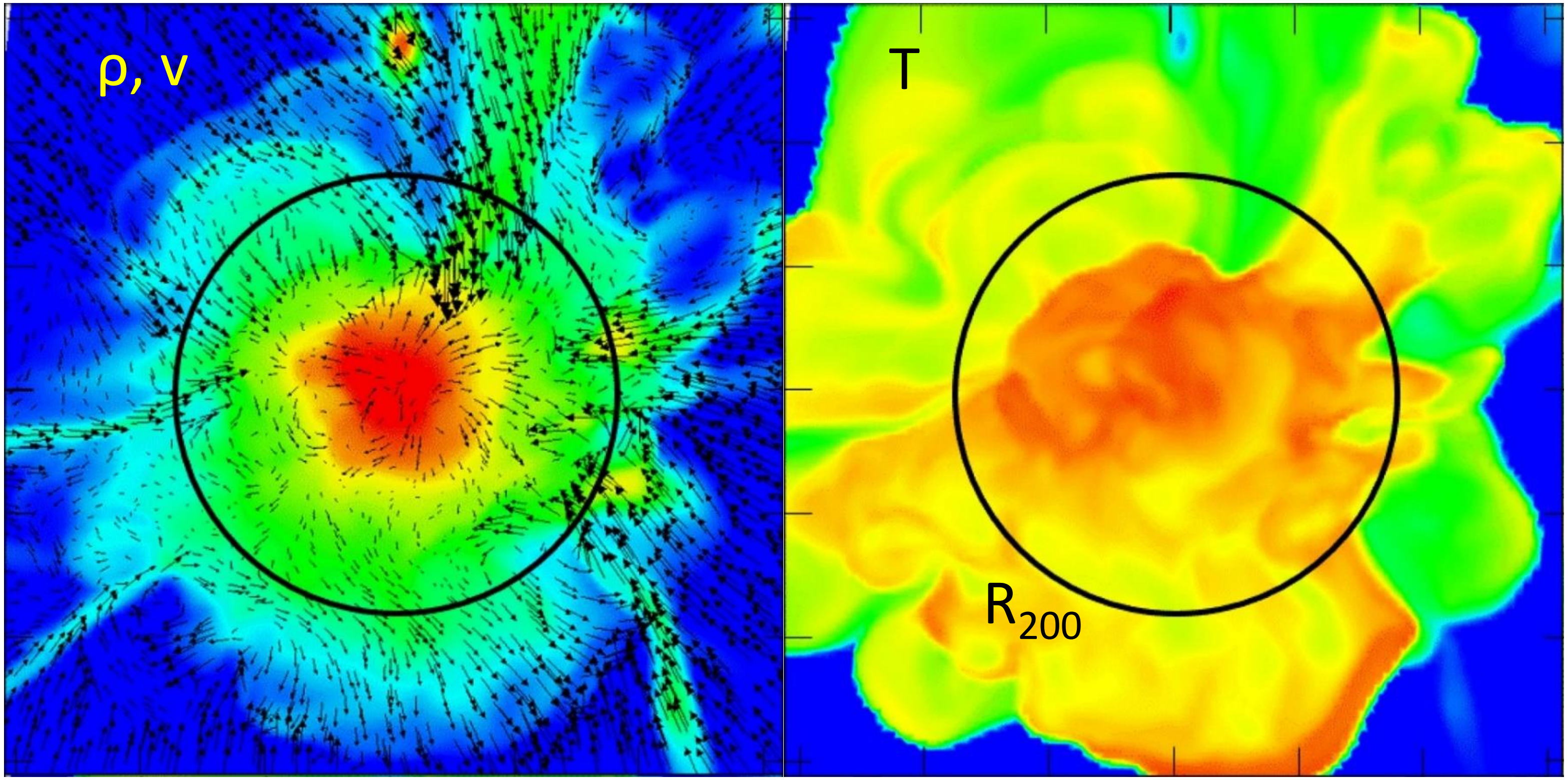
(Nature of) Shock Waves (and Particle Acceleration) in (the Outskirt of) Simulated Clusters of Galaxies



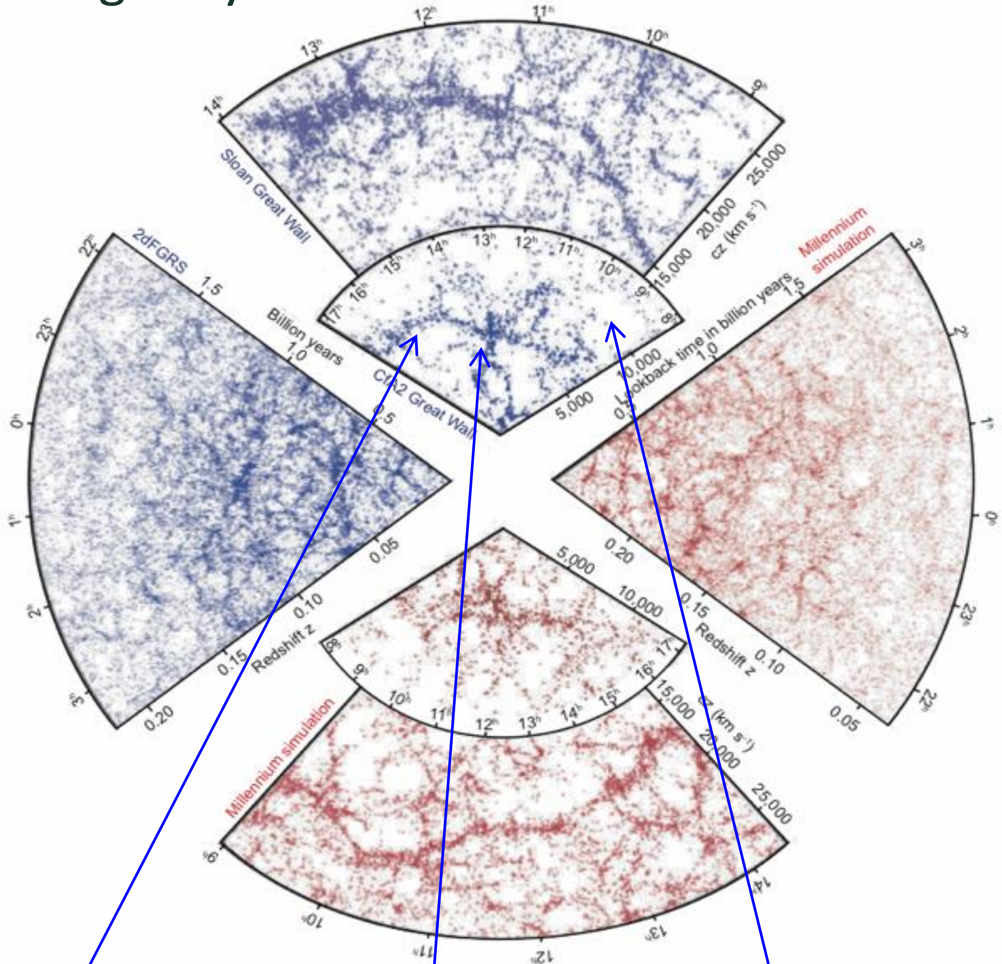
Dongsu Ryu

UNIST (Ulsan National Institute of Science and Technology, Korea)
KASI (Korea Astronomy and Space Science Institute, Korea)

Hyesung Kang (PNU, Korea), Ji-Hoon Ha (UNIST, Korea)
and others

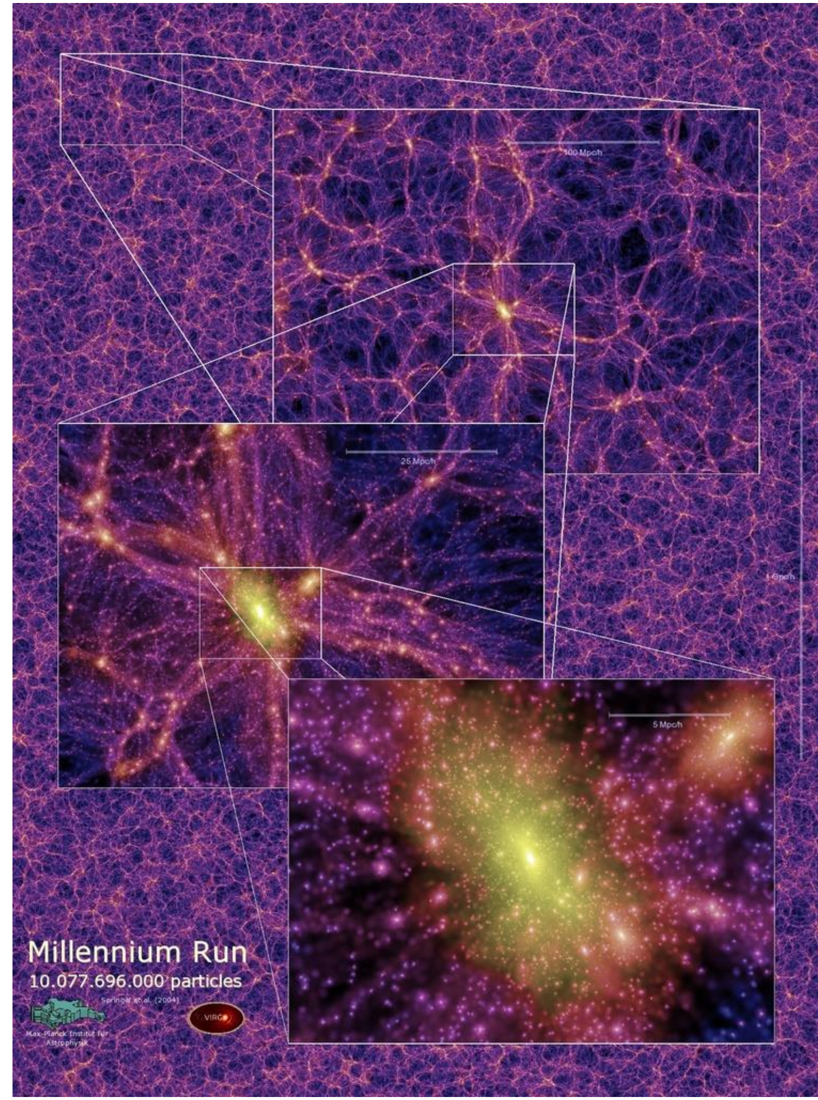
The large-scale structure of the universe

