A Model for the Intergalactic Magnetic Field and its Astrophysical Implications

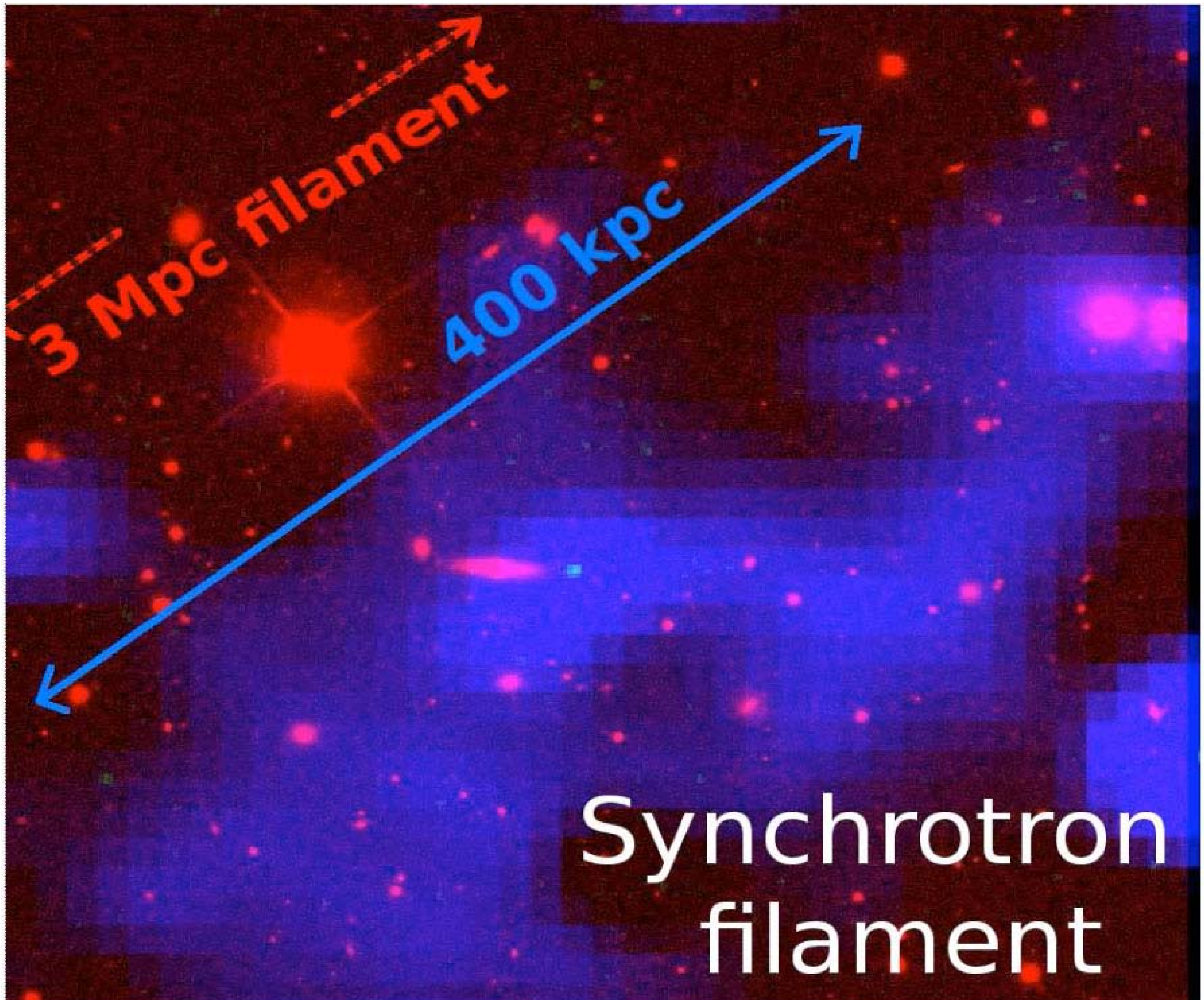
- Evidences for magnetic fields in the large-scale structure of the universe?
- Intergalactic magnetic field from a turbulence dynamo model
- Astrophysical implications of the intergalactic magnetic field

Dongsu Ryu (Chungnam National U, Korea)

Hyesung Kang (Pusan Nat U, Korea), Jungyeon Cho (Chungnam Nat U, Korea)

Takuya Akahori (Chungnam Nat U, Korea), Santa Das (IIT Guwahati, India)

Are there magnetic fields in the large-scale structure of the universe (outside clusters of galaxies)?



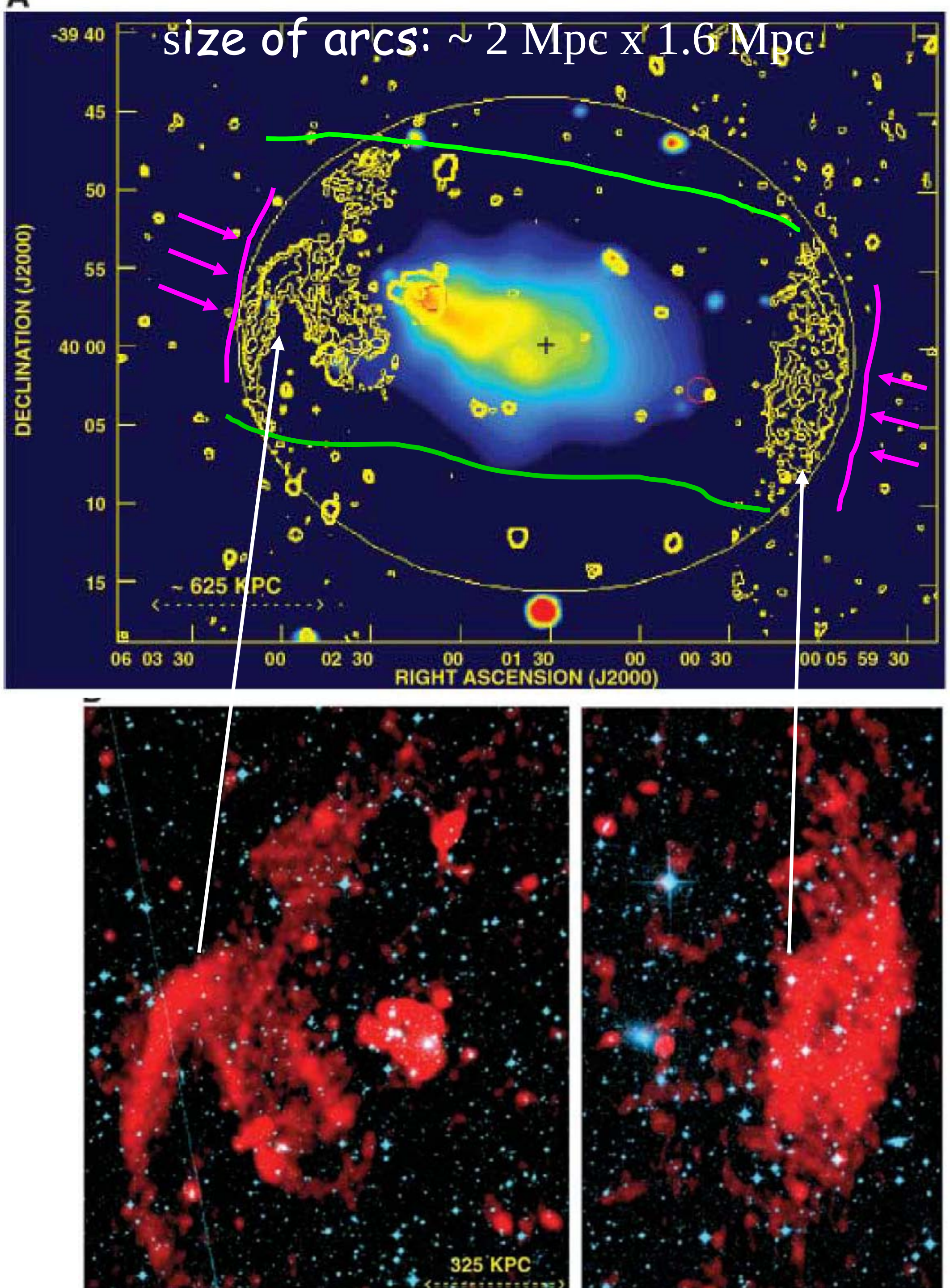
diffuse synchrotron from a filament?

(Rudnick private comm)

radio arcs in A3376

observational evidence for accretion shocks or merger shocks ?

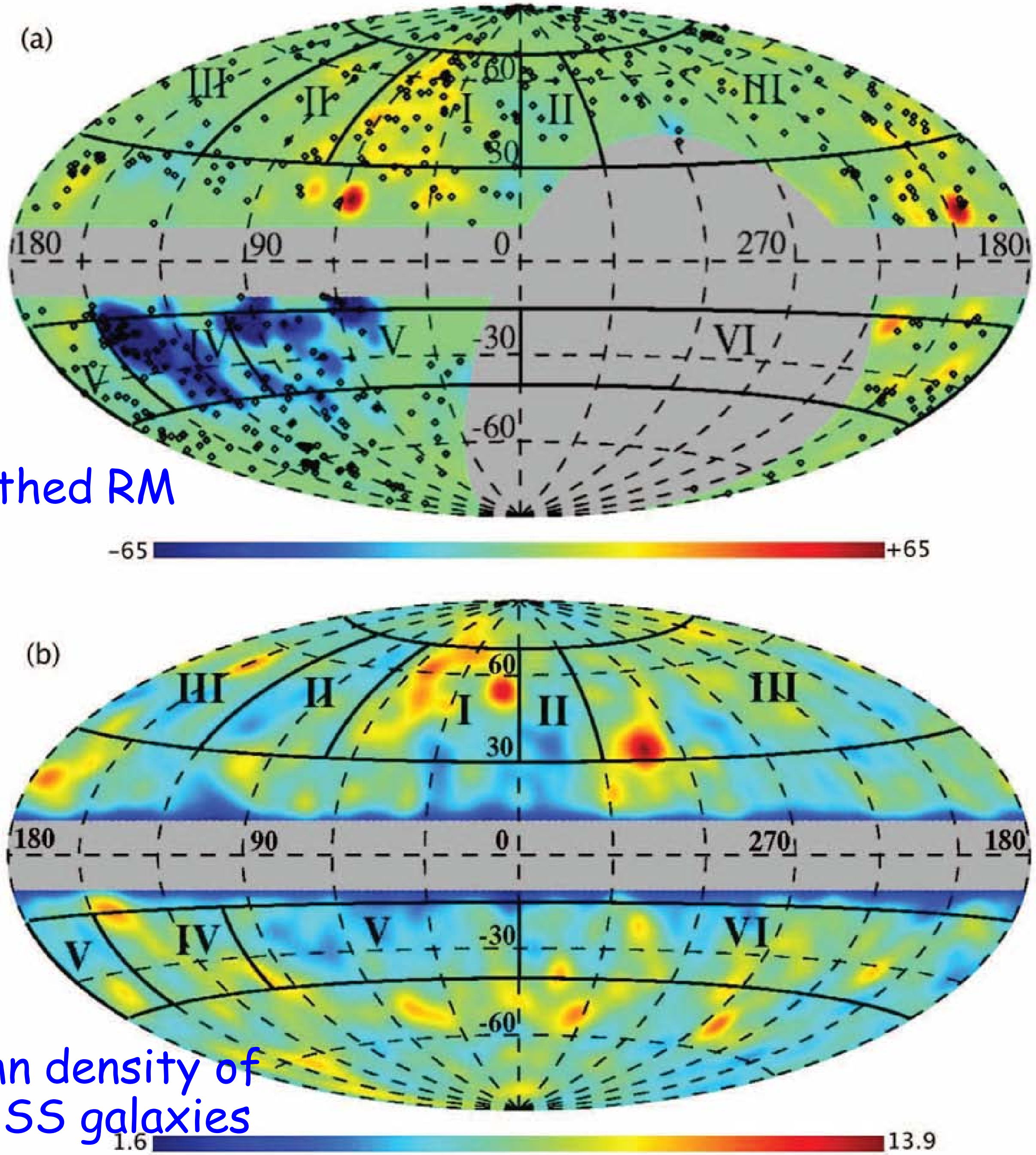
(Bagchi et al 2006)



