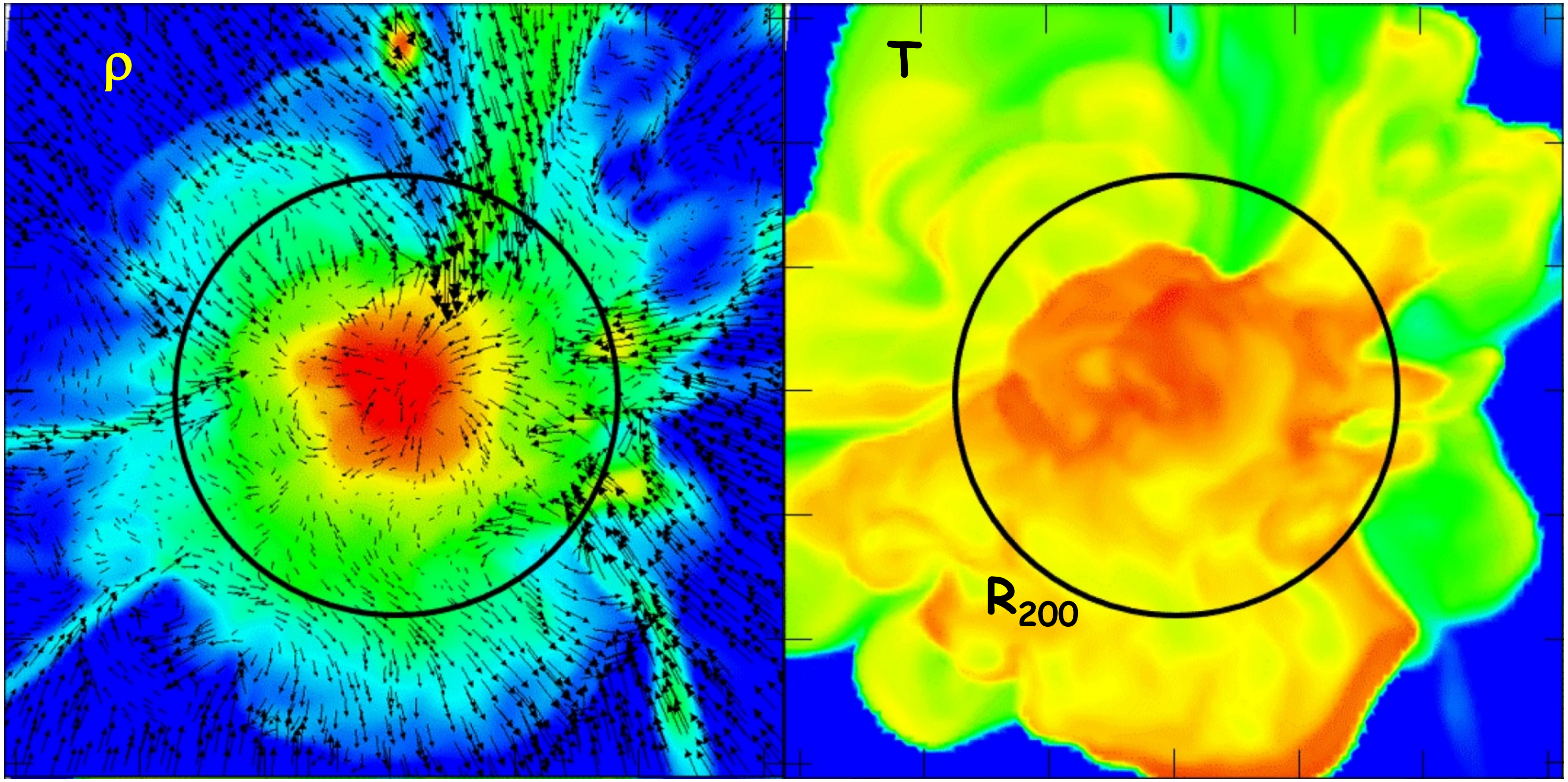
Intracluster Shock Waves



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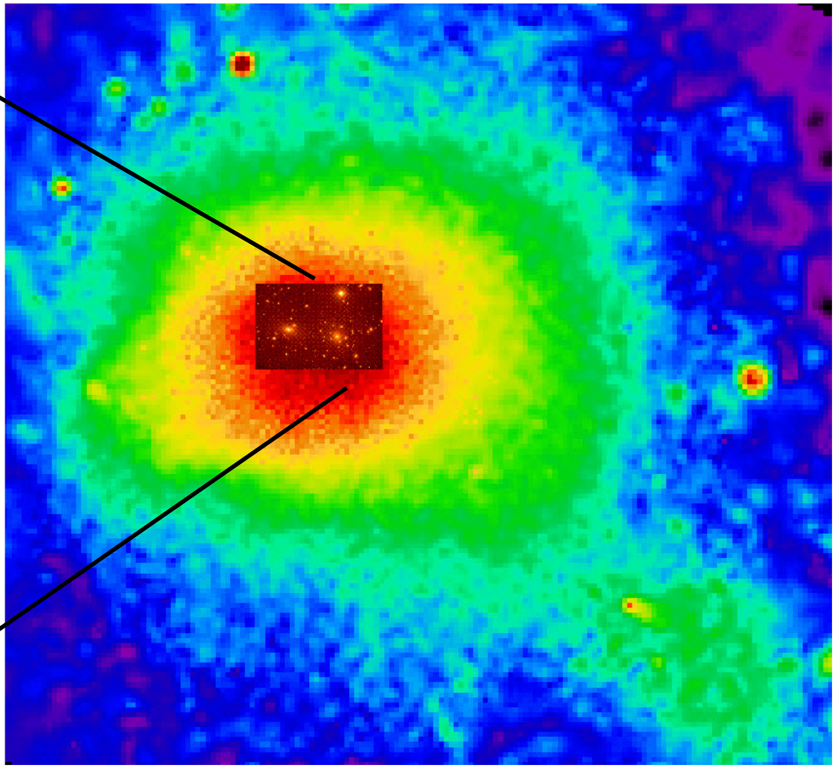
Hyesung Kang (Pusan National U, Korea)
Sungwook E. Hong (Korea Institute for Advanced Study)
and etc

Clusters of galaxies → aggregates of galaxies, which are the largest known gravitationally bound objects to have arisen thus far in the process of cosmic structure formation

Coma Cluster

in visible (core region) <- star light



in X-ray <- hot gas of T ~ 8 keV

The intracluster medium (ICM) → the superheated plasma with T ~ a few to several keV, presented in clusters of galaxies

Physical quantities in clusters of galaxies

size of clusters $L \sim \text{a few Mpc}$

density of baryonic matter $n \sim 10^{-2}\,\text{cm}^{-3}$

flow velocity $\upsilon \sim \text{several} \times 10^{2}\ \text{km/s}$

gas temperature $T \sim 10^{8}\,\text{K}$

magnetic fields $B \sim \text{a few}\ \mu\text{G}$

Energetics

gas thermal energy $E_{\text{thermal}} \sim 10^{-10}\,\text{erg/cm}^{3}$

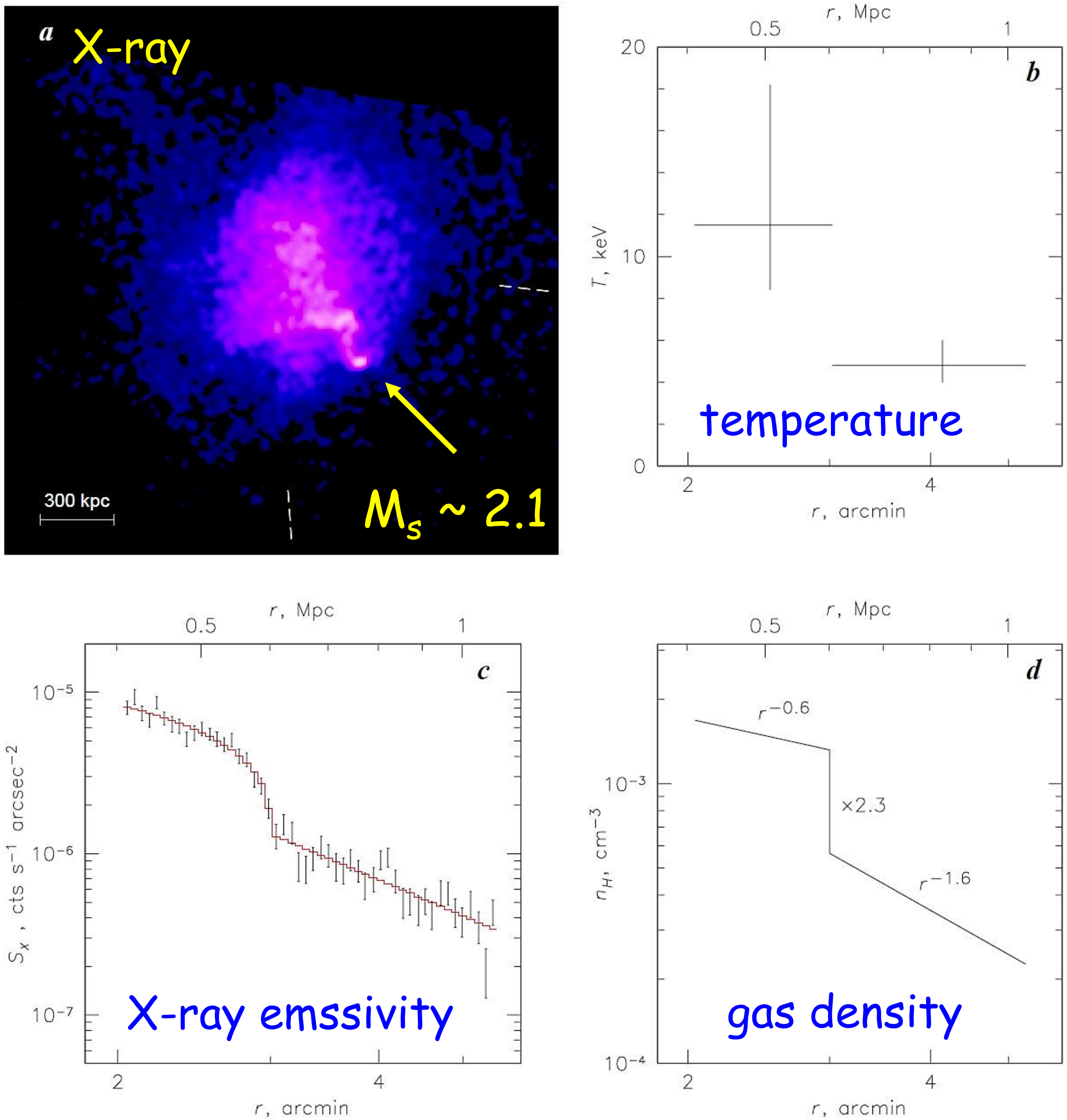
gas kinetic energy $E_{\text{kinetic}} \sim 10^{-11}\,\text{erg/cm}^{3}$

cosmic-ray energy $E_{\text{cosmic-ray}} \sim 10^{-12}\,\text{erg/cm}^{3}$

magnetic energy $E_{\text{magnetic}} \sim 10^{-12}\,\text{erg/cm}^{3}$

intracluster media contain plasmas with $\beta \sim 100$ $\left(\beta \equiv \dfrac{P_{\text{gas}}}{P_{\text{magnetic}}} \right)$