observed and simulated
galaxy distribution



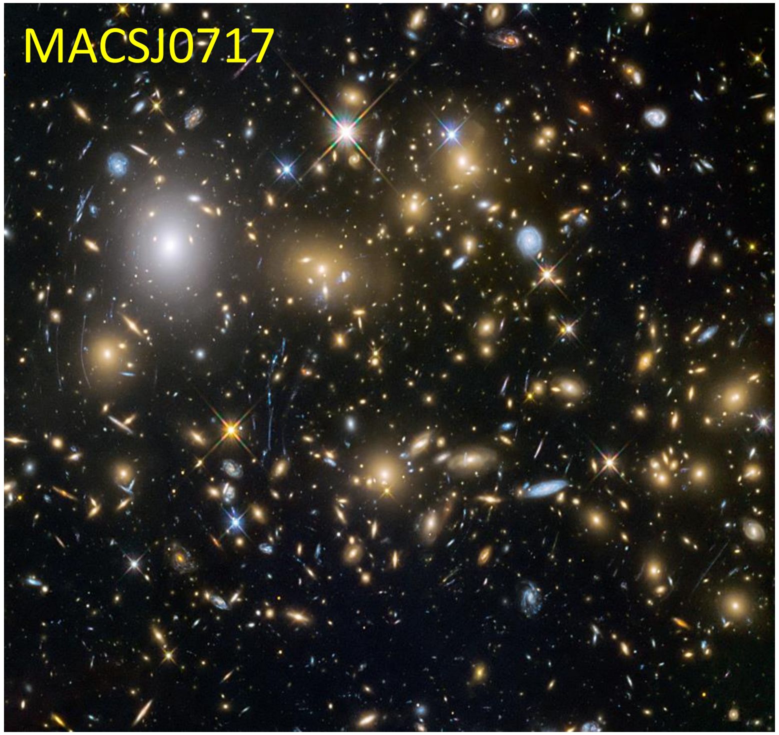
filaments clusters void regions

→ the cosmic web

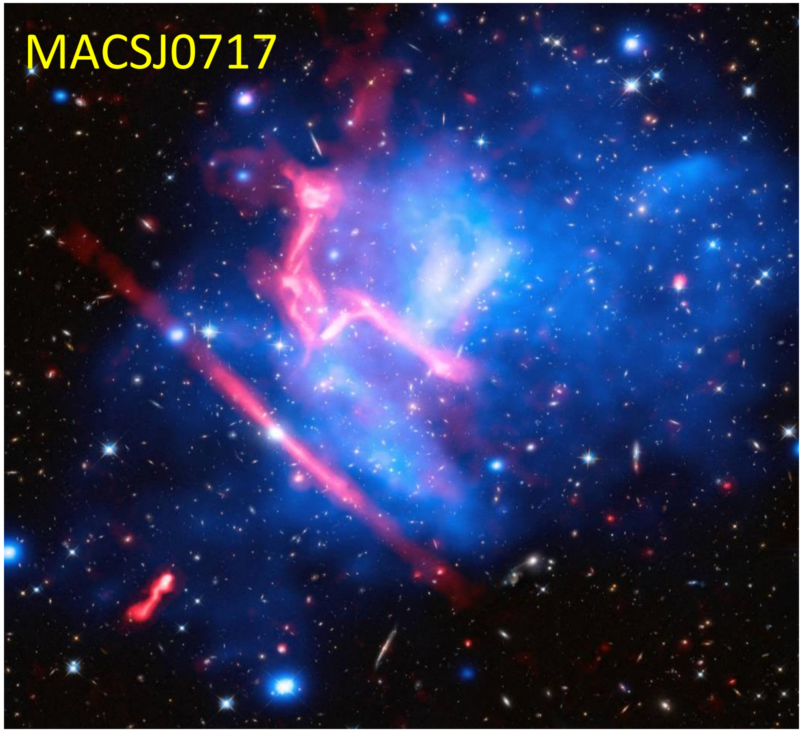


simulated matter distribution

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



Hubble space telescope image
← mostly star light

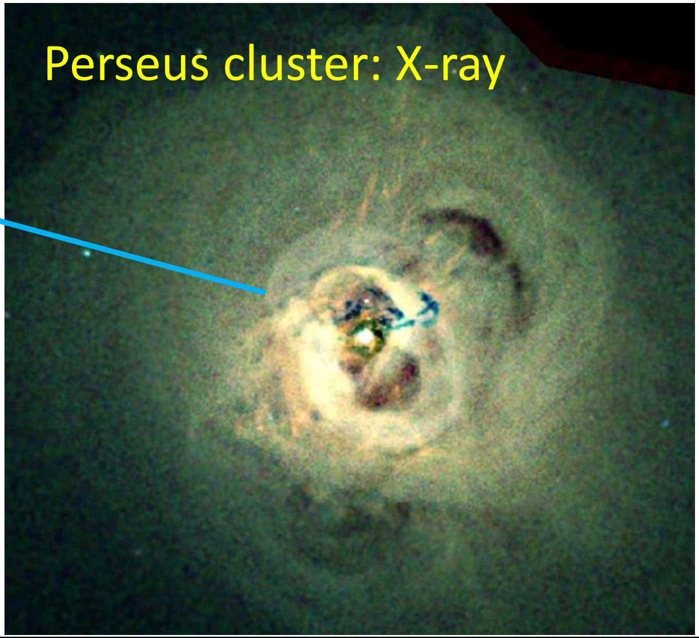


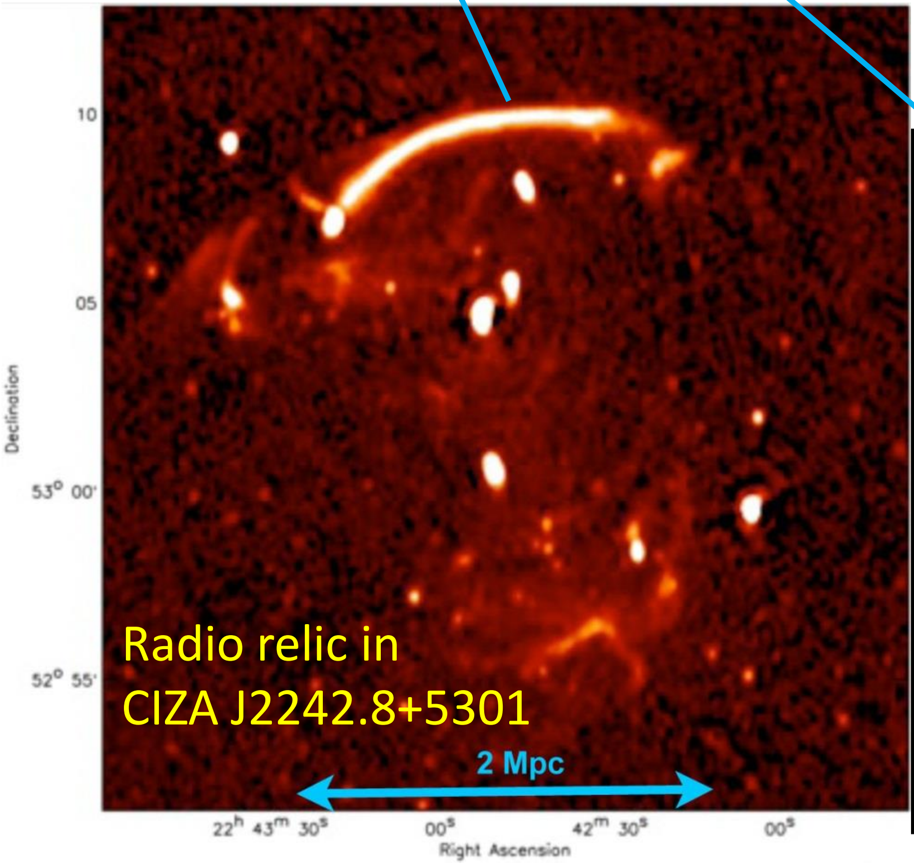
optical (Hubble, white)
X-ray (Chandra, blue) ← hot gas
radio (VLA, red) ← cosmic rays

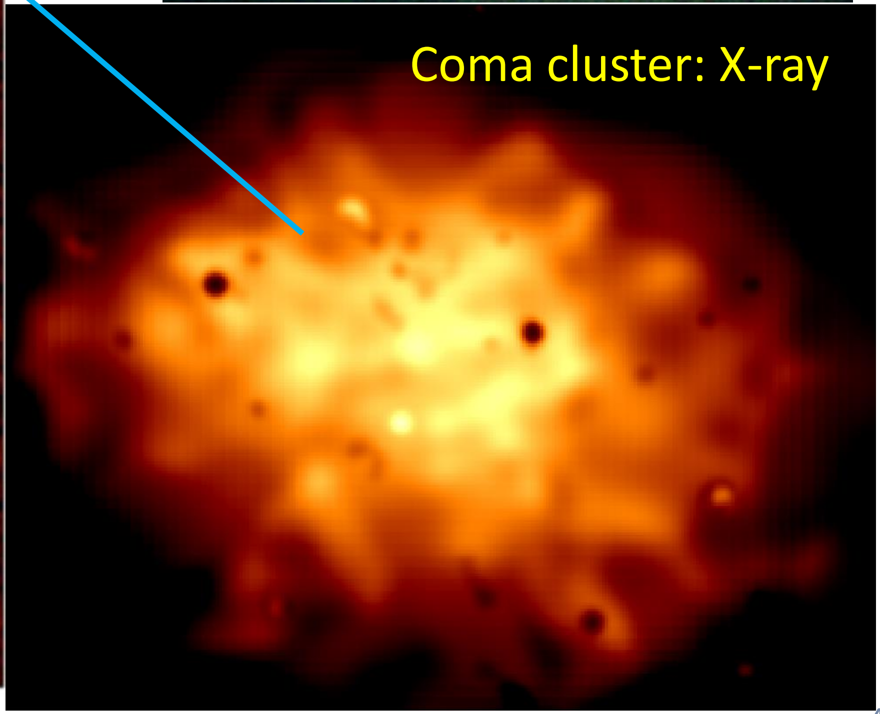
The intracluster medium (ICM) → the superheated plasma with T ~ a few to several keV, presented in clusters of galaxies

ICMs are dynamical:

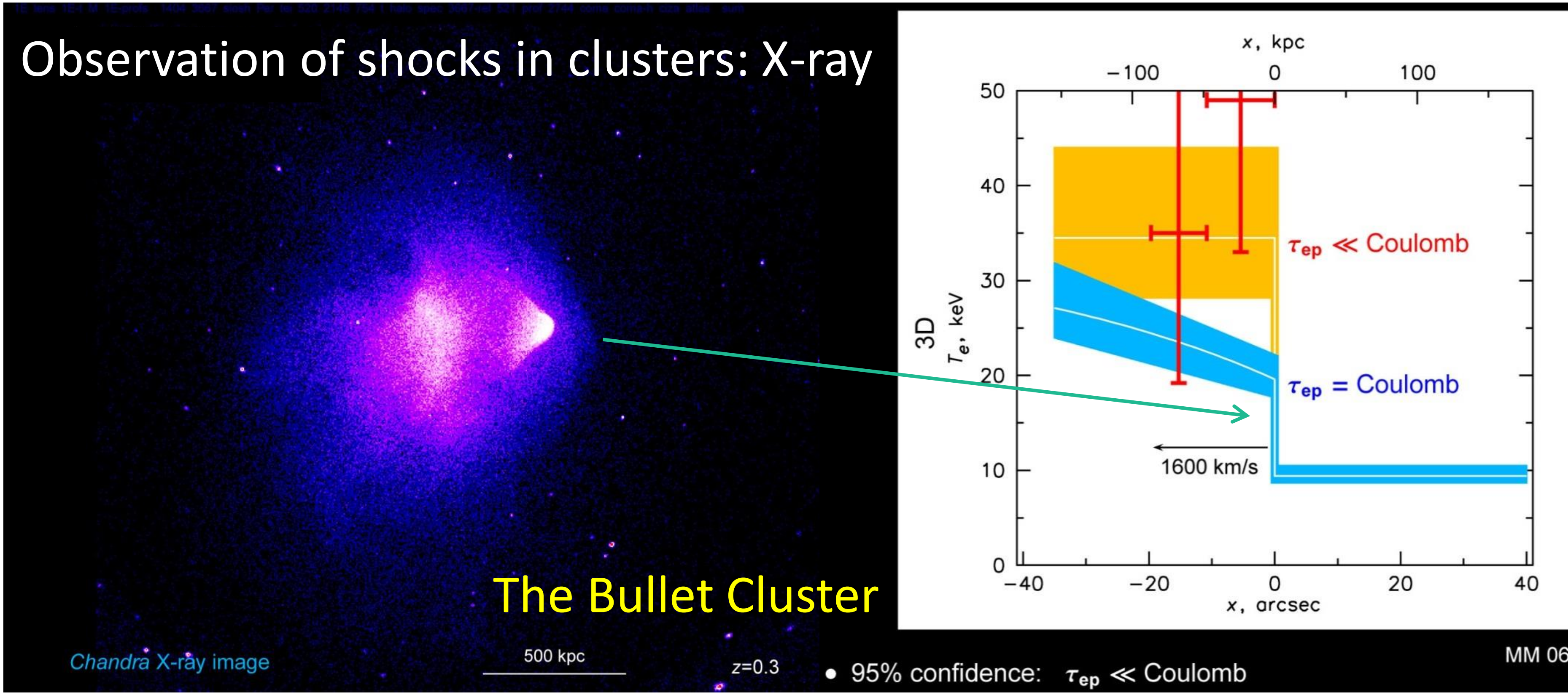
- large-scale flow motion
- turbulence
- shocks
- magnetic fields
- cosmic-rays



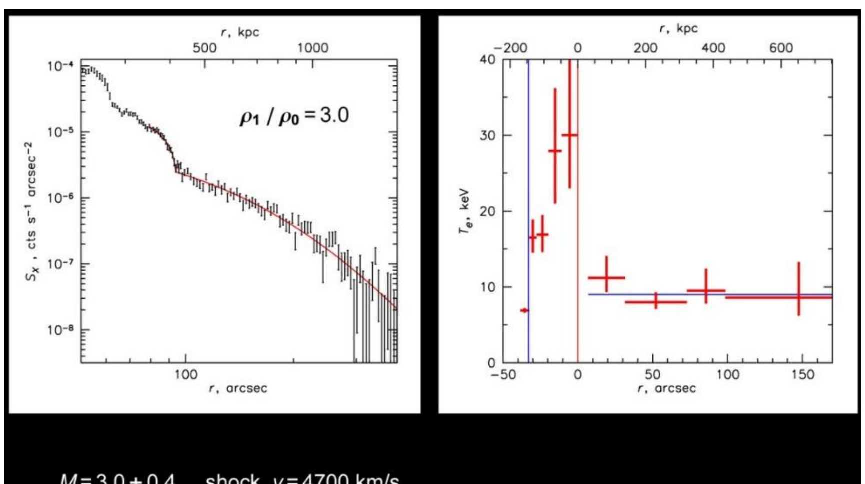




Observation of shocks in clusters: X-ray



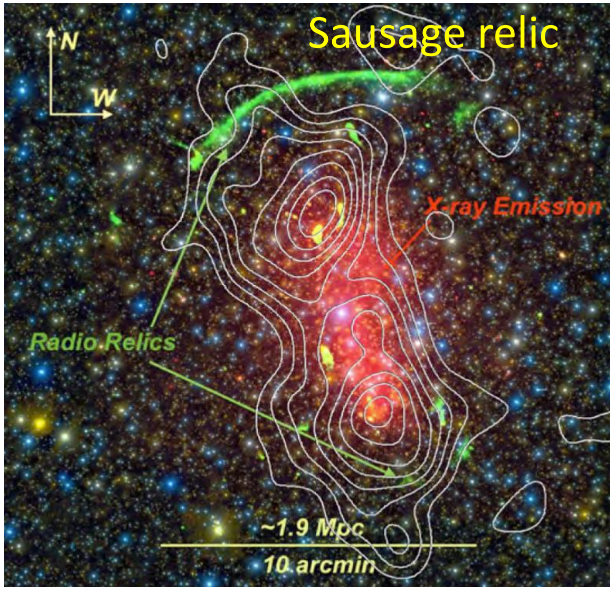
(Markevitch et al.)