radio + X-ray

radio + optical

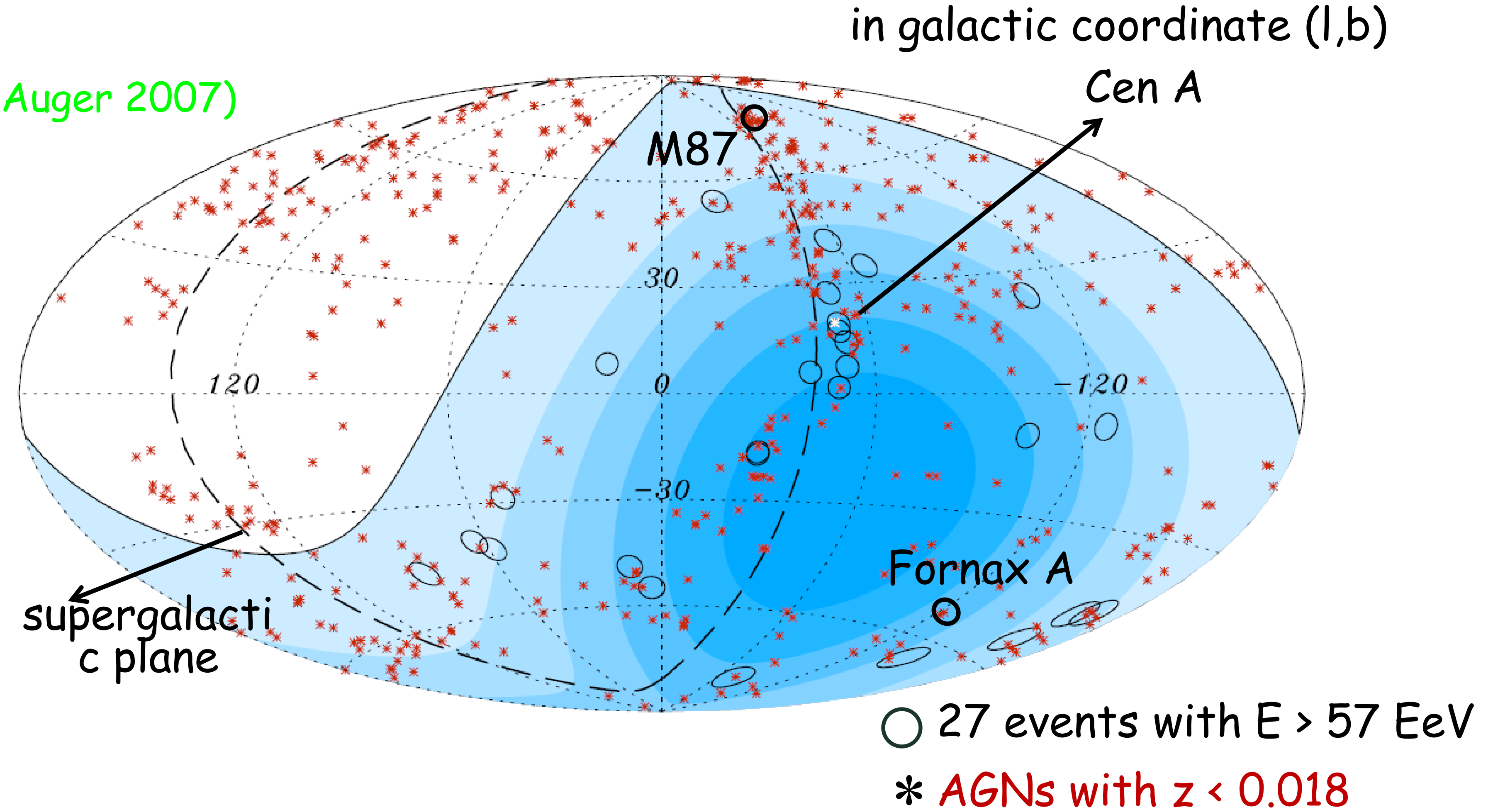
smoothed RM



column density of 2 MASS galaxies

RM up to ~ a few x 10 Rad/m^2 toward Hercules and Perseus-Pisces superclusters?

(Xu et al 2006)

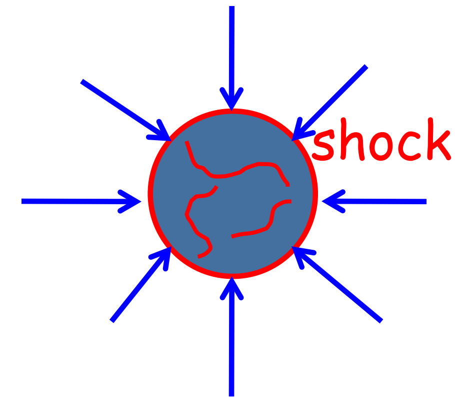


positional correlation between 27 UHECRs > 57 EeV and AGNs as tracers of matter in the Local universe within 75 Mpc for a search window S (angular separation) < 3.1°

deflection due to extragalactic as well as galactic magnetic fields?

How was the intergalactic magnetic field produced?

Overveiw for the origin of the IGMF



large-scale structure formation

gravitational collapse & flow motion

dynamic feedback on gas distribution

cosmological shocks

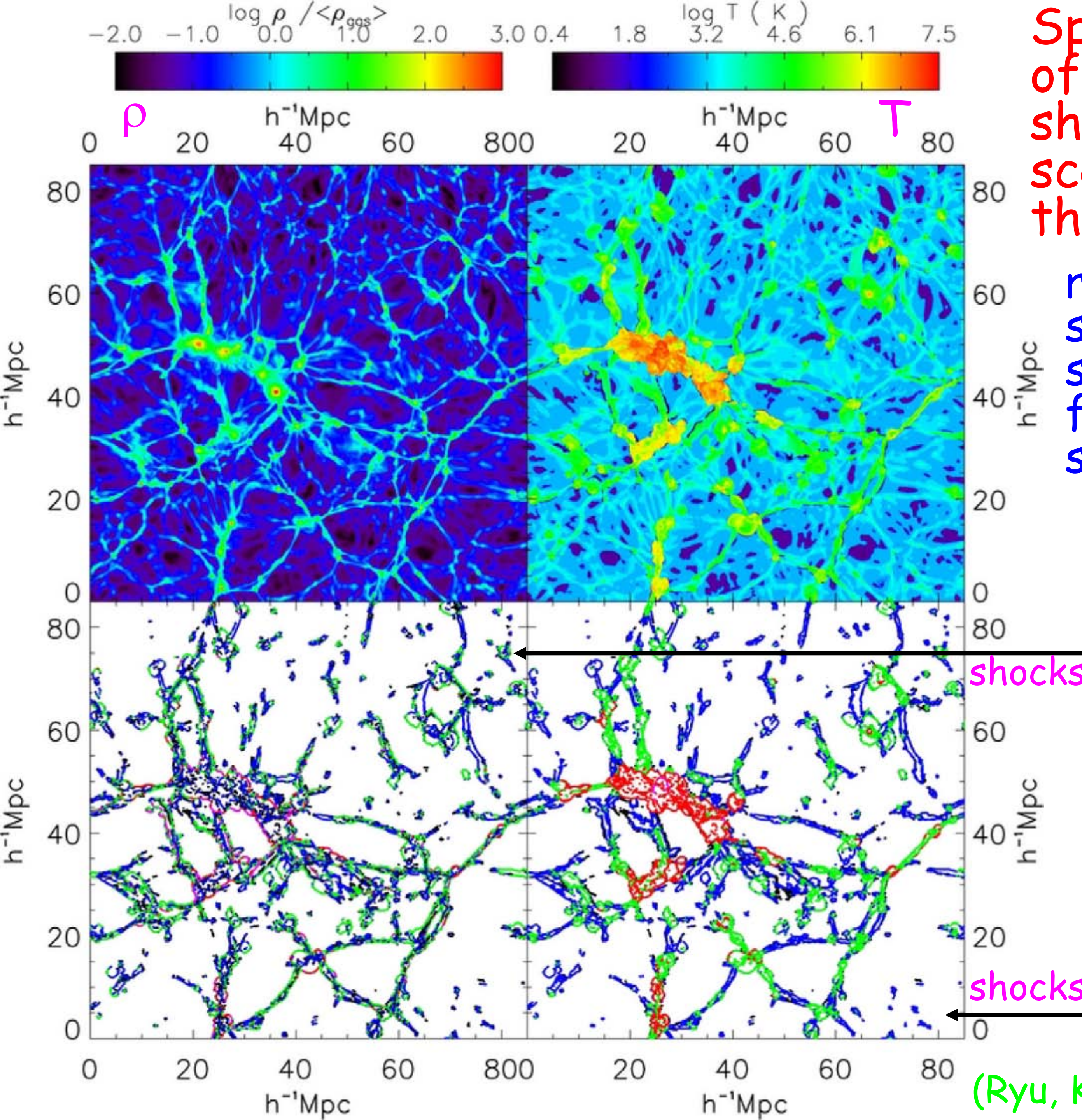
shock dissipation

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

vorticity into turbulence
further amp. of mag. field

other sources of heat, CRs, turbulence and magnetic field

Spatial distribution of cosmological shocks in the large scale structure of the universe



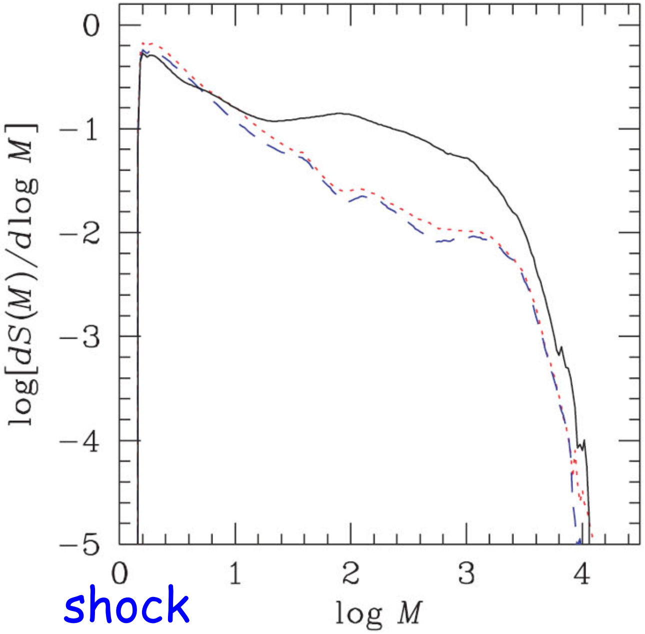
rich, complex shock morphology: shocks "reveal" filaments and sheets

black $M_s < 2$
blue $2 < M_s < 5$
green $5 < M_s < 40$
red $40 < M_s < 100$
magenta $M_s > 100$

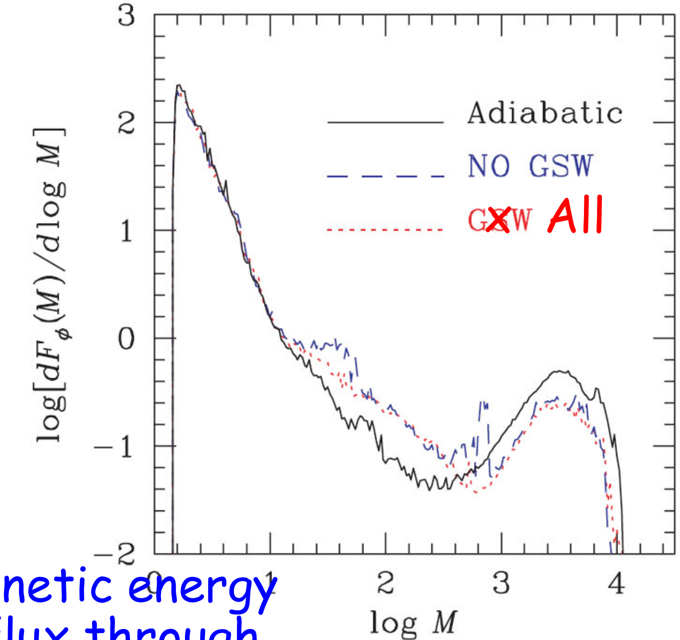
black $V_s < 15$ km/s
blue $15 < V_s < 65$
green $65 < V_s < 250$
red $250 < V_s < 1000$
magenta $V_s > 1000$

(Ryu, Kang, et al 2003, 2007)

Frequency and energetics of cosmological shocks



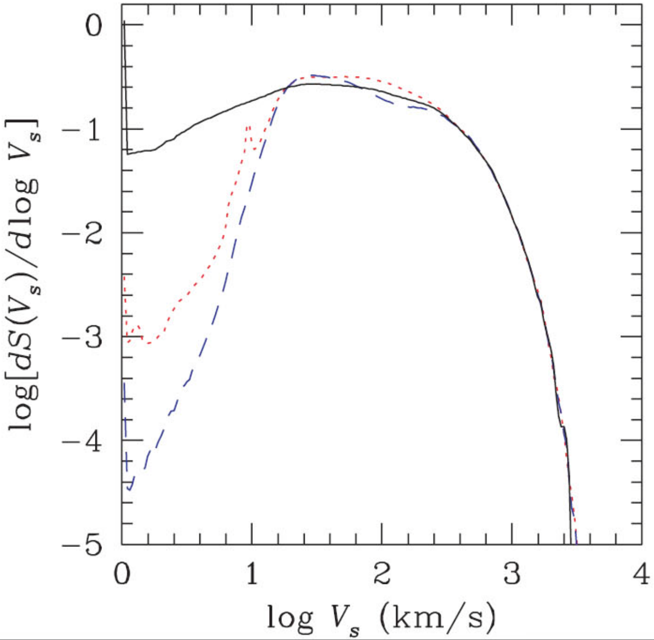
shock frequency

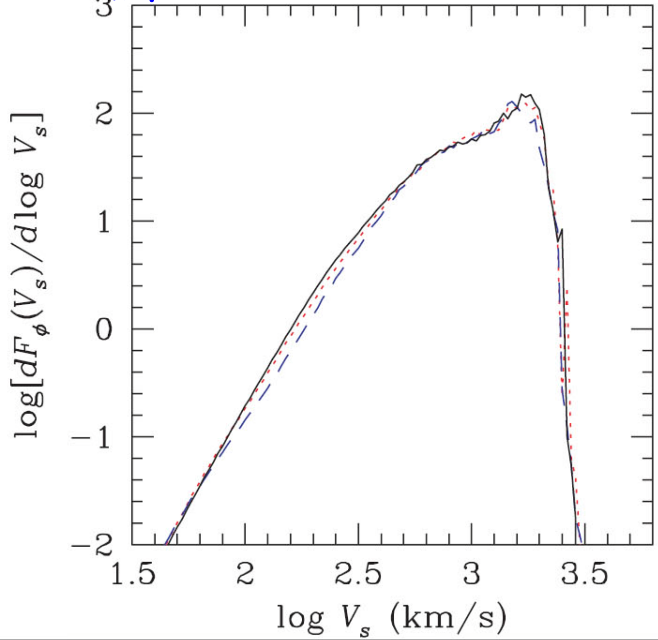


kinetic energy flux through shock surfaces

S = ~1/3 h[-1]Mpc with M > 1.5 at z = 0 (S = ~1 h[-1]Mpc with M > 1.5 at z = 0 inside nonlinear structures)

