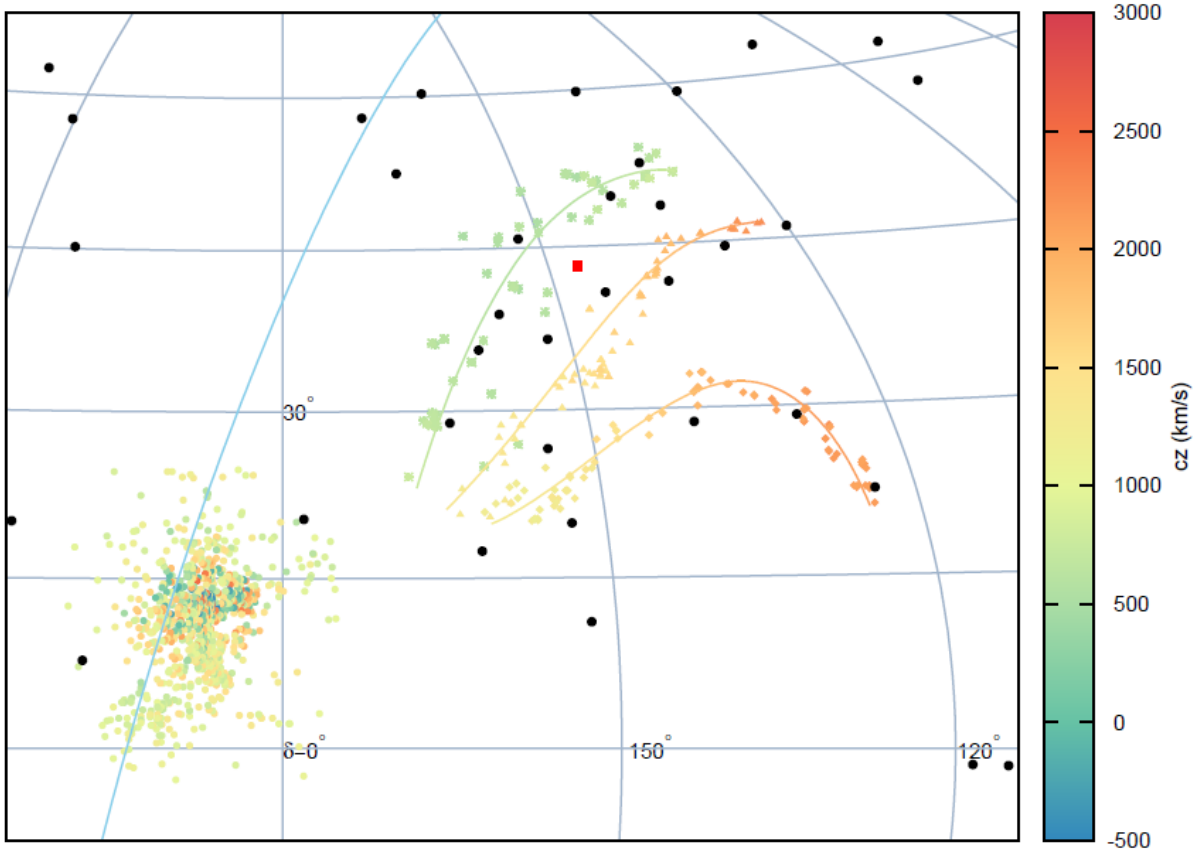
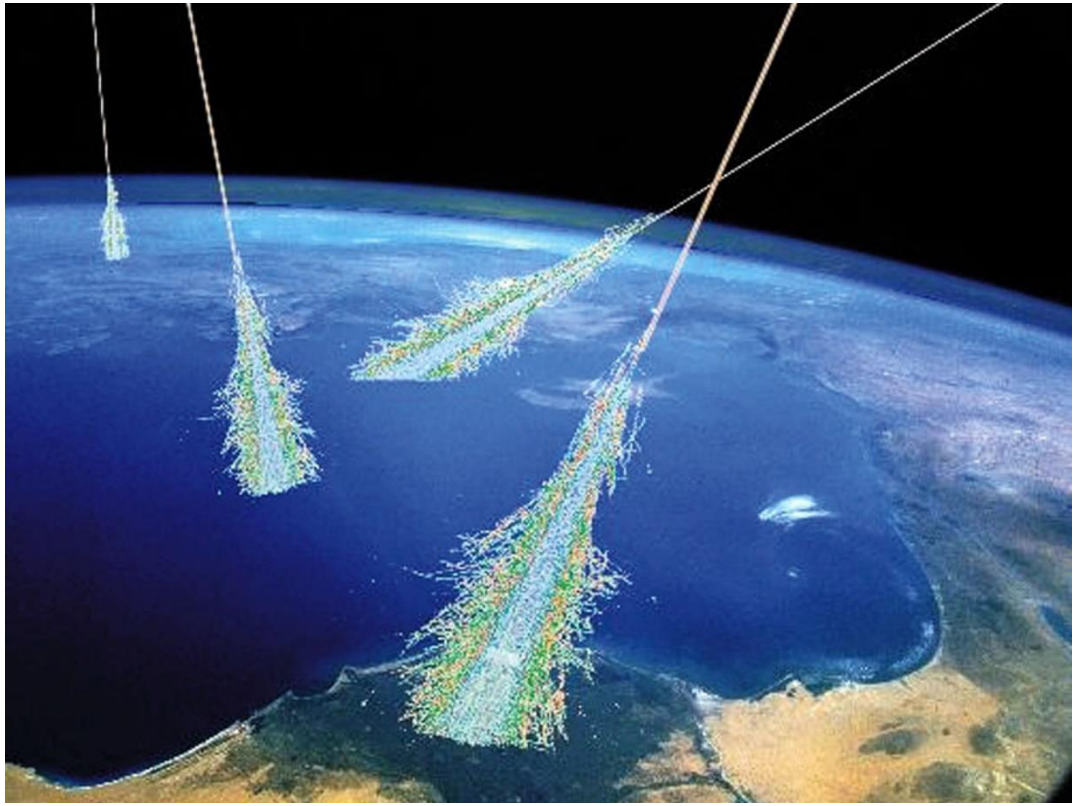
Intergalactic Magnetic Field and Correlation between UHECRs Events and Structures of Local Universe



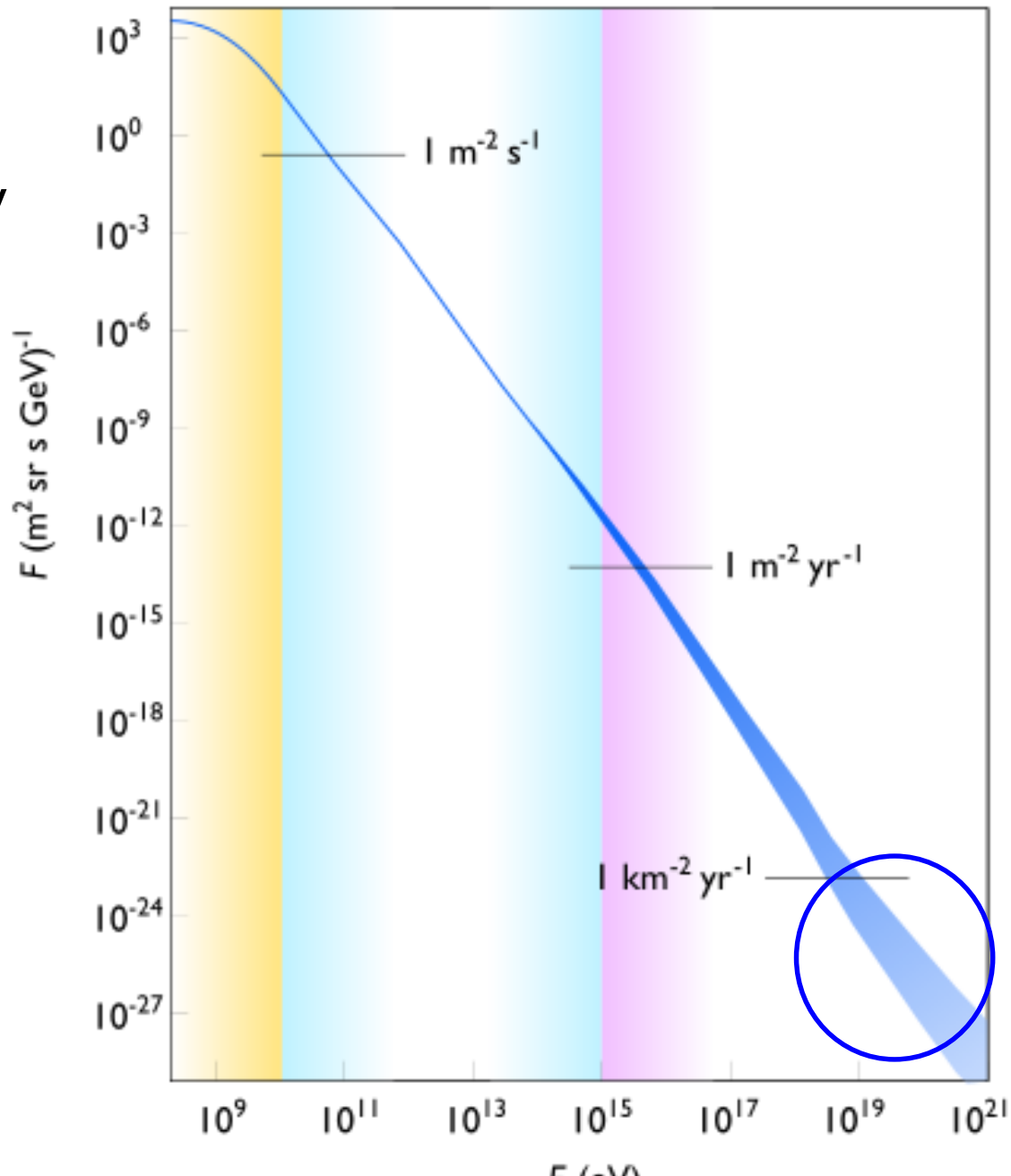
Dongsu Ryu (UNIST, KASI, Korea), Jihyun Kim (UNIST),
Suk Kim (CNU), Soo-Chang Rey (CNU), Hyesung Kang (PNU)

Cosmic rays: are high-energy radiation, mainly originating outside the Solar System, composed primarily of high-energy protons and atomic nuclei.