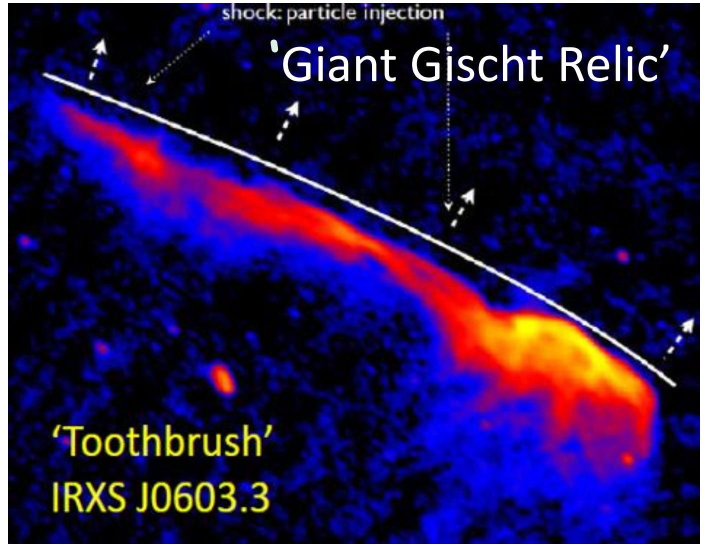


Shock wave in
1E0657-56 (Bullet cluster)

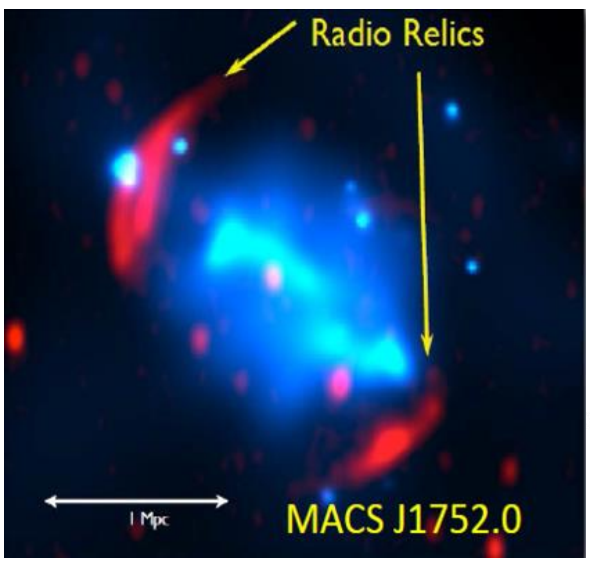
Mach number of X-ray shocks in ICMs: M_{shock} <~ a few

Observation of shocks in clusters: "radio relics"

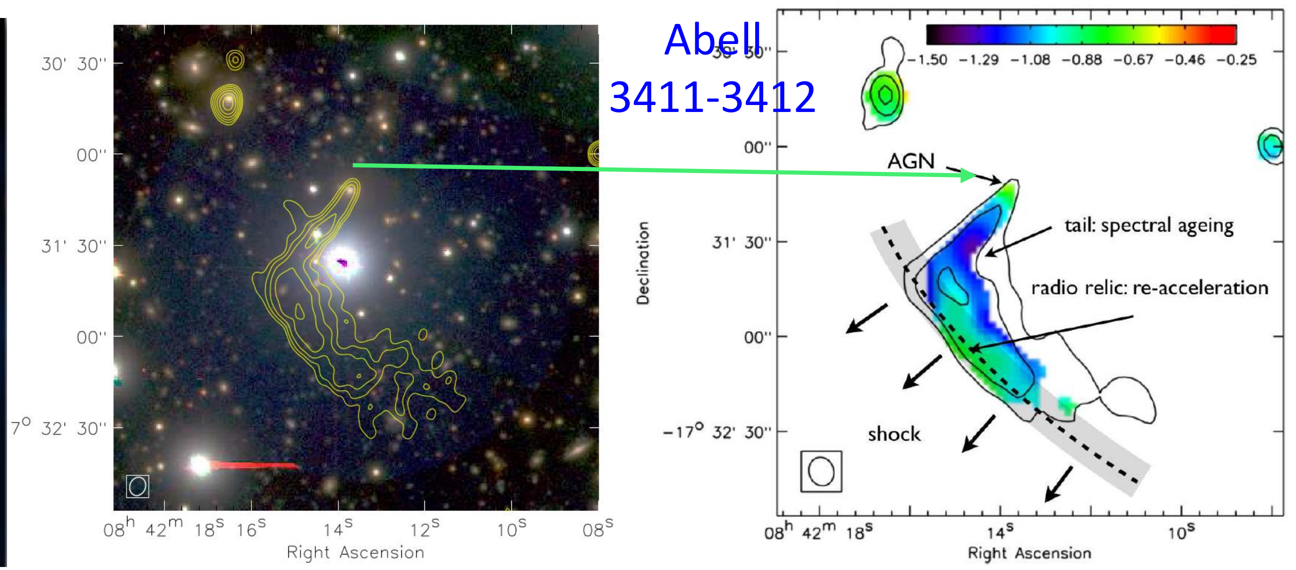




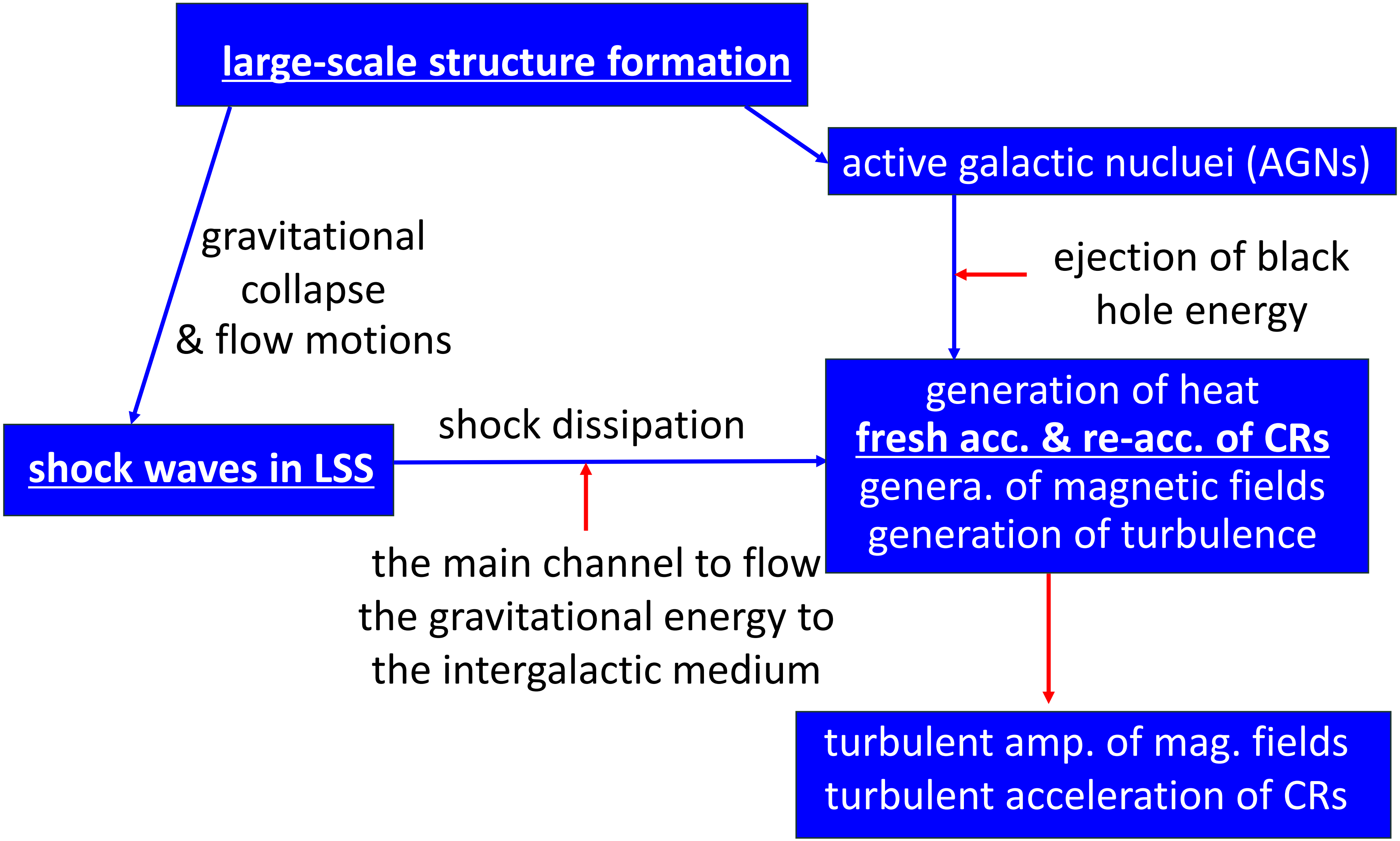
Mach number of radio shocks in ICMs: M_{shock} <~ several



Abell 3411-3412



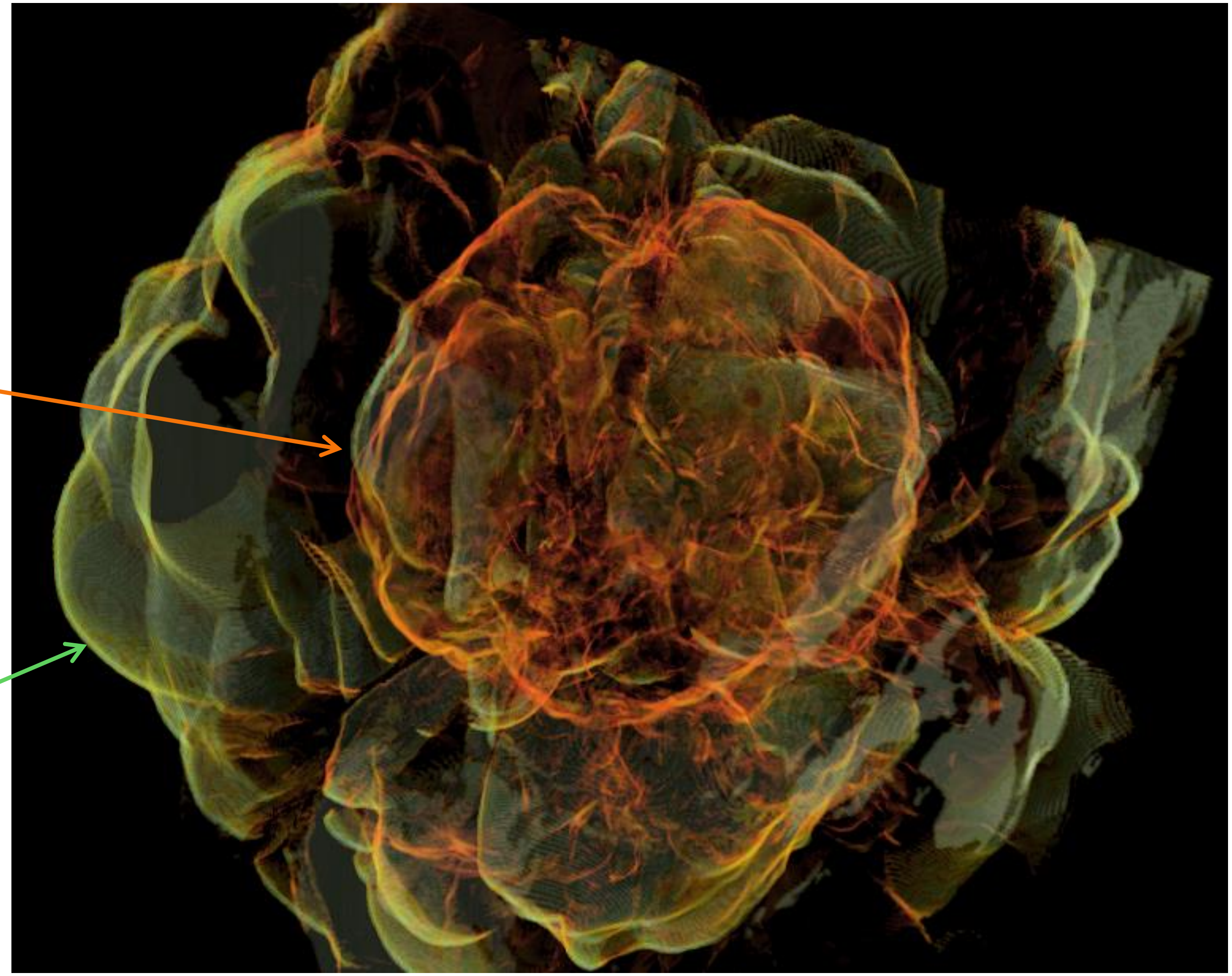
Overview for formation of shock waves and cosmic ray accleration in the large-scale structure of the universe



