Properties and Roles of Shock Waves in the LSS of the Universe

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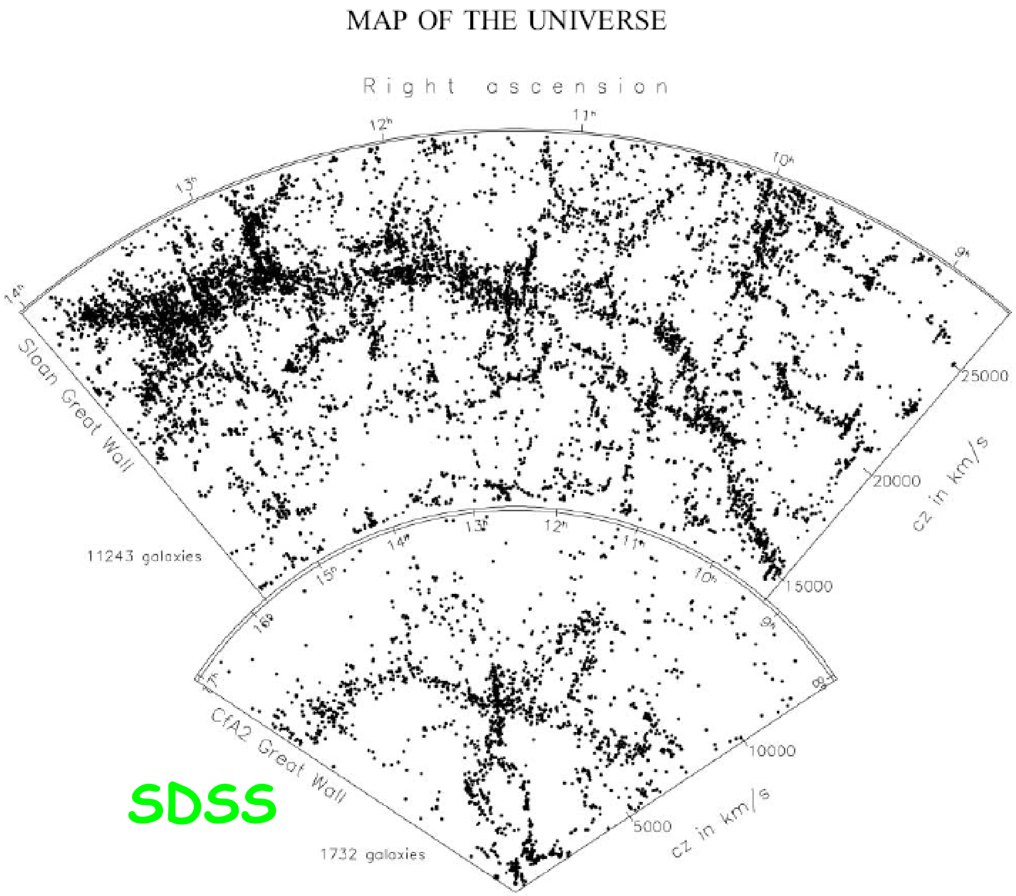
and Collaborators

- Statistics and energetics of shocks
- Cosmic rays acceleration at shocks
- Generation of vorticity at shocks
  -> developed into turbulence

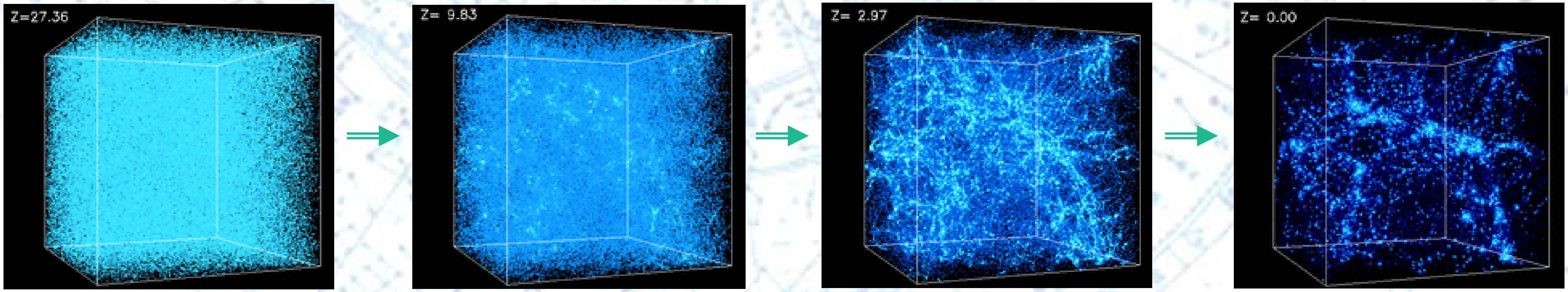
(Generation of magnetic field at shocks)



SDSS

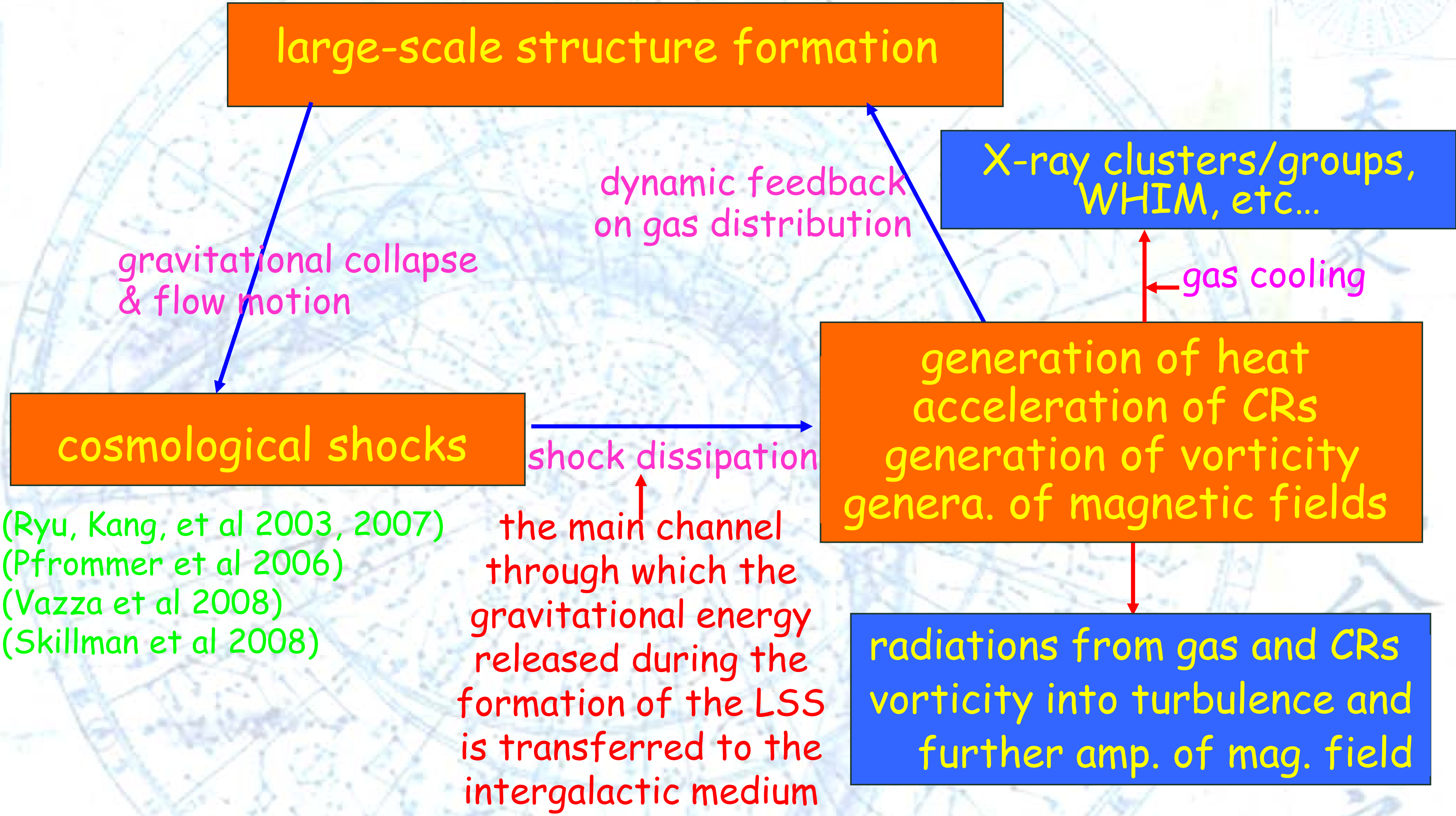
The large-scale structure of the universe seen in the galaxy distribution

"cosmic web of filaments"



growth of density perturbations via gravitational instability

Overveiw of large-scale structure formation



large-scale structure formation

gravitational collapse
& flow motion

cosmological shocks

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

shock dissipation

the main channel
through which the
gravitational energy
released during the
formation of the LSS
is transferred to the
intergalactic medium

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

dynamic feedback
on gas distribution

gas cooling

X-ray clusters/groups,
WHIM, etc…

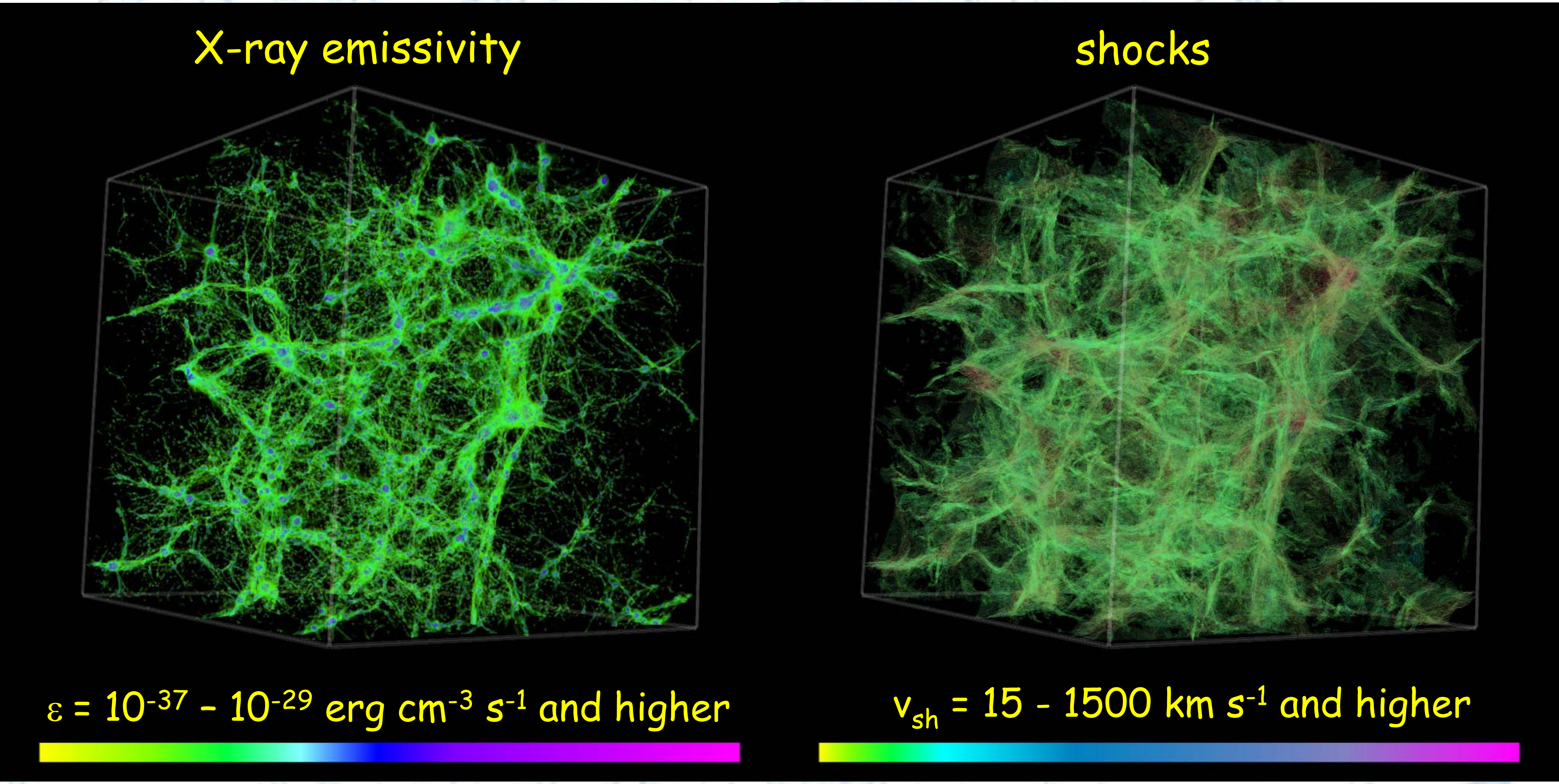
radiations from gas and CRs
vorticity into turbulence and
further amp. of mag. field

other sources of heat, CRs,
turbulence and magnetic field

Cosmological shock waves in a ΛCDM universe

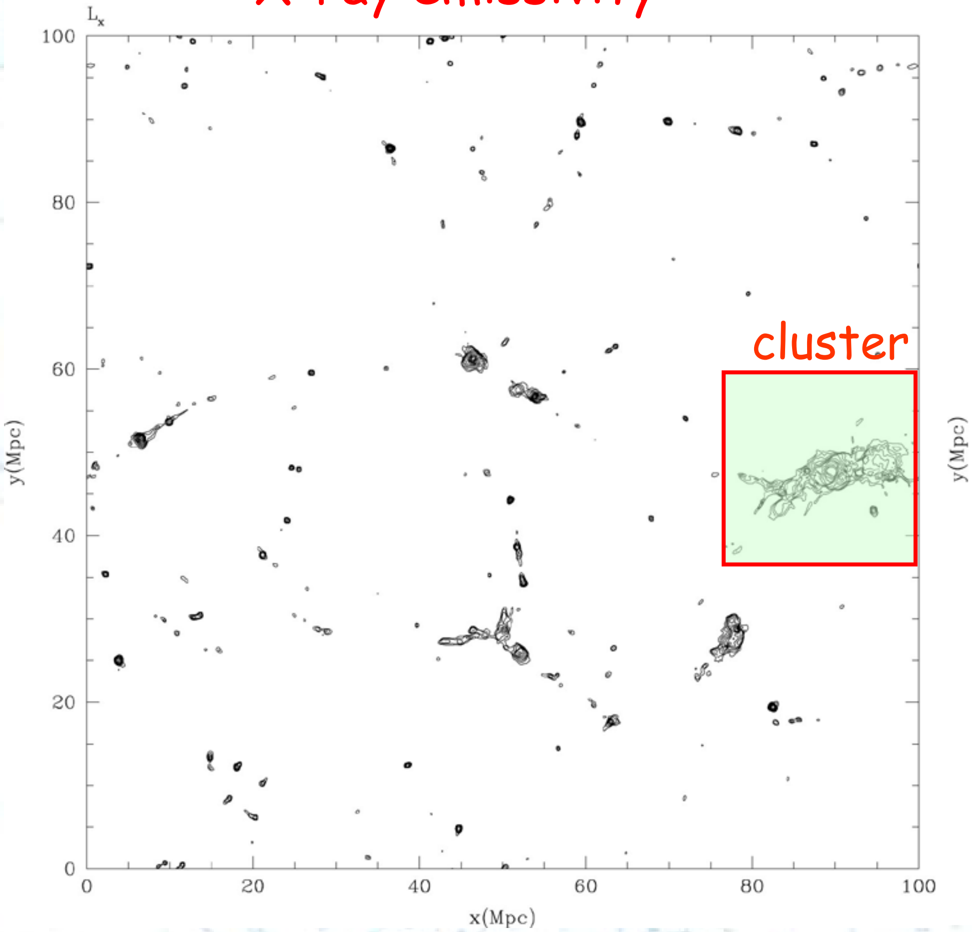
$(\Omega_\Lambda = 0.73,\ \Omega_{DM} = 0.27,\ \Omega_{gas} = 0.043,\ h = 0.7,\ n = 1,\ \sigma_8 = 0.8)$