<- average inverse comoving distance between shock surfaces





shocks with M <~ a few (weak), V_s ~ 2,000 km/s are energetically most important

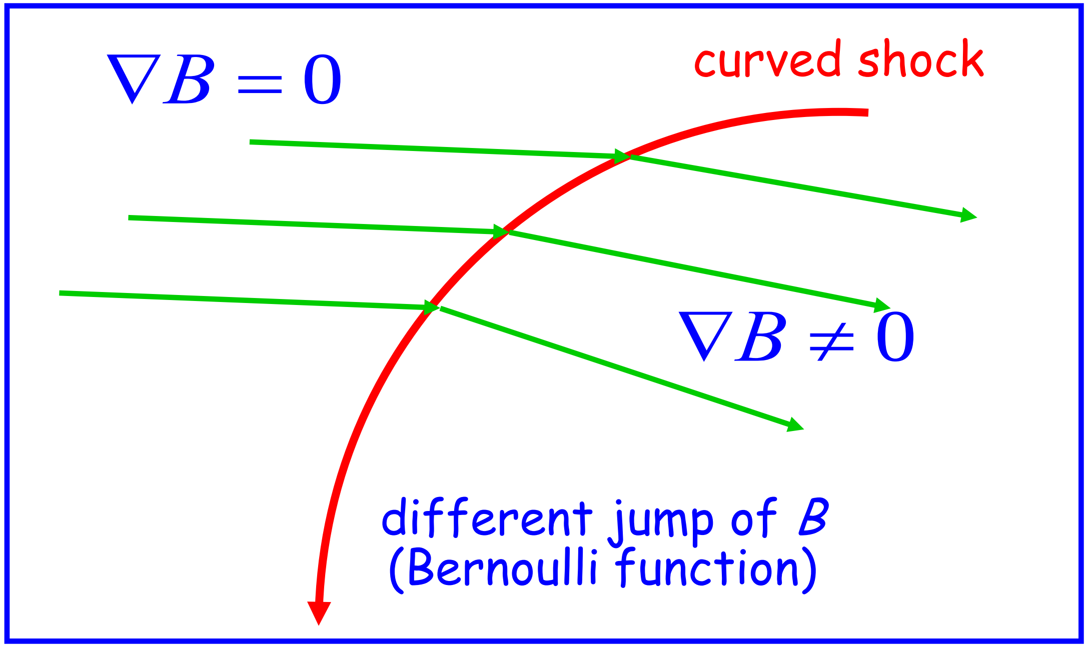
Adiabat: LCDM + DM + gas

NO GSM: Adiabat + cooling + heating

All: Adiabat + cooling + heating + feedbacks

Vorticity should have been generated at cosmological shocks

directly at curved shocks



⟹ at postshock

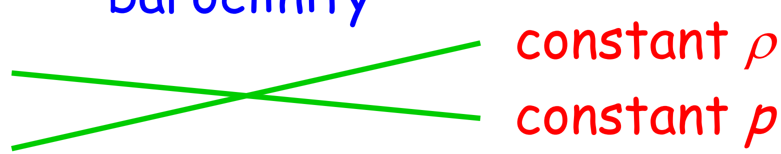
$$\varpi_{\rm cs} \sim \frac{(\rho_2 - \rho_1)^2}{\rho_2 \rho_1} \frac{\vec{U} \times \vec{n}}{R}$$

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

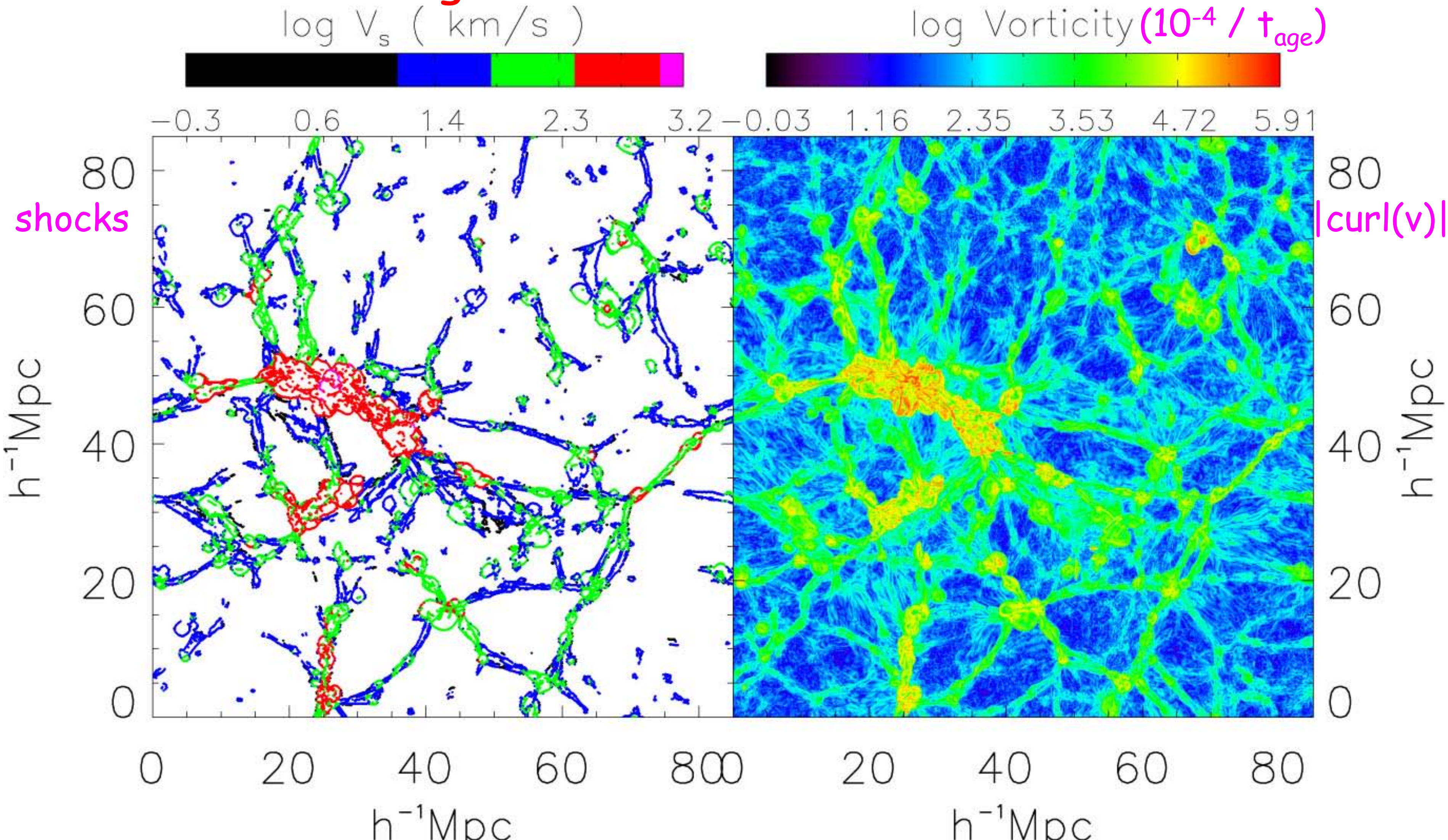
$$\dot{\varpi}_{\rm bc} = \frac{1}{\rho^2} \vec{\nabla}\rho \times \vec{\nabla} p$$

baroclinity



⟸ due to entropy variation induced at shocks

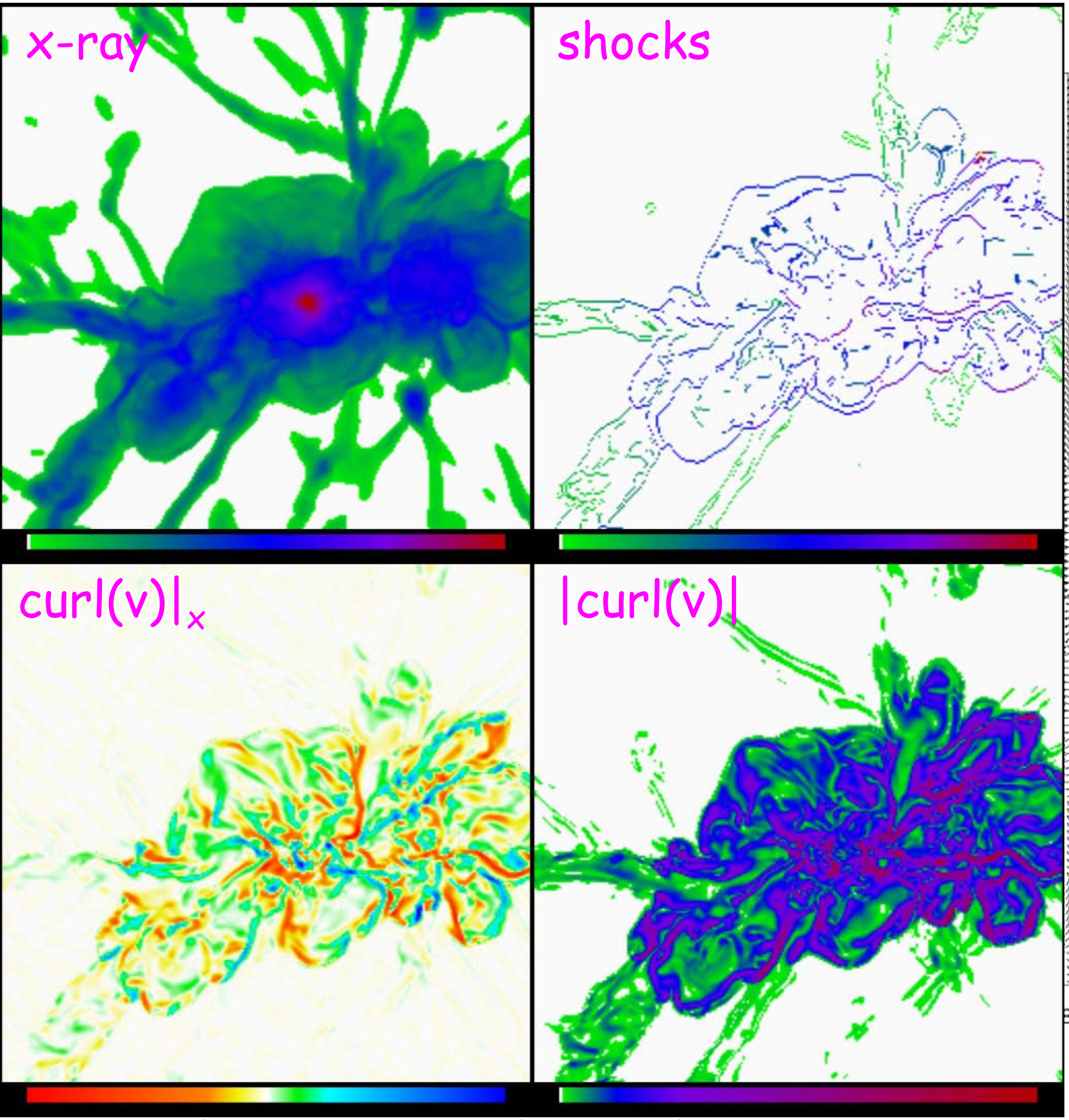
Spatial distribution of vorticity in the large scale structure of the universe



The distribution of vorticity follows the large scale structure of the universe

(Ryu, Kang, Cho, Das 2008)

Vorticity around a cluster complex



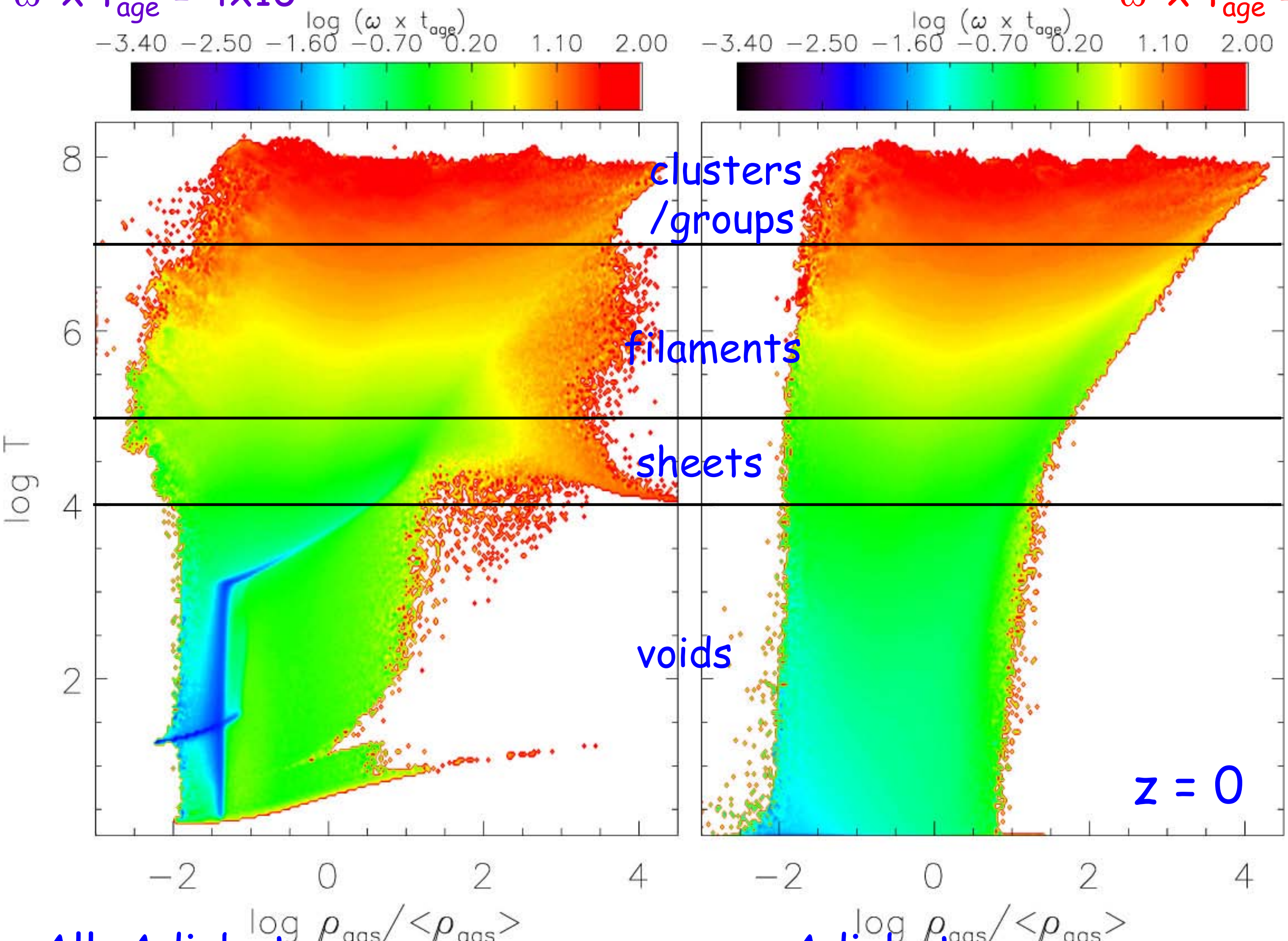
-1500 kms^{-1} / 300 kpc   1500 kms^{-1} / 300 kpc   6 kms^{-1} / 300 kpc   2000 kms^{-1} / 300 kpc