Observation of shocks in clusters: X-ray



X-ray shock in A520: $M_s \sim 2.1$

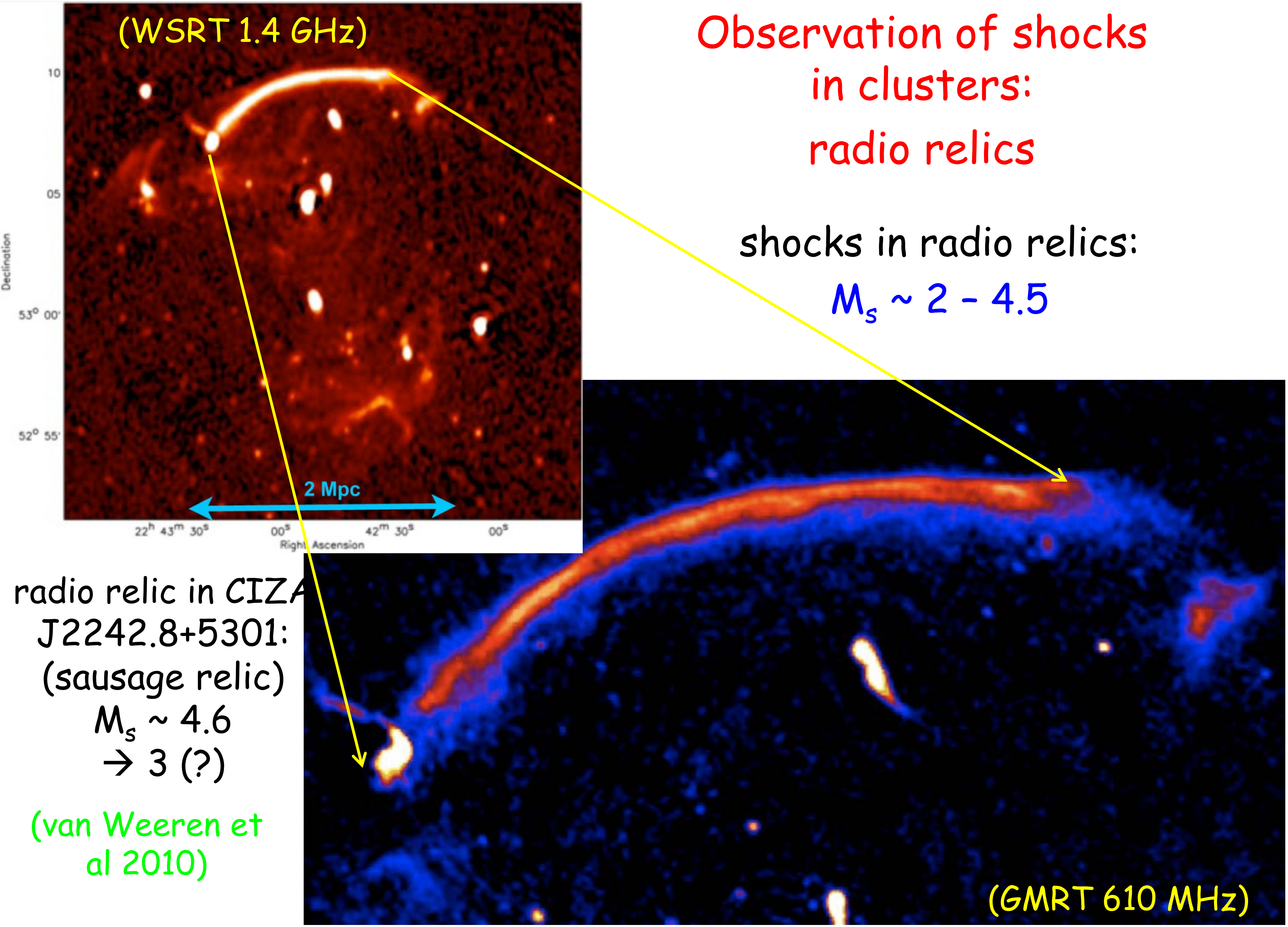
shocks in X-ray:

$M_s <\sim 3$,

mostly $M_s \sim 1 - 2$

(Markevitch & Vikhlinin 2007)

Observation of shocks in clusters: radio relics



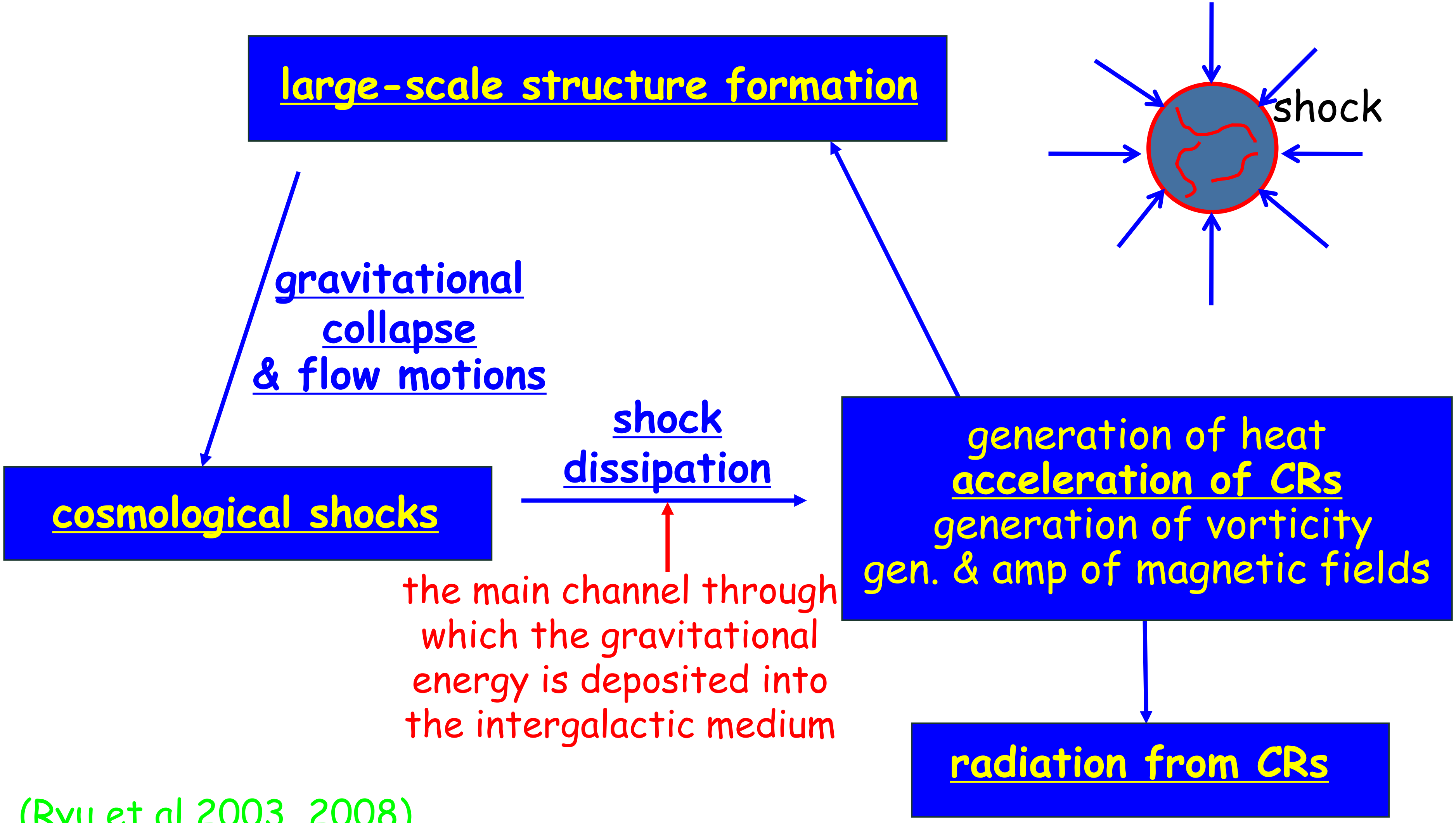
shocks in radio relics:

$M_s \sim 2 - 4.5$

radio relic in CIZA J2242.8+5301:
(sausage relic)
$M_s \sim 4.6$
→ 3 (?)

(van Weeren et al 2010)

Overview for formation and roles of shock waves in the large-scale structure of the universe



large-scale structure formation

gravitational collapse & flow motions

cosmological shocks

shock dissipation

the main channel through which the gravitational energy is deposited into the intergalactic medium

generation of heat
acceleration of CRs
generation of vorticity
gen. & amp of magnetic fields

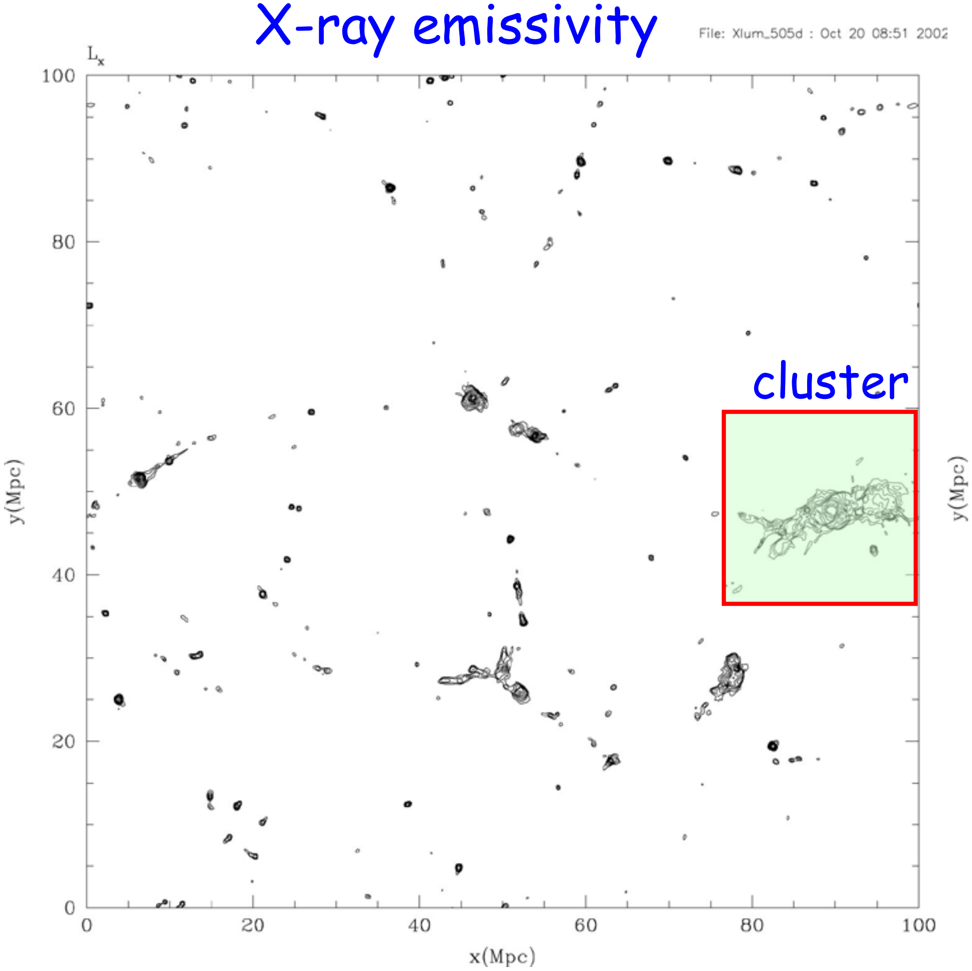
radiation from CRs

(Ryu et al 2003, 2008)

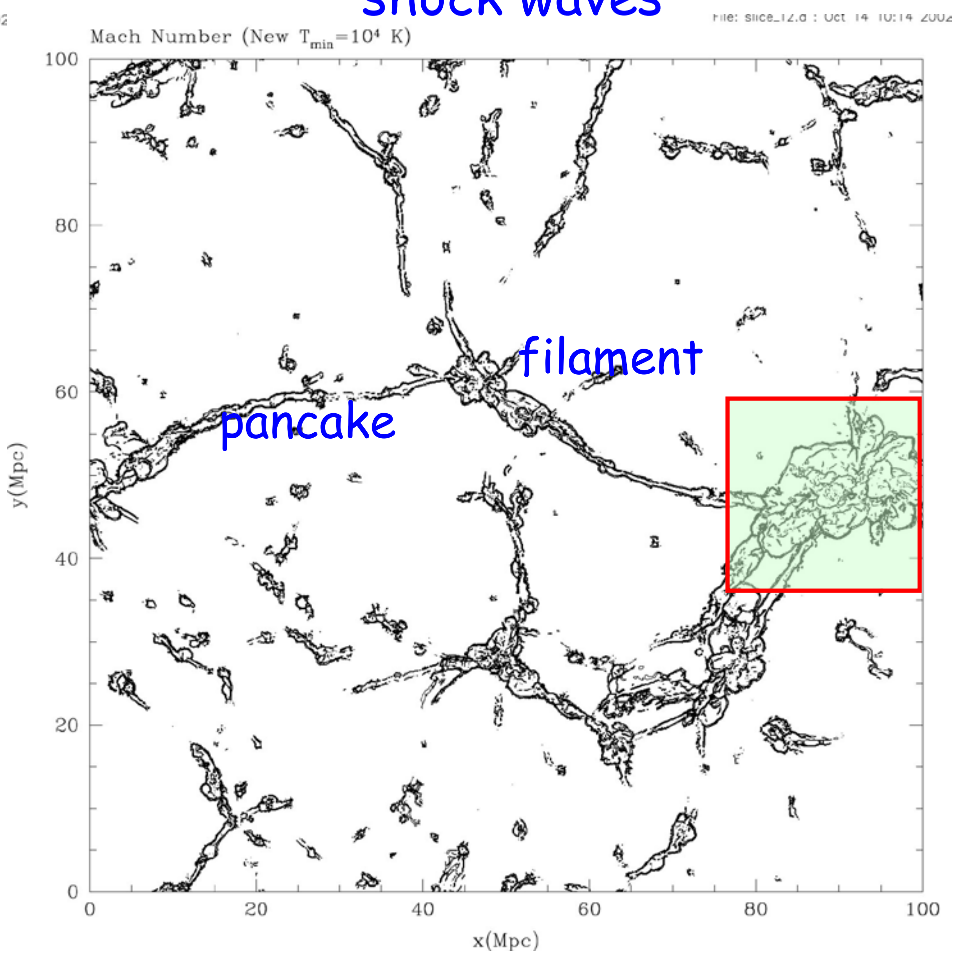
Spatial distribution of cosmological shocks in the large-scale structure of the universe

