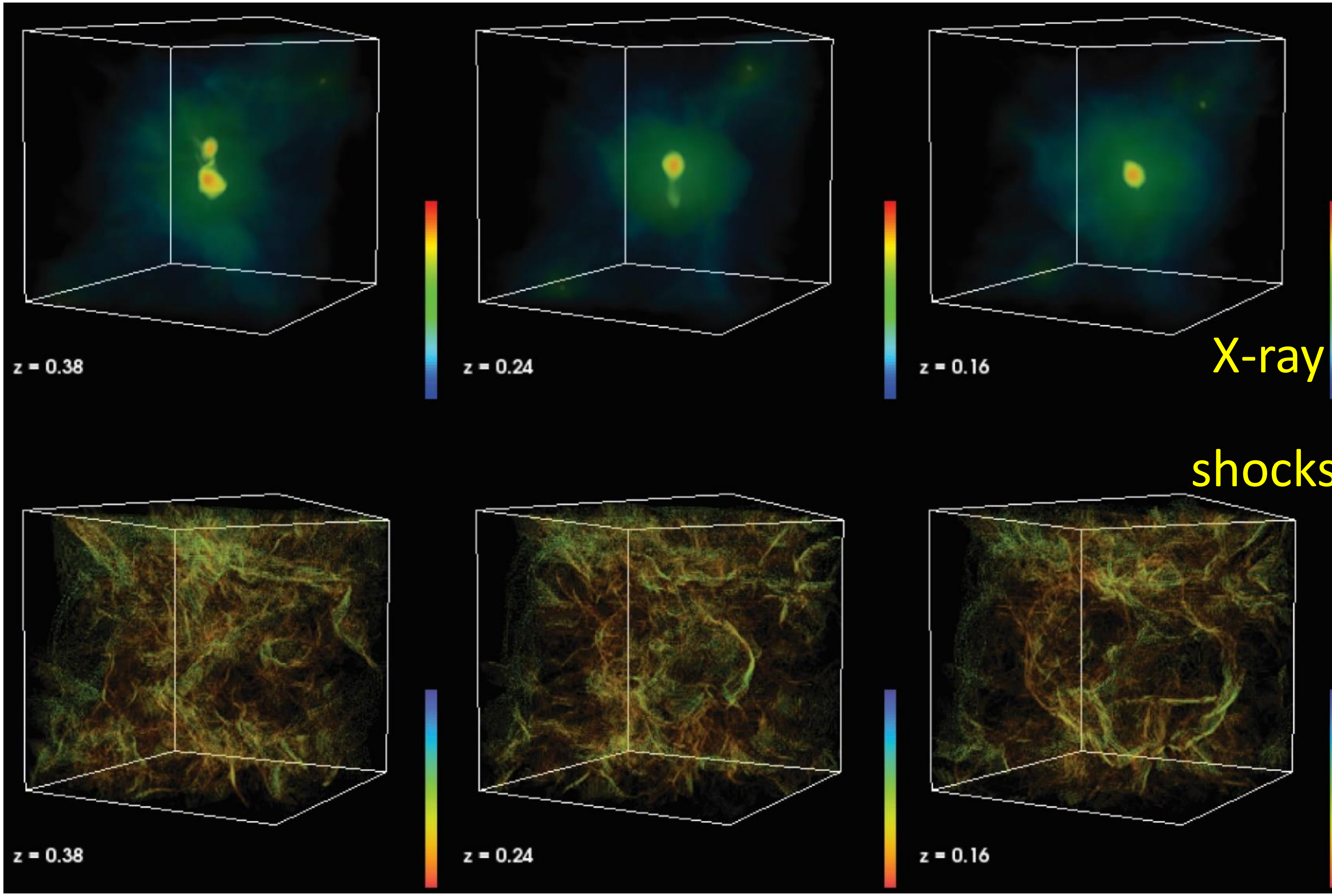
Properties of Merger-Driven Shocks in Galaxy Clusters

merging galaxy cluster



X-ray

shocks

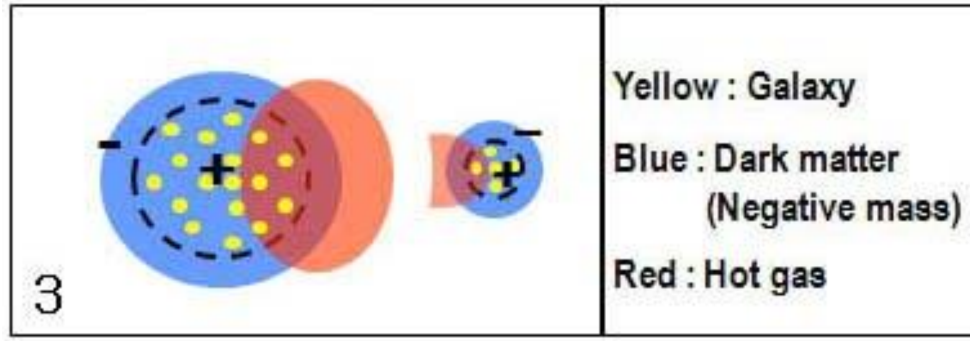
Dongsu Ryu, Ji-Hoon Ha (UNIST, Korea), Hyesung Kang (PNU, Korea)

Observations of merging galaxy clusters

Bullet Cluster (IE 0657-56)

(Markevitch et al)

a binary merger of mass ratio ~ a few

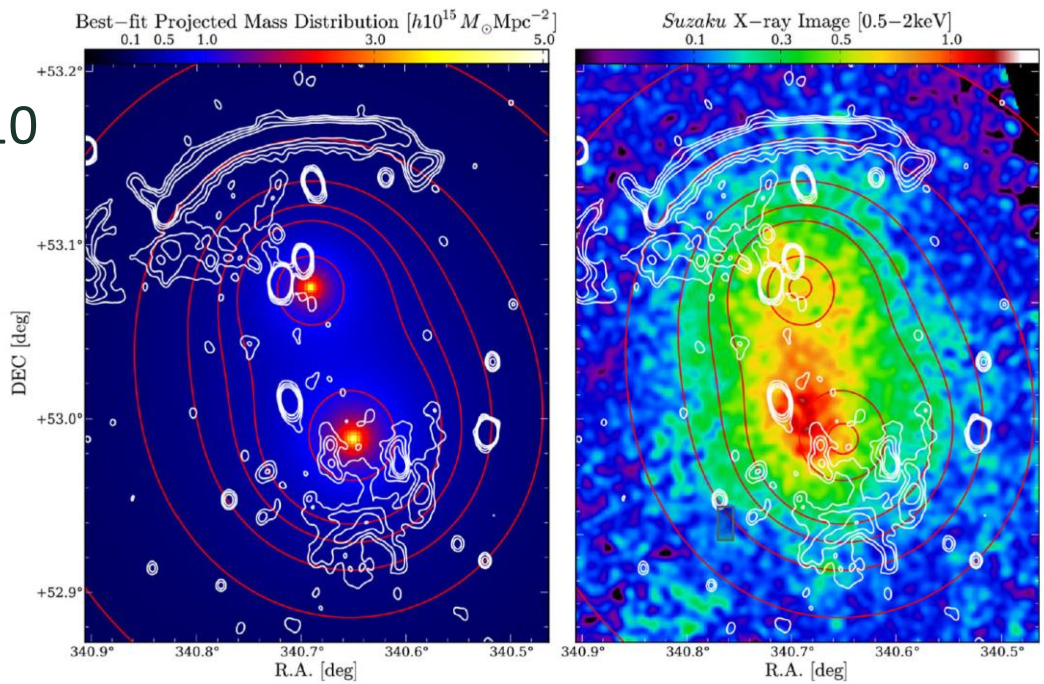


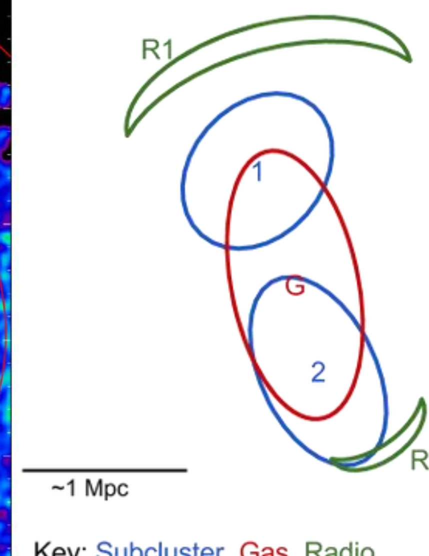
CIZA J2242.8+5310

(Sausage relics)

(vanWeeren et al, Okabe et al)

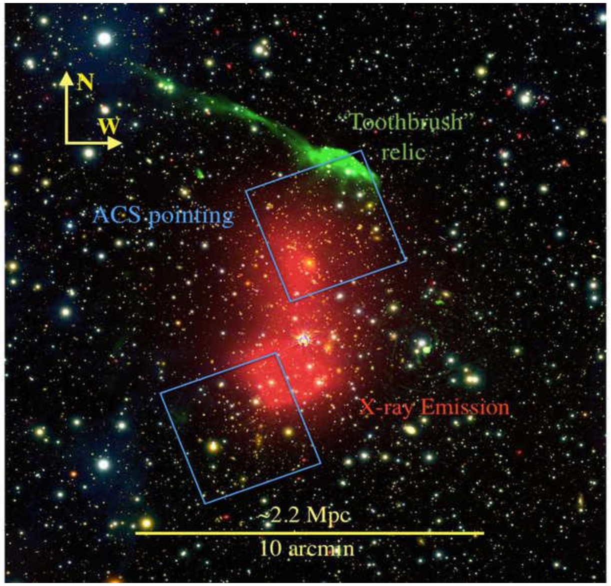
a binary merger of mass ratio ~ one -two

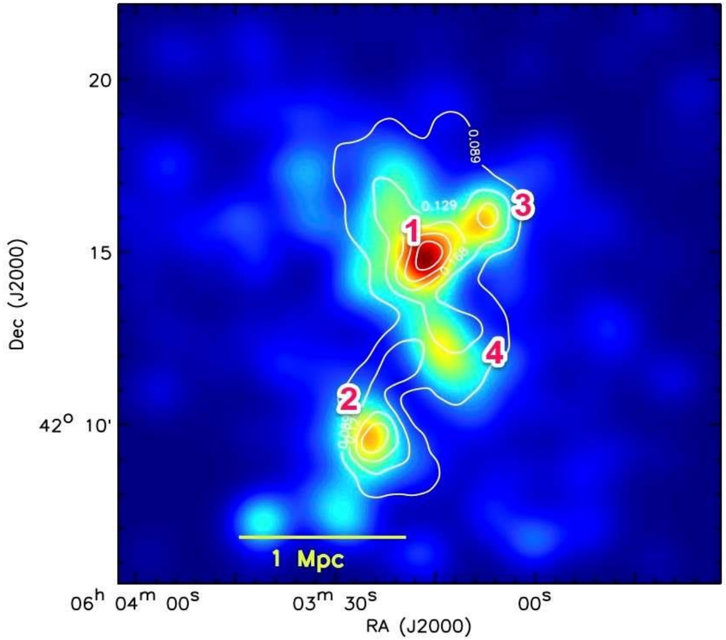




RX J0603.3+4214 (Toothbrush relic)

(vanWeeren et al, Jee et al)

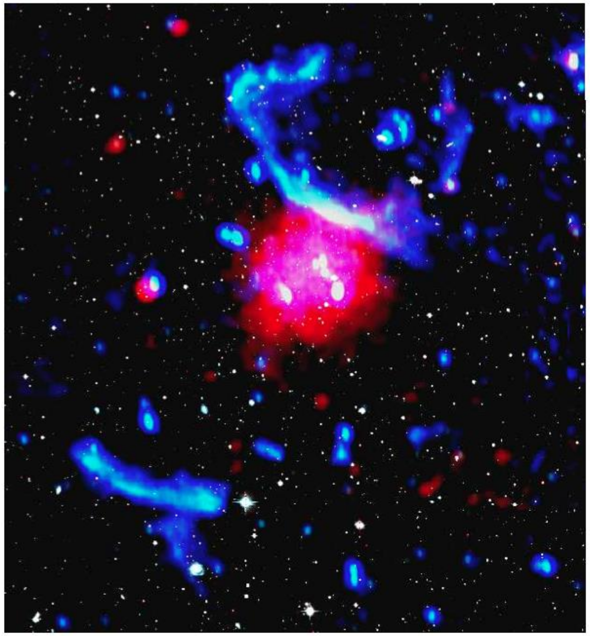


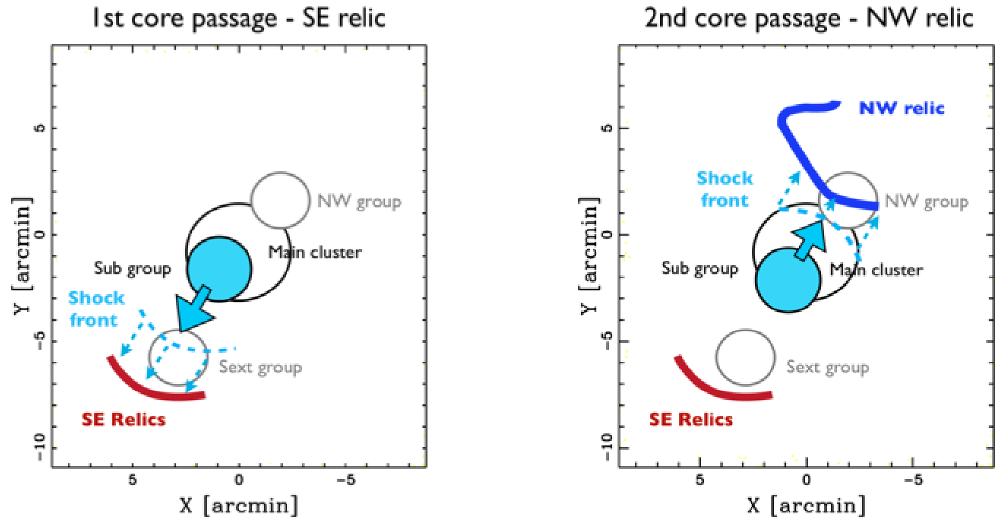


PLCK G287.0+32.9

(Bonafede et al)

X-ray + radio





a number of sub-clumps in both clusters!