(Ryu, Kang, et al 2003)

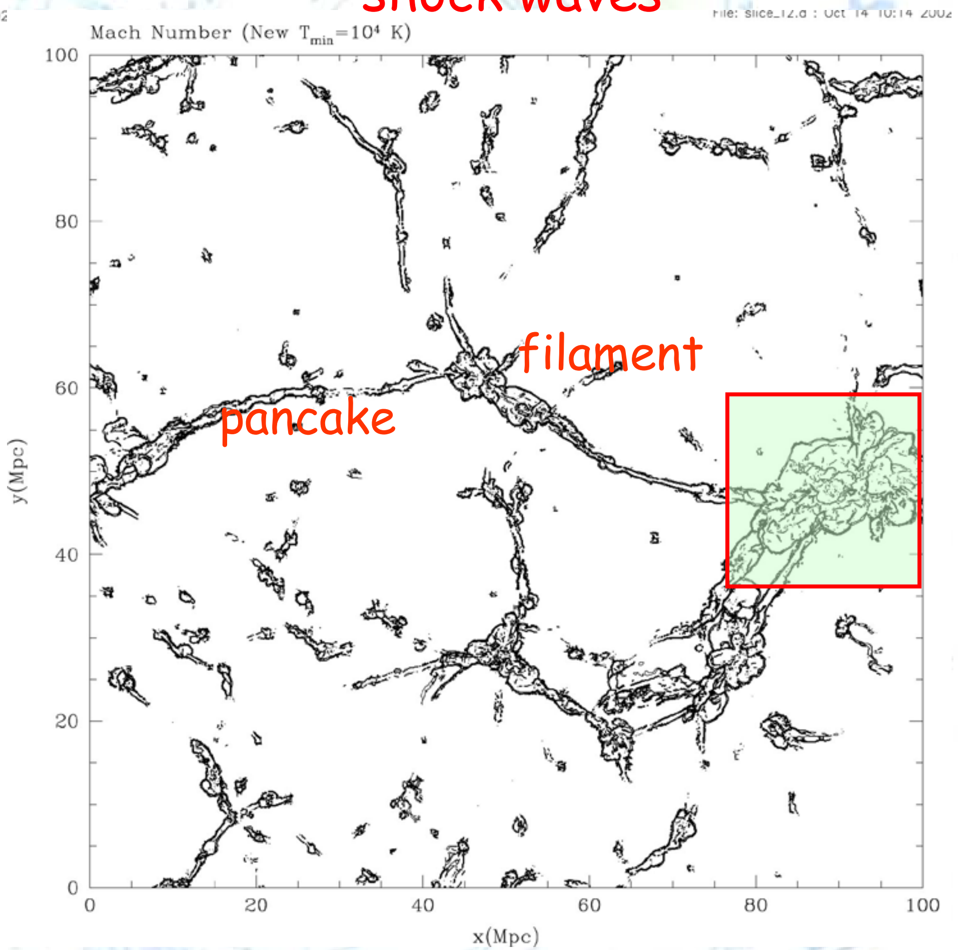


Spatial distribution of cosmological shocks in the large-scale structure of the universe

X-ray emissivity

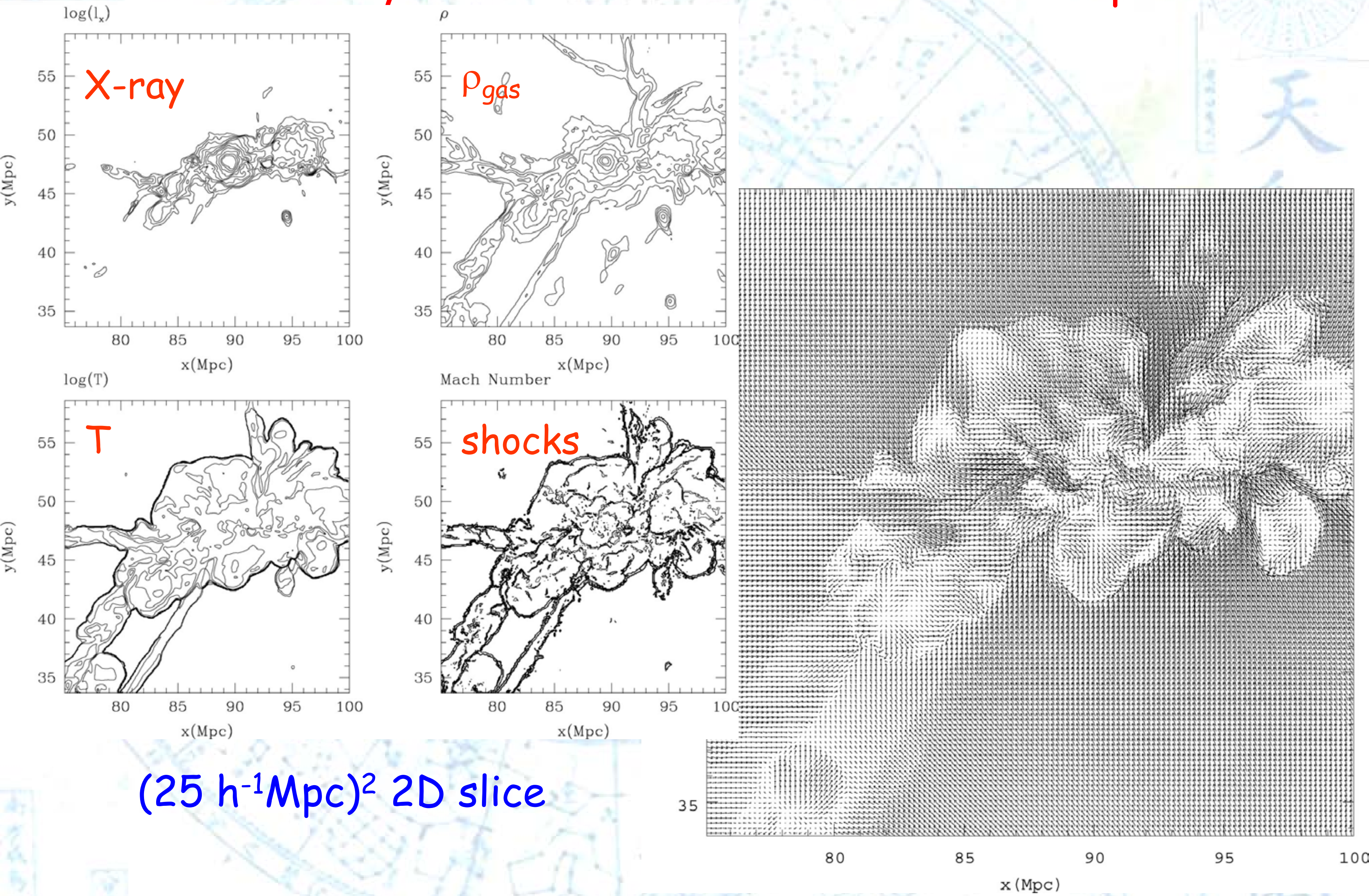


shock waves



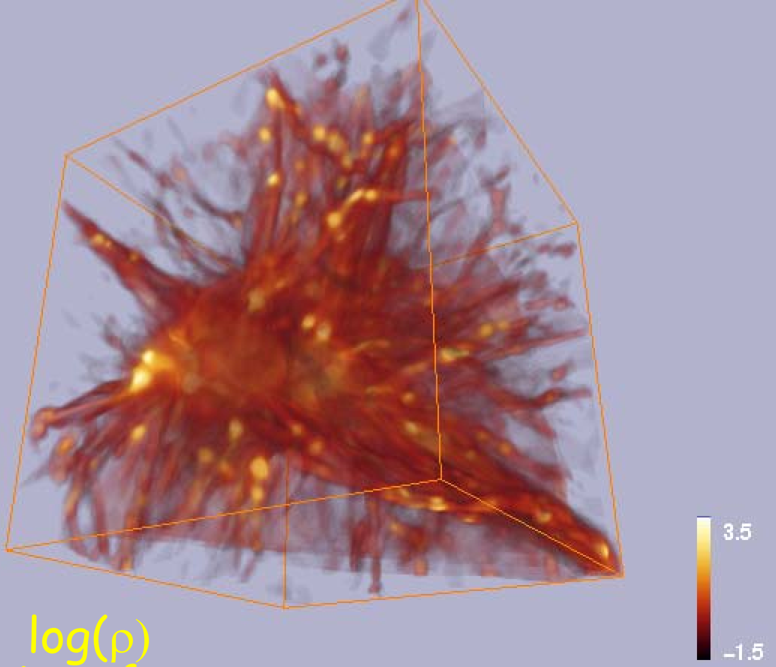
rich, complex shock morphology:
shocks “reveal” filaments and sheets (low density gas)