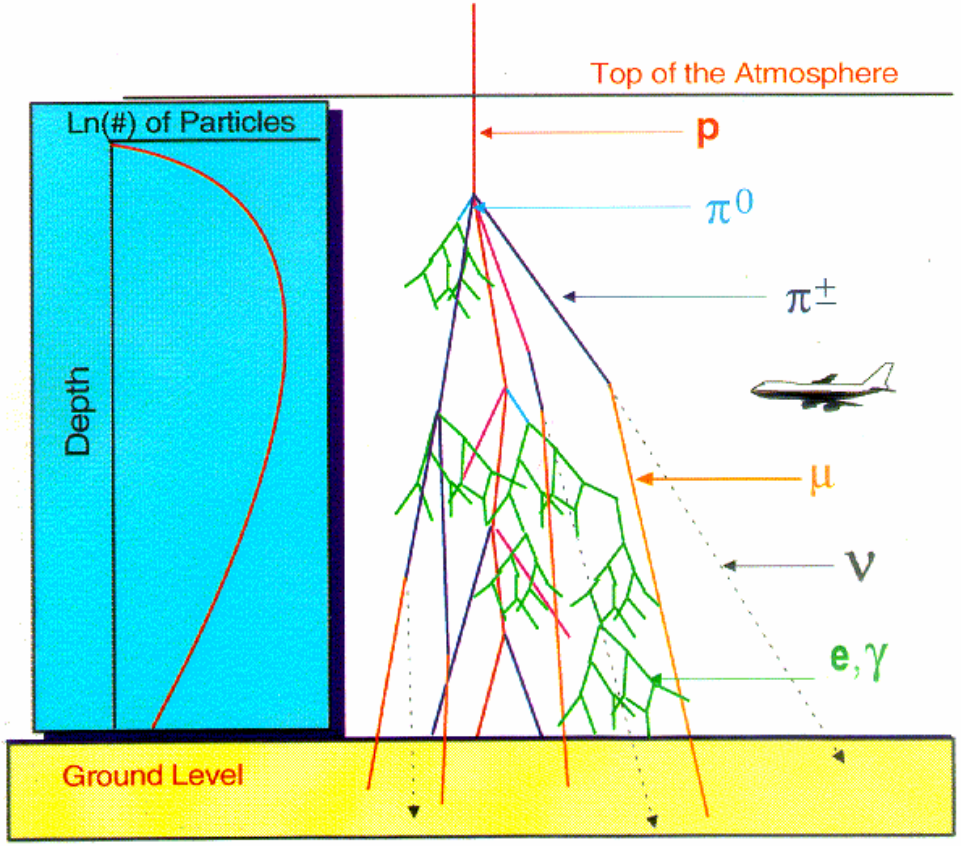
Hess on 1912



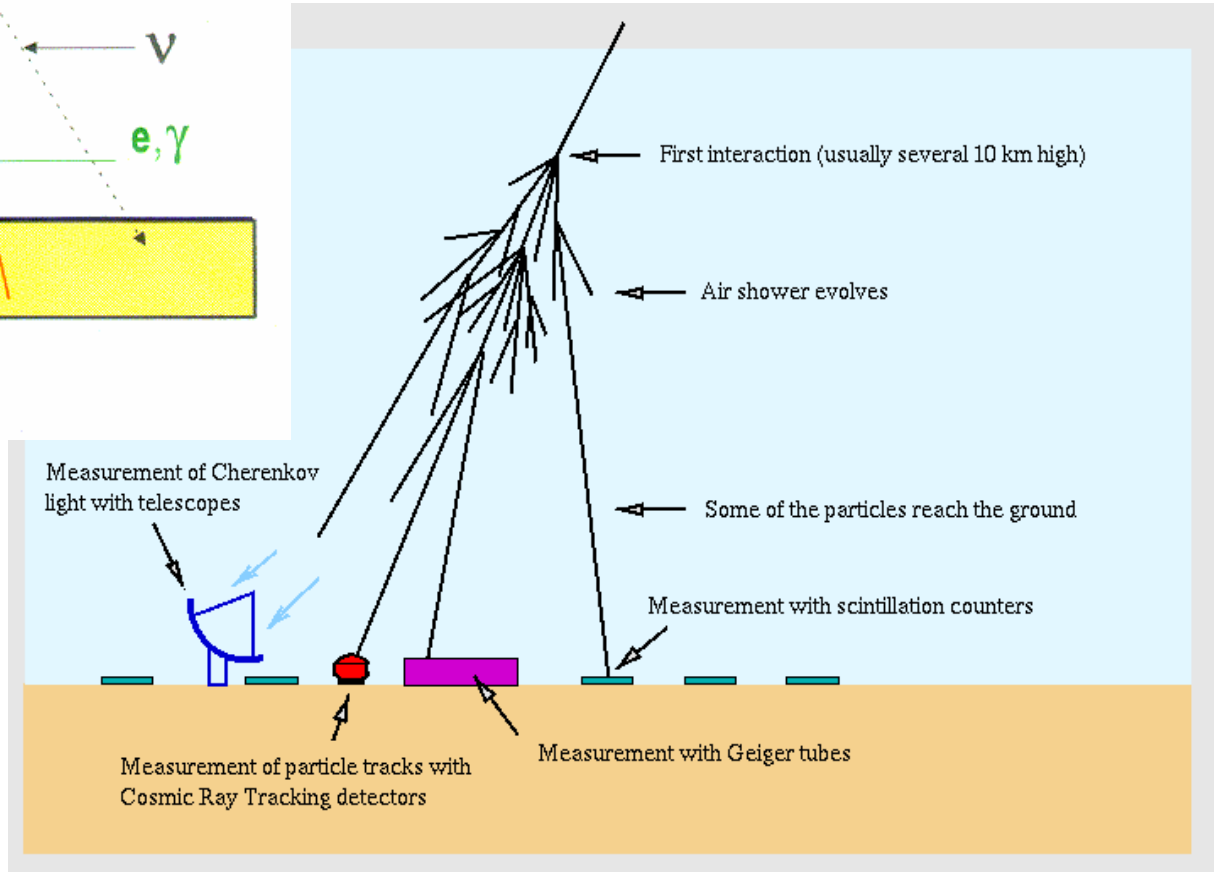
Ultra-high energy cosmic rays (UHECRs): cosmic ray particles with a kinetic energy greater than 10^{18} eV, far beyond both the rest mass and energies typical of other cosmic ray particles. Their origin is still un known



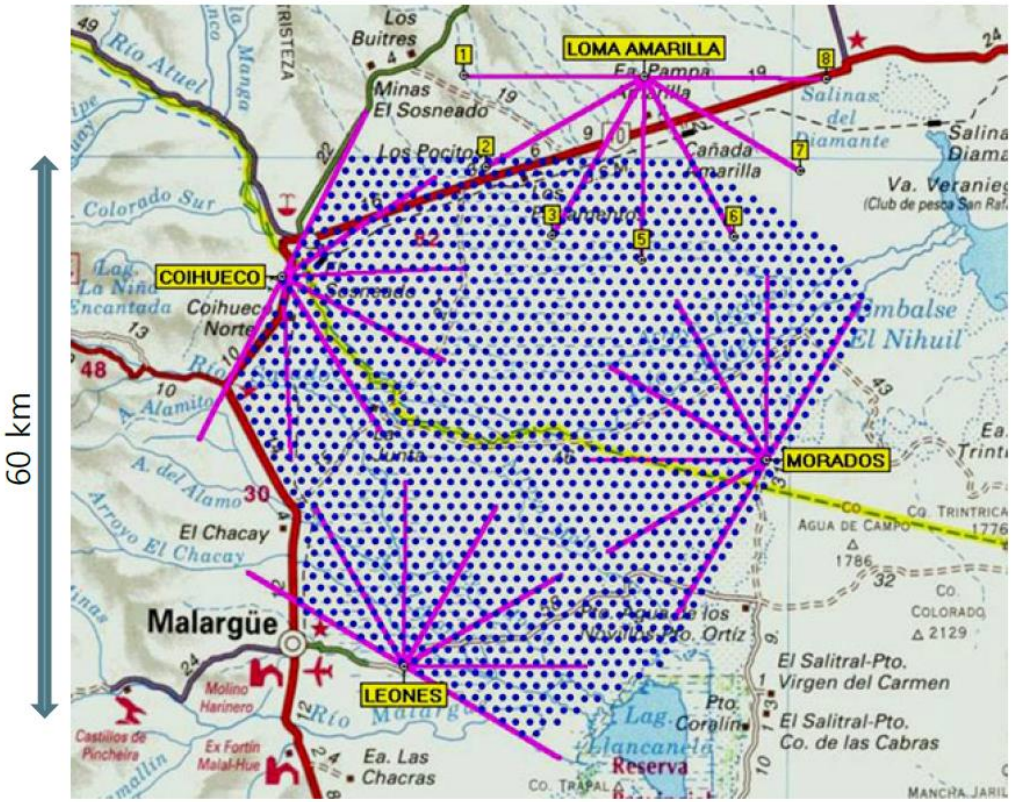
Detection of UHECR through Extensive Air Shower (EAS)



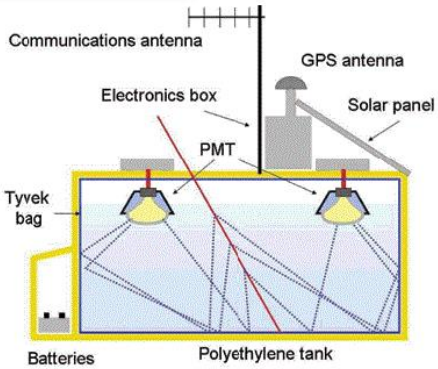
Extensive Air Showers



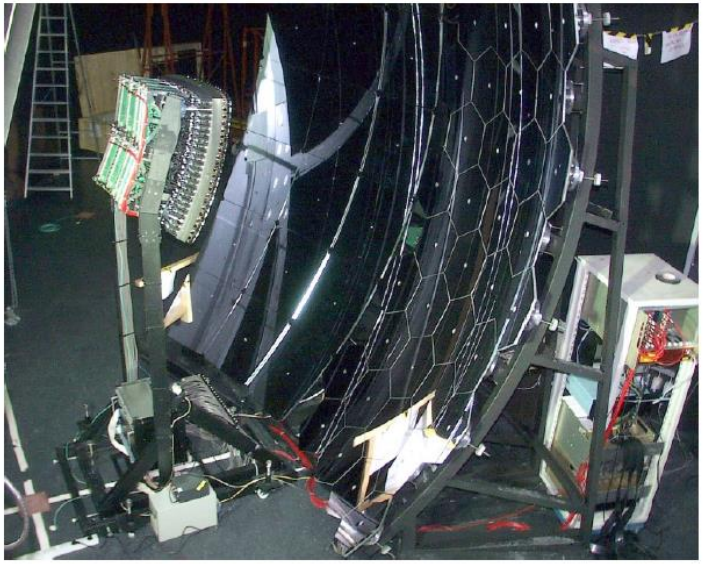
Experiment for UHECRs I: Pierre Auger Observatory in Southern Hemisphere