velocity field

(25 h^{-1}Mpc)^2 2D slice

Vorticity in the large scale structure of the universe

$\omega \times t_{age} = 4\text{x}10^{-4}$ $\omega \times t_{age} = 100$



$\omega \times t_{age}$

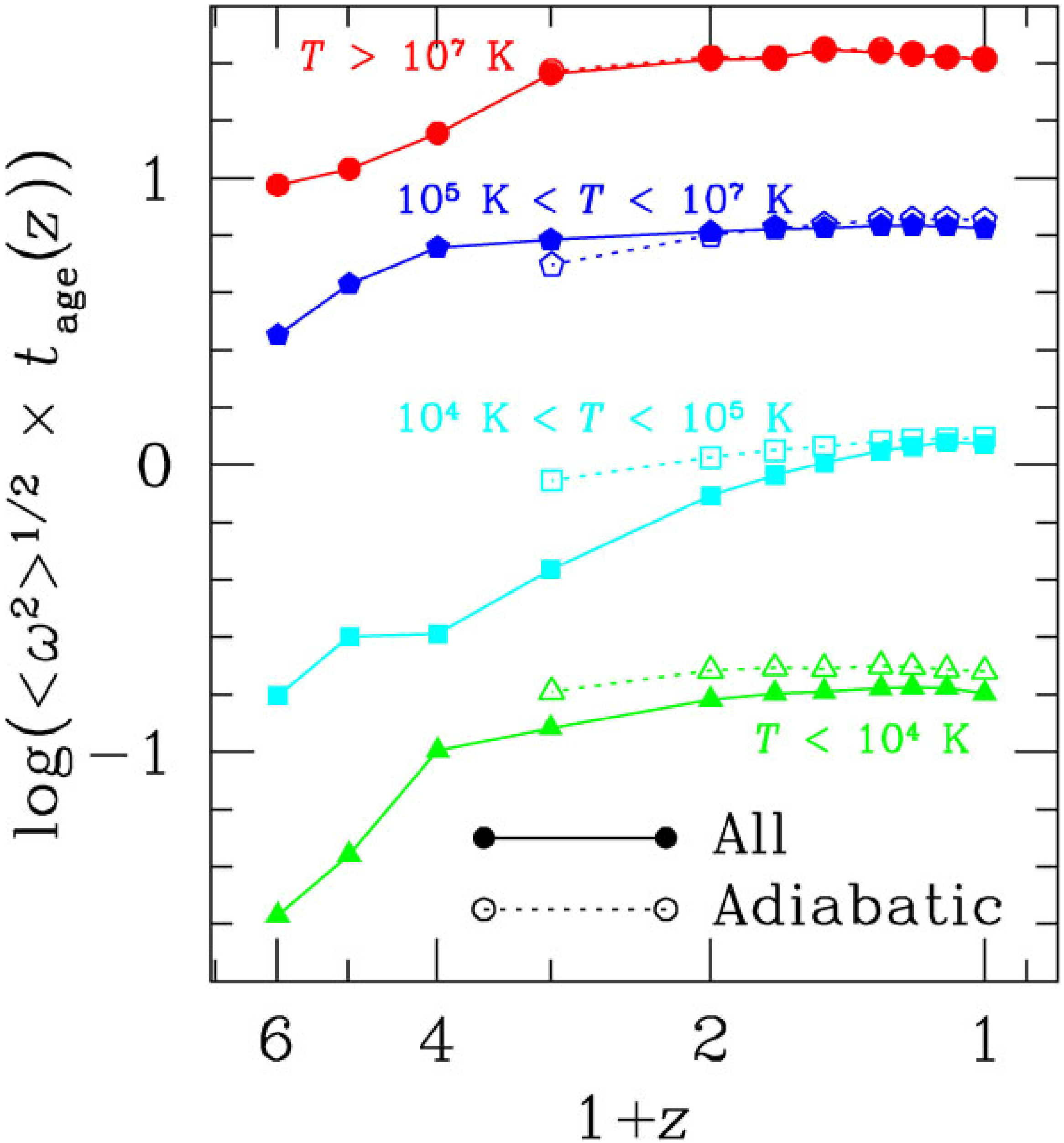
ω: |curl(v)|

t_{age}: age of the universe ($\sim 1.4\text{x}10^{10}$ yrs)

number of turnovers in the age of the universe

All: Adiabat
+ cooling + heating + feedbacks

Adiabat:
LCDM + DM + gas



- inside and around clusters/groups ($T > 10^7$ K):

  $\omega_{rms} * t_{age} \sim 25$

- in filaments (10^5 K < T < 10^7 K, or WHIM):

  $\omega_{rms} * t_{age} \sim 10$

- in sheets (10^4 K < T < 10^5 K):

  $\omega_{rms} * t_{age} \sim 1$

- in voids ($T < 10^4$ K):

  $\omega_{rms} * t_{age} \sim 0.1$

$\omega_{rms} \times t_{age}$
ω: |curl(v)|
t_{age}: age of the universe ($\sim 1.4 \times 10^{10}$ yrs)
number of turnovers in the age of the universe

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

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

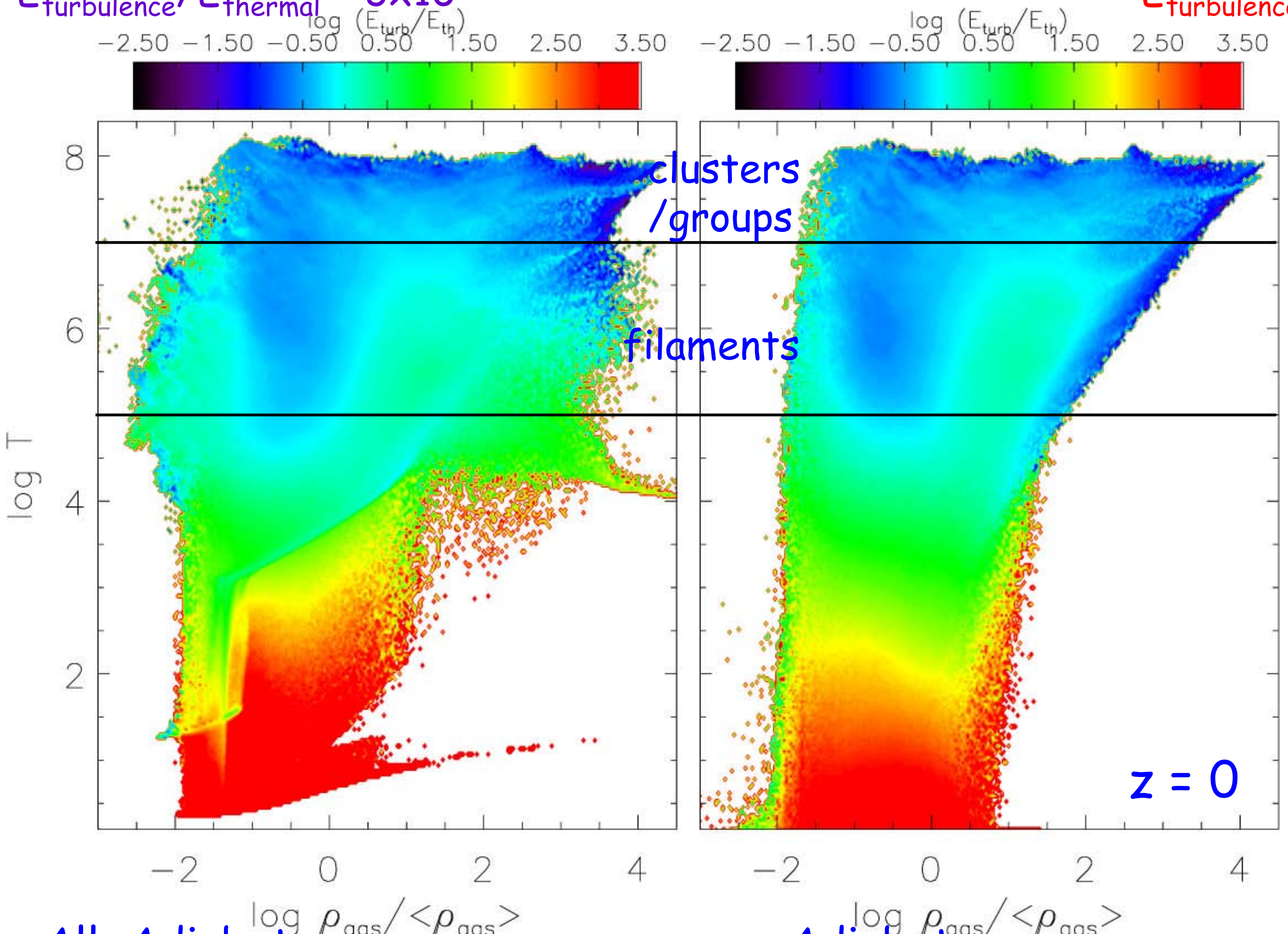
- inside clusters and around ($T > 10^7$ K): $\omega_{rms}{*}t_{age} \sim 25$
- in filaments (10^5 K < T < 10^7 K, or WHIM): $\omega_{rms}{*}t_{age} \sim 10$
- in sheets (10^4 K < T < 10^5 K, or lukewarm): $\omega_{rms}{*}t_{age} \sim 1$
- in voids ($T < 10^4$ K): $\omega_{rms}{*}t_{age} \sim 0.1$

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 turbulence in the intergalactic medium

$E_{turbulence}/E_{thermal} = 3\times10^{-3}$

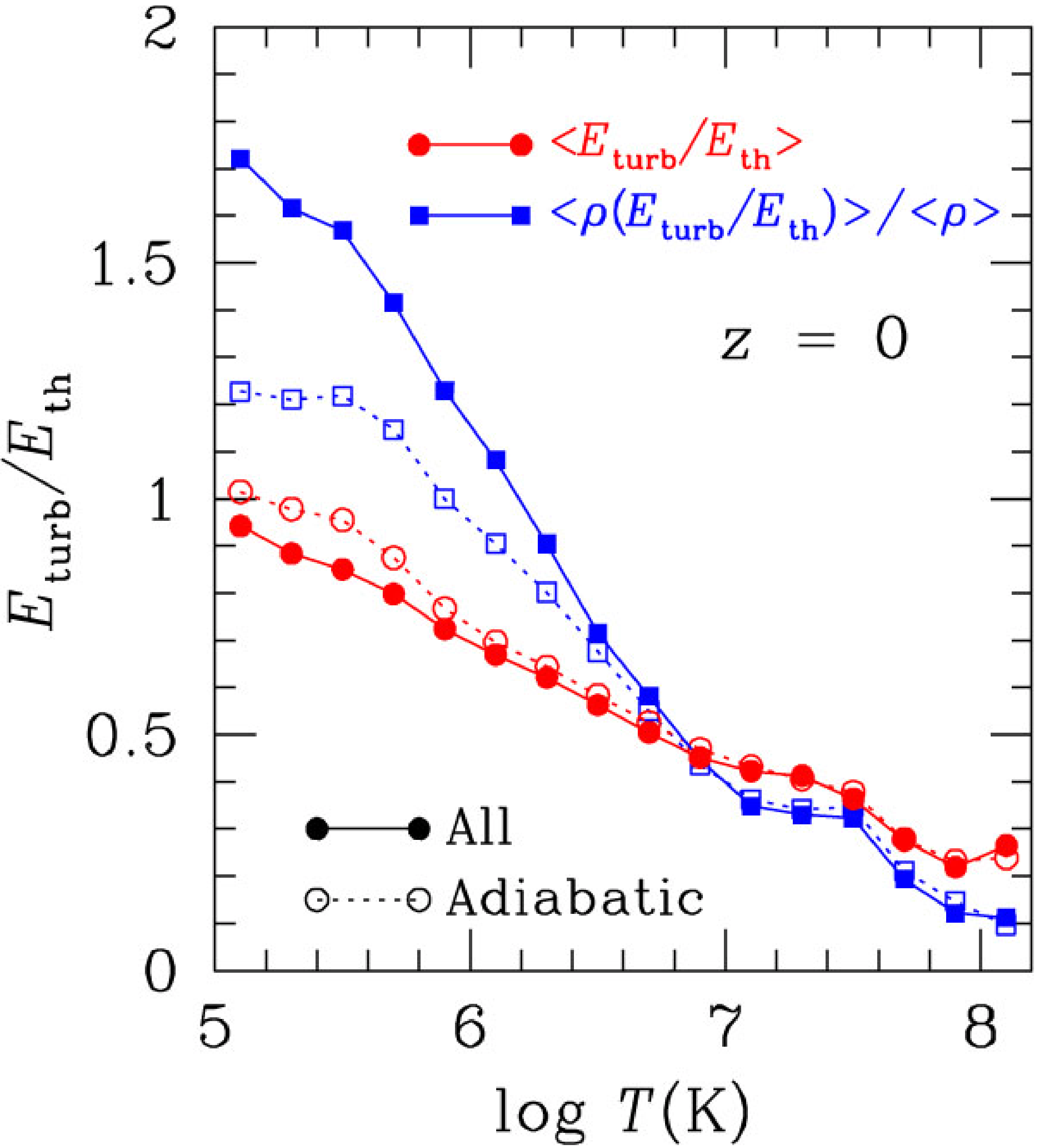
$E_{turbulence}/E_{thermal} = 3\times10^{3}$



assuming that the energy in vortical motions transfers to the energy of turbulence

All: Adiabat
+ cooling + heating + feedbacks

Adiabat:
LCDM + DM + gas



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

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

Magnetic fields in the intergalactic medium

Origin of seeds for comic magnetic fields is uncertain.