Velocity field and shocks in a cluster complex

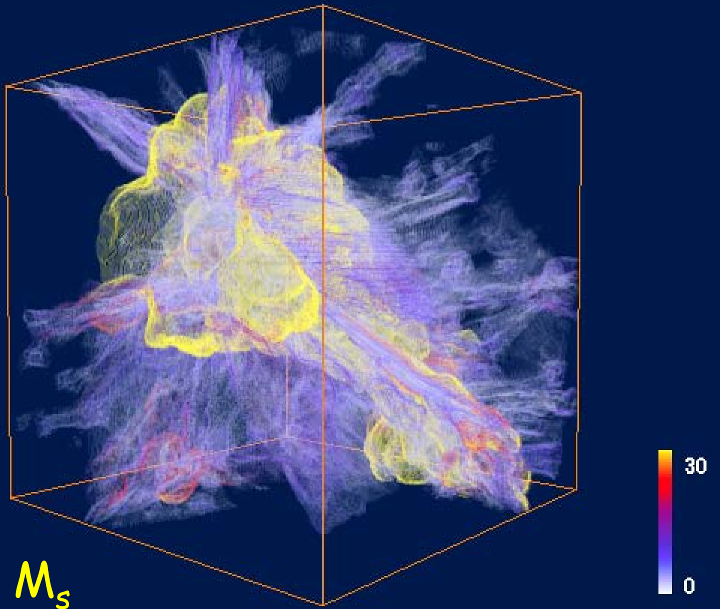


(25 h^{-1}Mpc)^2 2D slice

density, Mach number, temperature, X-ray emissivity

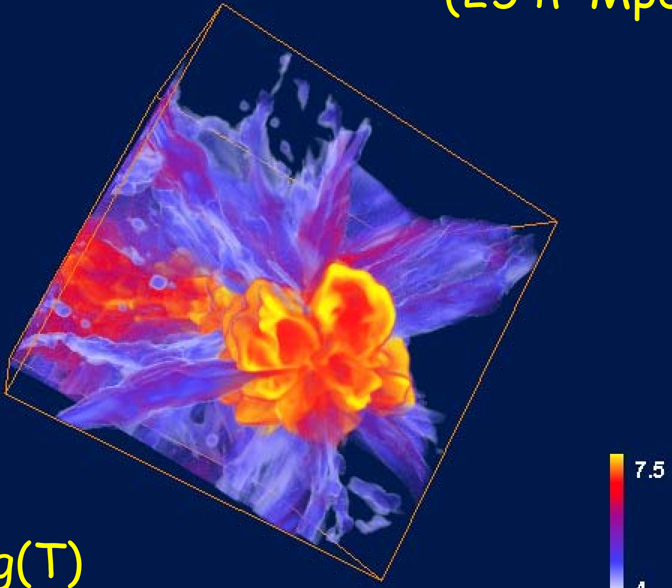


log(ρ)
in units of $\langle\rho_{gas}\rangle$

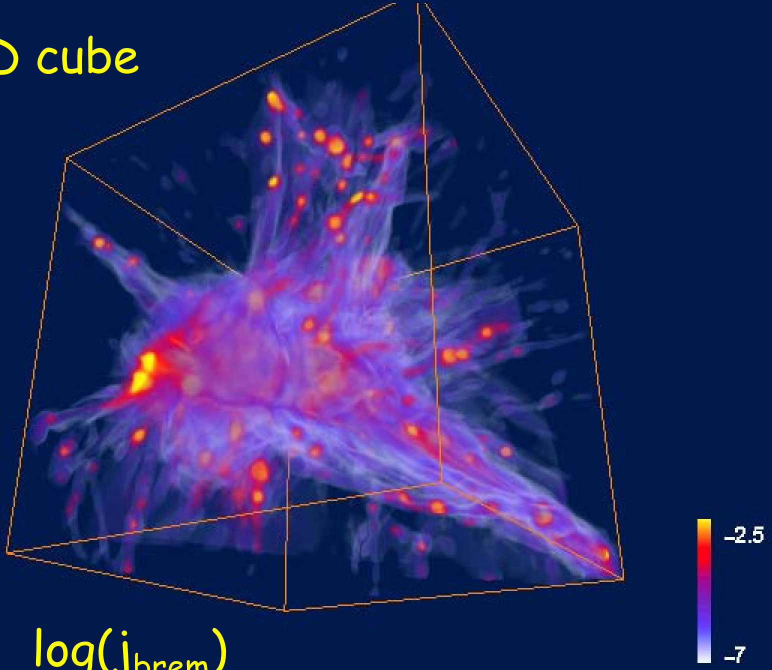


M_s

(25 h^{-1}Mpc)^3 3D cube

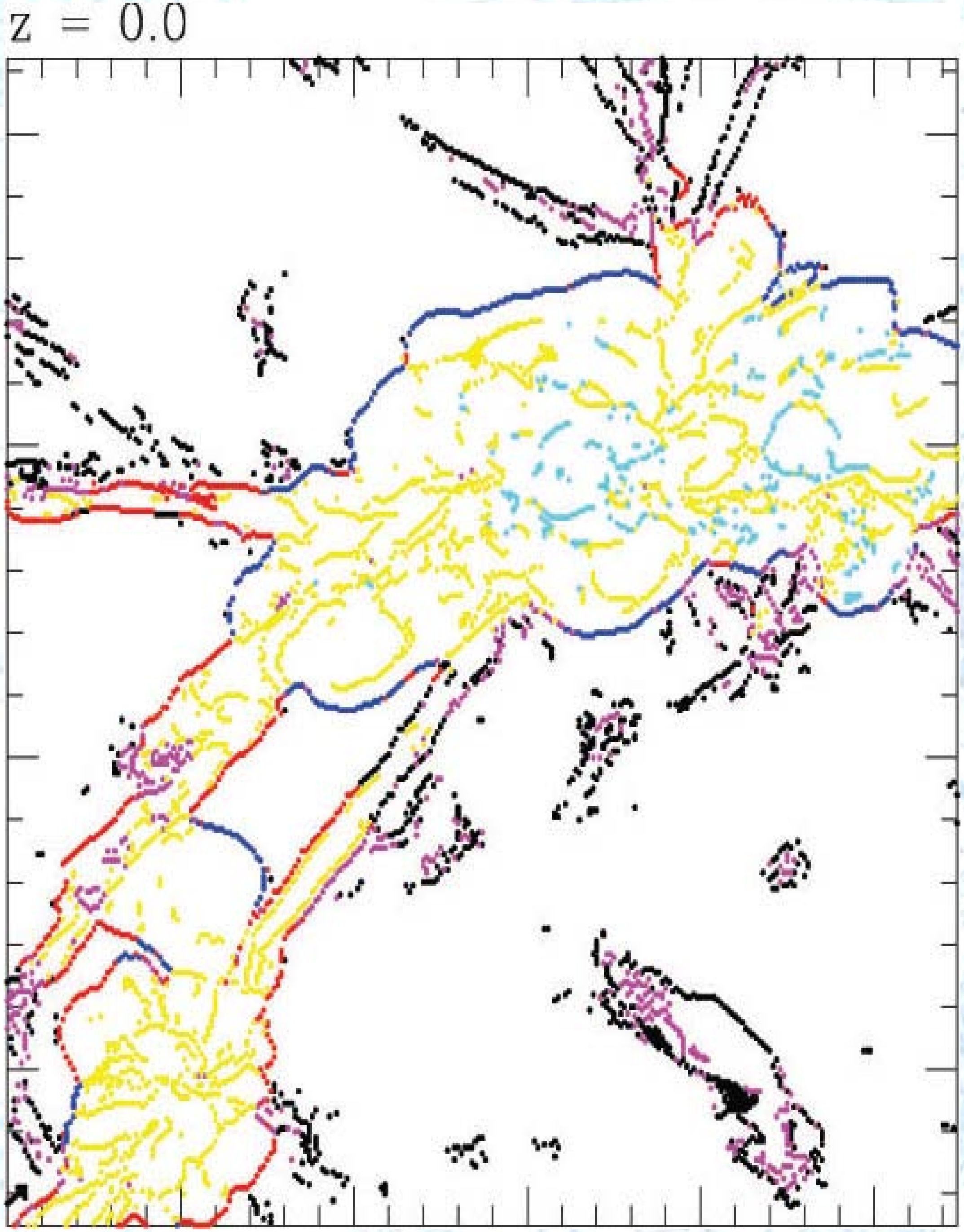


log(T)
in units of K



log(j_{brem})

Speed of shocks around the cluster complex



28 x 37 (h^{-1} Mpc)^2 slice

external shocks

v_{sh} < 150 km/s

150 < v_{sh} < 700 km/s

v_{sh} > 700 km/s

internal shocks

v_{sh} < 150 km/s

150 < v_{sh} < 700 km/s

v_{sh} > 700 km/s

external shocks:

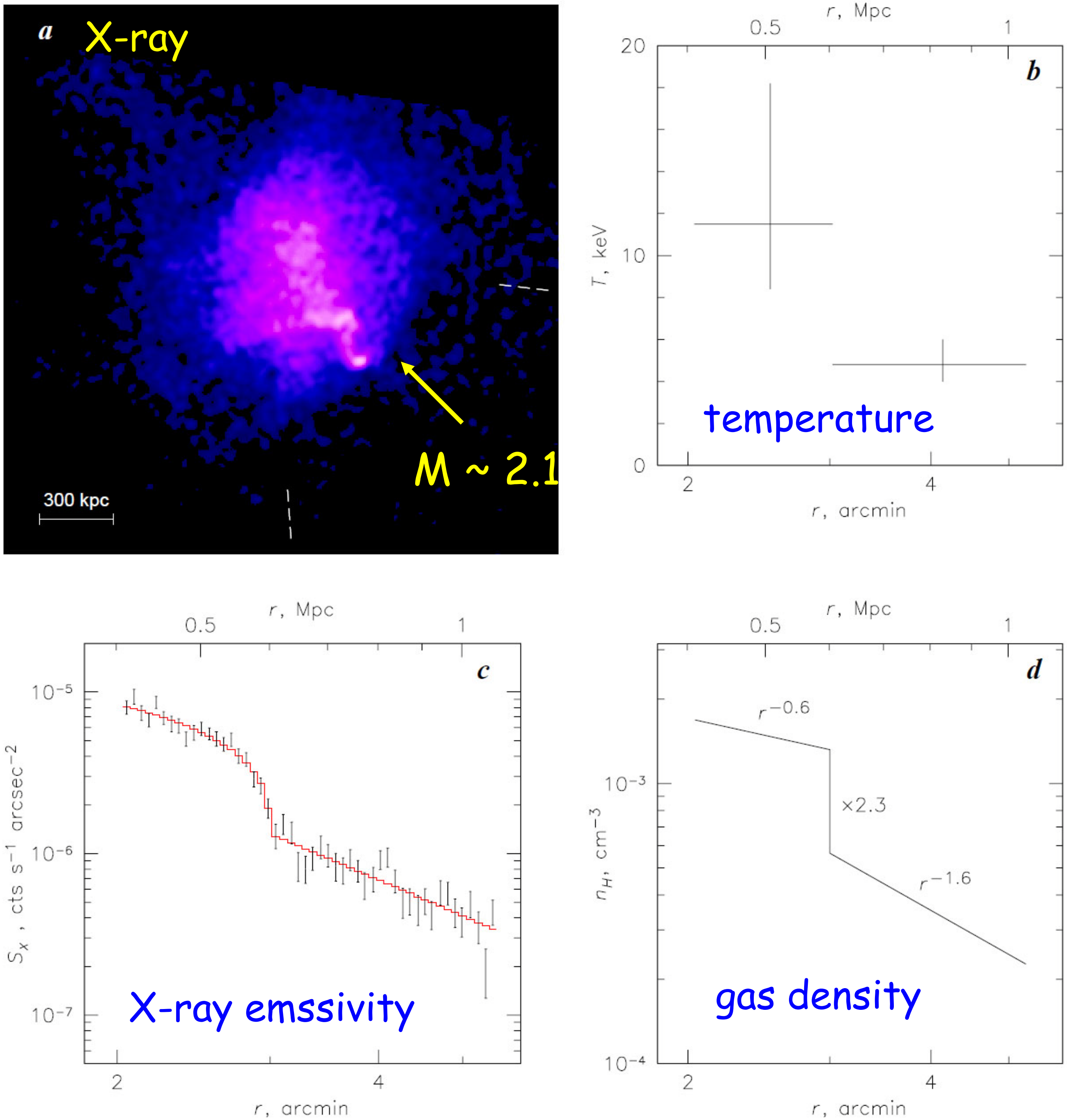
outer surfaces of nonlinear struct.

high Mach no. due to low $T_{preshock}$

internal shocks:

inside nonlinear structure

low Mach no. due to high $T_{preshock}$



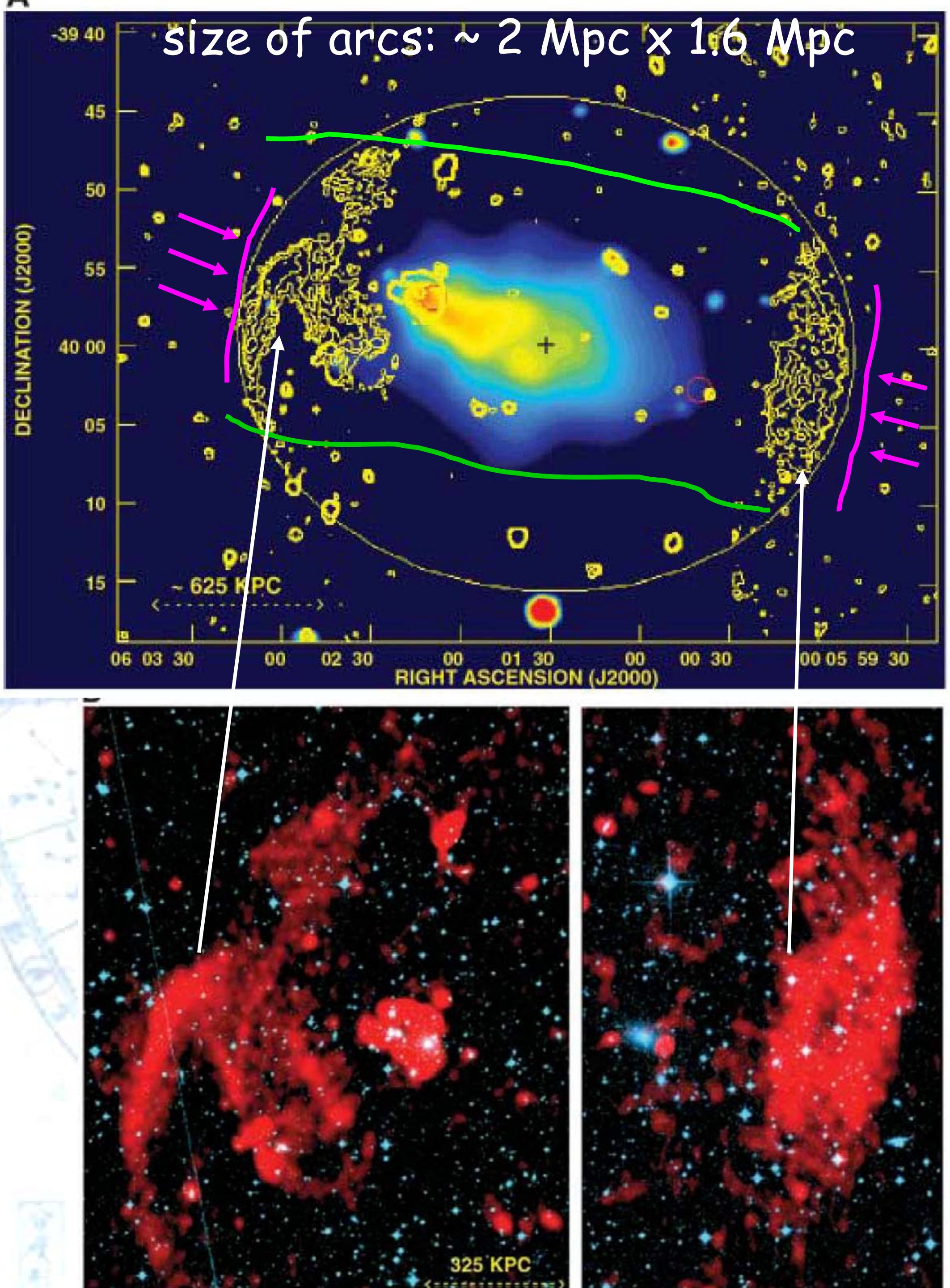
Observation of shocks in the LSS of the universe

- still scarce

X-ray observation of A520

-> a shock of M ~ 2.1

(Markevitch & Vikhlinin 2007)



size of arcs: ~ 2 Mpc x 1.6 Mpc

radio arcs in A3376

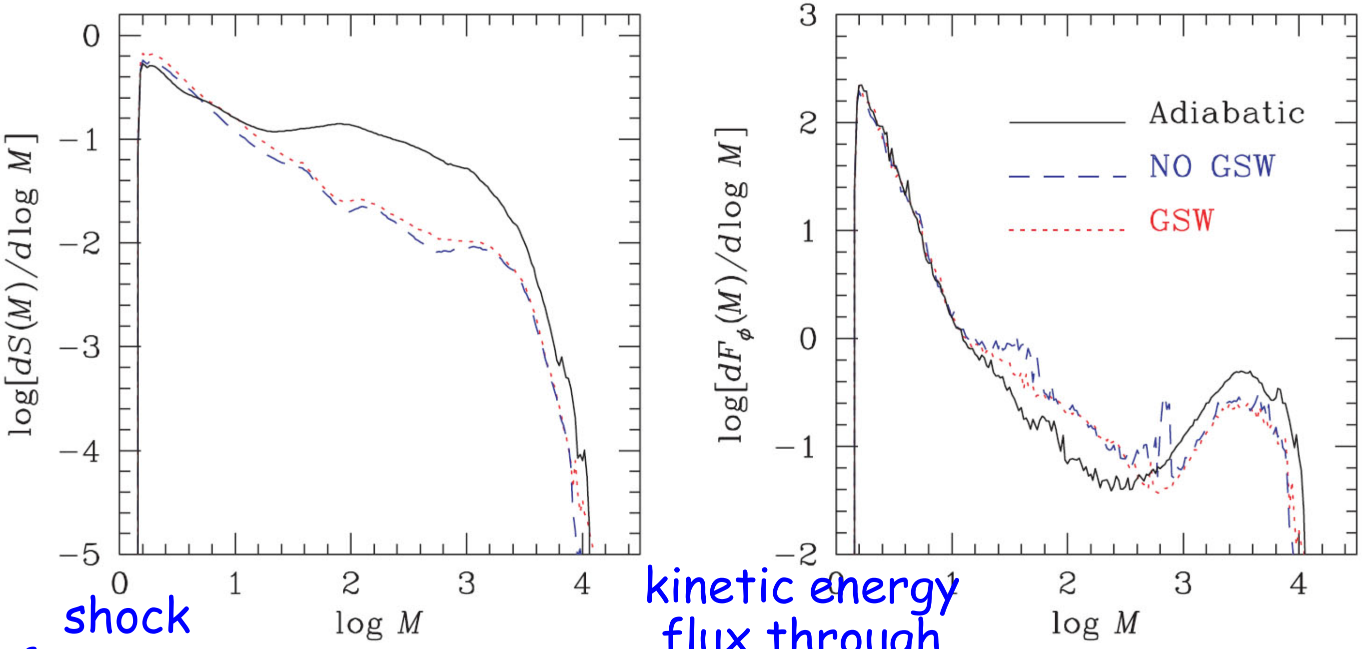
observational evidence for accretion shocks or merger shocks ?