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

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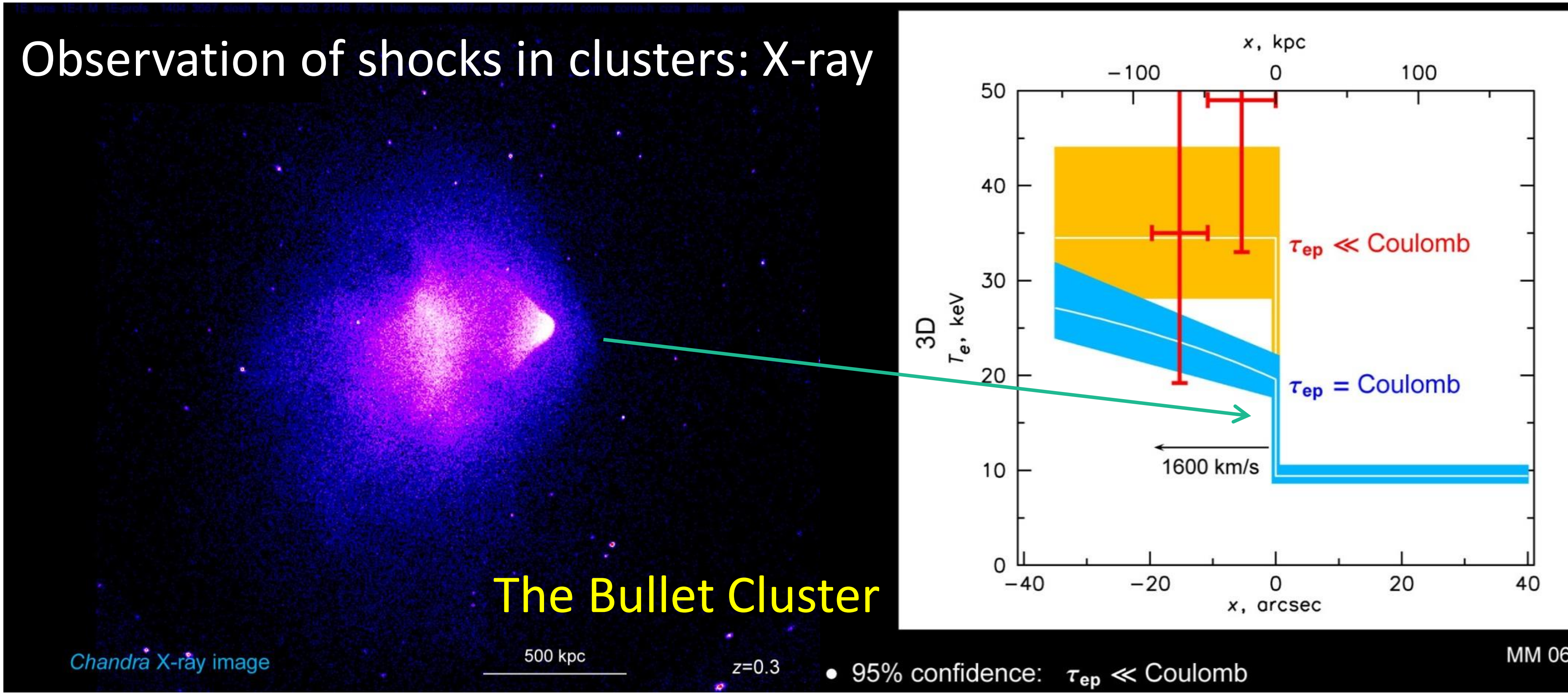
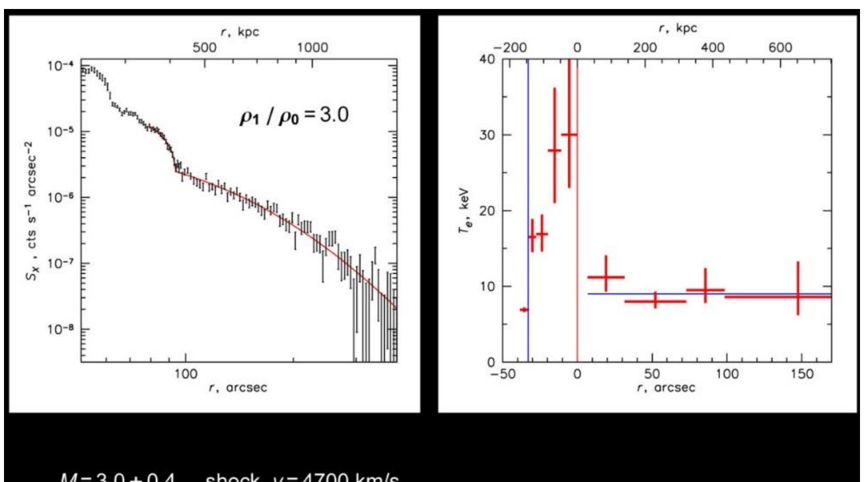
- Turbulent acceleration of electrons ← radio halo observation
- ...

➔ Shock waves play important roles and understanding their properties is important!

Observation of shocks in clusters: X-ray



(Markevitch et al.)

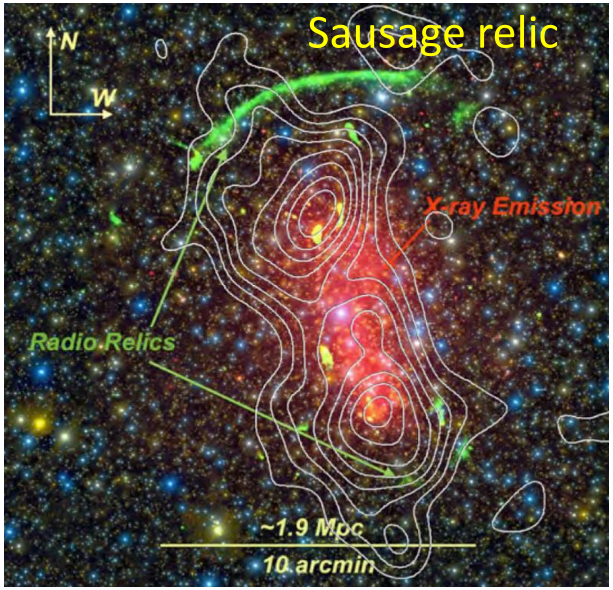


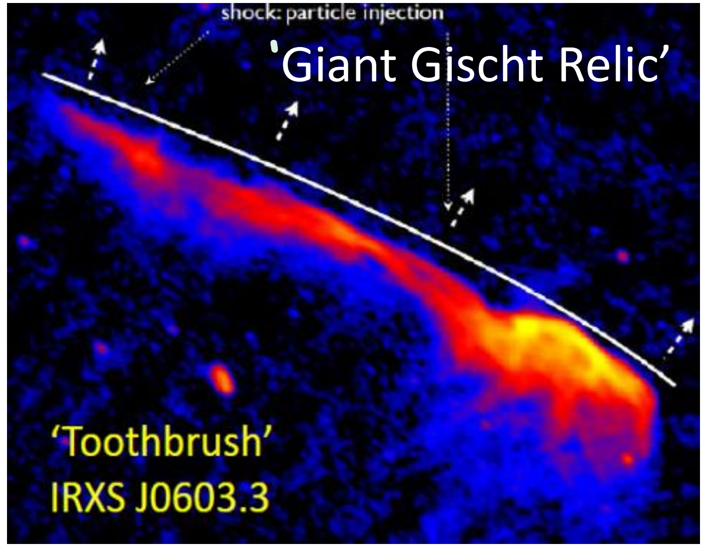
Shock wave in
1E0657-56 (Bullet cluster)

Mach number of X-ray shocks in ICMs:

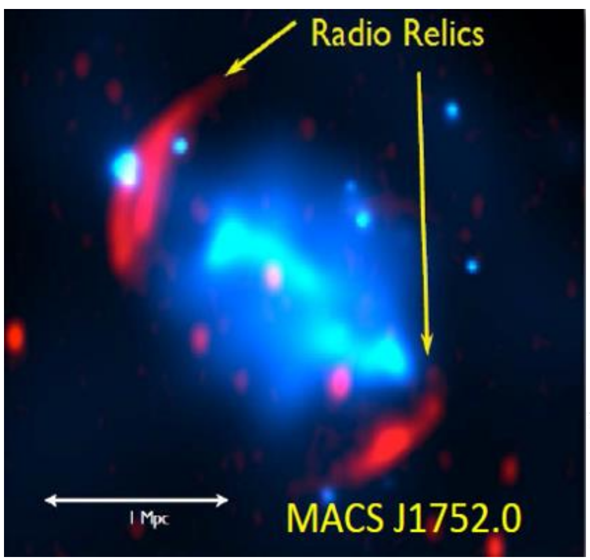
M_{shock} <~ a few

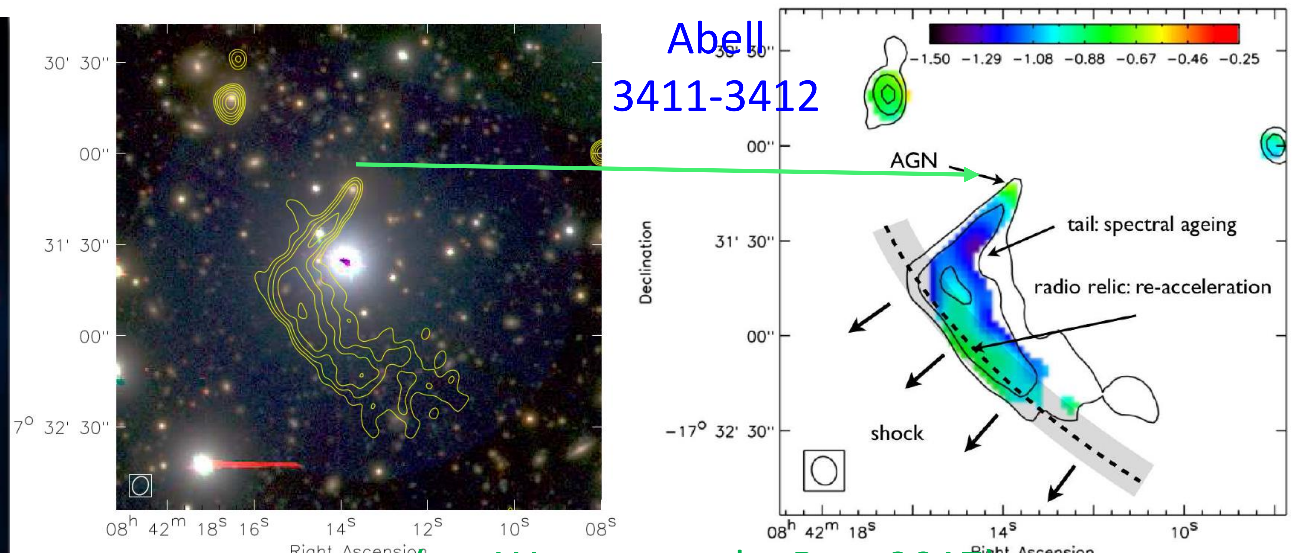
Observation of shocks in clusters: radio relics





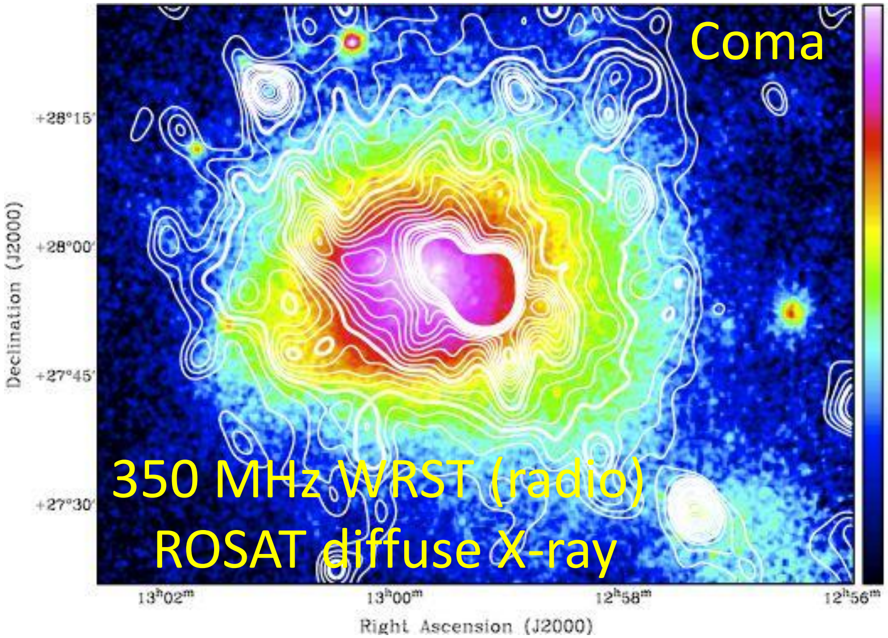
Mach number of radio shocks in ICMs: **M_{shock} <~ several**

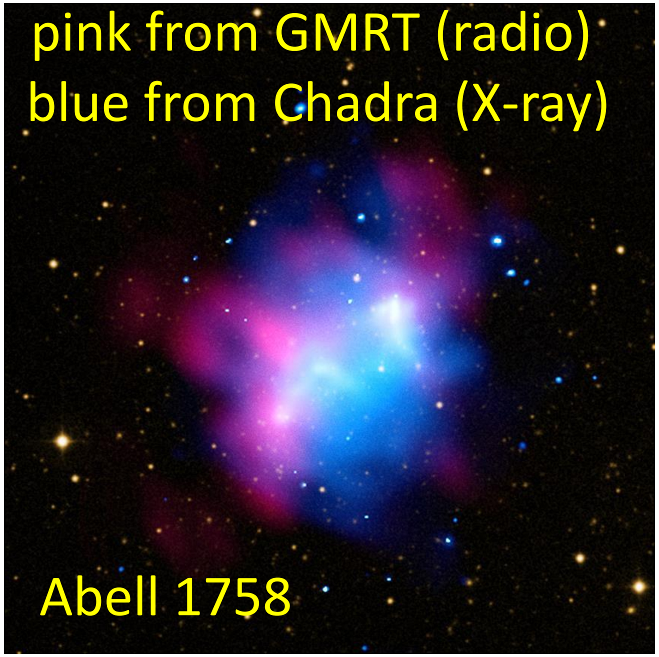


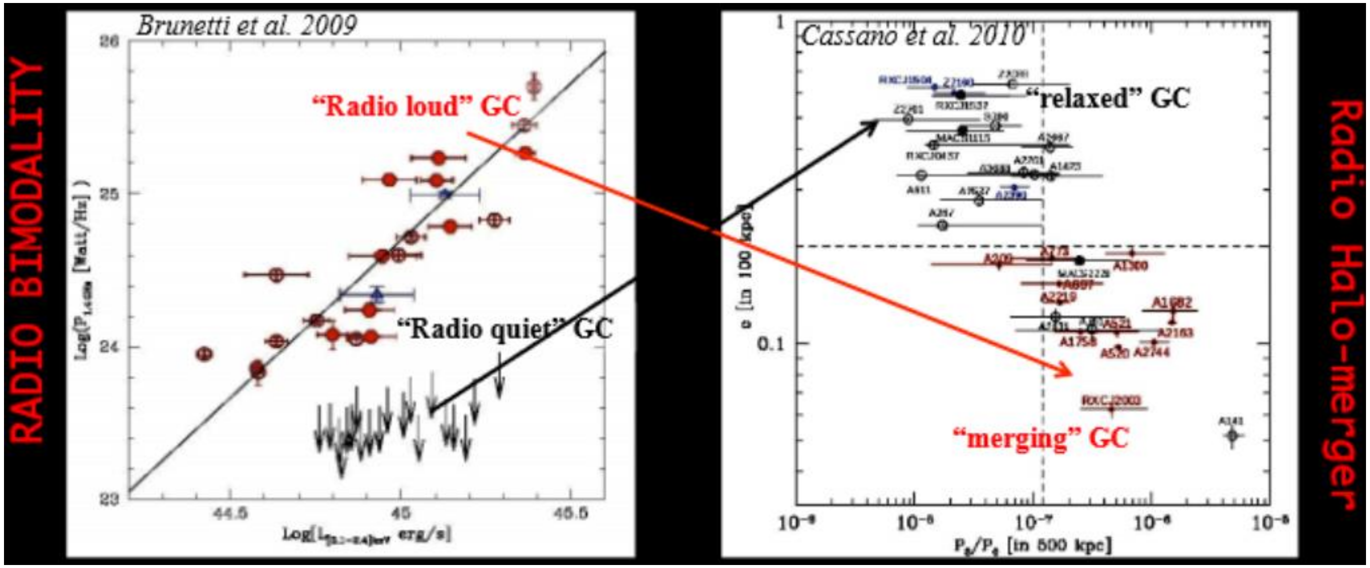


(vanWeeren et al + Ryu, 2017)

Observation of radio halos







Most clusters with radio halos are merging clusters!

(From Rossella Cassano)

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➔ **Shock waves play important roles** and understanding their properties is important!