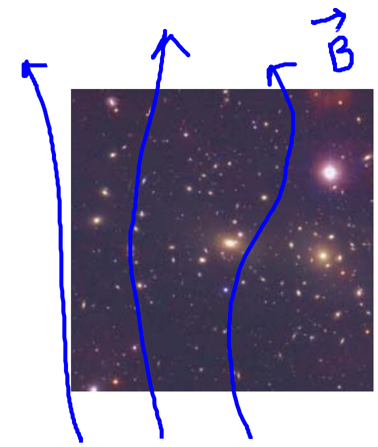
some suggestions:

1. generation in the early universe
   e.g.) during the electroweak phase transition (t~10^{-12}sec)?
   during the quark-hadron transition (t~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

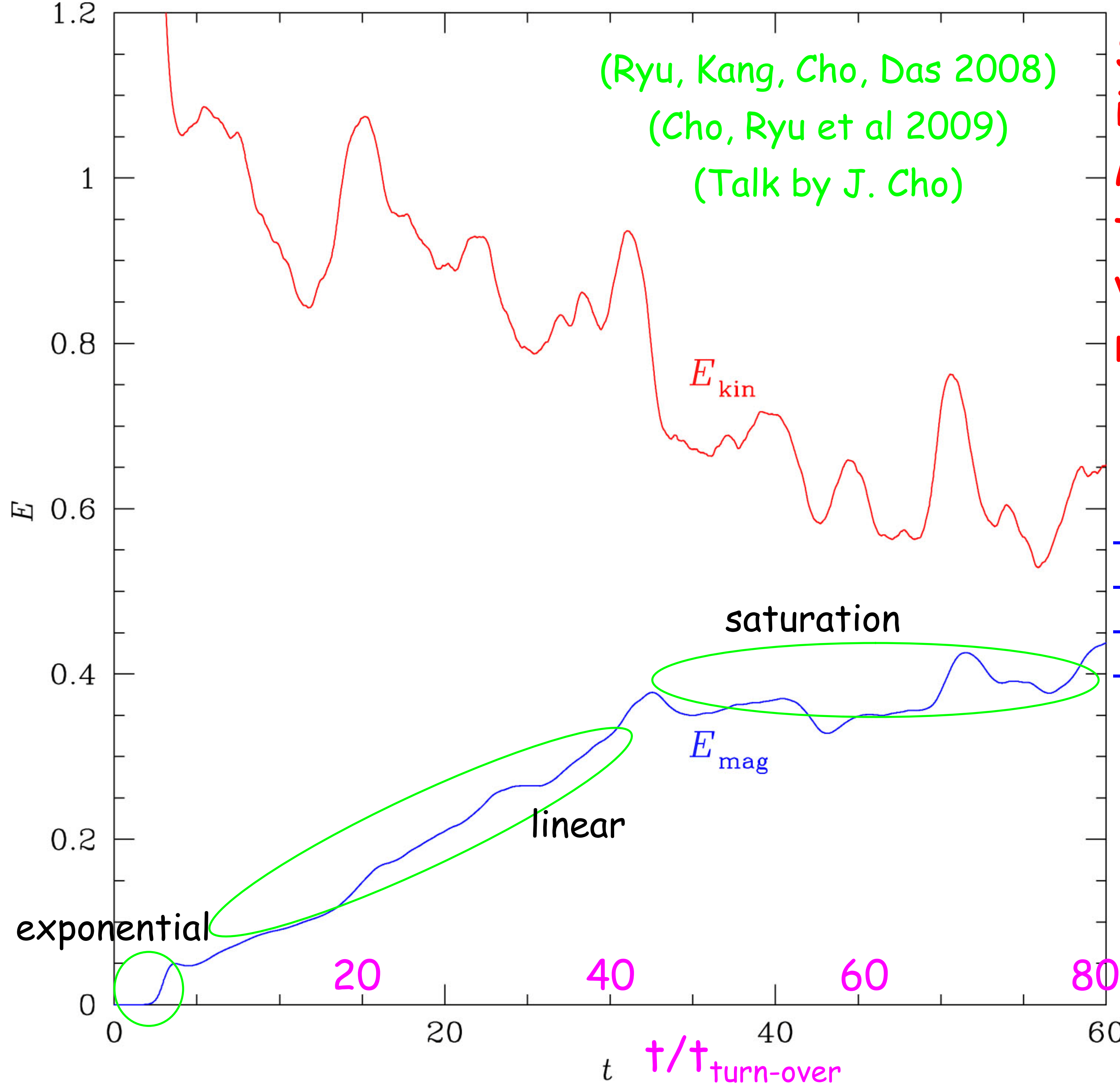
very weak B field before structure formation

