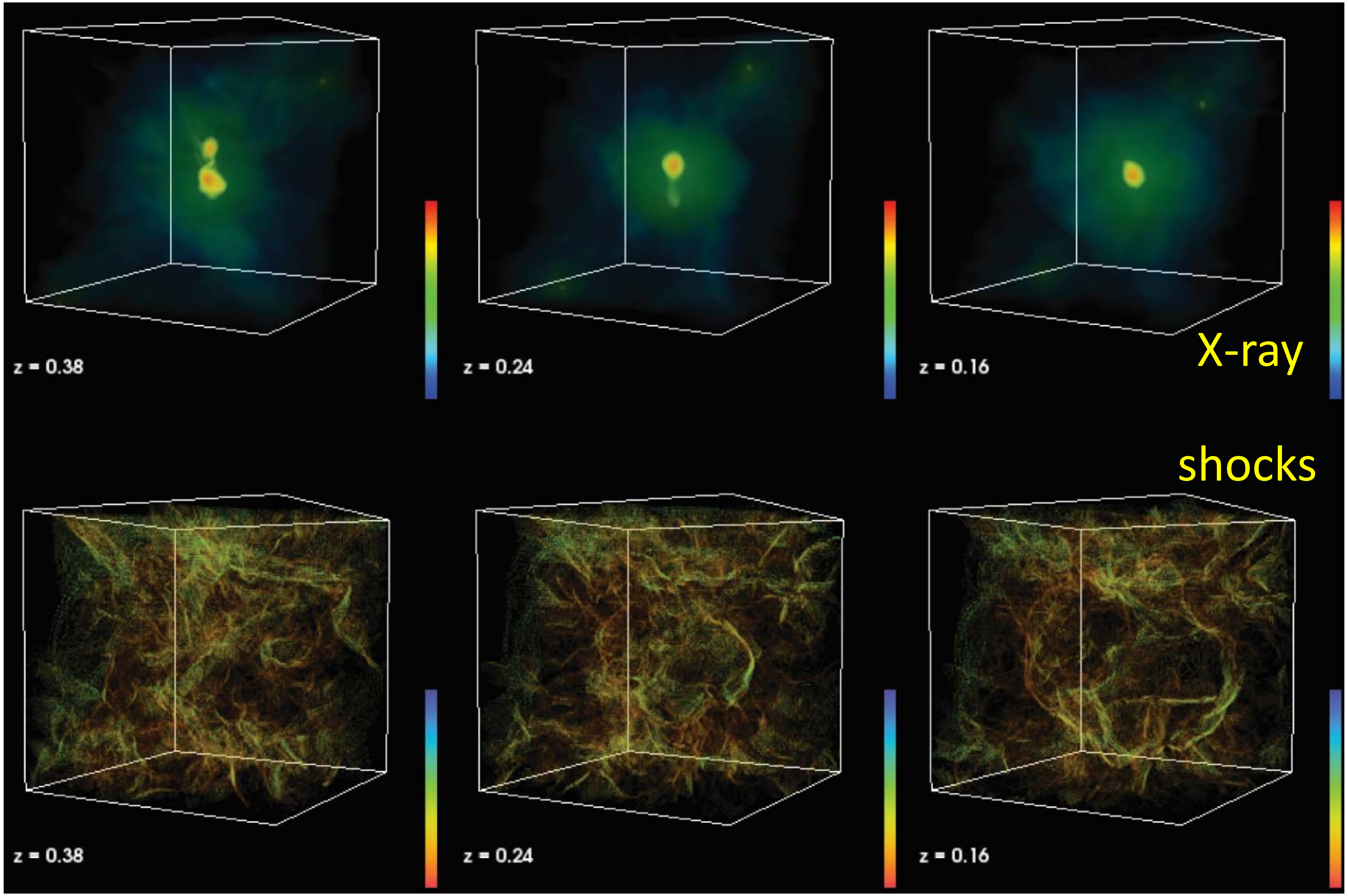
Shock Waves in Clusters of Galaxies: Nature and Properties

merging galaxy cluster

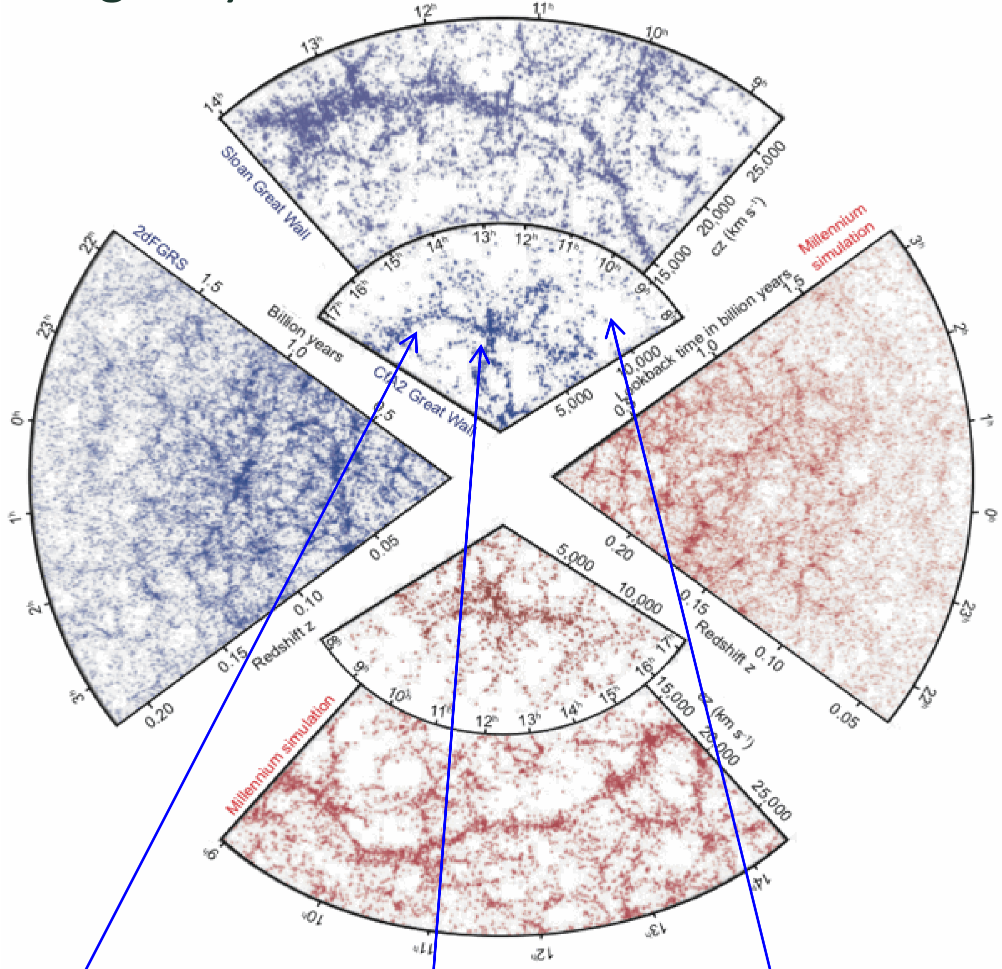


Dongsu Ryu, Ji-Hoon Ha (UNIST, Korea), Hyesung Kang (PNU, Korea)

July 3 - 7, 2017 APRIM 2017 Taipei, Taiwan

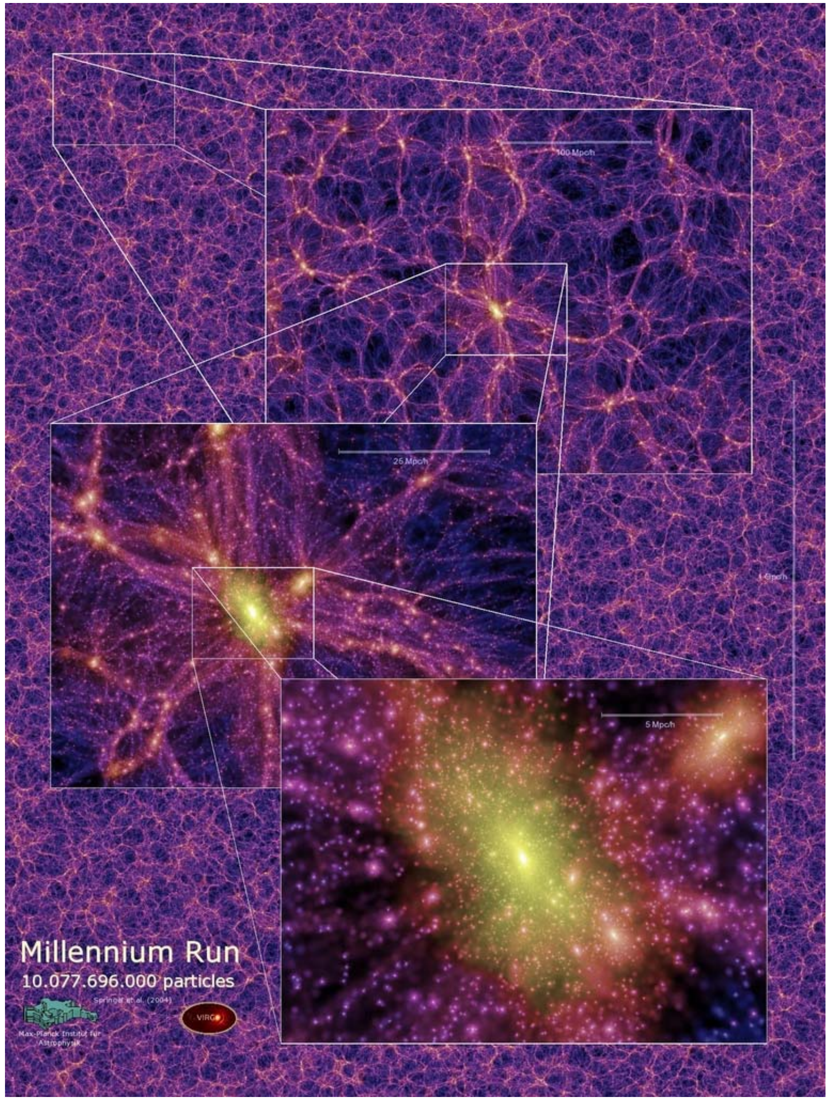
The large-scale structure of the universe

observed and simulated
galaxy distribution



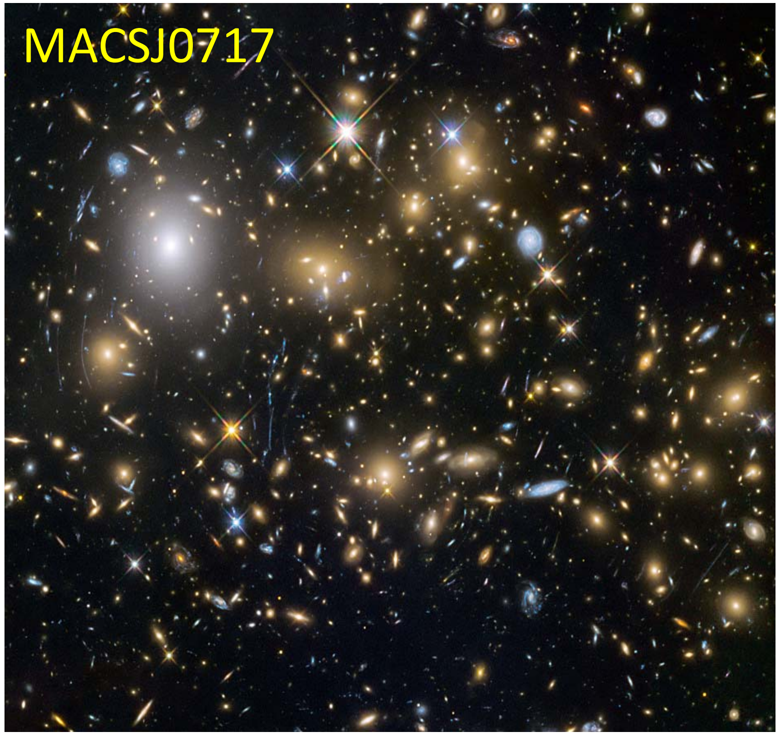
filaments clusters void regions

→ the cosmic web

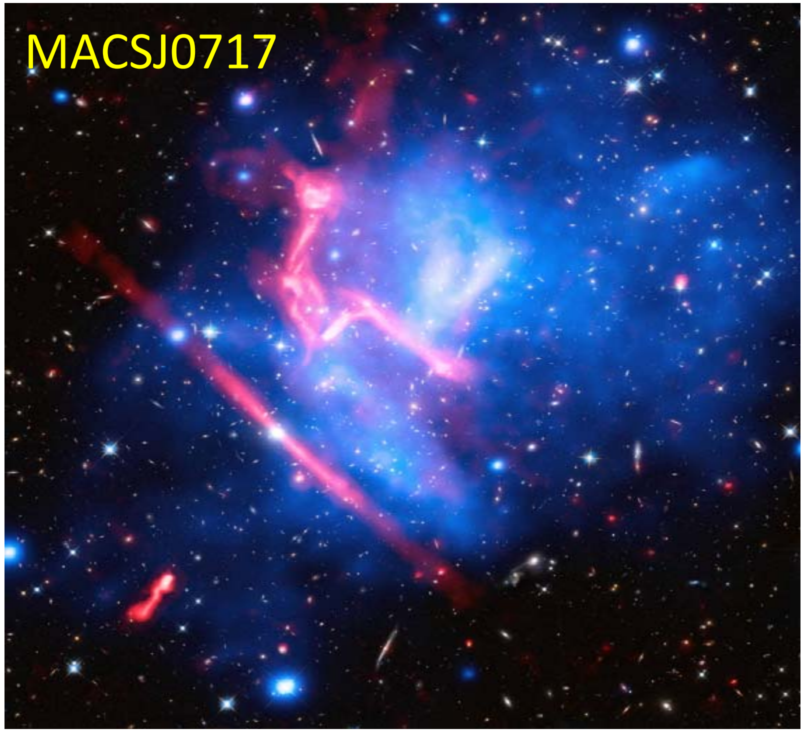


simulated matter distribution

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

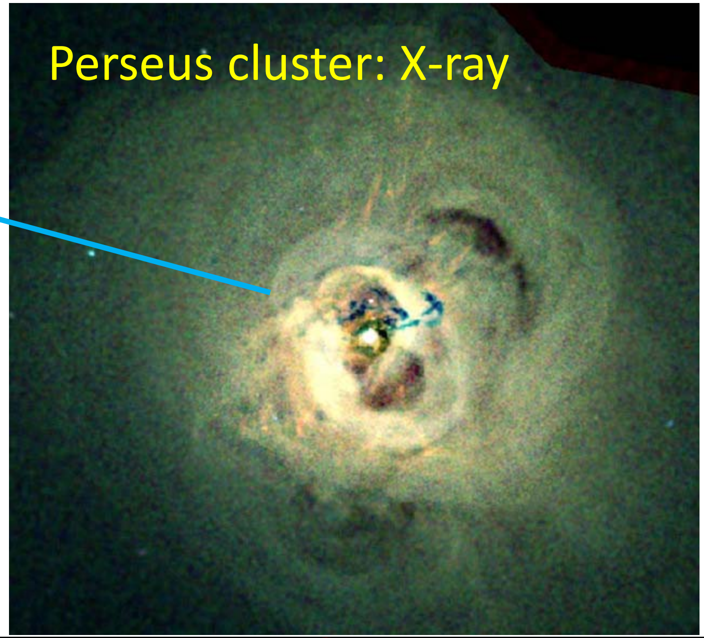


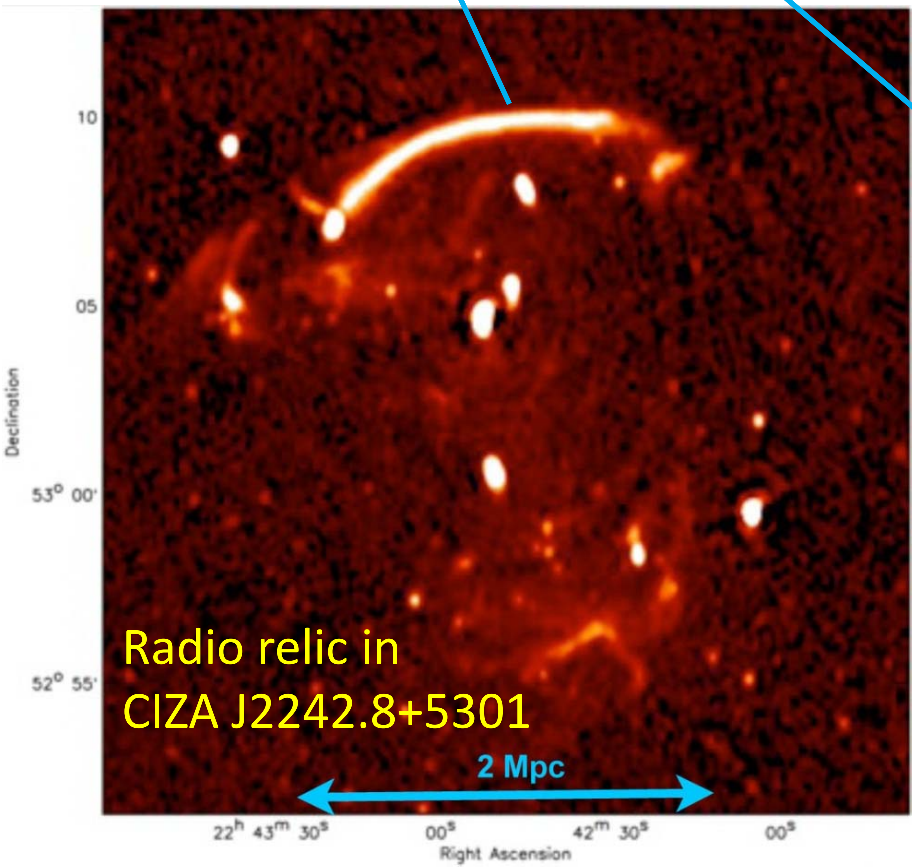
optical (Hubble, white)
X-ray (Chandra, blue) ← hot gas
radio (VLA, red) ← cosmic rays