(Bagchi et al 2006)

radio + X-ray

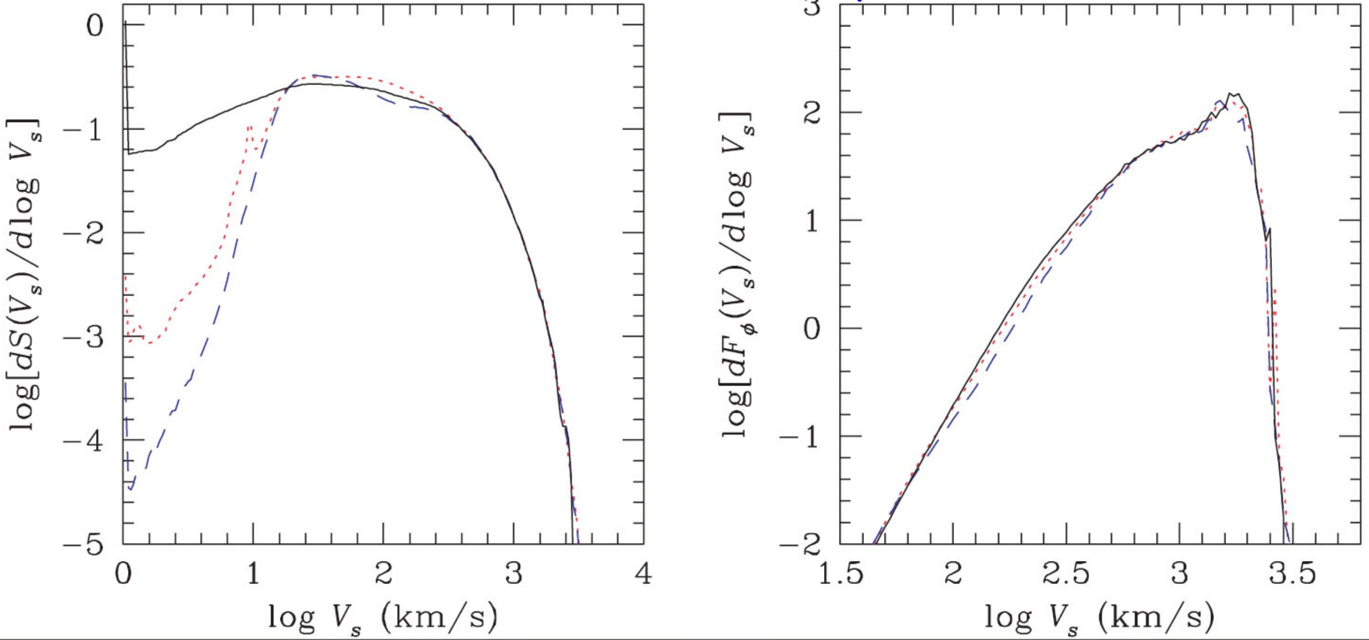
radio + optical

Frequency and energetics of cosmological shocks



shock frequency

kinetic energy flux through shock surfaces

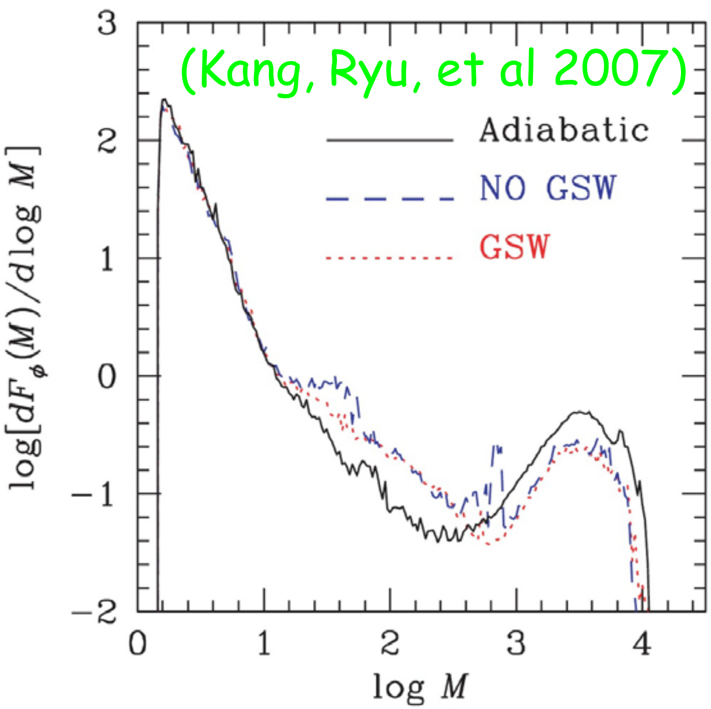


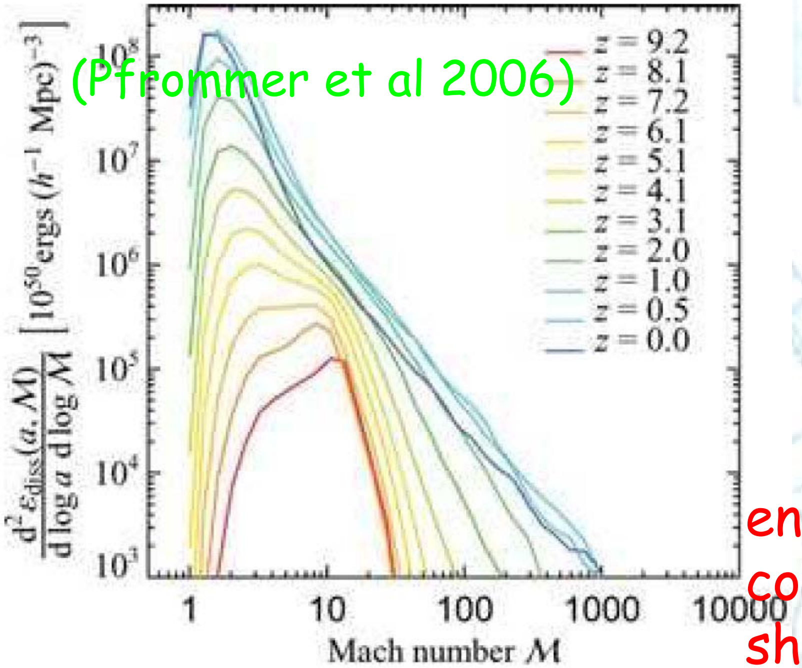
- S = ~1/3 h^{-1}Mpc with $M > 1.5$ at $z = 0$ (S = ~1 h^{-1}Mpc with $M > 1.5$ at $z = 0$ inside nonlinear structures)

<- average inverse comoving distance between shock surfaces

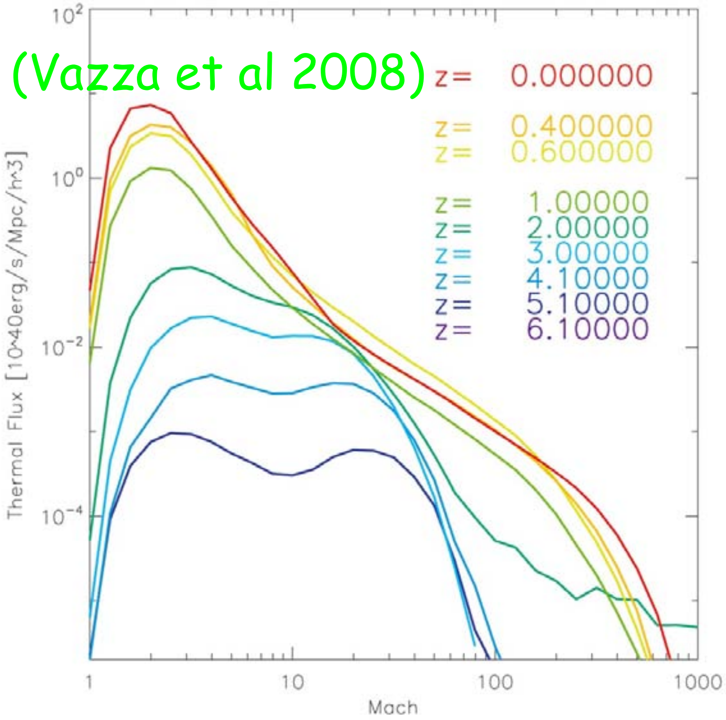
- shocks with M <~ a few (weak), V_s ~ 2,000 km/s are energetically most important

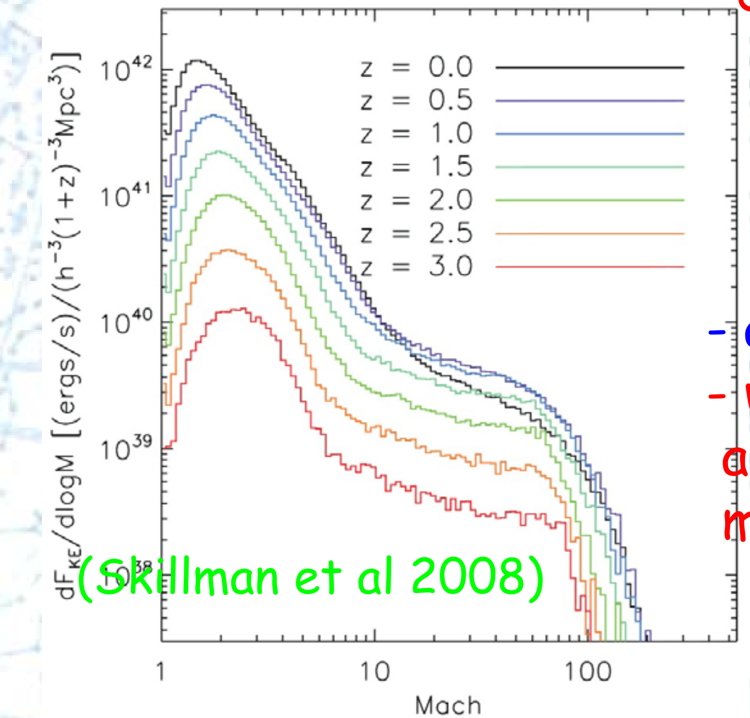
(Ryu, Kang, et al 2003, 2007)


(Kang, Ryu, et al 2007)


(Pfrommer et al 2006)

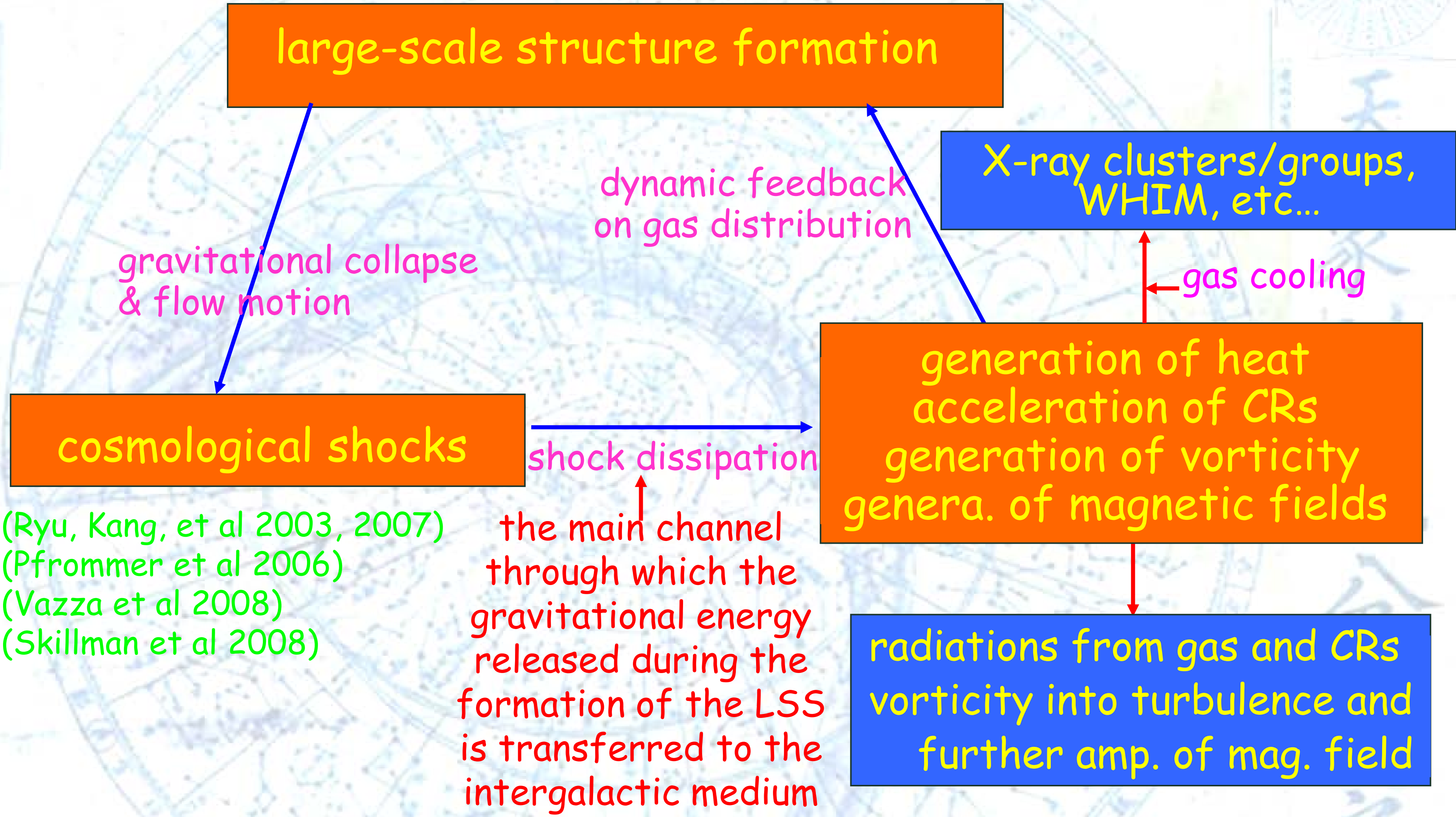
energetics of cosmological shocks in different works