The nature of shock waves in clusters of galaxies during the hierarchical structure formation

1) accretion shocks around clusters formed by accreting void gas

2) intracluster shocks inside cluster

   a) turbulence shocks (induced by turbulent flow motions)

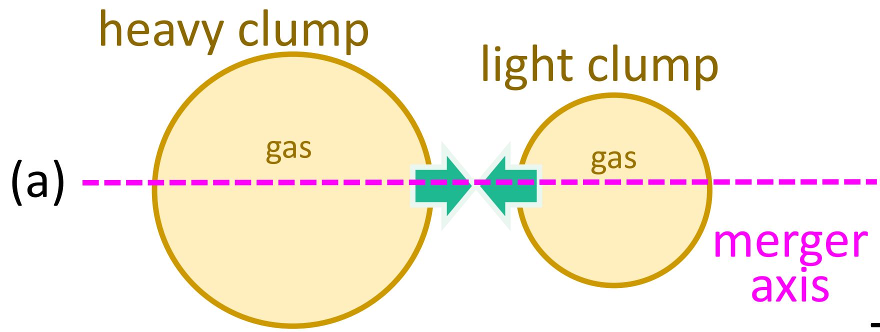
   b) infall shocks (accretion of the WHIM (Warm-Hot Intergalactic Medium to the hot intracluster medium along filaments)

   c) **merger shocks** (induced by merger of gas/DM clumps during the hierarchical formation of galaxy clusters)

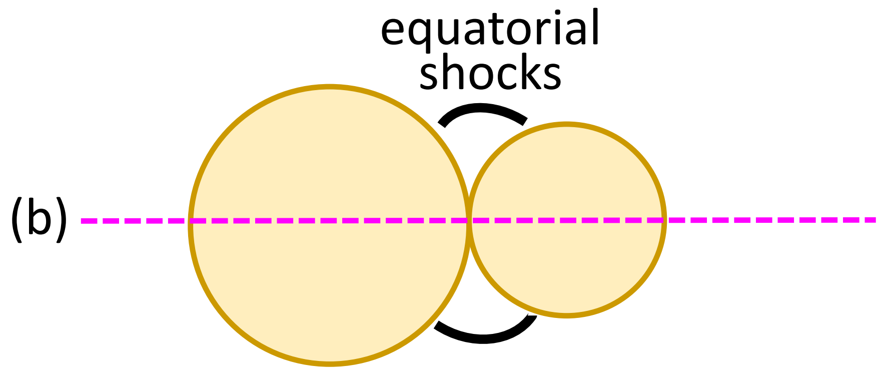
a major merger of $\sim 10^{13} - 10^{14}\ M_\odot$ of gas clumps with speed of ~1,000 km/s ➔ $E_{merger} \sim 10^{63} - 10^{64}$ ergs

→ "**energetically most important**"

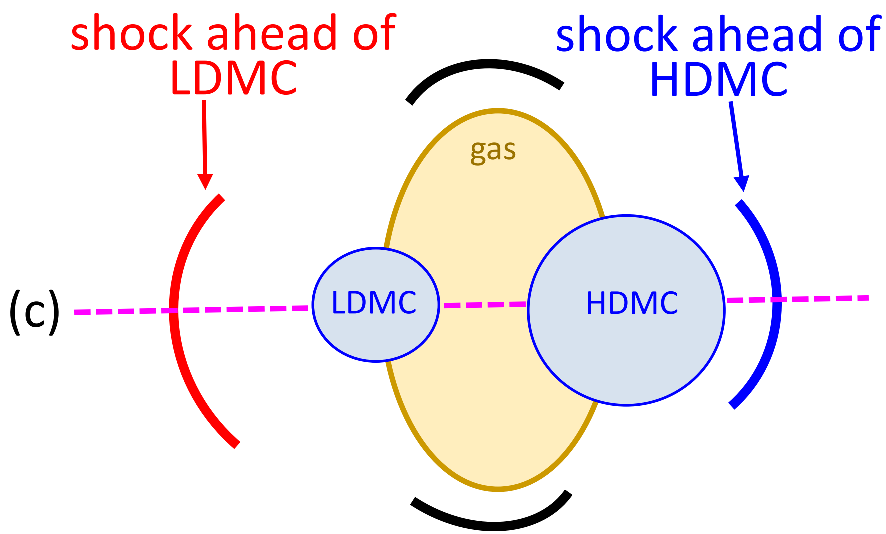
Simple binary merger – a cartoon picture



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

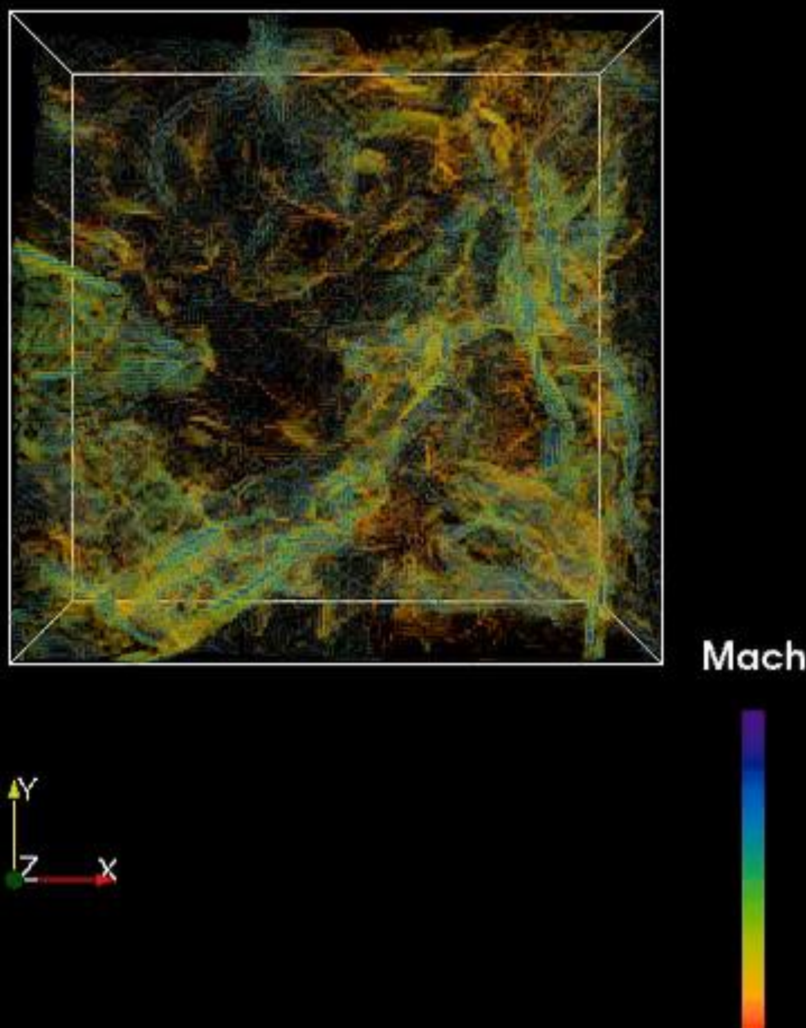
Shocks along the direction parallel to the merger axis form and propagate.

(Ha, Ryu, & Kang 2017)

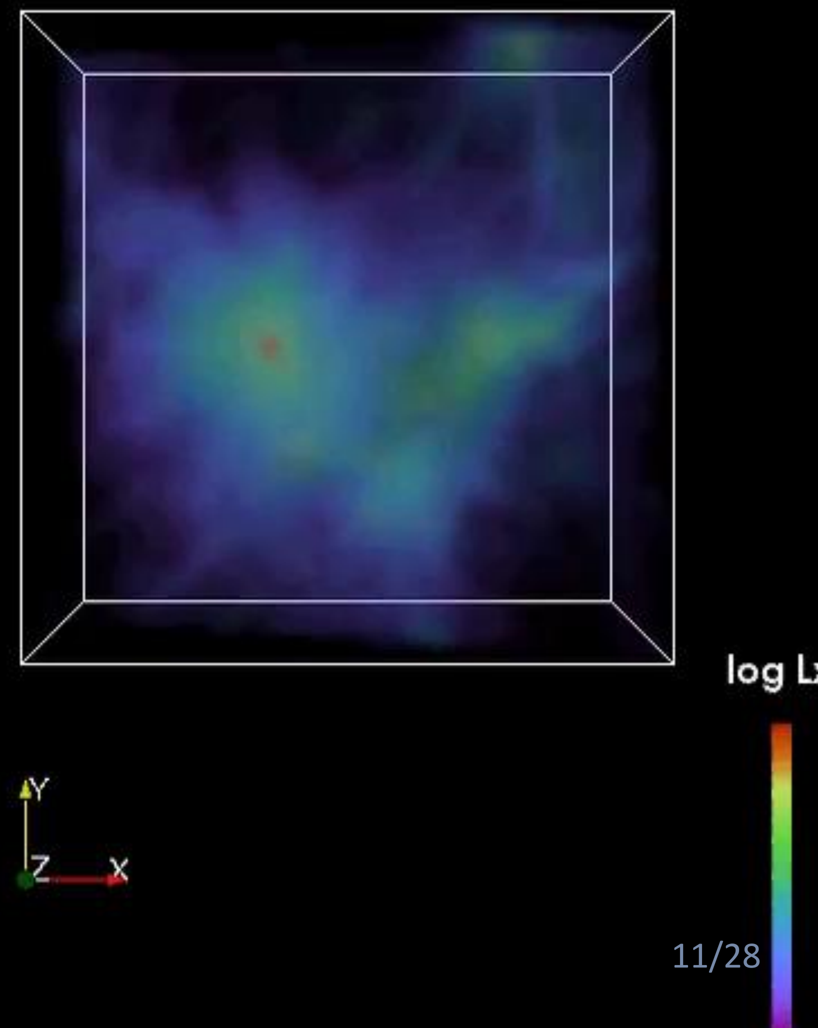
Shock waves in a merging cluster from a simulation for large-scale structure formation in 100 h^{-1} Mpc box: a binery merger case (intending for the Sausage relic)

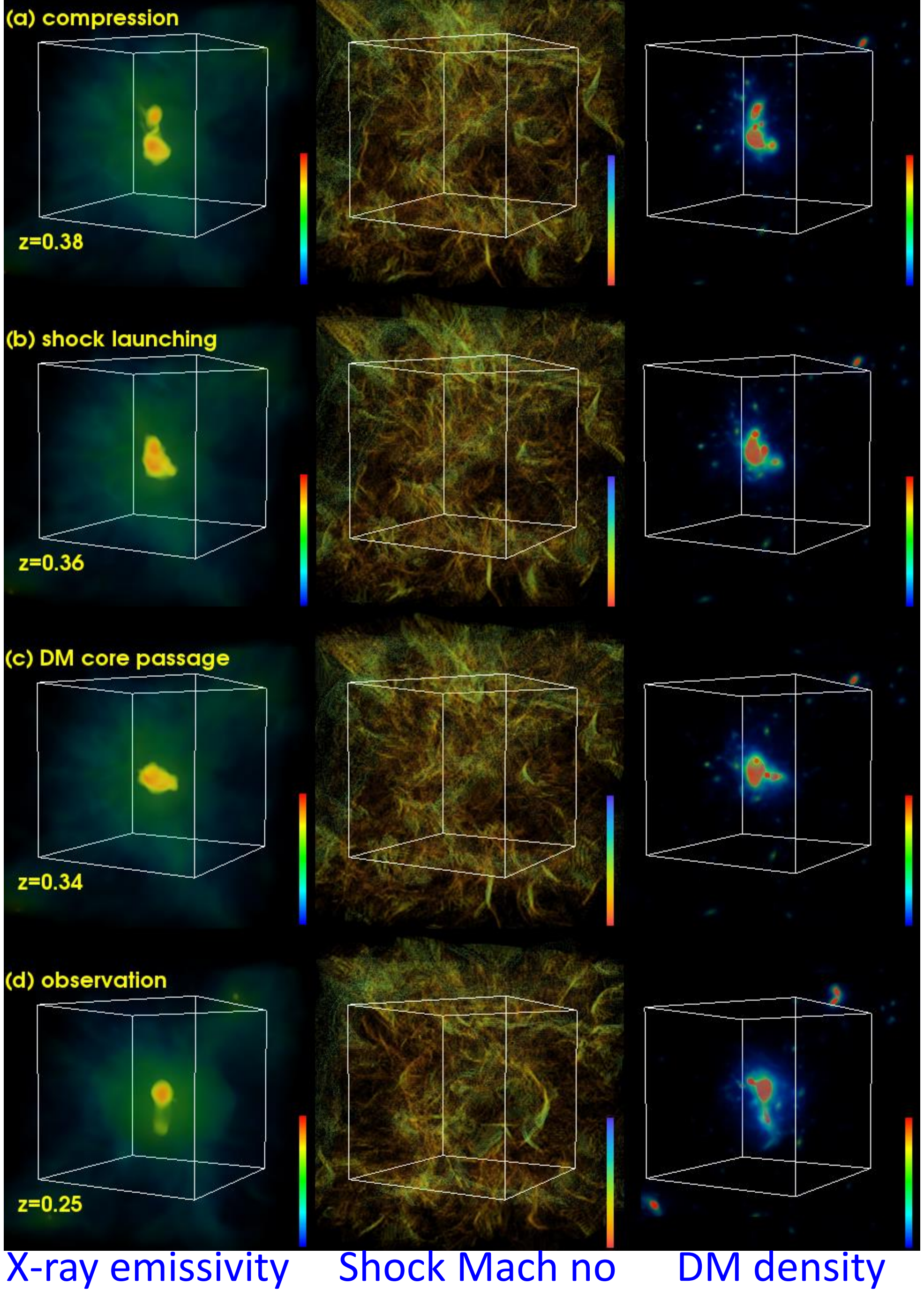
from z = 0.5 to 0.05, box size = 5 h^{-1} Mpc

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 ~ 5 keV cluster

(a) the two clumps are approaching

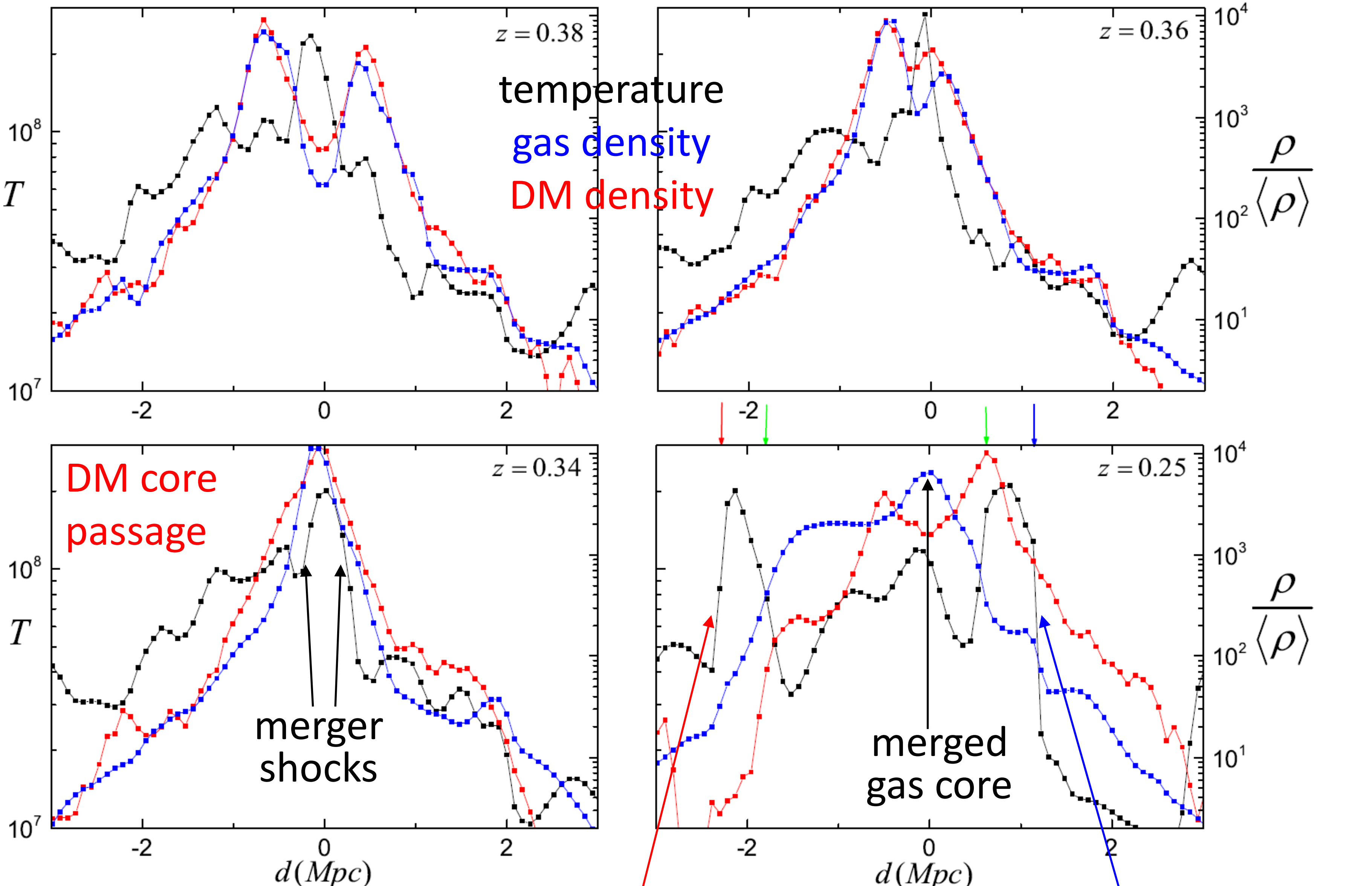
(b) shocks lunch along the merger axis

(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

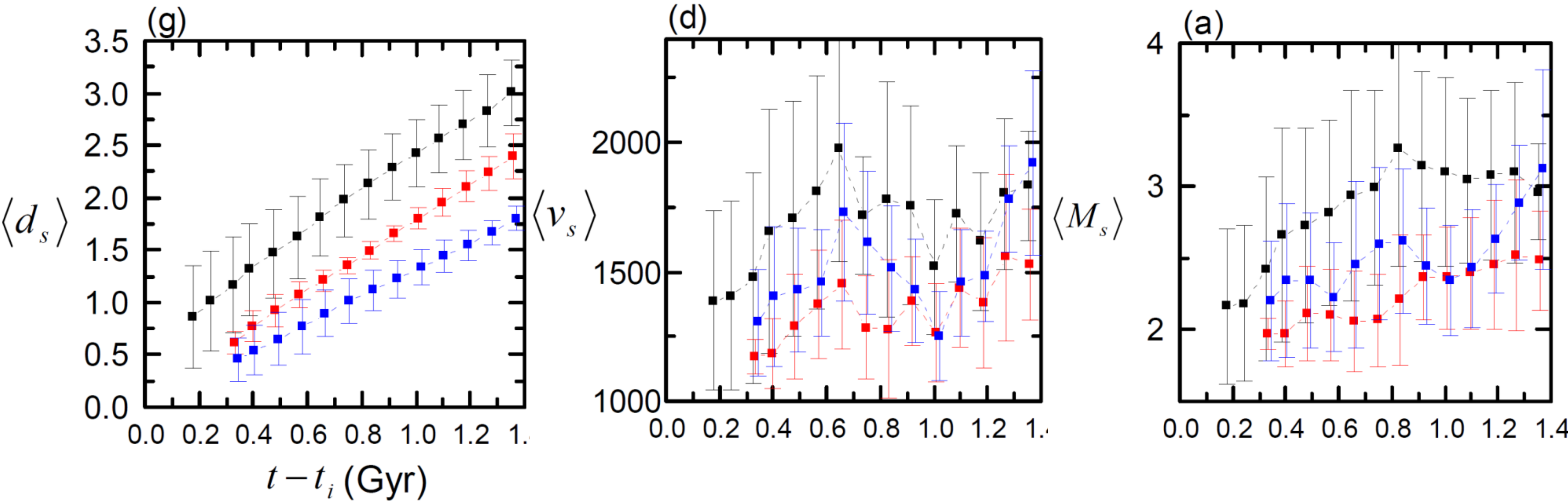
The surfaces of shocks are **non-uniform, and highly intermittent** with filamentary patches of high M_s parts!