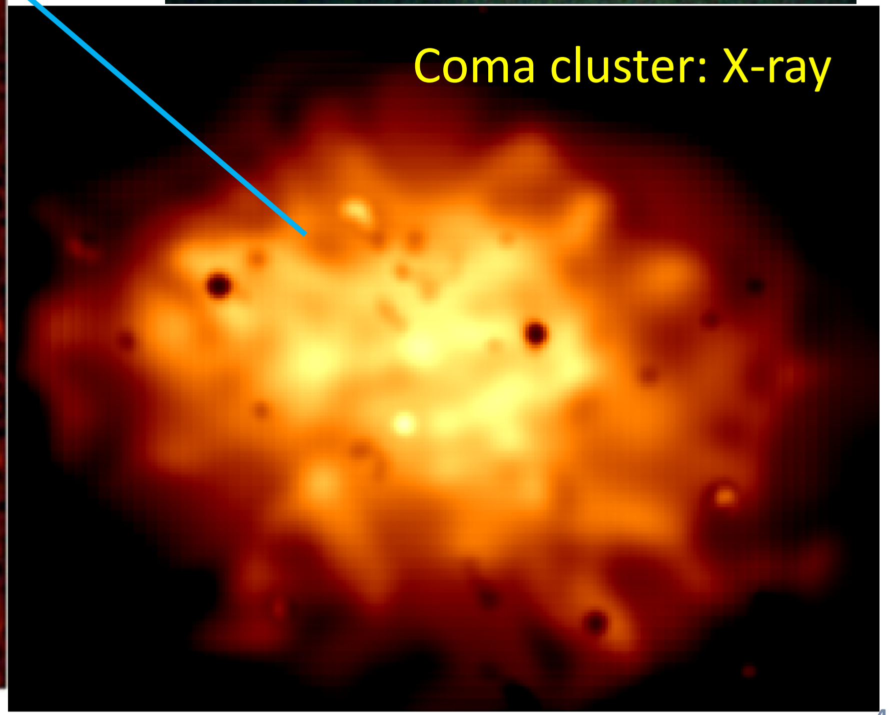
The intracluster medium (ICM) → the superheated plasma with T ~ a few to several keV, presented in clusters of galaxies

ICMs are dynamical:

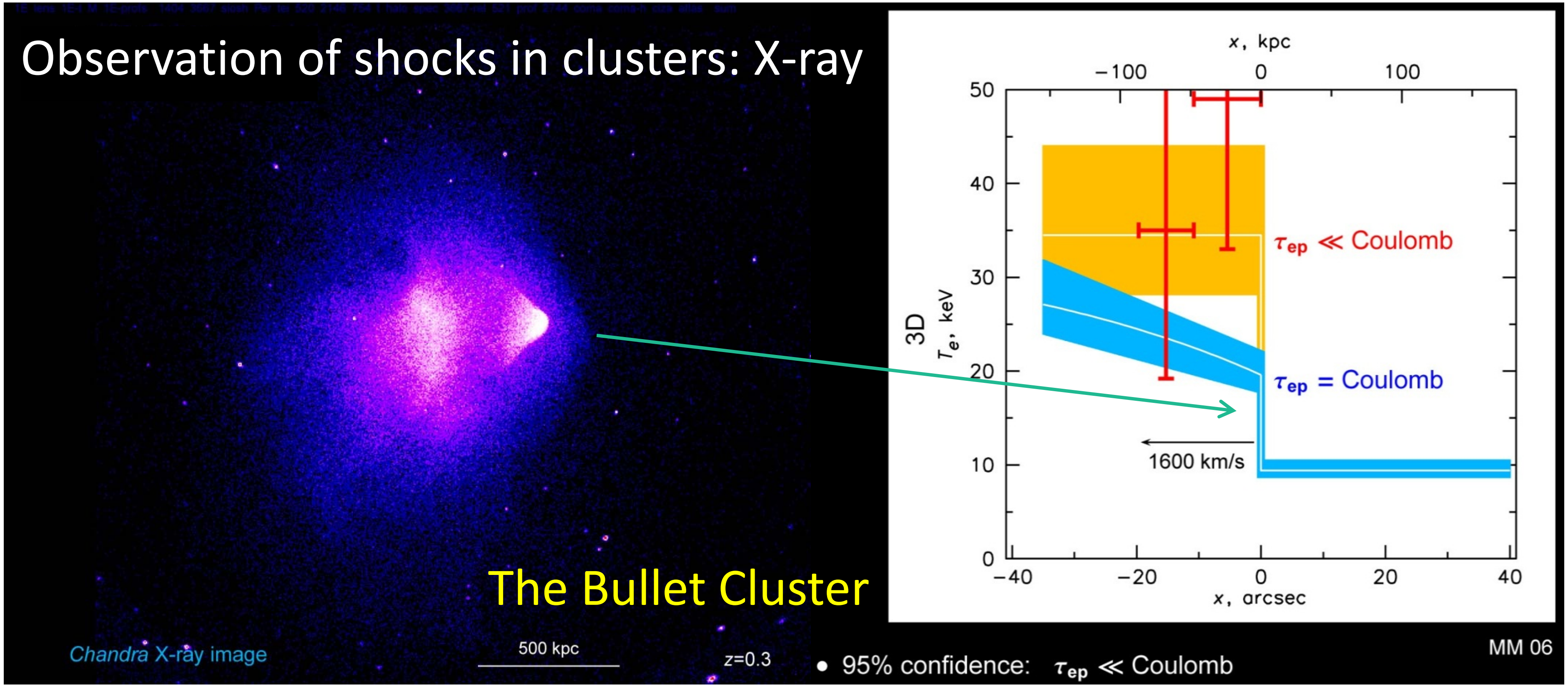
- large-scale flow motion
- turbulence
- shocks
- magnetic fields
- cosmic-rays



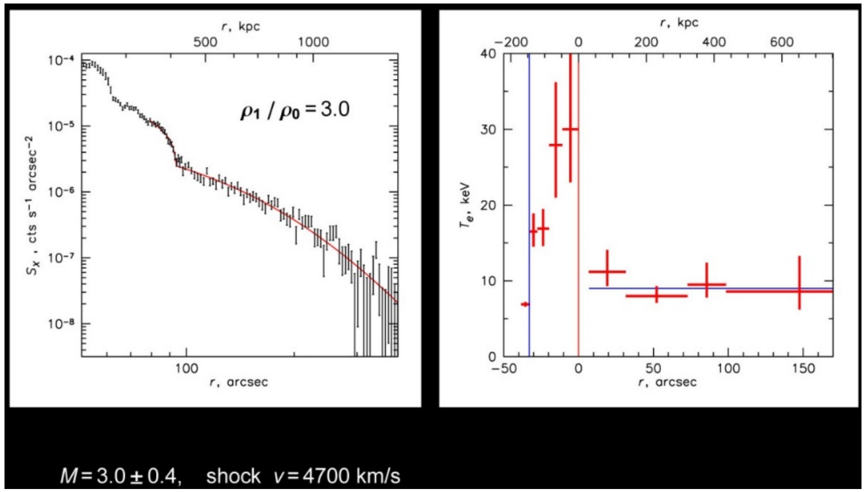




Observation of shocks in clusters: X-ray



(Markevitch et al.)

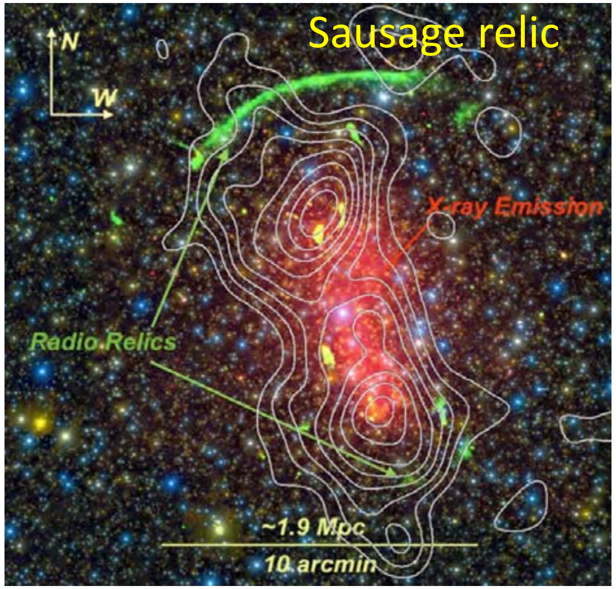


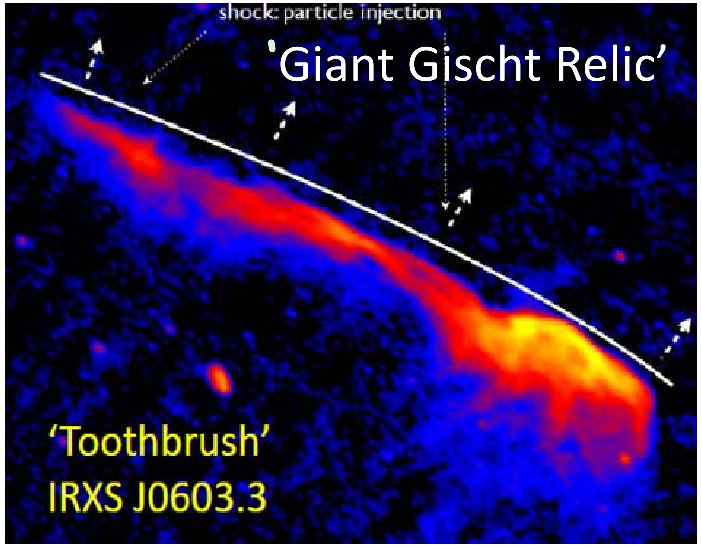
Shock wave in
1E0657-56 (Bullet cluster)

Mach number of X-ray shocks in ICMs:

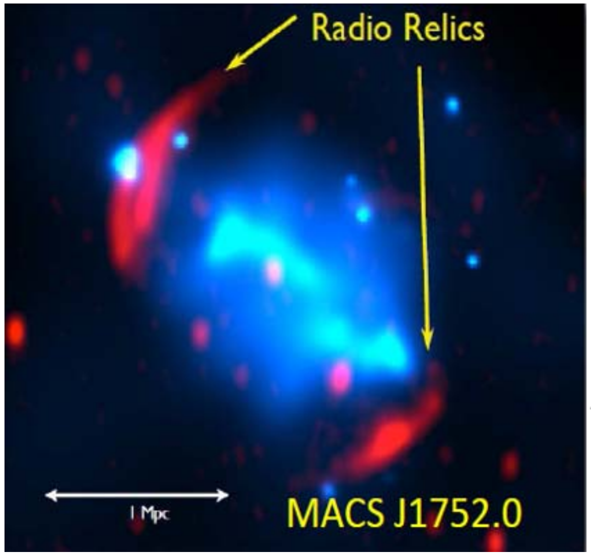
M_{shock} <~ a few

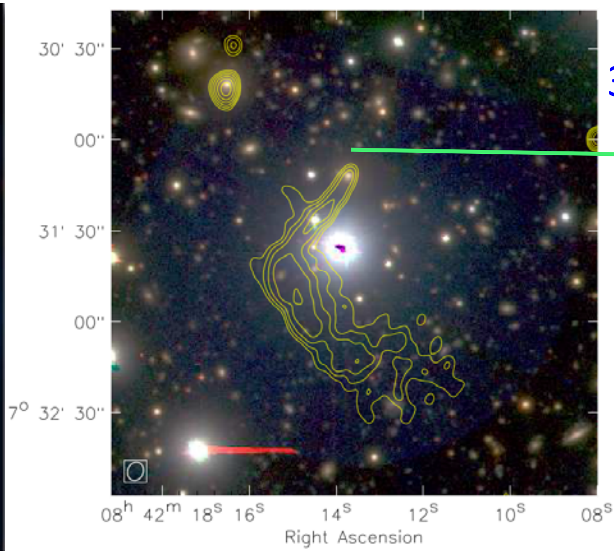
Observation of shocks in clusters: radio relics