(Vazza et al 2008)


(Skillman et al 2008)

- agreement is OK
- weak shocks are energetically most important

Overveiw of large-scale structure formation



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Cosmic rays accelerated at cosmological shocks

key ideas behind DSA (diffusive shock acceleration)

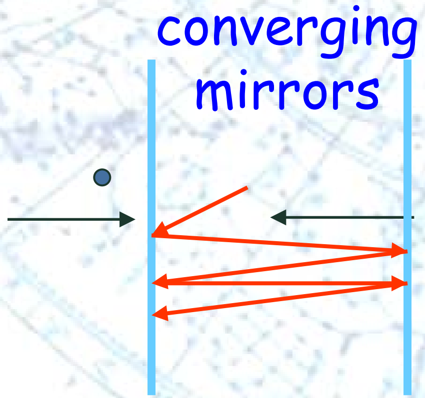
- Alfven waves in a converging flow act as converging mirrors

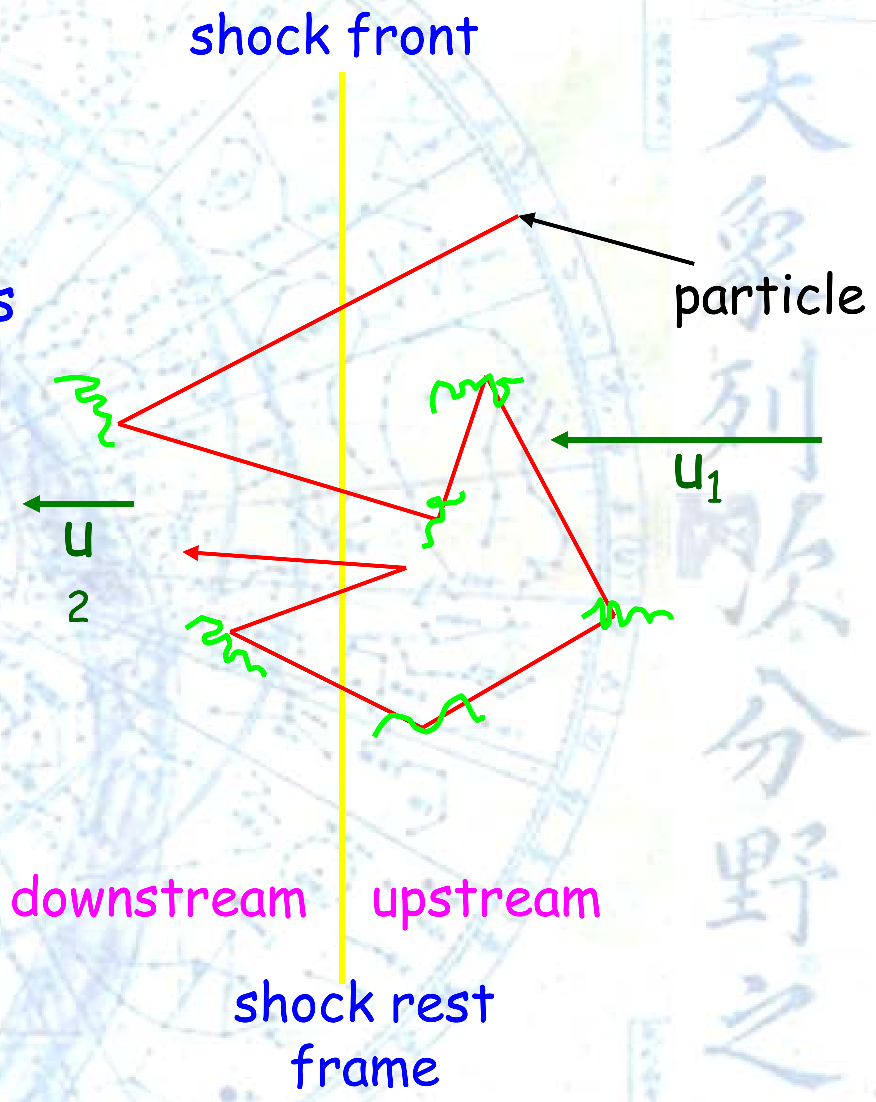
→ particles are scattered by waves

→ cross the shock many times

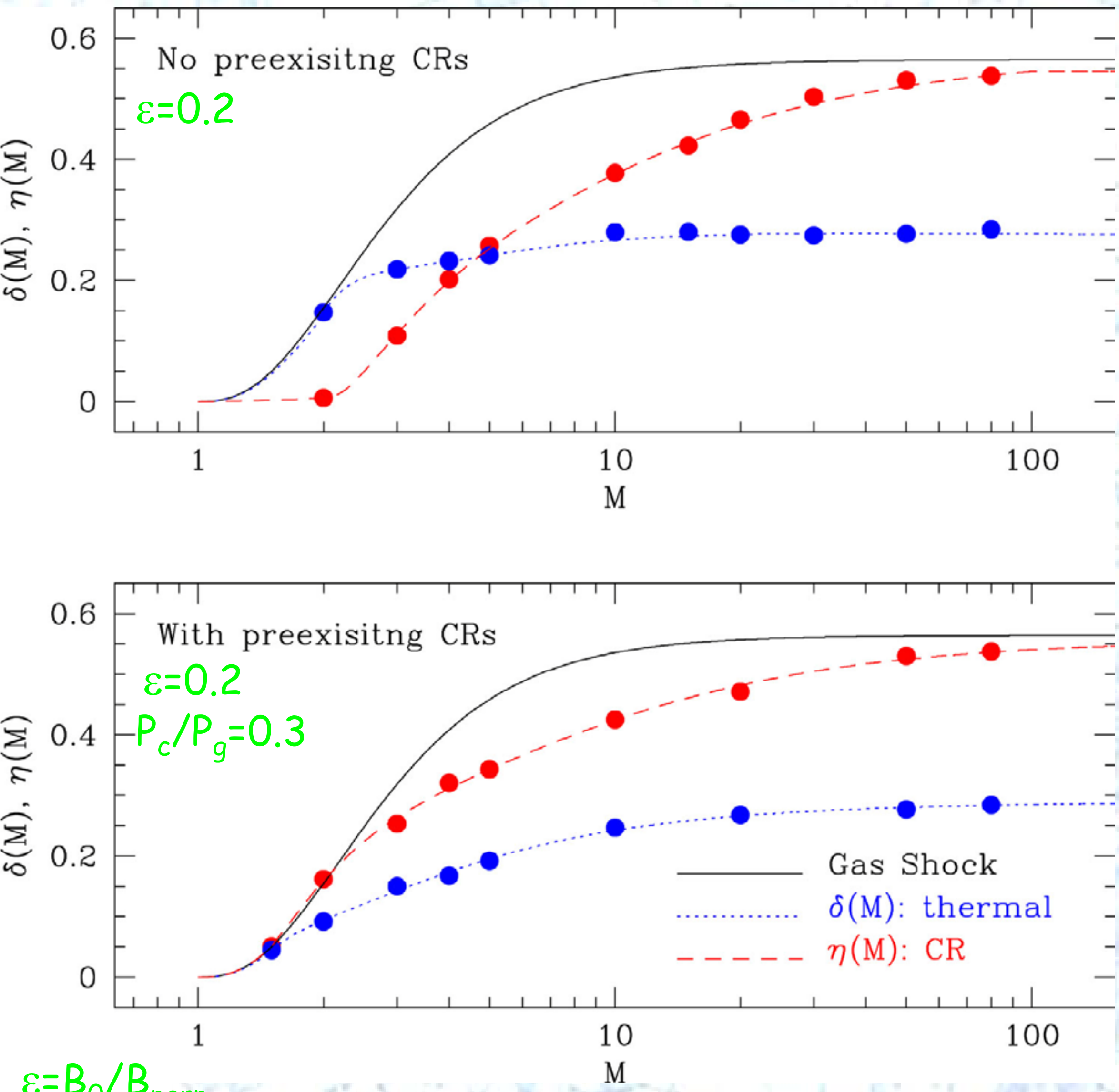
"Fermi first order process"

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





Cosmic ray acceleration efficiency at shocks

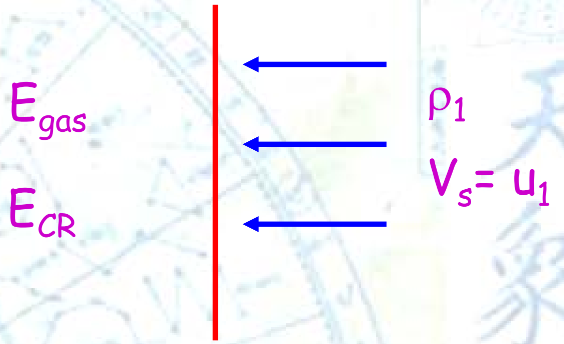


$\varepsilon=B_0/B_{perp}$

thermalization efficiency: δ(M)

CR acceleration efficiency: η(M)

for quasi-parallel shocks



- kinetic energy flux through shocks

$F_k = (1/2)r_1V_s^3$

- net thermal energy flux generated at shocks

$F_{th} = (3/2)\ [P_2-P_1(r_2/r_1)^g]\ u_2$

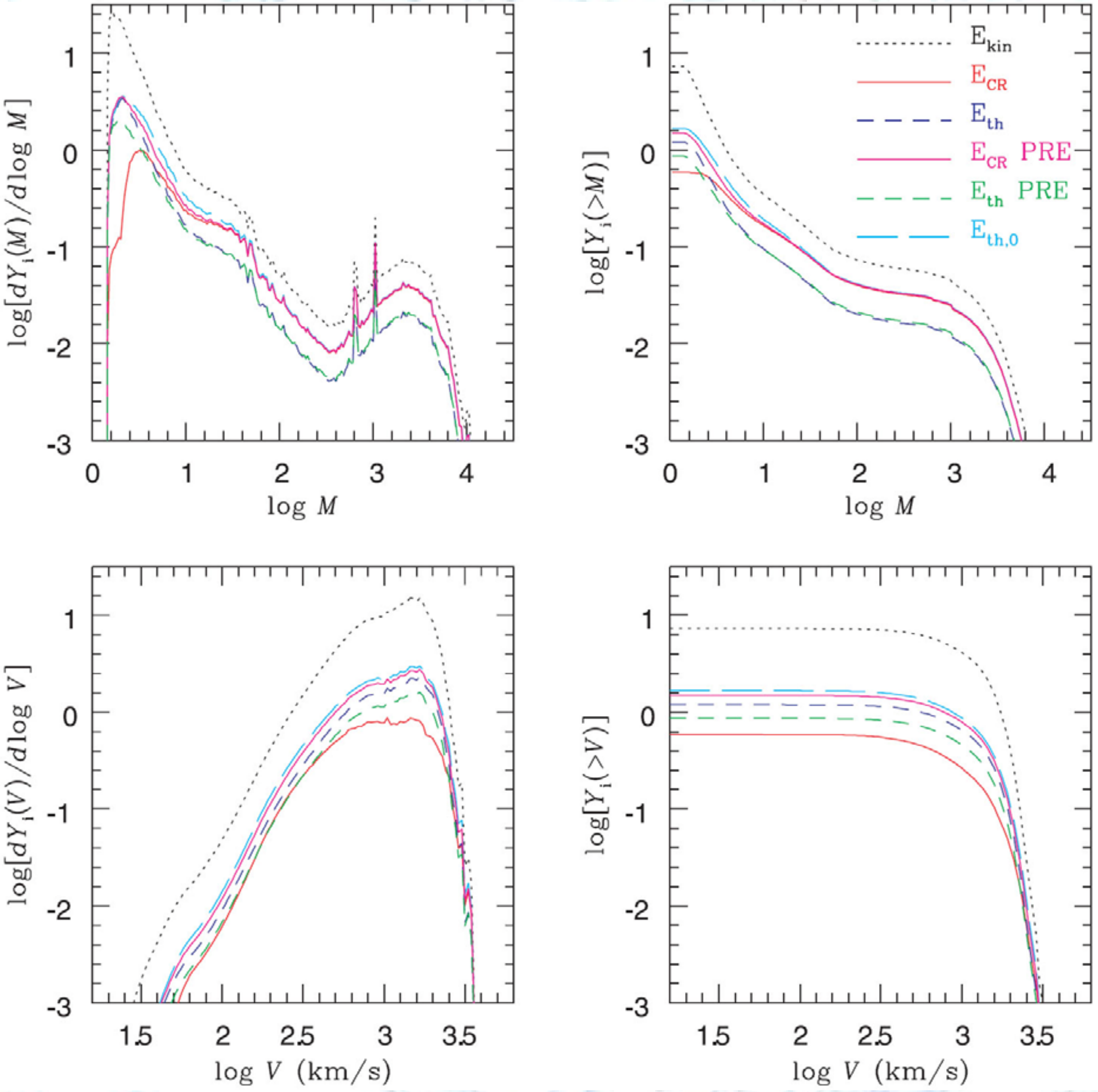
$= d(M)\ F_k$

- CR energy flux emerged from shocks

$F_{CR}= h(M)\ F_k$

(Kang, Ryu et al 2007)

Cosmic rays accelerated at cosmological shocks:
integrated over the evolution of the universe



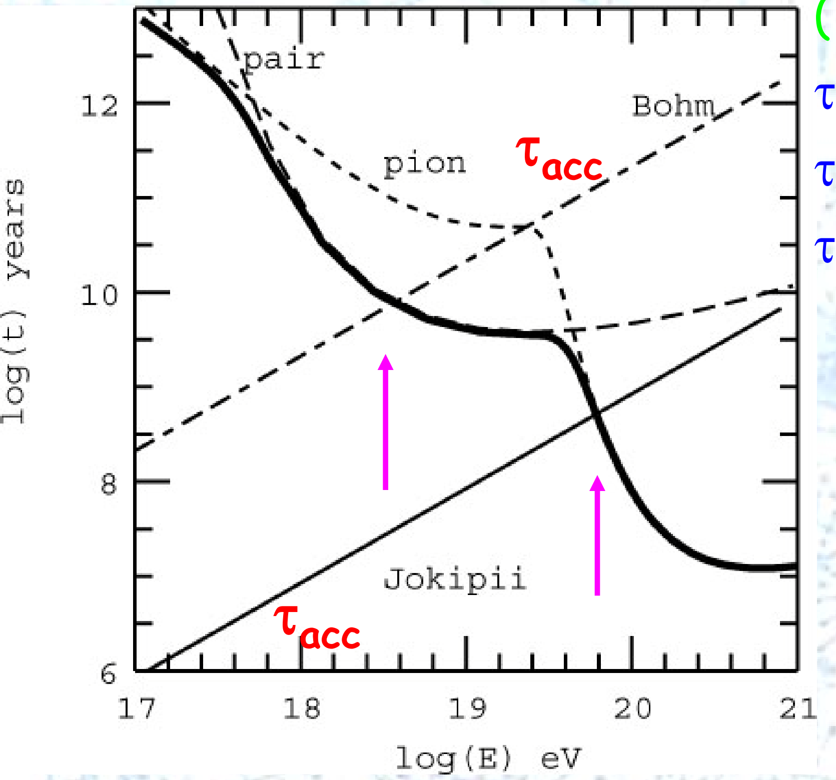
-CR acceleration
 ← shocks with
 M = 2~5
 V_s ~ 1,000 km/s

-E_{CR} accelerated at shocks = ~ 0.5 × E_{th} generated at shocks, assuming parallel shocks, and no pre-existing comp.