(Ryu, Kang, Hallman, Jones 2003)

X-ray emissivity

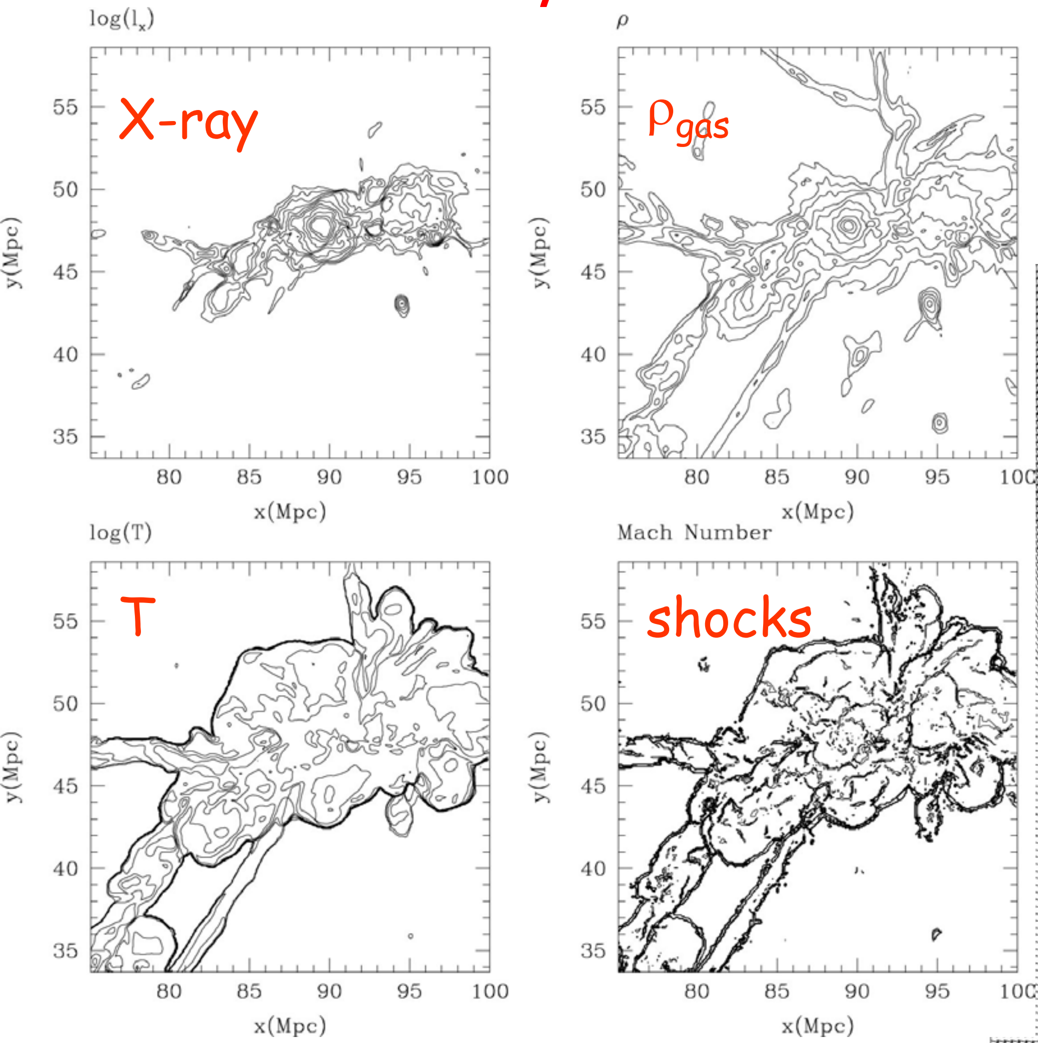


shock waves



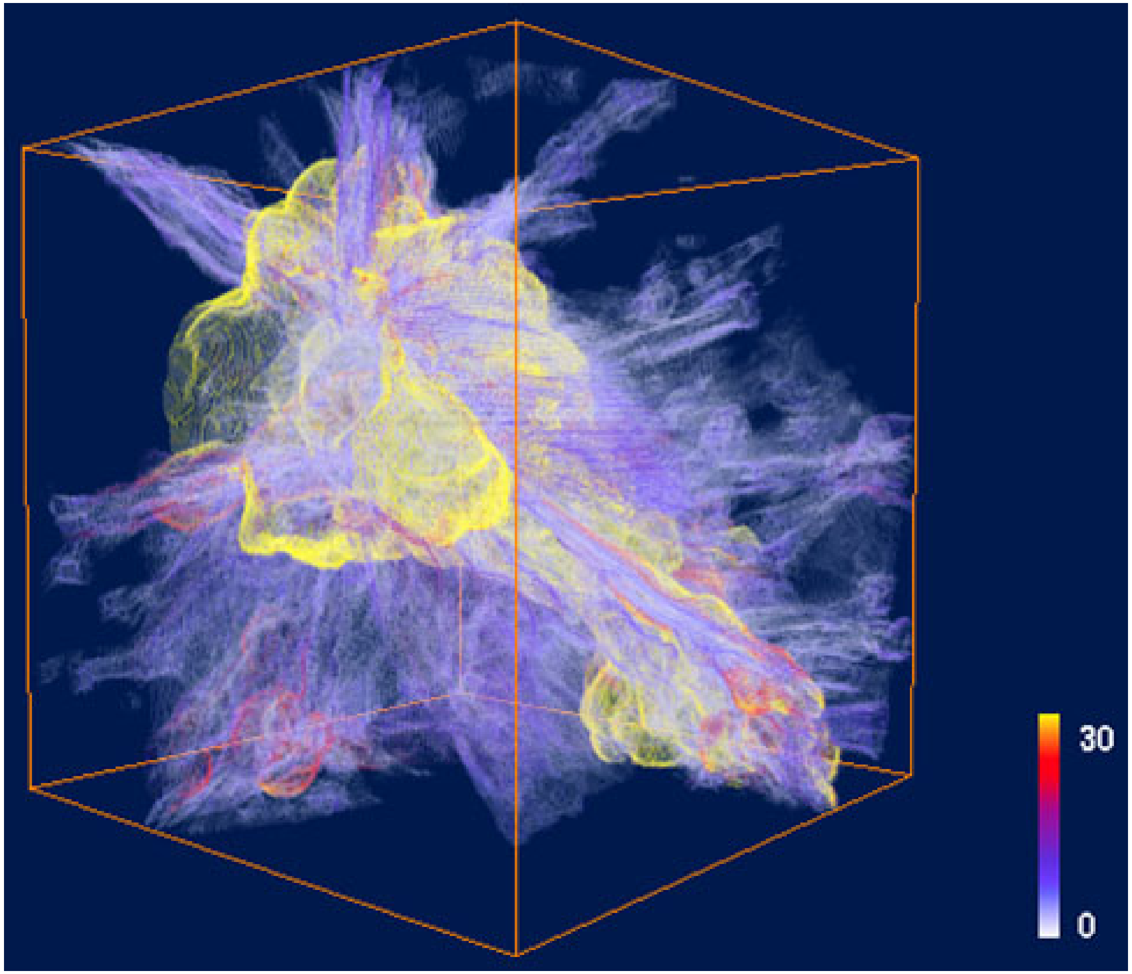
rich, complex shock morphology:
shocks “reveal” cluster, filaments, and sheets

Velocity field and shocks in a cluster complex



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

Mach number distribution of shocks around a cluster complex



external shocks surrounding the cluster complex:

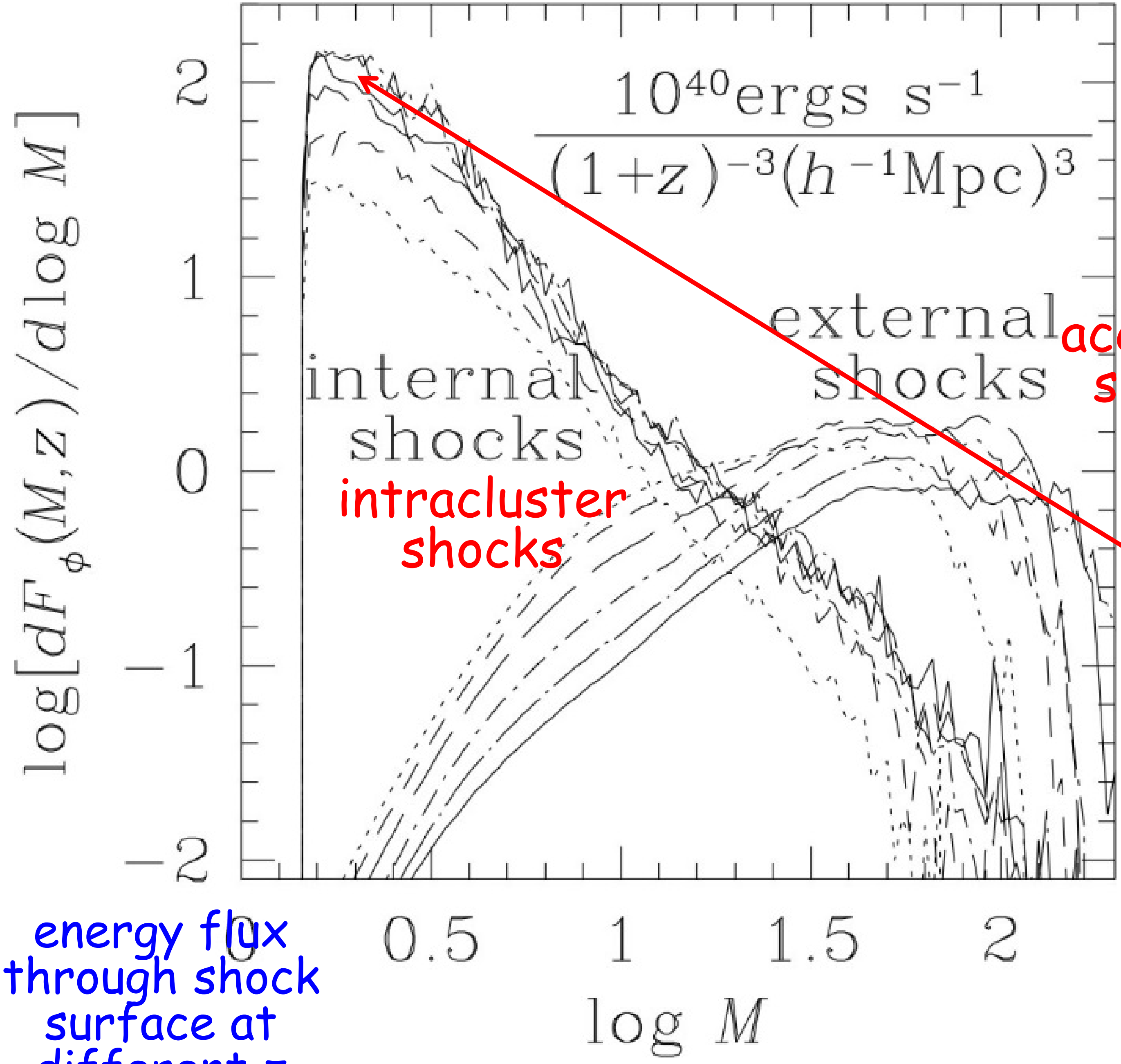
$M_s > \sim 10$

internal shocks inside the cluster complex

$M_s < \sim$ several

Energetics of shocks

(Ryu, Kang, Hallman, Jones 2003)