Surface Detector – Water Cherenkov

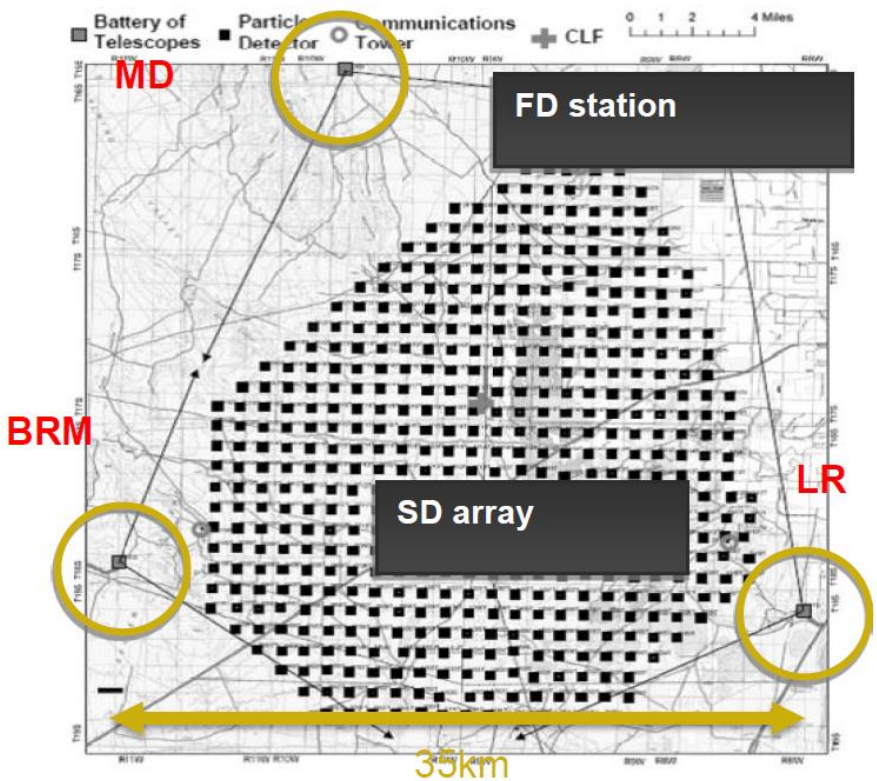


Fluorescence Detector – PMT

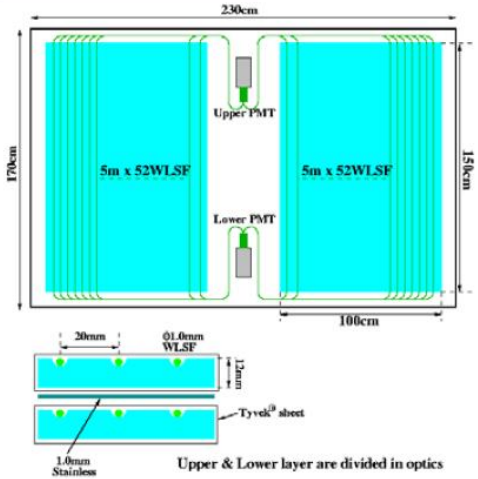


- Location : Mendoza, Argentina
- SD : 1600 water Cherenkov detector, 1.5 km spacing, ~3000 km^2
- FD : 24 telescopes in 4 stations

Experiment for UHECRs II: Telescope Array in Northern Hemisphere



Surface Detector – Plastic Scintillation



Fluorescence Detector – PMT

- Location : Utah, USA
- SD : 507 plastic scintillation detector, 1.2 km spacing, ~700 km^2
- FD : 18 telescopes in 3 stations

Issues of UHECRs to be addressed

- energy spectrum ?
- composition ?
- arrival direction ?

related

or correlation with astronomical objects ?

➔ sources of UHECRs ?

"Hotspot" in TA events

72 events

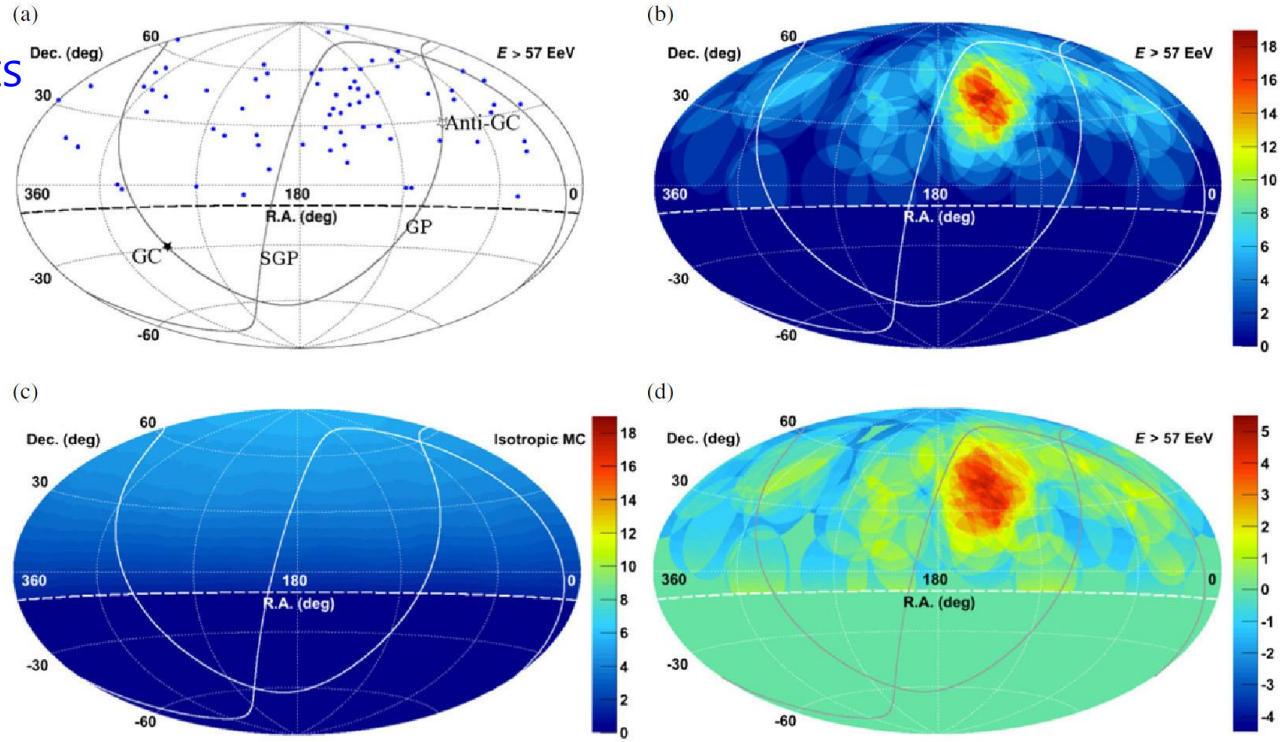


Figure 1. Aitoff projection of the UHECR maps in equatorial coordinates. The solid curves indicate the galactic plane (GP) and supergalactic plane (SGP). Our FoV is defined as the region above the dashed curve at decl. $= -10°$. (a) The points show the directions of the UHECRs $E > 57$ EeV observed by 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).

TA 2014

"… 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)."

Magnetic field is ubiquitous in the Universe!

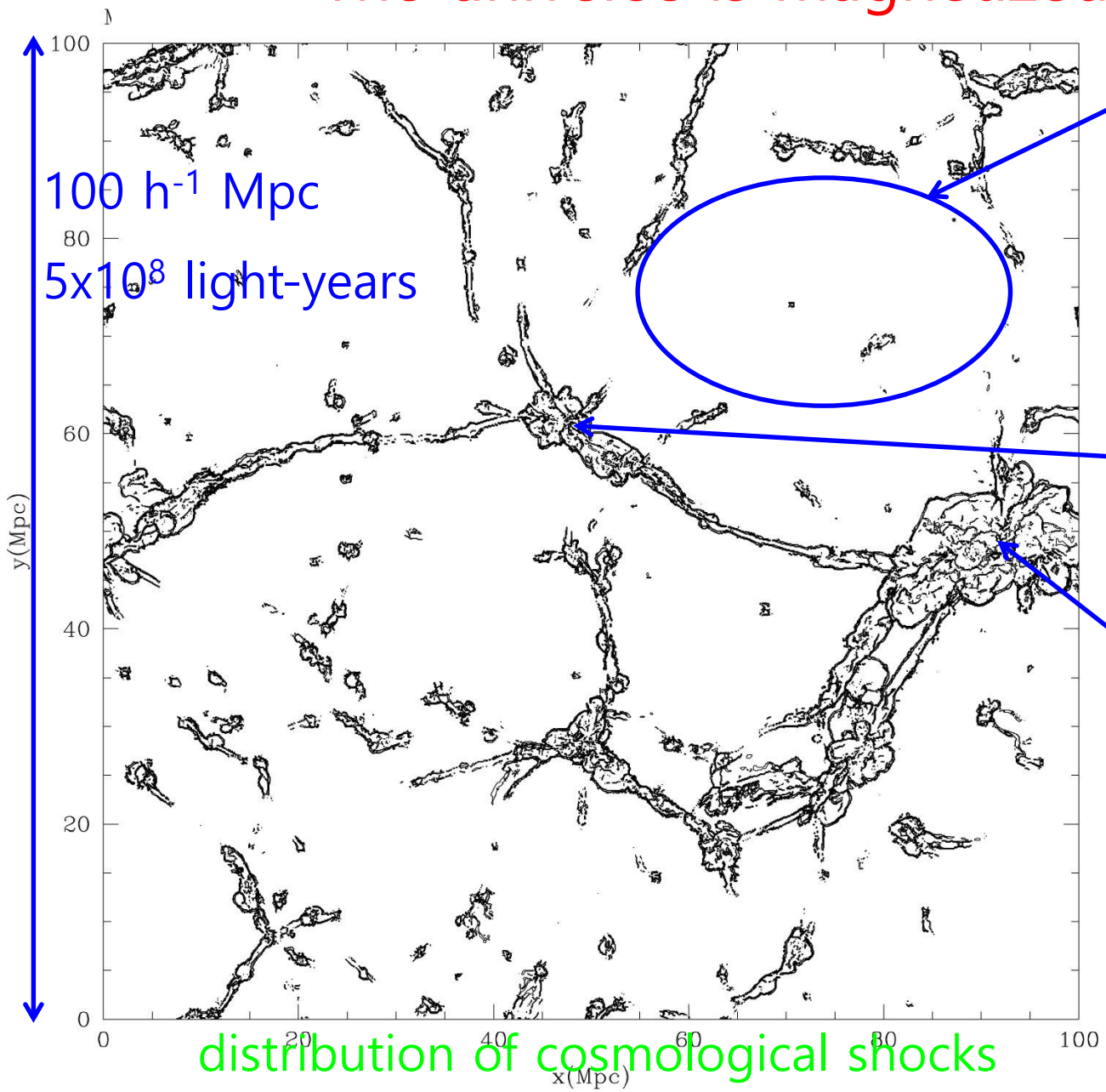
Star	
Magnetar	~ 10^{13} - 10^{15} G
Neutron star	~ 10^{11} - 10^{13} G
White dwarf	~ 10^{6} G
Ap/Bp star	~ 10^{3} G
Normal star	~ 1 G
Molecular cloud	~ 10^{-3} G
Interstellar medium	~ several x10^{-6} G
Cluster of galaxies	~ a few x 10^{-6} G
Filament of galaxies	~ 10^{-10} G (?)
Void	~ 10^{-16} – 10^{-14}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

stronger field

larger scale

intergalactic magnetic field

The universe is magnetized!