- the intergalactic space may be filled with the CR ions and electrons accelerated by cosmological shocks

- but E_{CR}/E_{th} too large?

Highest energy protons accelerated at cosmological shocks



(Kang, Rachen, Biermann 1997)

$\tau_{acc}(p) \sim 8\,\kappa(p)/V_s^2$ mean acceleration time

τ_{loss} = energy loss time scale due to CBR

$\tau_{acc} = t_{loss}$ → $E_{p,max} \sim 10^{18.5}$ eV for Bohm

$E_{p,max} \sim 10^{19.7}$ eV for Jokipii

Bohm diffusion in parallel shocks

→ $\kappa_B = r_g\, c\, /\, 3$

Jokipii diff. in perpendicular shocks

→ $\kappa_J \sim r_g\, V_s = 3(V_s/c)\,\kappa_B \sim 0.01\,\kappa_B$

$V_s = 1{,}000$ km/s, $B = 1\ \mu G$

diff. along field lines and drift across field are limited by the finite size

→ $E_{max} = Z\,\beta_a\,BR$: return back to "Hillas" constraint,

so $E_{p,max}$ ~ a few x 10^{18} eV for protons at cluster accretion shocks

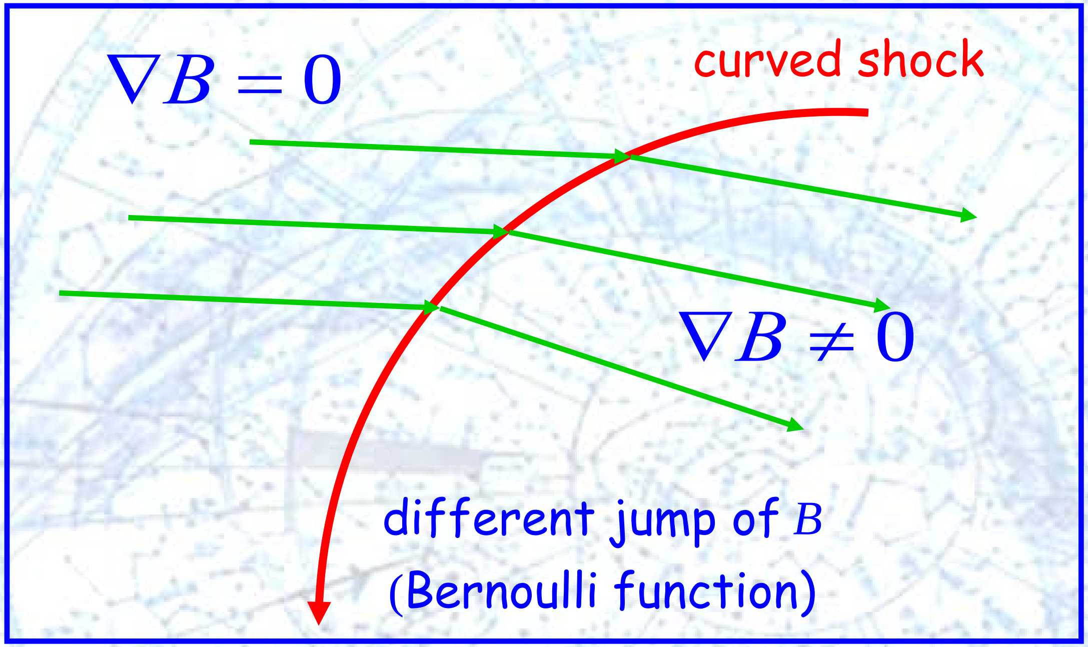
(Ostrowski & Siemieniec-Ozieblo 2002)

for irons, with $B = 1\ \mu G$ $V = 1{,}000$ km/s, $E_{Fe,\,max} \sim 10^{20}$ eV

Inoue et al (2007)

Vorticity generated at cosmological shocks

directly at curved shocks



$\nabla B = 0$

curved shock

$\nabla B \neq 0$

different jump of B

(Bernoulli function)

⟹ at postshock

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

ρ_1 preshock density

ρ_2 postshock density

$\vec{U}$ preshock flow speed

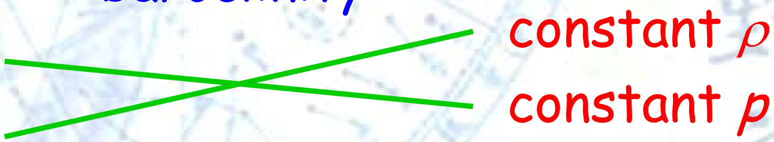
$\vec{n}$ unit normal to shock surf.

R curvature radius of surf.

by the baroclinic term

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

baroclinity

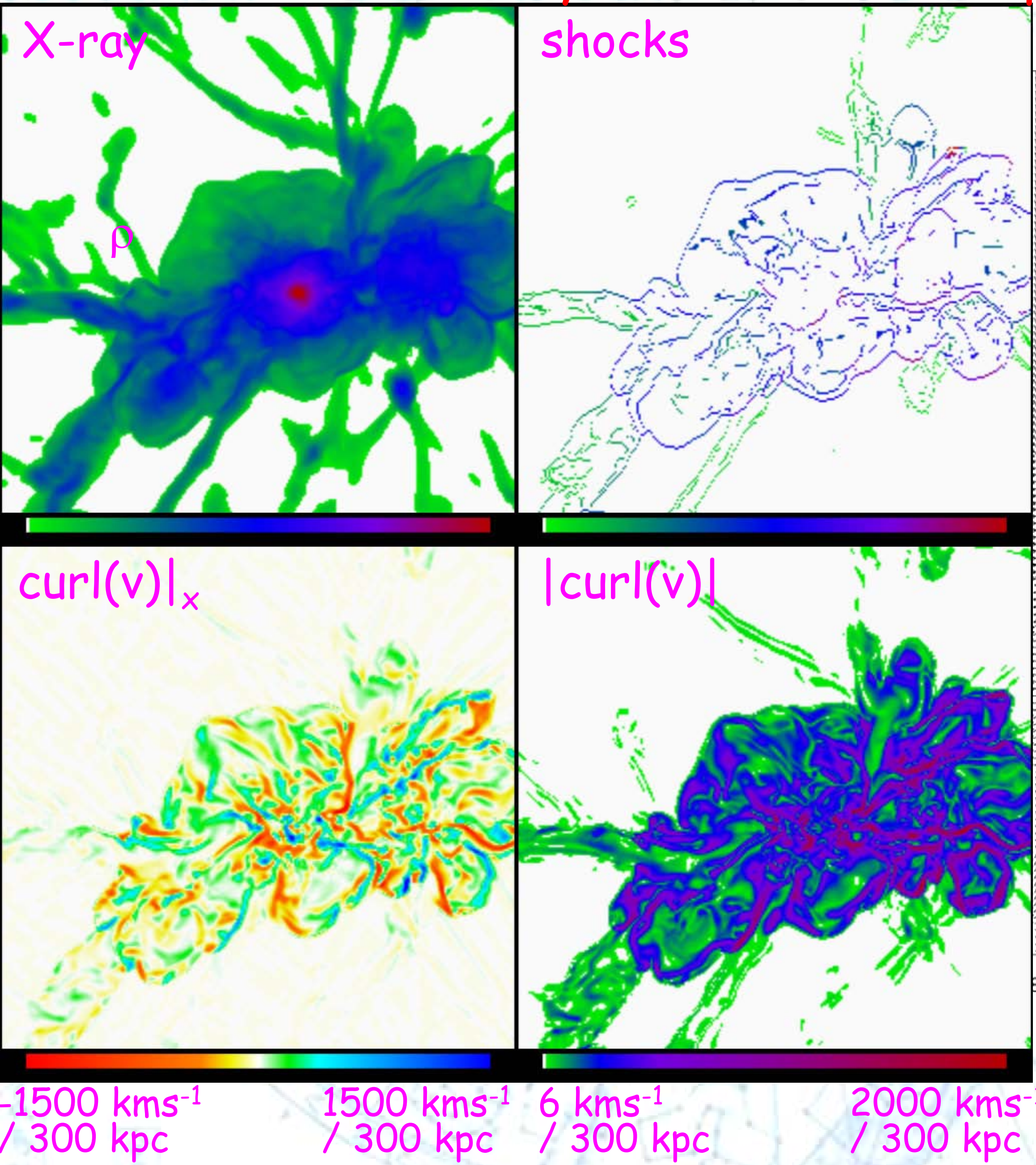


constant ρ

constant p

⟸ due to entropy variation induced at shocks

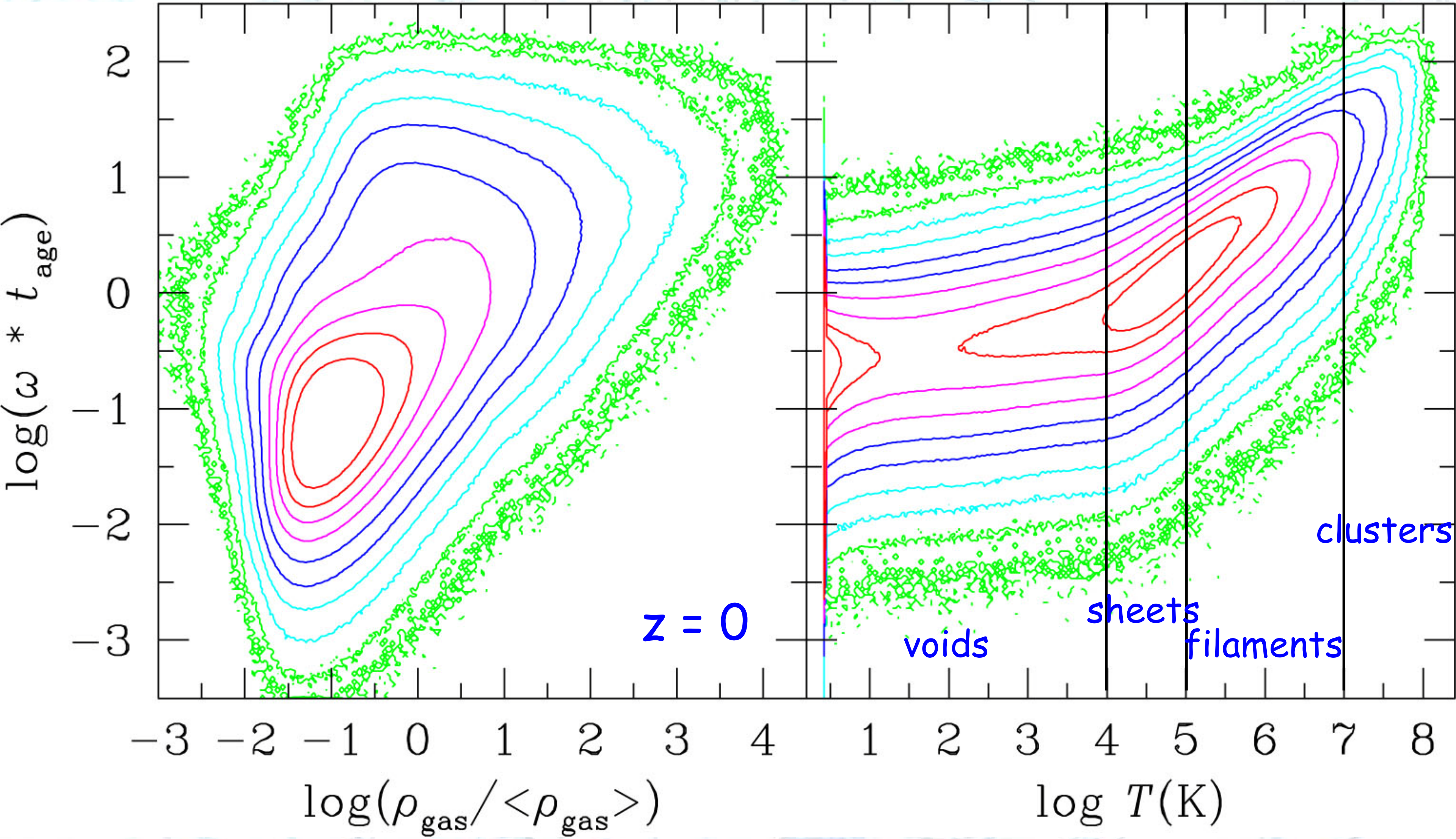
Vorticity in a cluster complex (Ryu, Kang, Cho et al 2008)



velocity field

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

Vorticity in the large-scale structure of the universe



ω: curl(v)