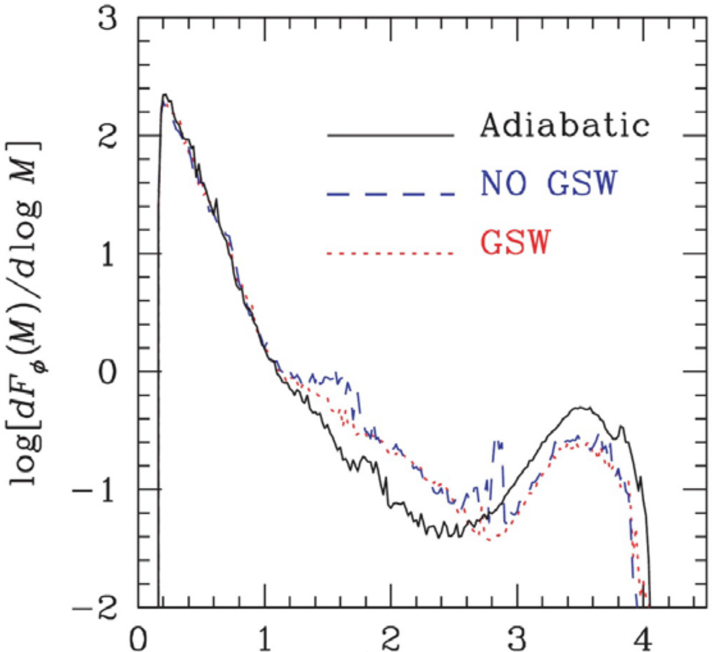
accretion shocks

intracluster shocks

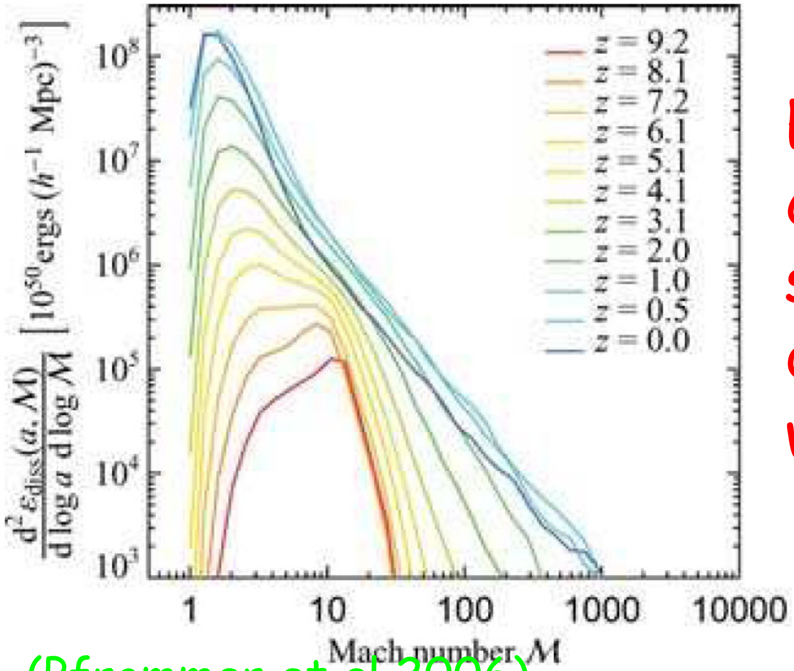
energy flux through shock surface at different z

Weak internal shocks with M <~ a few, V_s ~ 2,000 km/s are dominant inside the ICM and energetically important.

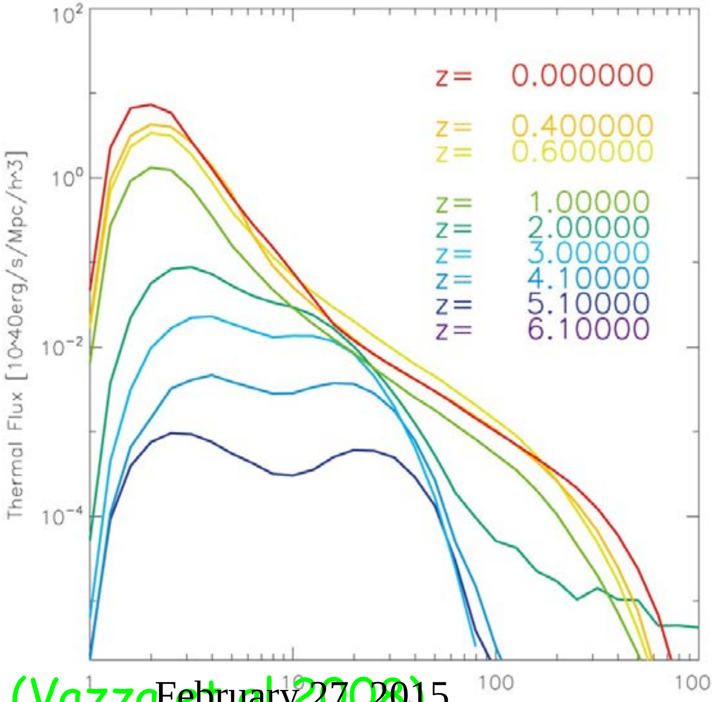
Energetics of cosmological shocks in different works



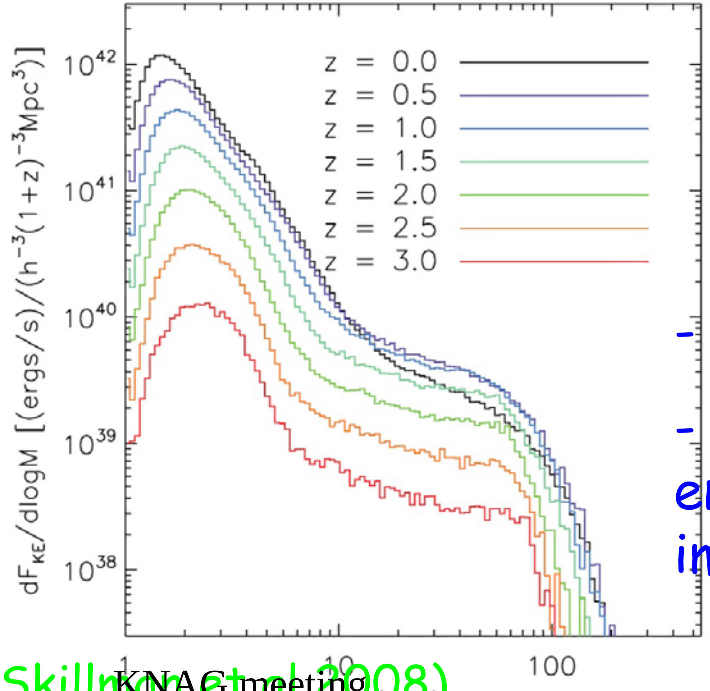
(Kang, Ryu, et al 2007)



(Pfrommer et al 2006)



(Vazza et al 2008)



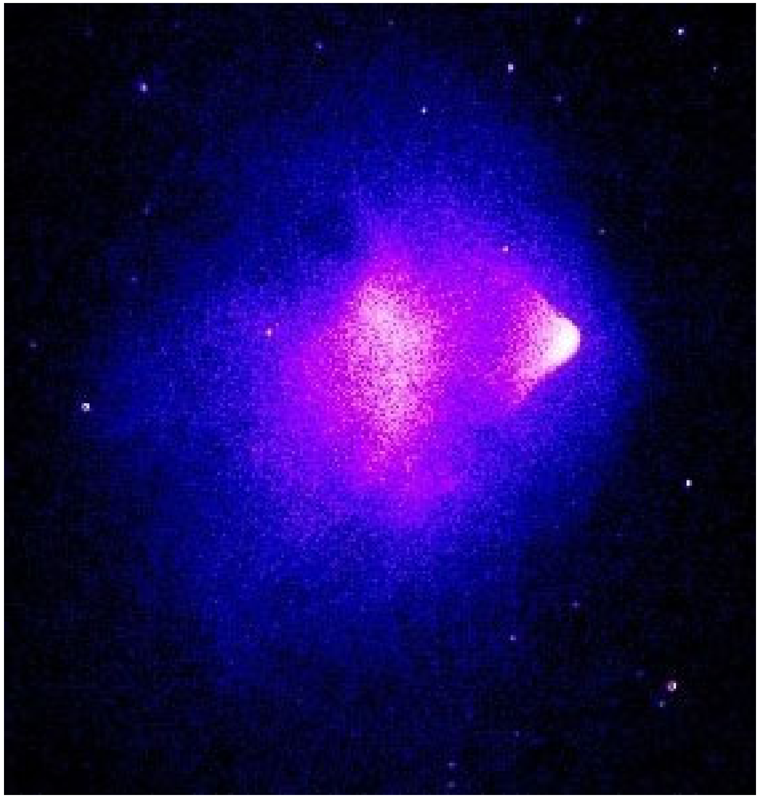
(Skillman et al 2008)

- agreement is OK
- weak shocks are energetically most important

The nature of shocks found in intracluster mediia

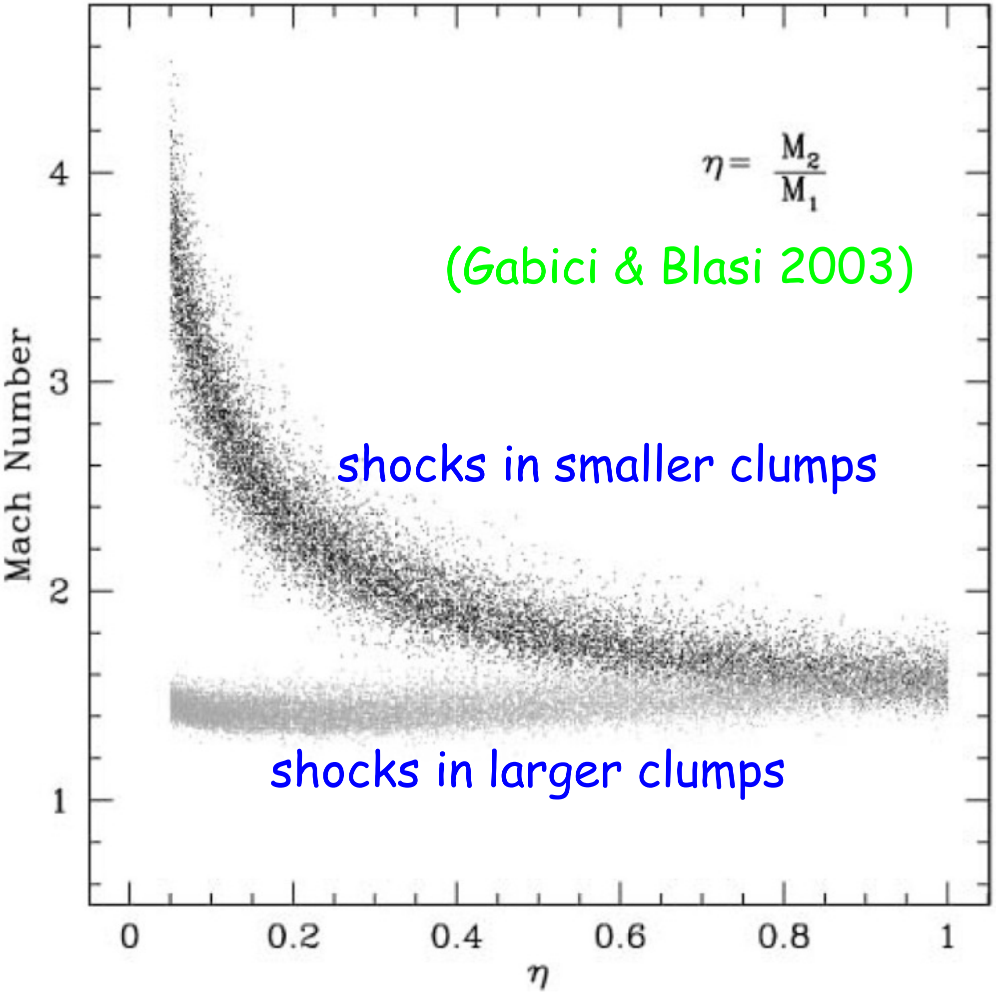
(Ryu et al 2003)

Merger shocks: $M_s < \sim 3 - 4$ (?)