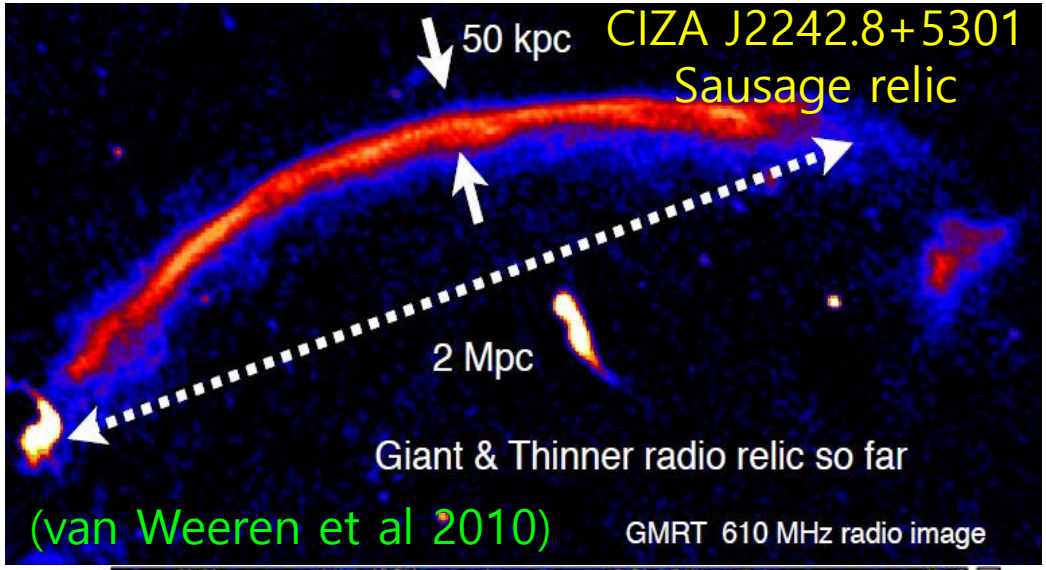
void regions:
B >~10^{-16} - 10^{-14} G

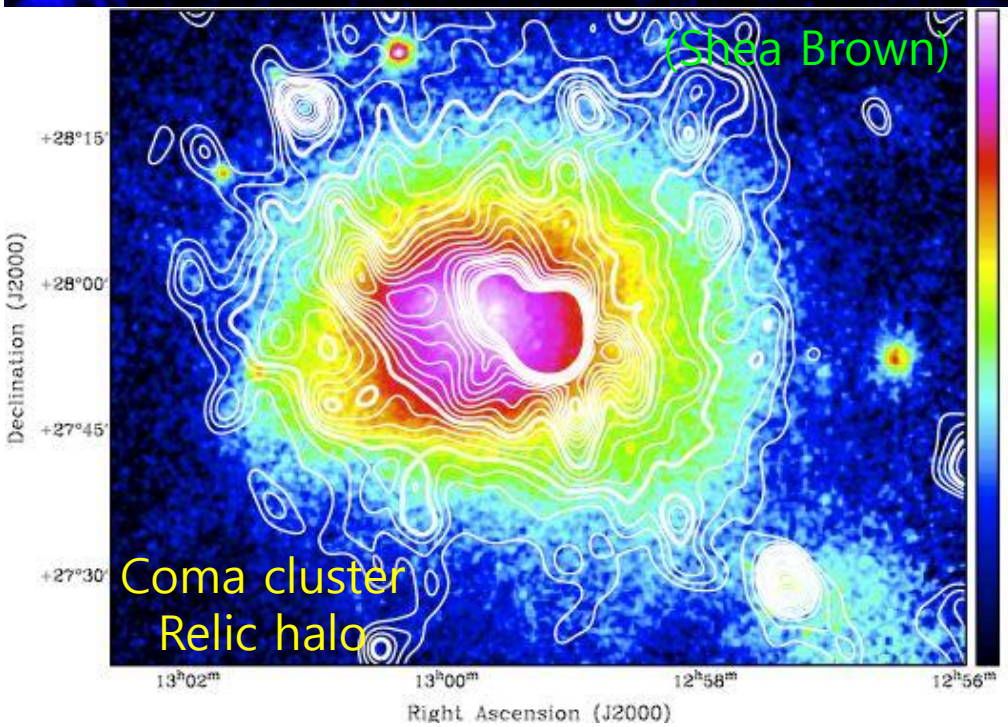
filaments of galaxies:
B ~ 10 nG

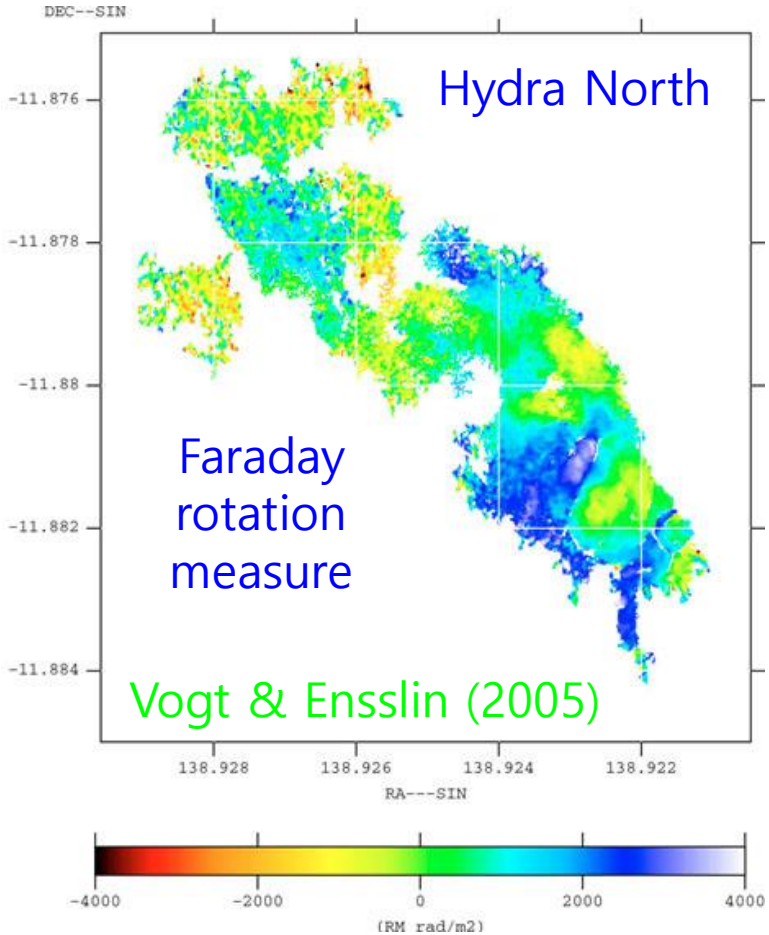
clusters of galaxies:
B ~ a few μG

distribution of cosmological shocks

Magnetic fields in galaxy clusters appears in observations







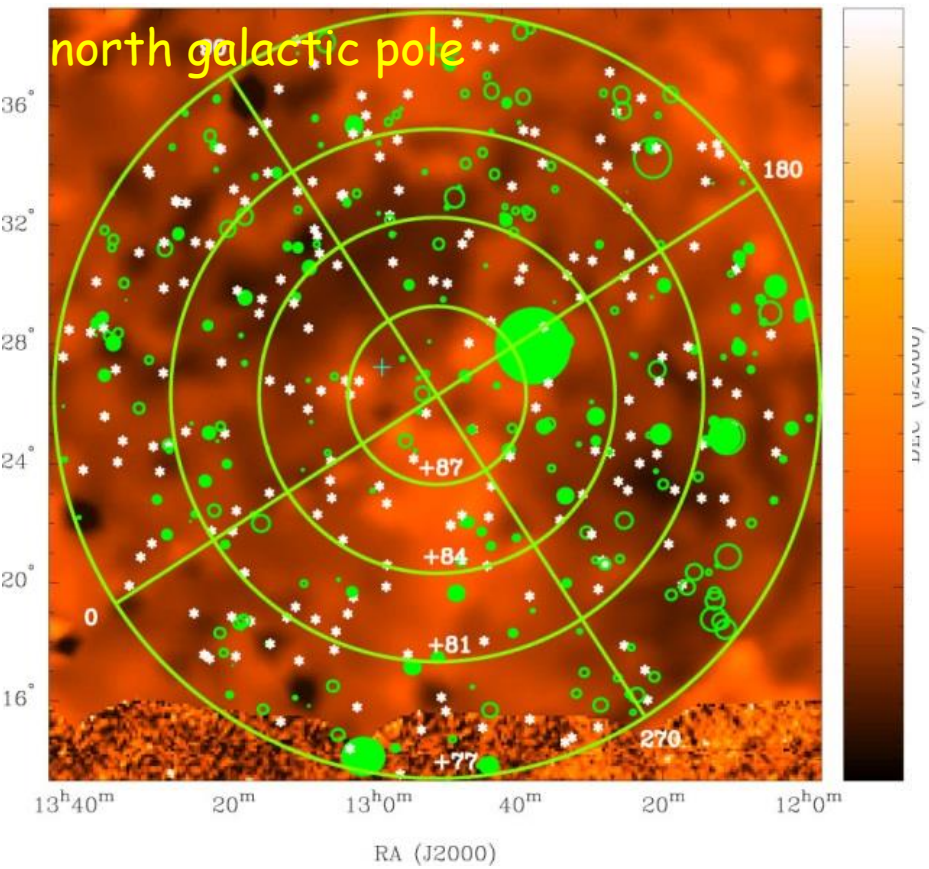
Clusters of galaxies – numbers and energetics