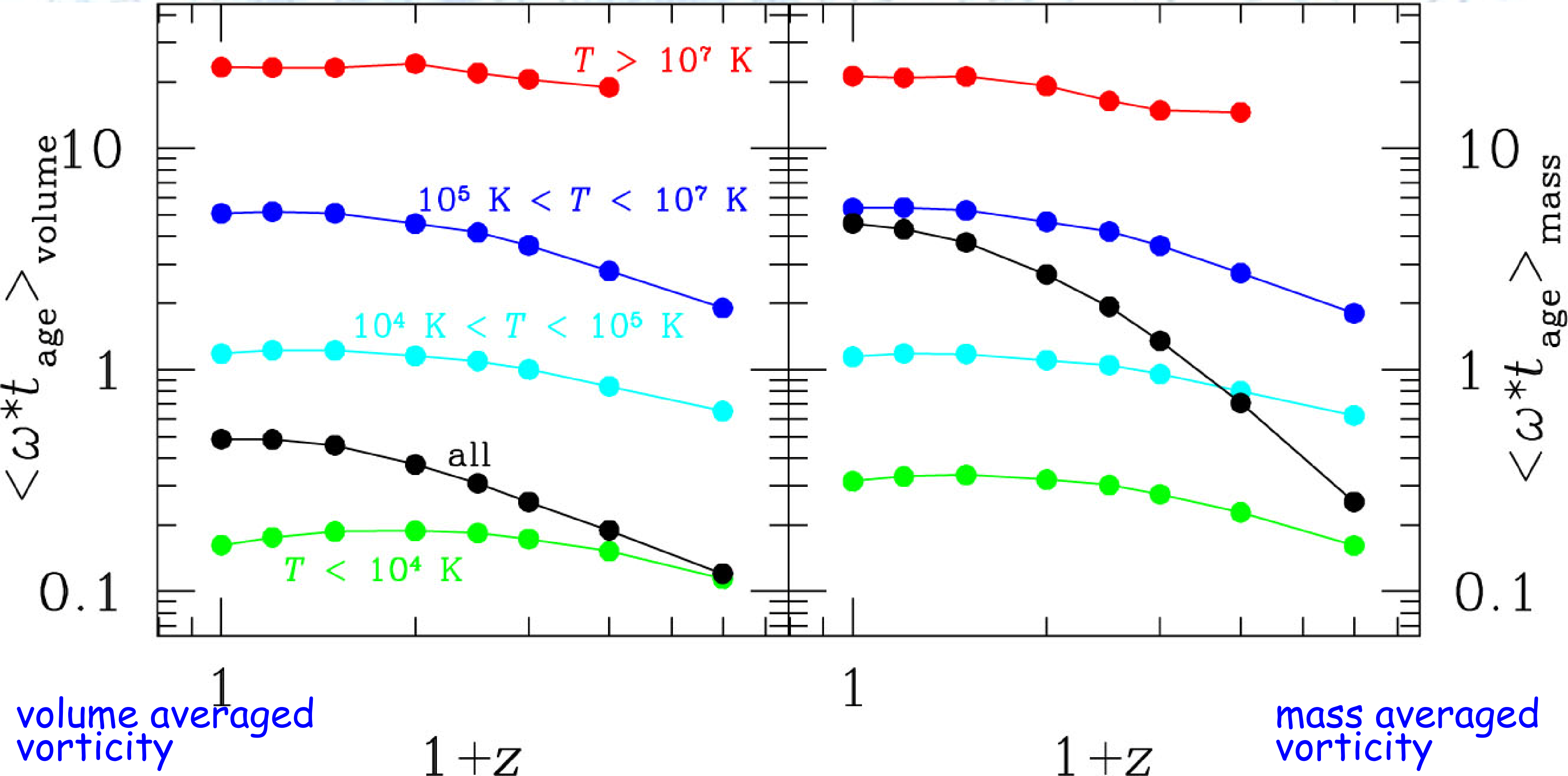
t_{age}: age of the universe (~1.4x10^{10} yrs)

Vorticity in the large-scale structure of the universe

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

ω: curl(v)

t_{age}: age of the universe



volume averaged vorticity

mass averaged vorticity

Turbulence in the intergalactic medium

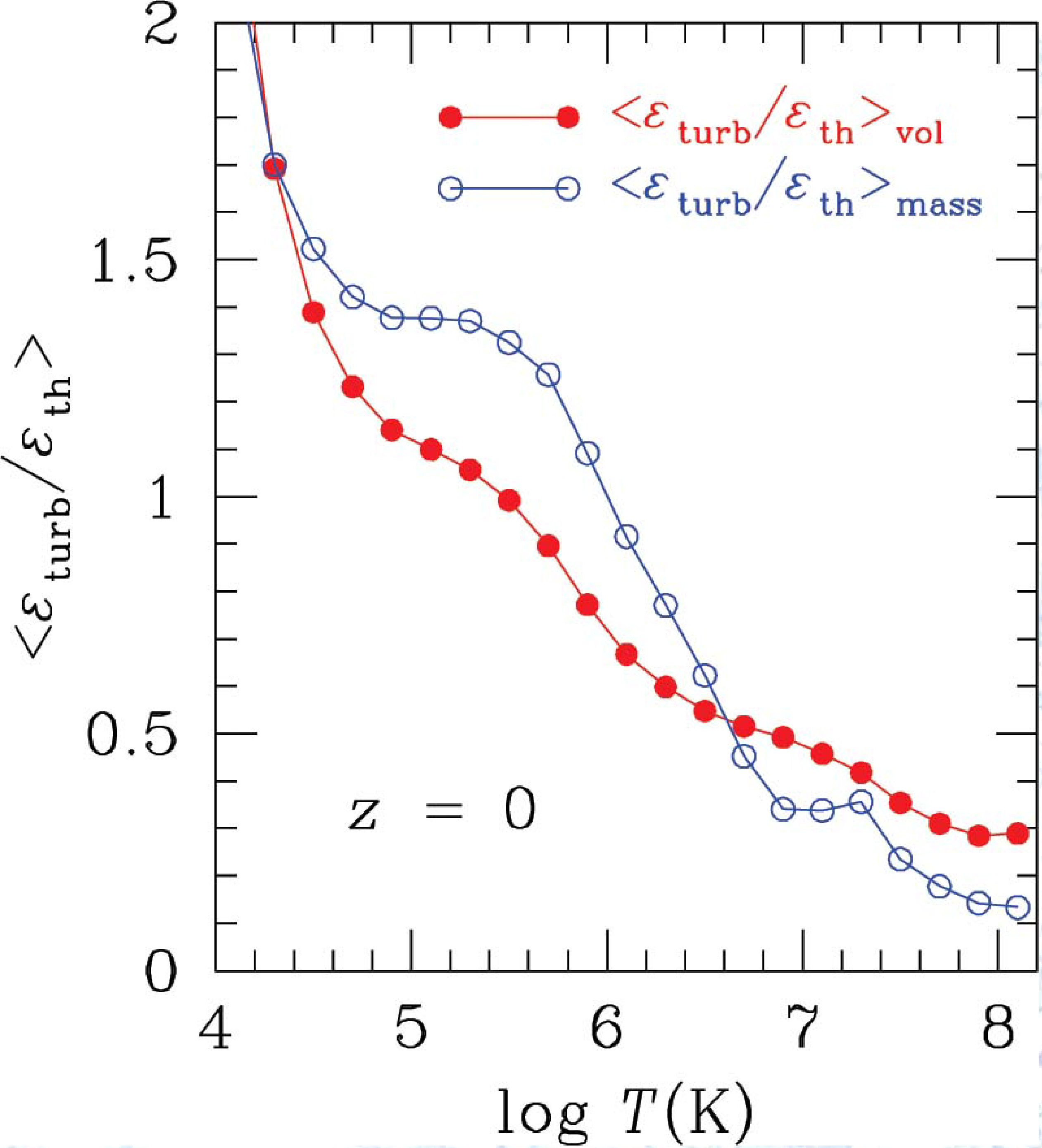
If $t/t_{\text{turn-over}}$ >~ a few, vorticity cascades to develop turbulence in the intergalactic medium.

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

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

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

(Ryu, Kang, Cho et al 2008)

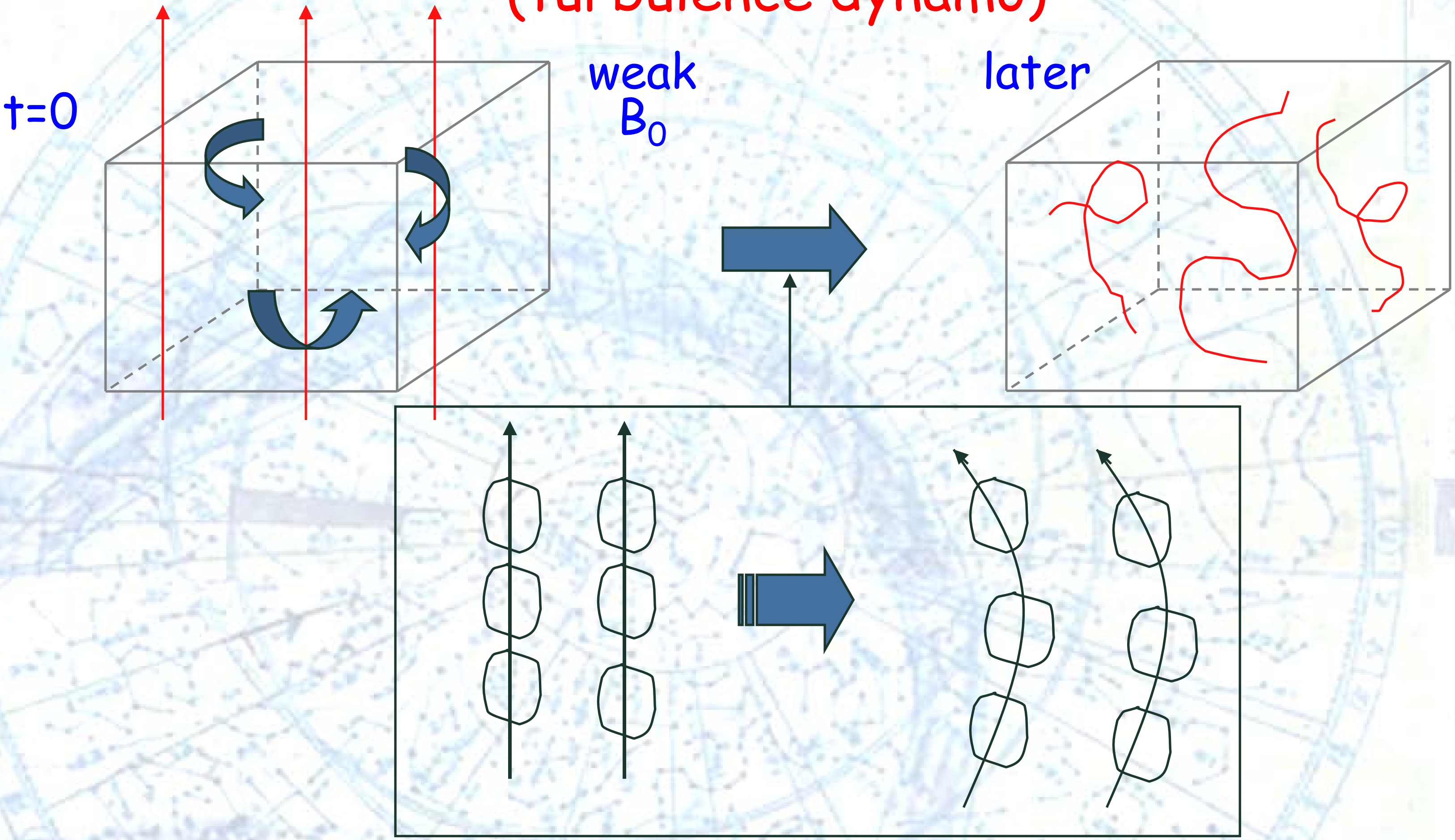


the turbulence energy of in the intergalactic medium, assuming that all the energy of vortical motions goes to turbulence

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

$M_{turb} \sim 1$
(transonic turbulence)
in filaments

Amplification of magnetic field by stretching (turbulence dynamo)