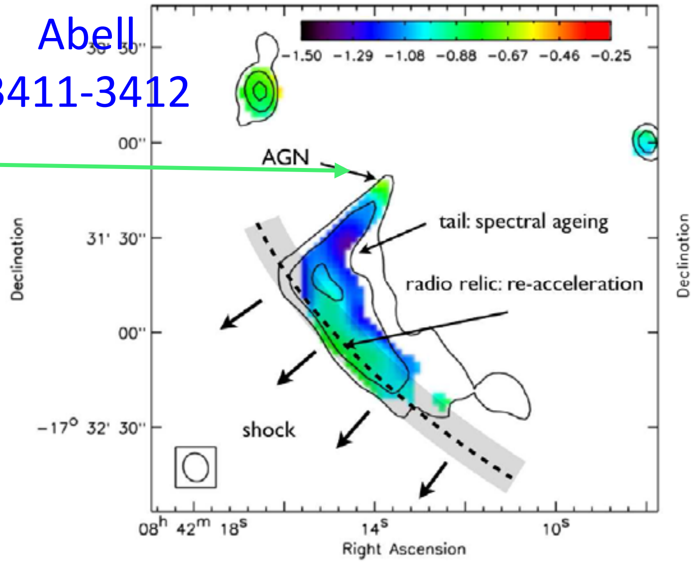


Mach number of radio shocks in ICMs: M_{shock} <~ several

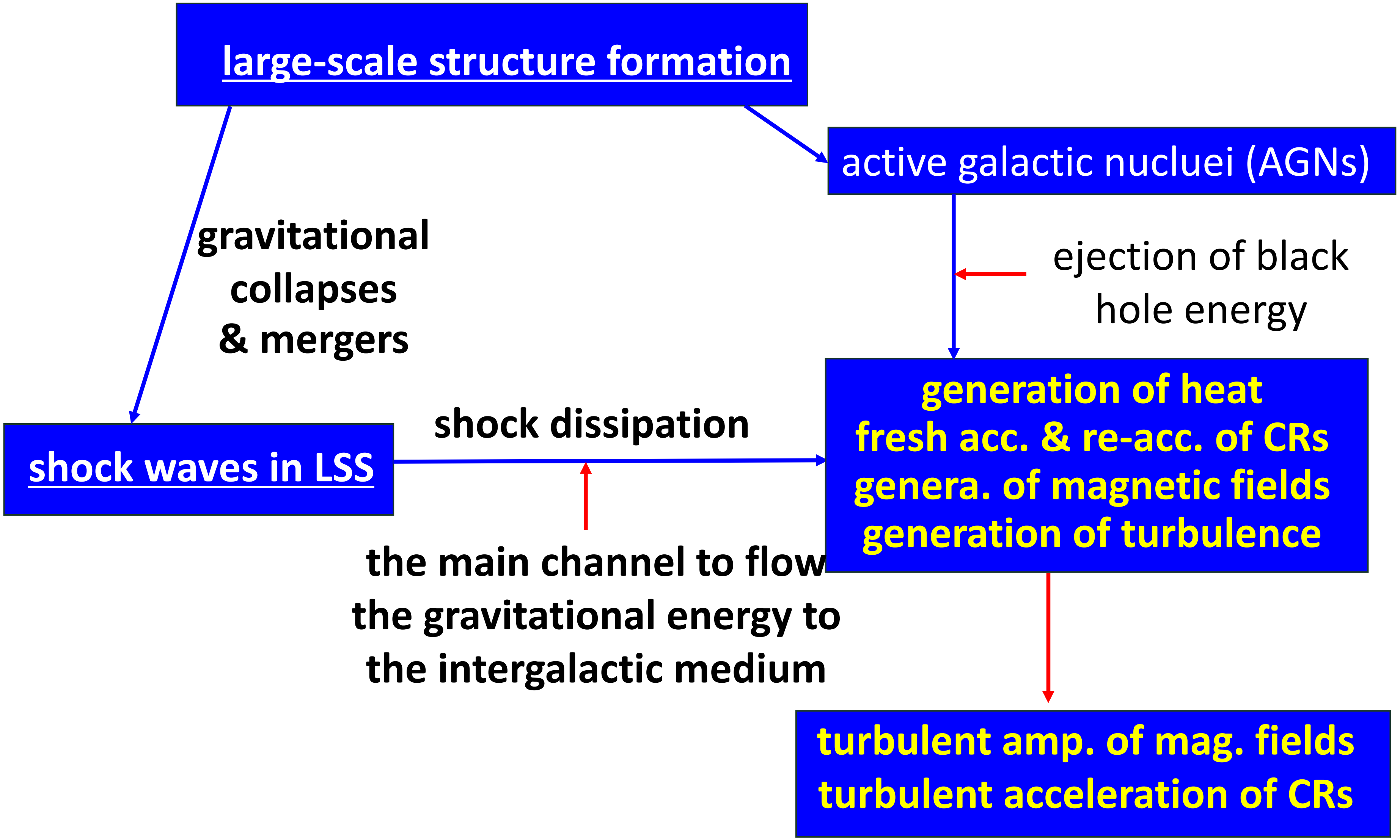




Abell 3411-3412

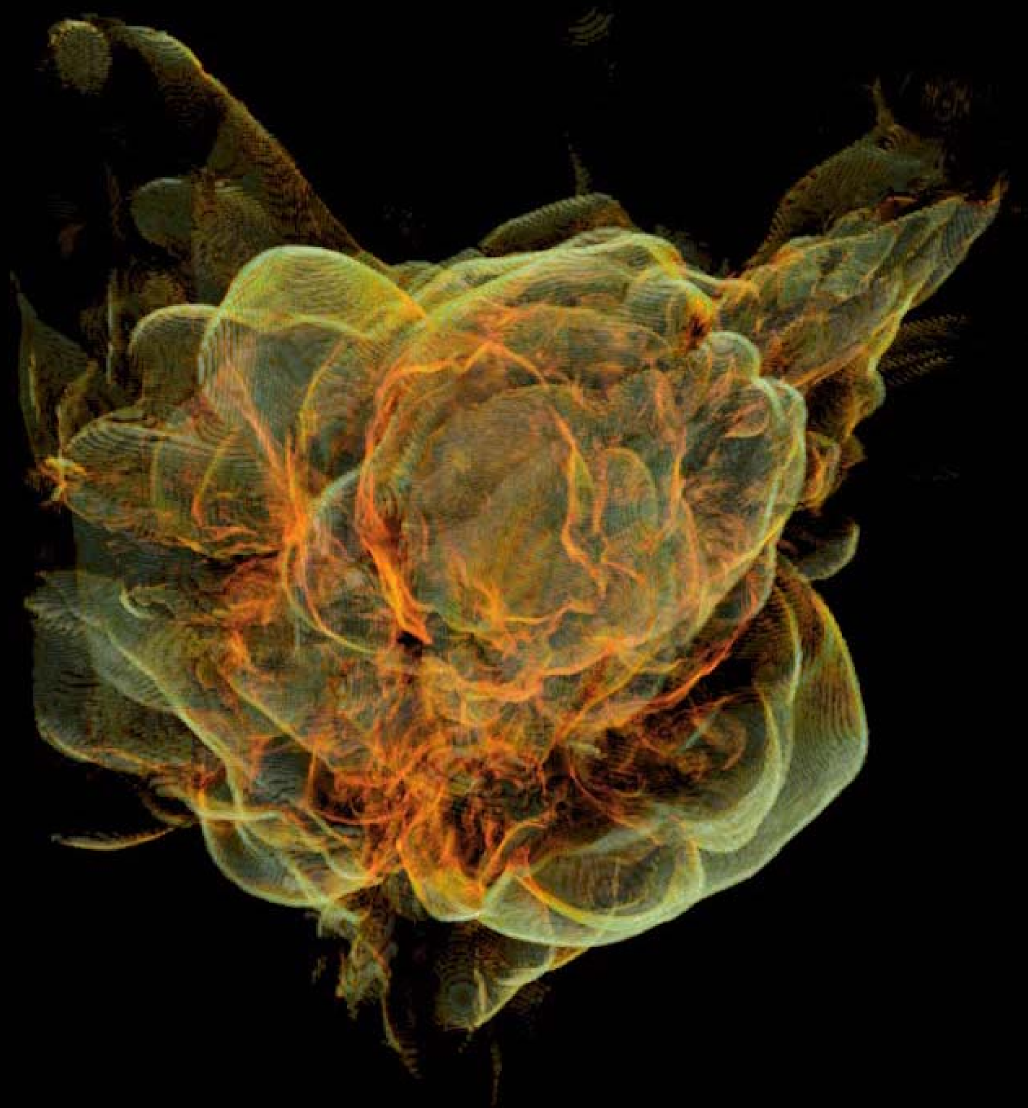


Overview for the formation and roles of shock waves in the large-scale structure of the universe



Shock waves in a simulated clusters of galaxies

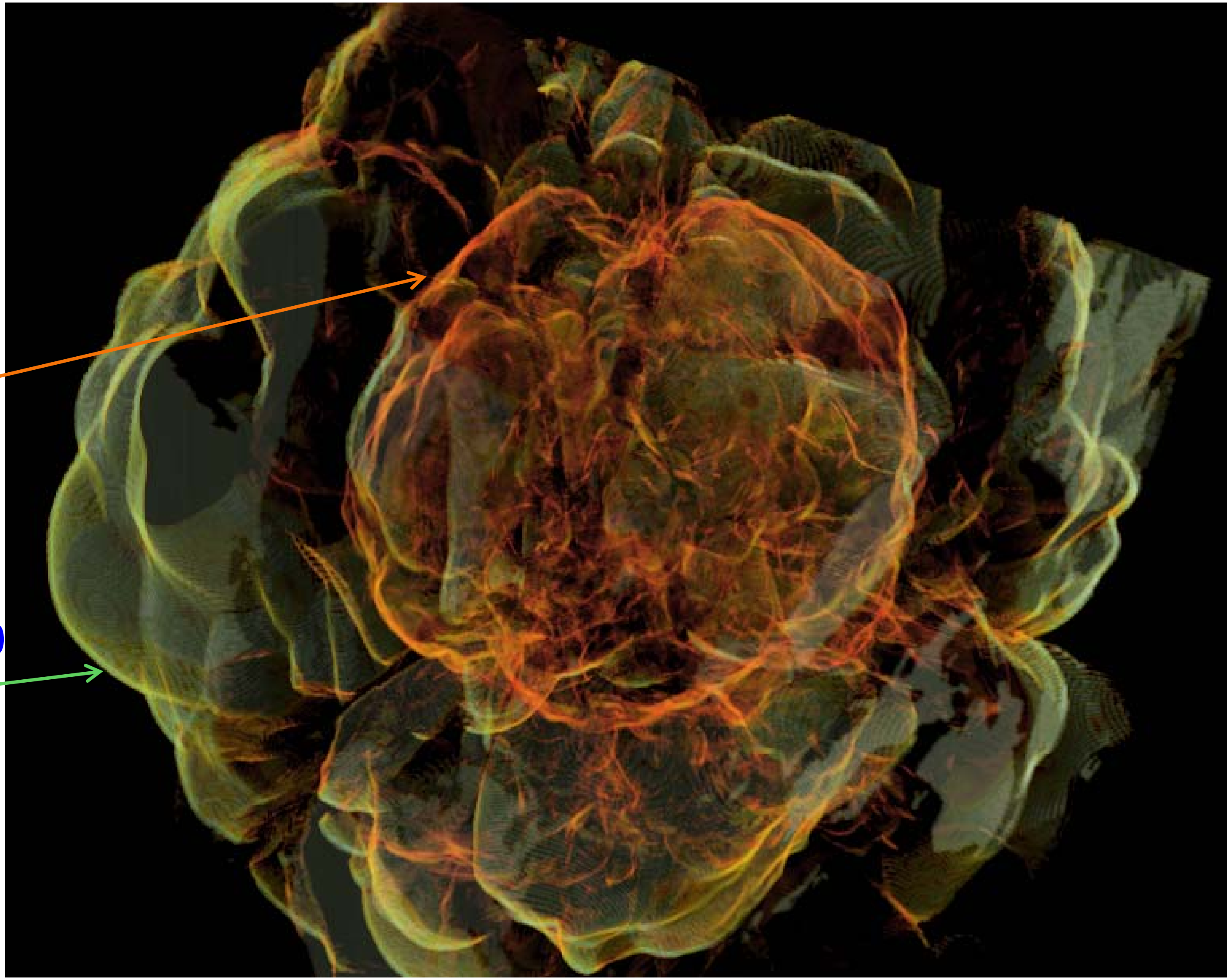
Vazza et al + Ryu



shock Mach number
M_s

https://www.youtube.com/watch?v=yV3KPz0cPqk weak inreacluster shocks with M<4 (orange)

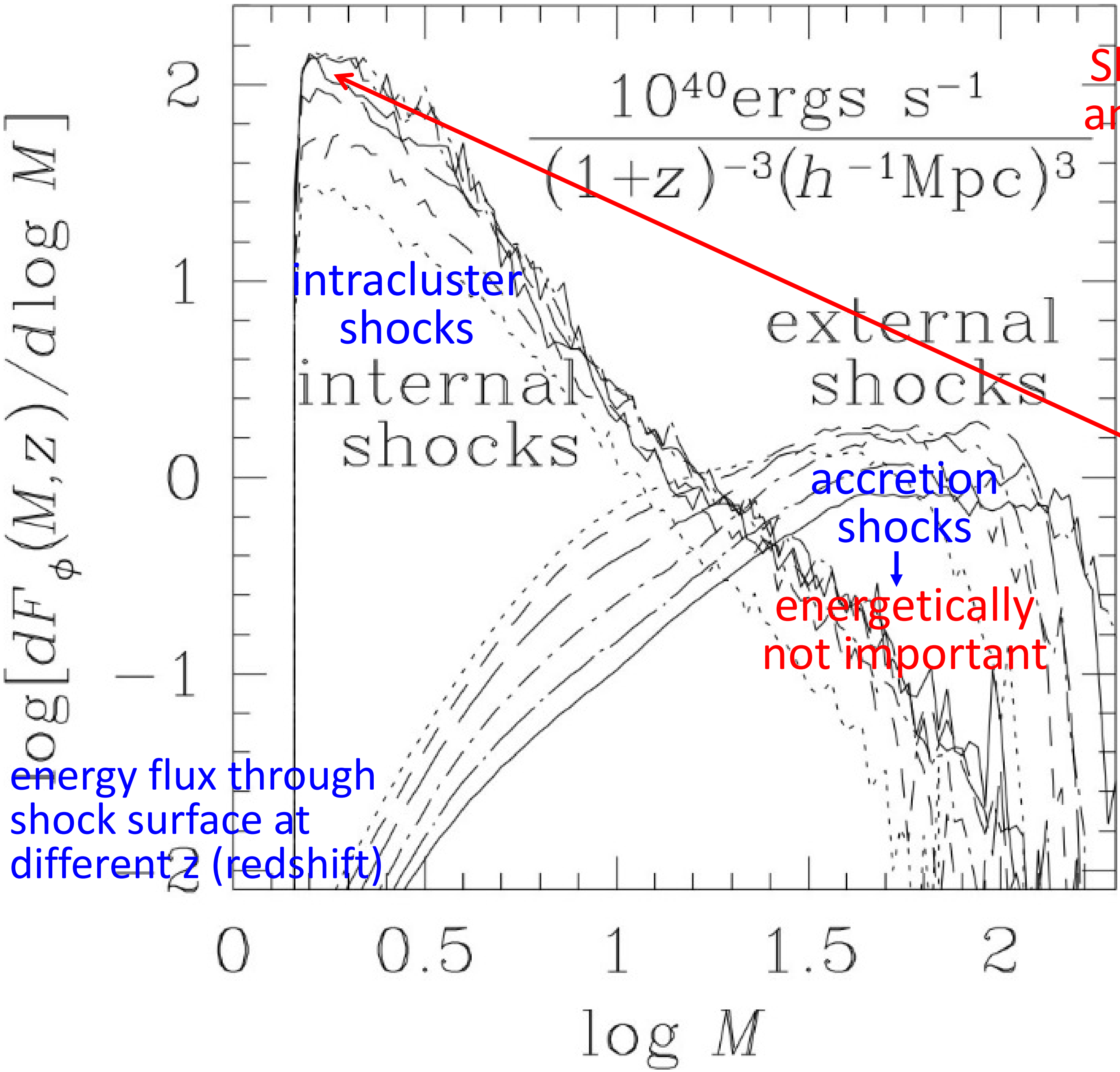
strong accretion shocks with M>10 (green)



(Vazza, Jones, Gheller, Bruggen, Brunetti & Ryu)

Shock waves inside and around clusters

(Ryu et al. 2003)



Weak intracluster shocks with M_s ~ a few, V_s ~ 2,000 km/s are energetically more important.

The nature of shocks found in intracluster media

1) turbulence shocks

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

3) **merger shocks** ➔ most energetic

a merger event of ~10^{13} $M_\odot$

(Ryu et al. 2003)

clumps with speed of ~1,000 km/s ➔ E_{merger} ~ 10^{63} ergs

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]

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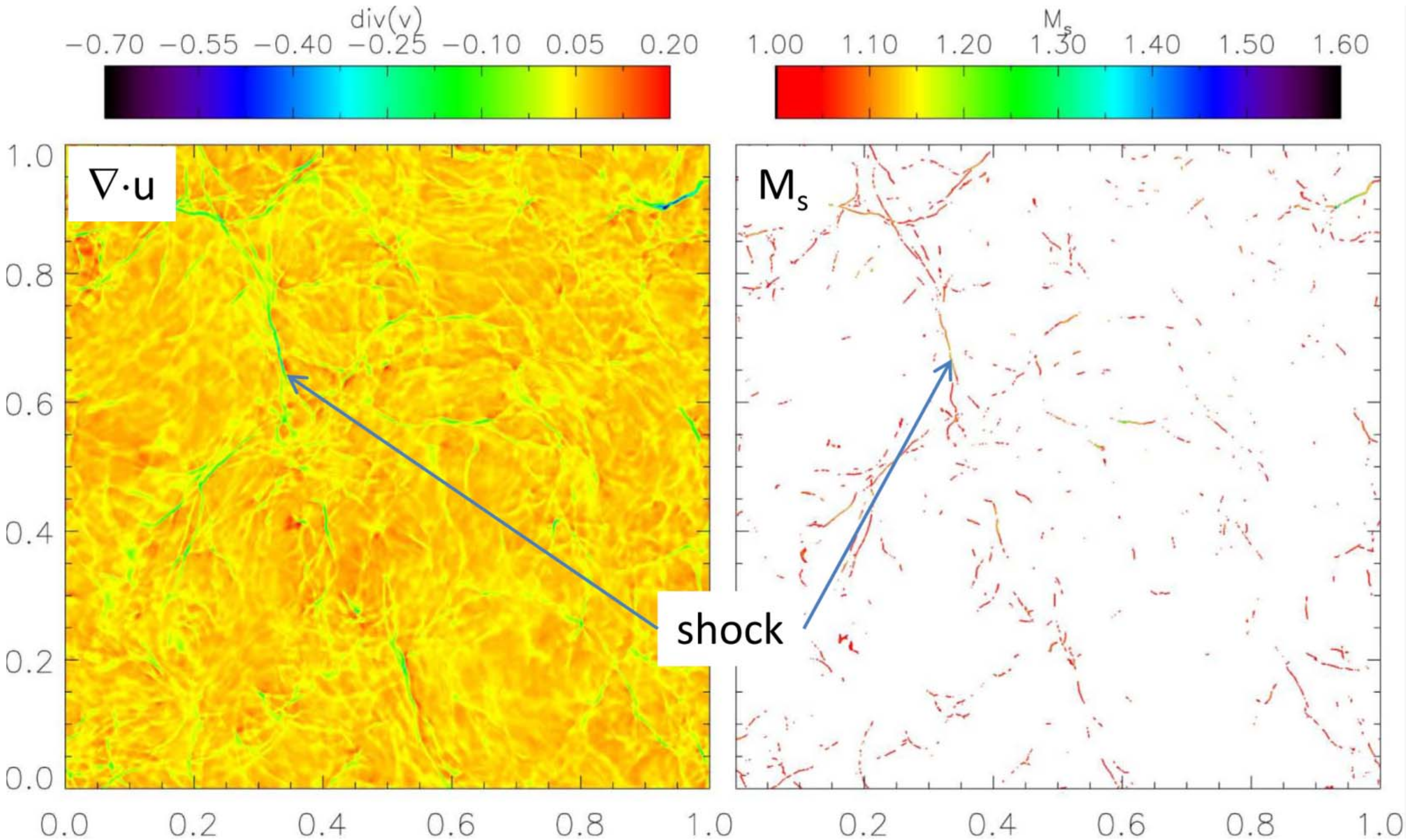
ABSTRACT