1D profiles along the merger axis at four epochs



shock ahead of LDMC ($M_s \approx 3.5$) shock ahead of HDMC ($M_s \approx 4$)

Statistical properties of merger shocks in simulated merging clusters I

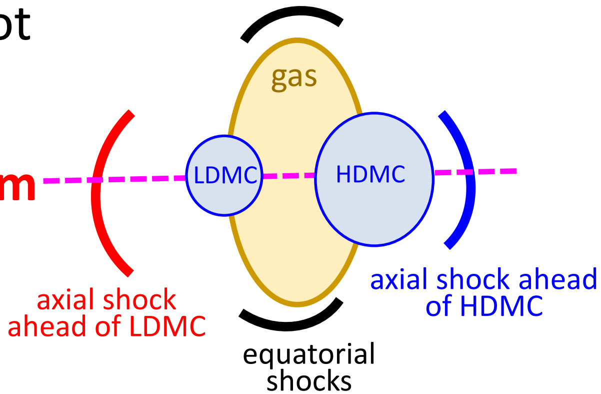


Shocks are found **at ~ 1 Mpc, ~ 1Gyrs after mergers**

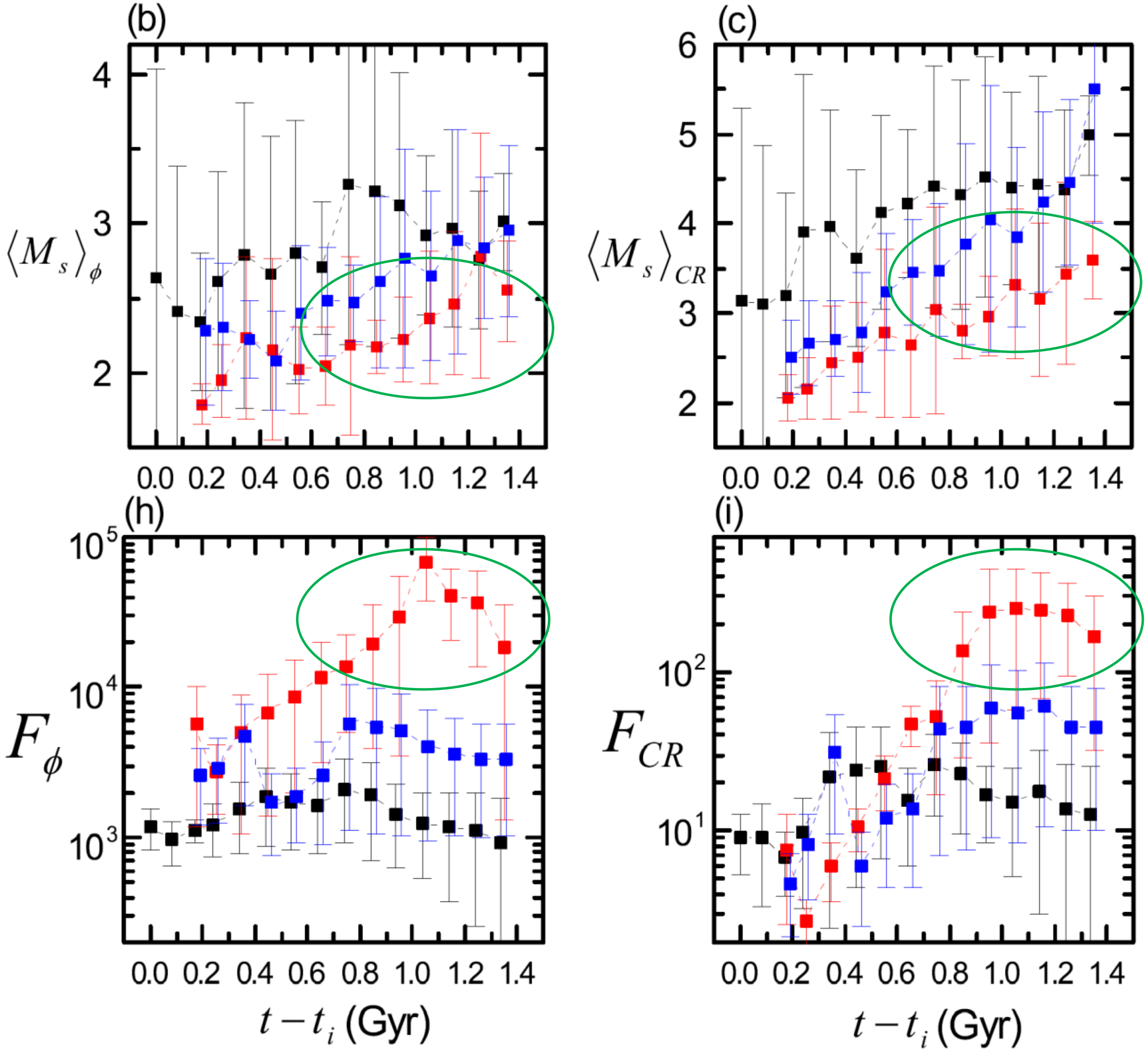
M_s increases as shocks move to outwards, while v_s does not necessarily

Large fluctuations in M_s → shock surfaces are non-uniform (with high M_s and low M_s), and intermittent

Shocks in front of LDMC are weakest with smallest M_s



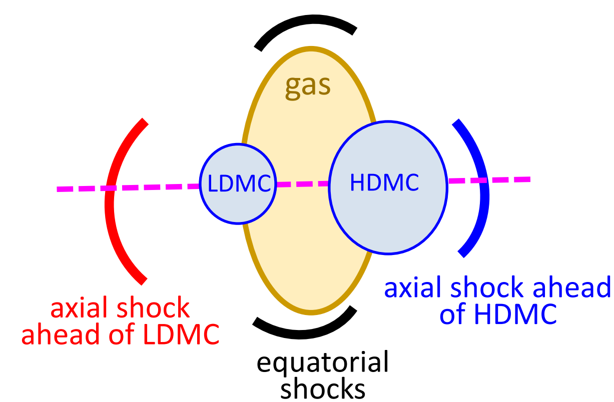
Statistical properties of merger shocks in simulated merging clusters II



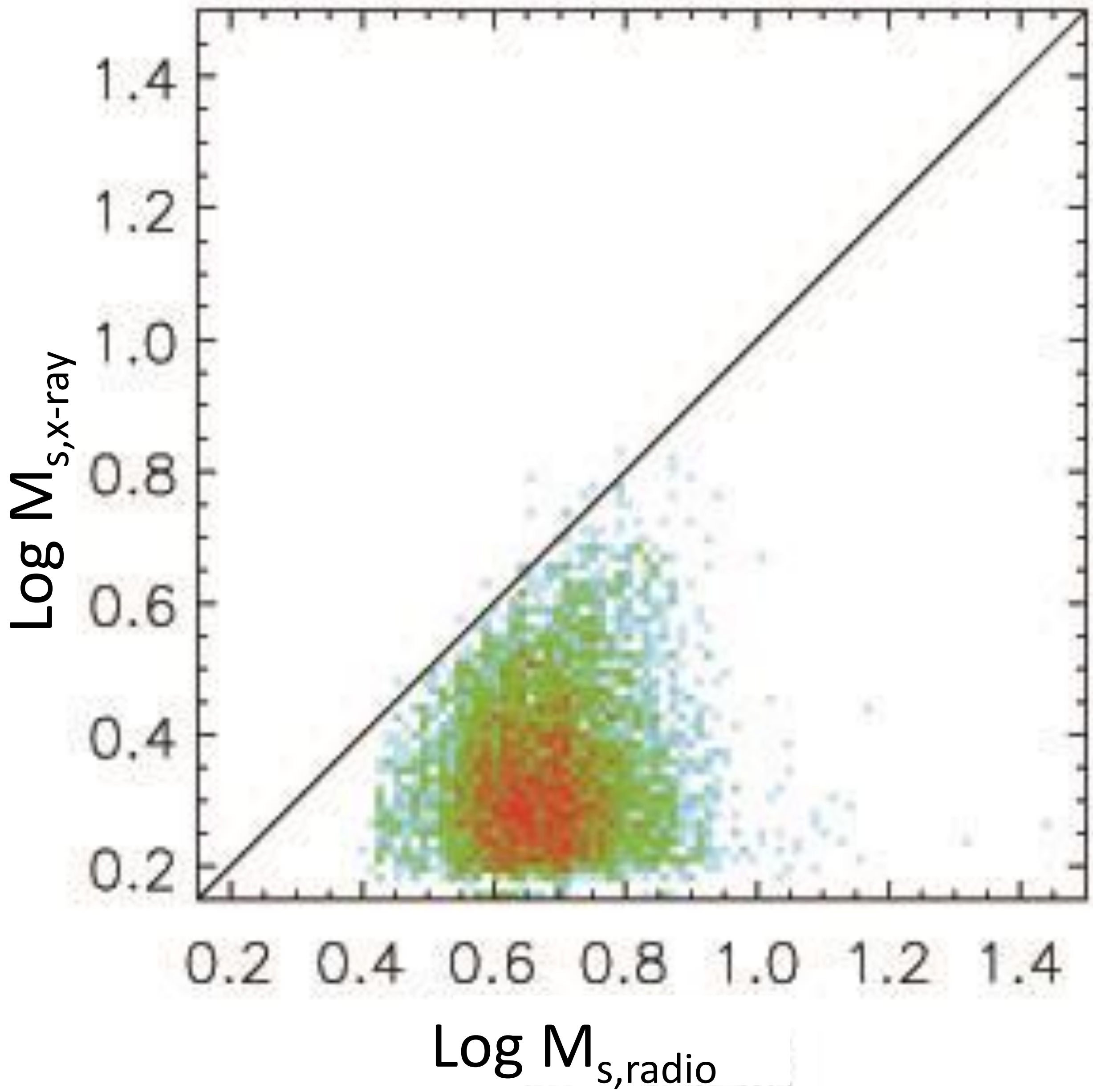
- F_ϕ kinetic energy through shock surface
- F_{CR} CR energy production at shock surface

For energetically important merger shocks

- **F_ϕ and F_{CR} of the shocks peak about ~ 1 Gyrs after the formation or at d_s ~ 1.5 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**



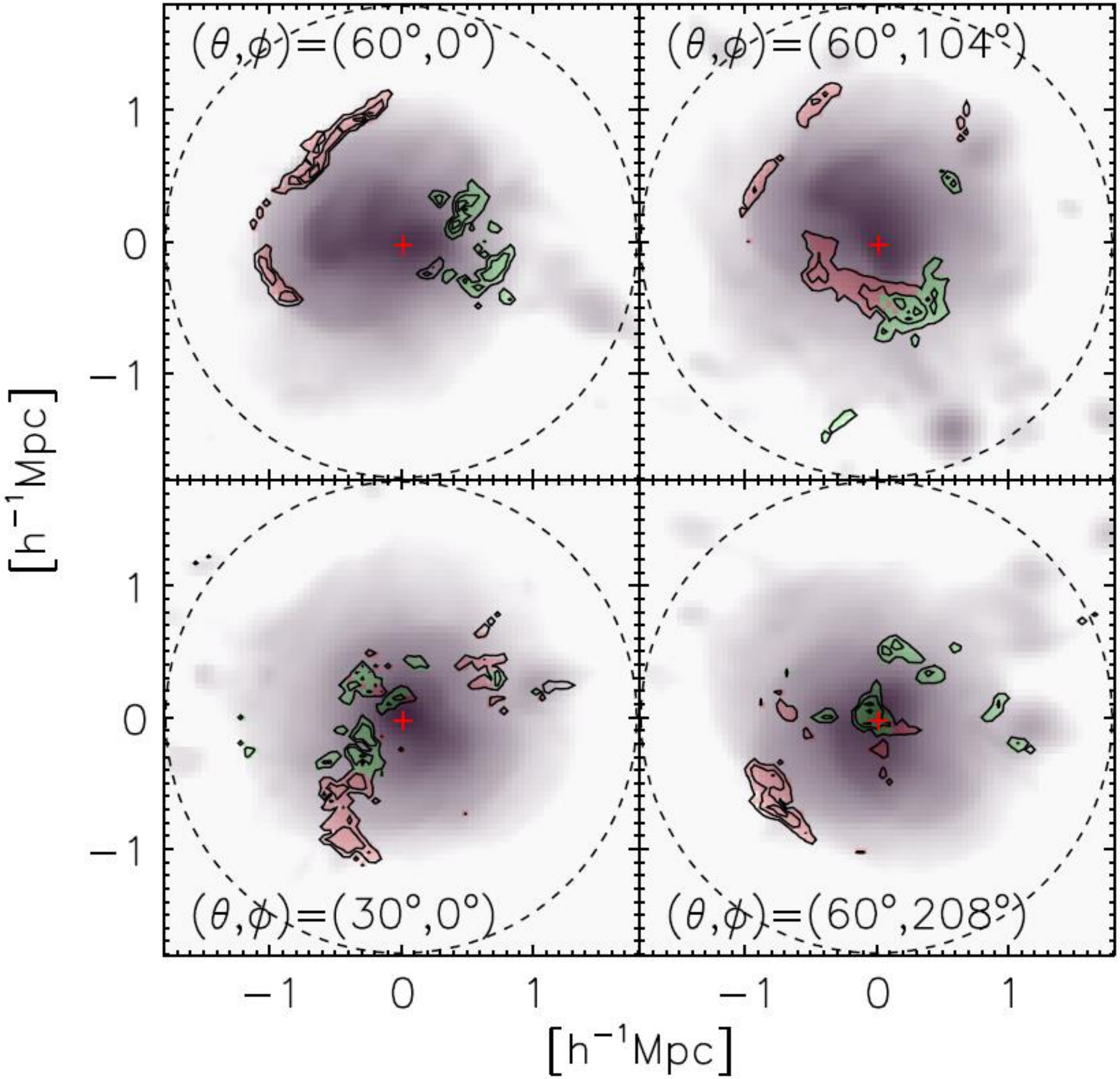
M_s from (mock) X-ray obs versus M_s from (mock) radio obs for radio relics



(Hong, Kang, & Ryu 2015)

radio relics – connected regions in 2d projection maps with $S_{1.4} > 10^{-1}$ mJy

X-ray observations tend to give smaller M_s than radio observations!



synchrotron emissivity of radio relics for a simulated cluster (no radio halo) at 4 different viewing angles: x-ray + 1.4 GHz

(Hong, Kang, & Ryu 2015)