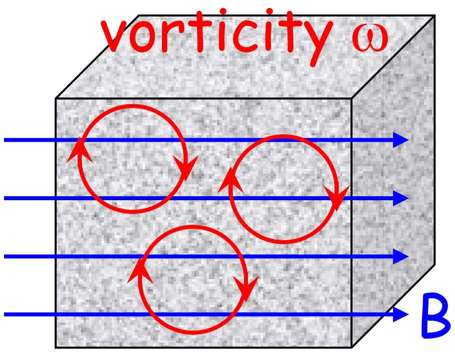


turbulence amplifies magnetic fields

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

Simulation of incompressible MHD turbulence with very weak regular field



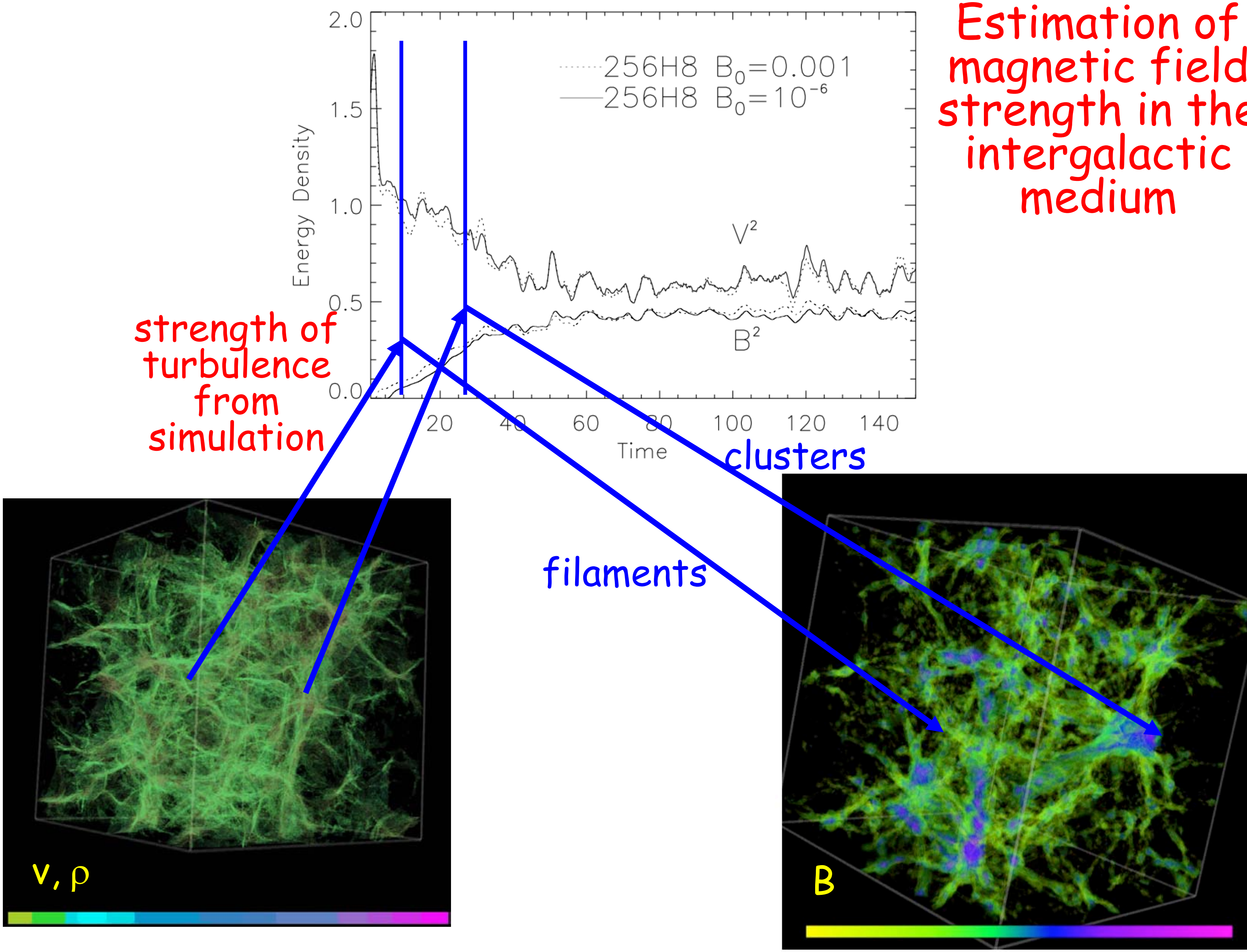


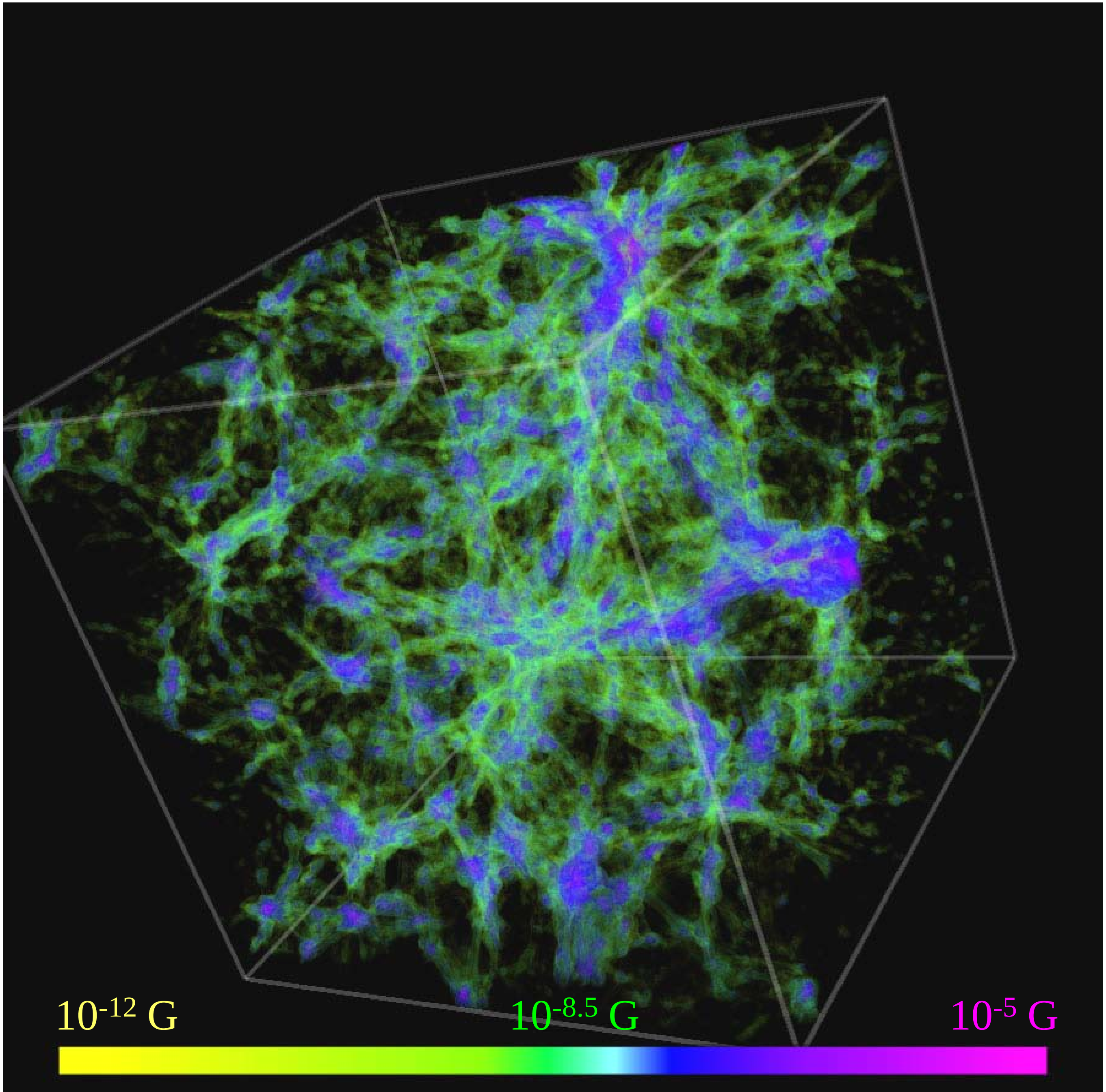
$E_{mag} \sim 2/3\ E_{kin}$

at saturation

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

Estimation of magnetic field strength in the intergalactic medium



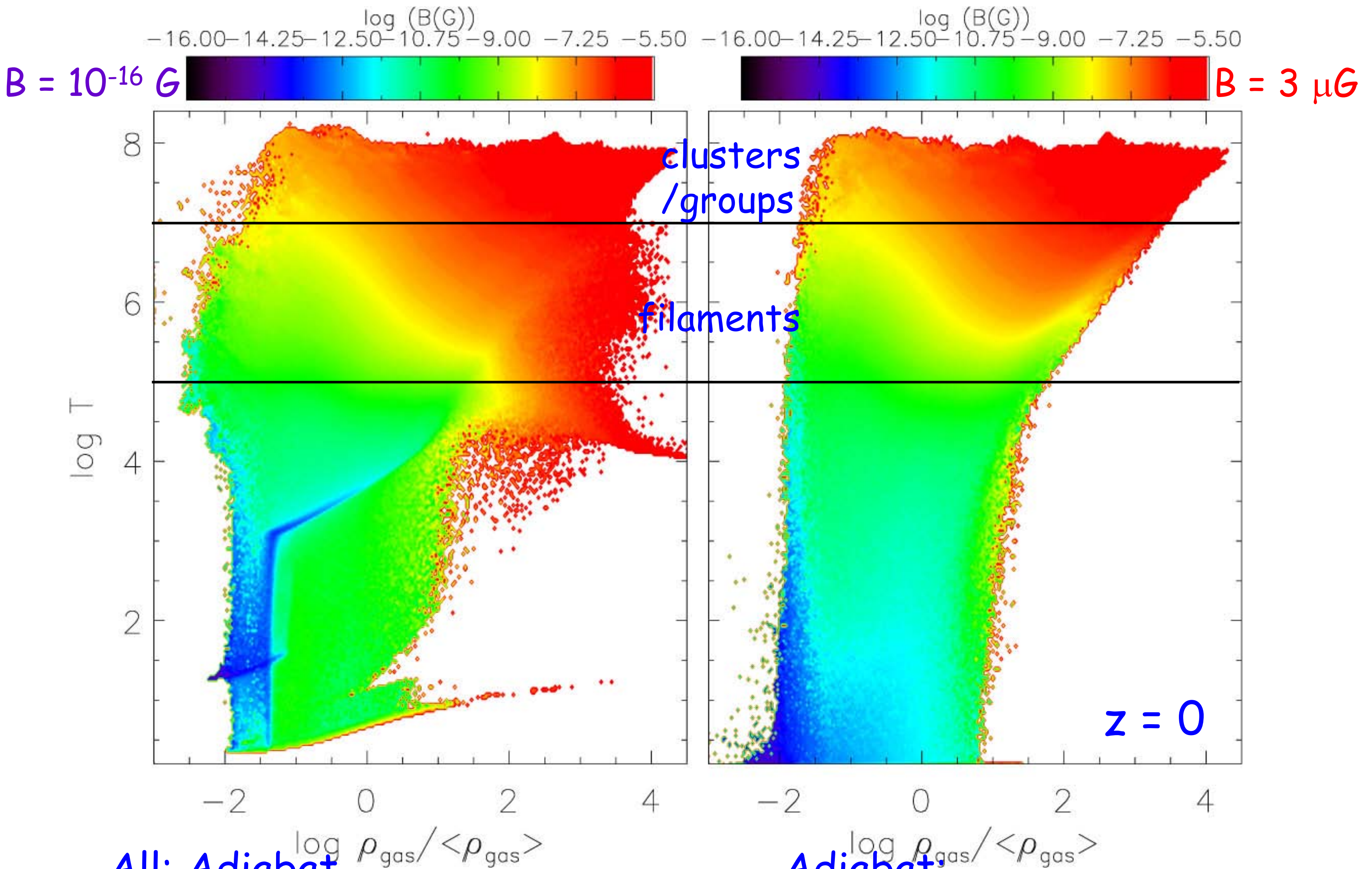


3D distribution of magnetic field strength in (100 h^{-1} Mpc)^3 box: concentrated in clusters and groups along filaments

-> "cosmic web of filaments"

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

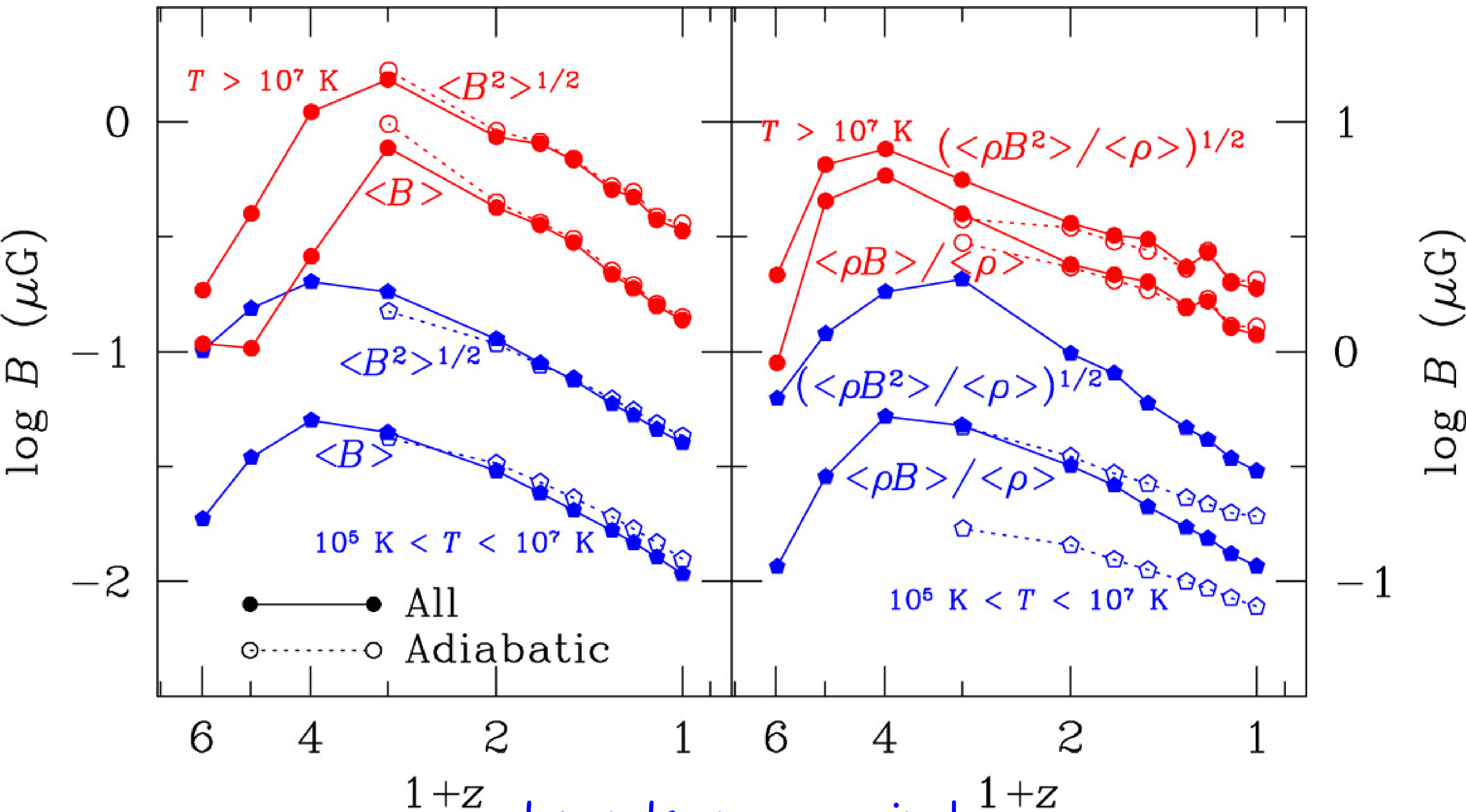
Magnetic field strength in the large scale structure of the universe



All: Adiabat
+ cooling + heating + feedbacks

Adiabat:
LCDM + DM + gas

Averaged magnetic field strength as a function of time



depends on averaging!

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

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

-> relevant to synchrotron emission

$\langle (\rho B)^2 \rangle^{1/2} / \langle \rho^2 \rangle^{1/2} \sim 1\ \mu$G

-> relevant to Faraday rotational measure

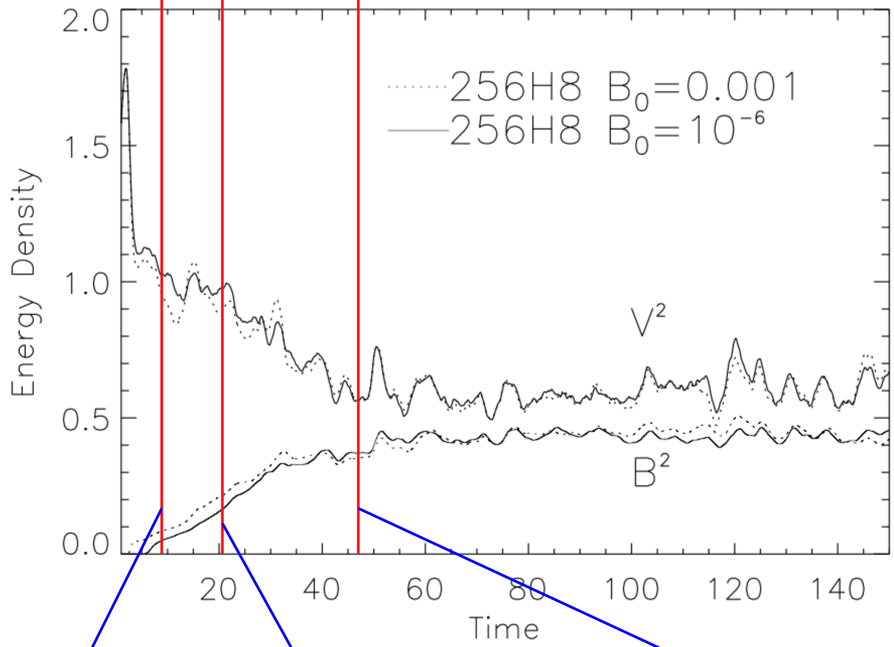
our model -> a minimal model

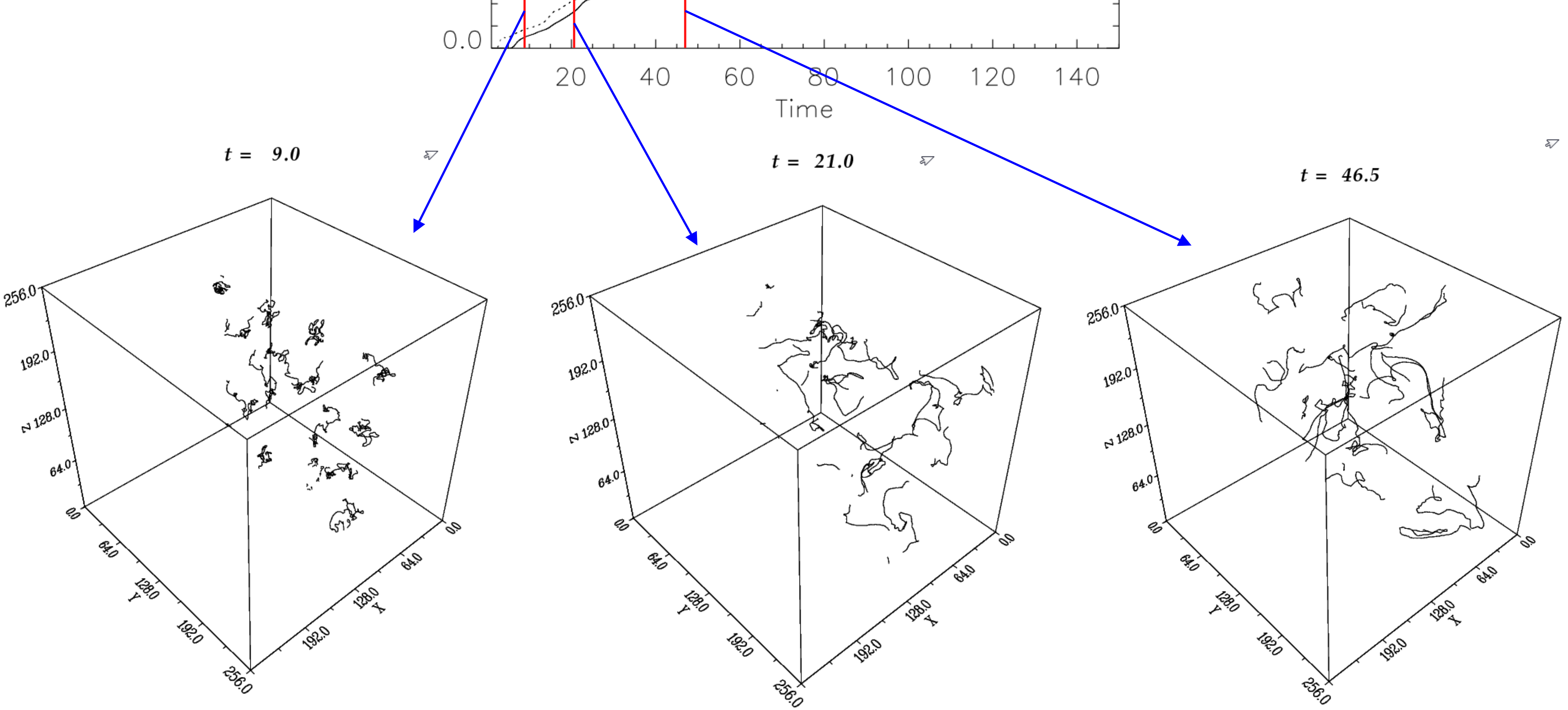
other processes such as AGN feedbacks would increase the predicted strength of the IGMF

Characteristic lengths of the IGMF?