Shock waves in a simulated clusters of galaxies

weak inreacluster shocks
with M<4 (orange)

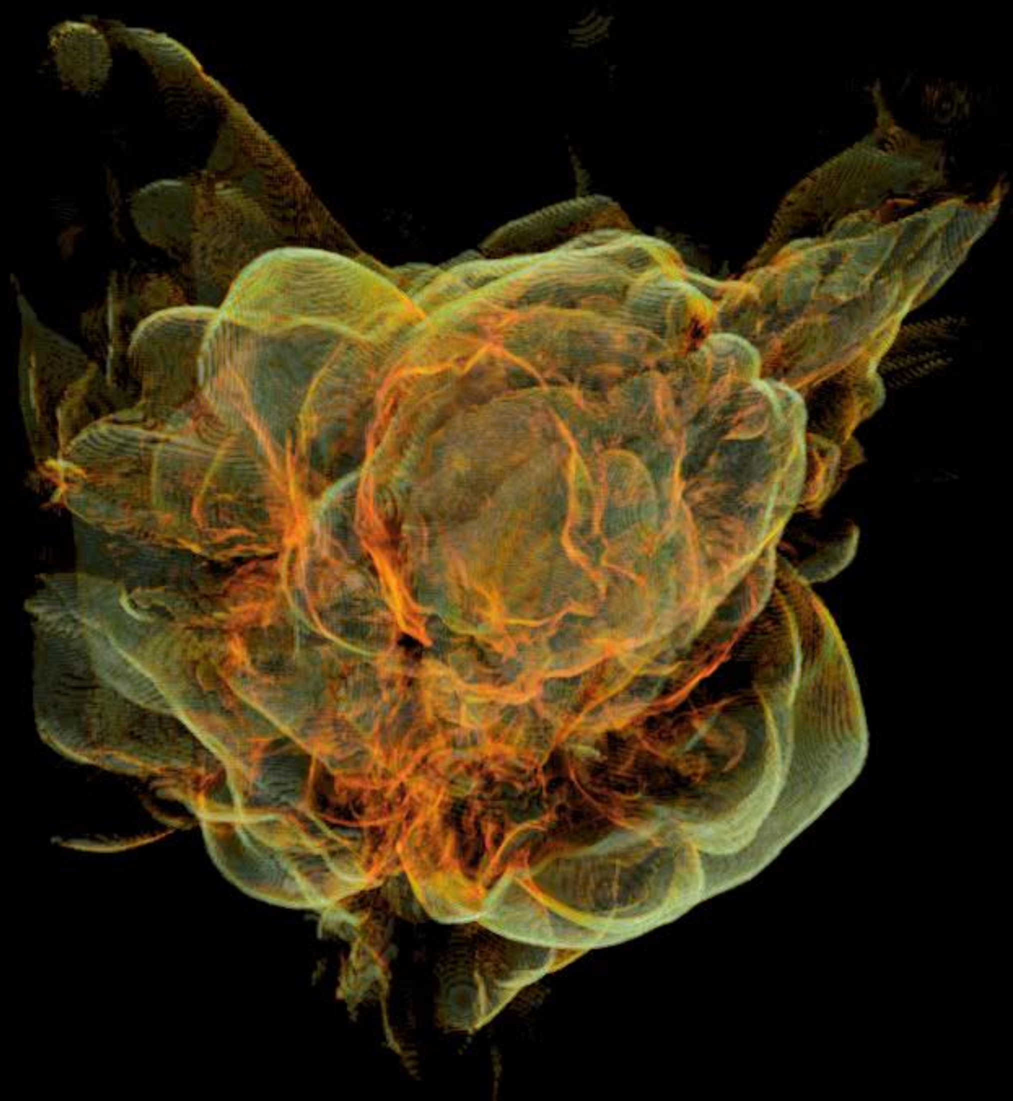
strong accretion shocks
with M>10 (green)



Simulation credits: Vazza, Jones, Gheller, Bruggen, Brunetti & Ryu, on ITASCA at Minnesota Supercomputing Institute (MSI). Visualization credits: 3D renderings (Jones) with Hierarchical Volume Rendering, 'HVR,‘ developed in the LCSE at the University of Minnesota. Critical support from MSI (D. Porter) and LCSE (M. Knox).

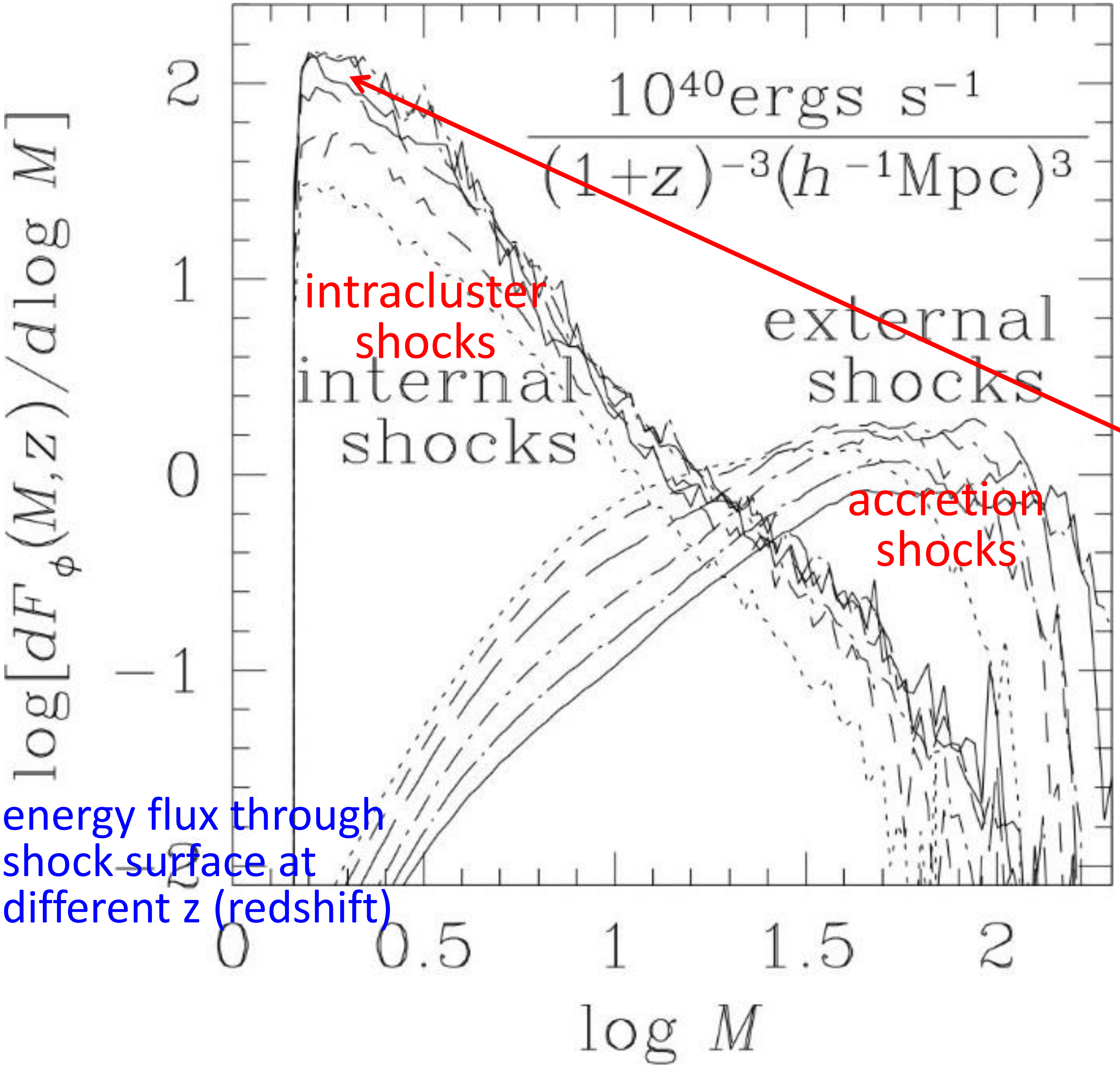
https://www.youtube.com/watch?v=yV3KPz0cPqk

Vazza et al



Energetics of shocks

(Ryu et al. 2003)



energy flux through shock surface at different z (redshift)

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

The nature of shocks found in intracluster media

1) merger shocks

2) infall shocks (accretion from WHIM to hot medium)

3) turbulence shocks

(Ryu et al. 2003)

COSMOLOGICAL SHOCK WAVES AND THEIR ROLE IN THE LARGE-SCALE STRUCTURE OF THE UNIVERSE

DONGSU RYU,[1,2] HYESUNG KANG,[2,3] ERIC HALLMAN,[2] AND T. W. JONES[2]

Received 2003 February 12; accepted 2003 May 7

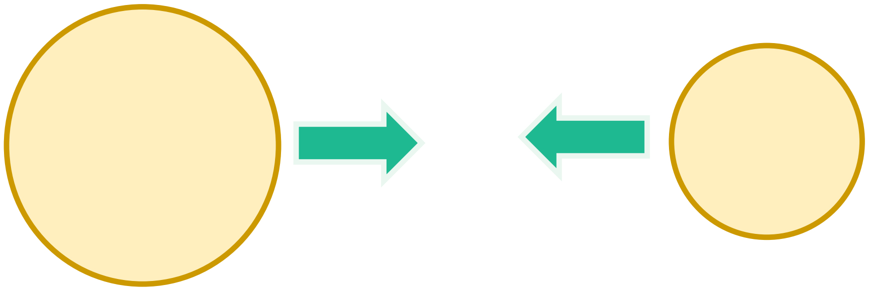
ABSTRACT

We study the properties of cosmological shock waves identified in high-resolution, N-body/hydrodynamic simulations of a ΛCDM universe and their role on thermalization of gas and acceleration of nonthermal, cosmic-ray (CR) particles. External shocks form around sheets, filaments, and knots of mass distribution when the gas in void regions accretes onto them. Within those nonlinear structures, internal shocks are produced by infall of previously shocked gas to filaments and knots and during subclump mergers, as well as by chaotic flow motions. Due to the low temperature of the accreting gas, the Mach number of external shocks is high, extending up to $M \sim 100$ or higher. In contrast, internal shocks have mostly low Mach numbers. For all shocks of $M \geq 1.5$, the mean distance between shock surfaces over the entire computed volume is $\sim 4\ h^{-1}$ Mpc at present, or $\sim 1\ h^{-1}$ Mpc for internal shocks within nonlinear structures. Identified external shocks are more extensive, with their surface area ~ 2 times larger than that of identified internal shocks at present. However, especially because of higher preshock densities but also due to higher shock speeds, internal shocks dissipate more energy. Hence, the internal shocks are mainly responsible for gas thermalization as well as CR acceleration. In fact, internal shocks with $2 \lesssim M \lesssim 4$ contribute about one-half of the total dissipation. Using a nonlinear diffusive shock acceleration model for CR protons, we estimate the ratio of CR energy to gas thermal energy dissipated at cosmological shock waves to be about one-half through the history of the universe. Our result supports scenarios in which the intracluster medium contains energetically significant populations of CRs.