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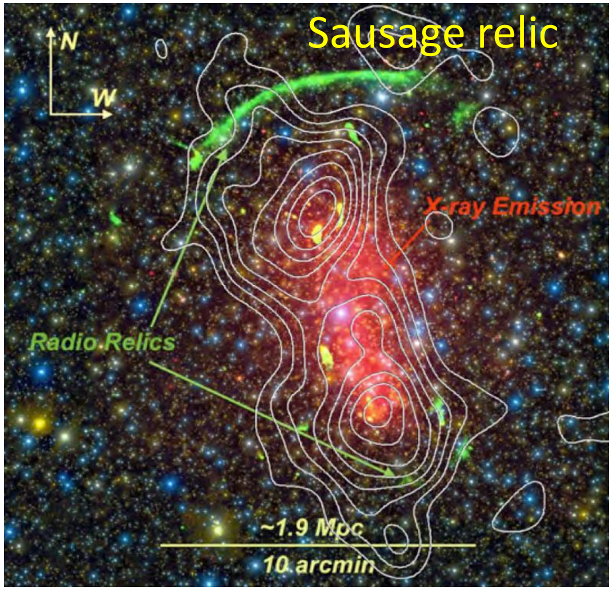
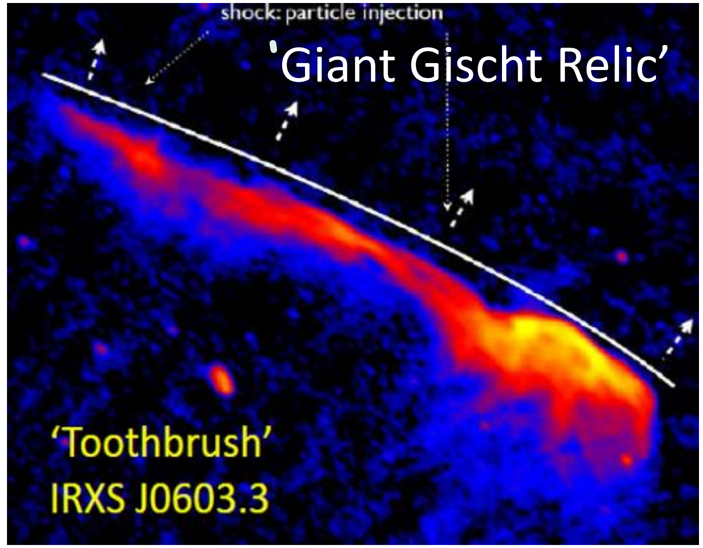
➔ Shock waves play important roles and **understanding their properties is important!**

Observation of radio relics in clusters

synchrotron emission due to CR electrons accelerated at shocks

→ E_{CRe} / E_{shock} ~ a few to 10 % at shocks

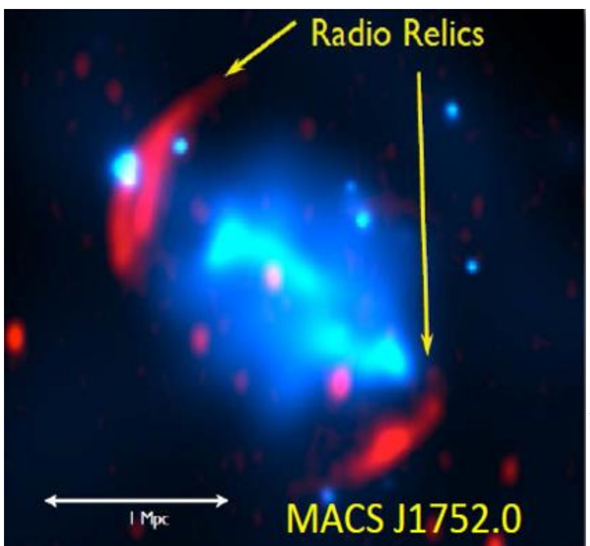




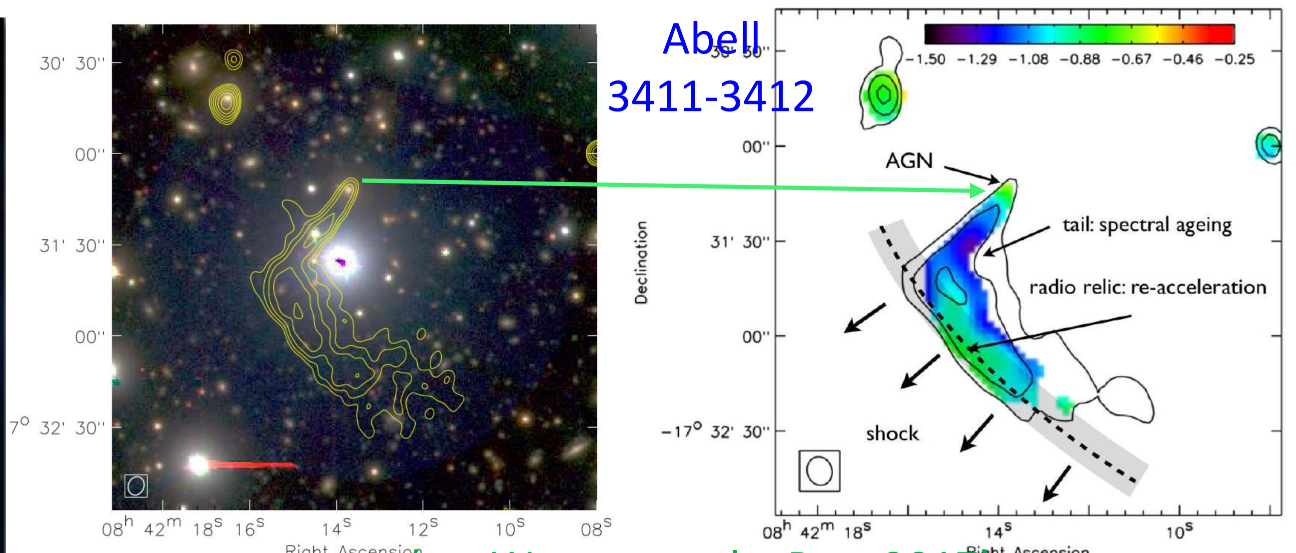
injection + acceleration?

or

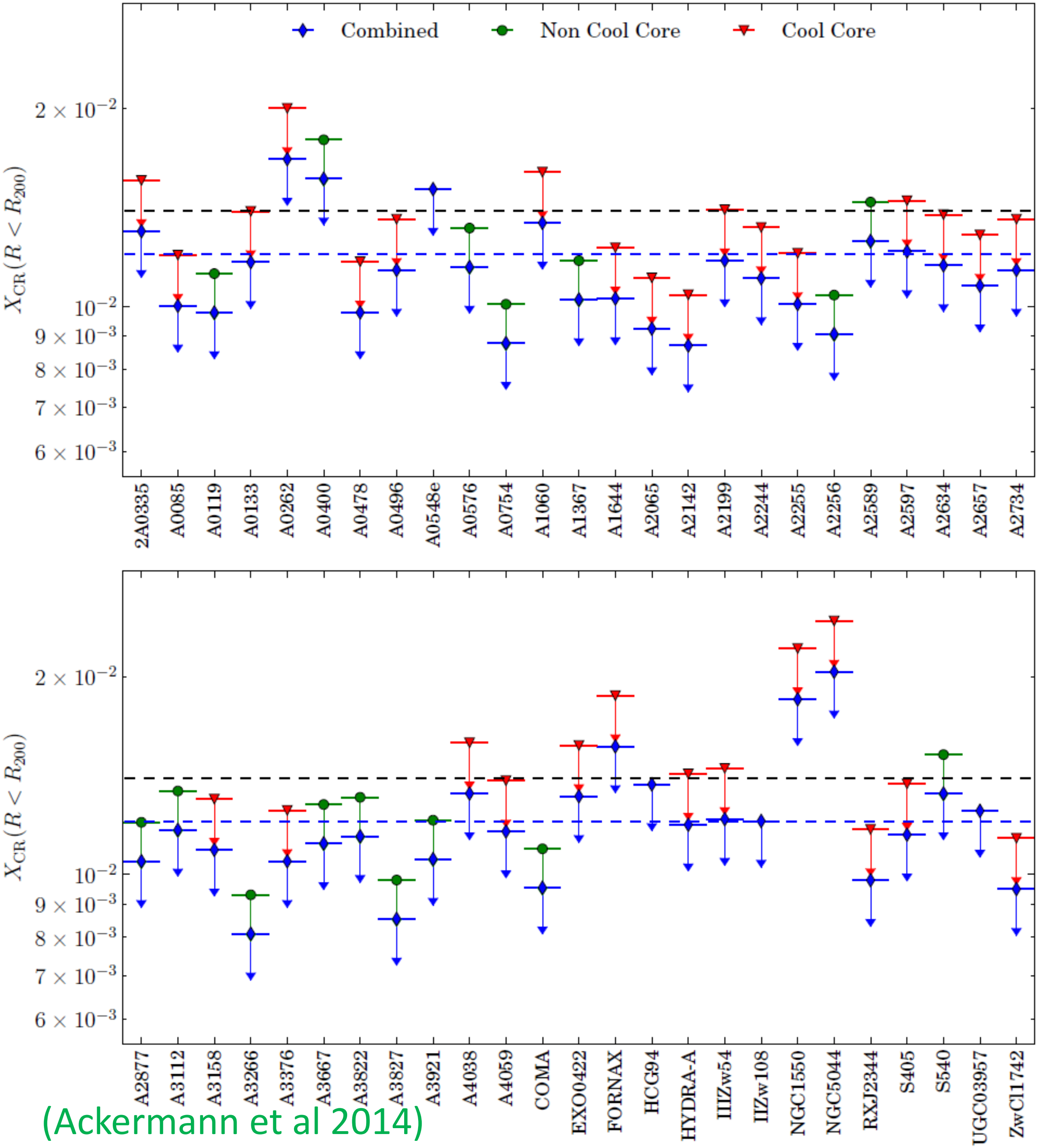
reacceleration of fossil population?



Abell 3411-3412



(vanWeeren et al + Ryu, 2017)



(Ackermann et al 2014)

No detection of gamma-ray from clusters!

Upper limits of CR proton contents in clusters se by Fermi LAT observation:

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

the fraction of shock energy converted to heat ~ 10 %

then, **the fraction of shock energy converted to CRs** (CR acceleration efficiency) **~ 0.1 %**

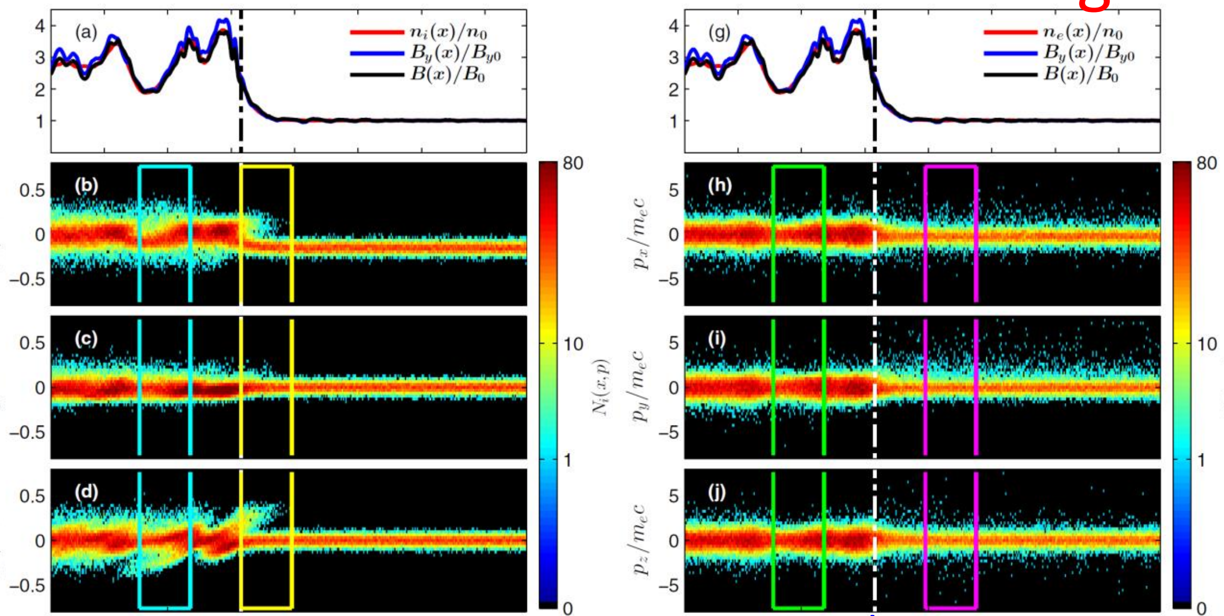
if most of the heat and CRs in clusters are produced at shocks

Conditions and properties of ICM merger shocks

- distance from cluster core	~ 1 - 2 Mpc
- gas density	~ 10^{-3} cm^{-3}
- gas temperature	~ 10^{8} K (8.6 keV)
→ sound speed	~ 1,500 km/s
→ Coulomb collision scale	~ kpc (**collisionless shocks**)
- magnetic field	~ a few μG
→ Alfven speed	~ 100 km/s
→ plasma beta (β_p)	~ 50 – 100
- shock sound Mach number (M_s)	**~ 2 – 4** (weak shocks ?)
→ shock speed	~ 3,000 – 6,000 km/s
→ shock Alfven Mach number (M_A)	**~ 30 – 60** (strong shocks ?)

"Electron" acceleration at ICM merger shocks

(Guo et al. 2014)



ions

electrons

2D & 3D PIC simulations using TRISTAN with

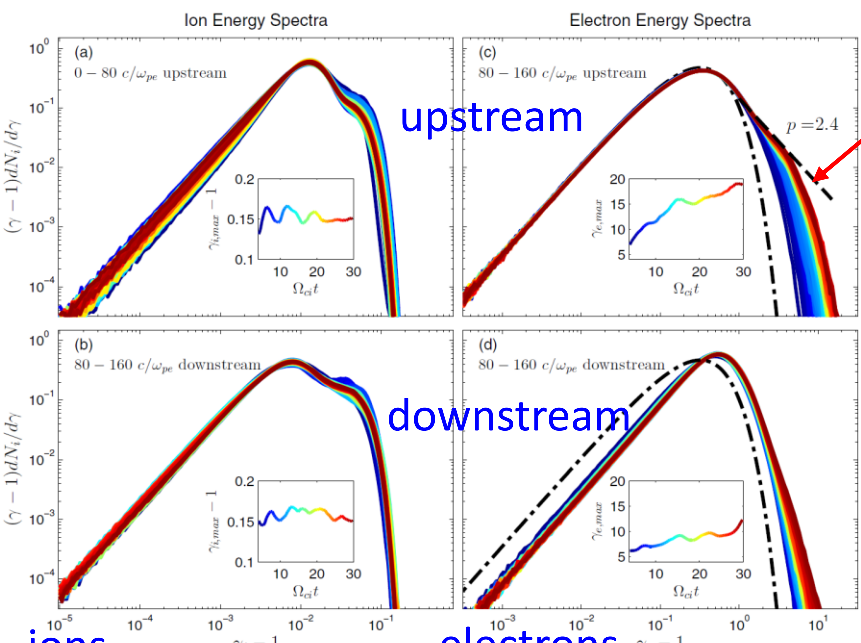
$m_i/m_e = 100$

$\theta = 63^o$ (**quasi-perpend.**)