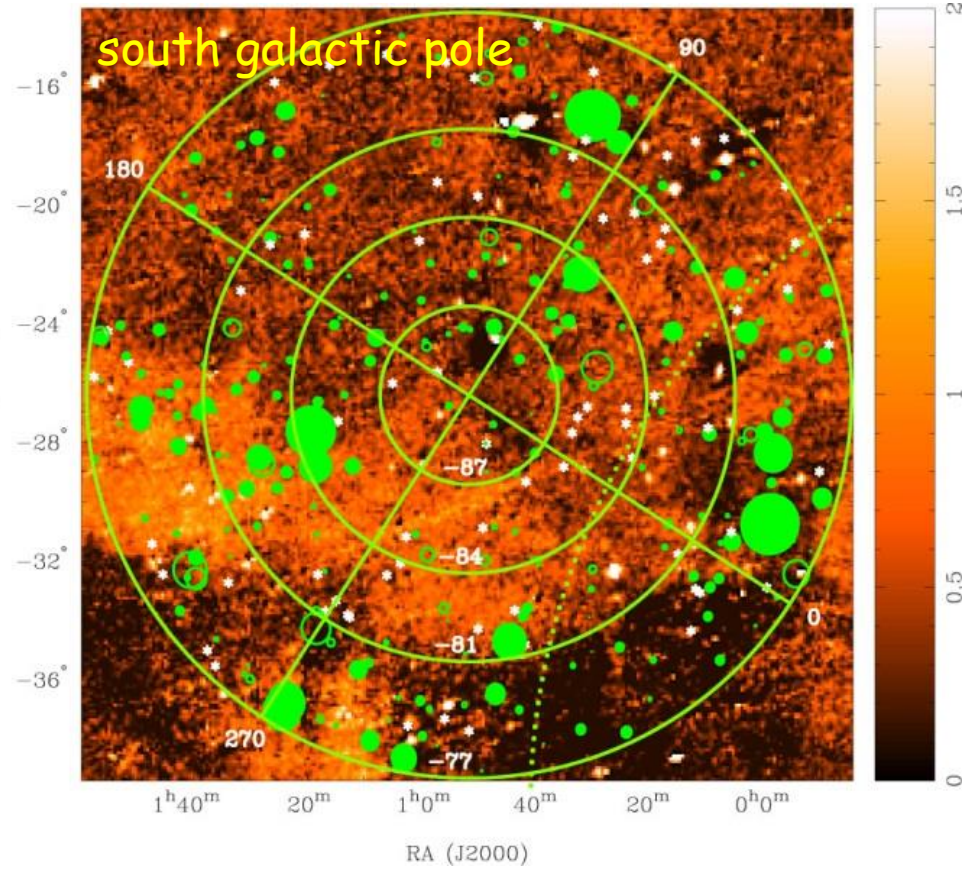
density of baryonic matter	$n \sim 10^{-2}\,\mathrm{cm}^{-3}$
flow velocity	$\upsilon \sim \text{several} \times 10^{2}\ \mathrm{km/s}$
gas temperature	$T \sim 10^{8}\,\mathrm{K}$
magnetic fields	$\boxed{B \sim \text{a few } \mu\mathrm{G}}$
gas kinetic energy	$E_{\mathrm{kinetic}} \sim 10^{-11}\,\mathrm{erg/cm}^{3}$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

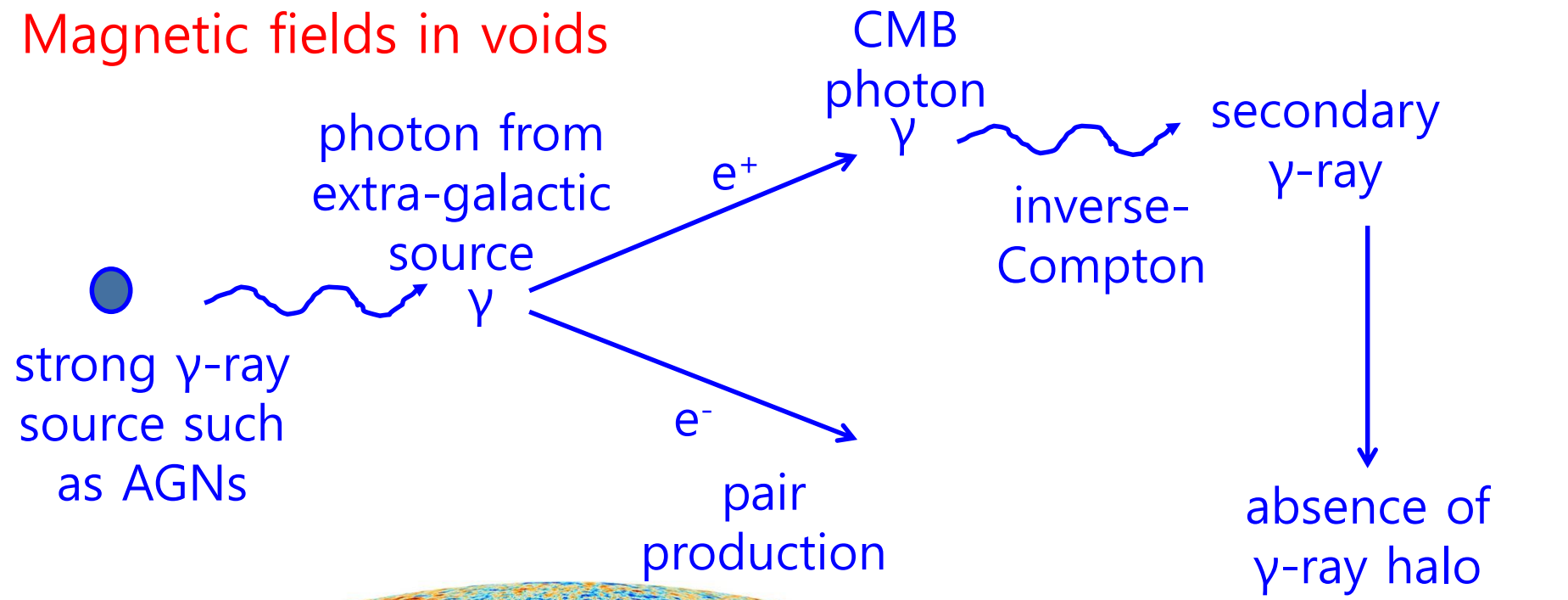
mostly due to magnetic fields in filaments of galaxies

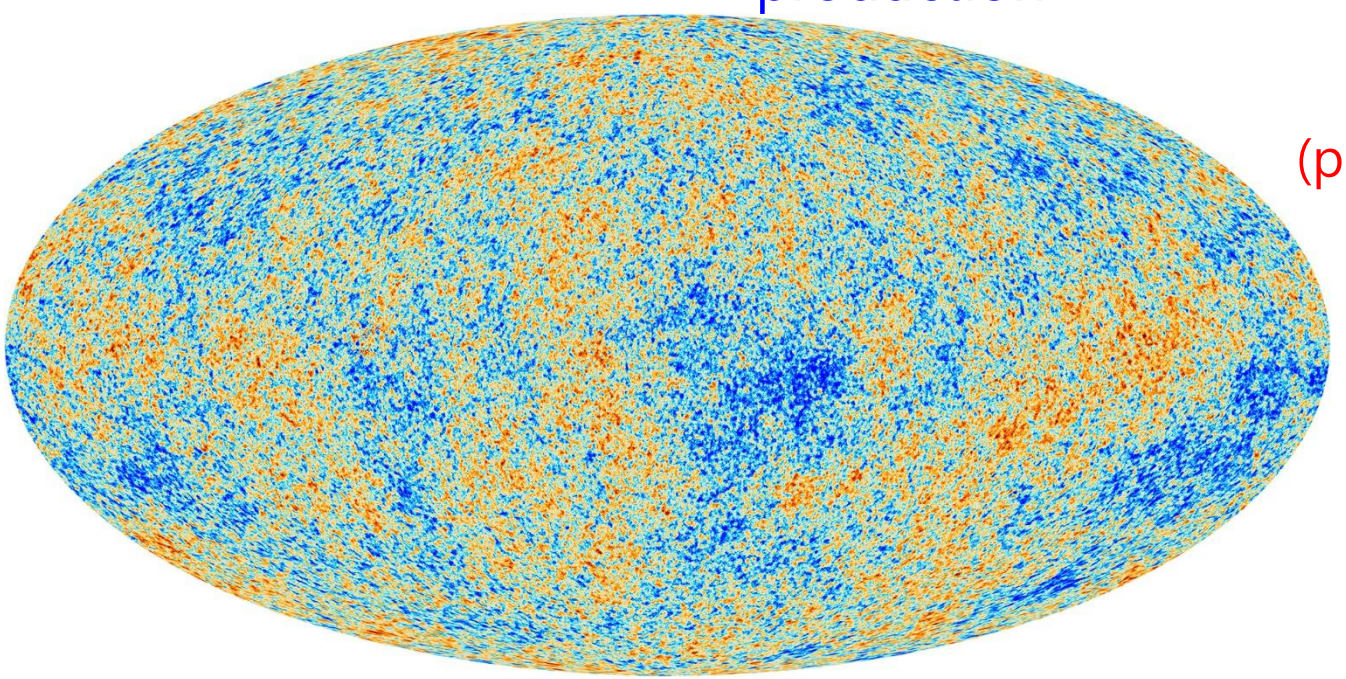
→ B ~ 10 nG (needs to be further confirmed)

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	$\boxed{B \sim 10\ \mathrm{nG}}$
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