Bullet cluster: $M_s = \sim 2 - 3$

(Markevitch et al 2002)

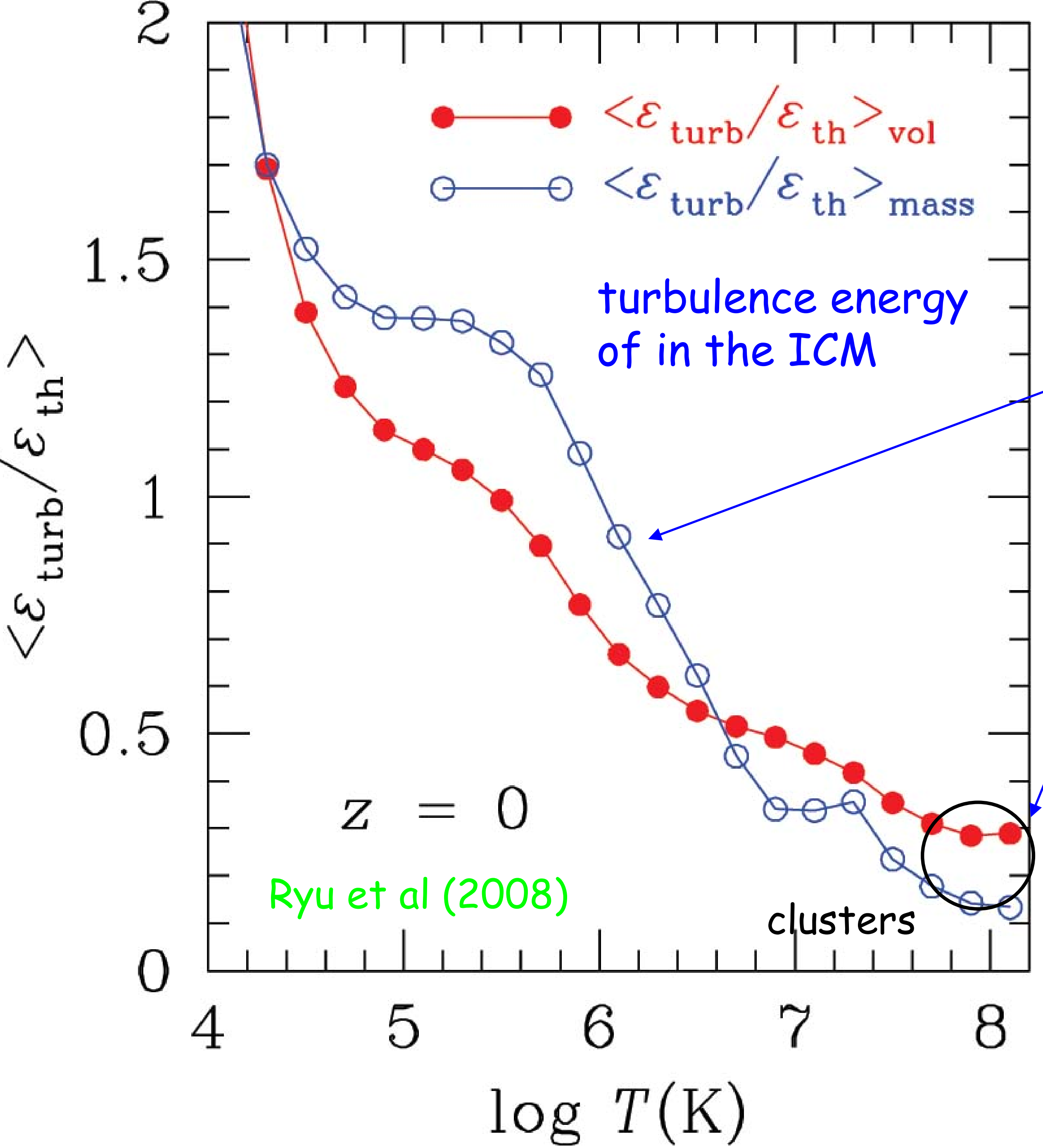


(Gabici & Blasi 2003)

shocks in smaller clumps

shocks in larger clumps

Turbulence shocks



turbulence energy of in the ICM

Ryu et al (2008)

clusters

E_{turb}/E_{therm} ~ 1 in filaments

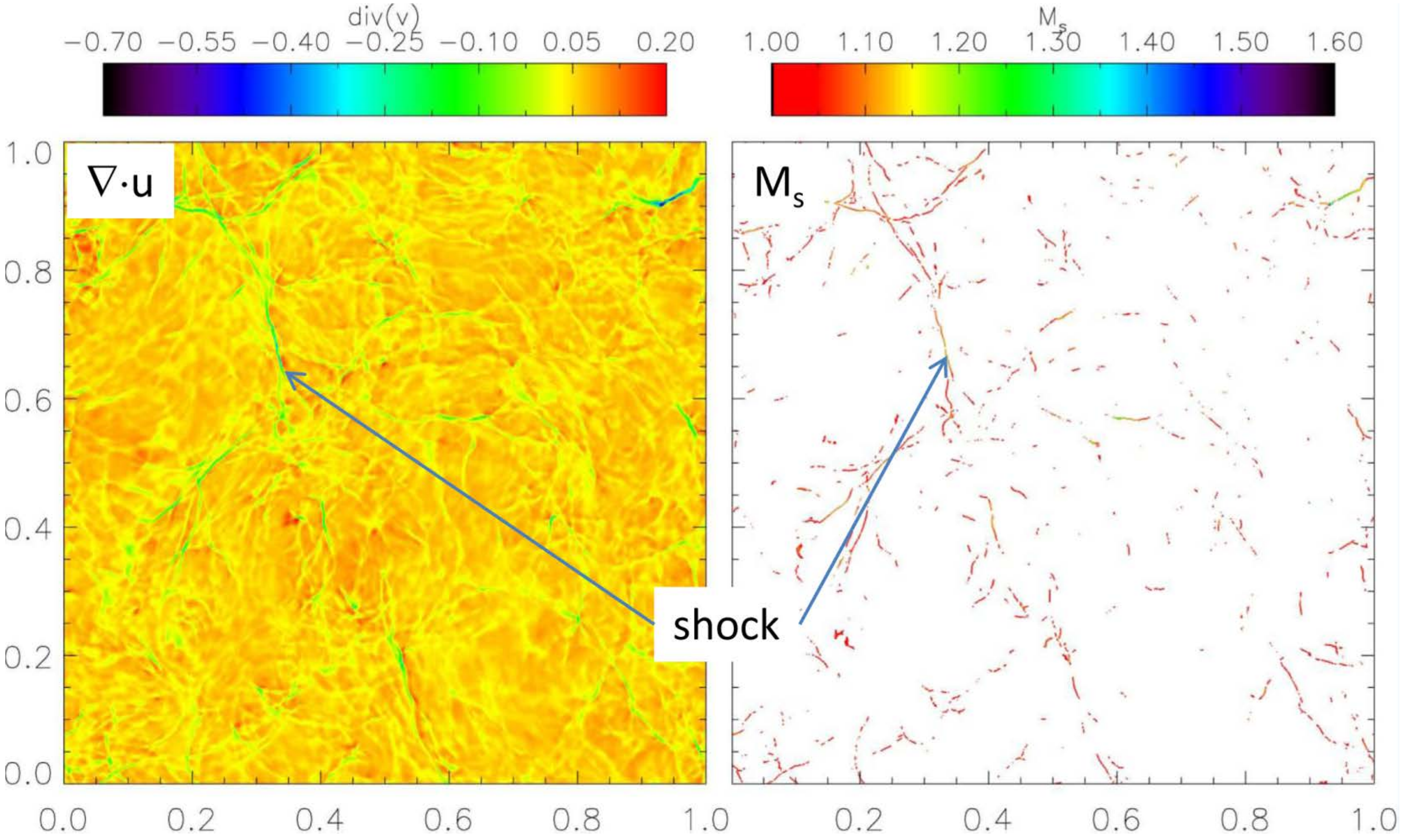
E_{turb}/E_{therm} ~ 0.1 – 0.3 inside and outskirts of clusters

rms Mach number of turbulence in clusters:

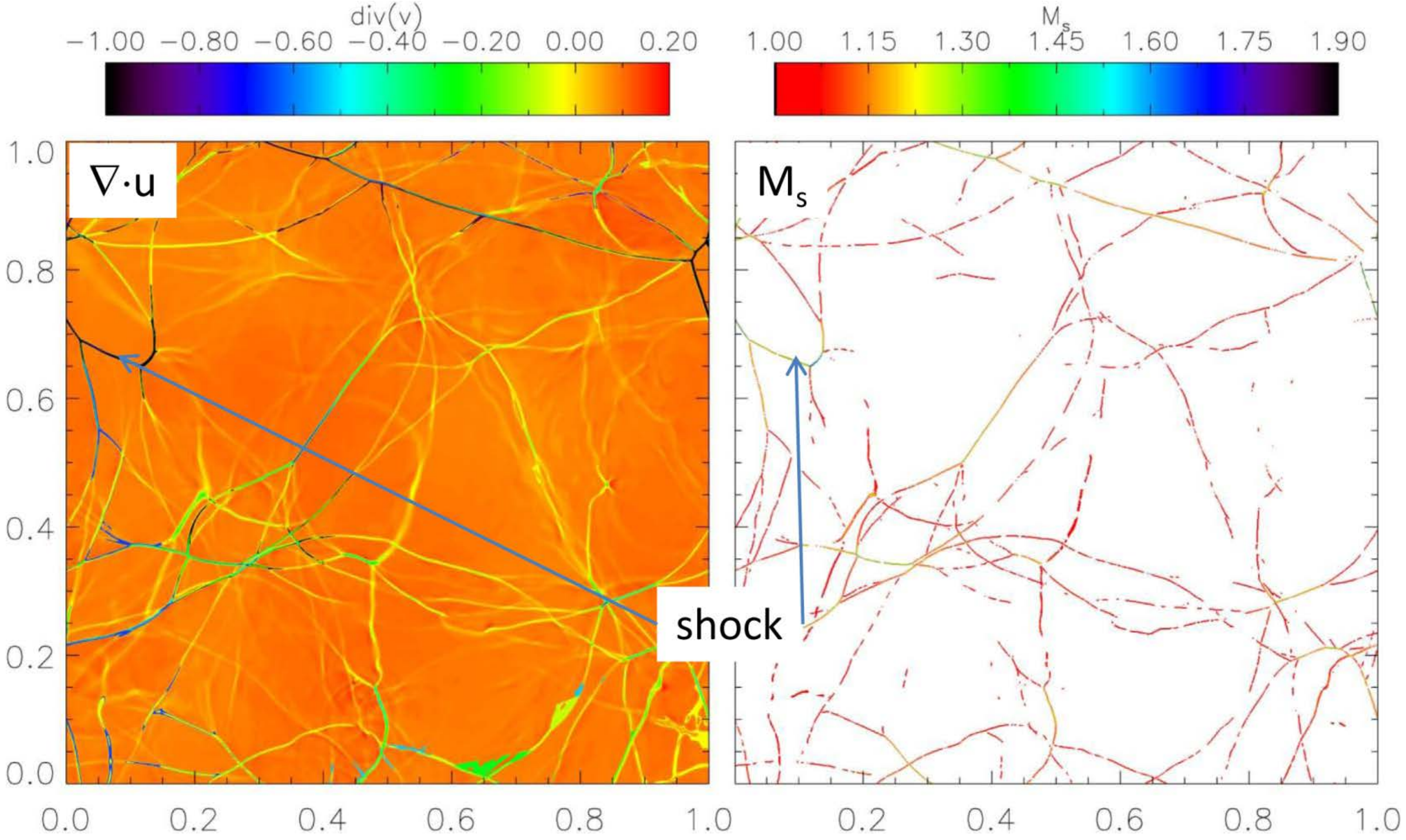
M_{turb} ~ 0.5

(Ryu et al 2008; Lau et al 2009)

distribution of shocks waves in MHD turbulence with $M_s = 0.45$ in high β plasma with solenoidal forcing

