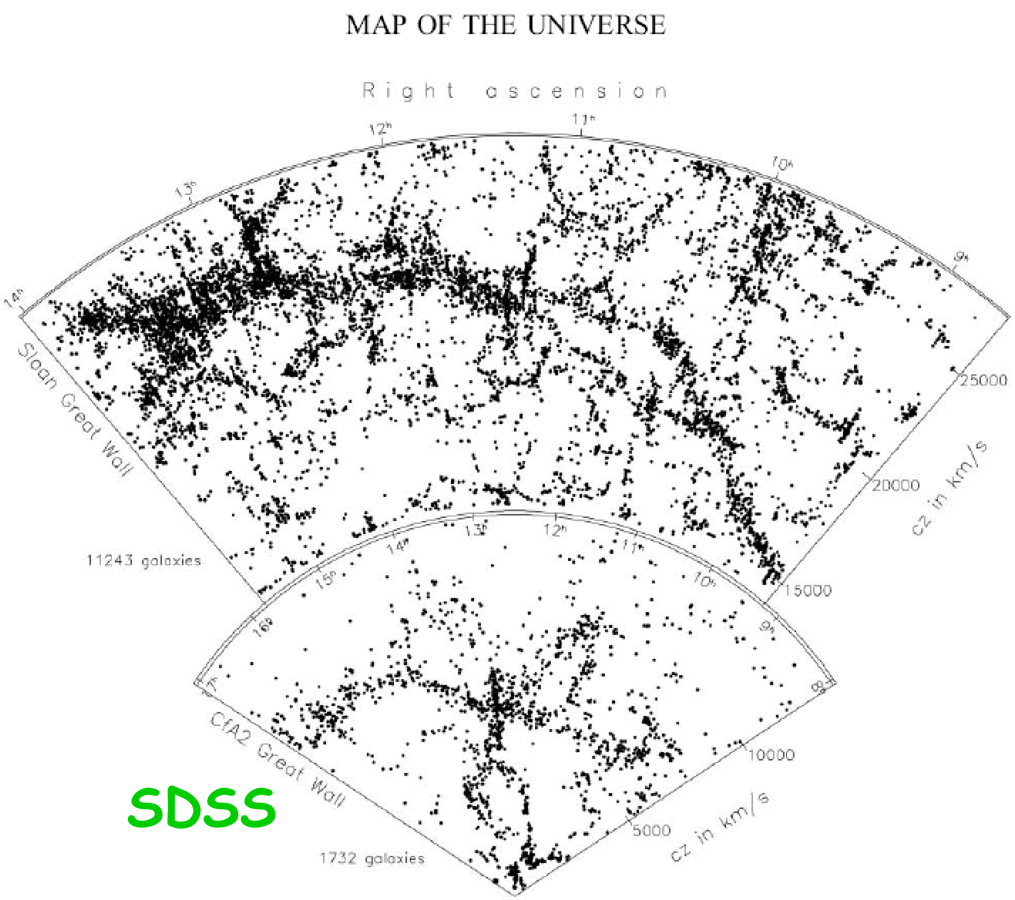
Turbulence and Magnetic Field in the Intergalactic Medium of the Universe

Dongsu Ryu (Chungnam National U, Korea)

Hyesung Kang (Pusan National U, Korea)

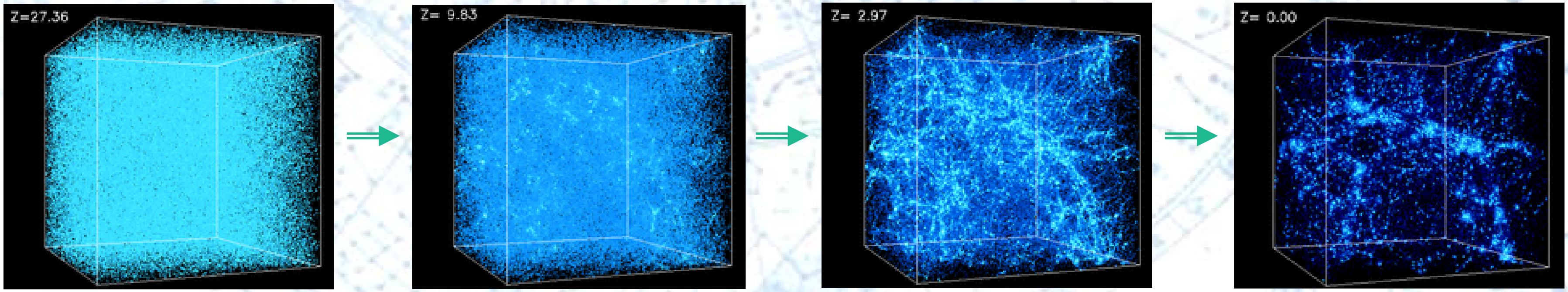
Jungyeon Cho (Chungnam National U, Korea)

- Intergalactic turbulence in simulations
- Intergalactic magnetic field from simulations
- Implications of the intergalactic magnetic field



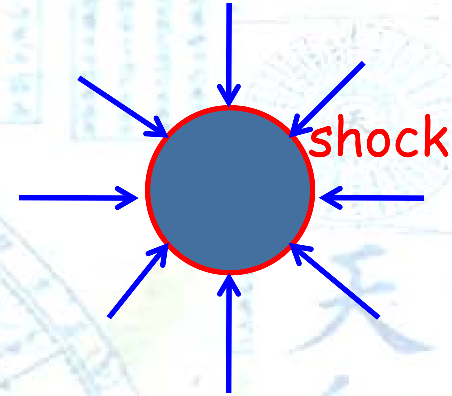
Large scale structure of the universe seen in the galaxy distribution

comic web of filaments



growth of density perturbations via gravitational instability

Overveiw of large-scale structure formation



large-scale structure formation

gravitational collapse
& flow motion

dynamic feedback
on gas distribution

X-ray clusters/groups,
WHIM, etc…

gas cooling

cosmological shocks

(Ryu, Kang, et al 2003, 2007)
(Pfrommer et al 2006)
(Vazza et al 2008)
(Skillman et al 2008)

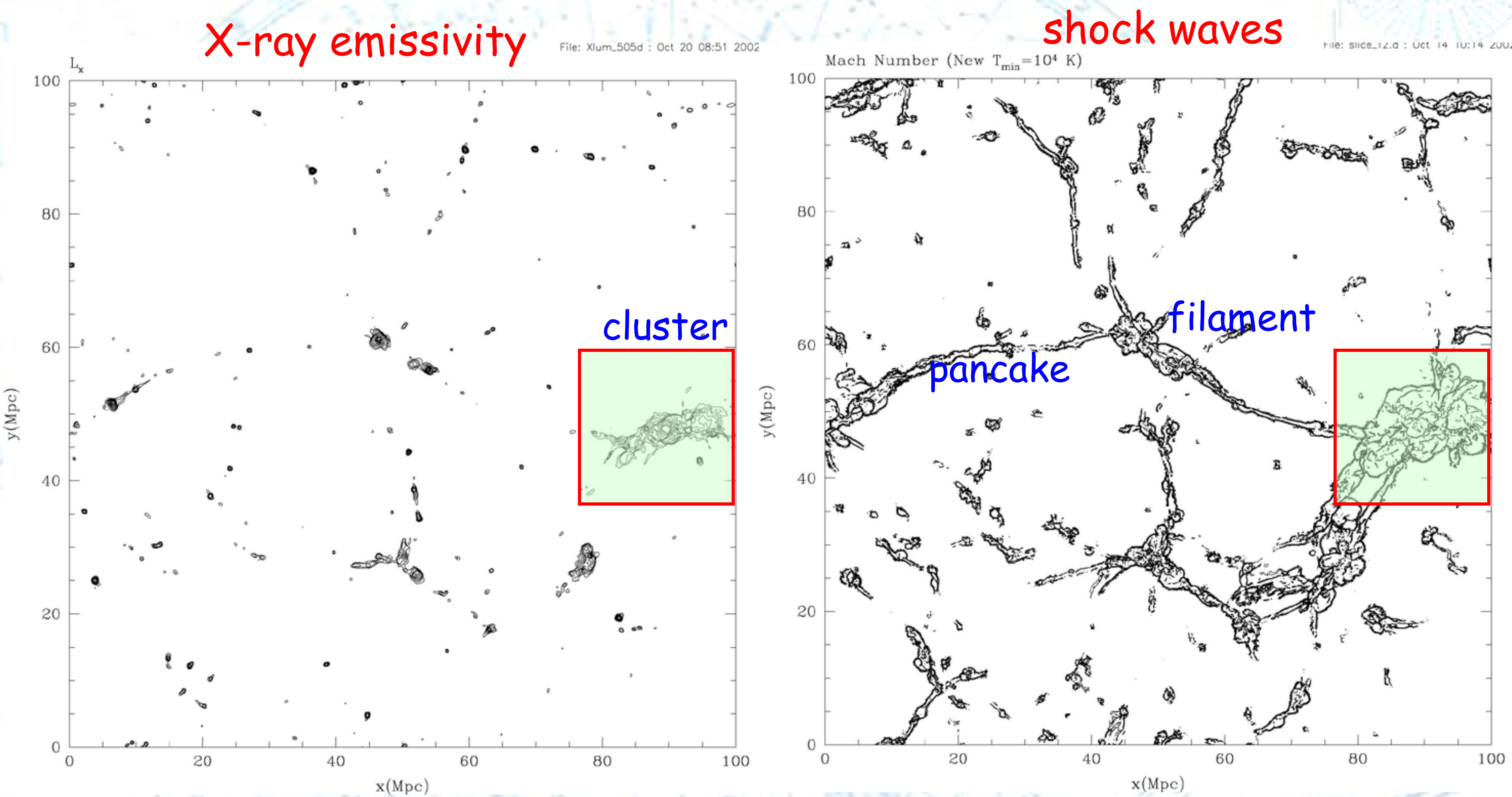
shock
dissipation

generation of heat
acceleration of CRs
generation of vorticity
genera. of magnetic fields

radiations from gas and CRs
vorticity into turbulence and
further amp. of mag. field

other sources of heat, CRs,
turbulence and magnetic field

Cosmological shocks in the large scale structure of the universe

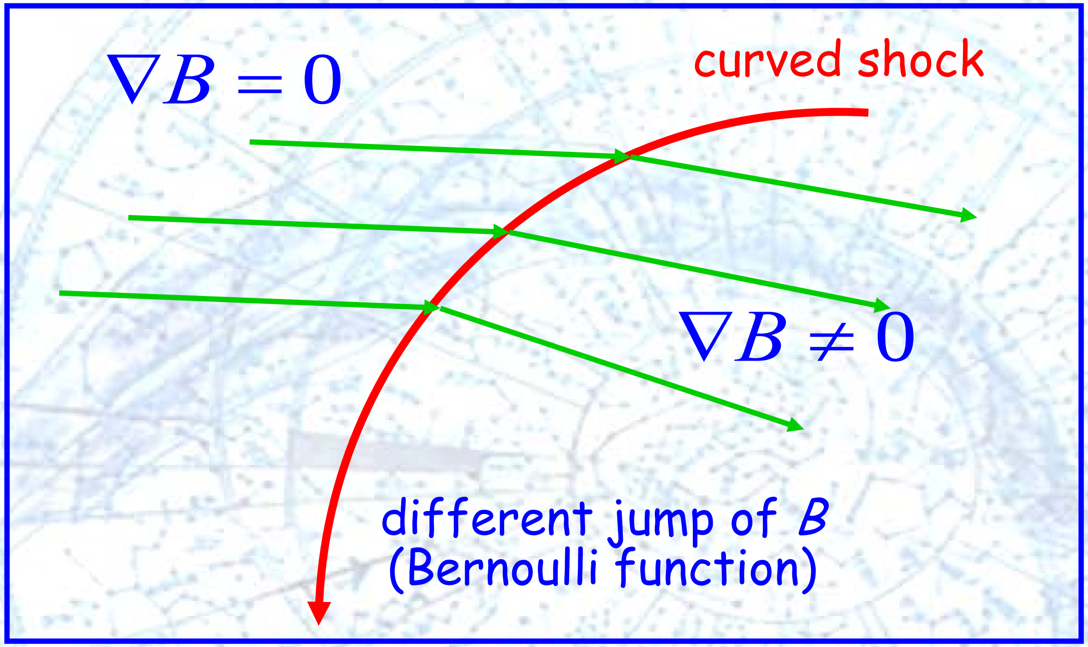


(Ryu, Kang et al 2003)

rich, complex shock morphology:
shocks "reveal" filaments and sheets (low density gas)

