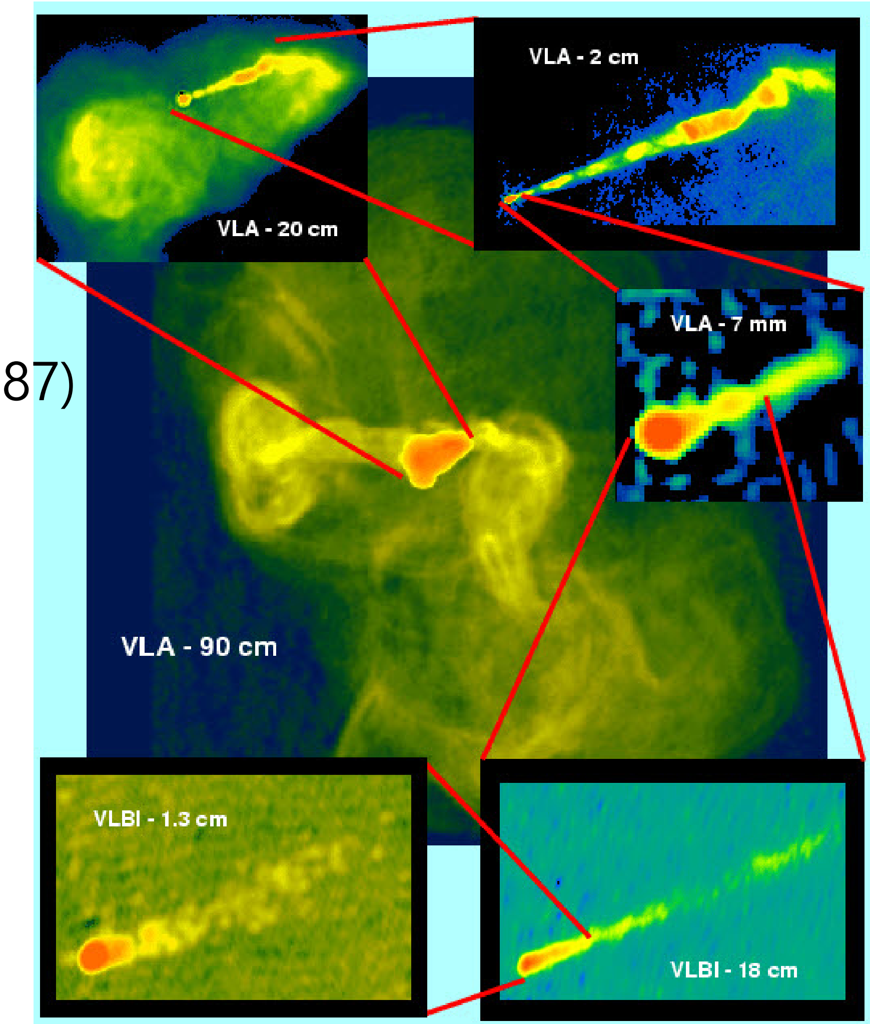
Virgo A, a radio galaxy, as sources of UHECRs ?

shock acceleration or
turbulent acceleration
→ OK for Fe, not for p ?

Centaurus A



Virgo A (M87)