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

$M_s = 3$

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



upstream

downstream

ions

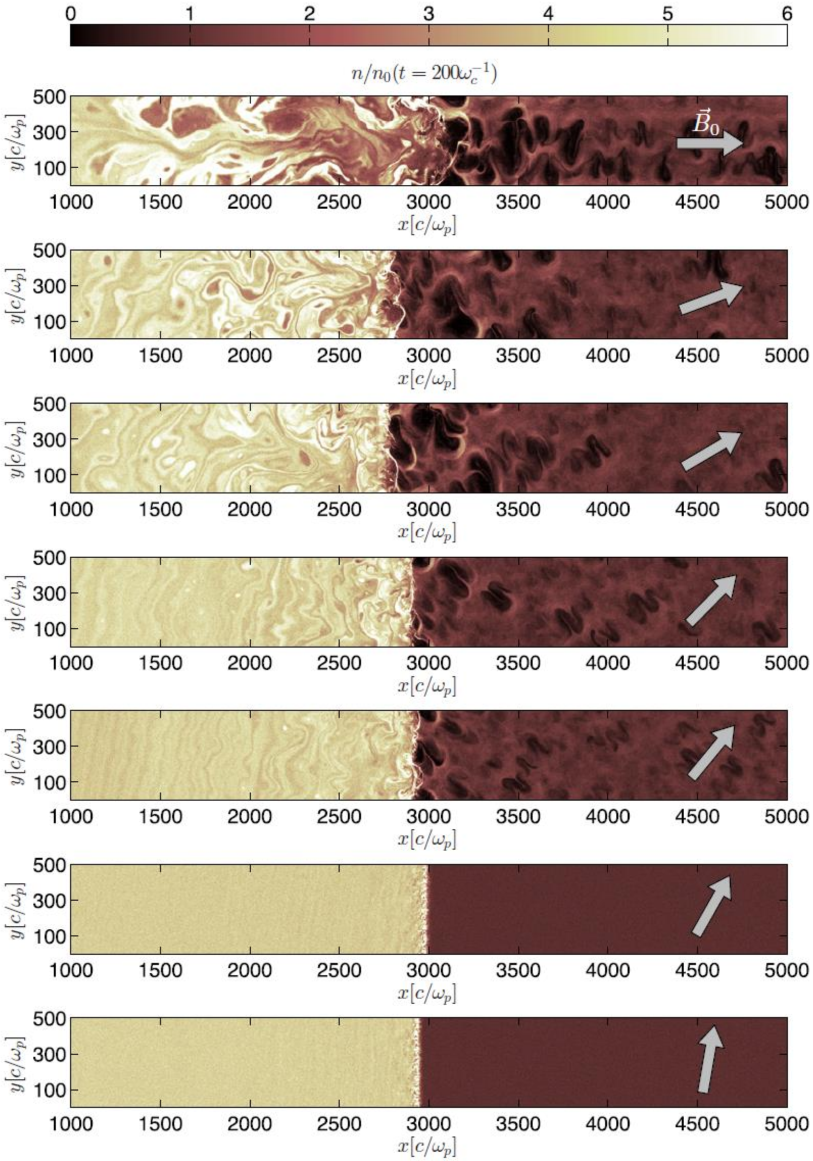
electrons

- **efficient acceleration of electrons at upstream due to SDA** (shock drift acceleration) → **the fraction of nonthermal electrons at upstream ~ 10^{-3}**

- **the expected efficiency of electron acceleration**, if electrons are further accelerated through DSA **~ a few %** → **consistent with radio relics obs ?**

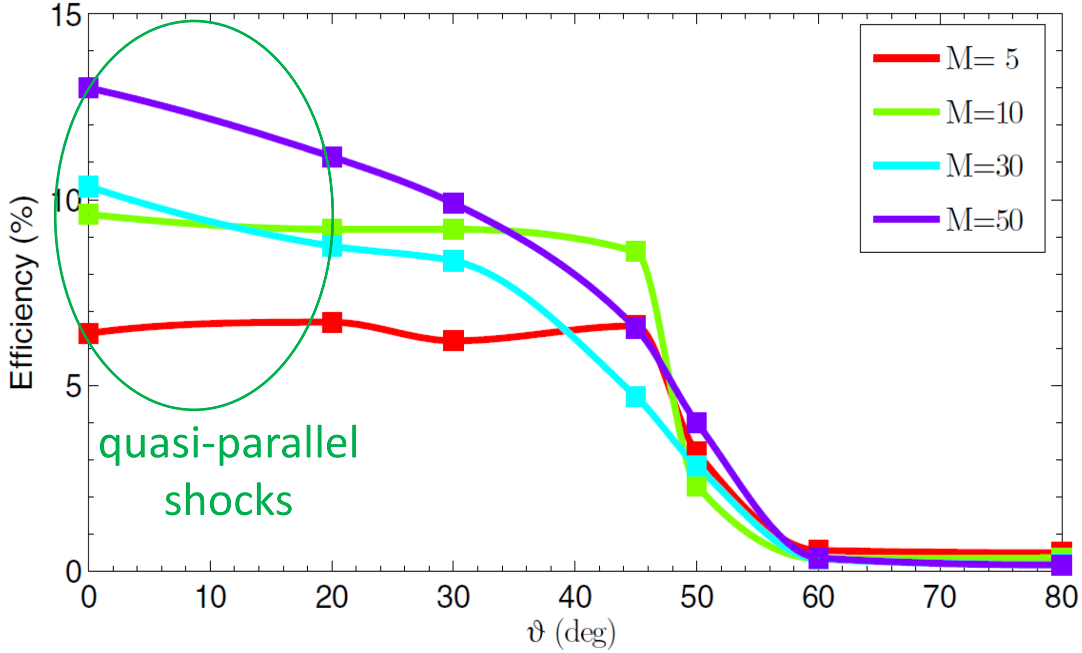
- **but will DSA (diffusive shock acceleration) operate at later time?**

"Proton" acceleration at shocks with $\beta_p = 1$ (Caprioli & Spitkovsky 2014)



ρ for M = 50 shocks with different θ's

2D & 3D simulations using a **hybrid code** for mostly shocks, T = 10^4 K, $\boldsymbol{\beta_p = 1}$ ($M_s = M_A$)

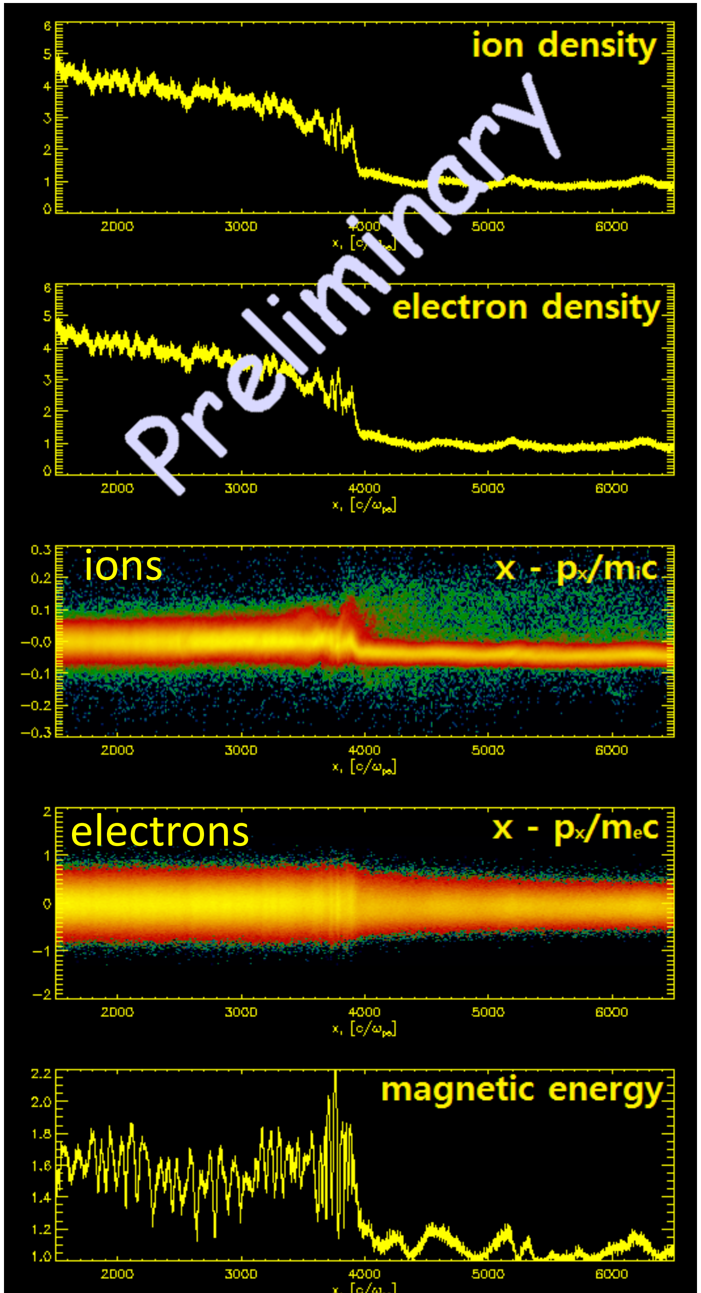


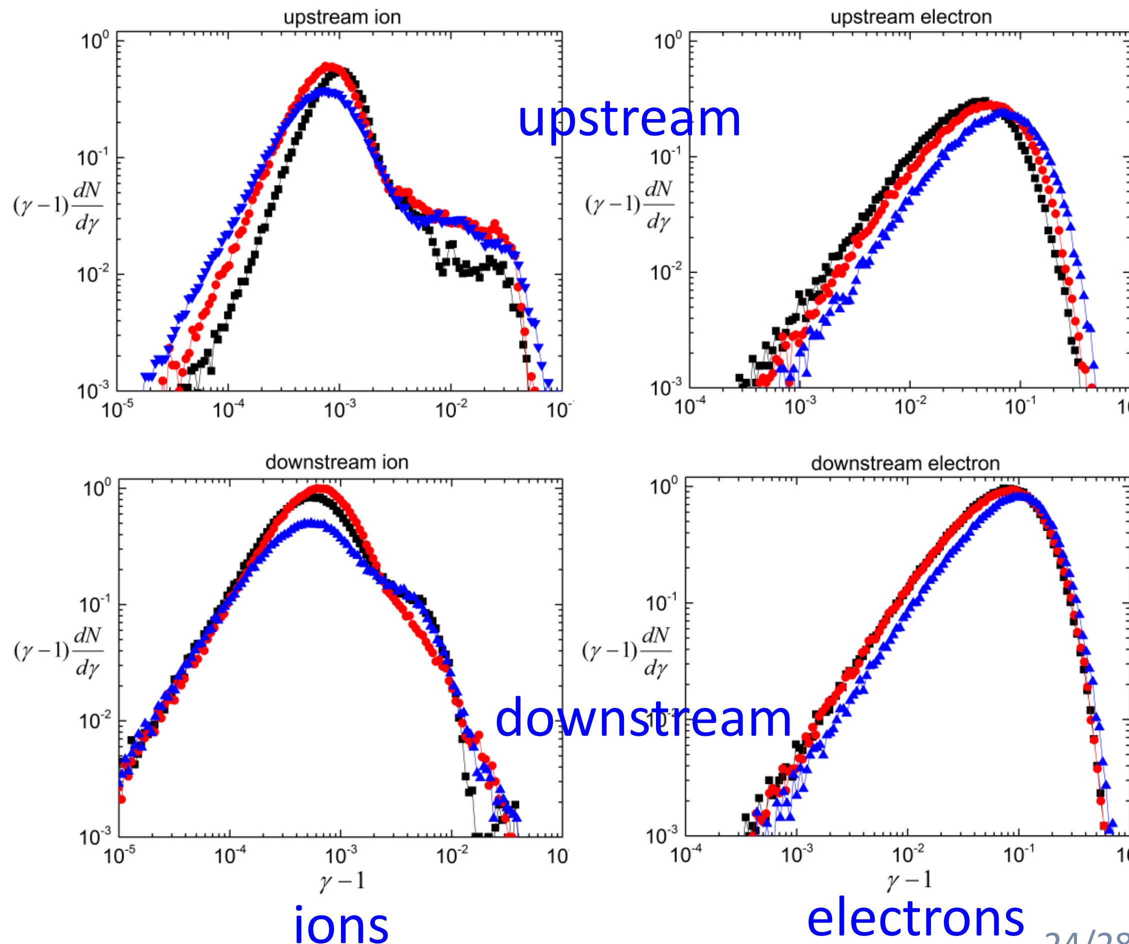
- efficient acceleration of protons with **acceleration efficiency of 10 – 20 %**, particularly for quasi-parallel shocks
- dependence on Mach number is small!

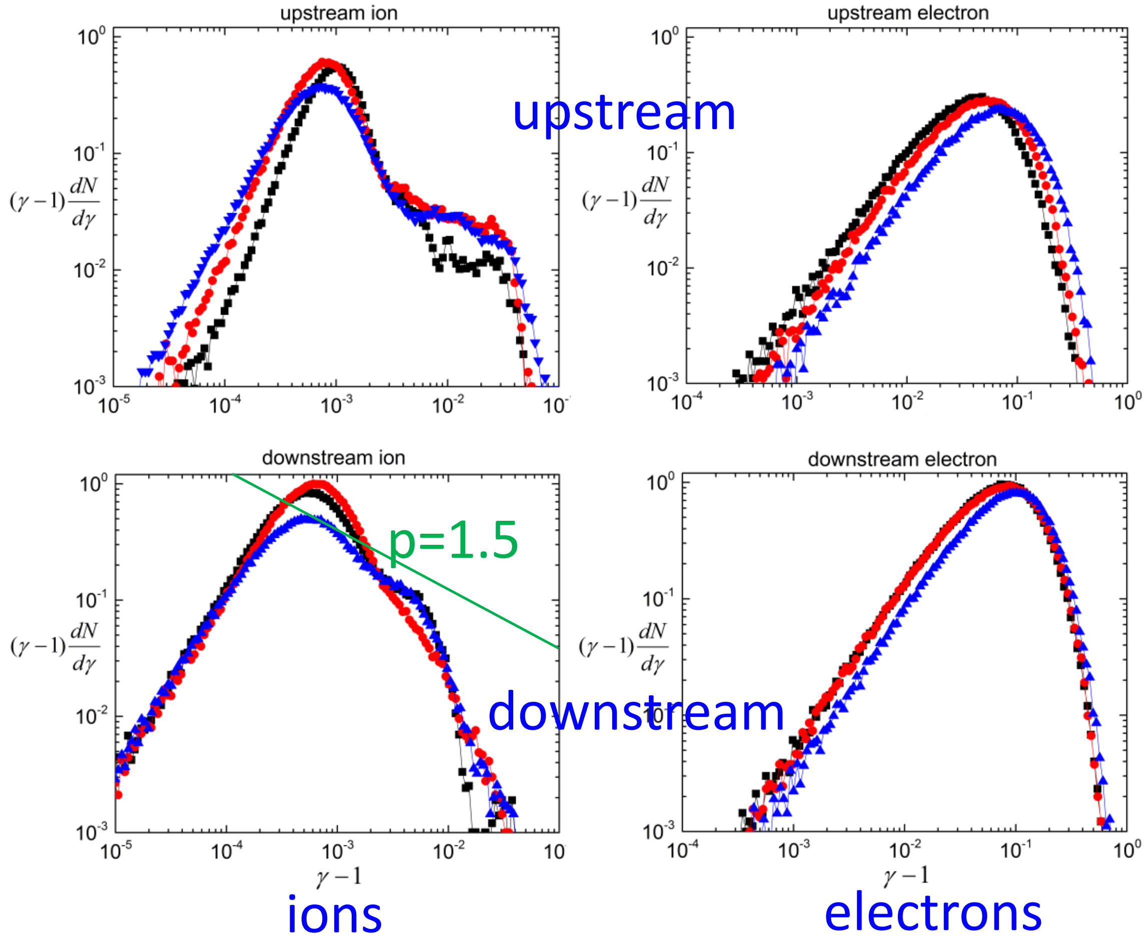
“Proton” acceleration at ICM merger shocks

(Ha, Ryu, & Kang, preliminary)

“almost 1D” PIC simulations using TRISTAN with $m_i/m_e = 100$, $\theta = 13^o$ (**quasi-parallel**), **$T = 10^8$ K** (8.6 keV), **$M_s = 3$**, **$M_A = 22.5$**, ($\beta_p = 100$)



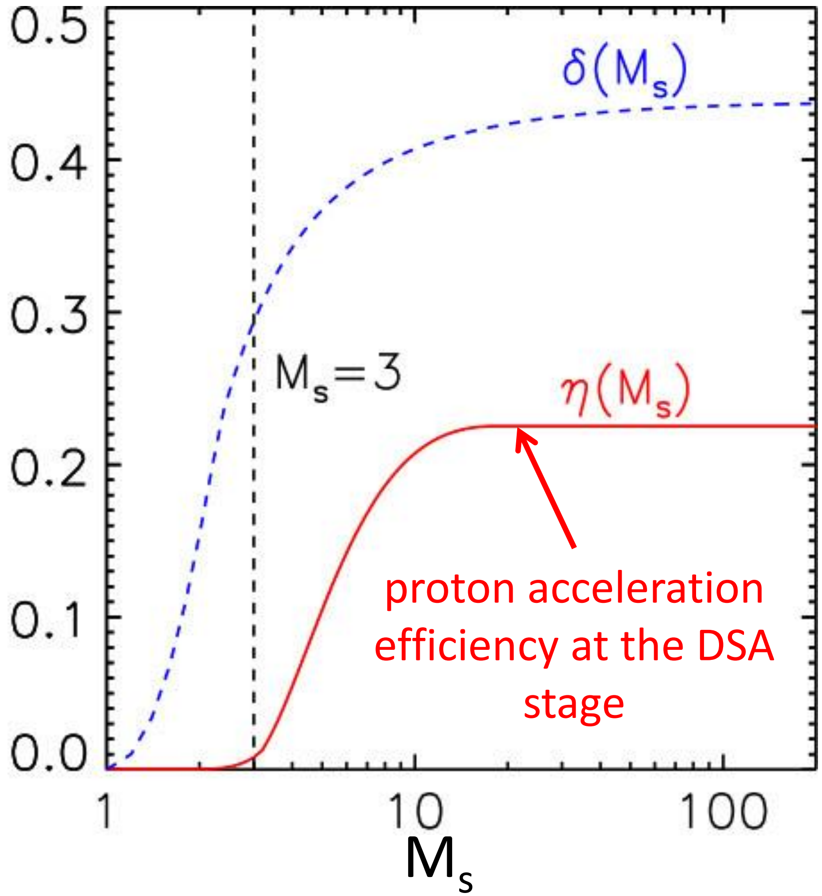




- **efficient acceleration of protons with slope ~1.5** → seems to agree with the results of hybrid simulations (Caprioli & Spitkovsky 2014)
- **the fraction of nonthermal electrons at downstream ~ 10^{-3}**