(Cho & Ryu 2009)

(talk by J. Cho)





in the intracluster medium,

the injection scale ~ 100 kpc

(density scale height)

-> characteristic length scales ~ a few x 10 kpc

in filaments,

the injection scale ~ a few Mpc

(radius of filaments)

-> characteristic length scales ~ a few x 100 kpc

Faraday rotation measure

$$\sigma_{\rm RM} = 0.81\, n_e \left\langle B_{\parallel}^2 \right\rangle^{1/2} l \left(\frac{L_{\rm path\,length}}{l} \right)^{1/2}$$

coherence length

$$l = \frac{3}{4} L_{\rm int}$$

~ a few x 10 kpc in the ICM

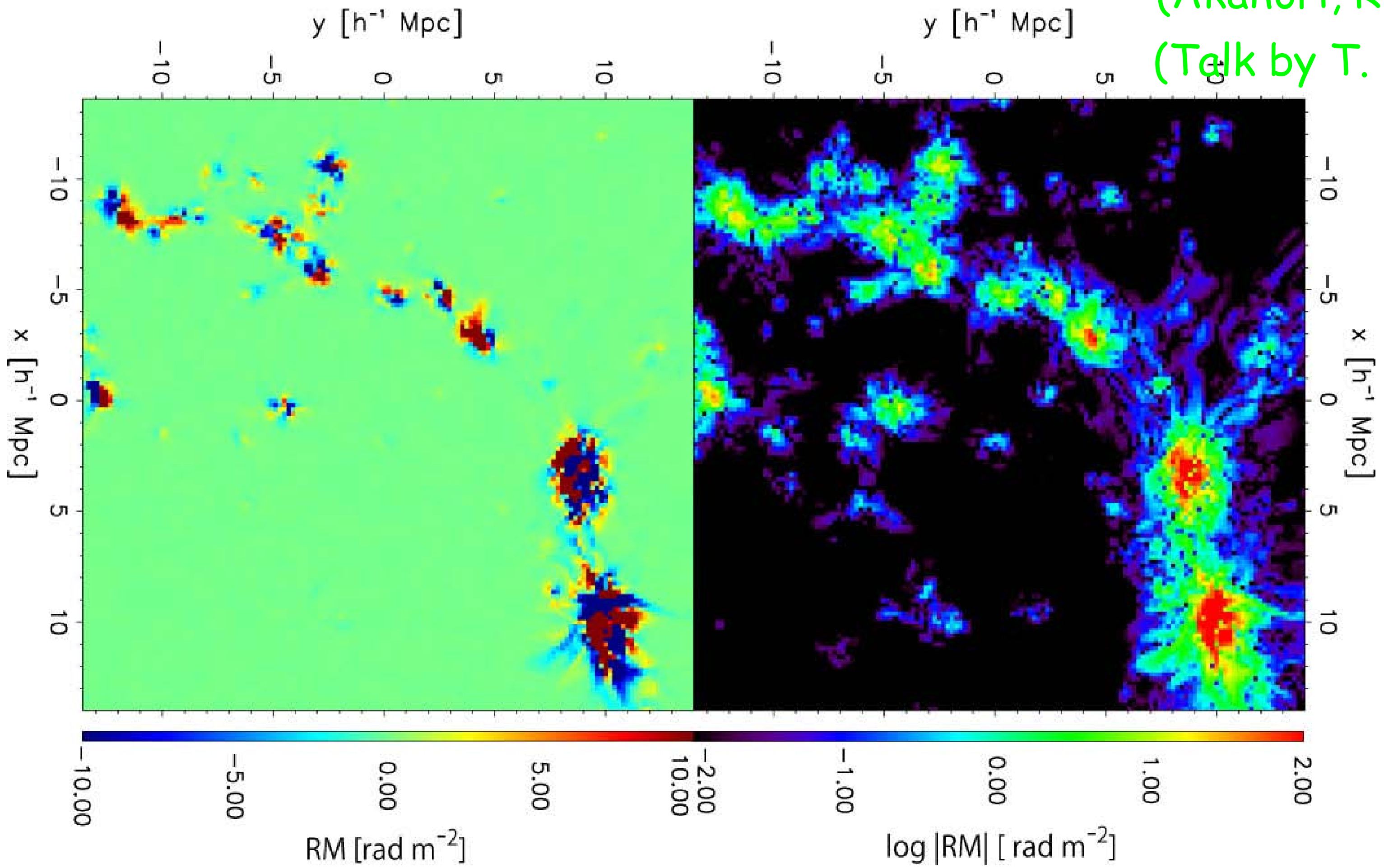
~ a few x 100 kpc in filaments

Astrophysical implications of the IGMF?

Faraday rotational measure (RM) due to the IGMF

(Akahori, Ryu 2010)

(Talk by T. Akahori)



our model IGMF predicts

- RM ~ a few x 100 rad m^{-2} through clusters (resolution affected)
- RM ~ 1 rad m^{-2} through filaments

Synchrotron from the intergalactic magnetic field and cosmic rays

Cosmic rays accelerated at cosmological shocks

key ideas behind DSA (diffusive shock acceleration)

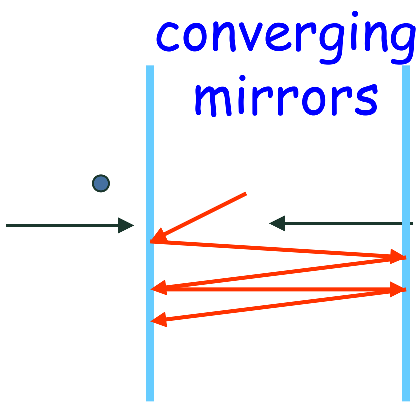
- Alfven waves in a converging flow act as converging mirrors

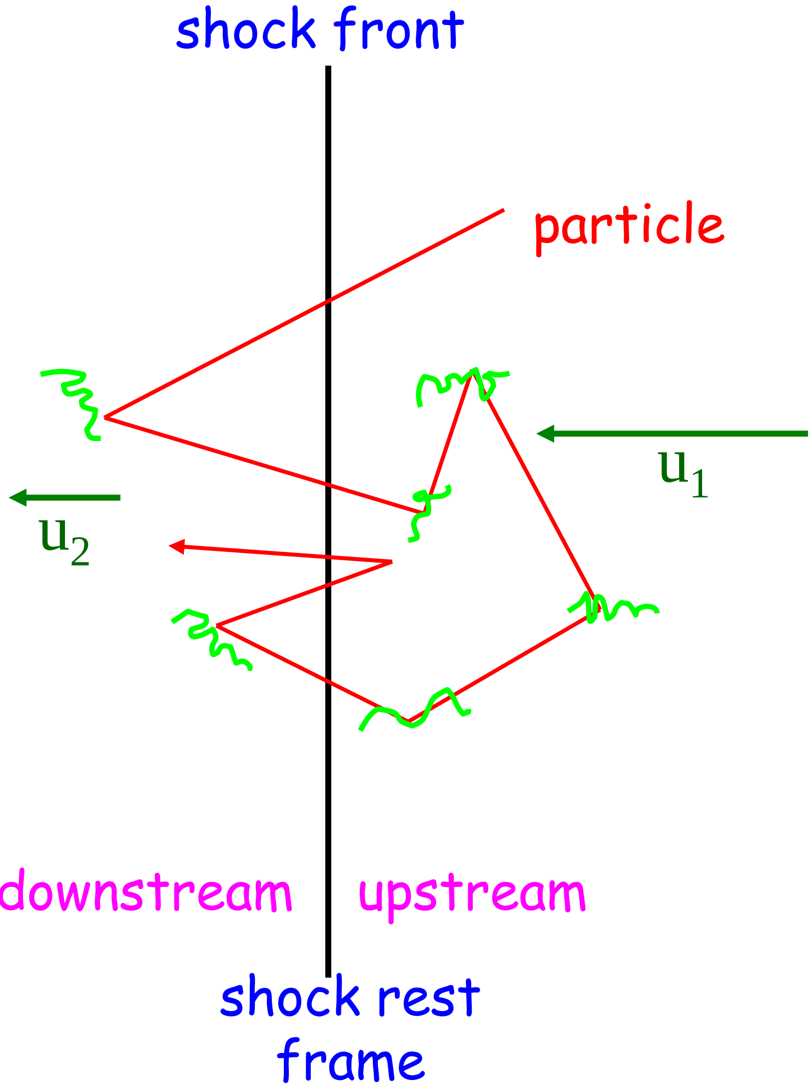
→ particles are scattered by waves

→ cross the shock many times

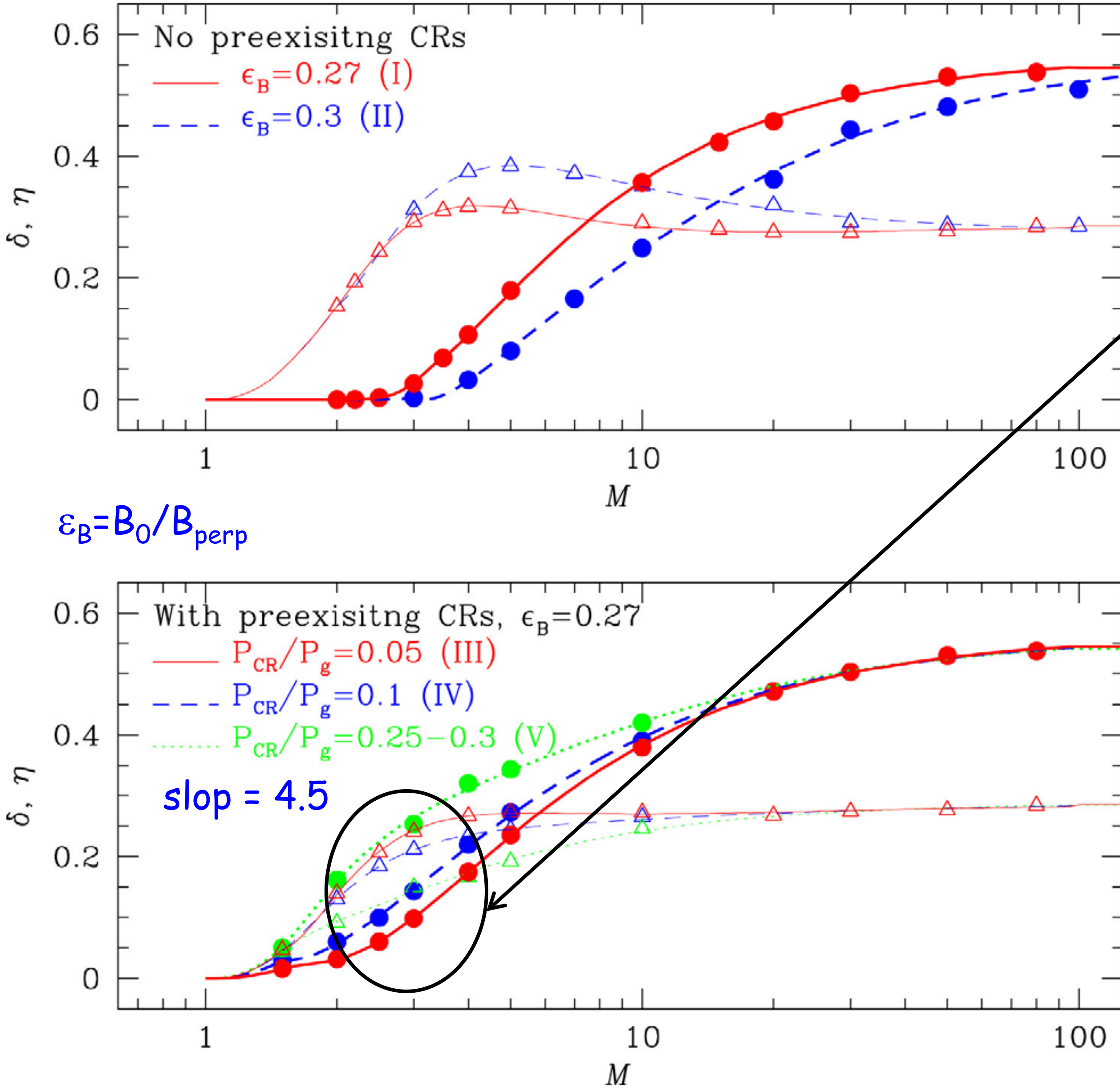
"Fermi first order process"

$$\frac{\Delta p}{p} \sim \frac{|\Delta u|}{u}$$ energy gain at each crossing





(Ma, Kang, Ryu in preparation)



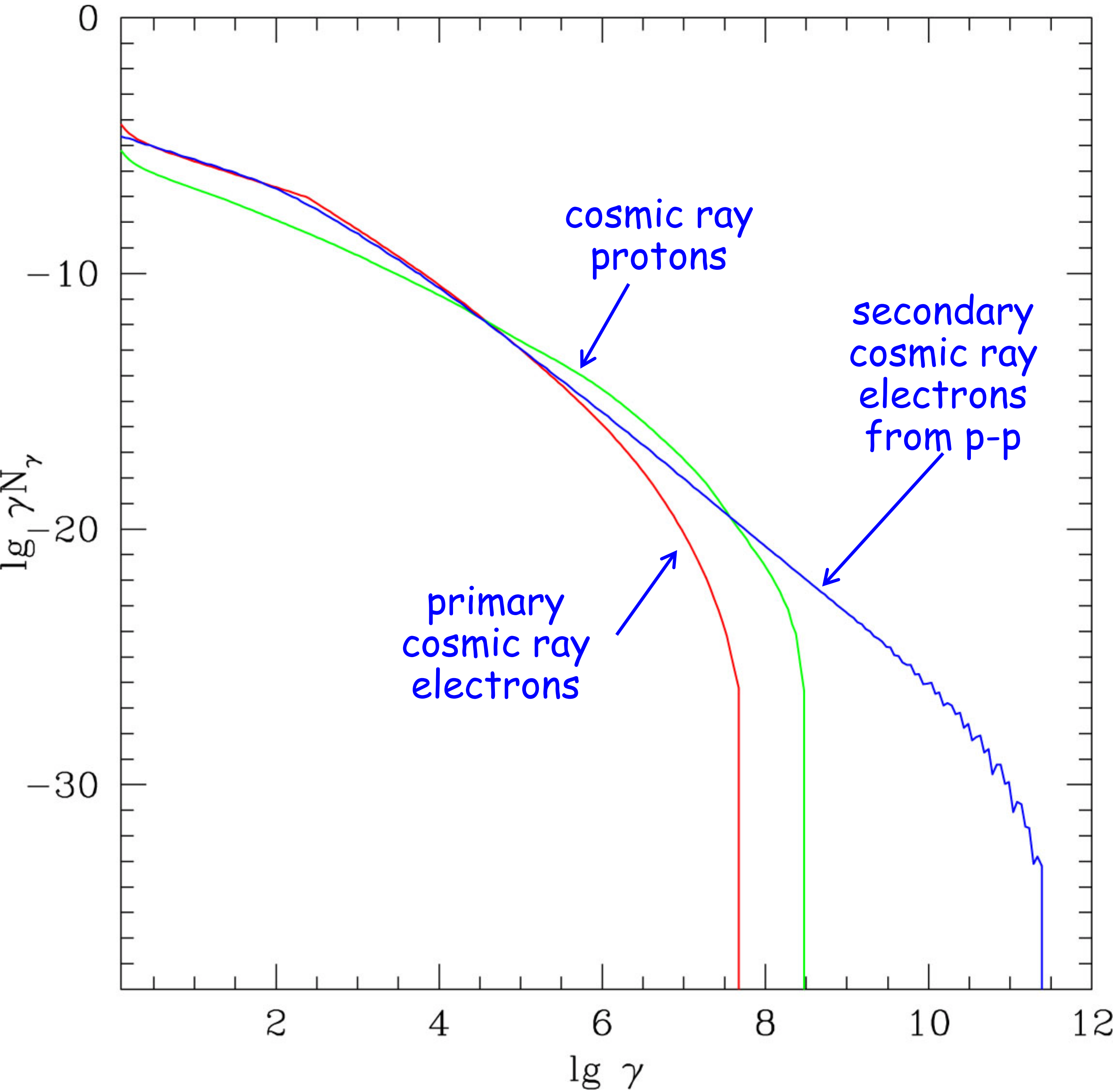
- most relevant to shocks in clusters

- however, the physics of weak shocks are not well understood

- on the top of it, shocks with pre-existing CRs have not studied so far

thermalization efficiency: d(M)