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

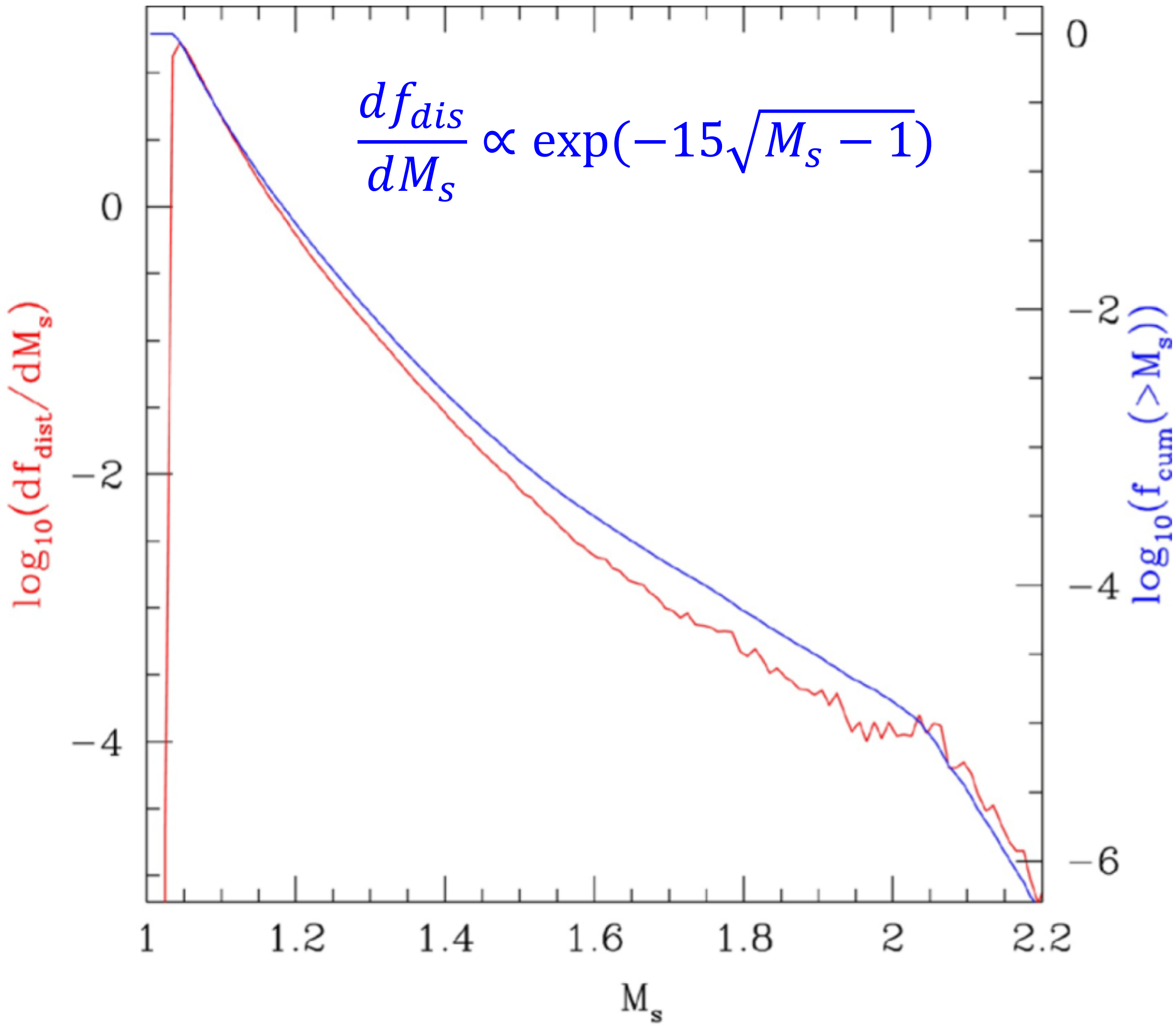
The ICM is in the state of turbulence with M_{turb} ~ 0.5

Turbulence shocks - formed by turbulent flow motions



(Porter, Jones, & Ryu 2015)

Shock Mach number PDF

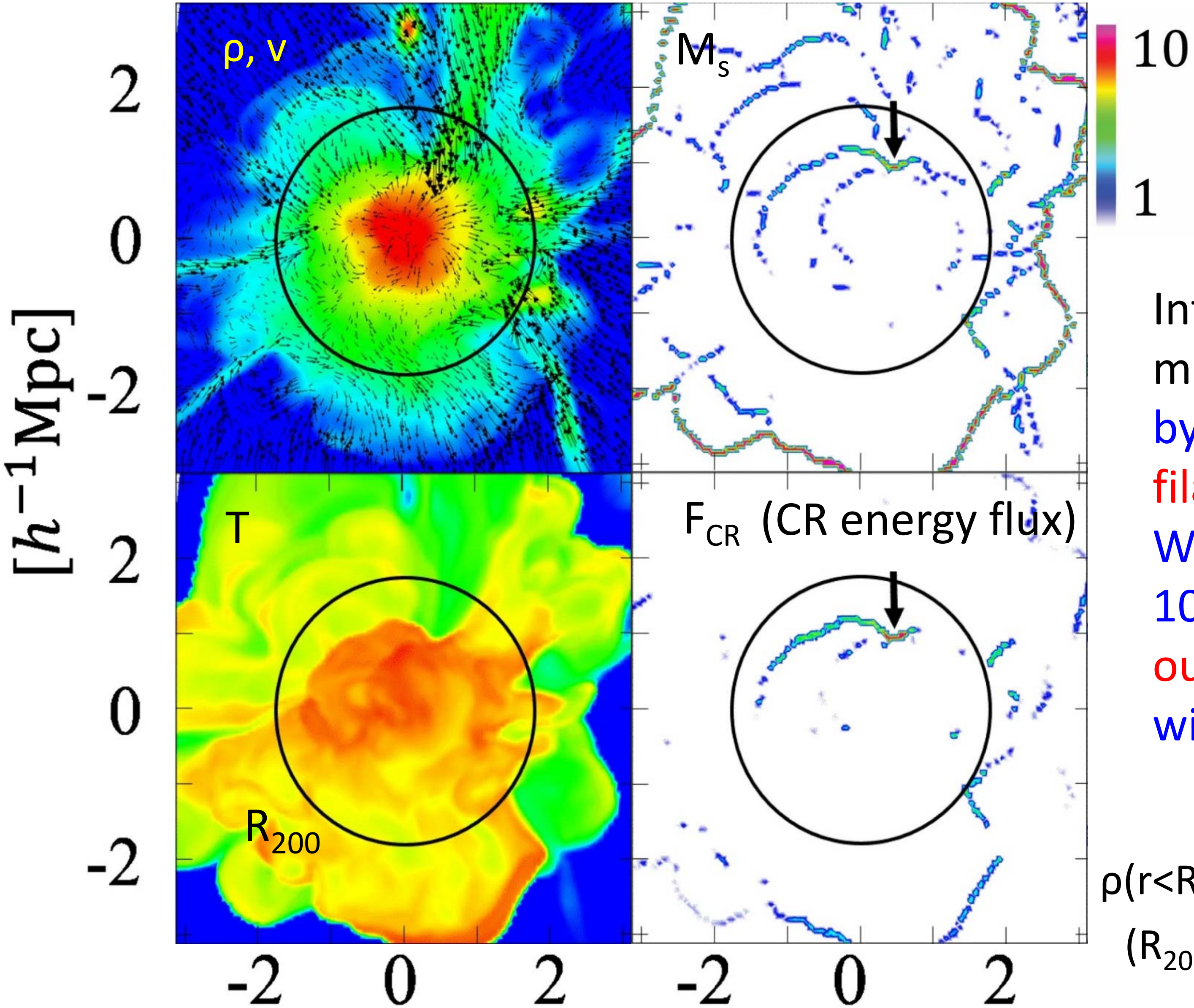


Turbulence shocks in ICMs are mostly weak with M_{shock} <~ 2 and short-lived !

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

Infall shocks

(Hong, Ryu, Kang, & Cen 2014)

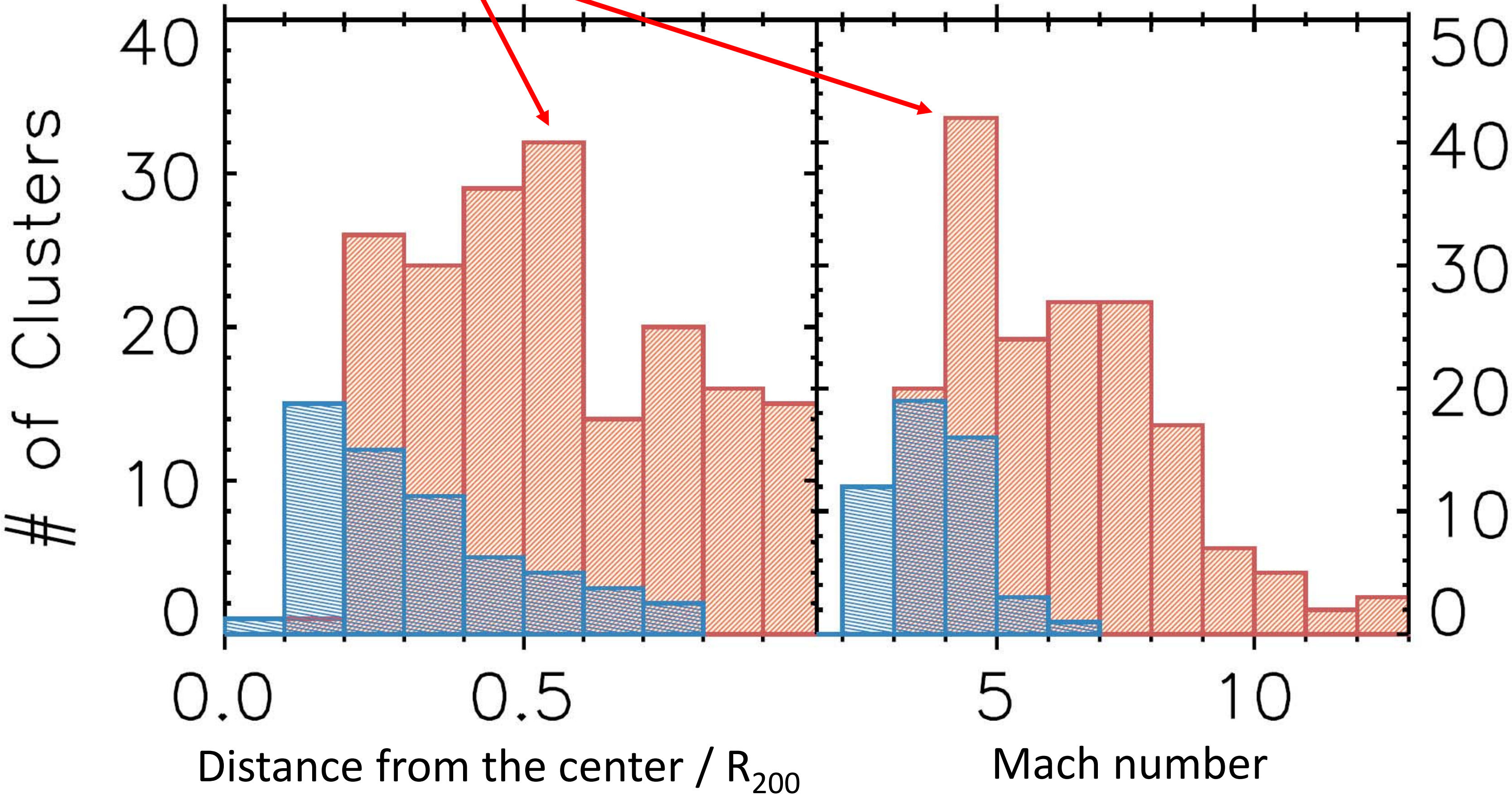


Infall shocks formed mostly at the outskirts, by gas inflow from filaments of the WHIM with T ~ 10^5 – 10^7 K to cluster outskirts of hot gas with T ~ 10^7 - 10^8 K

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

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

Statistics of infall shocks



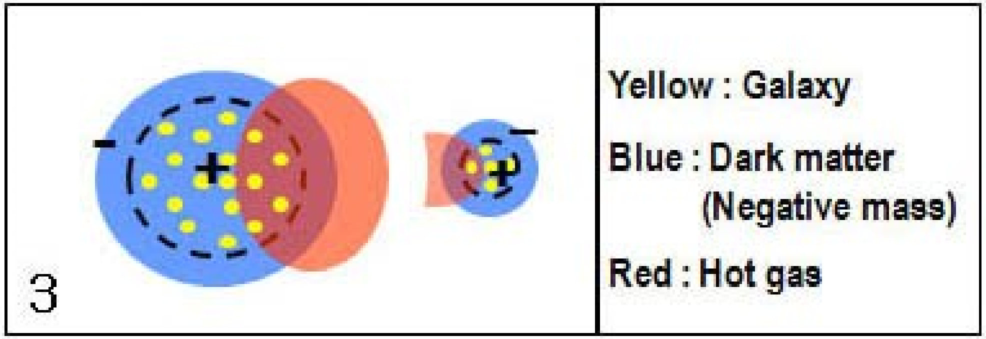
- infall shocks are strong with, M_s = a few ~ 10, stronger than merger shocks
- they are found mostly in outskirts, and their surface area is small
- energetically infall shocks are less important than merger shocks

Merger shocks: observations of merging galaxy clusters

Bullet Cluster (IE 0657-56)

(Markevitch et al)

a binary merger of mass ratio ~ a few

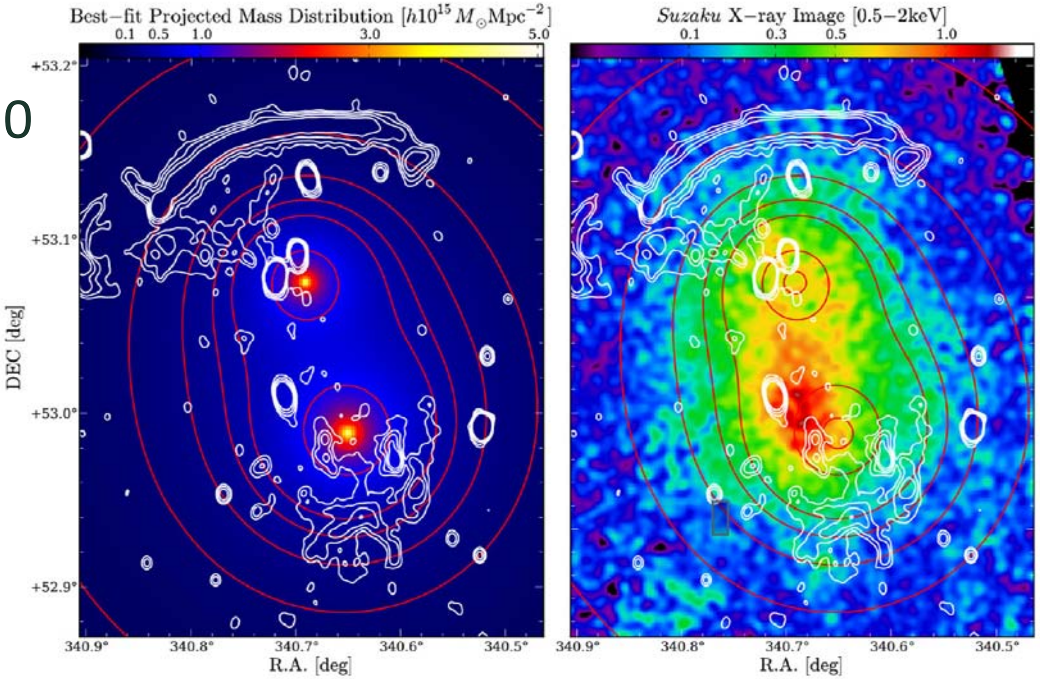


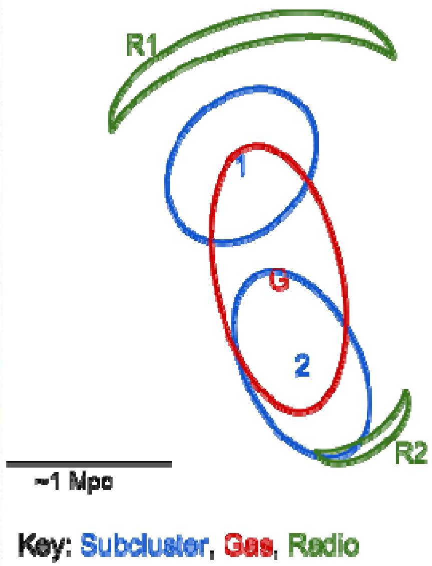
CIZA J2242.8+5310

(Sausage relics)

(vanWeeren et al, Okabe et al)

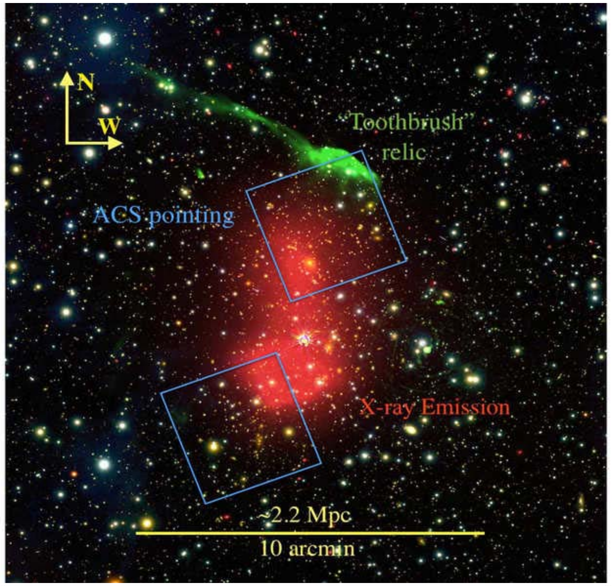
a binary merger of mass ratio ~ one -two

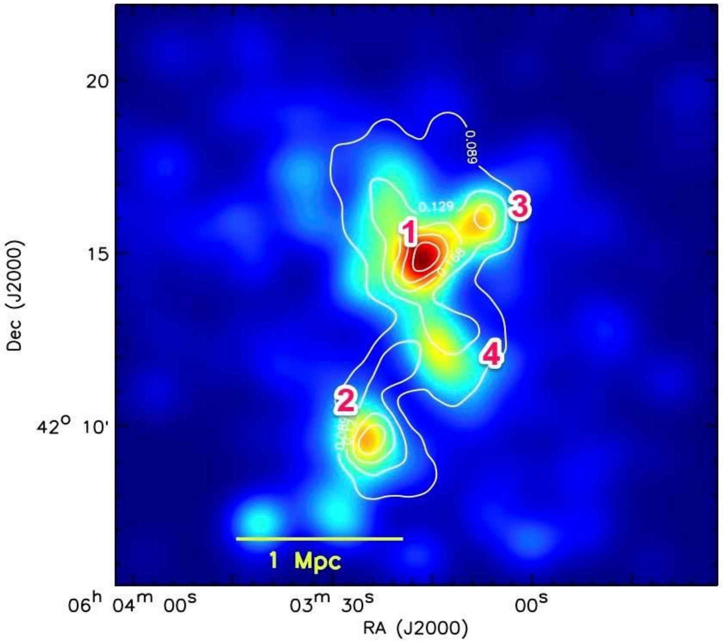




RX J0603.3+4214 (Toothbrush relic)