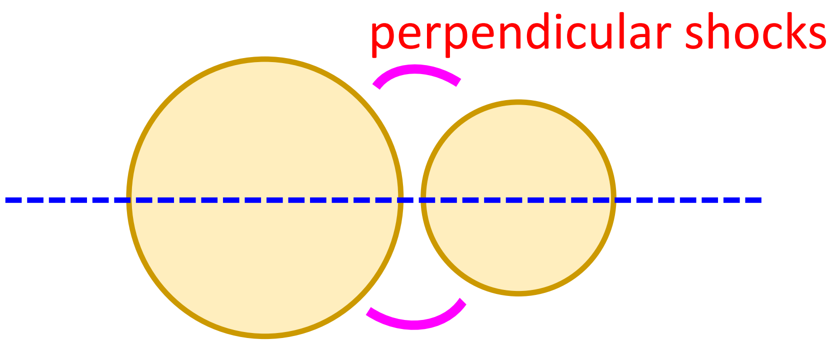
Subject headings: large-scale structure of universe — methods: numerical — shock waves

1) Merger shocks

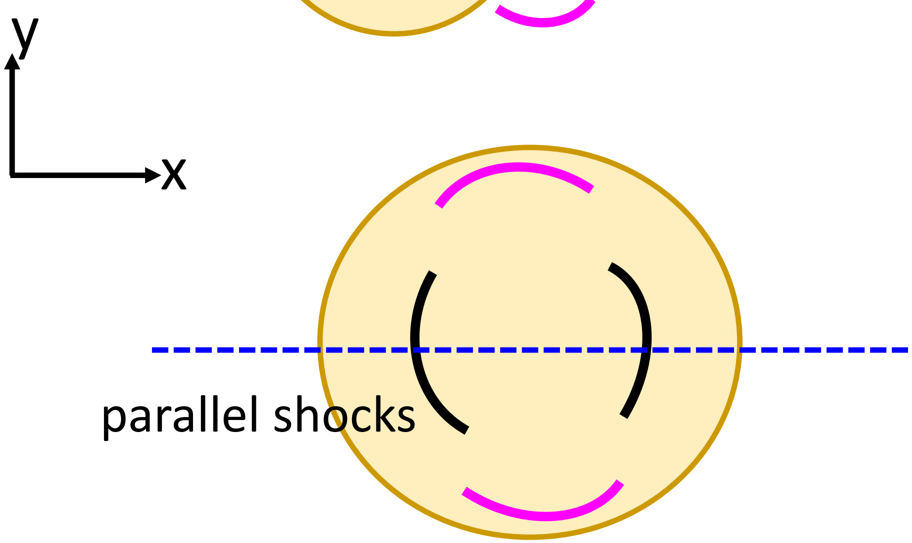
A cartoon picture based on toy model



Two clumps are approaching.



Before merger, shocks along the direction perpendicular to the merger axis (y-direction) are first launched.

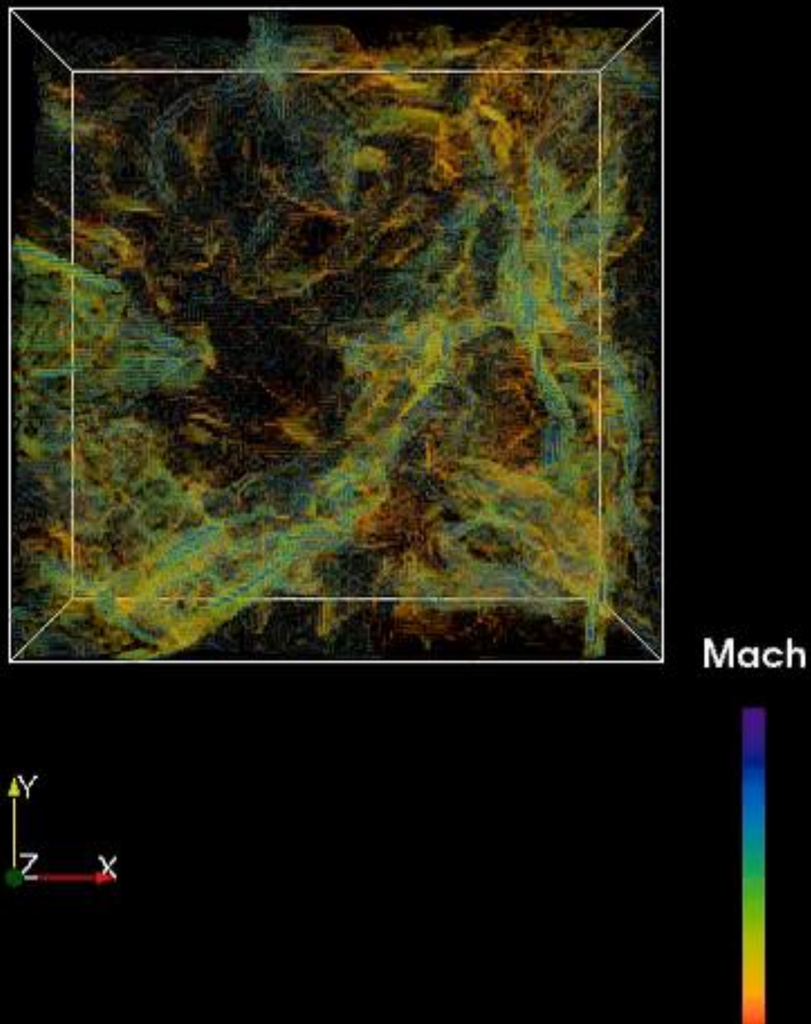


After merger, shocks along the direction parallel to the merger axis (x-direction) form and propagate.

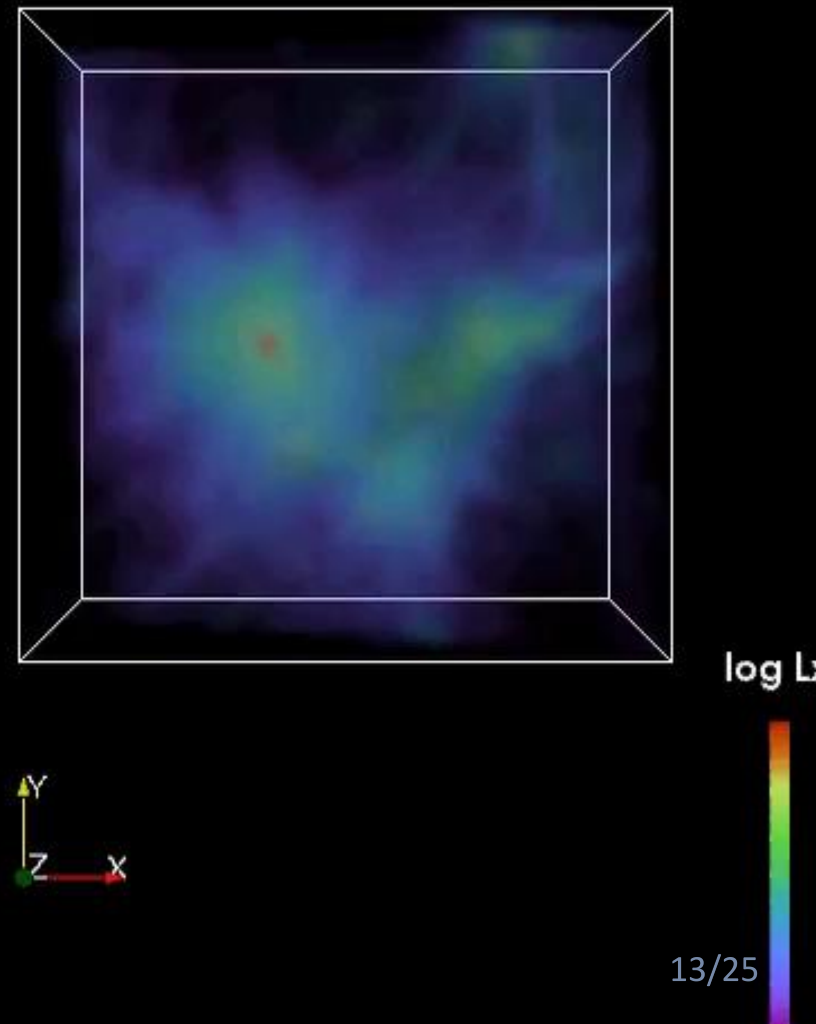
Shock waves in a simulated merging clusters (Ha, Ryu, & Kang In preparation)

from z = 0.5 to 0.05, a major merger at z = 0.34
box size = 5 h^{-1} Mpc

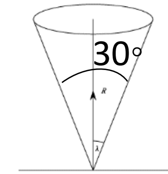
shocks with $1 < M_s < 10$

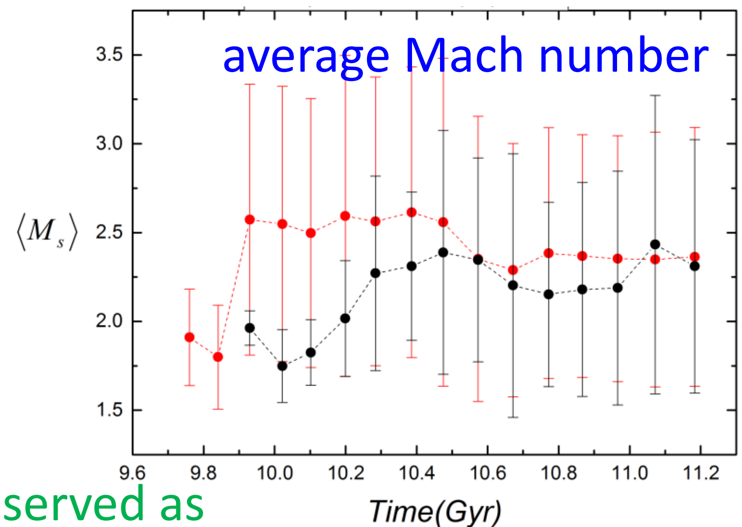


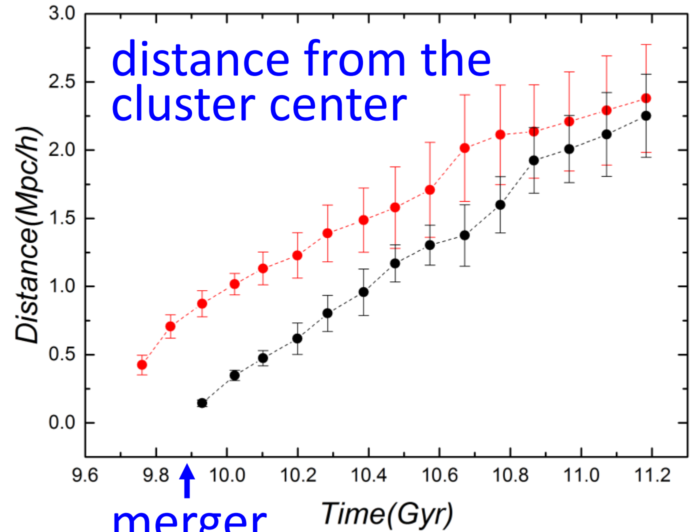
X-ray emissivity



Statistics of merger-induced shocks in 30◦ cones along the direction parallel (+x) and perpendicular (+y) to the merger axis