CR acceleration efficiency: h(M) for quasi-parallel shocks

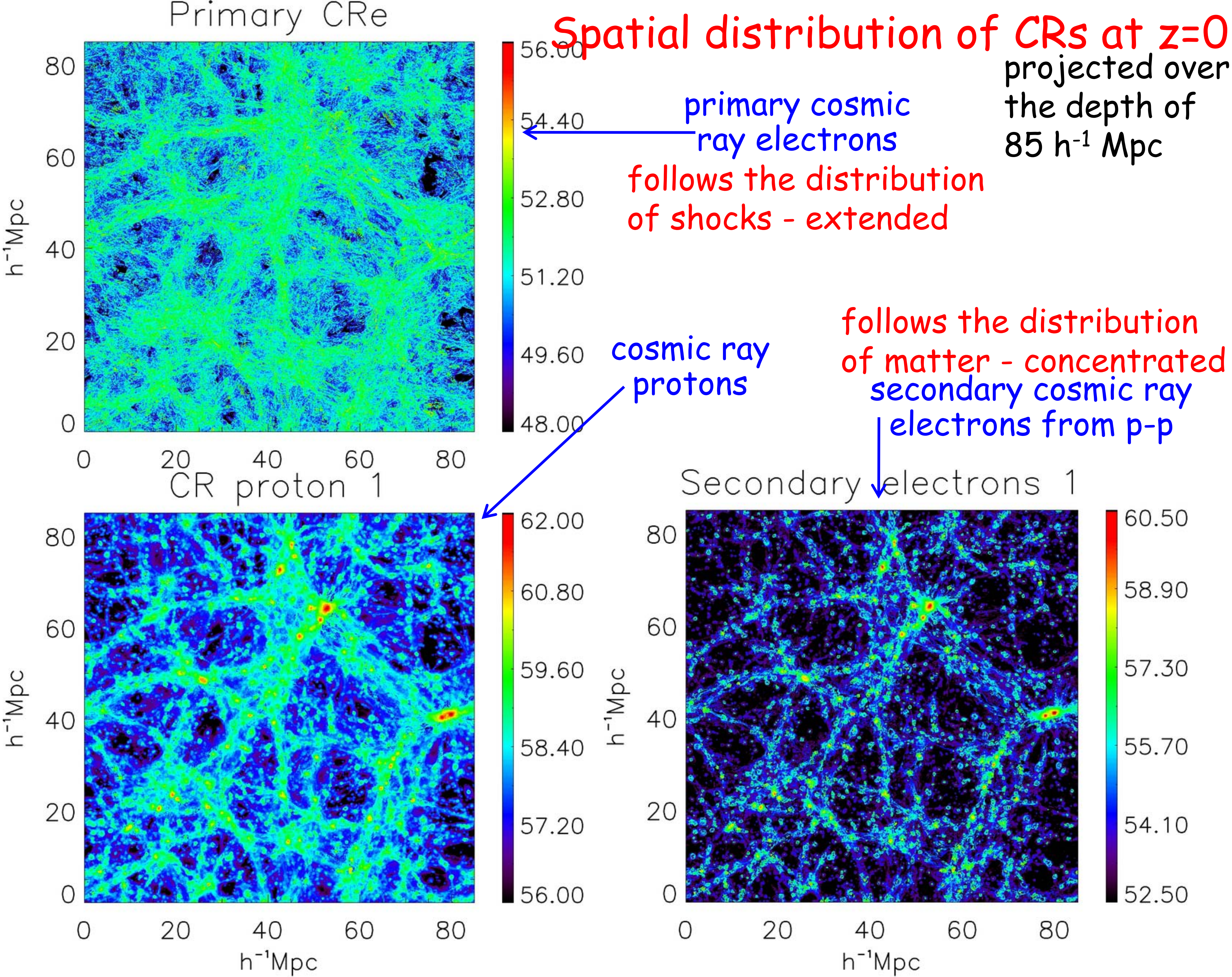


Resulting spectrum of CRs

the ratio of E_{CRe}/E_{CRp} at shocks is arbitrary in this plot

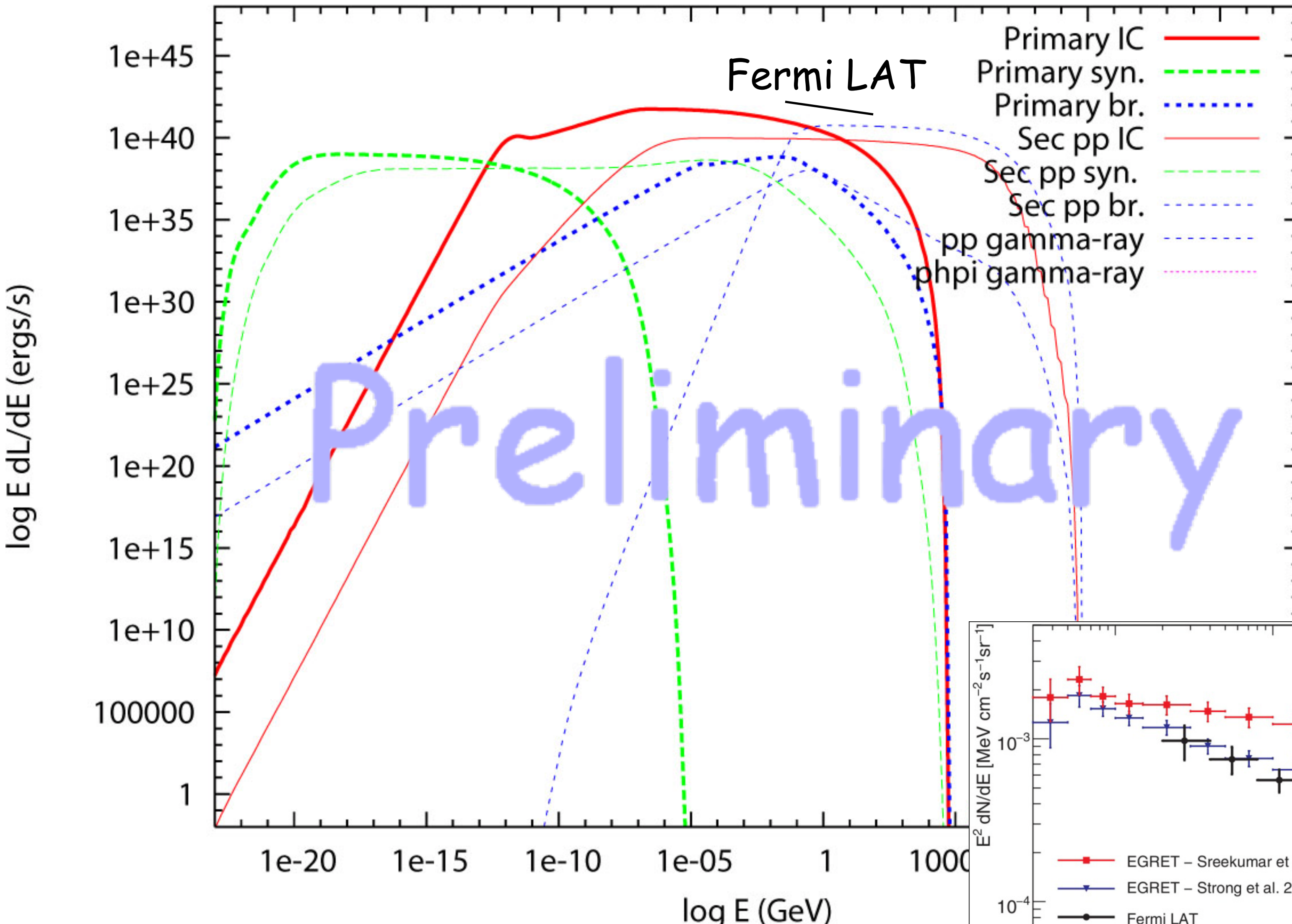
Spatial distribution of CRs at z=0

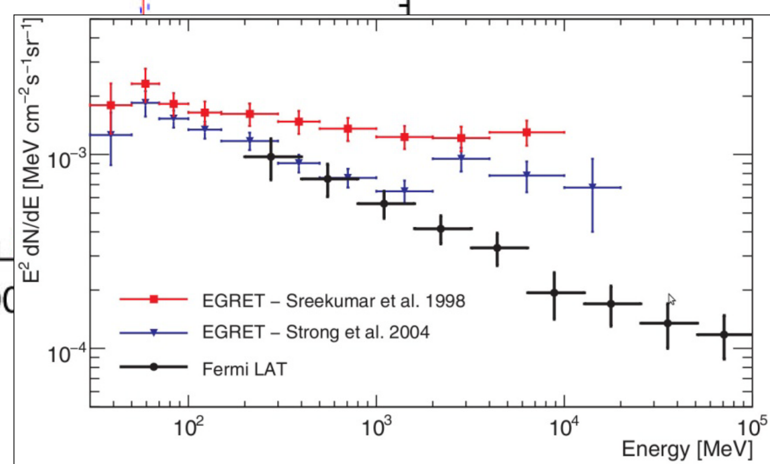
projected over the depth of 85 h^{-1} Mpc

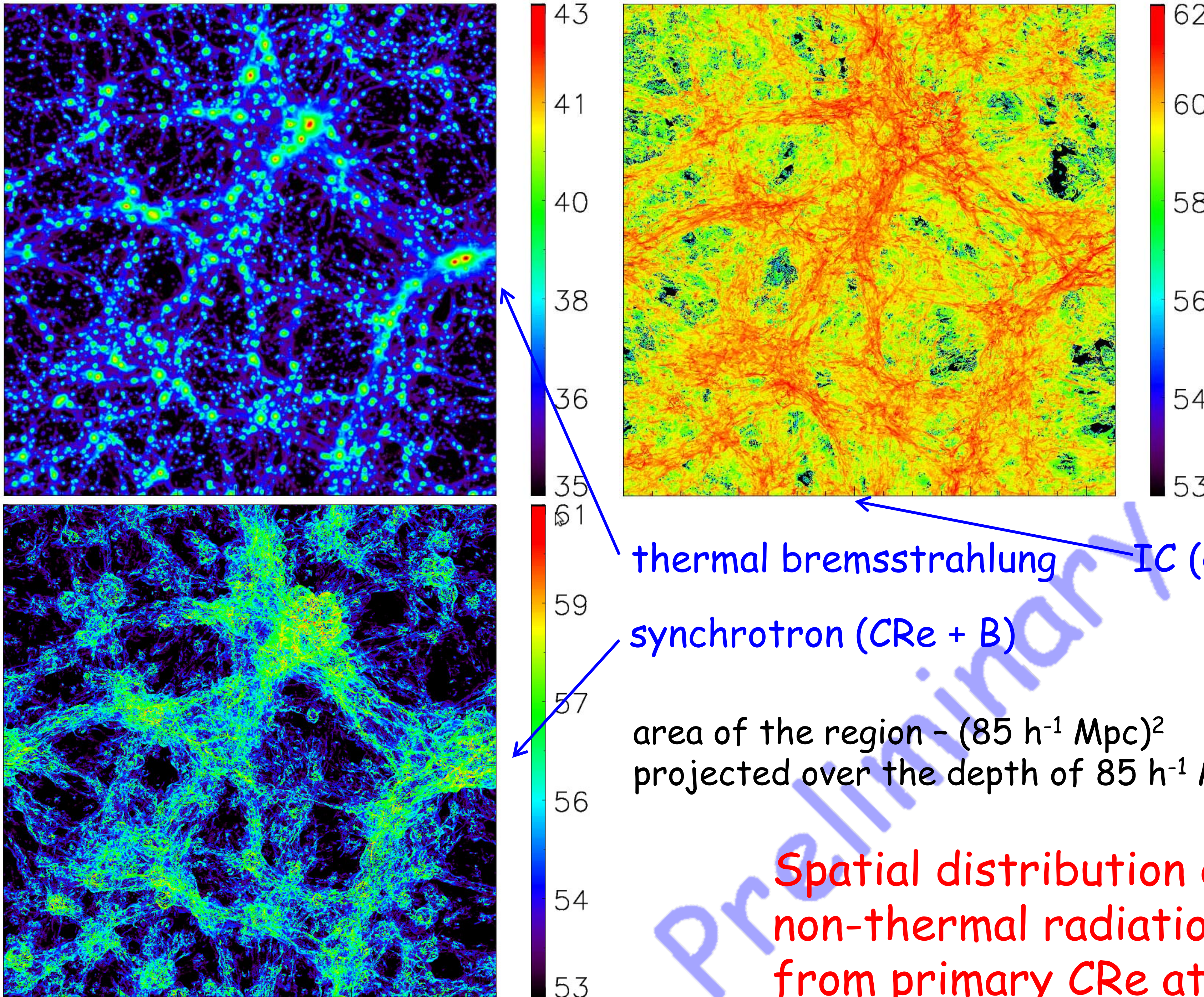


Nonthermal radiation from the intergalactic CRs

$E_{prim\ CRe}/E_{second\ CRe} \sim 5$







thermal bremsstrahlung

IC (CRe)

synchrotron (CRe + B)

area of the region – (85 h^{-1} Mpc)^2
projected over the depth of 85 h^{-1} Mpc

Spatial distribution of non-thermal radiations from primary CRe at z=0

Thank you !