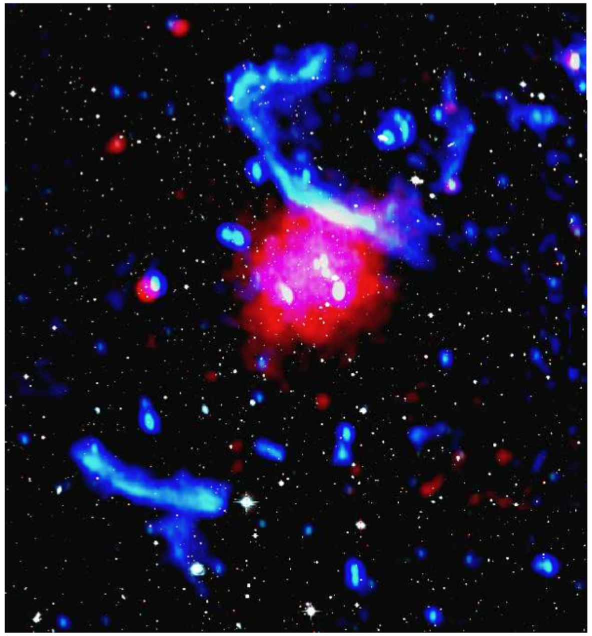
(vanWeeren et al, Jee et al)



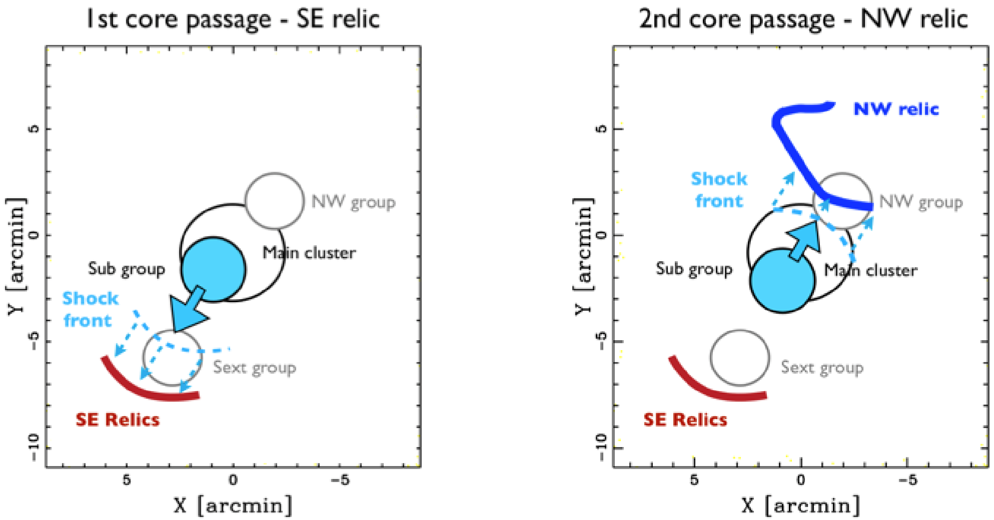


PLCK G287.0+32.9

(Bonafede et al)

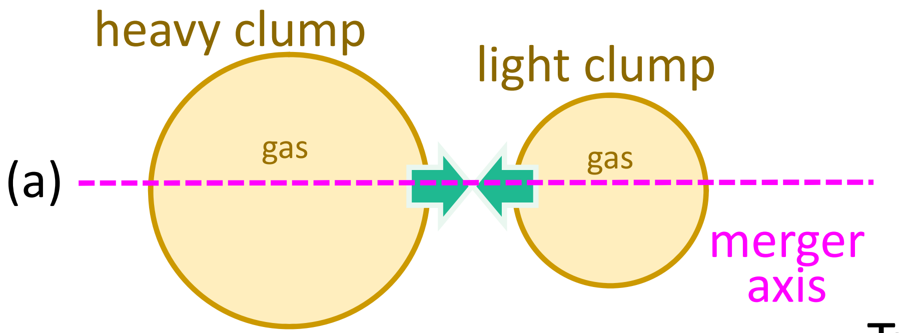


X-ray
+
radio

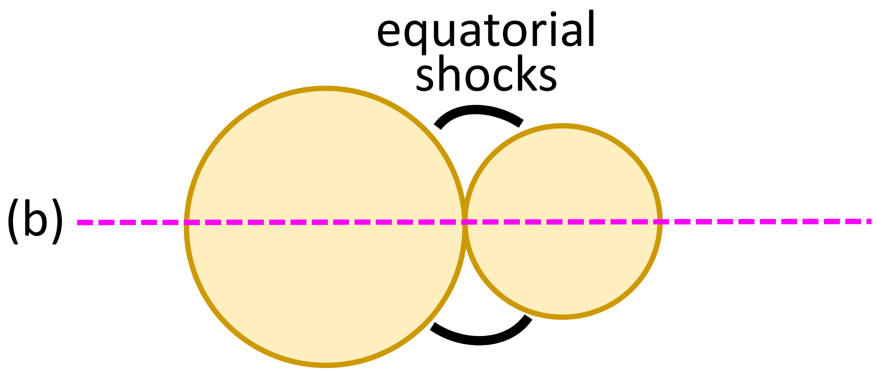


a number of sub-clumps in both clusters!

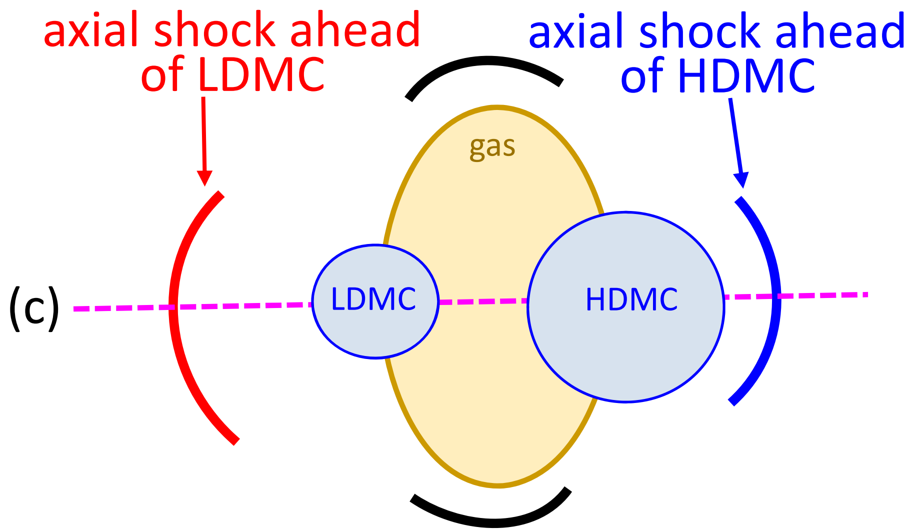
Simple binary merger – a cartoon picture



Two clumps are approaching.



Shocks along the direction perpendicular to the merger axis are first launched.



LDMC – light dark matter core

HDMC – heavy dark matter core

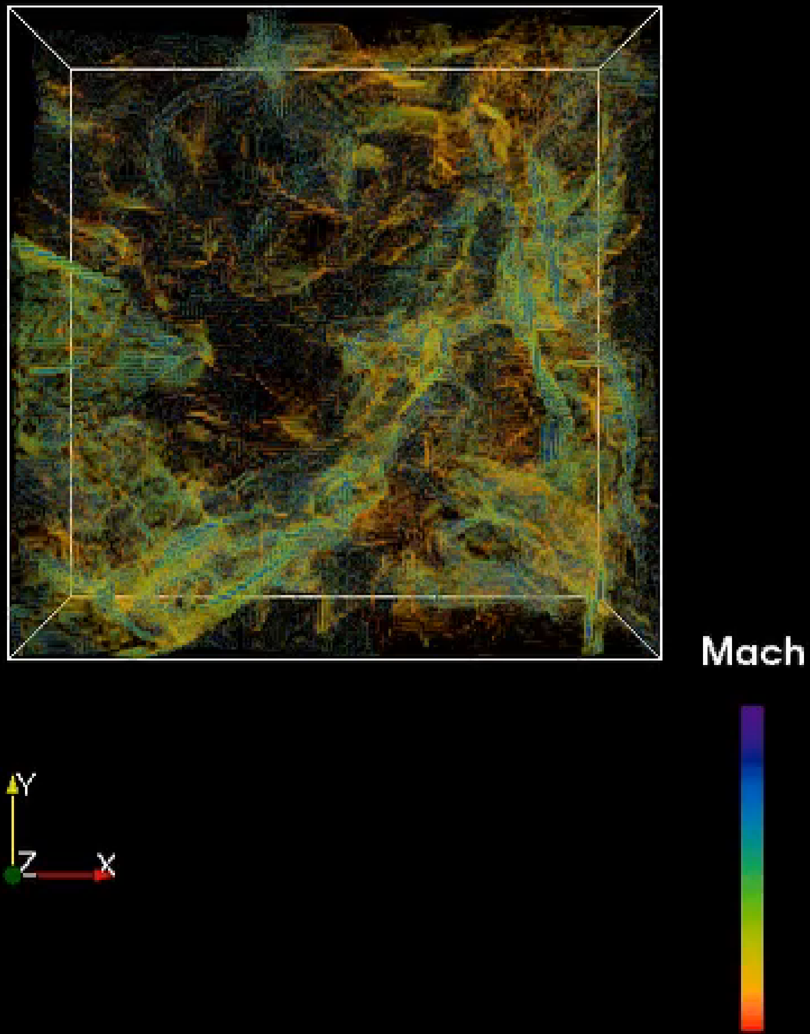
Shocks along the direction parallel to the merger axis form and propagate.

Shock waves in a merging cluster from a simulation for large-scale structure formation in 100 h^{-1} Mpc box

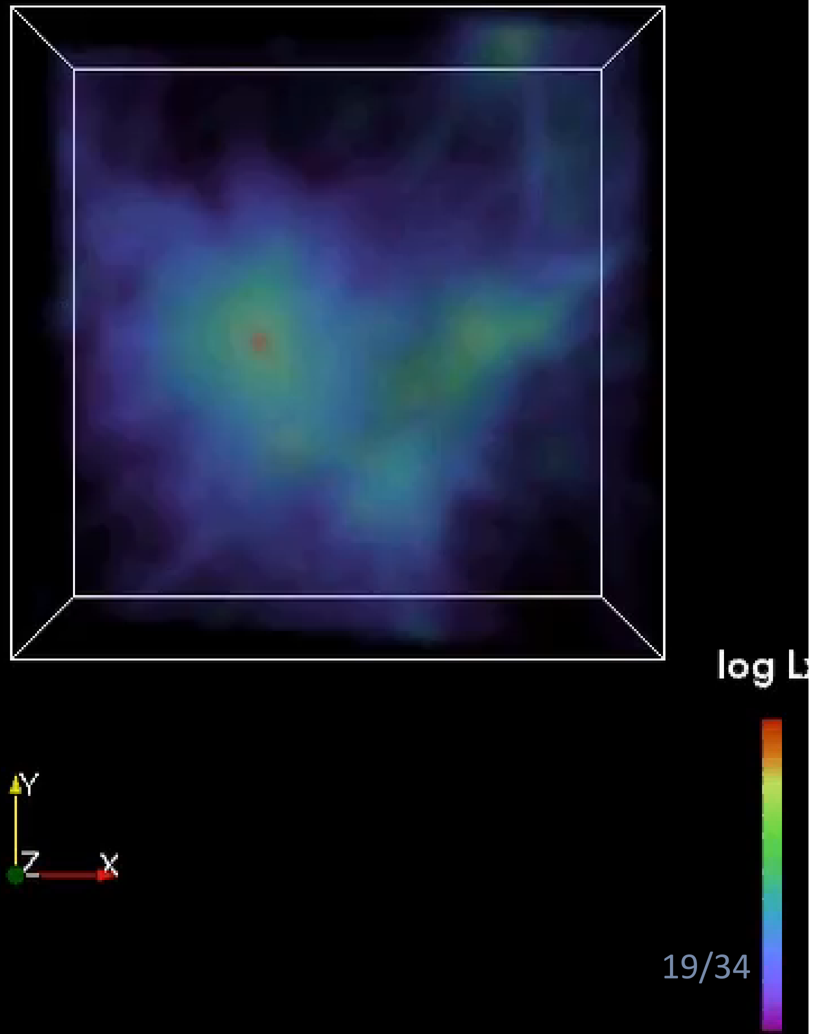
(Ha, Ryu, & Kang 2017)

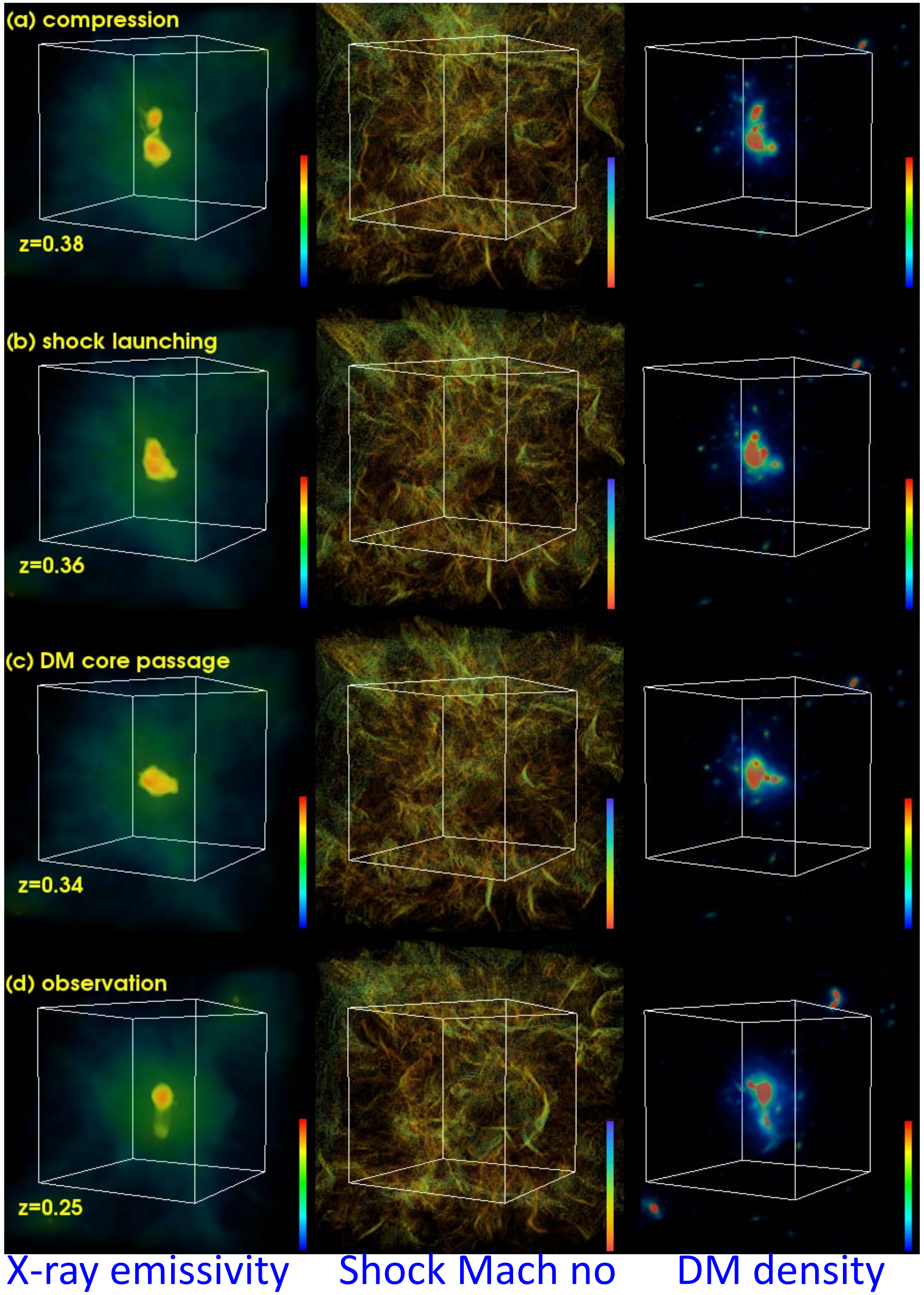
from z = 0.5 to 0.05, box size = 5 h^{-1} Mpc

shocks with $1 < M_s < 10$



X-ray emissivity





Merging process

in an almost head-on collision of two clumps with mass ratio ~2 that results in a $T_x \sim$ 5 keV cluster