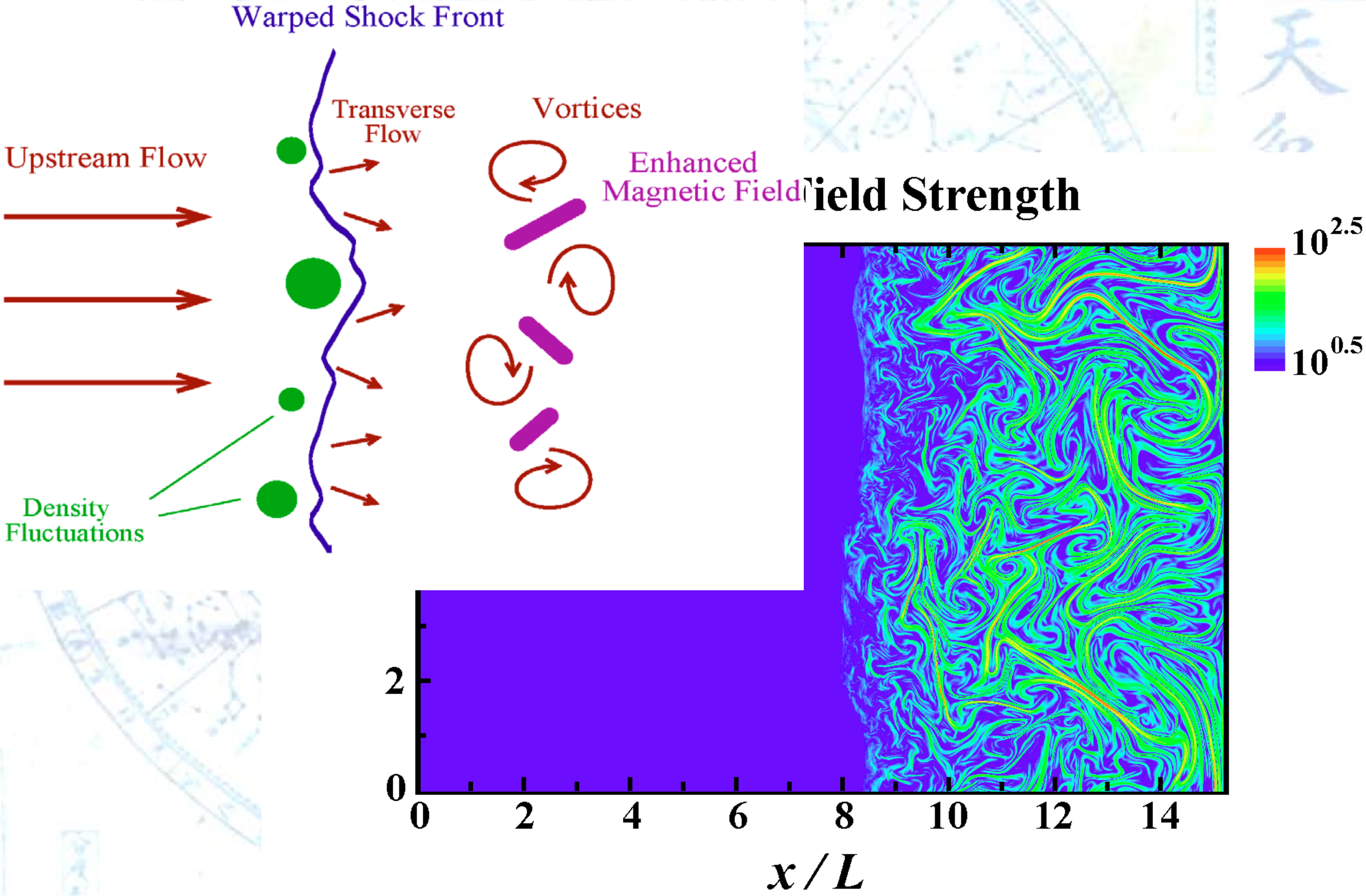


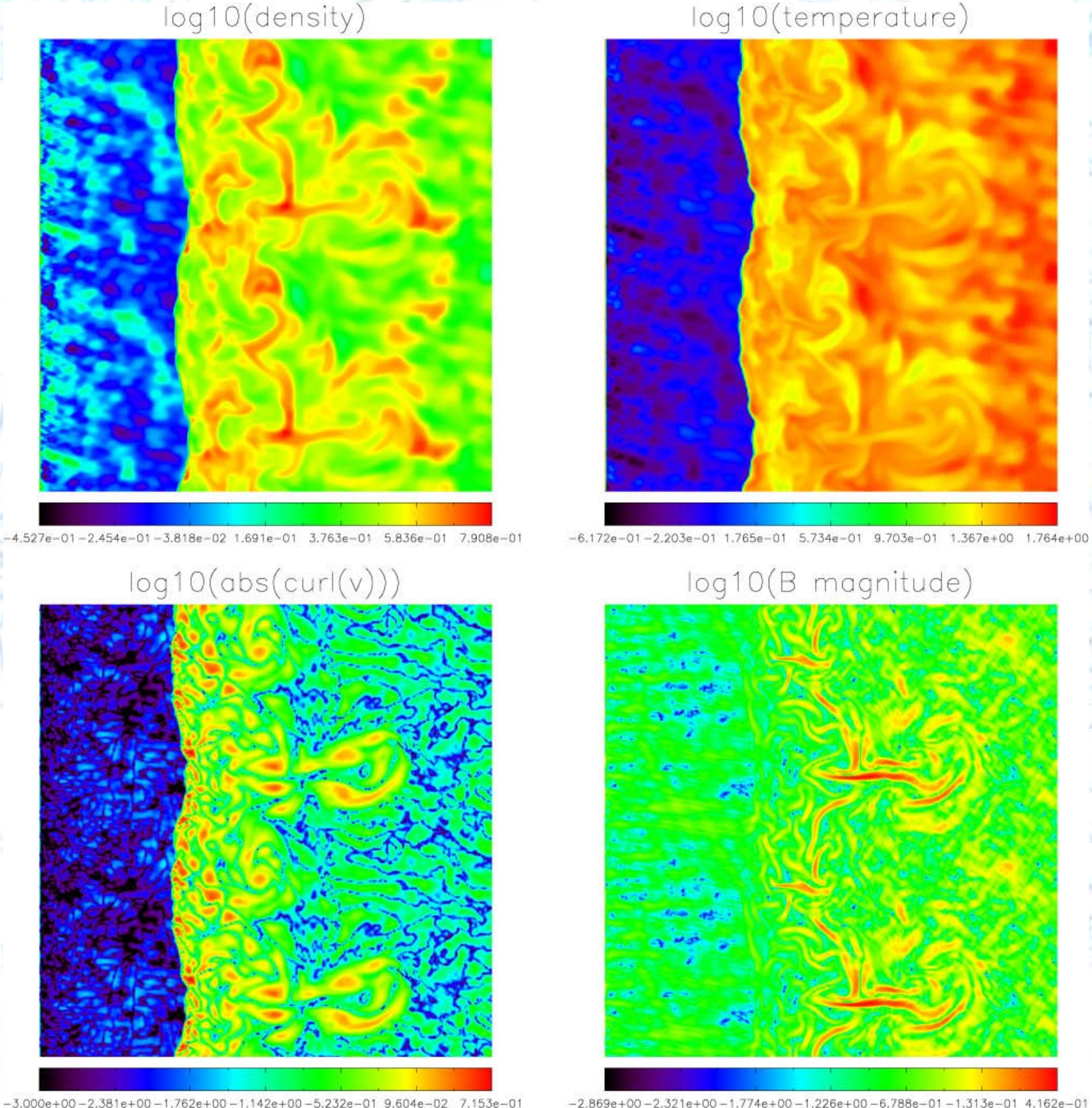
fluid elements and field lines move together

back reaction is negligible if $E_{mag} < E_{kin}$

-> the intergalactic magnetic field of <B> ~ a few μG in clusters and ~10 nG in filaments results in

Development of turbulence and amplification of magnetic fields behind shocks (Giacalone & Jokipii 2007)




log10(density)

log10(temperature)

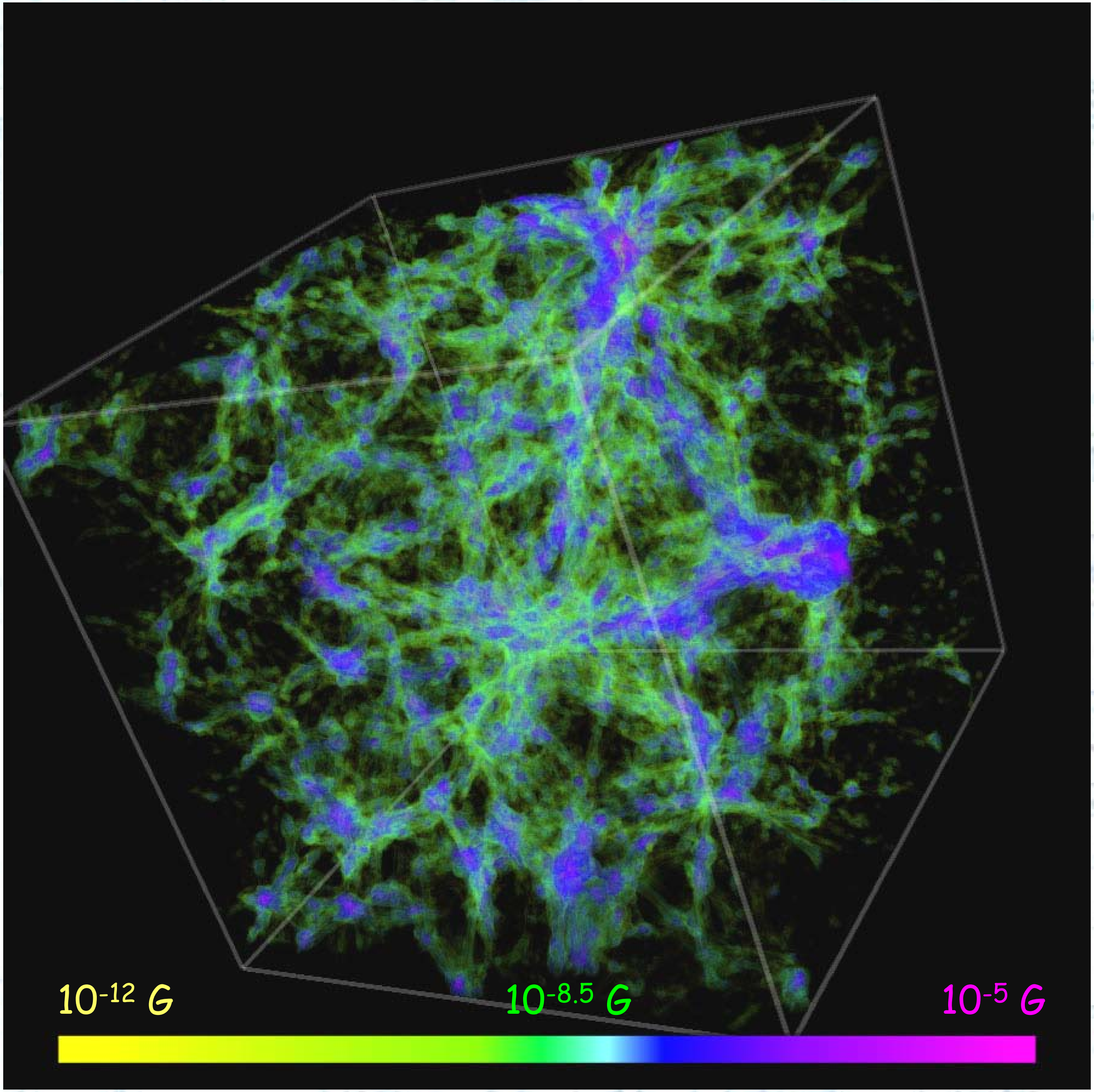
log10(abs(curl(v)))

log10(B magnitude)

reproduction of
Giacalone & Jokipii
2007

still 2D
need 3D

preliminary



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

(Ryu, Kang, Cho et al 2008)

Summary

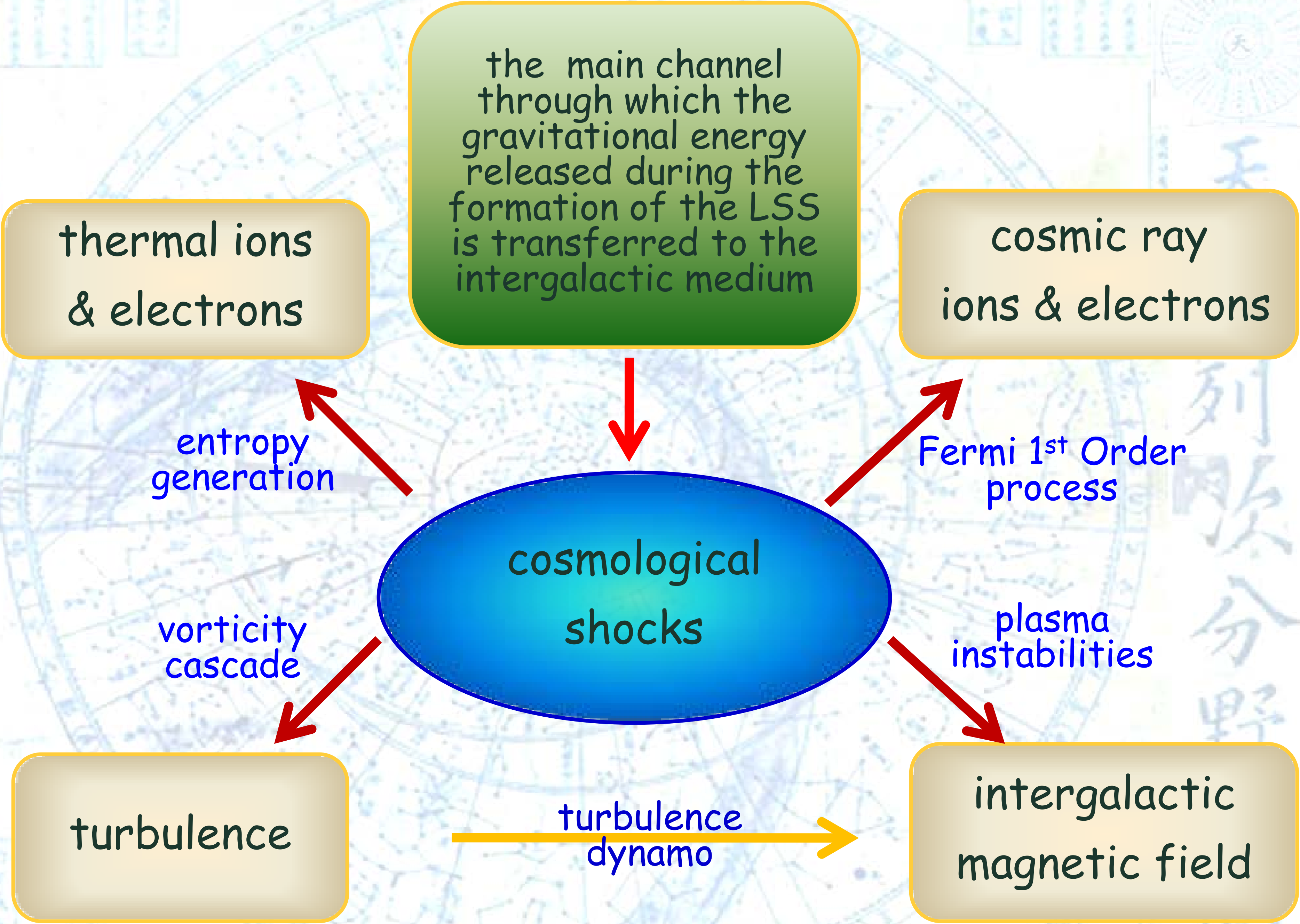
Cosmological shocks are common, at least, in numerical works, although observations are still scarce.

Energetically most relevant shocks in the LSS of the universe

- weak with sonic Much number M_s ~ 2 - 4
- non-relativistic with shock speed Vs ~ 2000 km/s
- Alfven Mach number M_A >~ 10
- magnetized with all turbulent field in upstream
- pre-existing cosmic rays
- …

-> different from shocks in heliosphere, SNRs, GRBs, …

We need to better understand the physics of cosmological shocks!



the main channel through which the gravitational energy released during the formation of the LSS is transferred to the intergalactic medium

thermal ions & electrons

cosmic ray ions & electrons

entropy generation

Fermi 1st Order process

cosmological shocks

vorticity cascade

plasma instabilities

turbulence

turbulence dynamo

intergalactic magnetic field

Thank you !