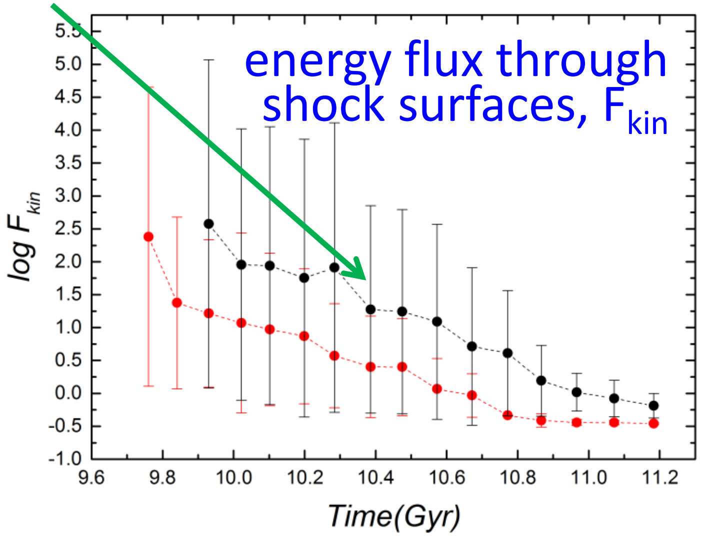






observed as X-ray & radio shocks

10^{40} ers/s/(Mpc h^{-1})^2

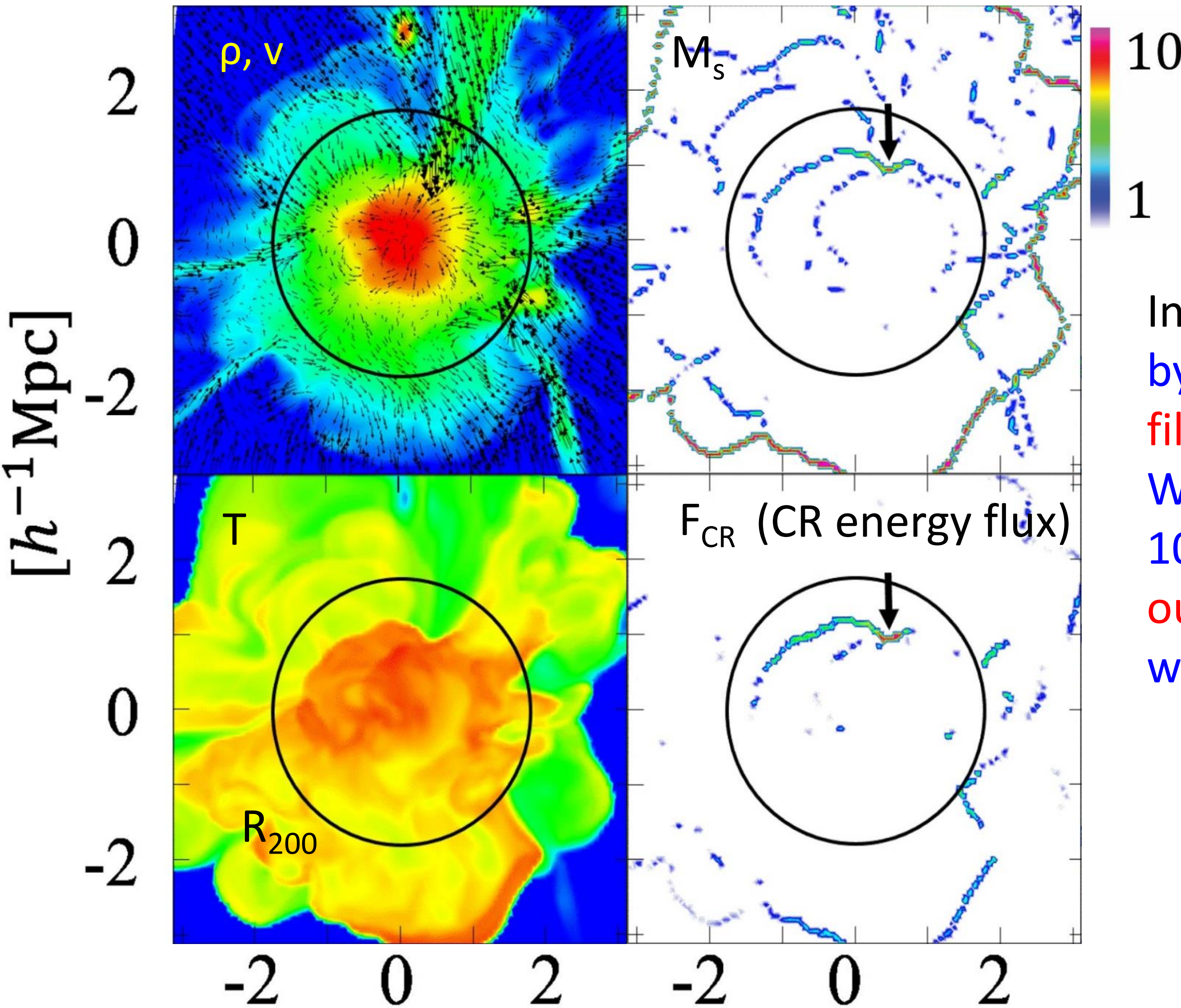


- perpendicular shock is first launched and parallel shocks follows
- shocks initially have M_s <~2, become stronger but have mostly M_s < ~ 3
- perpendicular shock has stronger (higher M_s) than parallel shock
- parallel shock is more energetic (larger F_{kin}) than perpendicular shock
- shocks become energetically less important as they propagate outwards

2) Infall shocks

found mostly in cluster outskirts

(Hong, Ryu, Kang, & Cen 2014)

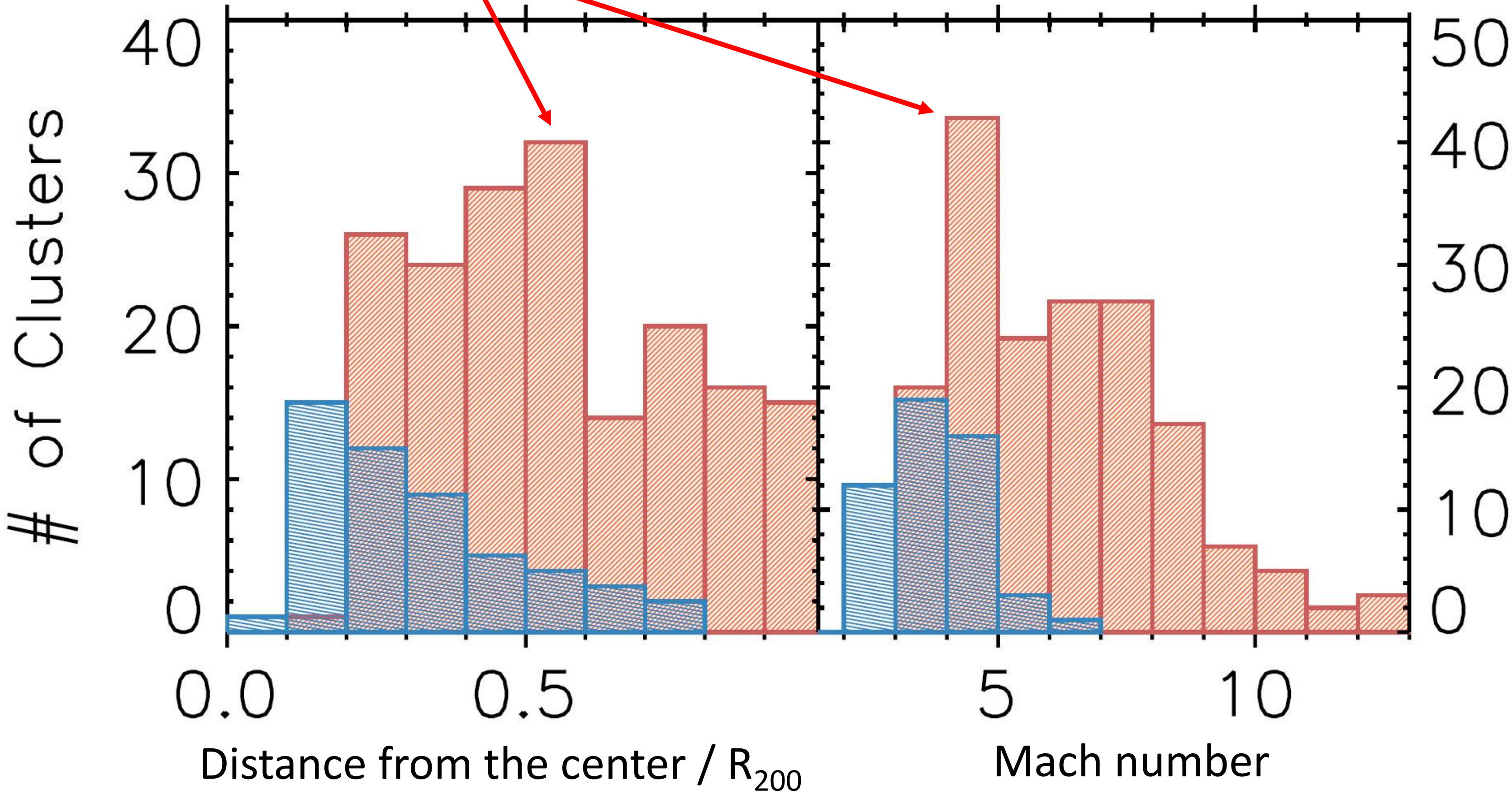


Infall shocks formed by gas inflow from filaments of the WHIM with $T \sim 10^5 - 10^7$ K to cluster outskirts of hot gas with $T \sim 10^7 - 10^8$ K