(a) the two clumps are approaching

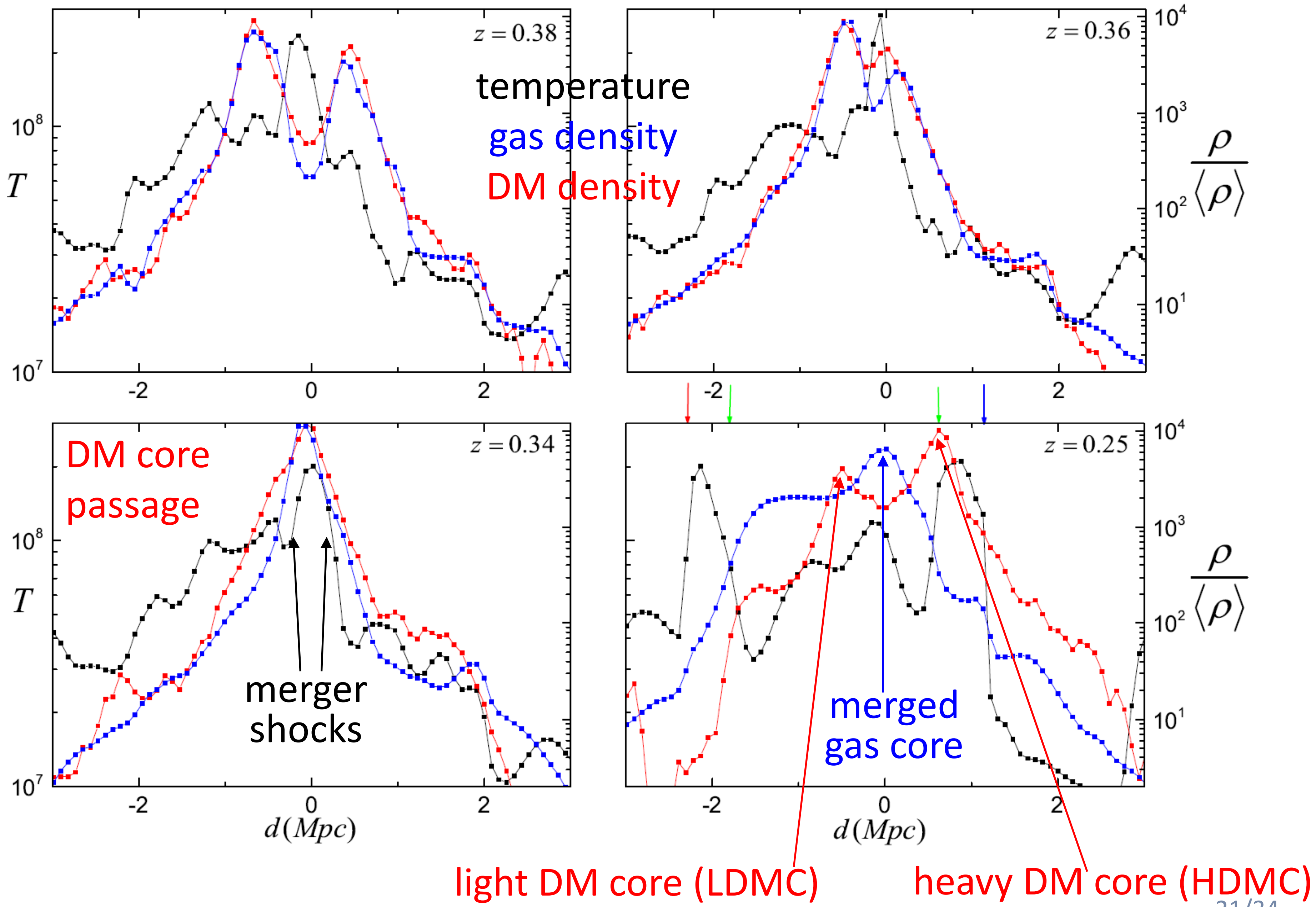
(b) shocks lunch along the merger axis

(c) two DM cores pass each other and two gas clumps merge to form a single core

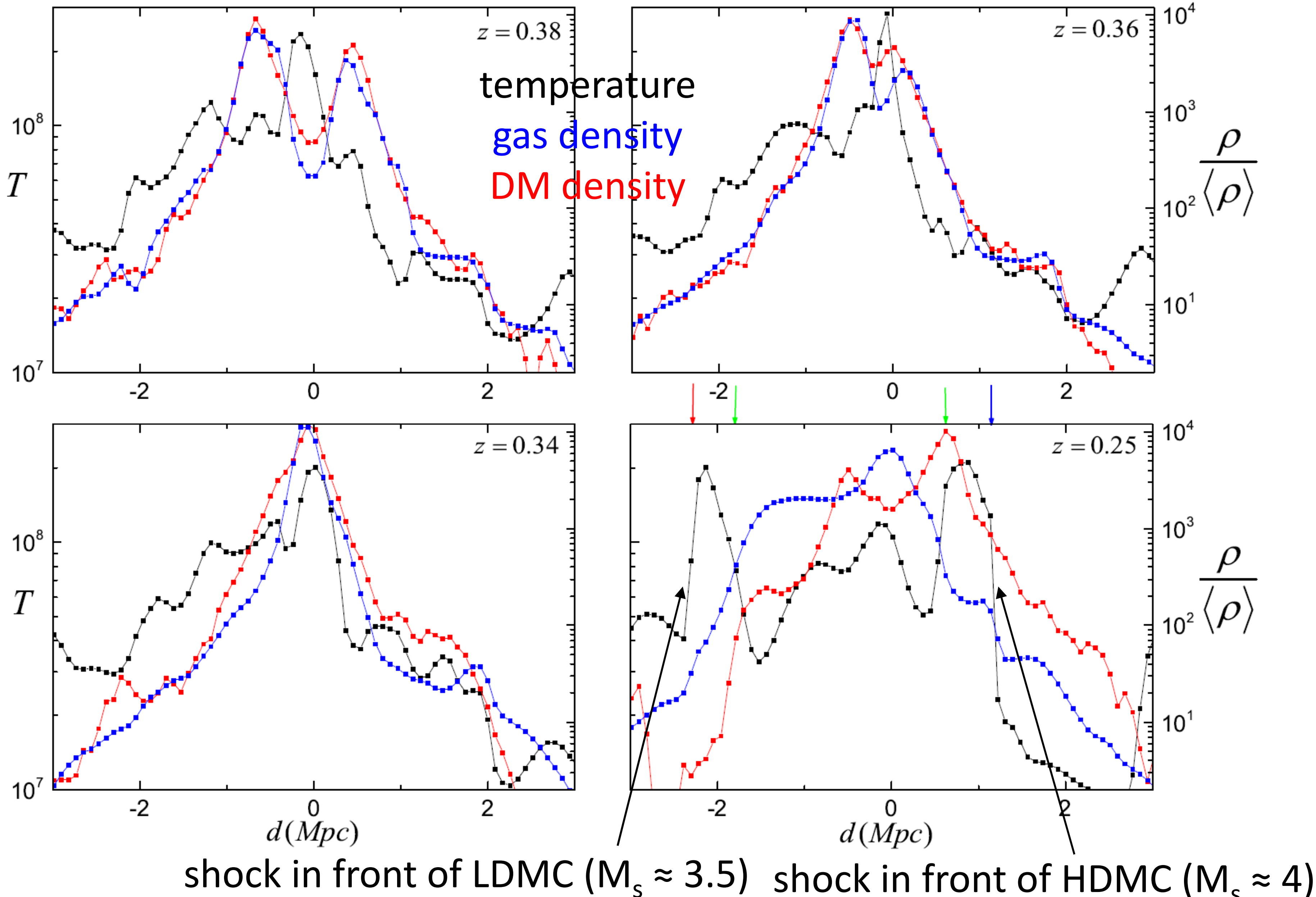
(d) the time when shocks have the best chance to appear as radio relics

The surfaces of shocks are not uniform, but highly intermittent with filamentary patches of high M_s parts!

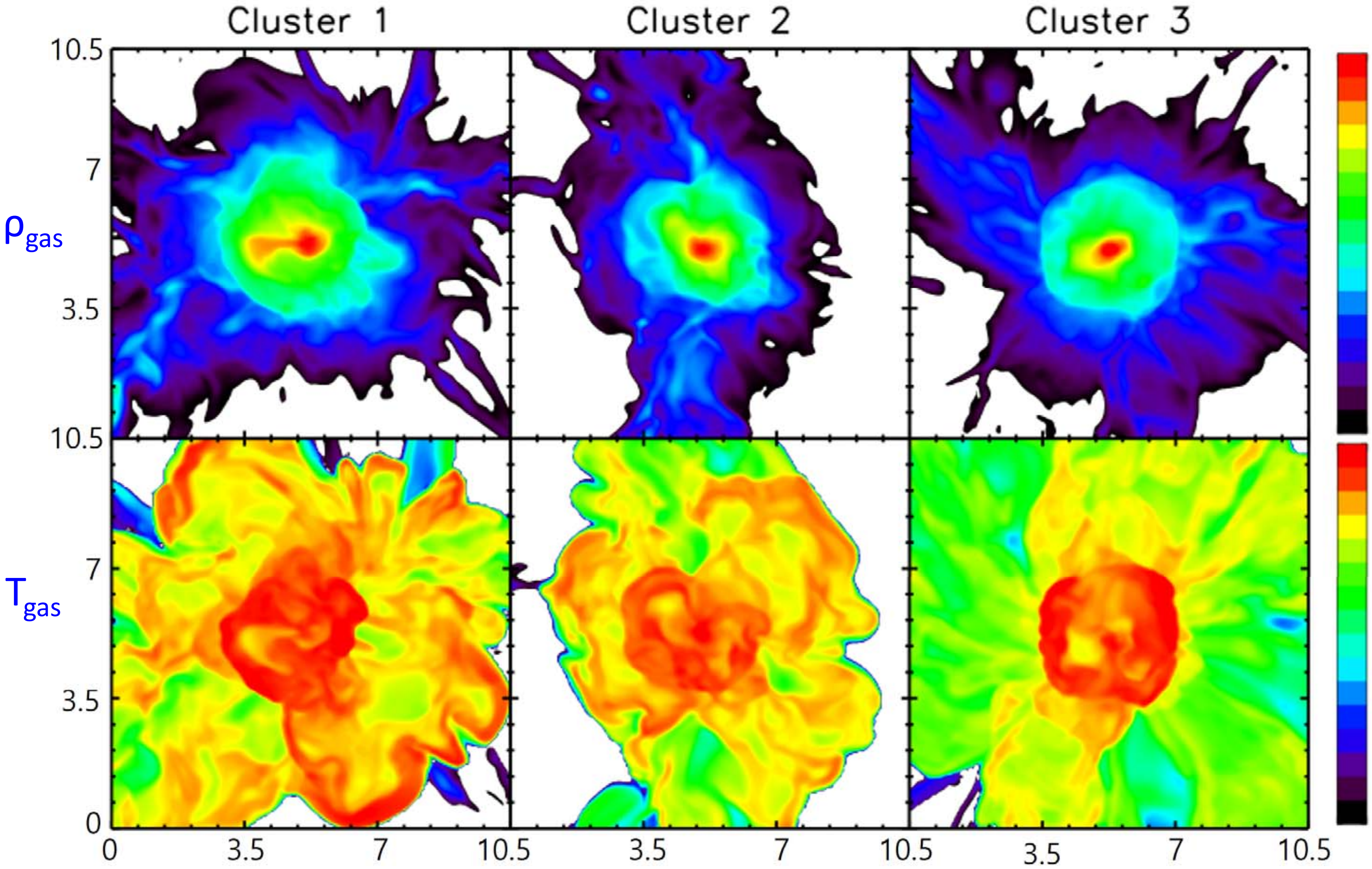
1D profiles along the merger axis at four epochs



1D profiles along the merger axis at four epochs

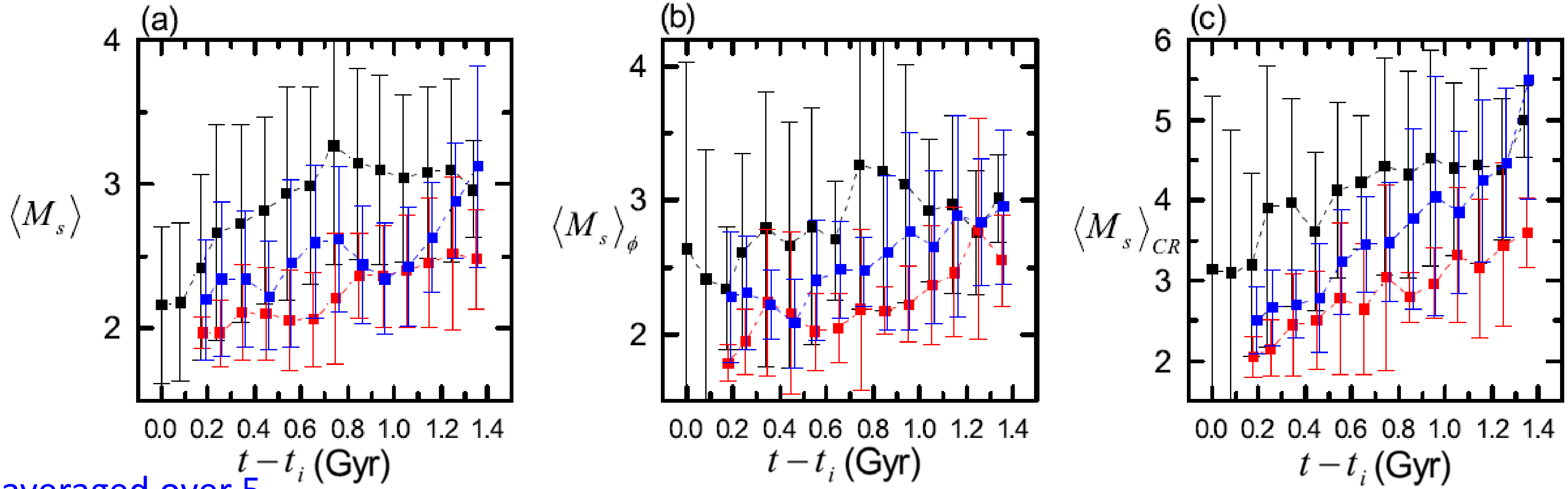


Quantification of merger shock properties in simulated merging clusters

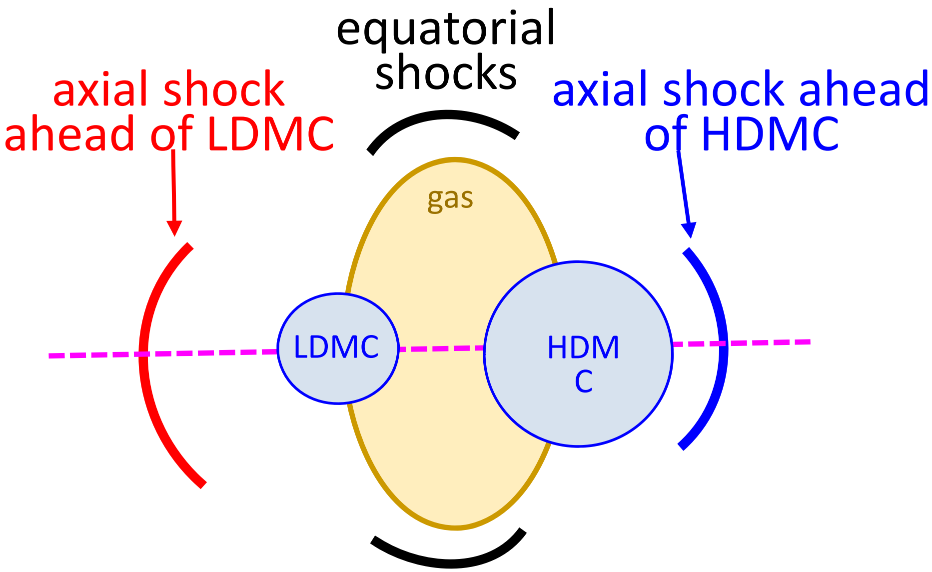


2D slices of three sample clusters through X-ray peak

Statistical properties of merger shocks in simulated merging clusters



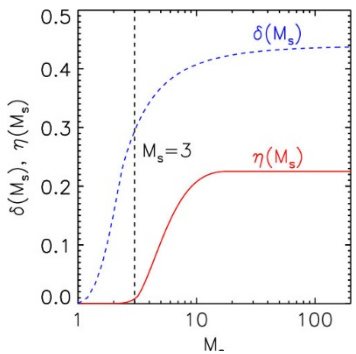
averaged over 5 merging clusters



$<M_s>$: average shock number

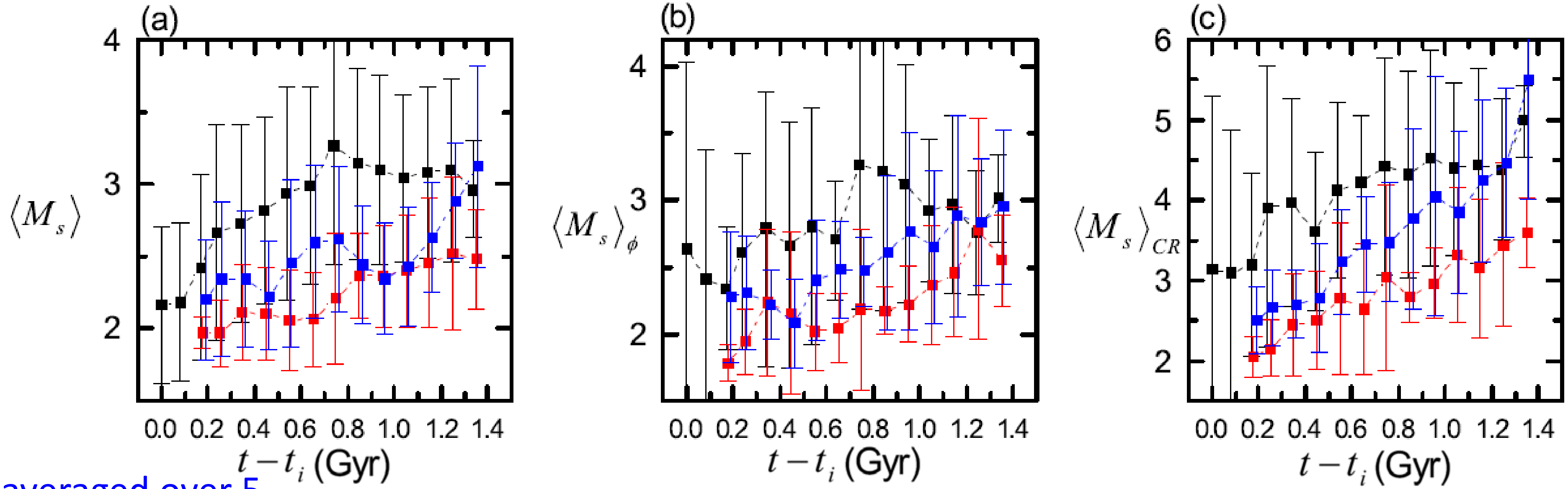
$<M_s>_\phi$: average shock number weighted with shock kinetic energy flux $f_\phi = (1/2)\rho_1 v_s^3$