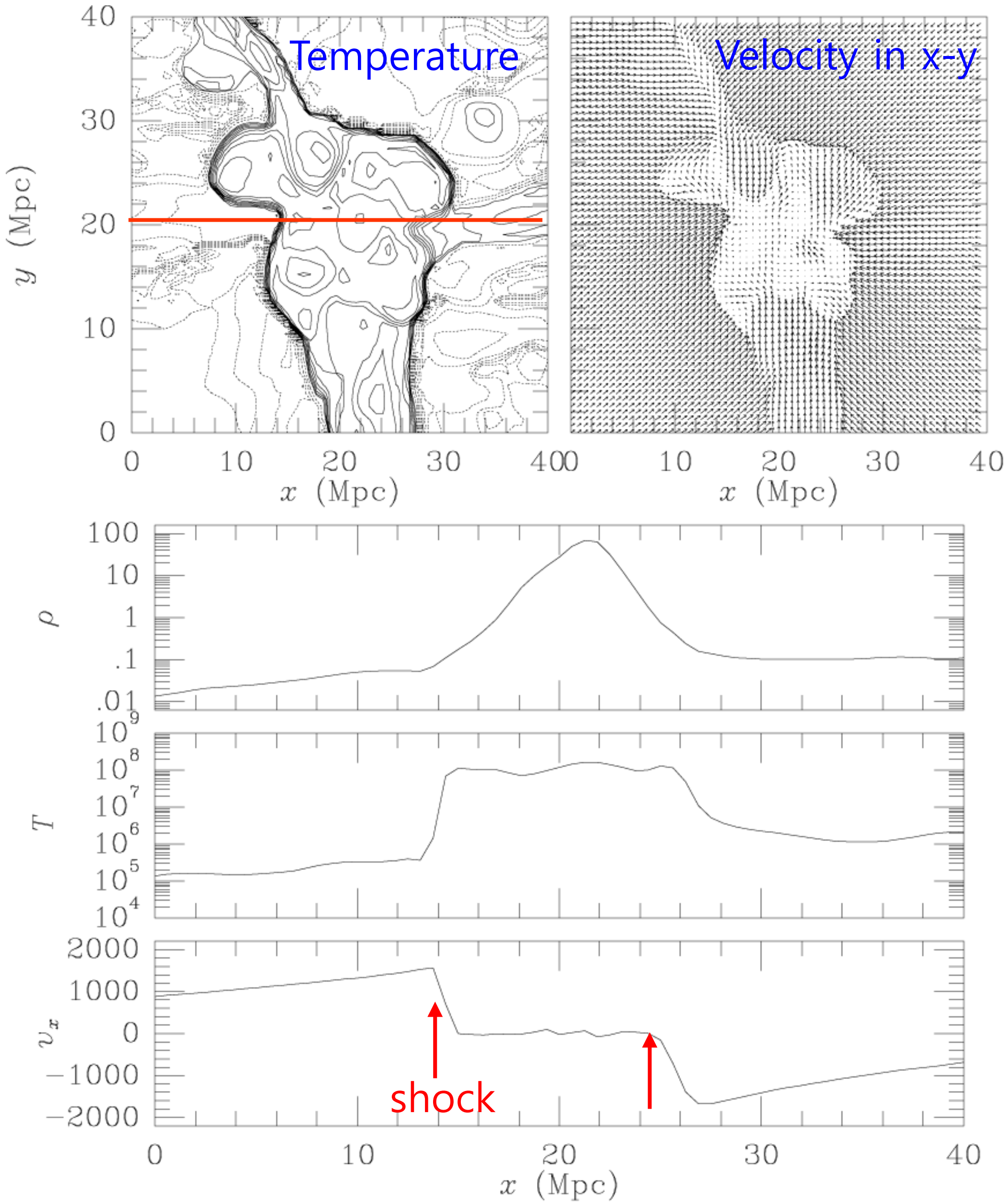


Properties of the FR I radio galaxies Cen A, M 87 and Fornax A.

source	size (kpc)	d (Mpc)	L_{radio} (erg s^{-1})	M_{BH} ($M_\odot$)	L_j (erg s^{-1})	θ (°)	V_{GL} (pc^{-3})	B_{GL} (μG)
Cen A	600	3.8		$5.5\ 10^7$	$1\ 10^{43}$	50		0.9
M 87	70	16.7		$3.2\ 10^9$	$4\ 10^{44}$	15 - 25		7.0
Fornax A	290	18.6		$1.5\ 10^8$				1.3

Cluster shocks as sources of UHECRs (?)

(Kang, Ryu, & Jones 1996)