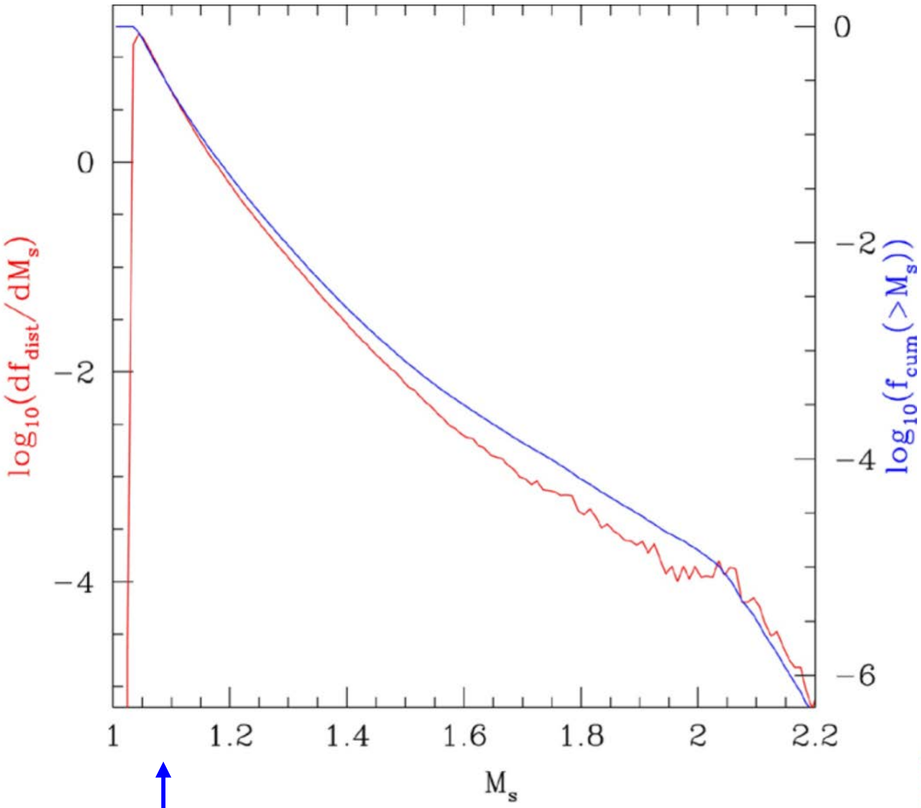


distribution of shocks waves in MHD turbulence with $M_s = 0.45$ in high β plasma with compressive forcing



Turbulence shocks:

M_s < ~ 2 (?)



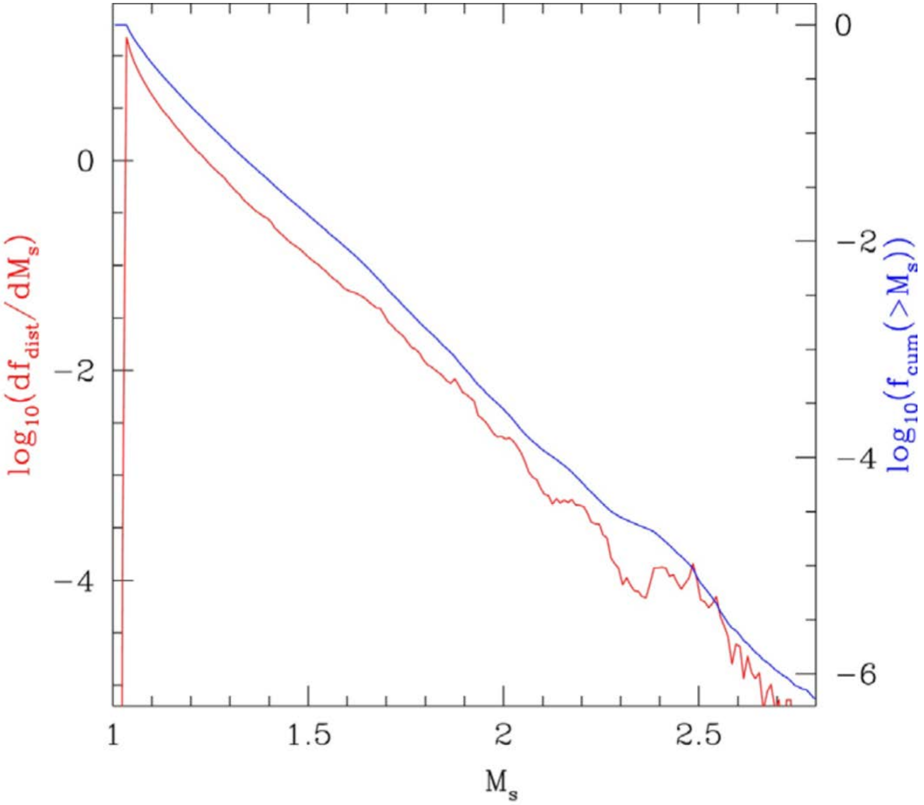
↑ solenoidal forcing

$$\frac{df_{dis}}{dM_s} \propto \exp(-15\sqrt{M_s - 1})$$

(Porter, Jones, Ryu, & Cho, to be submited)

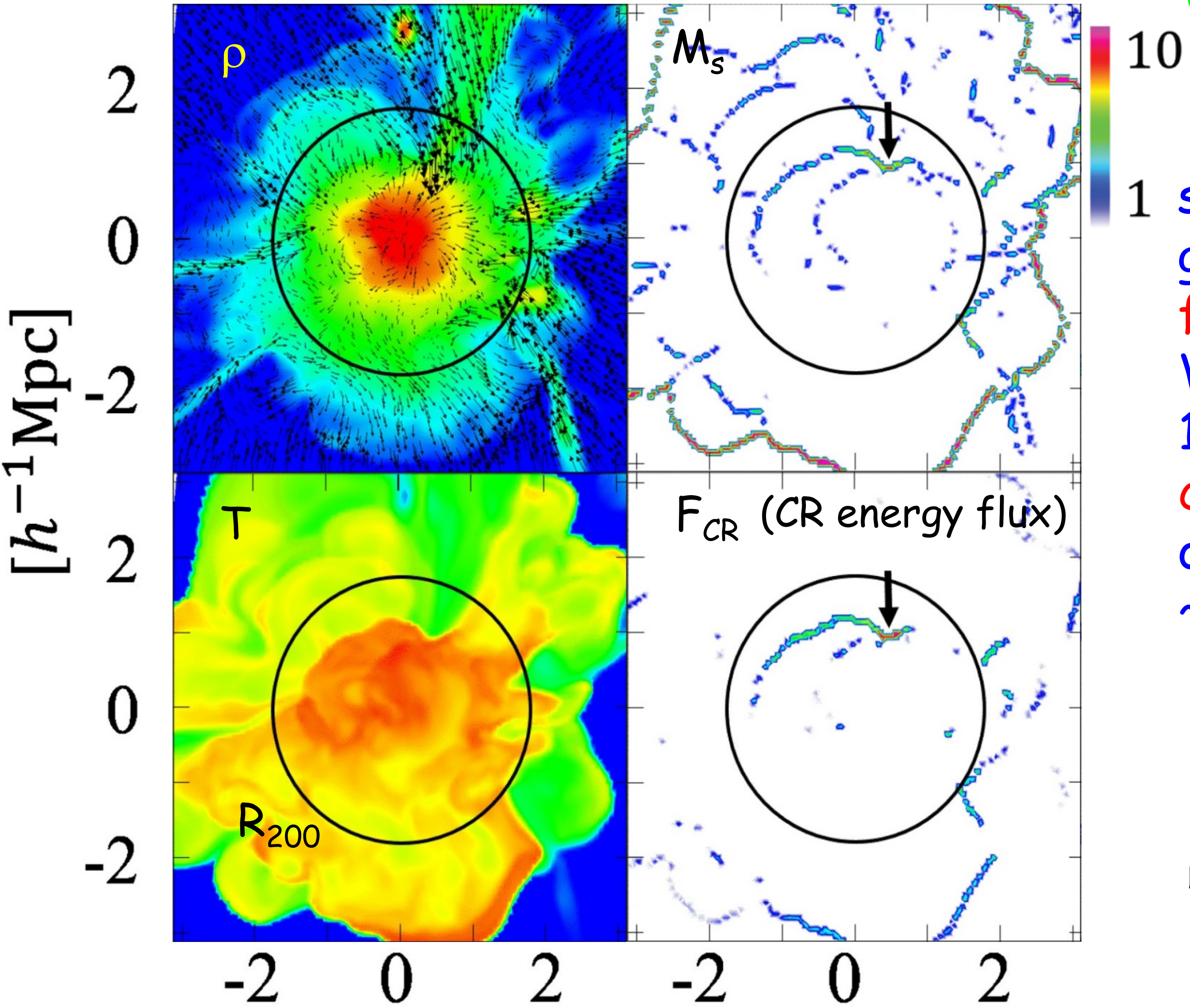
$$\frac{df_{dis}}{dM_s} \propto \exp(-8\sqrt{M_s - 1})$$

compressive forcing ↓



Infall (accretion) shocks found mostly in cluster outskirts

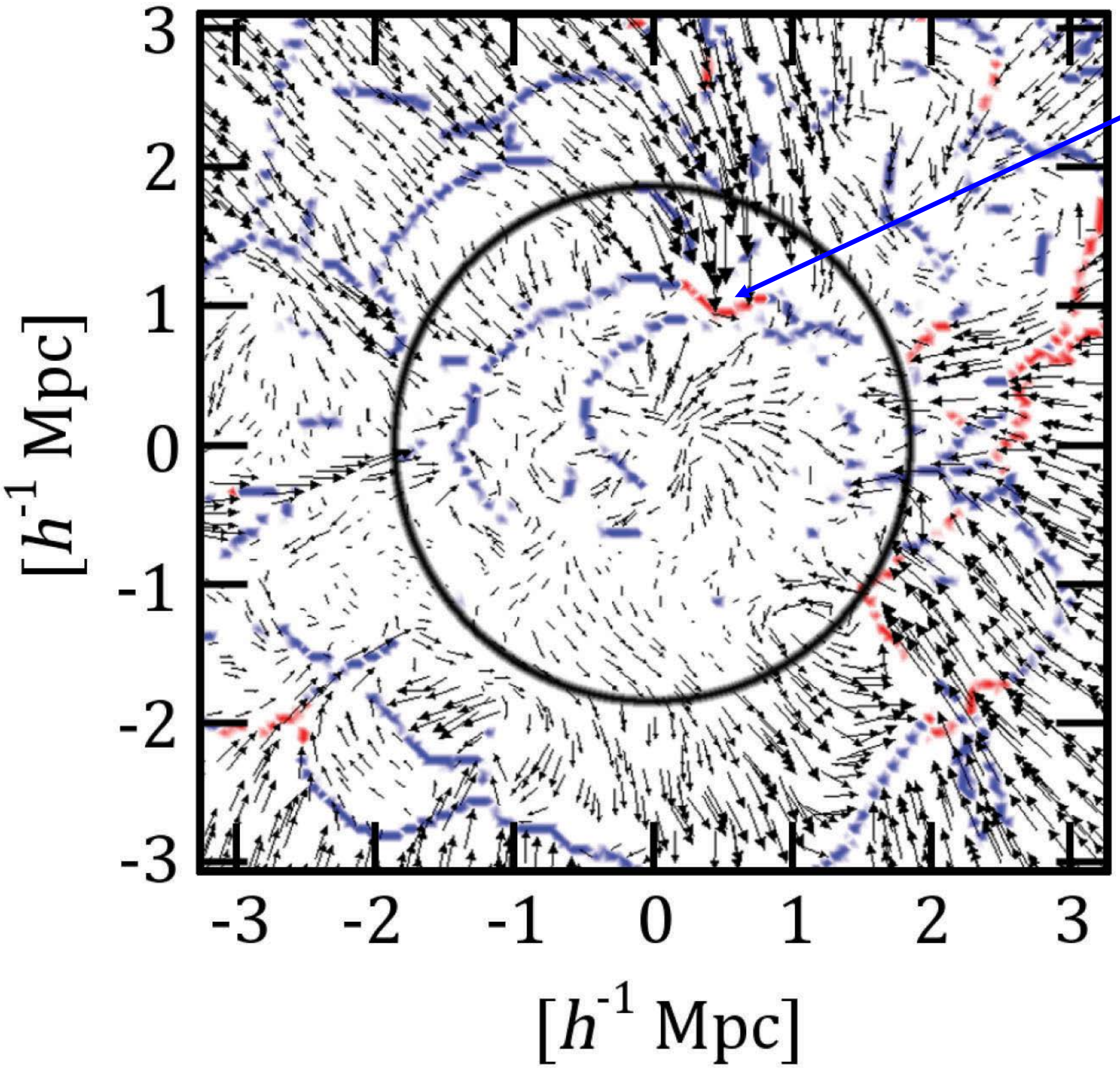
(Hong, Ryu, Kang, Cen 2014)



shocks formed by gas inflow from filaments of the WHIM with T ~ 10^5 – 10^7 K to cluster outskirts of hot gas with T ~ 10^7 - 10^8 K:

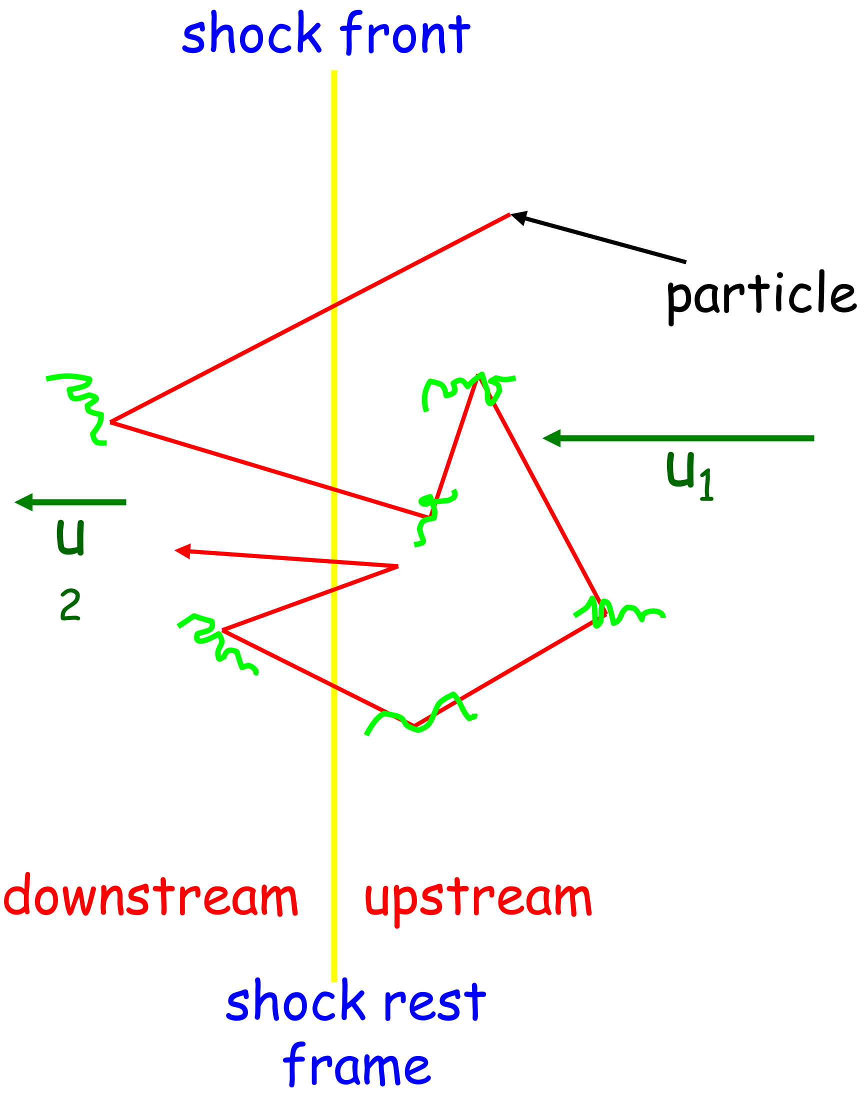
M_s >~ a few

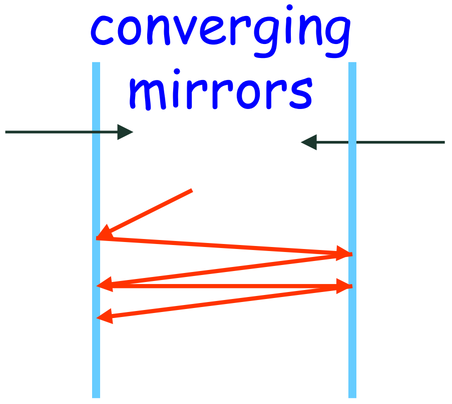
$\rho(r<R_{200}) = 200\,\bar{\rho}$
(R_{200} ~ 1.3 R_{vir})



infall shock

Diffusive shock acceleration (DSA) at cosmological shocks





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

Fermi first order process

Efficiency of cosmic ray acceleration at shocks (protons)

DSA simulations with MFA (magnetic field amplification at shocks) and AD (Alfvenic drift)

(Kang & Ryu 2013)

Diffusion convection eq with wave drift effect

$$\frac{\partial f}{\partial t}+(u+u_w)\frac{\partial f}{\partial x}=\frac{1}{3}\frac{\partial}{\partial x}(u+u_w)\cdot p\frac{\partial f}{\partial p}+\frac{\partial}{\partial x}\left[\kappa(x,p)\frac{\partial f}{\partial x}\right]+Q(x,p)$$

$u_w \approx \text{wave drift speed} \approx V_A = B/\sqrt{4\pi\rho}$

$\kappa(x,p) \approx \kappa^* p(\rho/\rho_0)^{-1}$: Bohm - like diffusion

$Q(x,p) =$ thermal leakage injection

Ordinary gasdynamics eqs + P_c terms

$$\frac{\partial\rho}{\partial t}+\frac{\partial(u\rho)}{\partial x}=0$$

(1D plane quasi-parallel shock)

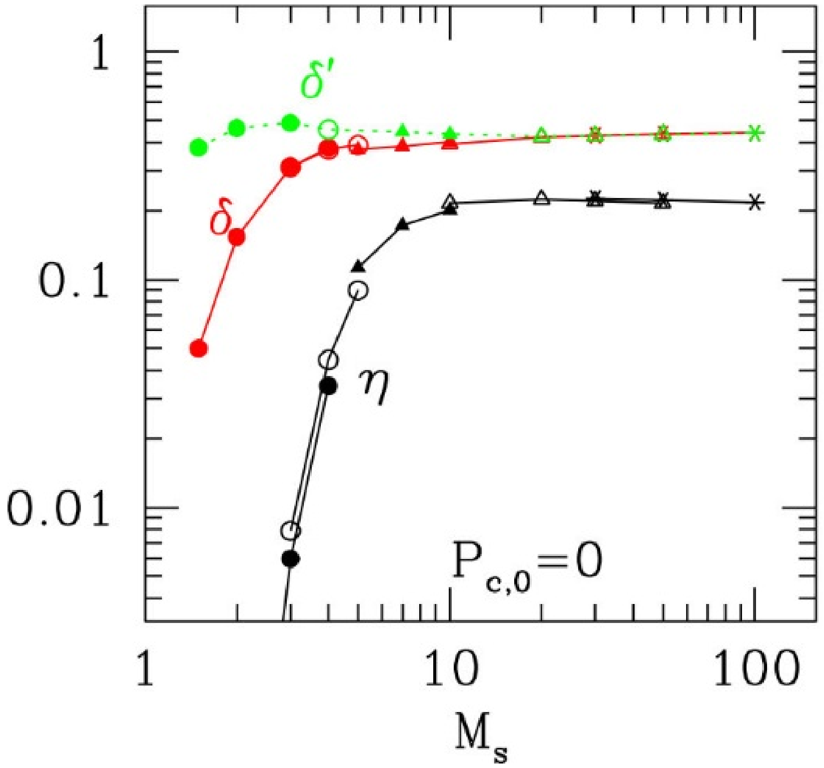
$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial}{\partial x}(\rho u^2+P_g+P_c)=0$$

$$\frac{\partial(\rho e_g)}{\partial t}+\frac{\partial}{\partial x}(\rho e_g u+P_g u)=-u\frac{\partial P_c}{\partial x}+W-L$$

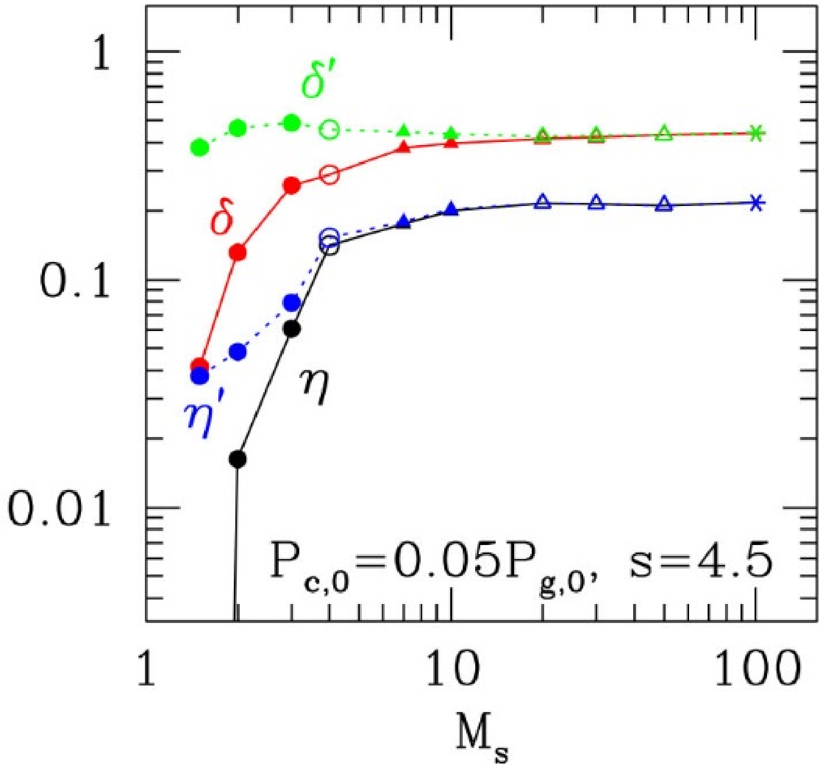
W = wave dissipation heating, L = thermal energy loss due to injection

$$\delta(M_s) \equiv \frac{[e_{g,2} - e_{g,0}(\rho_2/\rho_0)^{\gamma_g}]u_2}{(1/2)\rho_0 u_s^3},$$ gas thermalization efficiency

$$\eta(M_s) \equiv \frac{[e_{c,2} - e_{c,0}(\rho_2/\rho_0)^{\gamma_c}]u_2}{(1/2)\rho_0 u_s^3},$$ cosmic-ray acceleration efficiency