$<M_s>_{CR}$: average shock number weighted with shock CR energy flux $f_{\rm CR} = \eta(M_s) \times f_\phi$

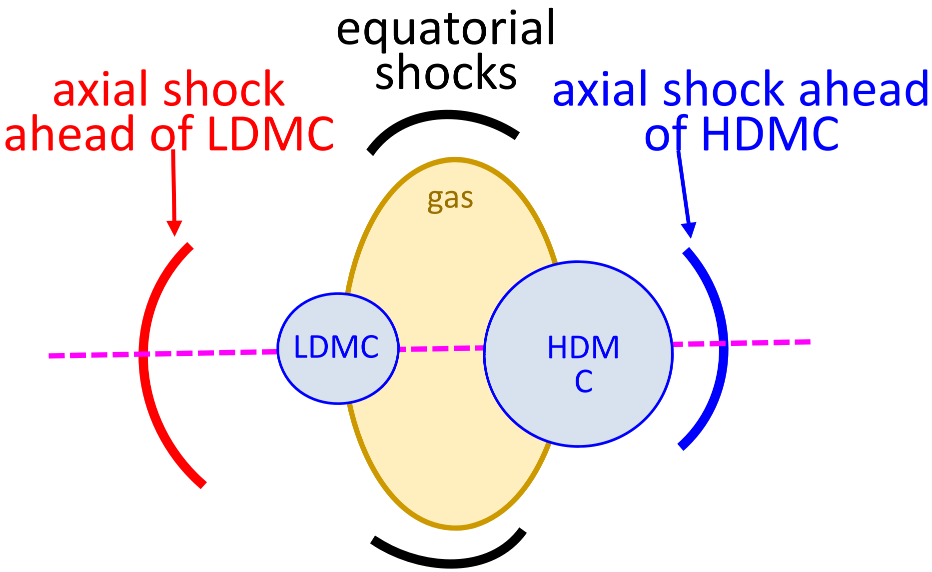


η: CR acceleration efficiency - the fraction of shock kinetic energy converted to CRs at shocks

Statistical properties of merger shocks in simulated merging clusters



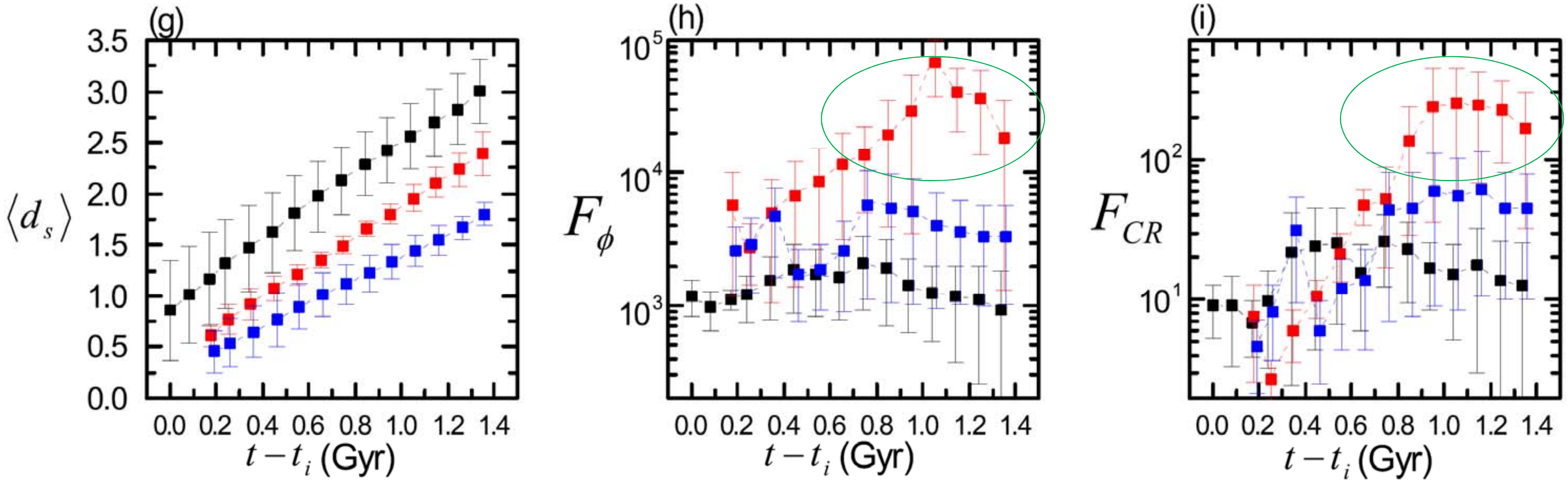
averaged over 5 merging clusters



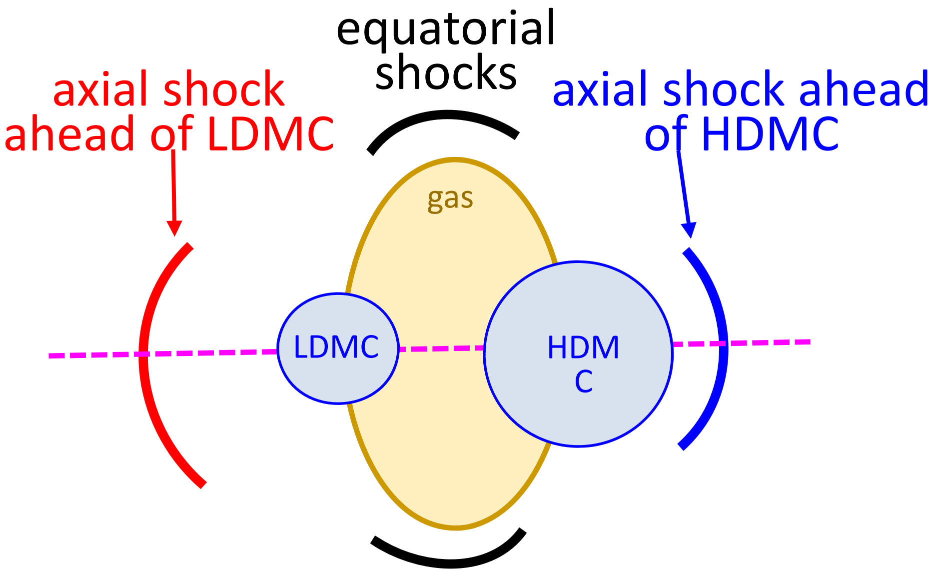
- M_s increases as shocks move to outwards
- $\langle M_s \rangle_{CR}$, weighted with shock CR energy flux, is larger than $\langle M_s \rangle_\phi$, weighted with shock kinetic energy flux, by ~ unity

(CR acceleration is more efficient at higher M_s shocks.)

Statistical properties of merger shocks in simulated merging clusters

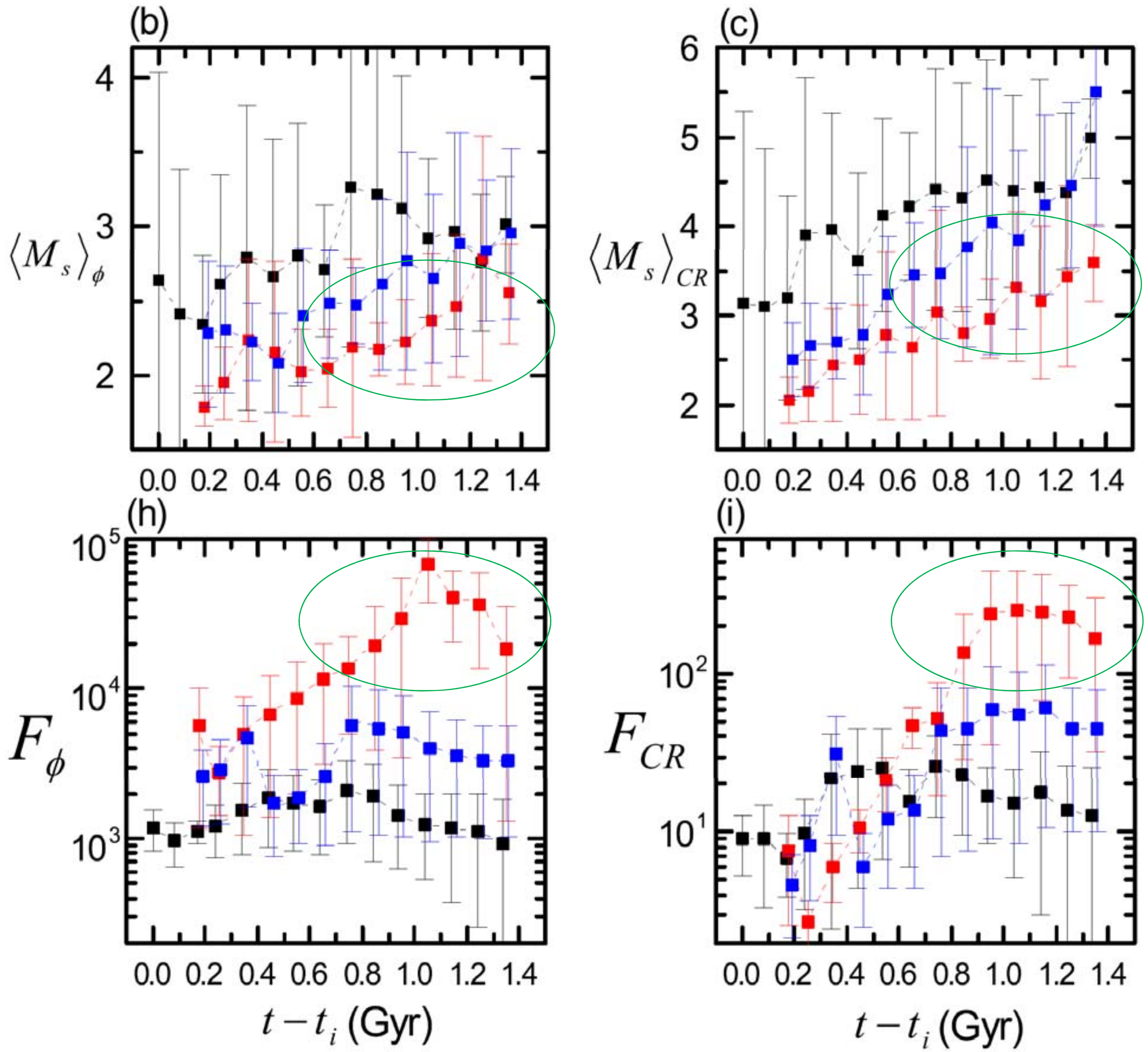


$$F_{\phi \text{ or CR}} = \sum_{\text{shocks}} f_{\phi \text{ or CR}} \, \Delta S$$



- F_ϕ kinetic energy through shock surface
- F_{CR} CR energy production at shock surface
- Shocks in front of LDMC are most energetic, which dissipate up to ~10 % of merger energy during the life
- Shocks in front of LDMC have the best chance to be manifested as X-ray shocks and radio relics

Statistical properties of merger shocks in simulated merging clusters



For shocks in front of LDMC

- F_ϕ and F_{CR} of the shocks peak about ~ 0.8 – 1.4 Gyrs after the formation or at d_s ~ 1 – 2 Mpc from cluster core
- $\langle M_s \rangle_\phi$ ~ 2 – 2.5 → about M_s of X-ray shocks
- $\langle M_s \rangle_{CR}$ ~ 3 – 3.5 → about M_s estimated with spectral index of radio relics

Merging galaxy clusters display phenomena including

- Shock waves in X-ray observation
- Radio relics (interpreted to be associated with shocks)
- Radio halos (diffuse radio emission)
- …

Yet, puzzles remain including the followings

- Mach numbers estimated in X-ray and radio do not always coincide
- Not all merging clusters host, for instance, radio relics
- Sufficient (sometime too much) acceleration of electrons at shocks
- Little acceleration of protons at shocks ← no ϒ-ray observation yet
- Large-scale magnetic field around radio relics ← polarization obs.
- Turbulent acceleration of electrons ← radio halo observation
- …

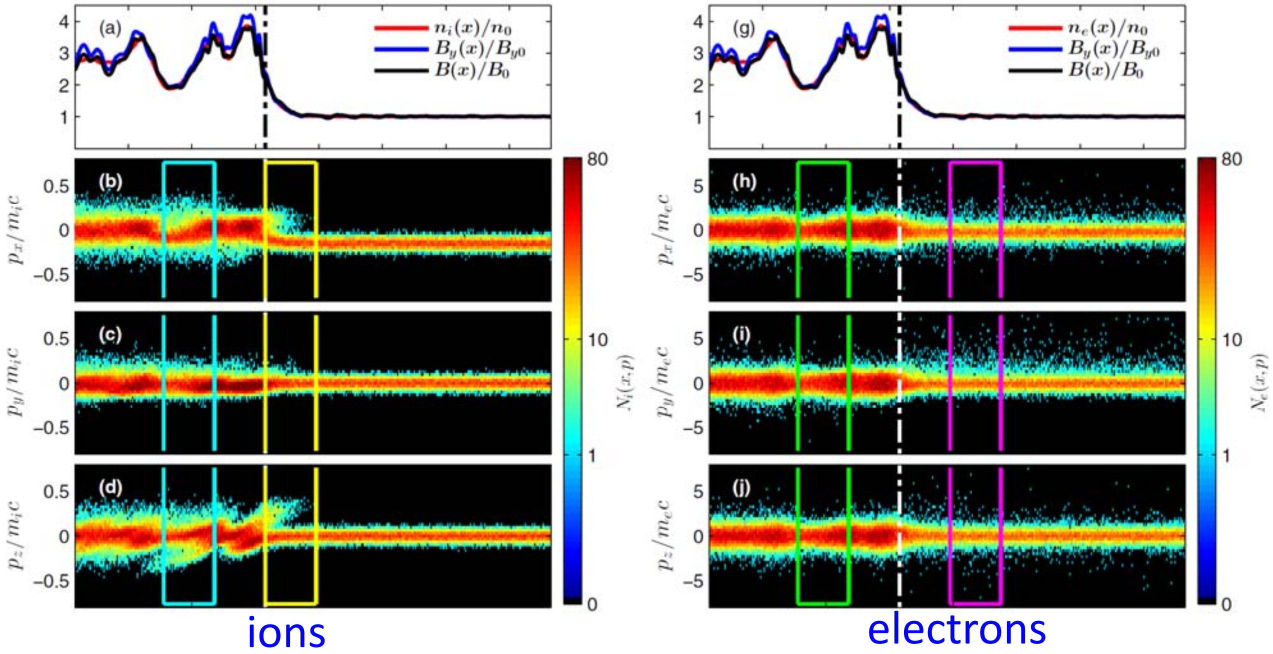
➔ Shock waves play important roles and understanding collisionless shocks in the ICM would be essential!

Fluid quantities for merger shocks

- distance from cluster core	~ 1 - 2 Mpc
- gas density	~ 10^{-4} cm^{-3}
- gas temperature	~ 10^{8} K (8.6 keV)
→ sound speed	~ 1,500 km/s
→ Coulomb collision scale	~ kpc (collisionless shocks)
- magnetic field	~ 1 μG
→ Alfven speed	~ 200 km/s
→ plasma beta (β_p)	~ 100
- shock sound Mach number (M_s)	~ 2 – 4 (weak shock ?)
→ shock speed	~ 3,000 – 6,000 km/s
→ shock Alfven Mach number (M_A)	~ 15 – 30 (strong shock ?)