Vorticity should have been generated at cosmological shocks

directly at curved shocks



⟹ at postshock

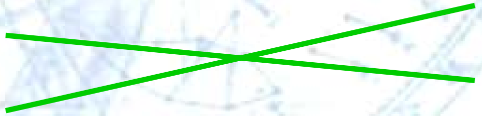
$$\varpi_{cs} \sim \frac{(\rho_2 - \rho_1)^2}{\rho_2 \rho_1} \frac{\vec{U} \times \vec{n}}{R}$$

ρ_1 preshock density
ρ_2 postshock density
$\vec{U}$ preshock flow speed
$\vec{n}$ unit normal to shock surf.
R curvature radius of surf.

by the baroclinic term

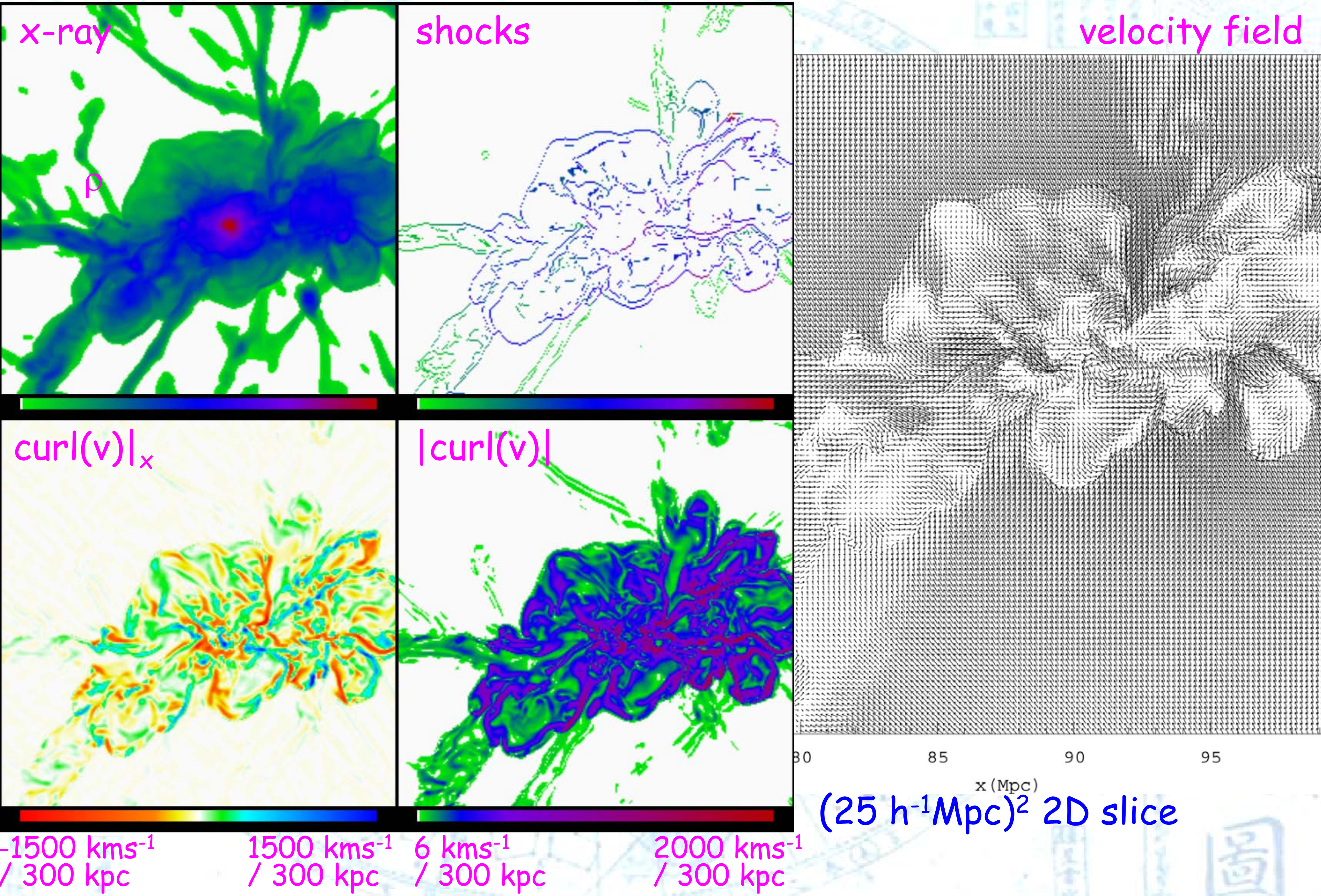
$$\dot{\varpi}_{bc} = \frac{1}{\rho^2} \vec{\nabla}\rho \times \vec{\nabla}p$$

baroclinity

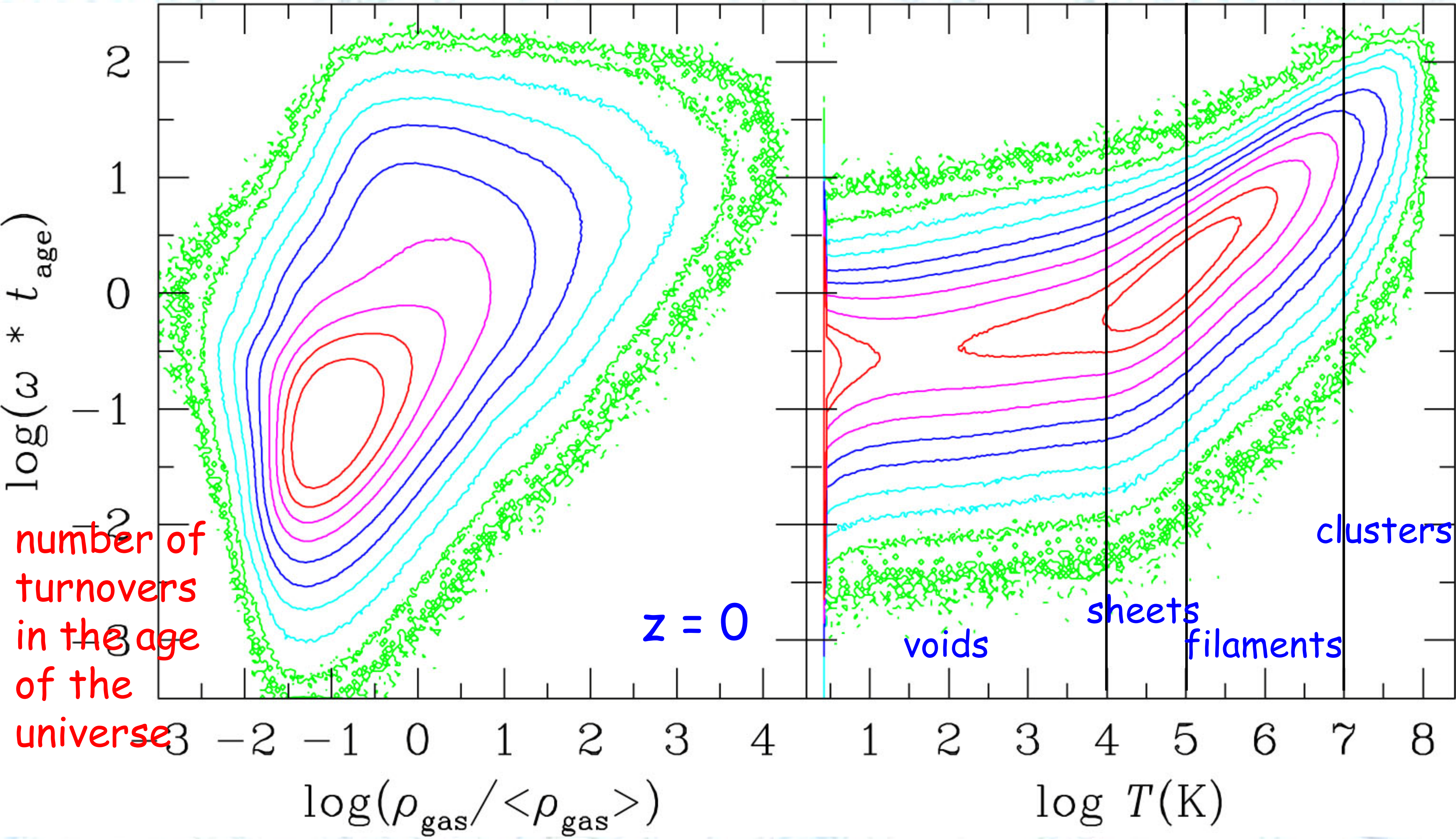


⟸ due to entropy variation induced at shocks

Vorticity around a cluster complex



Vorticity in the large scale structure of the universe



ω: curl(v)

t_{age}: age of the universe (~1.4x10^{10} yrs)

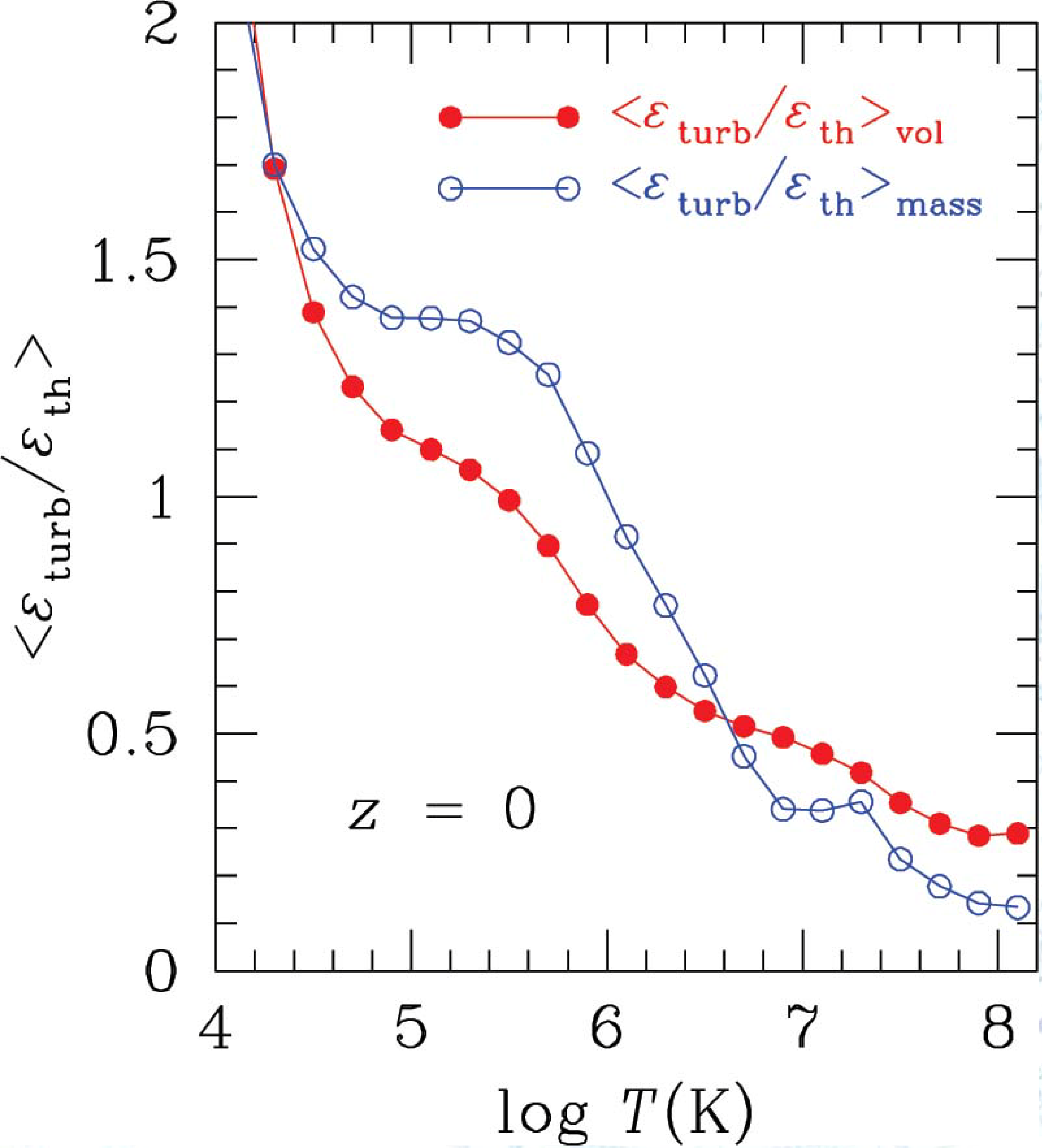
(Ryu, Kang, Cho et al 2008)

If $t/t_{turn\text{-}over}$ >~ a few, vorticity cascades to develop turbulence in the intergalactic medium.

Here, $t_{turn\text{-}over} \sim 1/\omega$.