  → **the expected efficiency of proton acceleration: >~ 10 %**
- **inconsistent with no detection of gamma-ray from clusters ?**
- **DSA in longer time scale ?**

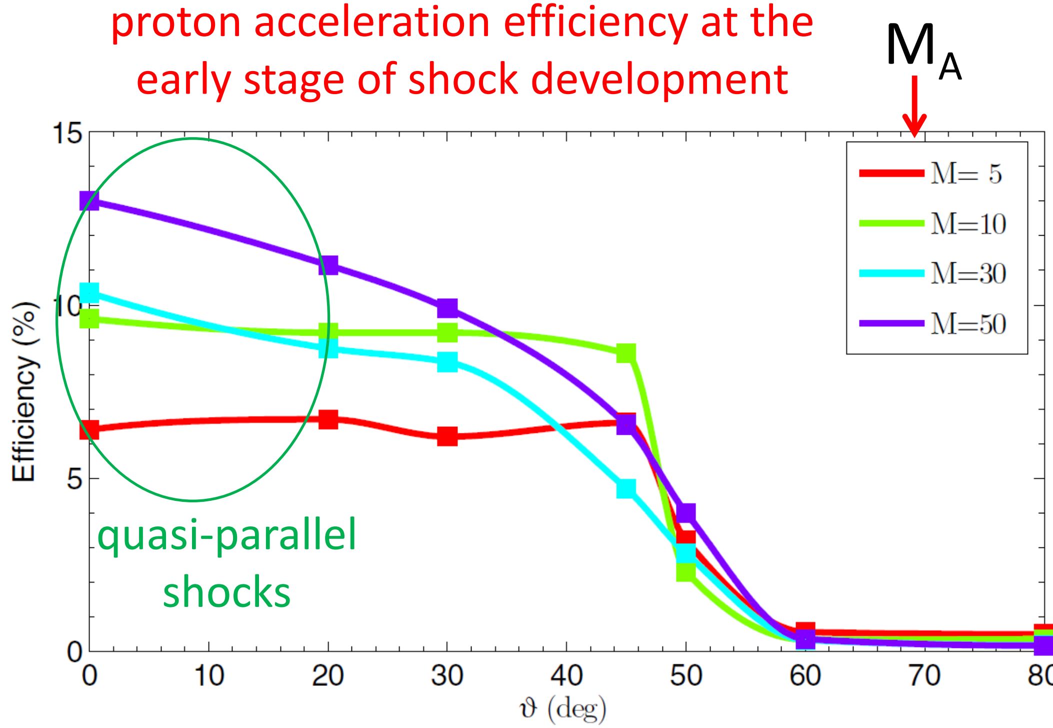
(Kang & Ryu 2013)



Particle acceleration at shocks

(Caprioli & Spitkovsky 2014)

proton acceleration efficiency at the early stage of shock development



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

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

➔ **reconciling them?**

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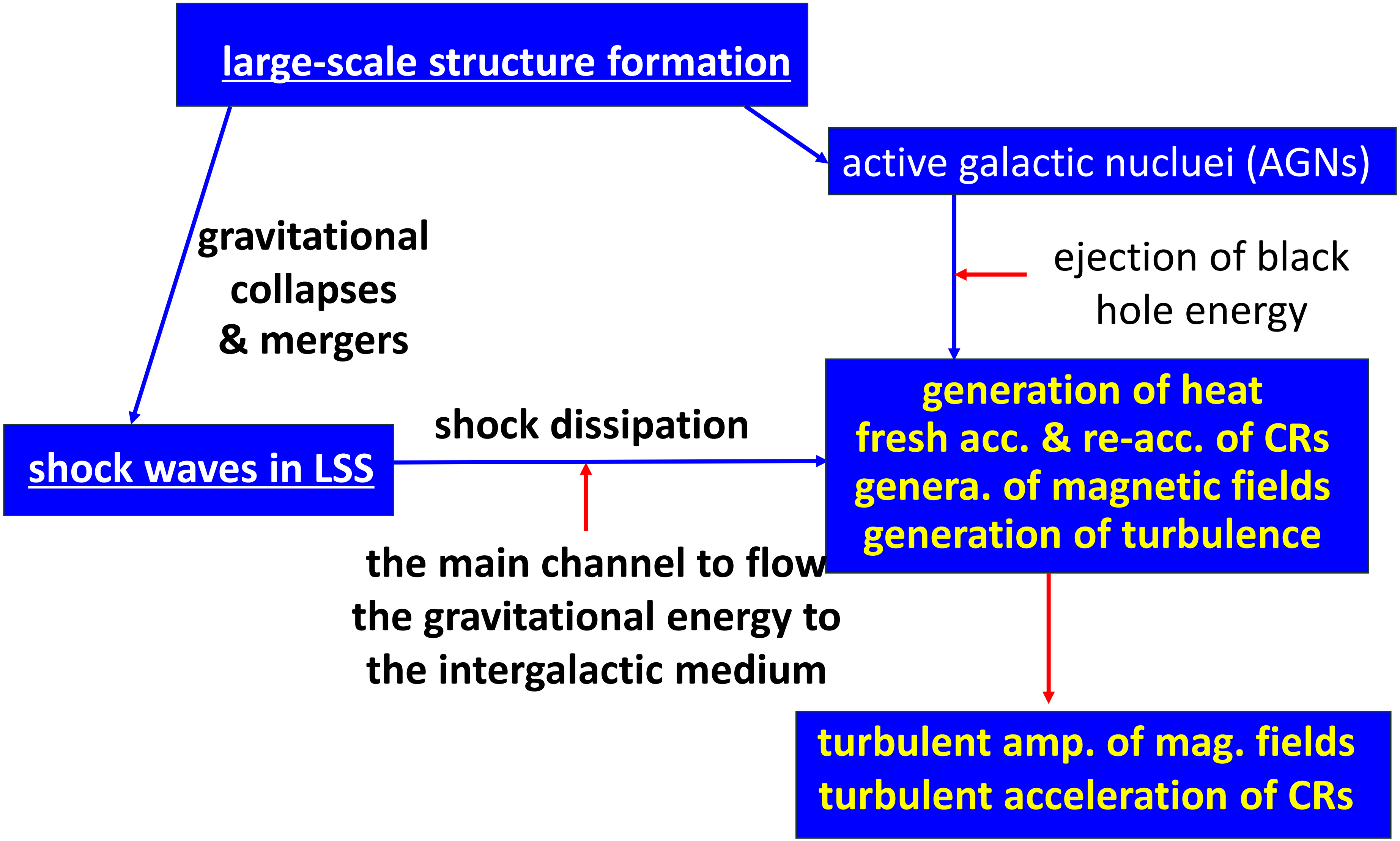
Thank you !

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

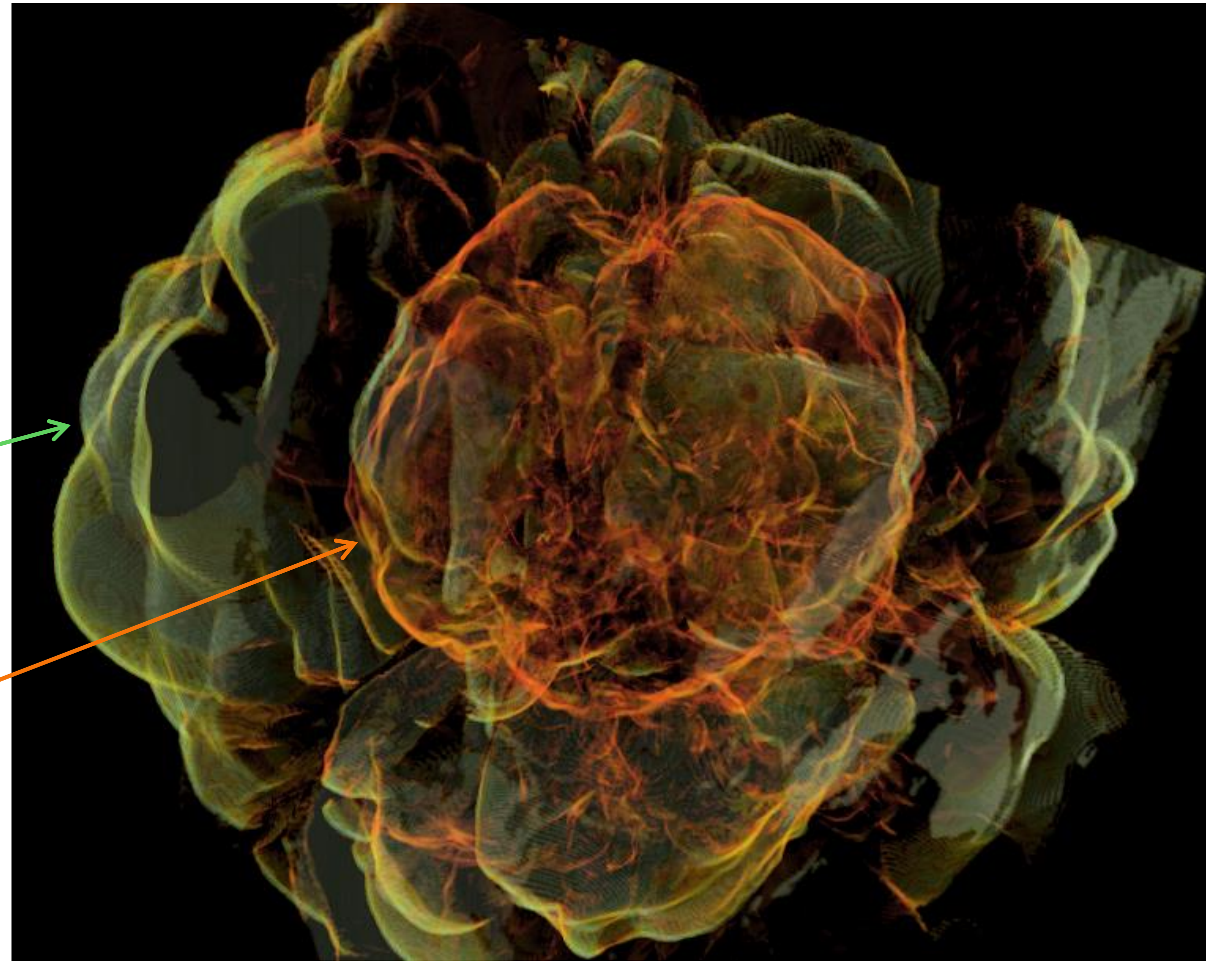


Shock waves induced during the formation of the large-scale structure of the universe

Shock waves in a simulated clusters of galaxies

strong accretion shocks with M>10 (green)

weak inreacluster shocks with M<4 (orange)



(Vazza et al + Ryu)

The nature of shock waves in clusters of galaxies

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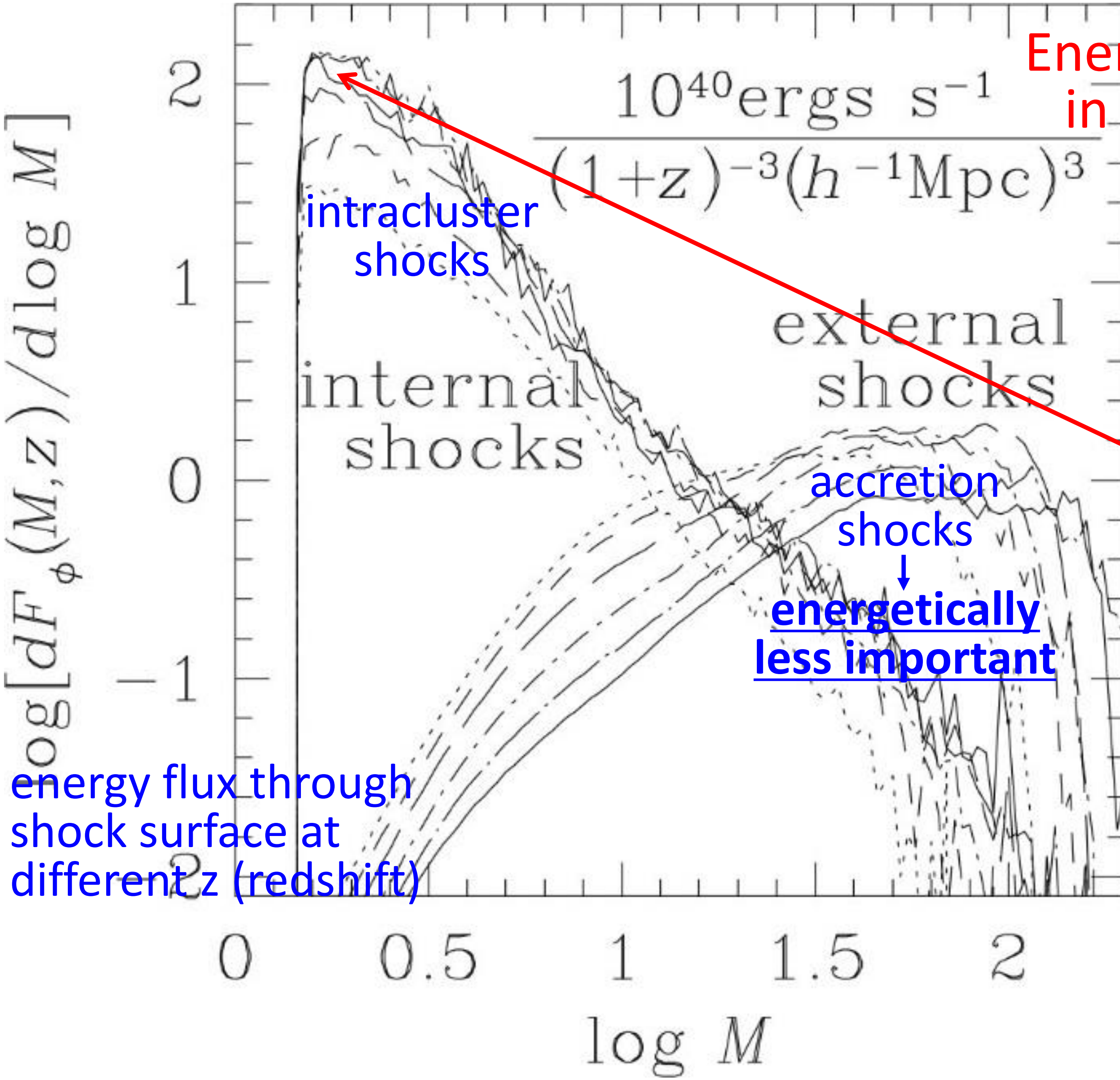
2) **intracluster shocks** inside cluster
    a) turbulence shocks (induced by turbulent flow motions)
    b) infall shocks (accretion of the WHIM (Warm-Hot Intergalactic Medium to the hot intracluster medium along filaments)
    c) merger shocks (induced by merger of gas/DM clumps during the hierarchical formation of galaxy clusters)