“Electron” acceleration at merger shocks

(Guo et al. 2014)



2D & 3D PIC simulations using TRISTAN with

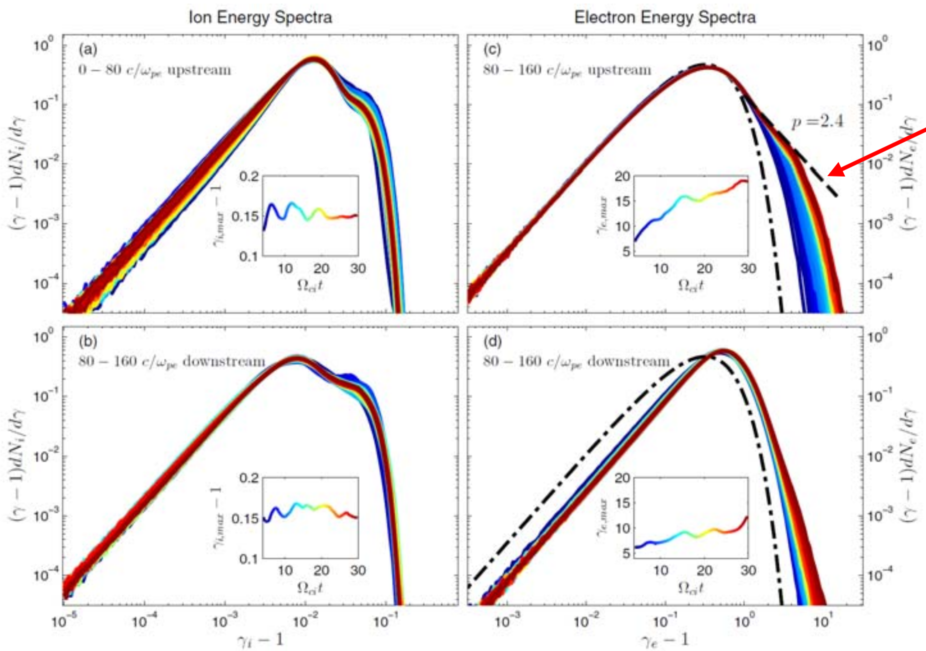
$m_i/m_e = 100$

$\theta = 63^o$ (quasi-perpendicular)

$T = 10^9$ K (86 keV)

$M_s = 3$

$\beta_p = 20$ ($M_A = 10$)

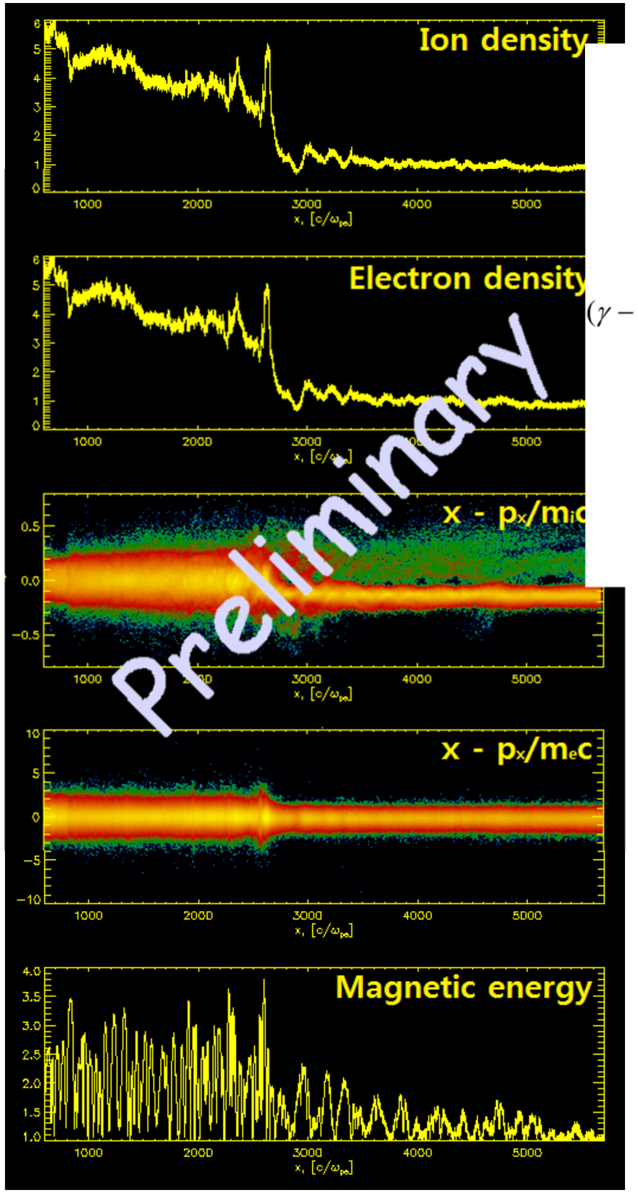


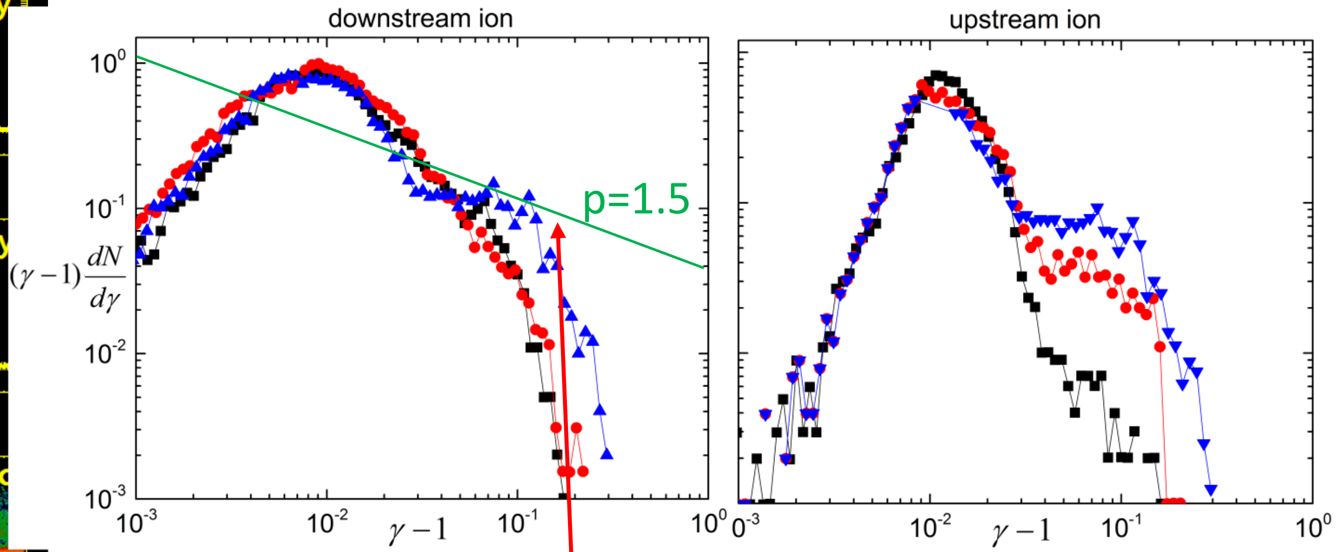
- efficient acceleration of electrons at upstream due to SDA (shock drift acceleration) mediated by firehose instability
- the expected efficiency of electron acceleration: ~ a few % ??? ➔ seems to be consistent with radio relics obs ???
- what about at the later DSA stage???

"Proton" acceleration at merger shocks

(Ha, Ryu, Kang, preliminary)

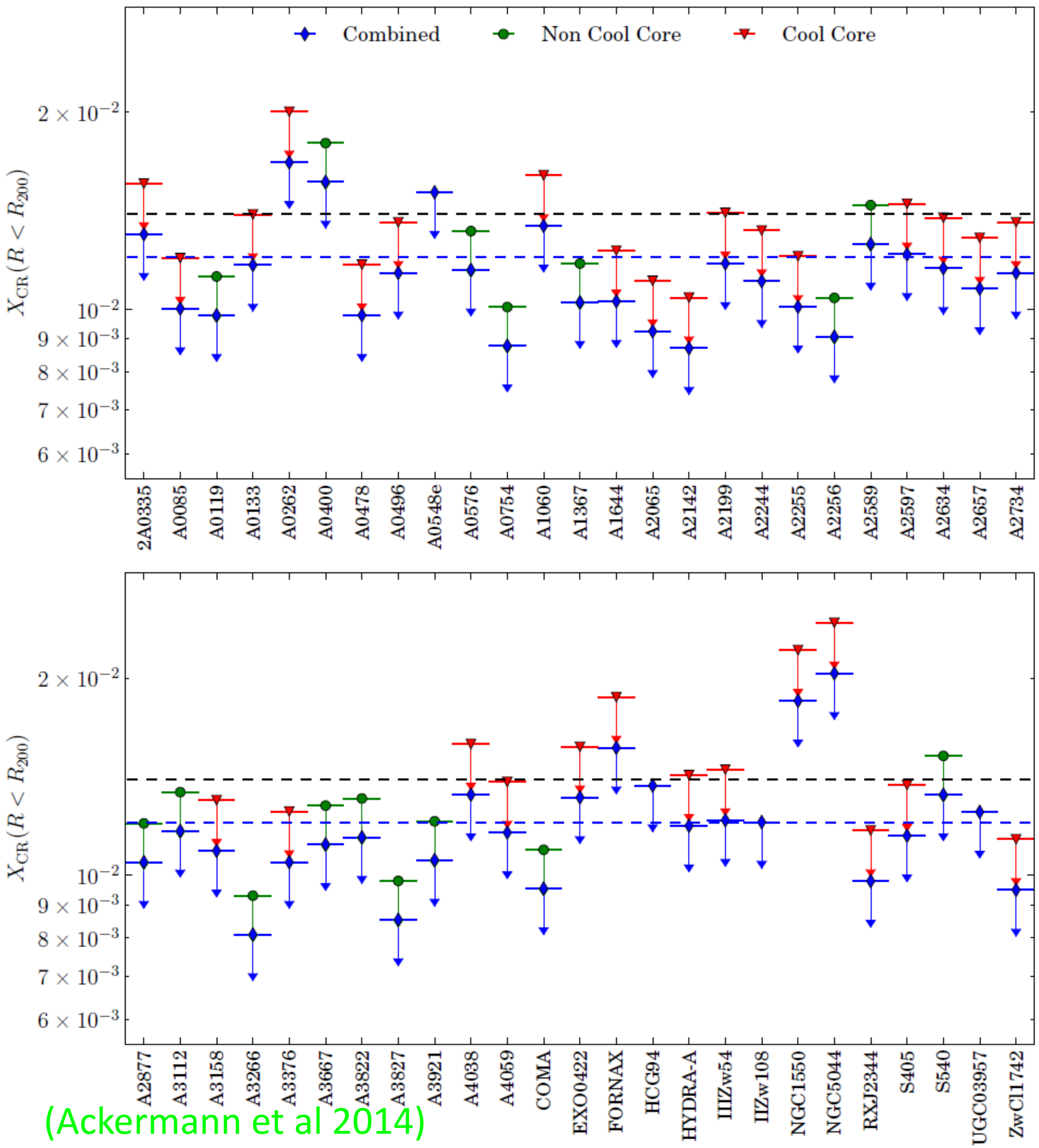
2D PIC simulations using TRISTAN with
$m_i/m_e = 100$, $\theta = 13^o$ (quasi-parallel), $T = 10^9$ K (86 keV), $M_s = 3$, $\beta_p = 100$ ($M_A = 22.5$)





- efficient acceleration of protons with slope ~1.5 due to DSA (diffusive shock acceleration) ???
- the efficiency of proton acceleration: >~ 10 % ???
- results seem to agree with those of Caprioli & Spitkovsky (2014) (hybrid simulations for larger M_s, smaller β_p, etc)

➔ no observation of gamma-ray from clusters ???



(Ackermann et al 2014)

No observation gamma-ray from clusters

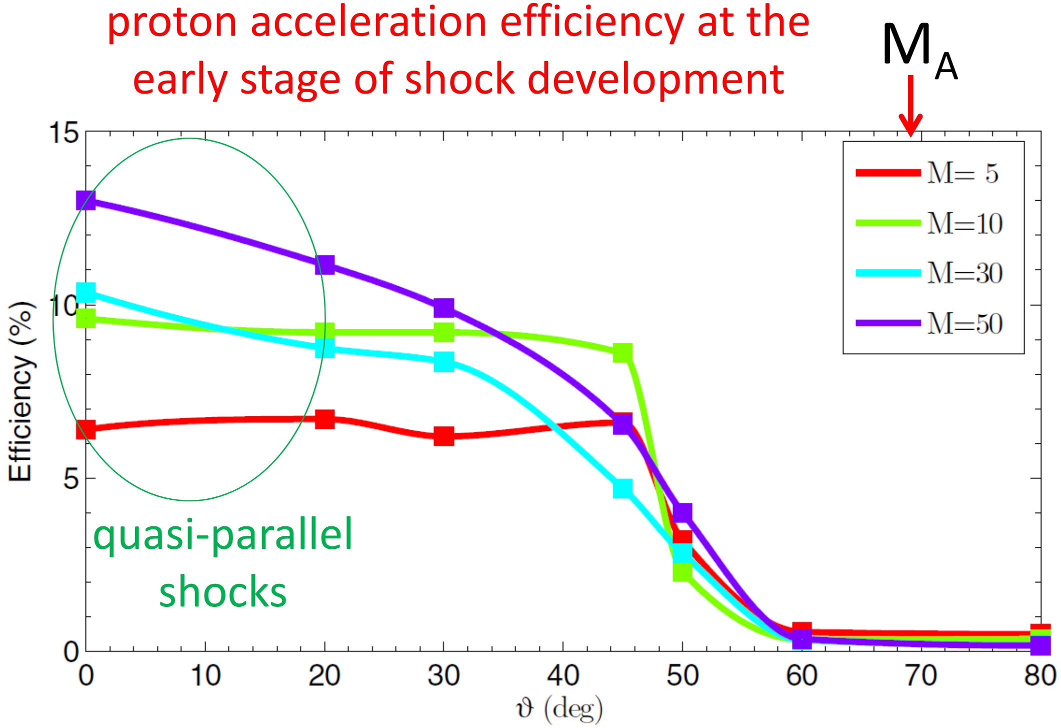
Fermi LAT observation:

P_{CR} / $P_{thermal}$ <~ 1 %

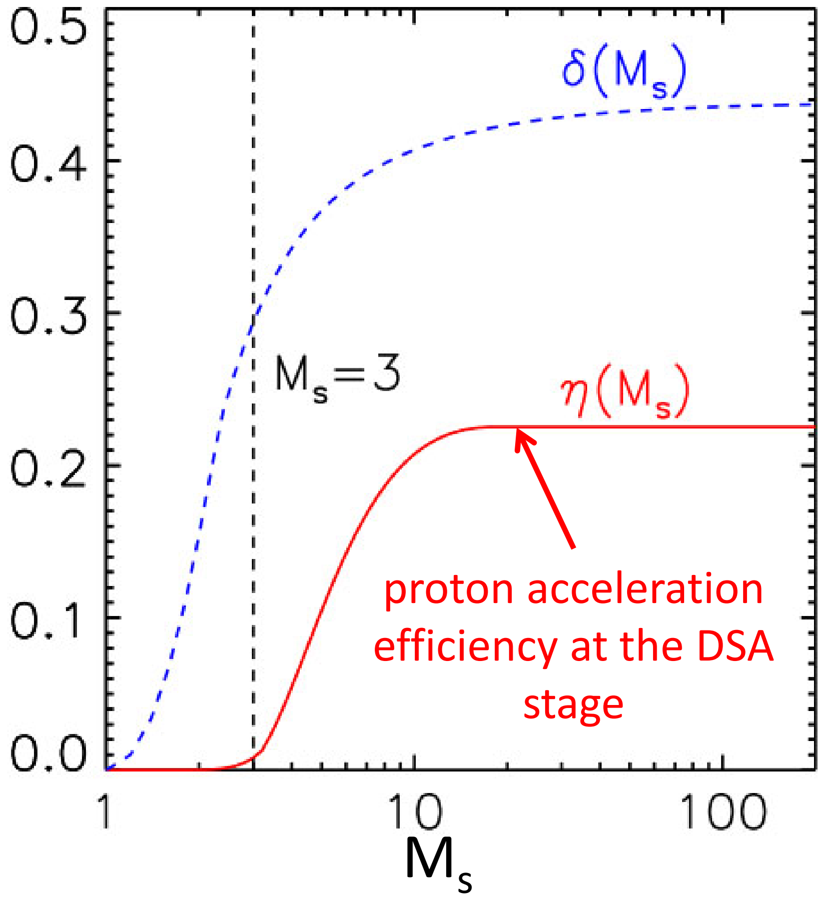
➔ Proton acceleration efficiency <~ 0.1 %!
(the fraction of the shock energy that goes to CR population)

(Caprioli & Spitkovsky 2014)

proton acceleration efficiency at the early stage of shock development



(Kang & Ryu 2013)



M_A (shock speed/ Alfven speed) matters to the early development of shock waves, including the injection of thermal particles to the nonthermal component.

M_s (shock speed/ sound speed) matters to the proton acceleration efficiency at the late DSA (diffusive shock acceleration) stage

➔ How to reconcile them?

Merging galaxy clusters display phenomena including

- Shock waves in X-ray observation
- Radio relics (interpreted to be associated with shocks)
- Radio halos (diffuse radio emission)
- ...

Yet, puzzles remain including the followings

- Mach numbers estimated in X-ray and radio do not always coincide
- Not all merging clusters host, for instance, radio relics
- Sufficient (sometime too much) acceleration of electrons at shocks
- Little acceleration of protons at shocks ← no ϒ-ray observation yet
- Large-scale magnetic field around radio relics ← polarization obs.
- Turbulent acceleration of electrons ← radio halo observation
- ...

➔ There are issues to be resolved, and understanding collisionless shocks in the ICM would be essential for it!

Thank you !