- inside clusters and around ($T > 10^7$ K): $\langle \omega^* t_{age} \rangle \sim 20$
- in filaments (10^5 K $< T <$ 10^7 K, or WHIM): $\langle \omega^* t_{age} \rangle \sim 10$
- in sheets (10^4 K $< T <$ 10^5 K, or lukewarm): $\langle \omega^* t_{age} \rangle \sim 1$
- in voids ($T < 10^4$ K): $\langle \omega^* t_{age} \rangle \sim 0.1$

It is likely that turbulence is well developed in clusters and filaments, but the flow is mostly non-turbulent in sheets and voids.



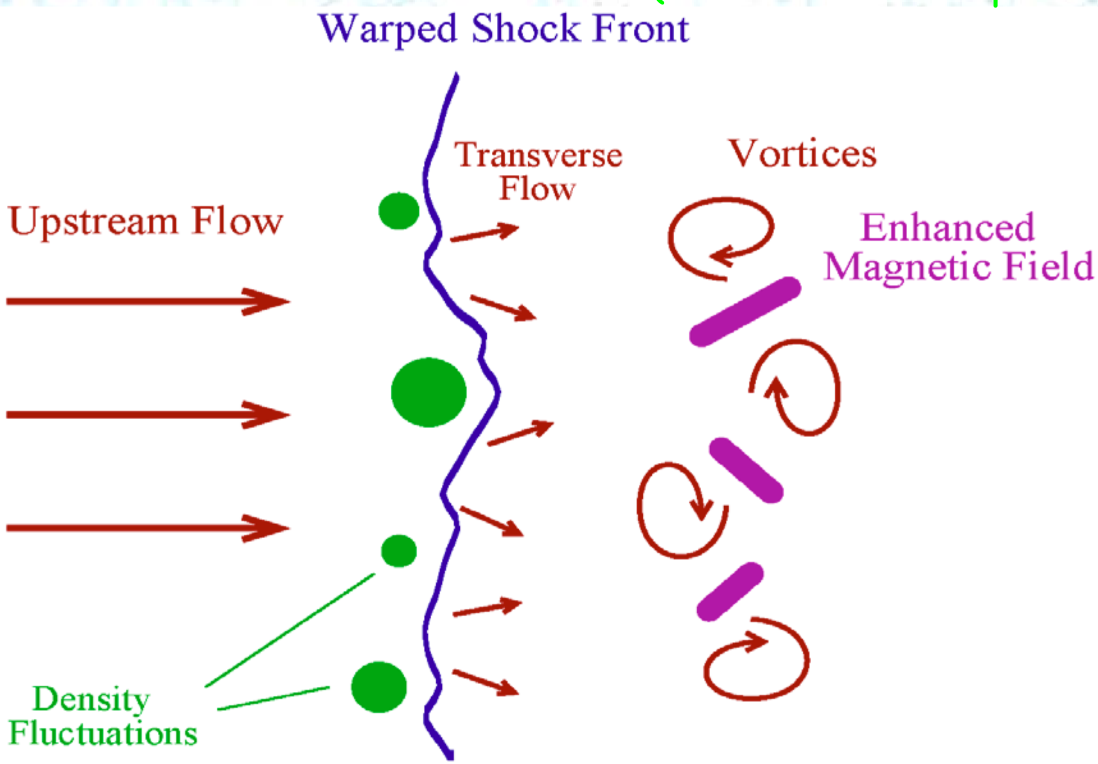
The energy of the turbulence in the intergalactic medium

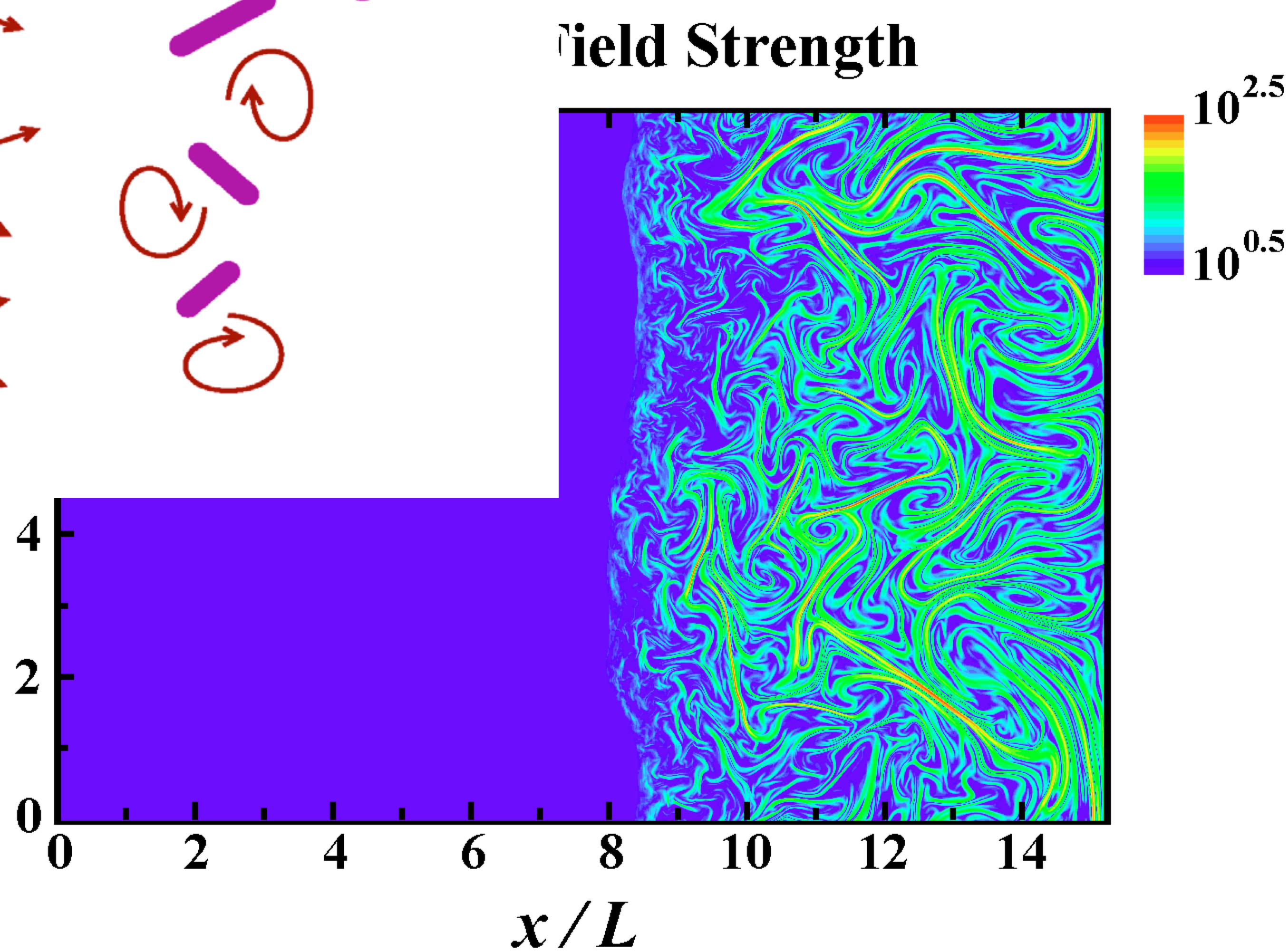
M_{turb} <~ 1 (subsonic turbulence) in clusters

M_{turb} ~ 1 (transonic turbulence) in filaments

Development of turbulence and amplification of magnetic fields

(Giacalone & Jokipii 2007)





Magnetic fields in the intergalactic medium

Origin of seeds for comic magnetic fields is uncertain.

some suggestions:

1. generation in the early universe
   e.g.) during the electroweak phase transition ($t \sim 10^{-12}$sec)?
   during the quark-hadron transition ($t \sim 10^{-5}$sec)?
2. generation just before cluster formation, eg. in shocks
3. magnetic fields from the first stars and active galaxies

…

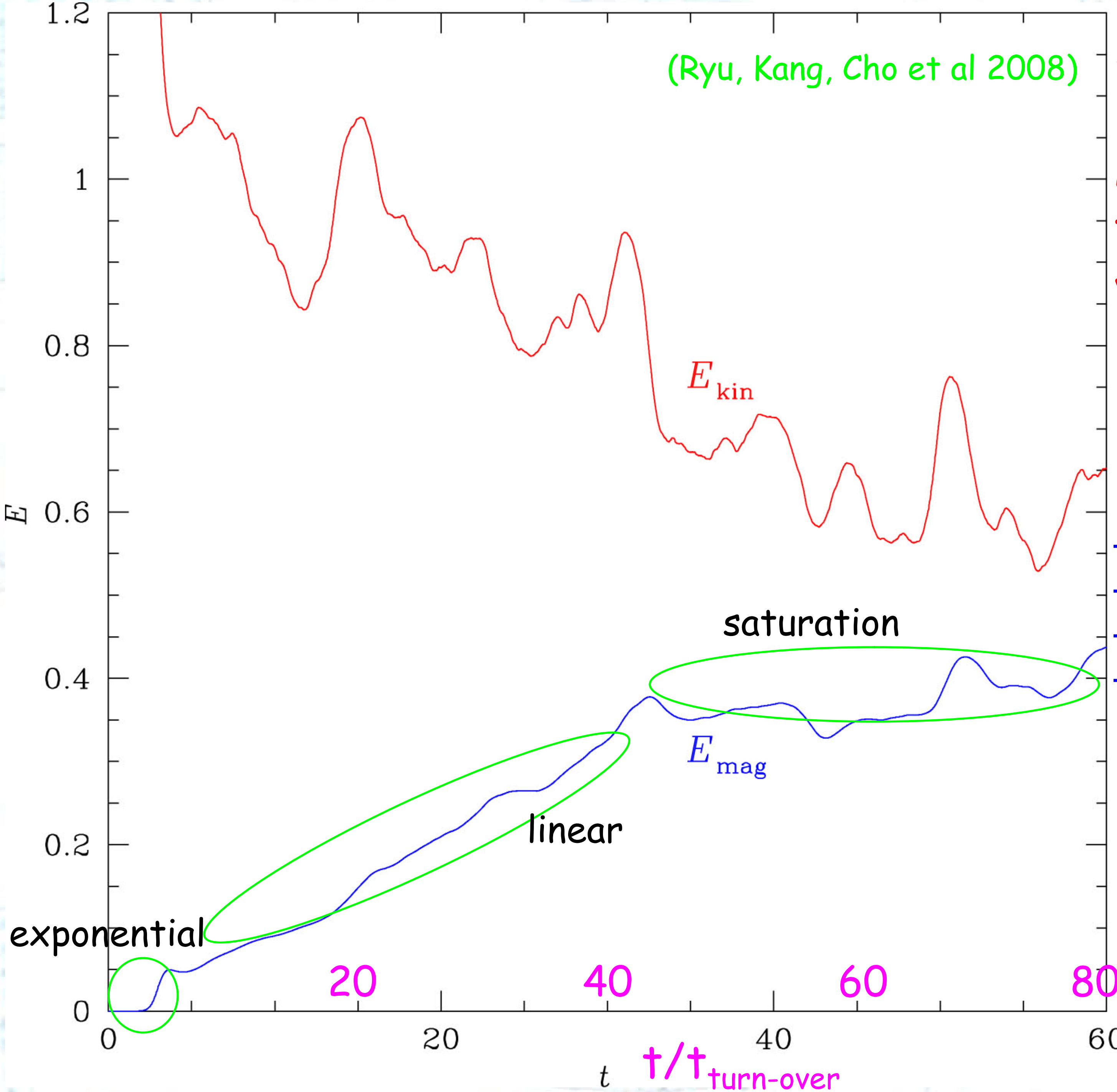
It is difficult to produce strong coherent magnetic fields in the IGM before the formation of the large-scale structure of the universe, but it is reasonable to assume that week seed fields were created

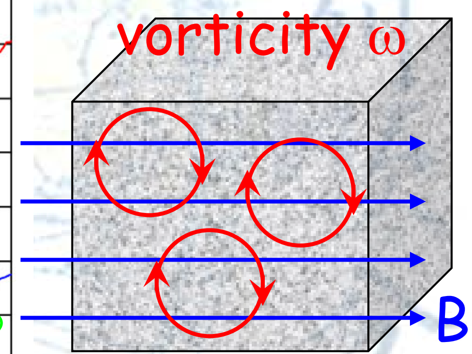
very weak B field before structure formation

turbulence amplifies magnetic fields

⟹ $B_0 << \delta B$ in the IGM (while $B_0 \sim \delta B$ in the ISM)