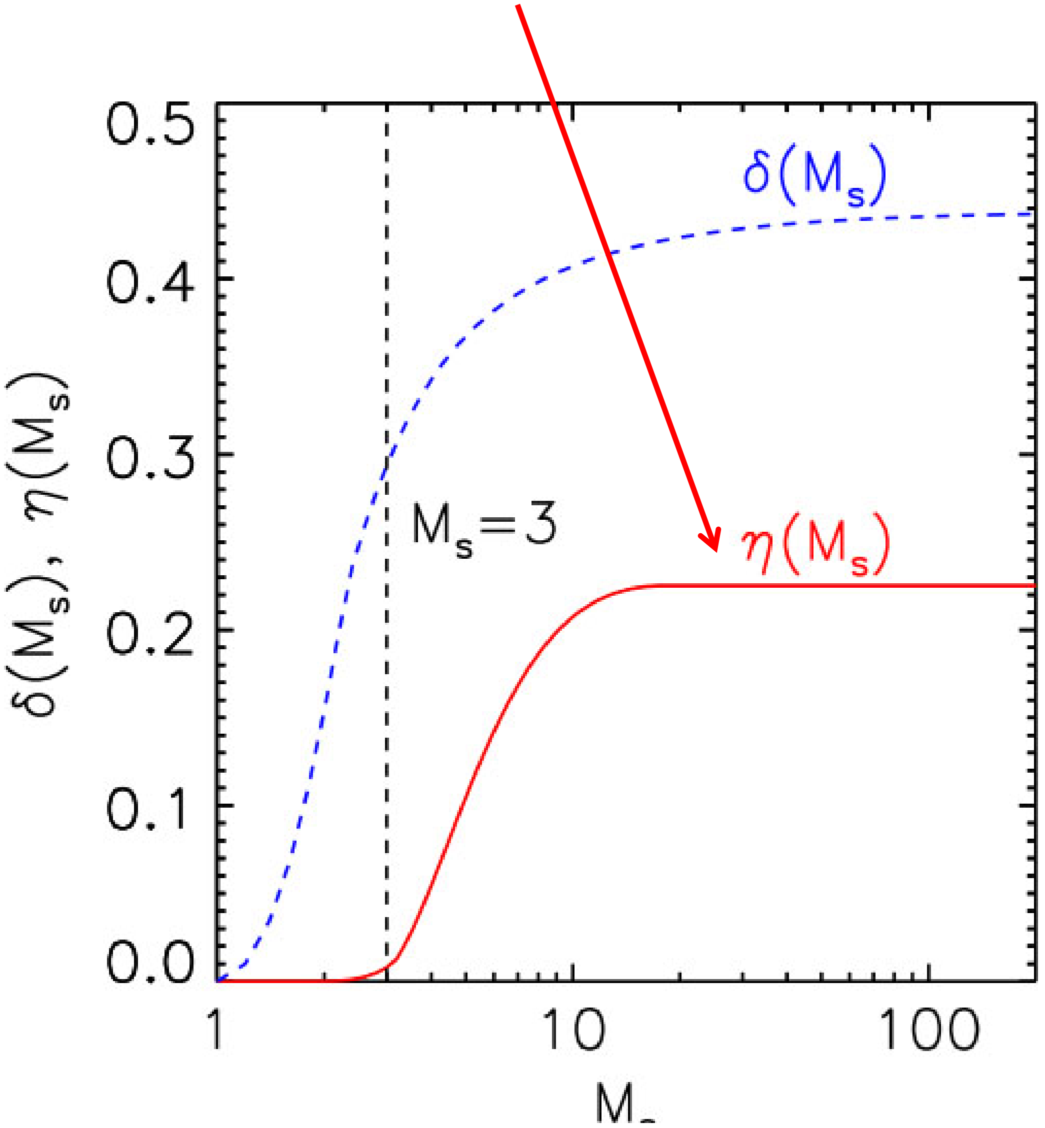


without pre-existing CRs



with pre-existing CRs

CR acceleration efficiency at shocks (protons)



(Kang & Ryu 2013)

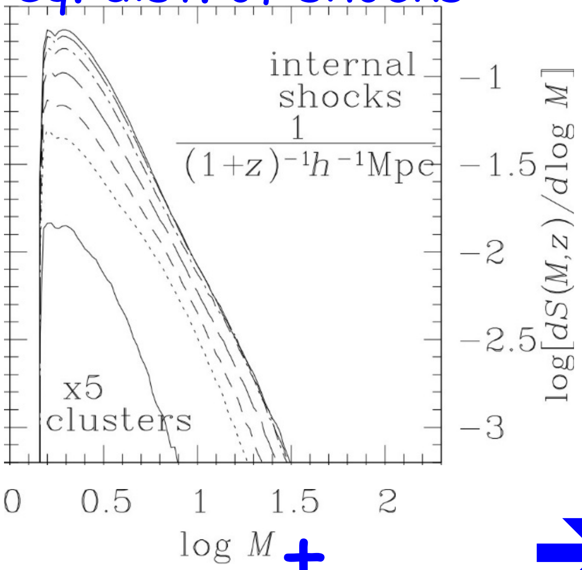
1) CR acceleration efficiency is larger at stronger (higher M_s) shock, η → ~20 % at large M_s

2) X (=P_{CR}/P_{th}) = $\frac{1}{2}$ E_{CR}/E_{th} <~ 0.01 for M_s <~ 3

3) the efficiency is based on phenomenological models

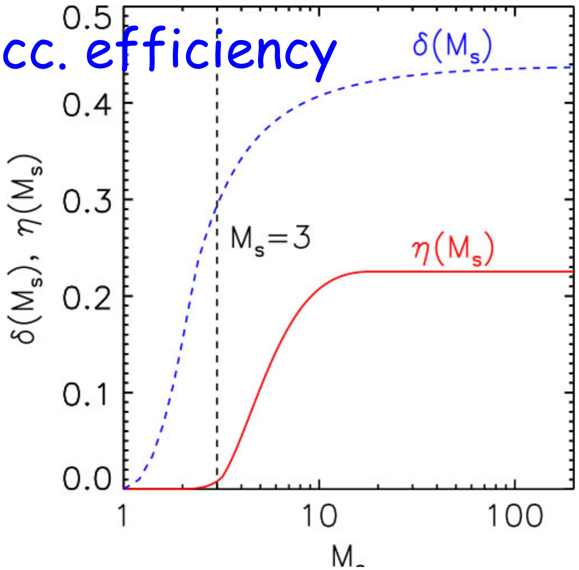
CR acceleration (protons) at intracluster shocks

freq. dist. of shocks

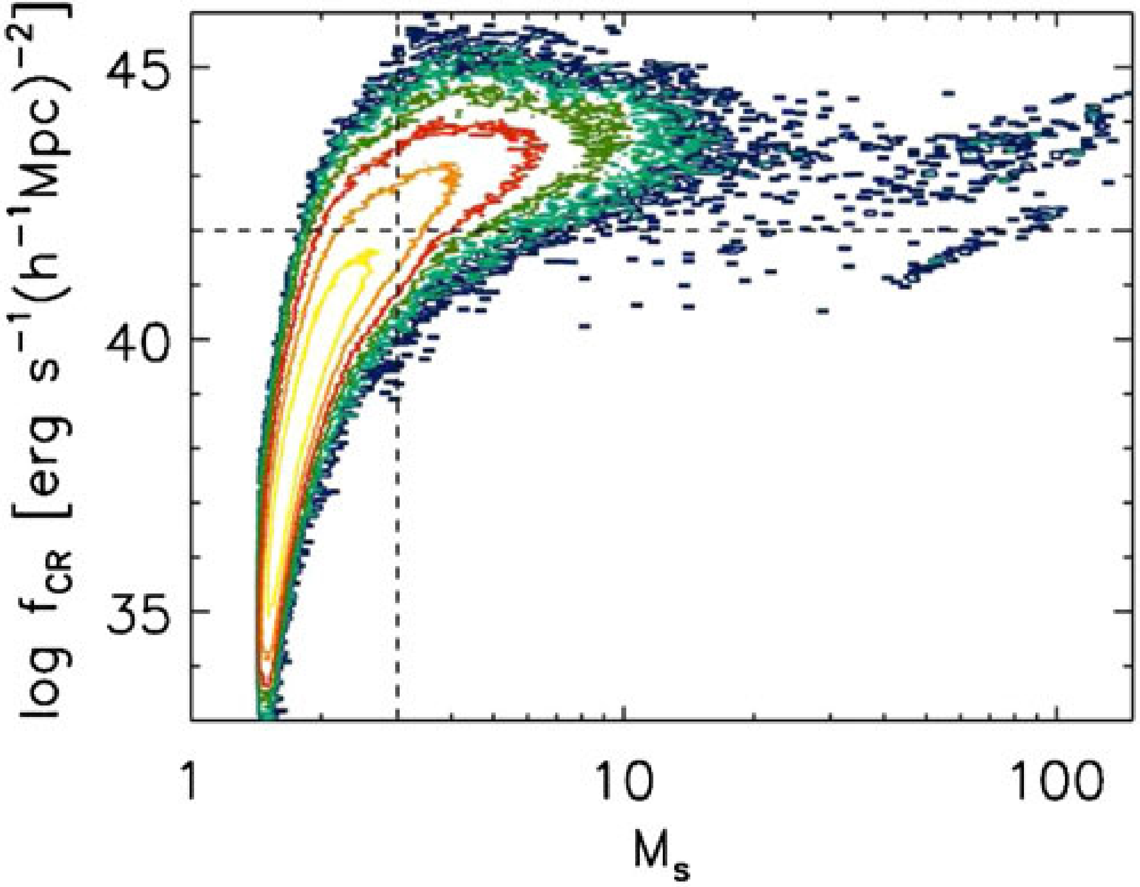


+

acc. efficiency

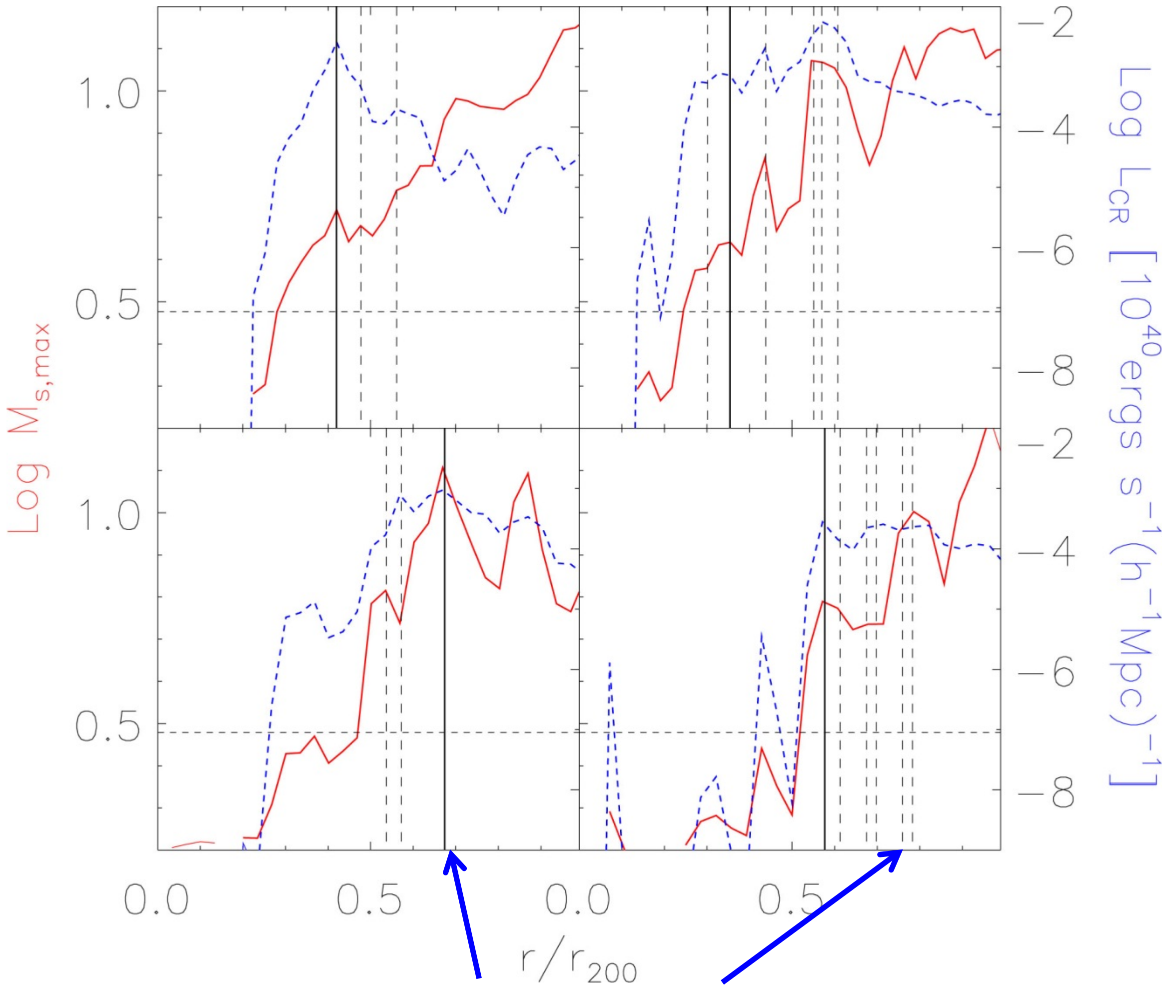


Internal shocks with M ~ a few to several are most important in CR production in clusters



(Hong, Ryu, Kang, Cen 2014)

maximum Mach number of shocks (red) and the CR energy luminosity per unit radius (blue) in the radial bin (r, r+dr) for four clusters



bins with energetic infall shocks

- infall shocks produce a substantial fraction of CRs in clusters
- CRs are produced mostly in cluster outskirts (>~ 0.5 R_{vir})
- mixing and diffusion of CRs (?)

(Hong, Ryu, Kang, Cen 2014)

Summary

- Shocks waves with M_s <~ 10 are common in intracluster media.
- They are classified inti merger shocks, turbulence shocks, and infall shocks.
- While the gas heating is induced mostly at weak (merger ?) shocks, a substantial of CRs may be produced at infall shocks.