- Shocks around clusters of galaxies

- Maximum energy for t_{age} ~ 10^{10} years according to DSA theory

$E_{max} = 5 \times 10^{19}$ eV x Z $(V_s / 2000$ km/s$)^2$ B_μ

B_μ = in units of mG

- Limited by loss

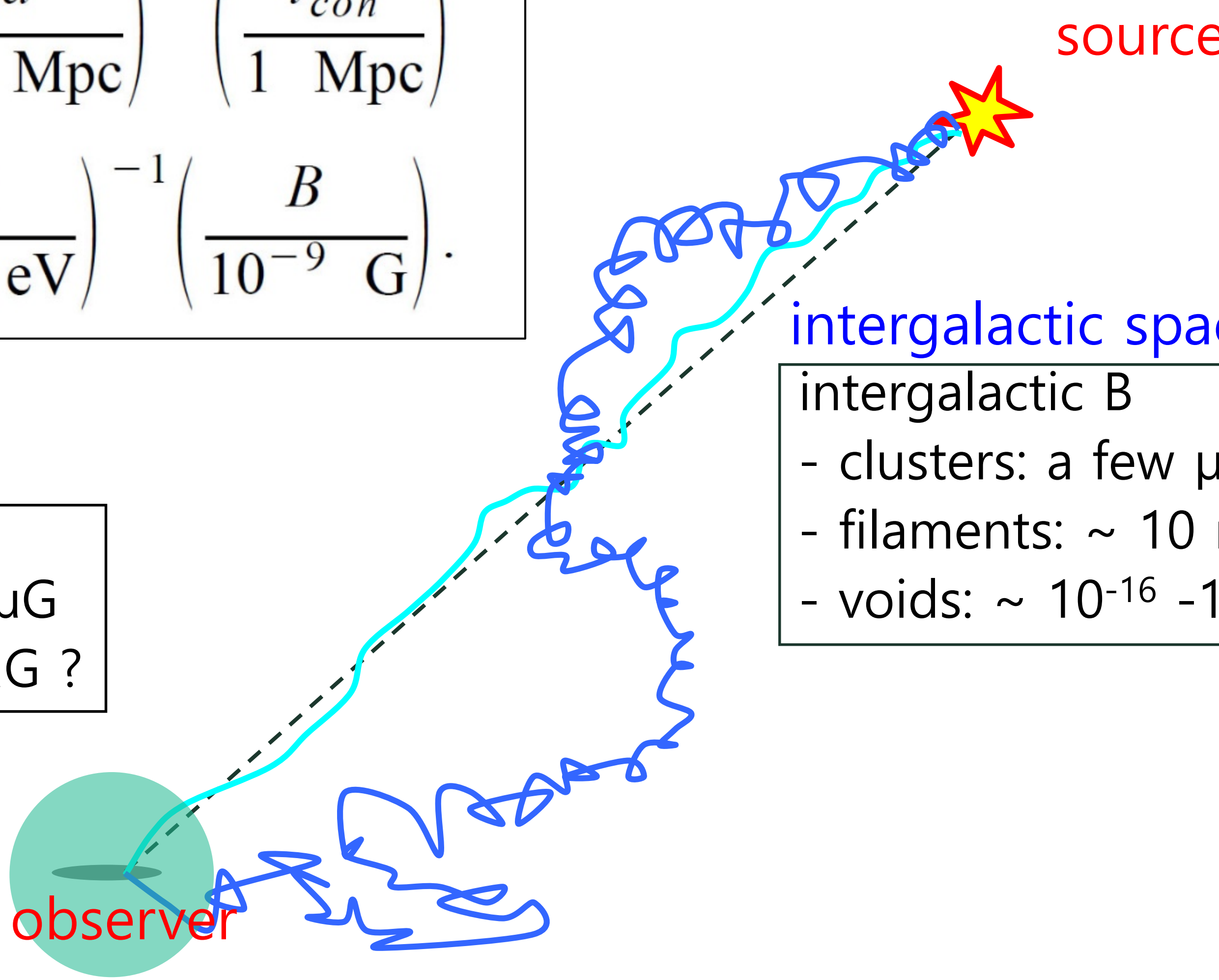
$E_{max} \sim 10^{19}$ Z eV

OK for Fe, not for p ?

- For proton with 10^{20} eV, need something else, such as adiabatic compression, further acceleration at internal shocks, and etc

Deflection of UHECRs due to intergalactic and galactic magnetic fields

$$\theta(E) \simeq 3.8^\circ \left(\frac{d}{50\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{l_{coh}}{1\ \mathrm{Mpc}}\right)^{1/2} \times \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1}\left(\frac{B}{10^{-9}\ \mathrm{G}}\right).$$