Simulation of incompressible MHD turbulence with very weak regular field

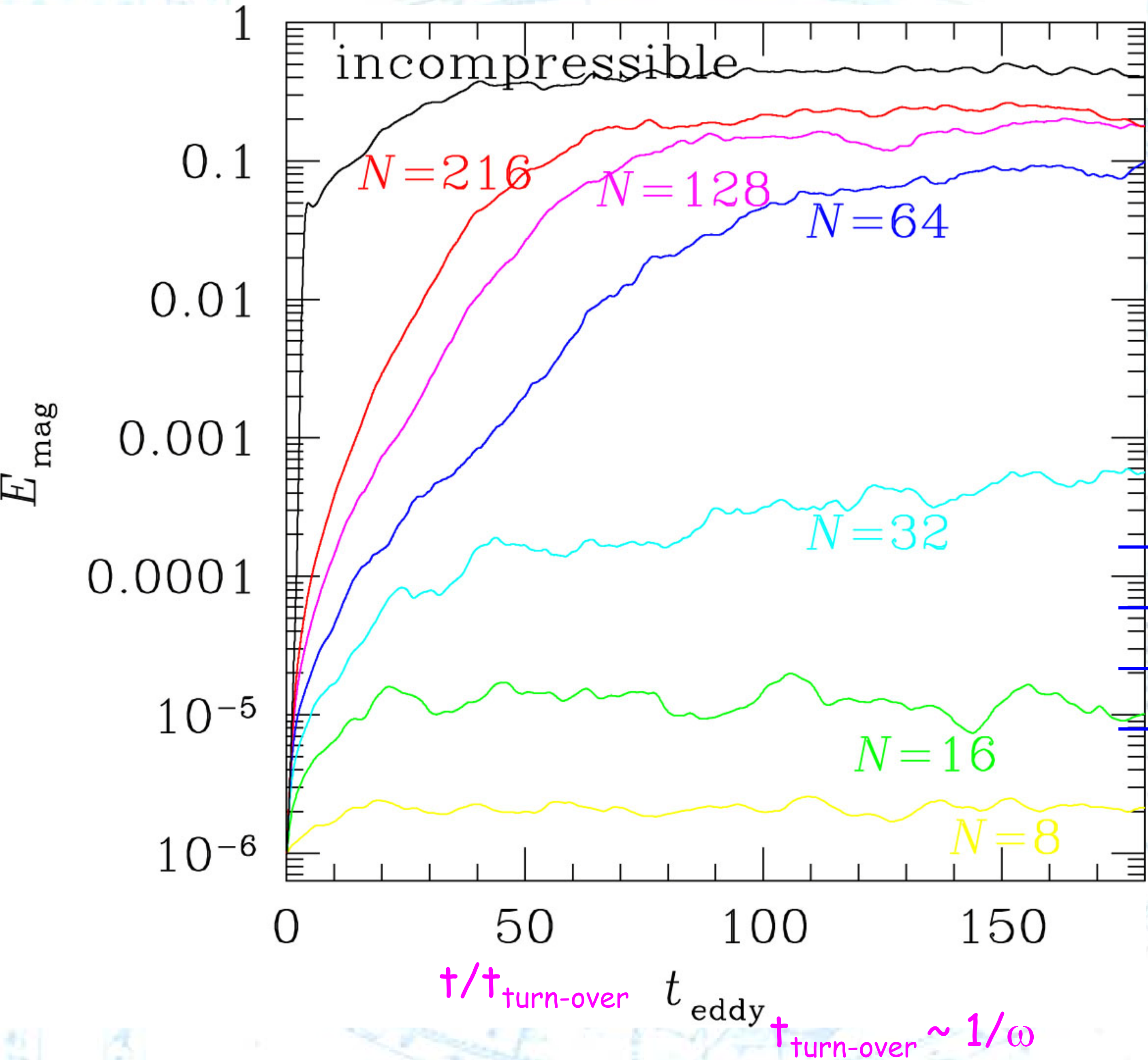




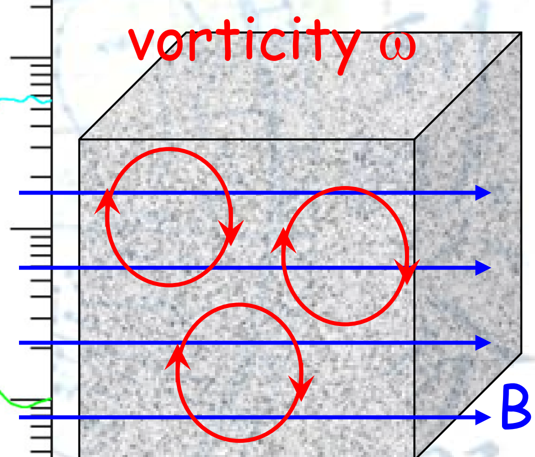
$E_{mag} \sim 2/3\ E_{kin}$

at saturation

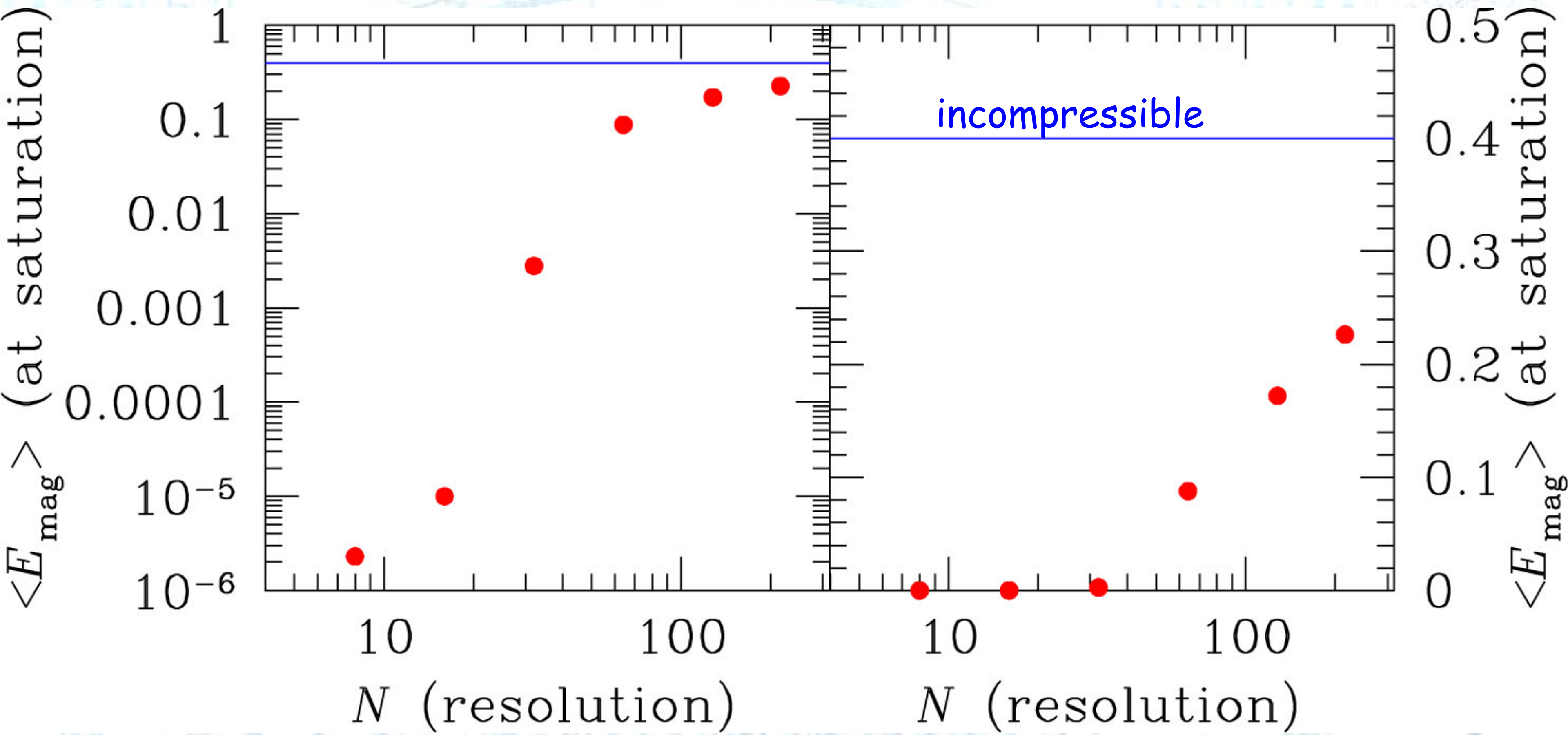
$t_{turn\text{-}over} \sim 1/\omega$



MHD simulations for large scale structure formation do not work!



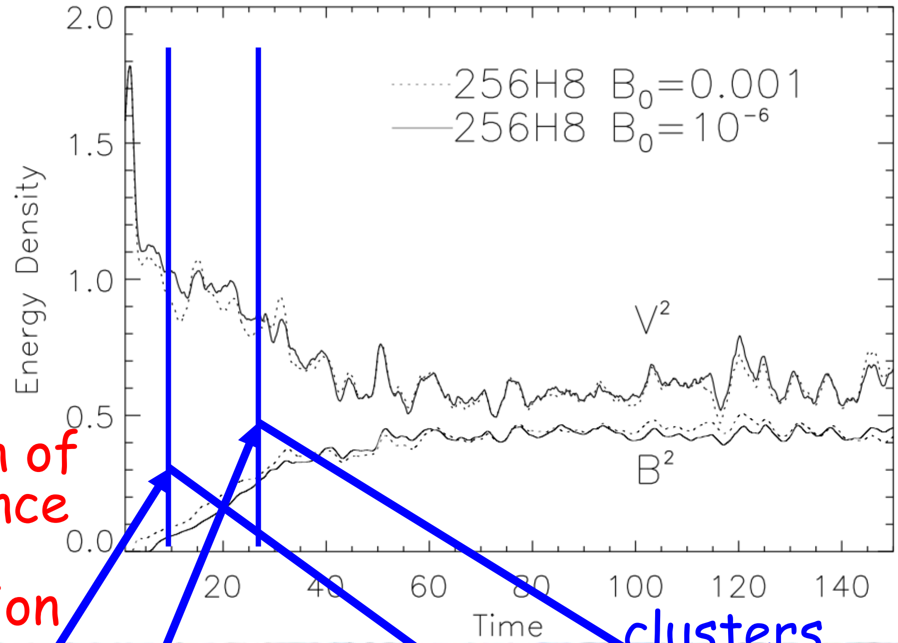
from compressible simulations with various resolutions and an incompressible simulation

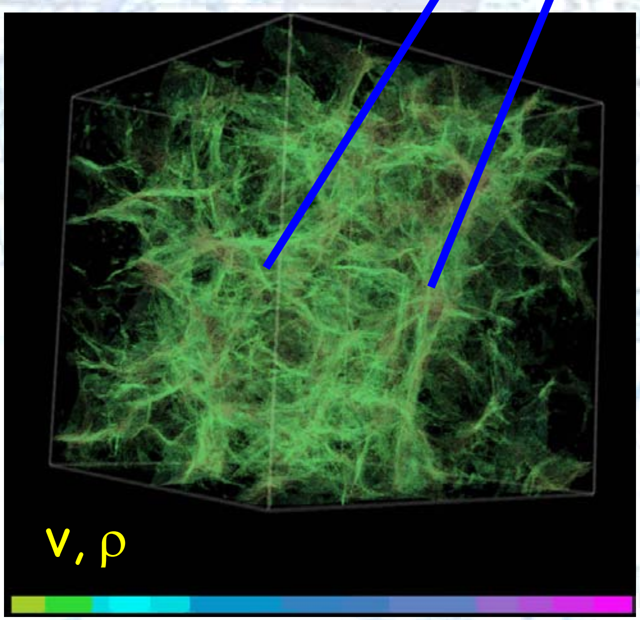


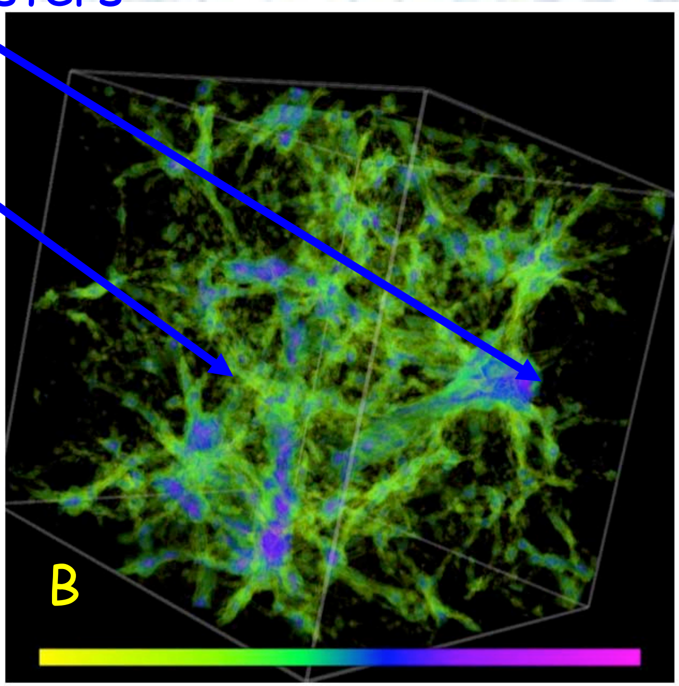
⇒ very high resolution MHD simulations are necessary for large scale structure formation