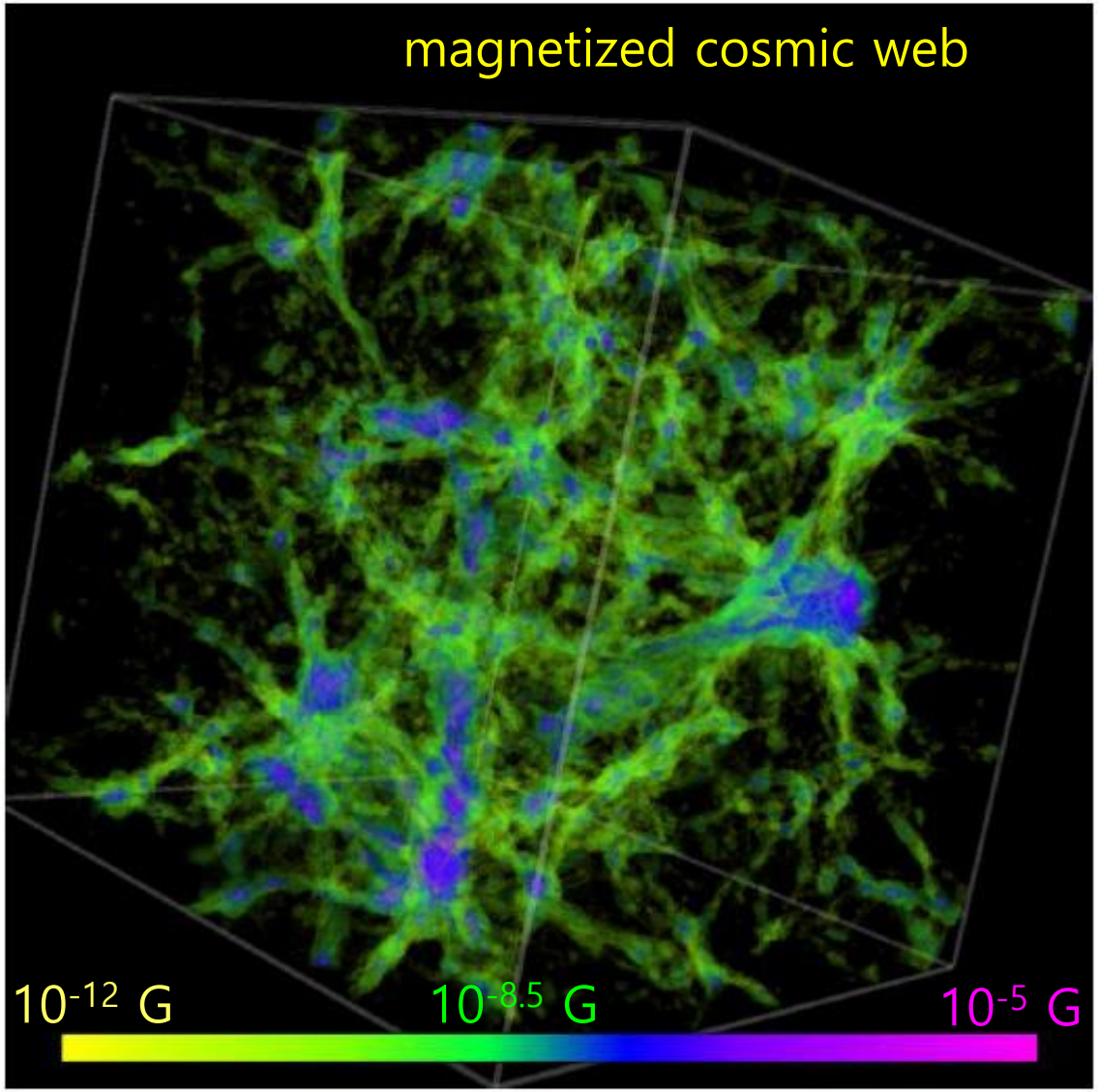
➔ B <~ 10^{-9} G

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	$\boxed{B >\sim 10^{-16} - 10^{-14}\ \mathrm{G}}$

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	$E_{\mathrm{magnetic}} \sim 10^{-33}$ - $10^{-29}\ \mathrm{erg/cm}^{3}$

Magnetic fields in the large-scale structure from simulation



distribution of the intergalactic magnetic field in a (~100 h^{-1} 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.

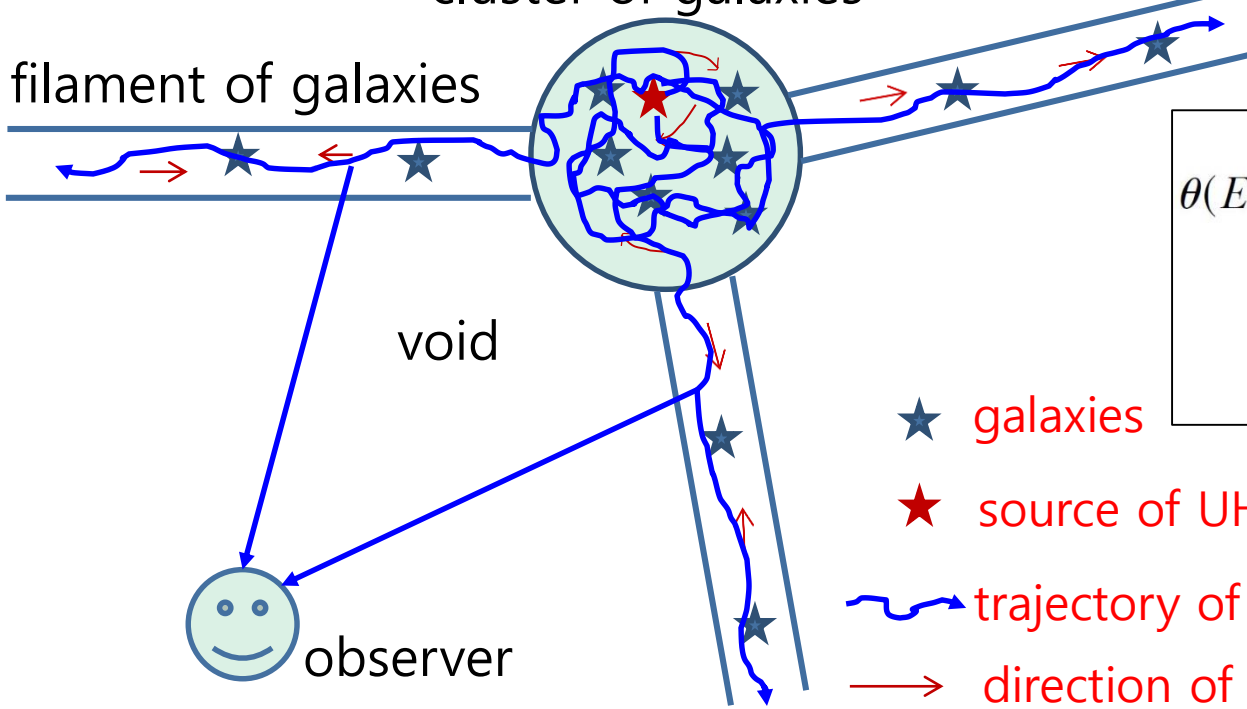
Larmor radius:

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

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

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

(Blasi & Olinto 1990)