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

$(R_{200} \sim 1.3\ R_{vir})$

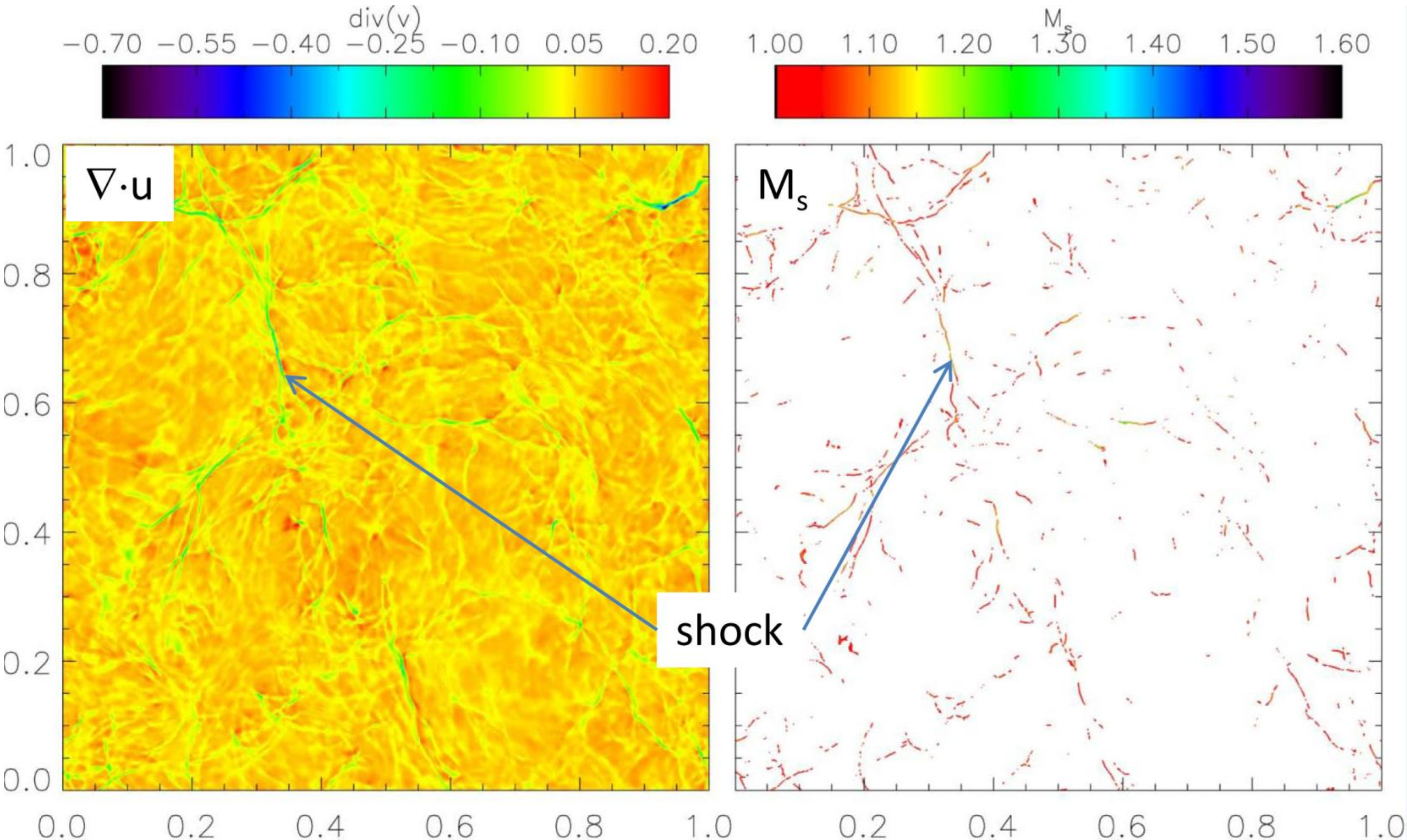
Statistics of infall shocks



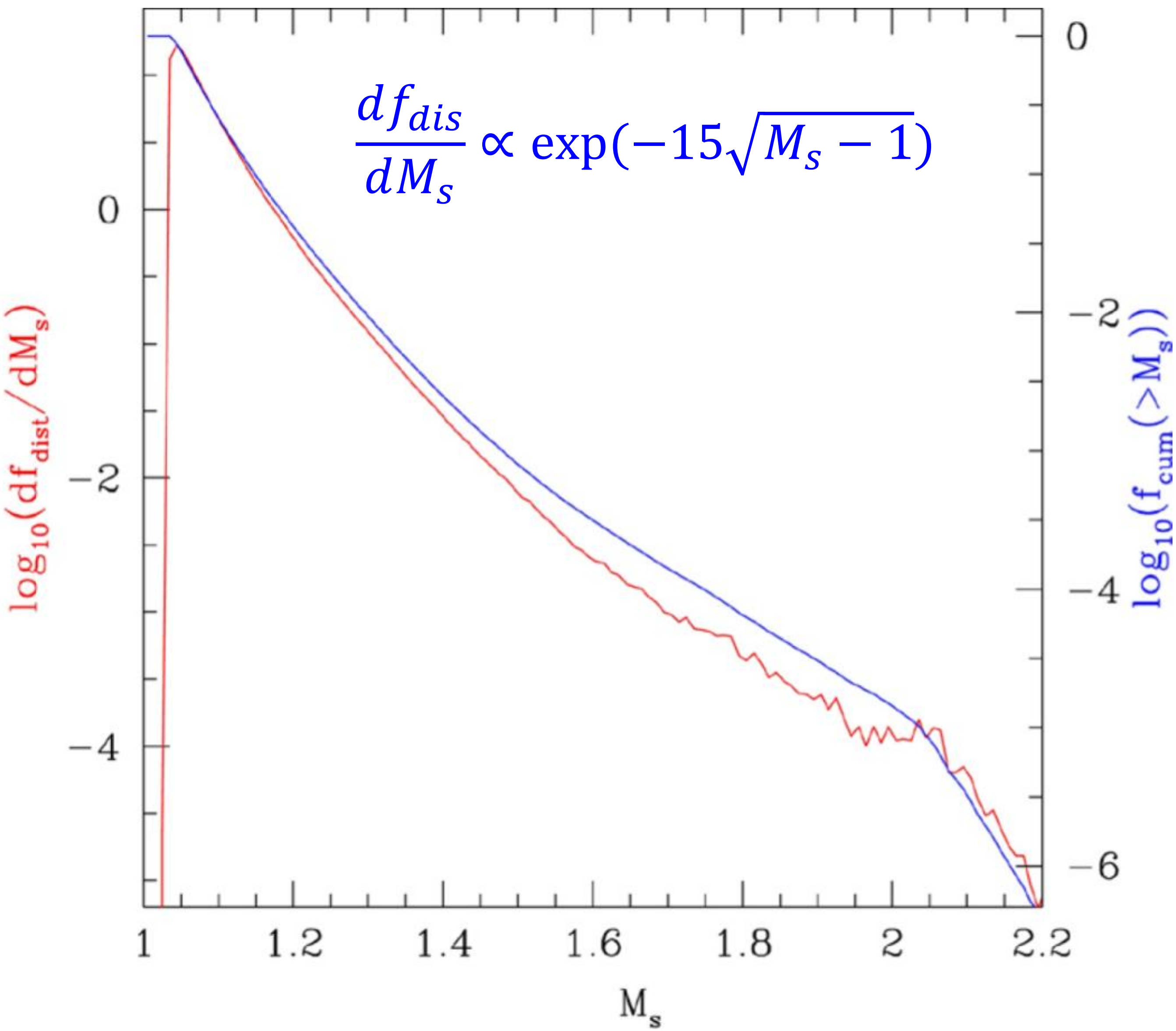
- infall shocks are strong with, M_s = a few ~ 10, stronger than merger shocks
- they are found mostly in outskirts
- their surface area is smaller than that of merger shocks

3) Turbulence shocks - formed by turbulent flow motions of M_s ~ 0.5

(Porter, Jones, & Ryu 2015)



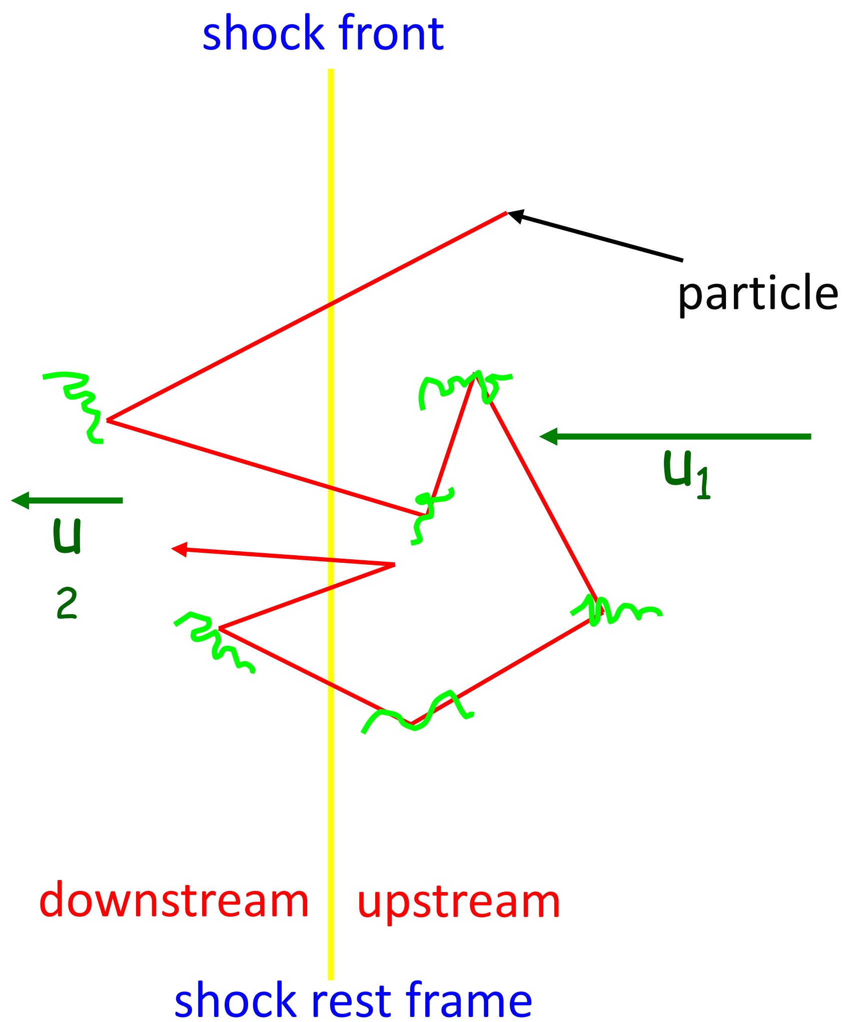
Shock Mach number PDF

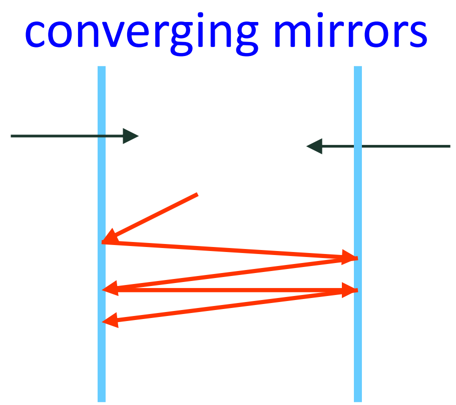


Turbulence shocks in ICMs are mostly weak with M_s >~ 1 and short-lived !

→ probably dynamically / energetically are not important but contribute to gas heating

Diffusive shock acceleration (DSA) at collisionless intracluster shocks



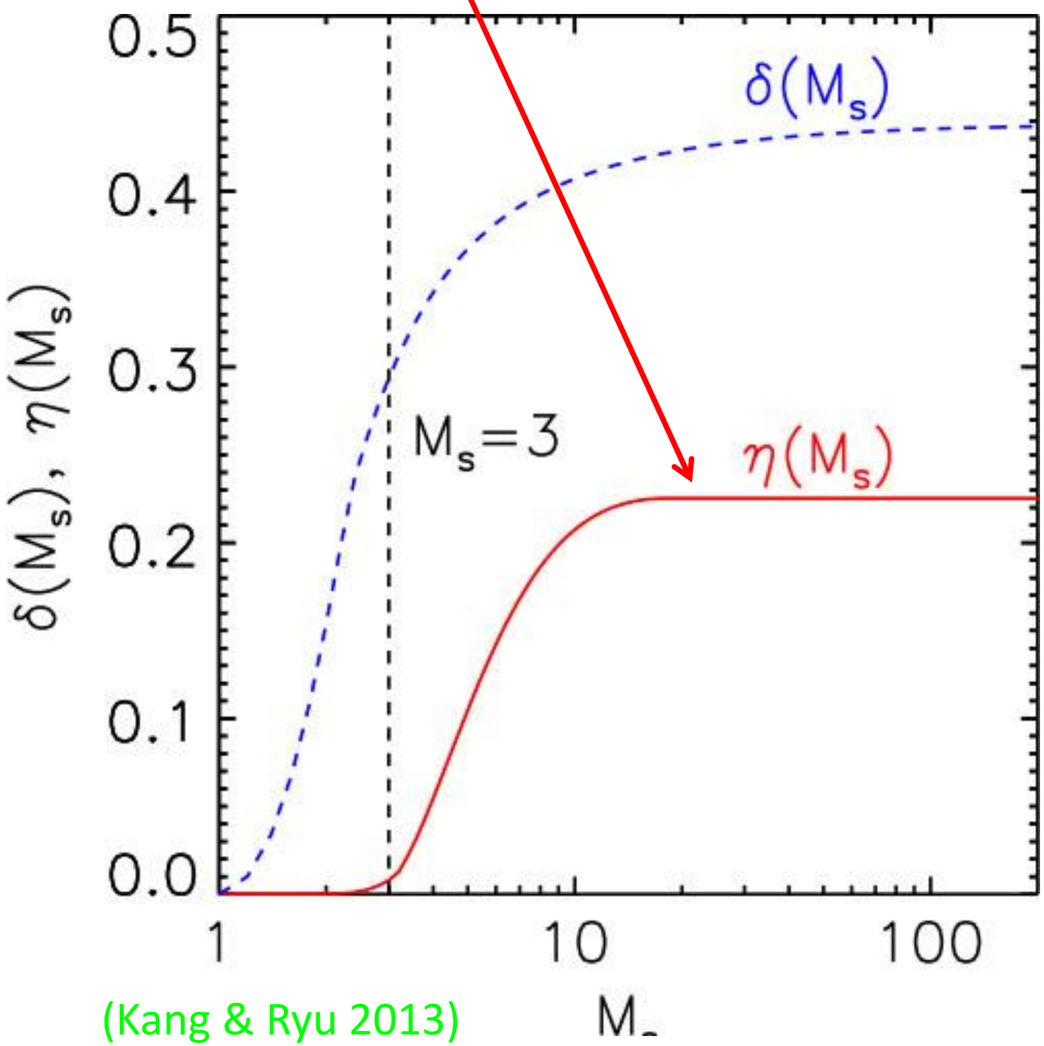


$$\frac{\Delta p}{p} \sim \frac{|\Delta u|}{u}$$ energy gain at each crossing

Fermi first order process

CR proton acceleration efficiency at shocks:

The fraction of shock kinetic energy that goes to CR protons

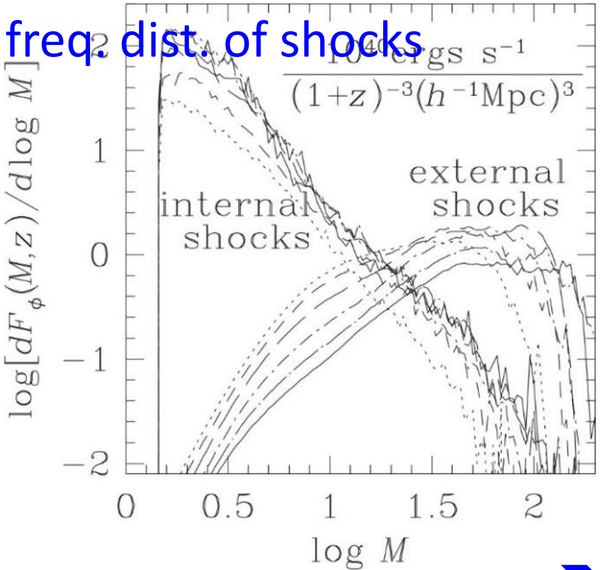


(Kang & Ryu 2013)

1) CR acceleration efficiency is larger at stronger (higher M_s) shock, $\eta \rightarrow$ ~20 % at large M_s
2) X (=P_{CR}/P_{th}) = ½ E_{CR}/E_{th} < ~0.01 for M_s <~ 3
3) the efficiency is based on phenomenological models