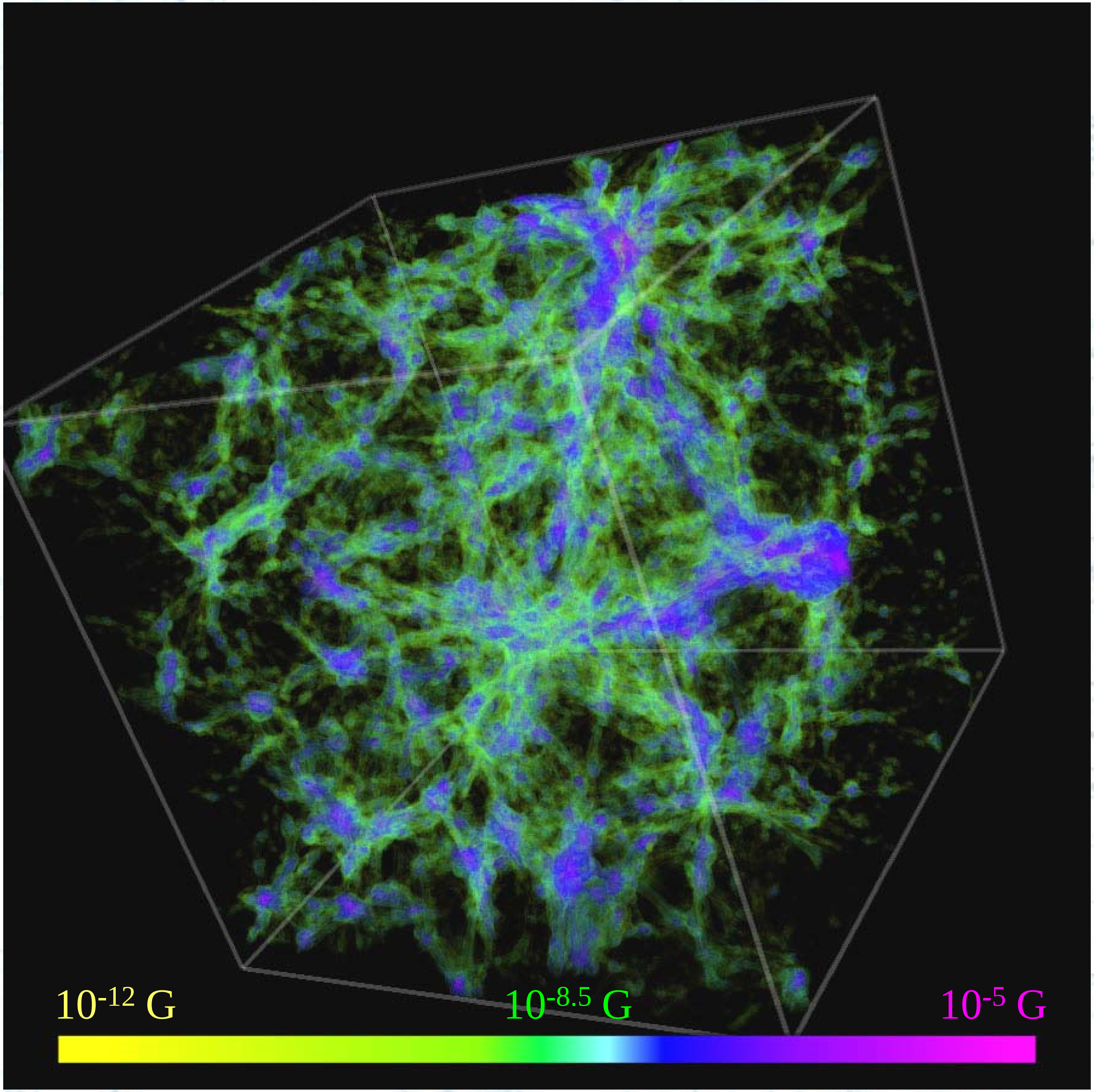
(a few 100 zones for formation of vorticity in LSS
X a few 100 zones for further evolution of vortivity
= ~10^5 zones)

Estimation of magnetic field strength in the intergalactic medium







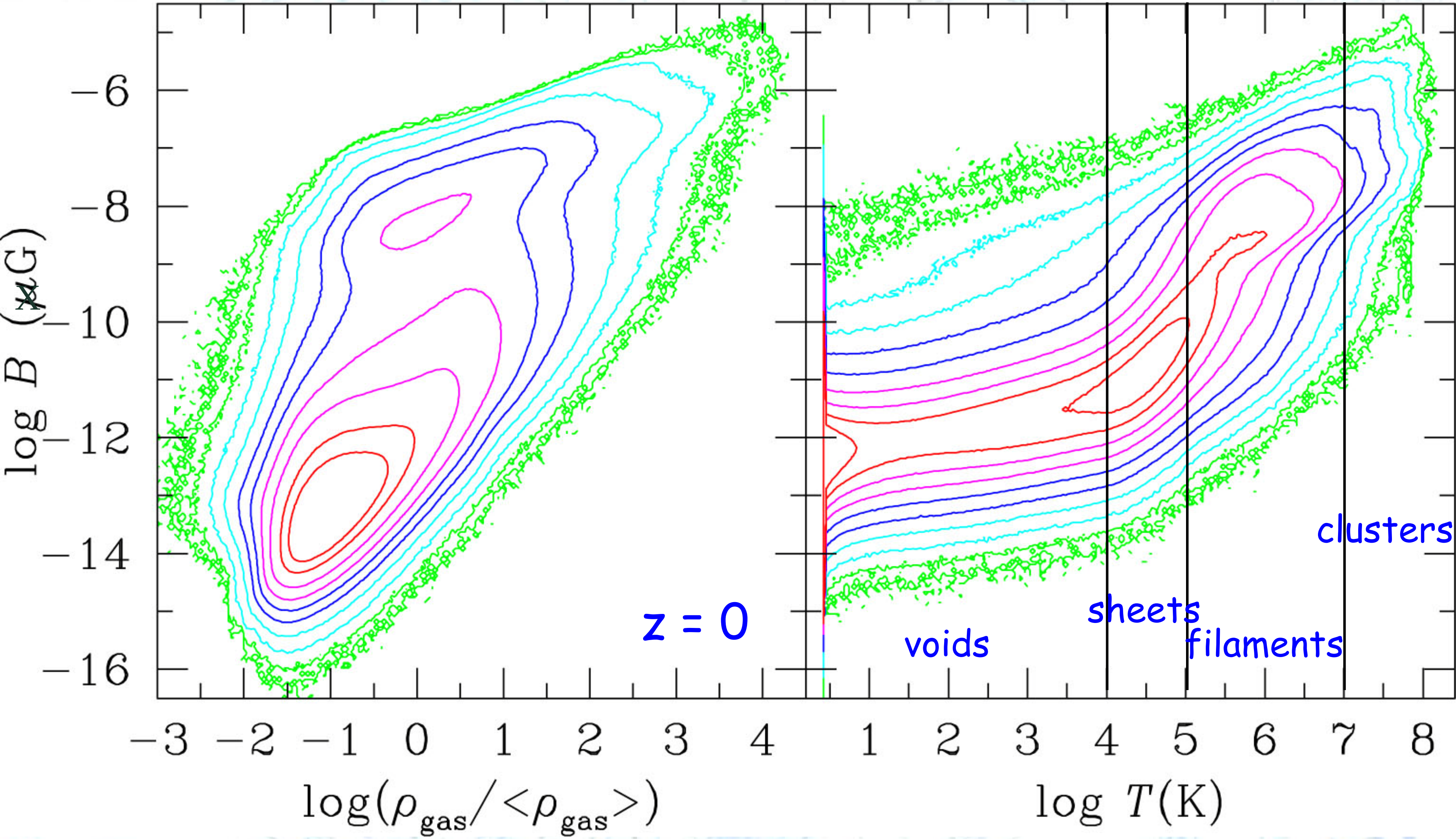


3D distribution of magnetic field strength in (100 h^{-1} Mpc)^3 box: concentrated in clusters and groups along filaments

-> "cosmic web of filaments"

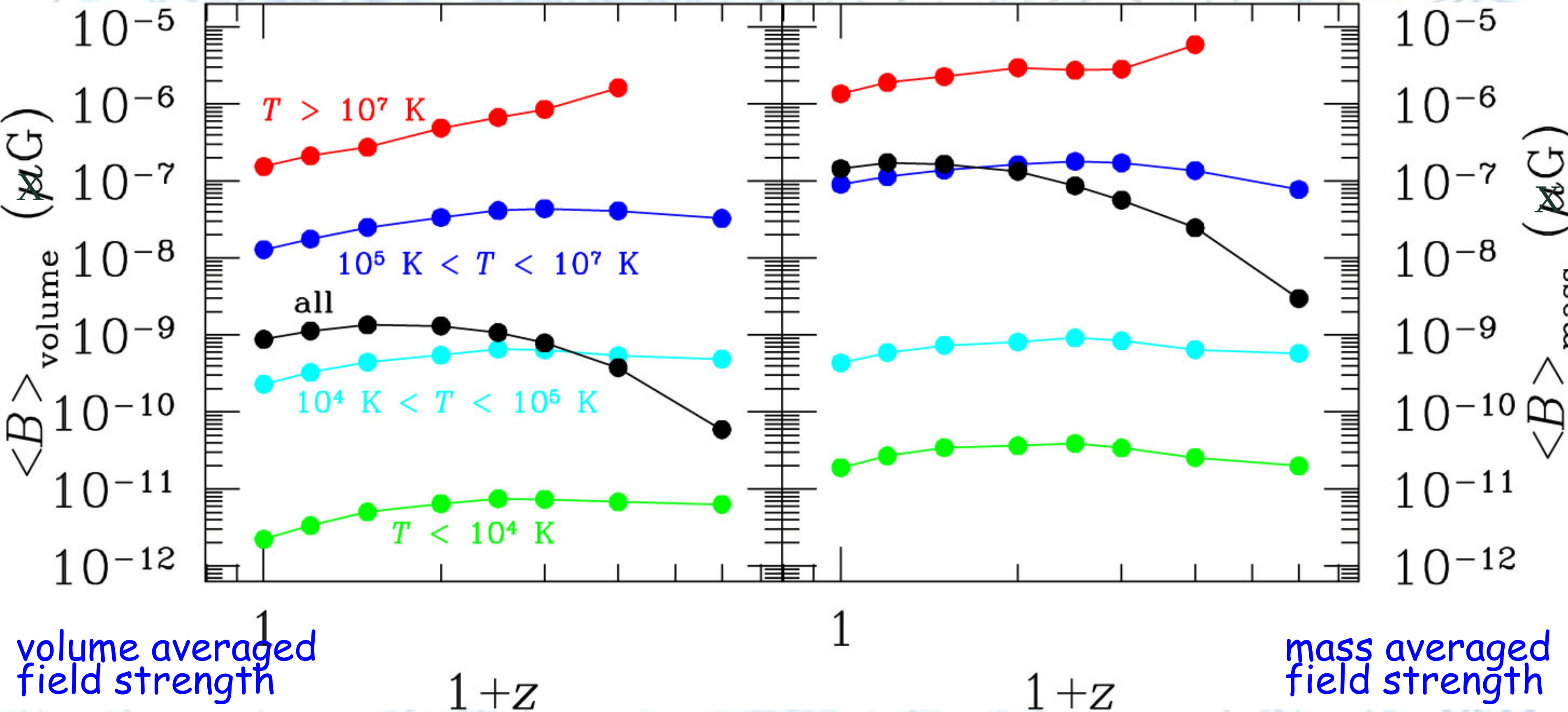
volume filling factor: f (B > 10 nG) ~ 0.01

Magnetic field strength
in the large scale structure of the universe



Averaged magnetic field strength in the large-scale structure of the universe at $z = 0$

- inside clusters, $\langle B \rangle$ ~ a few μG
- around clusters ($T > 10^7$ K), $\langle B \rangle$ ~ 0.1 μG
- in filaments (10^5 K < T < 10^7 K, or WHIM), $\langle B \rangle$ ~ 10 nG