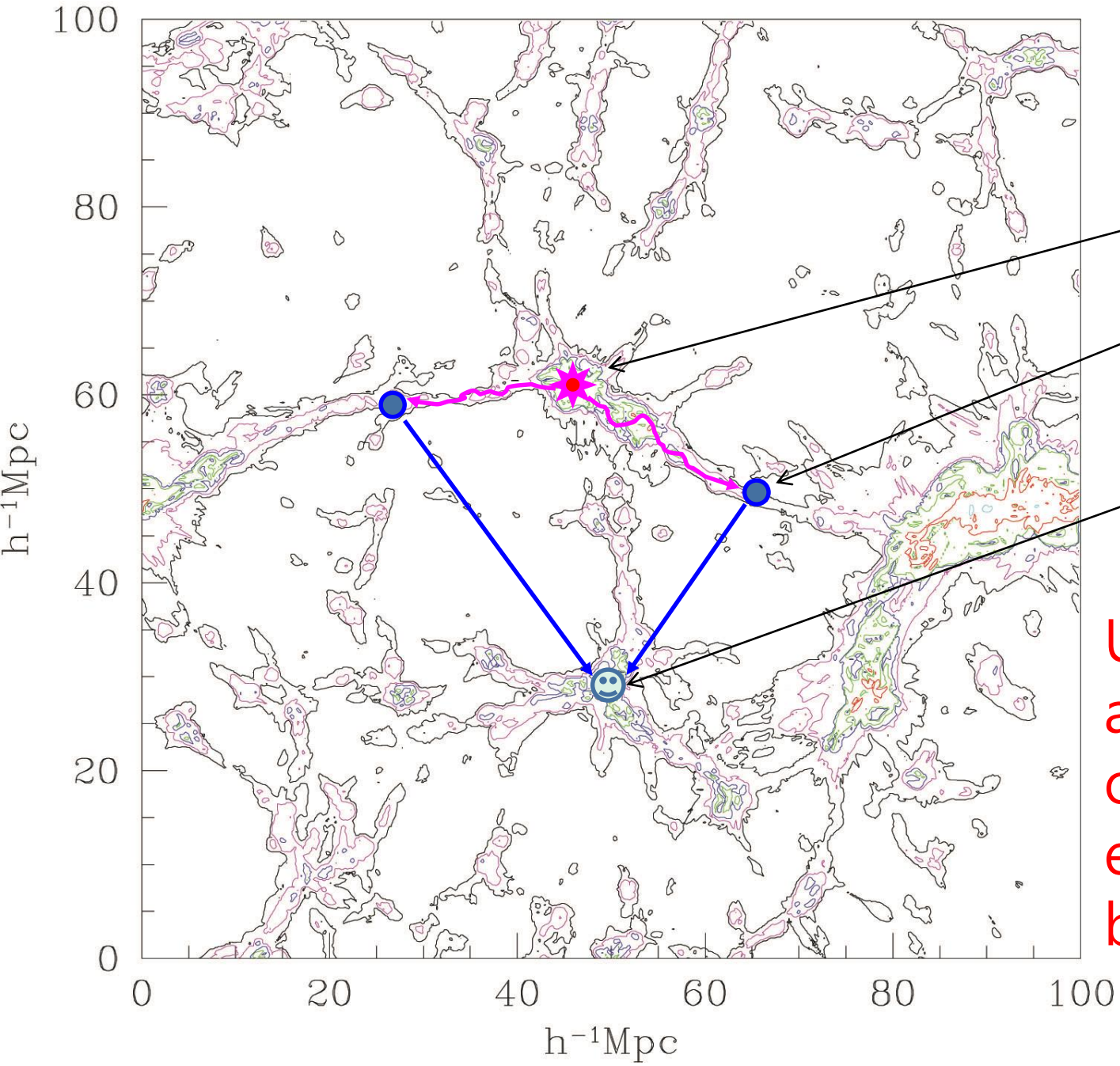


galaxies

source of UHECRs

trajectory of UHECRs

direction of magnetic fields



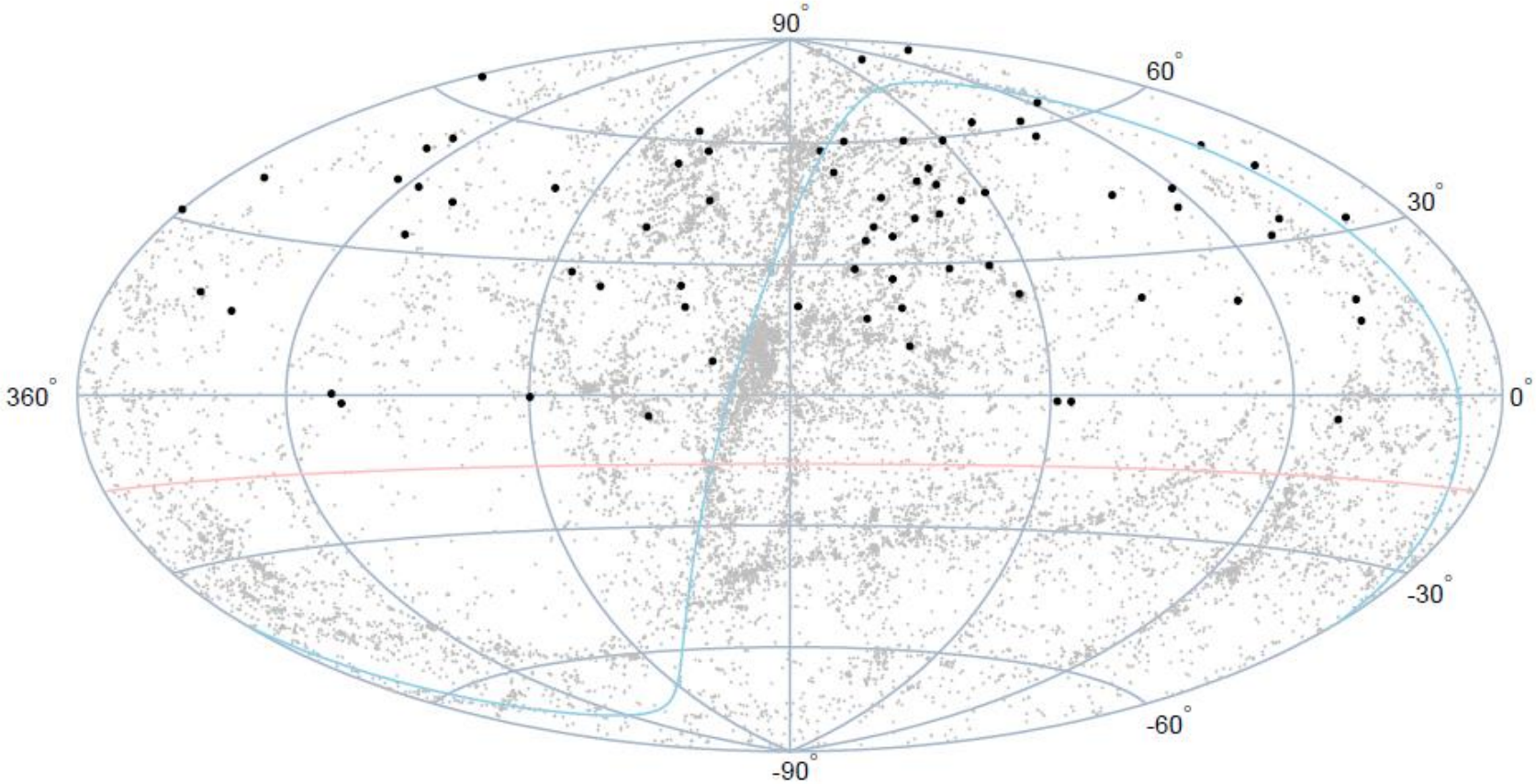
Source of UHECRs

Directions of observed UHECR events

Observer

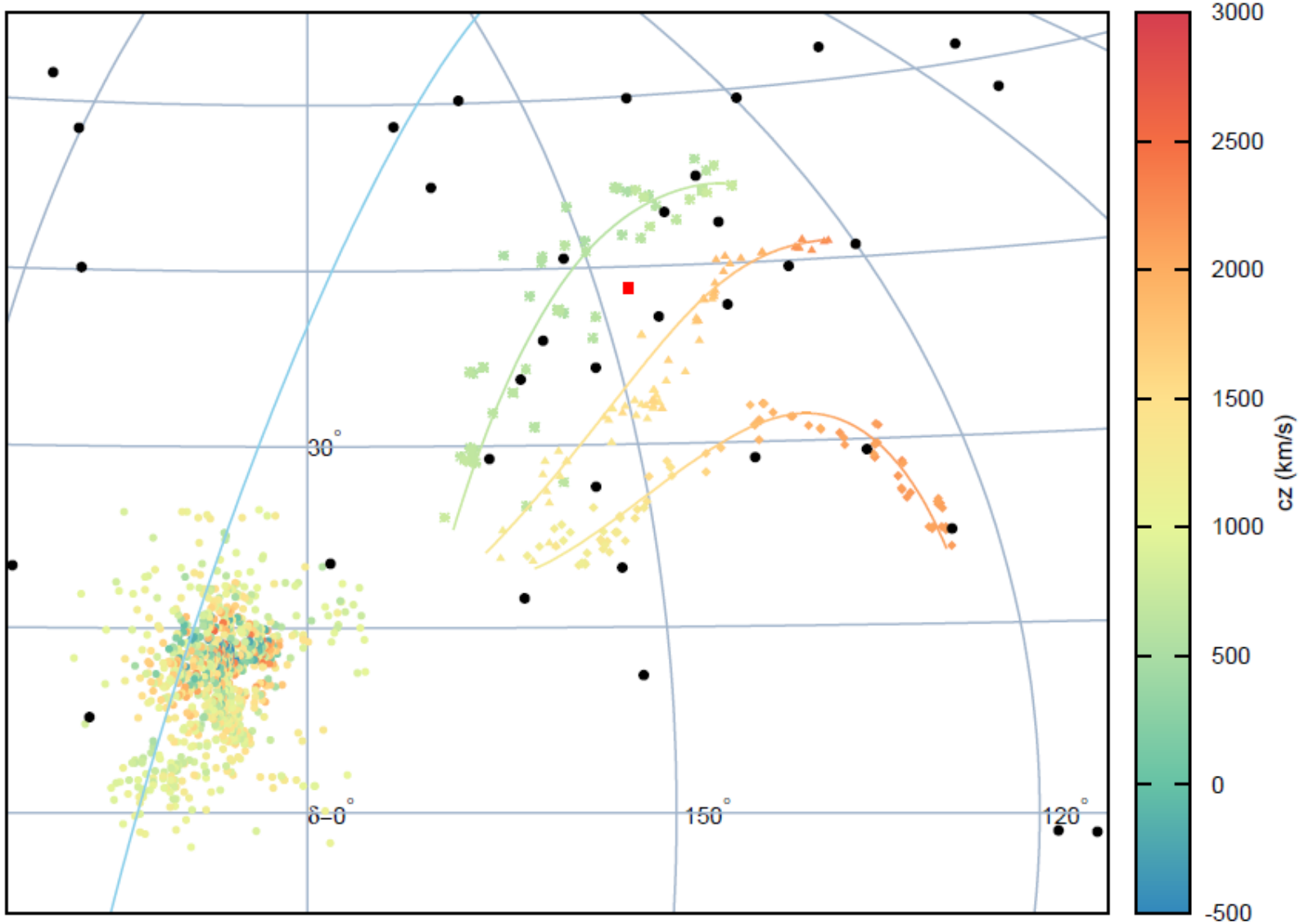
UHECR events and filaments of galaxies are expected to be correlated!

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 ?

Zoom-up around the hotspot region: correlation between 72 TA events and three filaments?

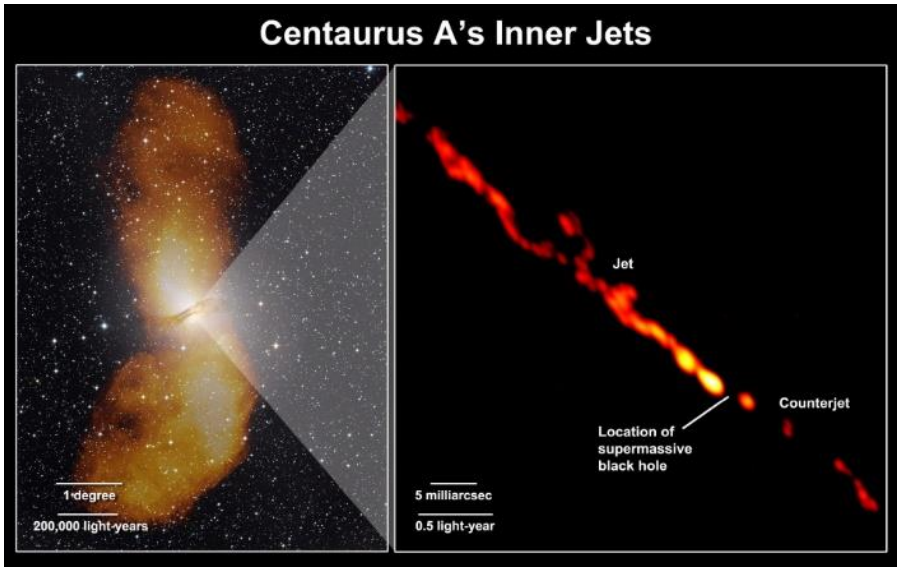


Virgo A, a radio galaxy, as sources of UHECRs ?

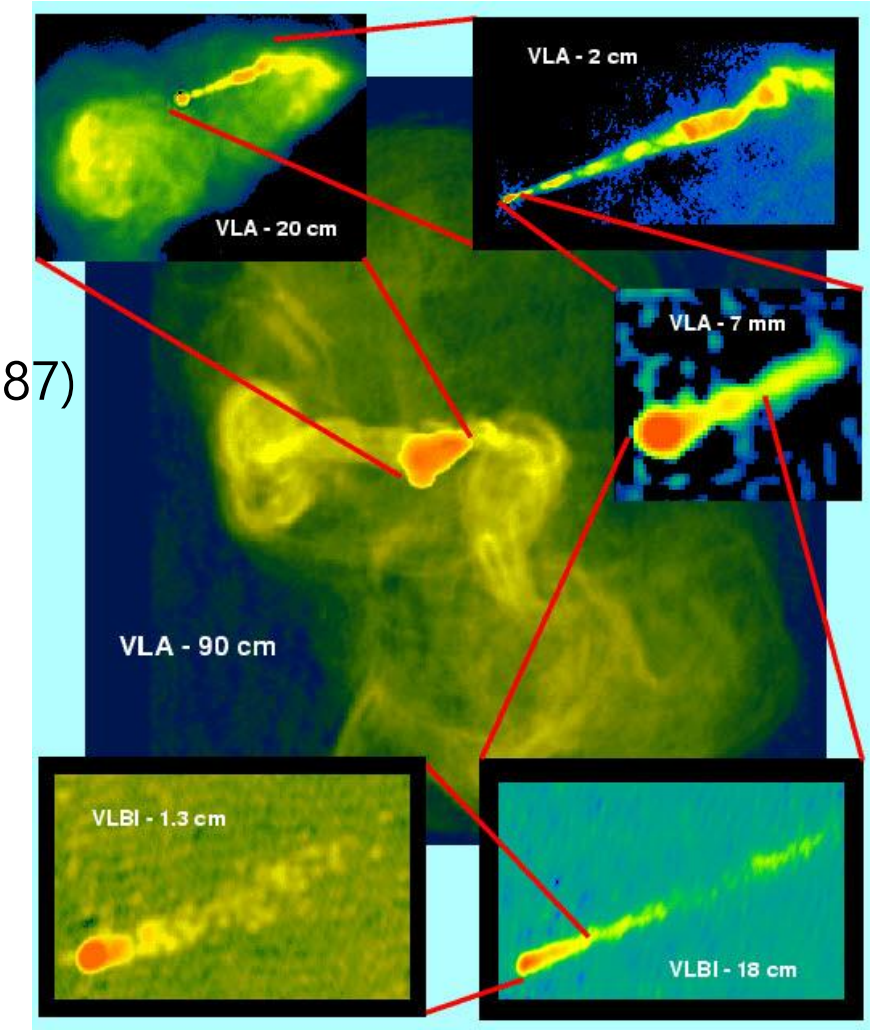
shock acceleration or turbulent acceleration

→ OK for Fe, not for p ?