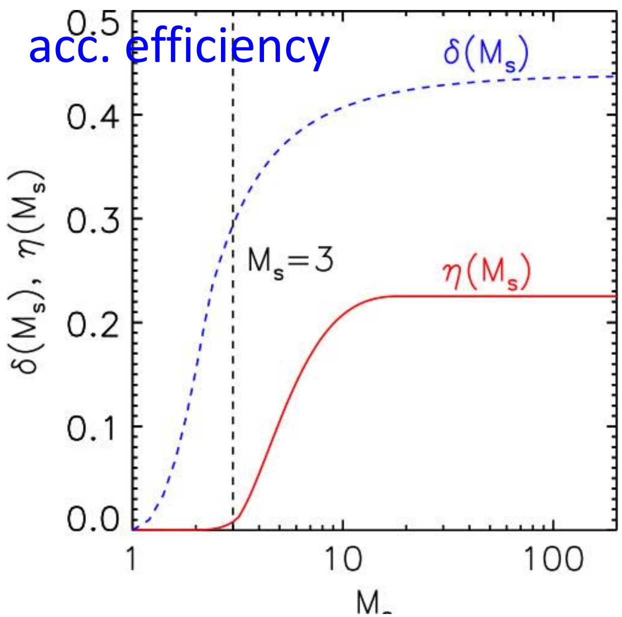
CR acceleration (protons) at intracluster shocks

freq. dist. of shocks

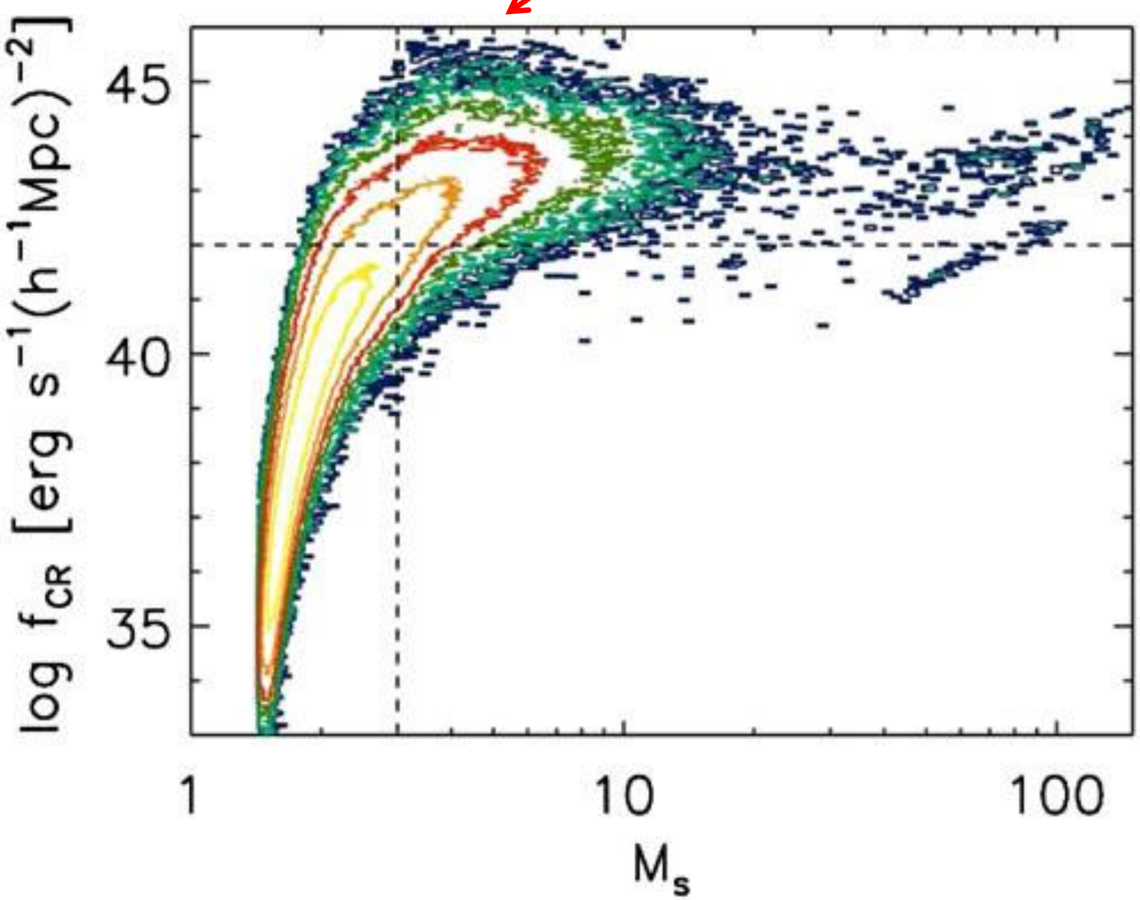


+

acc. efficiency

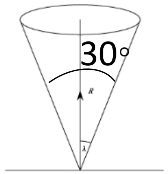


Intracluster shocks with M_s ~ a few to several are most important in CR production in clusters



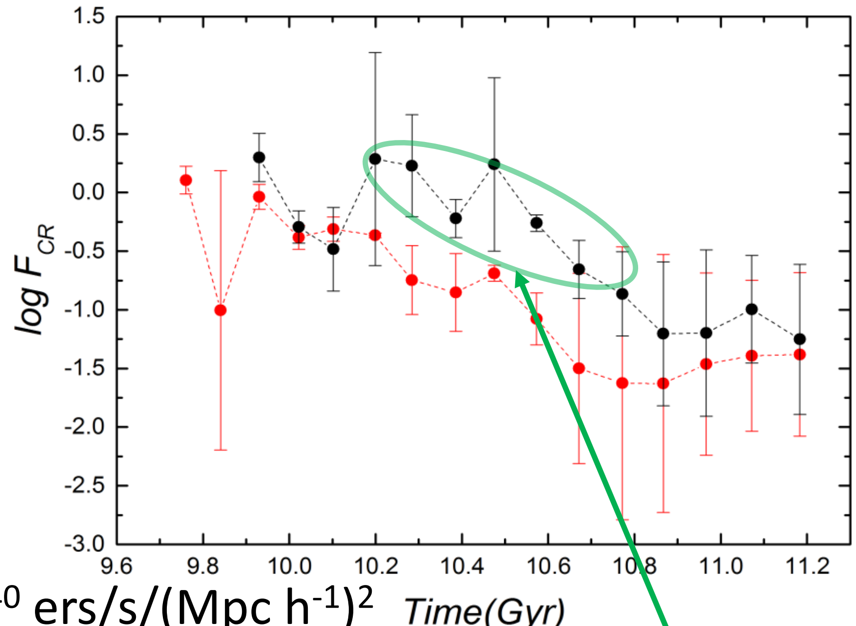
(Hong, Ryu, Kang, Cen 2014)

Acceleration of CRs at merger-induced shocks



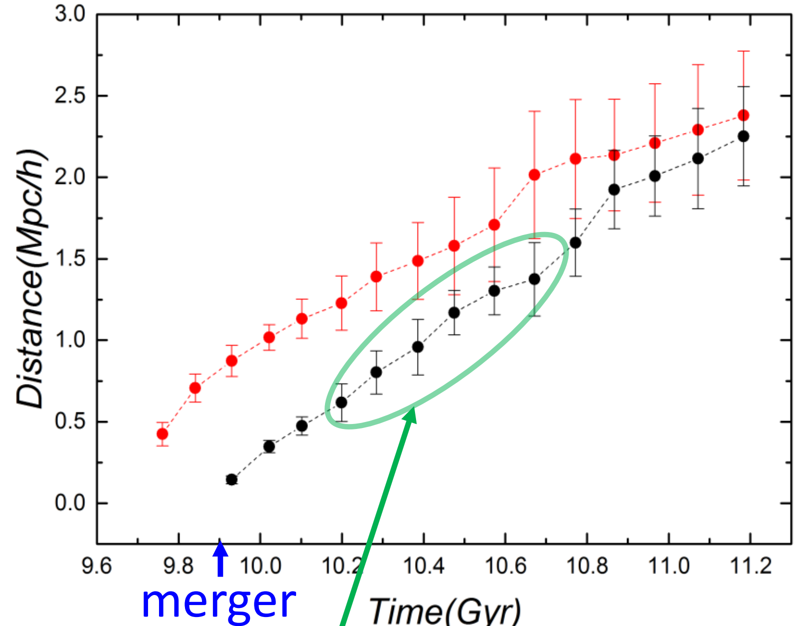
in 30° cones along the direction parallel (+x) and perpendicular (+y) to the merger axis in a simulated cluster

CR flux produced at shock surfaces, F_{CR}



10^{40} ers/s/(Mpc h^{-1})^2

distance from the cluster center



most efficient acceleration of CRs

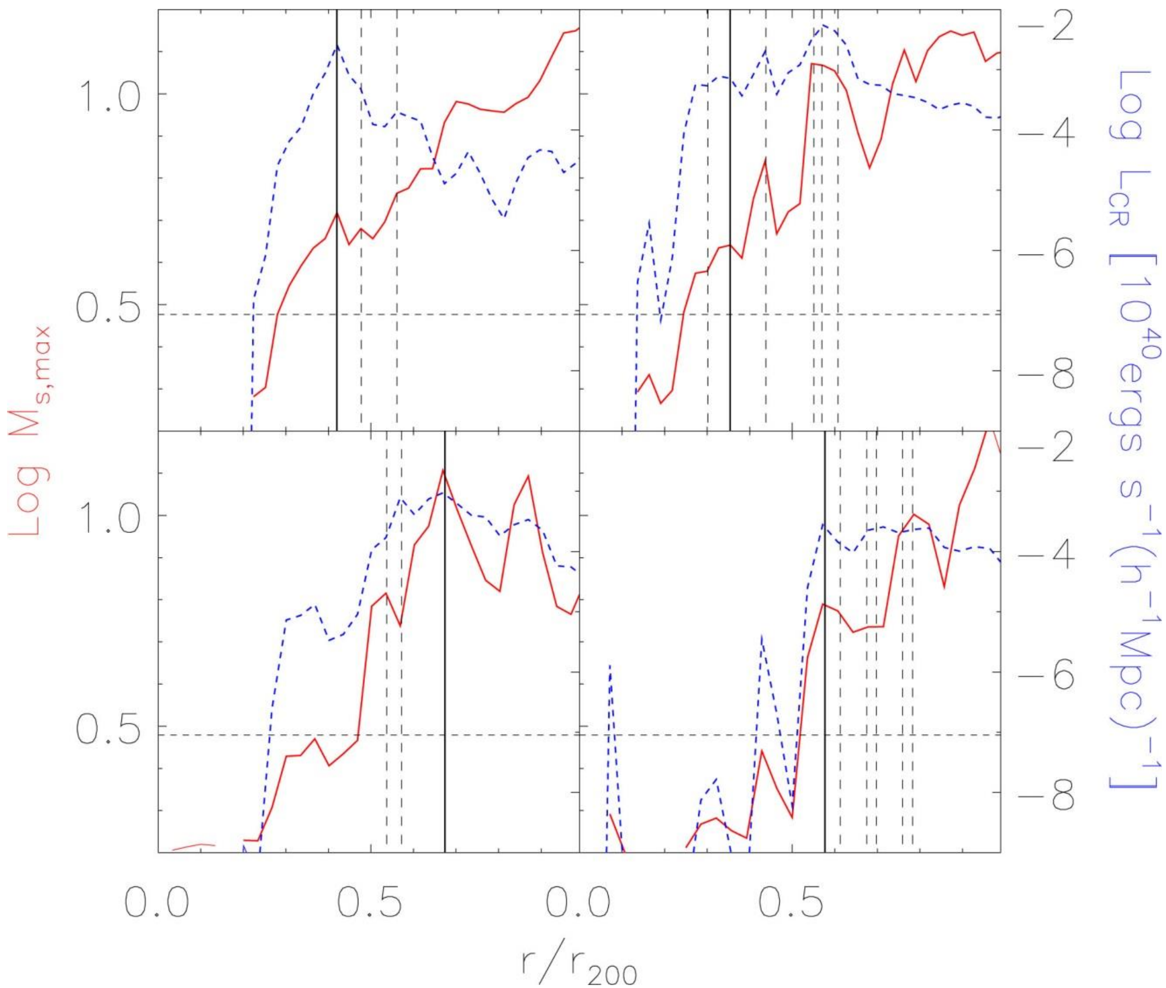
→ merger shocks observed radio shocks

(Ha, Ryu, & Kang In preparation)

Acceleration of CRs at infall shocks

(Hong, Ryu, Kang, & Cen 2014)

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



- shocks with M_s > ~3 are founds mostly in cluster outskirts
- CR protons are produced mostly in cluster outskirts (>~ 0.5 R_{vir})
- infall shocks takes a good fraction of shocks with M_s > ~3
- infall shocks contributes to a fraction of CR protons produced at clusters of galaxies

Summary

- Shocks waves are common in intracluster media: merger shocks, infall shocks, turbulence shocks
- Energetically most important merger shocks have Mach numbers, M_s <~ 3 - 4
- Infall shocks, that form by gas inflow from filaments of the WHIM to cluster outskirts of hot gas, are strong with M_s = a few ~ 10
- Turbulence shocks, that form by turbulent flow motions with turbulence Mach numbr M_{turb} ~ 0.5, are mostly weak with M_s ~ 1 - 2 and short-lived
- It is likely the merger shocks along the merger axis that may be realized as radio relics.
- CRs are produced by merger shocks and infall shocks mostly at cluster outskirts.

Thank you !