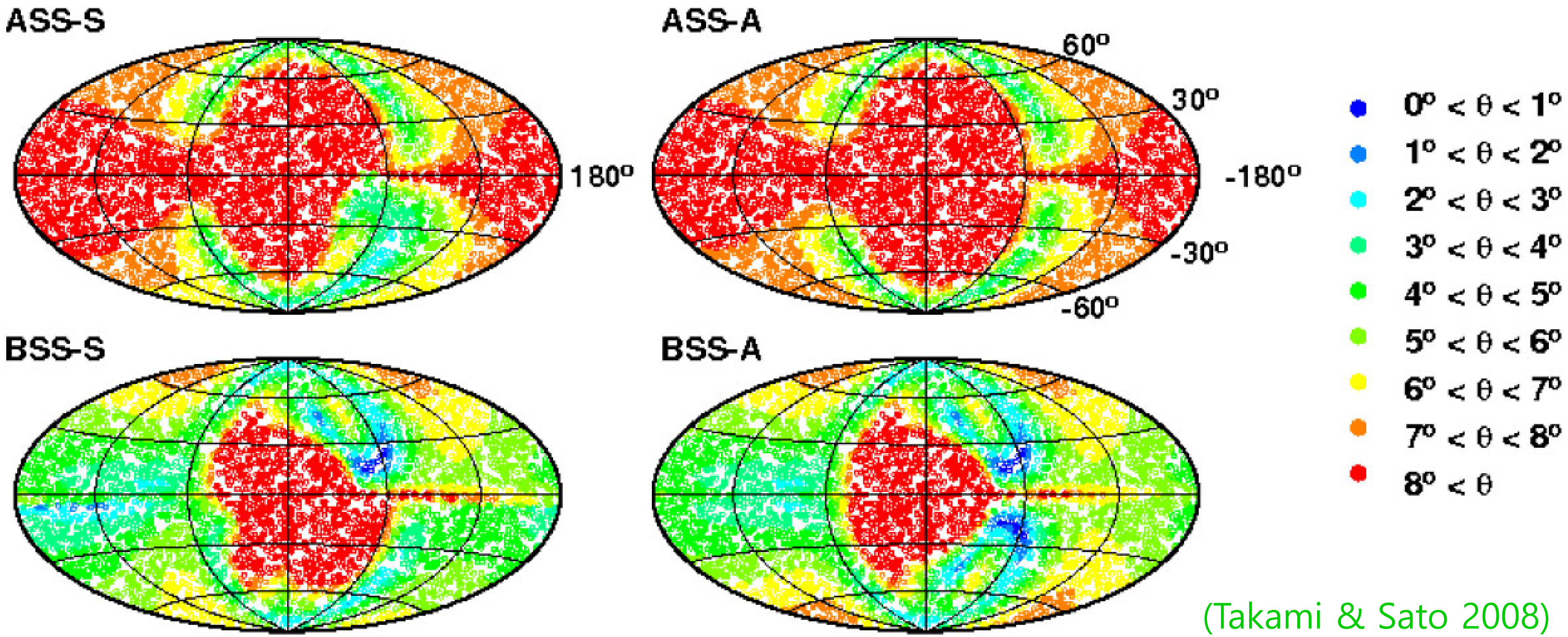


intergalactic B
- clusters: a few μG
- filaments: ~ 10 nG
- voids: ~ 10^{-16} -10^{-14} G

Milky Way

Galactic B
- disk: several μG
- halo: < ~ 1 μG ?

Deflection due to the galactic magnetic field



(Takami & Sato 2008)

- Deflection of ~60 EeV proton events due to the GMF: ~ a few to several degree, comparable (or somewhat larger than) the maximum correlation angle between the TA hotspot events and local filaments!

- Deflection of heavier UHECR events: more than tens degree!

Points to think

- Intergalactic magnetic field (IGMF): a few μG in clusters and ~10 nG in filaments
- A close correlation of $\theta \sim 3 - 4°$ between TA hotspot events and galaxy filaments attached to Virgo Cluster
- UHECRs are confined in clusters, escape toward and propagate along filaments, are deflected to observer; propagation distance $D_p \leq \sim 100$ Mpc → sources are likely in the local universe at source distance $D_s \leq$ a few ~ several x 10 Mpc (note $D_s < D_p$)
- With filaments attached to Virgo Cluster, source (or sources) is likely in Virgo Cluster, Virgo A (M87, radio galaxy), cluster shocks, or something else ?
- Close correlation with $\theta \sim 3 - 4°$; deflection due to the GMF, a few to several degree for protons but much large for irons at E ~60 EeV → TA hotspot events are mostly protons, if the correlation is real.
- Search for finding structures such as filaments towards Centaurus A and Centaurus Cluster failed → not necessarily no structure, but need more work.

Thank you !