Energetics of shocks in galaxy clusters

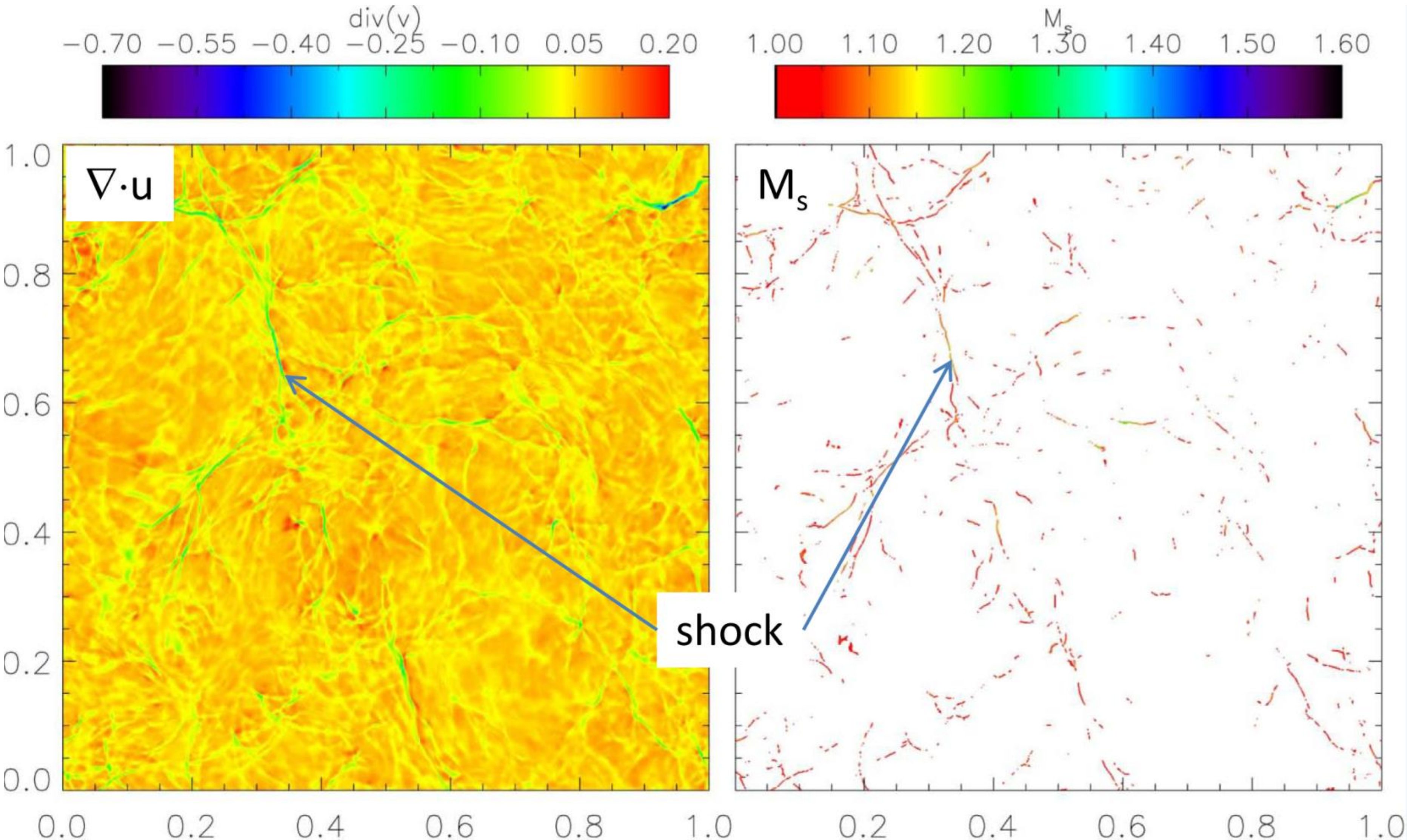
(Ryu, Kang, Jones, & Hallman 2003)



weak intracluster shocks with M_s ~ a few, V_s ~ 1,000 - 2,000 km/s → **energetically more important.**

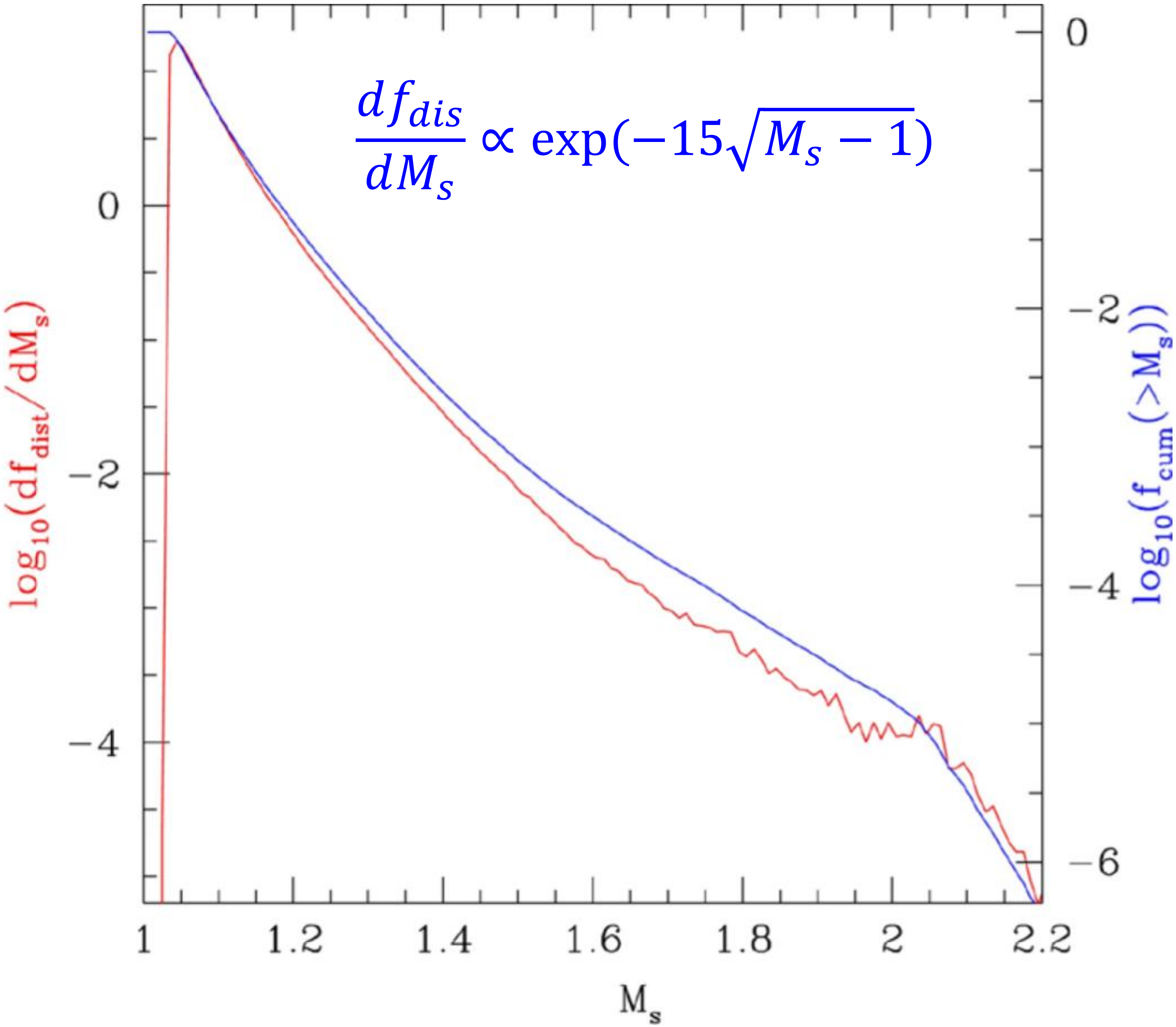
The ICM is in the state of turbulence with $M_{turb} \sim 0.5$.

Turbulence shocks are induced by turbulent flow motions.



(Porter, Jones, & Ryu 2015)

Shock Mach number PDF

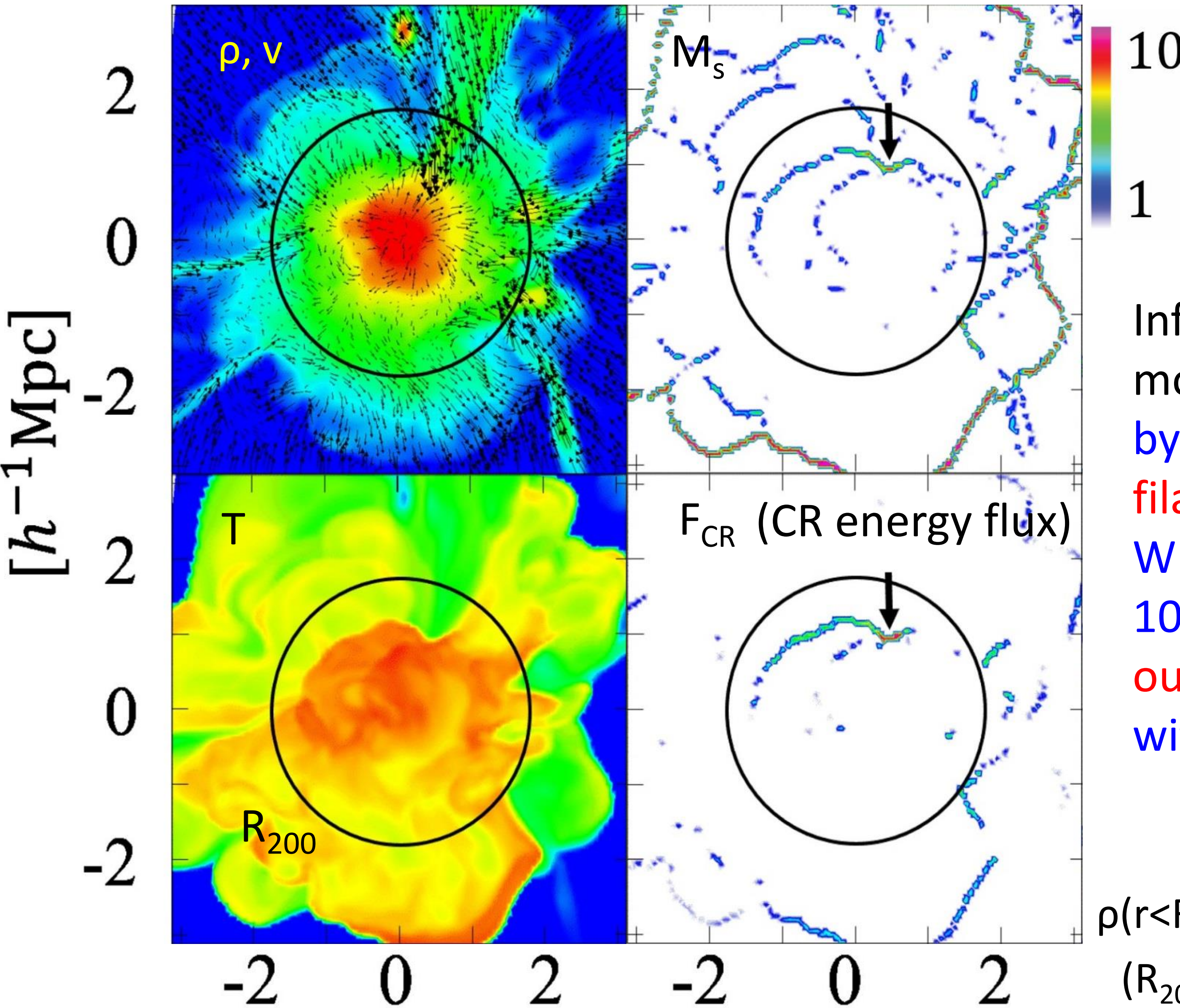


Turbulence shocks in ICMs are mostly weak with M_{shock} <~ 2 and short-lived !

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

Infall shocks

(Hong, Ryu, Kang, & Cen 2014)

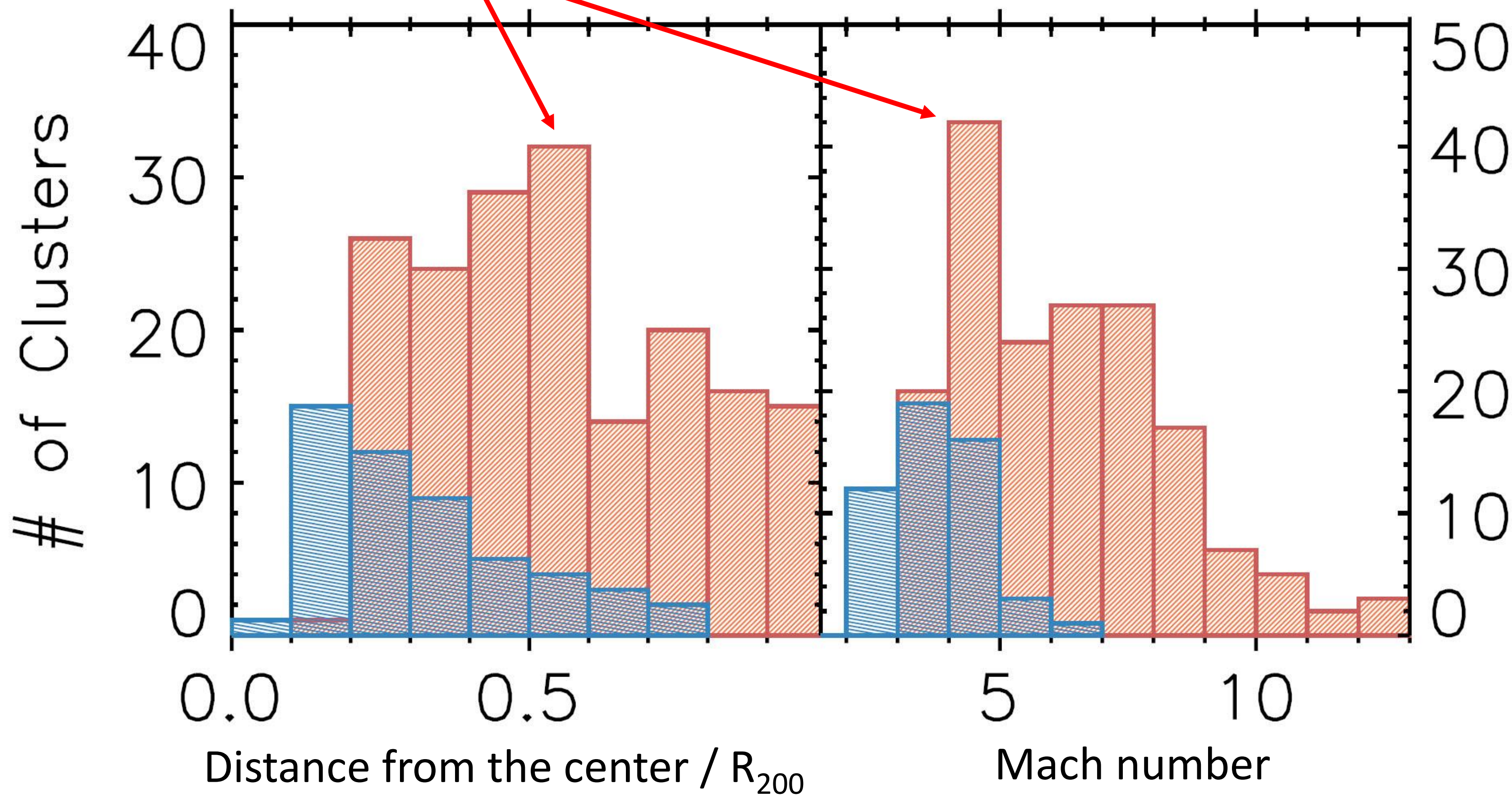


Infall shocks formed mostly at the outskirts, by gas inflow from filaments of the WHIM with T ~ 10^5 – 10^7 K to cluster outskirts of hot gas with T ~ 10^7 - 10^8 K

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

(R_{200} ~ 1.3 R_{vir})

Statistics of infall shocks



- infall shocks are strong with, M_s = a few ~ 10
- they are found mostly in outskirts, and their surface area is small
- infall shocks are energetically less important than merger shocks, but the particle acceleration there could be important!

Fluid quantities in ICM outskirts

size of clusters	$L_{cluster}$ ~ a few Mpc ~ 10^{25} cm
baryon number density	n ~ 10^{-3} cm
flow velocity	v ~ several x 100 km/s
gas temperature	T ~ 10^{8} K (8.6 keV) → c_s ~ 1,500 km/s
magnetic fields	B ~ a few x μG → c_A ~ 100 km/s

→ flows are subsonic (M_s ~ 0.5) but super-Alfvenic (M_A > 1)

gas thermal energy	$E_{thermal}$ ~ a few x 10^{-11} erg/cm^3
gas kinetic energy	$E_{kinetic}$ ~ a few x 10^{-12} erg/cm^3
magnetic energy	$E_{magnetic}$ ~ a few x 10^{-13} erg/cm^3
cosmic-ray energy	E_{CR} <~ a few x 10^{-13} erg/cm^3 ($E_{thermal}$ / 100)

→ plasma beta is high with β ~ 50 - 100 $\left(\beta \equiv \frac{P_{thermal}}{P_{magnetic}} \equiv \frac{2E_{thermal}}{3E_{magnetic}}\right)$