Centaurus A



Virgo A (M87)

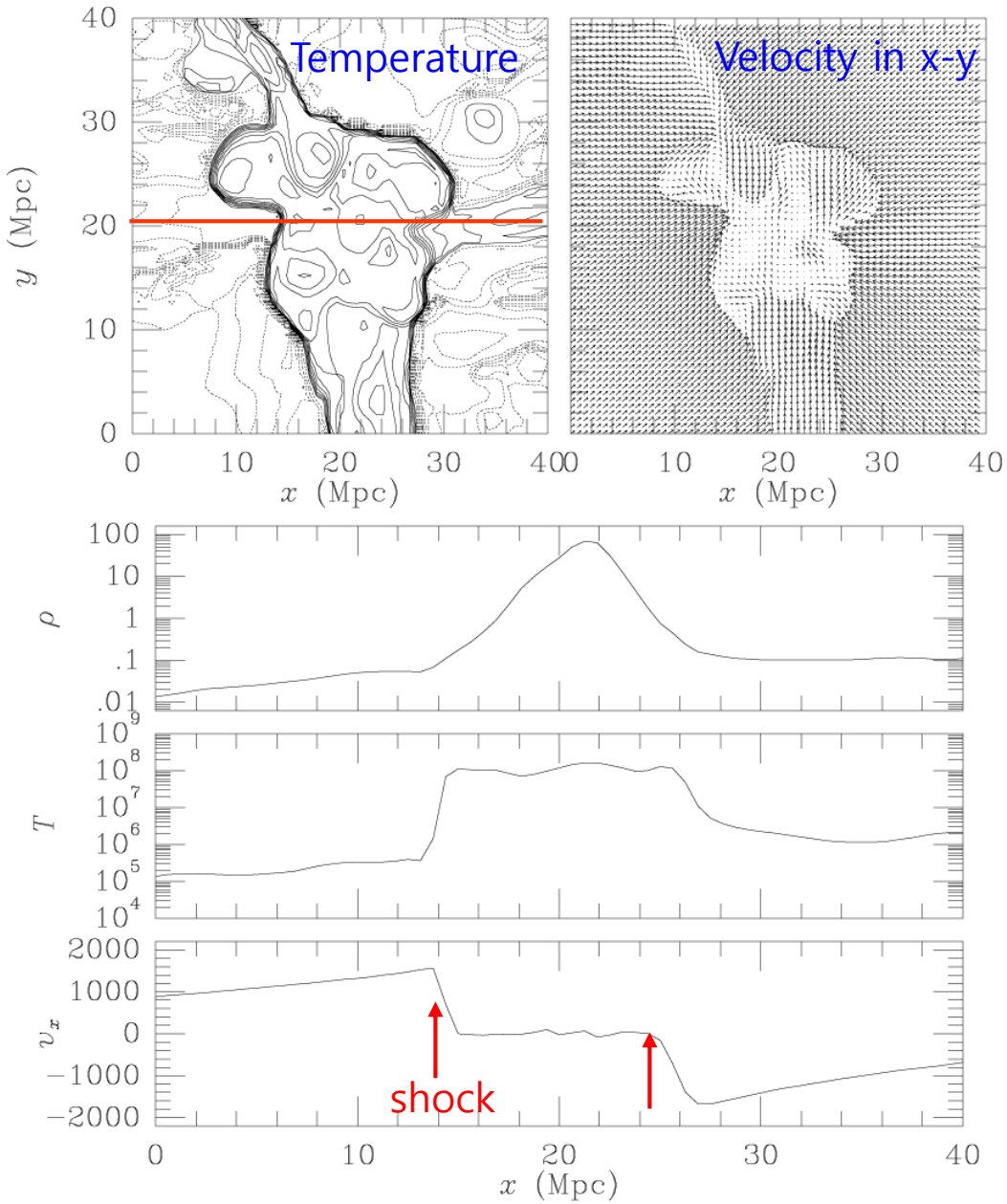


Properties of the FR I radio galaxies Cen A, M 87 and Fornax A.

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 $t_{age} \sim 10^{10}$ years according to DSA theory

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

B_μ = in units of mG

- Limited by loss

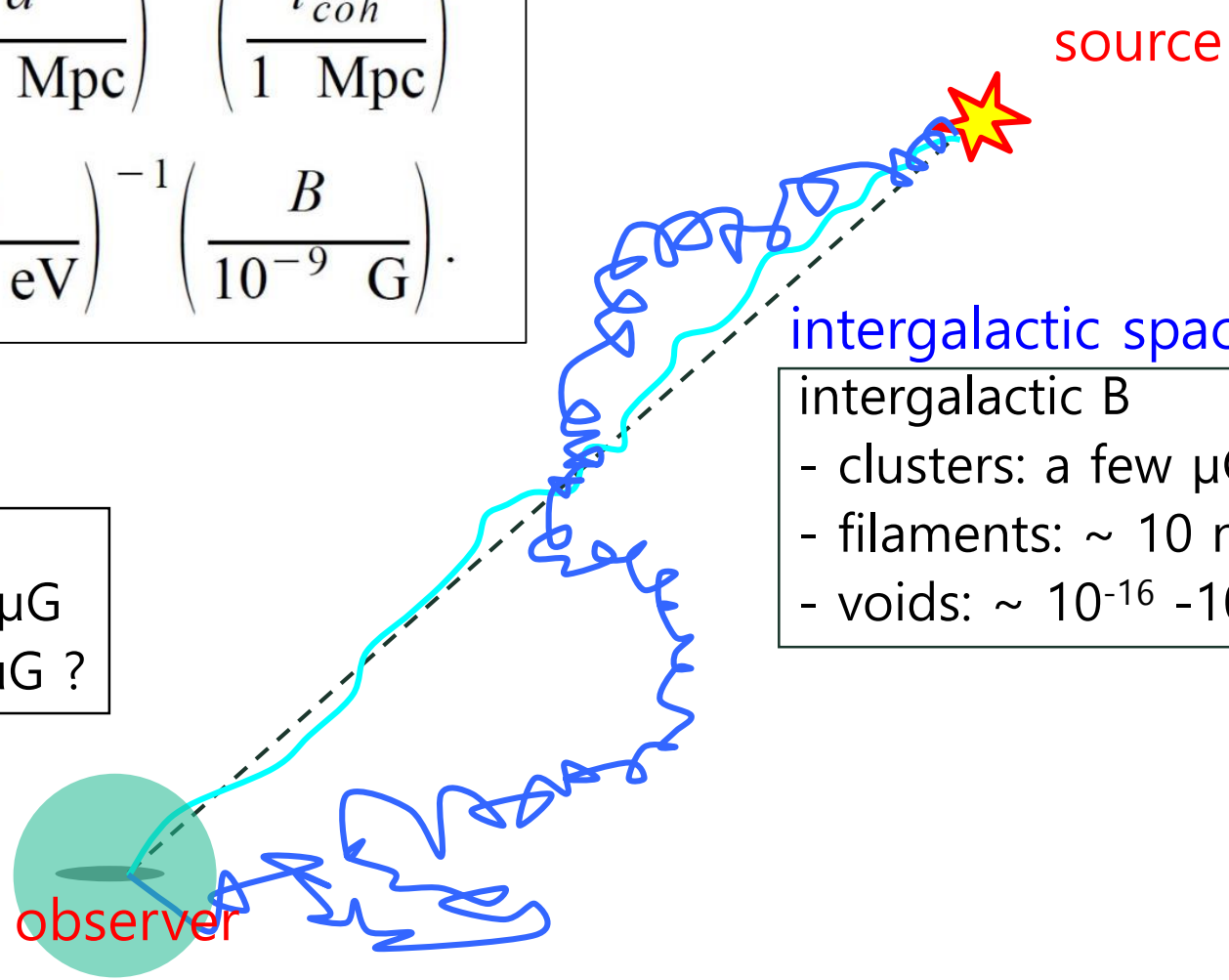
$E_{max} \sim 10^{19}$ Z eV

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

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



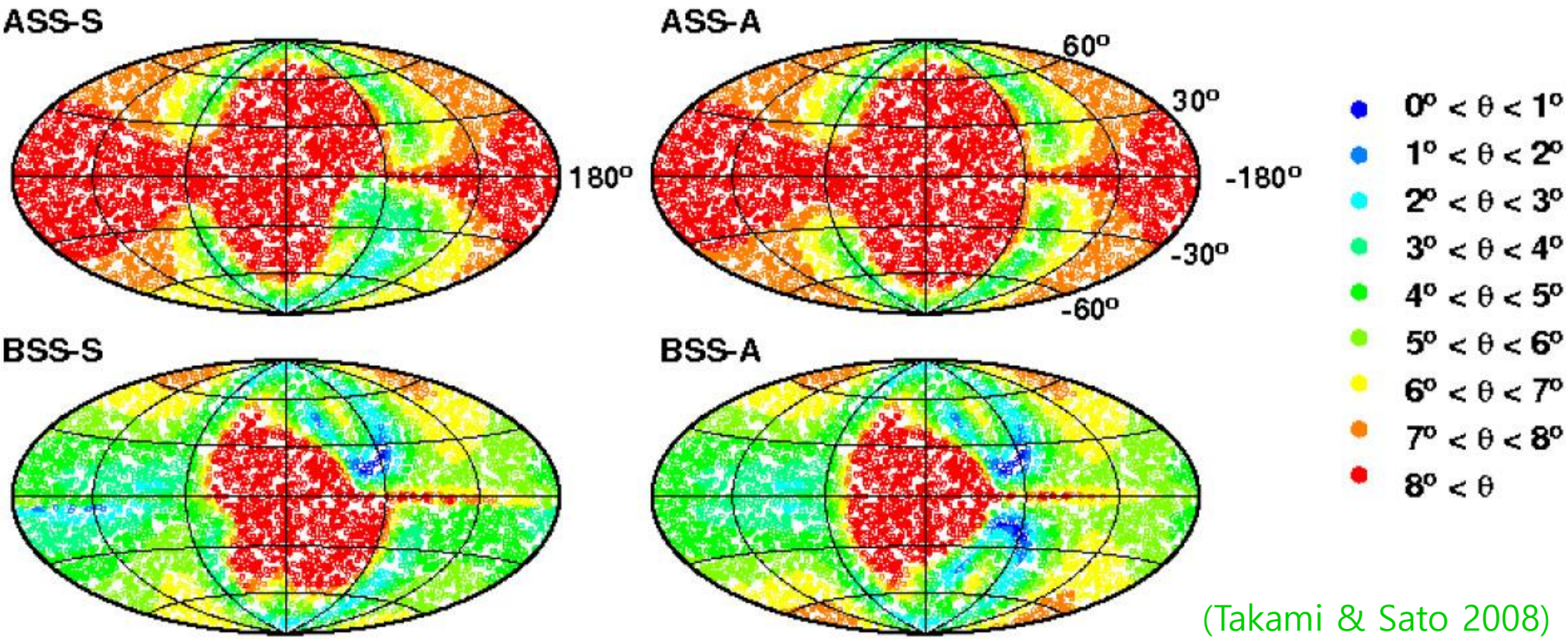
intergalactic space

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!

Thank you !