Average values of the intergalactic magnetic field

in filaments (10^5 K < T < 10^7 K, or WHIM) at present

$\langle B \rangle \sim 10$ nG

-> relevant to the propagation of ultra-high-energy CRs

$\langle B^2 \rangle^{1/2} = B_{rms} \sim$ a few x 10 nG

$\langle \rho B \rangle / \langle \rho \rangle \sim 0.1\ \mu G$

$\langle \rho B^2 \rangle^{1/2} / \langle \rho \rangle^{1/2} \sim$ a couple x 0.1 μG

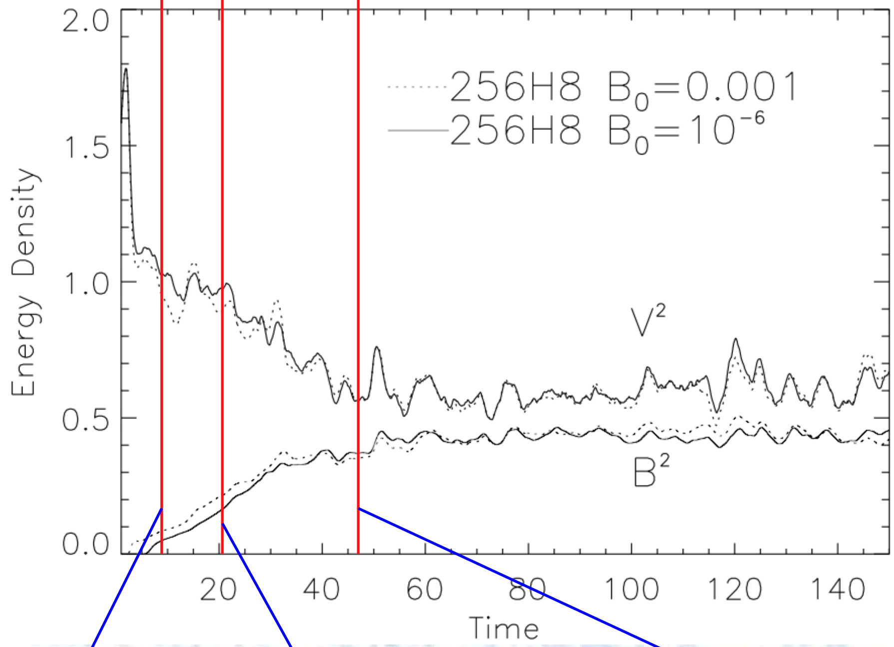
-> relevant to synchrotron emission

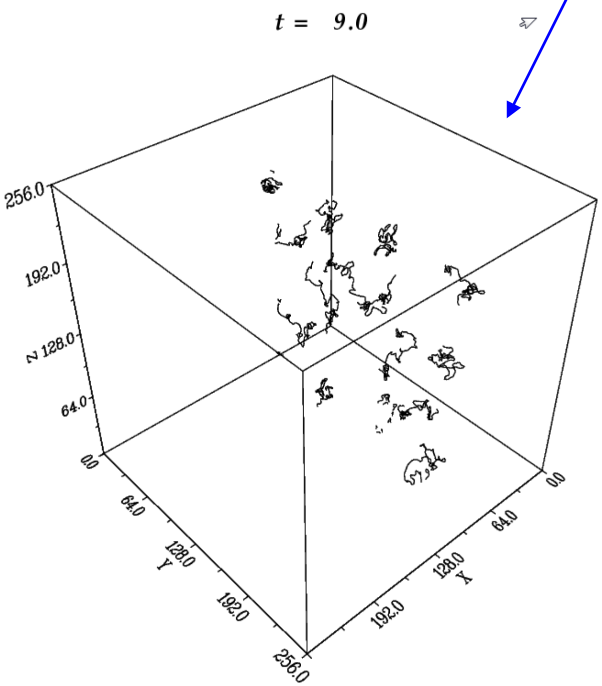
$\langle (\rho B)^2 \rangle^{1/2} / \langle \rho^2 \rangle^{1/2} \sim$ a few x 0.1 μG

-> relevant to Faraday rotational measure

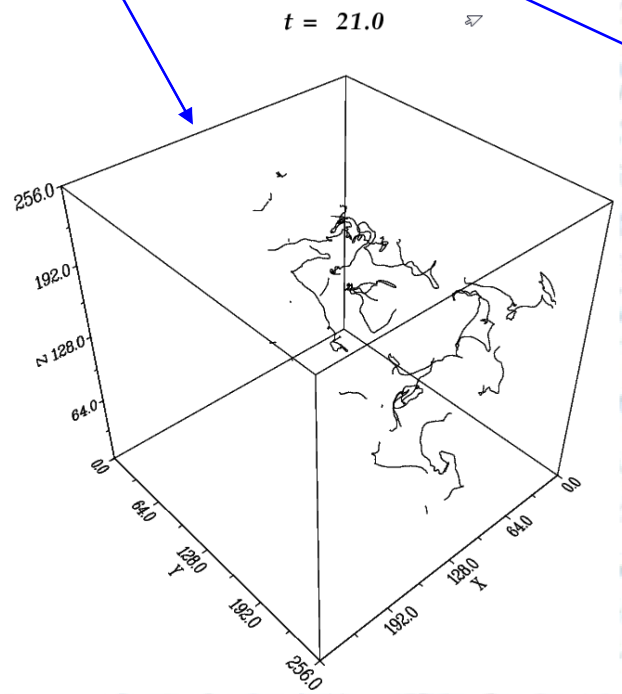
Characteristic lengths of the IGMF?

(Cho & Ryu 2009 submitted)

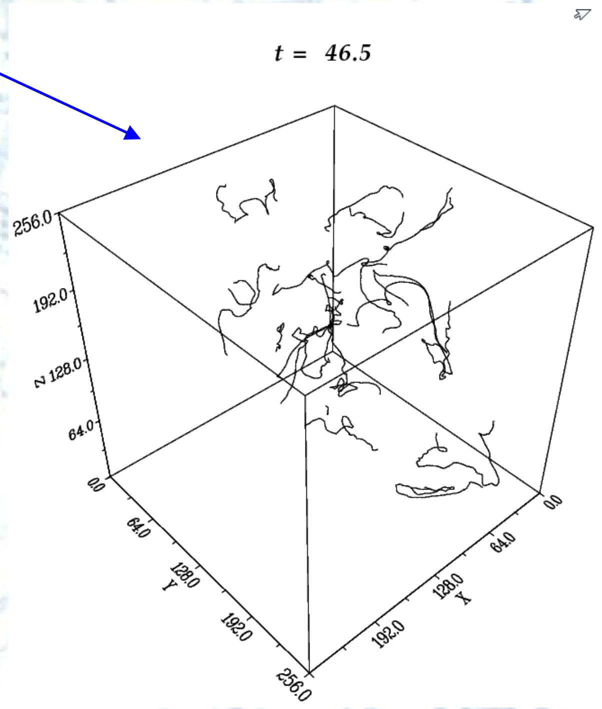




June 29 to July 3, 2009

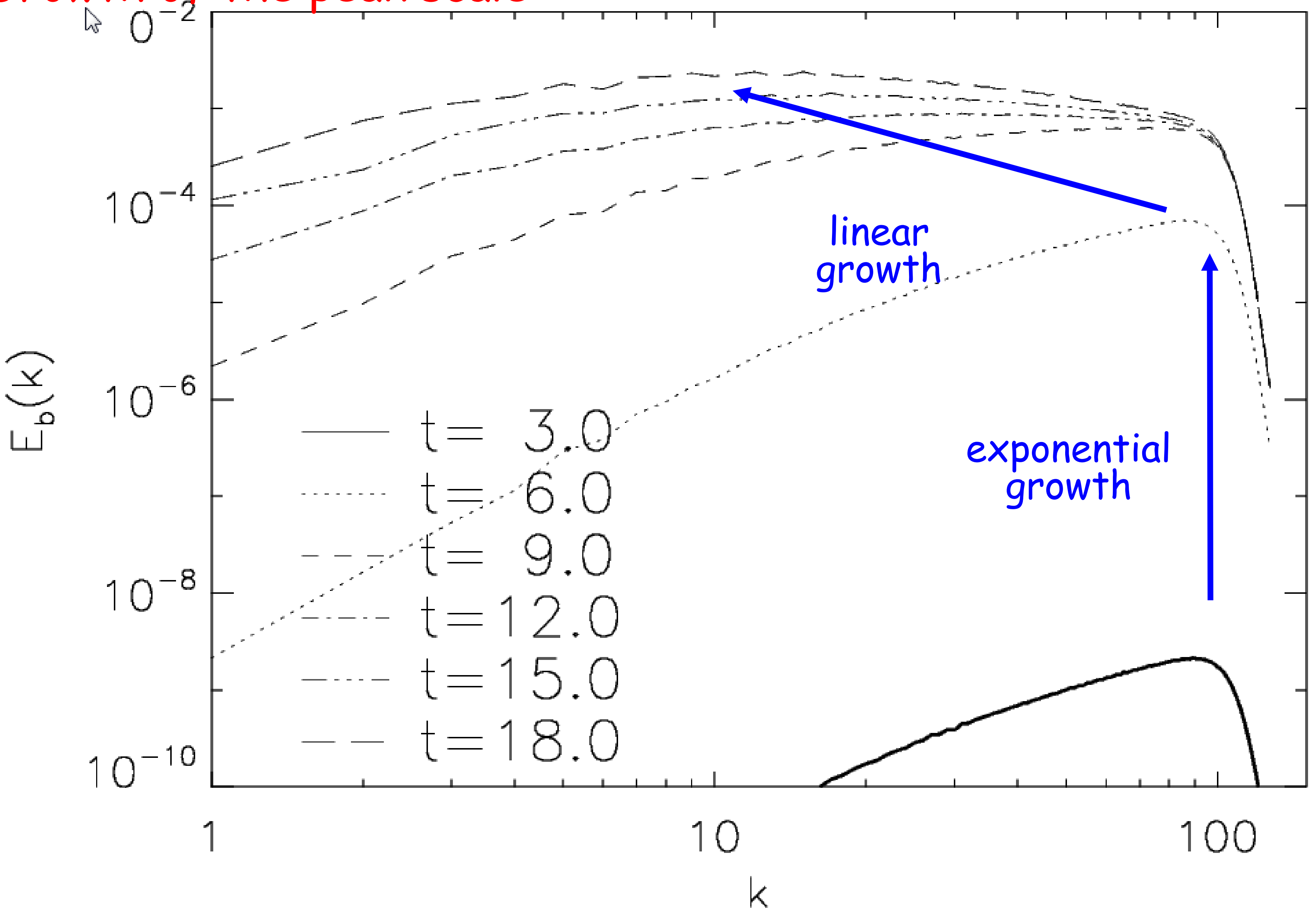


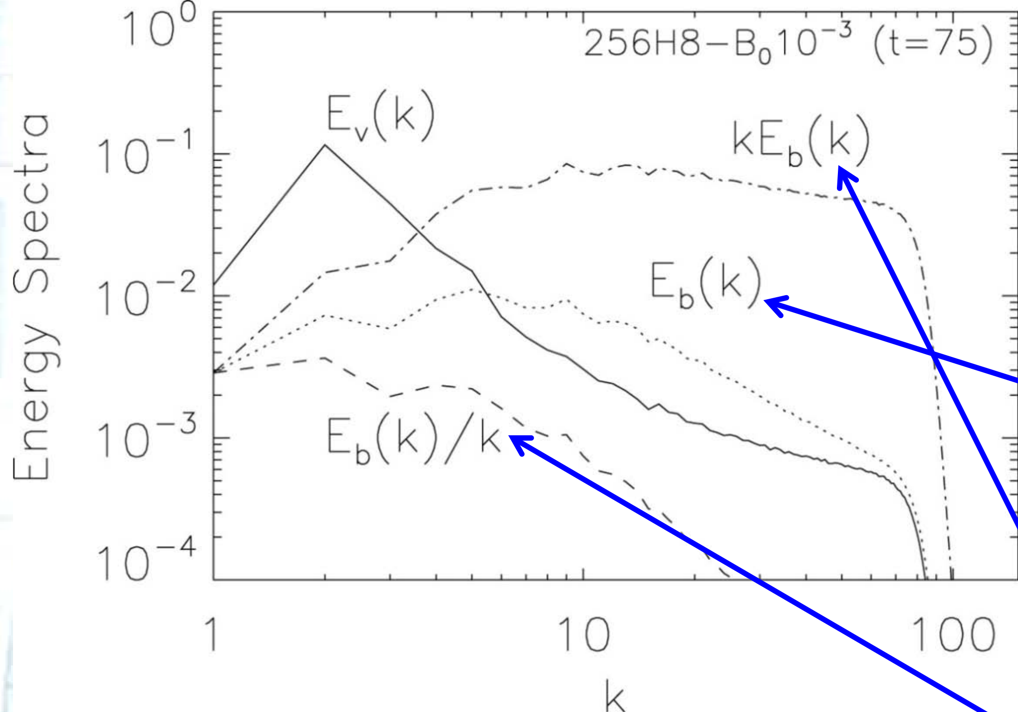
Astronum 2009



Chamonix, France

Growth of the peak scale





power spectra of velocity and magnetic fields at saturation

the peak scale of magnetic field spectrum

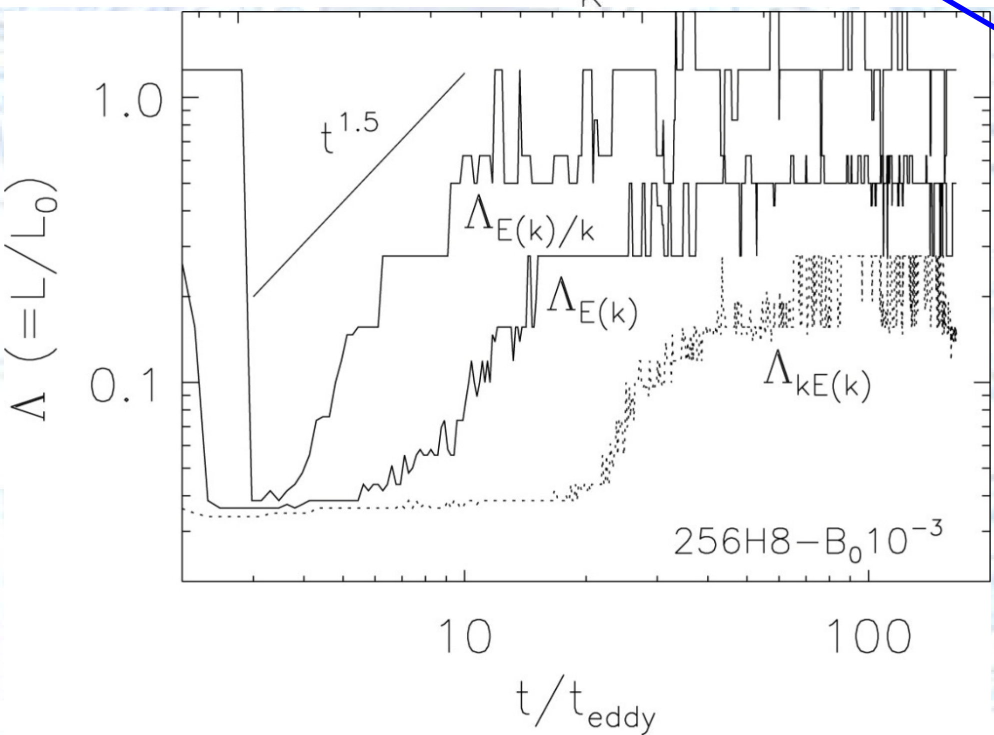
$L_{E(k)}$ ~ 1/2 $L_{energy\ injection}$

the most energy containing scale

$L_{kE(k)}$ ~ 1/4 $L_{energy\ injection}$

the peak scale of spectrum of projected 2d field

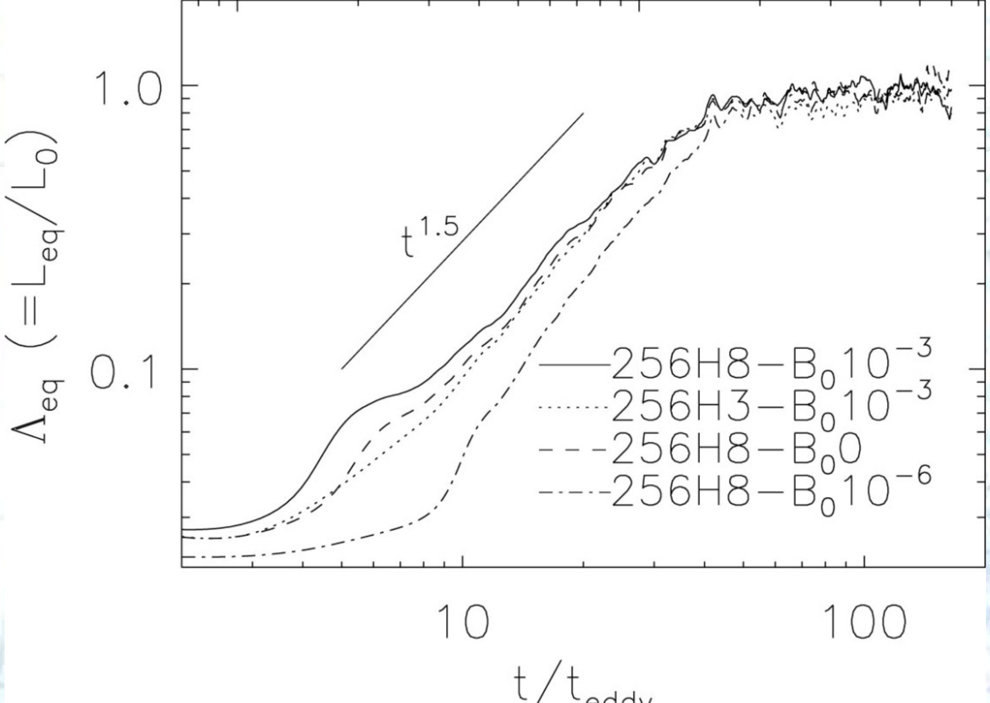
$L_{E(k)/k}$ ~ $L_{energy\ injection}$



growth of the scales

L ~ $t^{1.5}$?

(insufficient resolution)



energy equipartition scale

$$\int_{k_{eq}}^{k_{max}} E_v(k)dk = \int_0^{k_{max}} E_b(k)dk$$

$L_{eq} \sim t^{1.5}$ <- scaling relation

$L_{eq} \sim L_{energy\ injection}$ at saturation

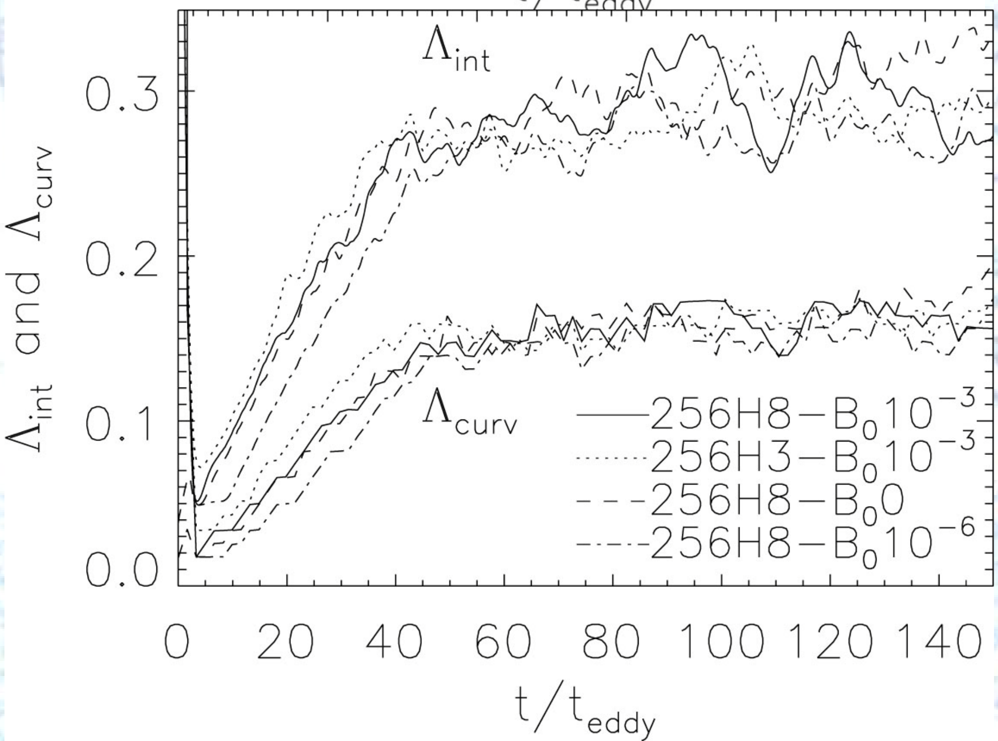
integral scale

$$L_{int} = 2\pi \frac{\int (E_b/k)dk}{\int E_b dk}$$

$L_{int} \sim t$ (insufficient resolution ?)

$L_{int} \sim 0.3\ L_{energy\ injection}$ at saturation

-> relevant to Faraday RM (coherence length for RM)



curvature scale

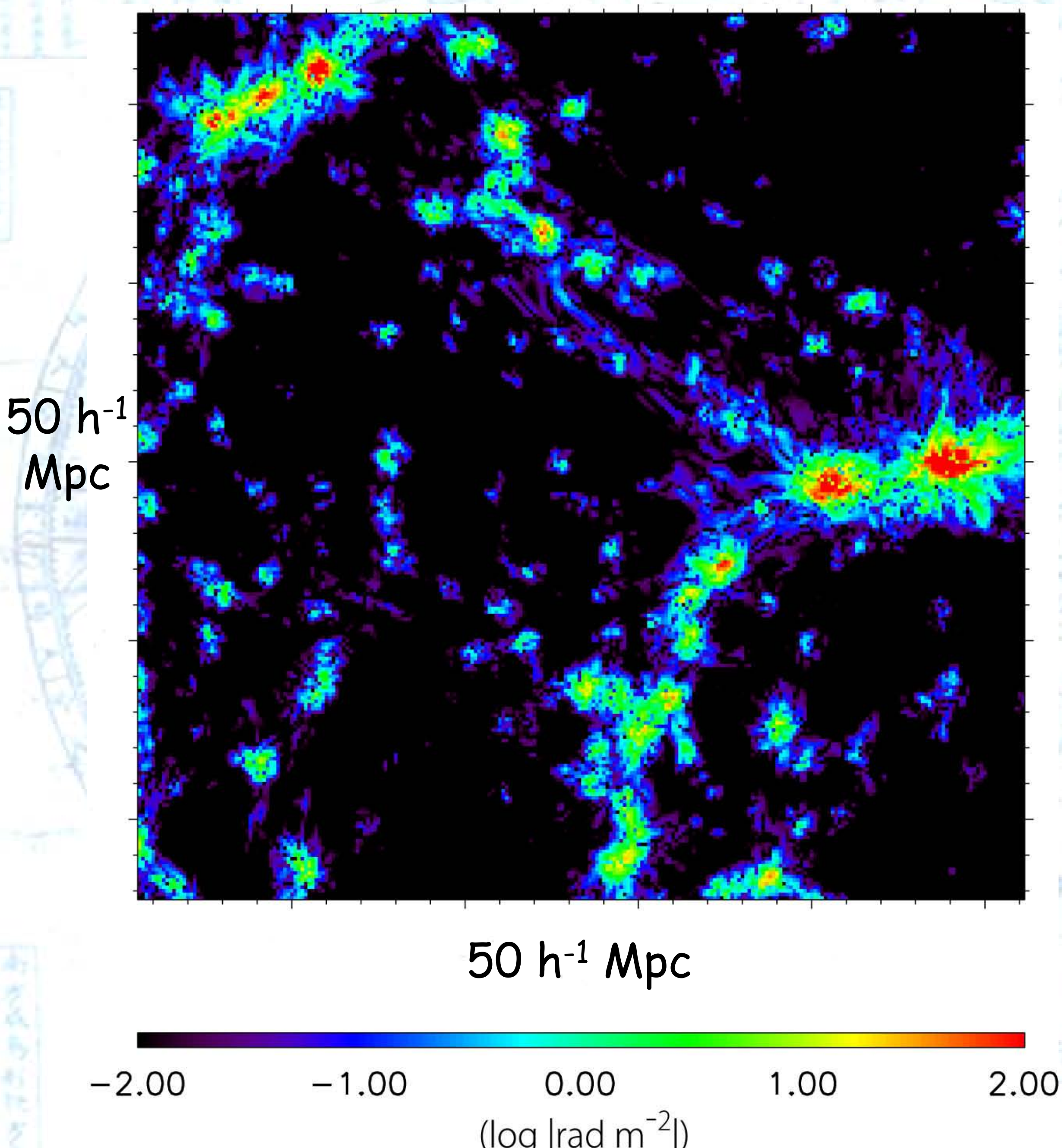
$$\frac{\langle B(x)\cdot B(x+r)\rangle_x}{\langle B(x)\cdot B(x)\rangle_x} = \frac{1}{e}$$

$L_{curv} \sim t$ (insufficient resolution ?)

$L_{curv} \sim 0.15\ L_{energy\ injection}$ at saturatio

Faraday rotational measure (RM) due to the intergalactic MF

(Akahiro, Ryu et al 2009, in preparation)



our model IGMF predicts

- RM ~ a few x 100 rad m^{-2} through clusters
- RM ~ 1 rad m^{-2} intersecting filaments
- consistent with observations:
  Clarke et al. 2001
  Xu et al. 2006

Propagation of ultra-high-energy cosmic rays through the intergalactic magnetic field

(Ryu, Das, Kang 2009, in preparation)

Larmor radius:

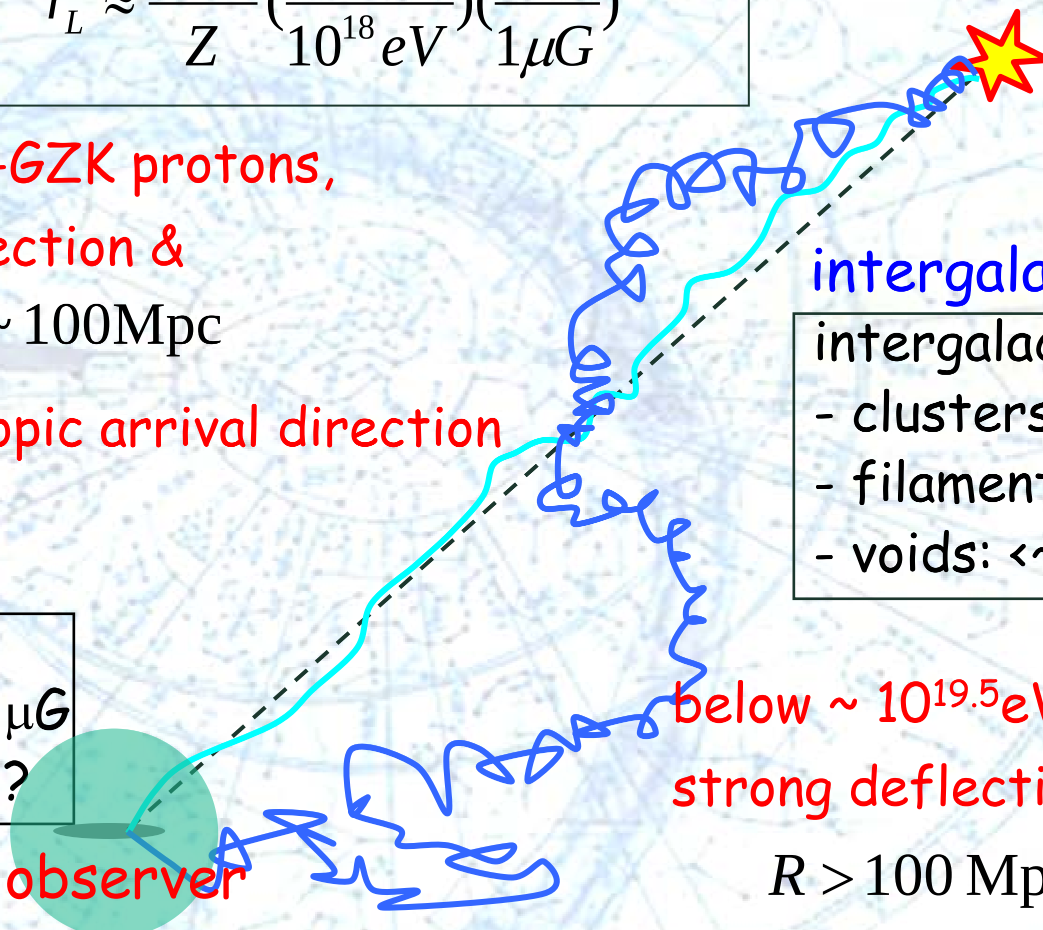
$$r_L \approx \frac{1kpc}{Z}\left(\frac{E}{10^{18}eV}\right)\left(\frac{B}{1\mu G}\right)^{-1}$$

for Super-GZK protons,

weak deflection &

$$R_{GZK} \sim 100\text{Mpc}$$

→ anisotropic arrival direction



intergalactic space

intergalactic B
- clusters: 1 - 10 μG
- filaments: ~ 10^{-8} G
- voids: <~ 10^{-12} G

Milky Way

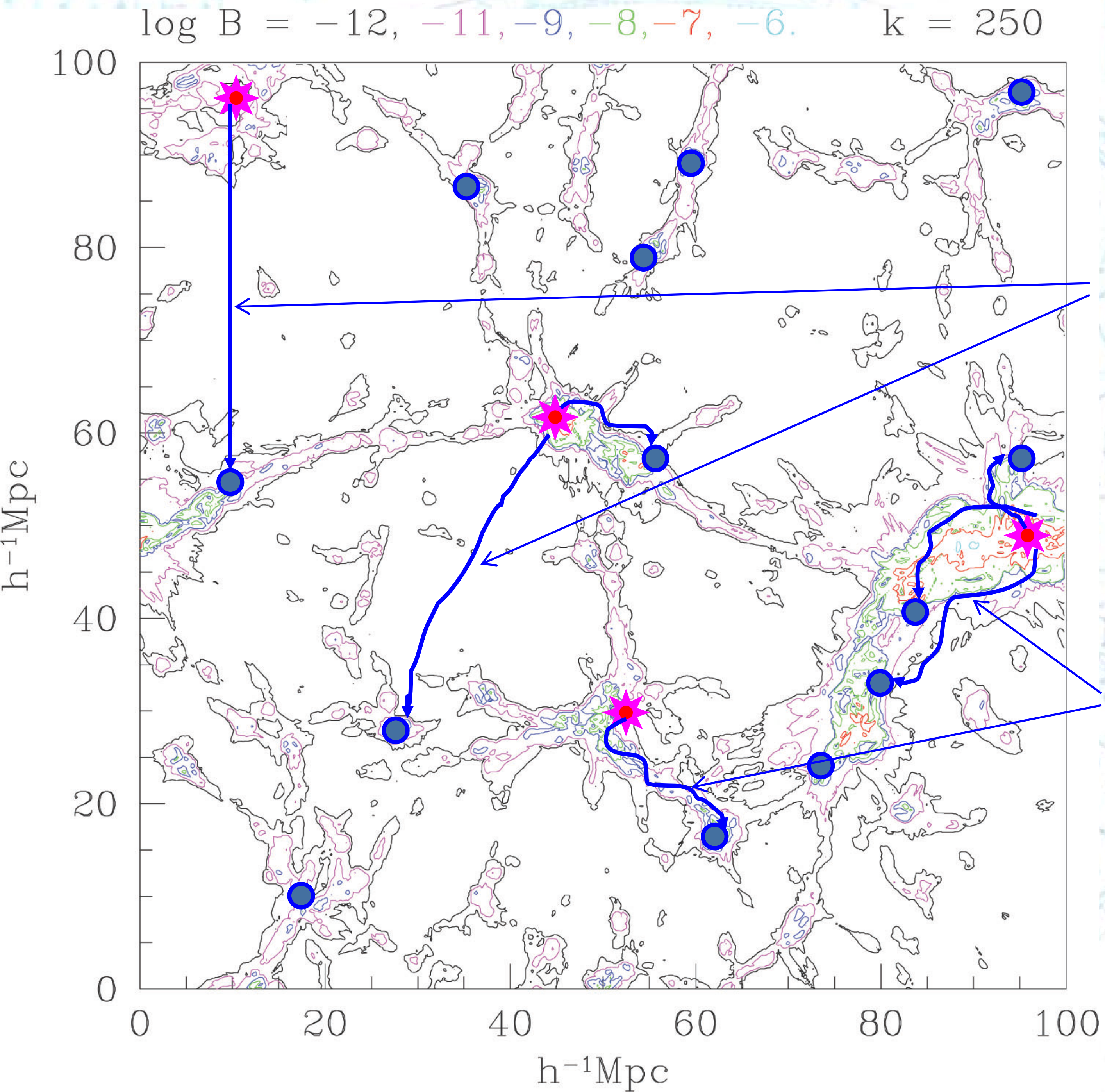
Galactic B
- disk: 5 - 10 μG
- halo: < 1 μG ?

below ~ $10^{19.5}$eV,

strong deflection &

$$R > 100 \text{ Mpc and larger}$$

→ isotropic arrival direction



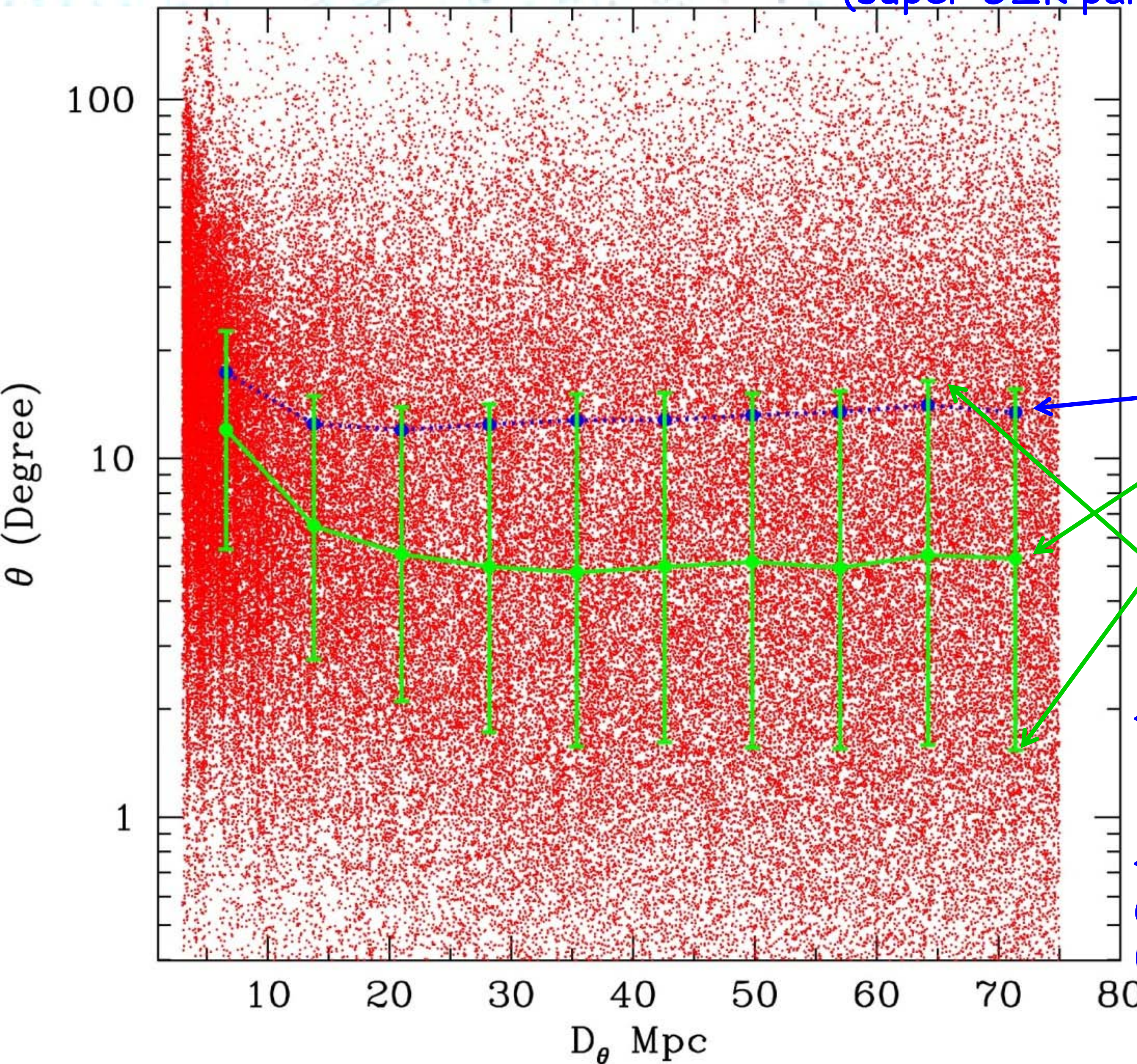
if source and observer are in different filaments, rectilinear flight across voids

→ small deflection angle

if source and observer are in the same filaments, deflected flight along the filament

→ large deflection angle even for close sources θ = deflection angle

for observed events with E >= 60 EeV (super GZK particles)



mean

median

quartile

$\langle\theta\rangle \sim 14^o$

$\theta_{median} \sim 7^o$

$\langle\theta\rangle$ due to the IGMF

>>

$\langle\theta\rangle$ due to the Galactic field ~ 3.5^o (BBS-S model)

Thank you !