Electron Acceleration in Weak ICM Shocks as the Origin of Radio Relics

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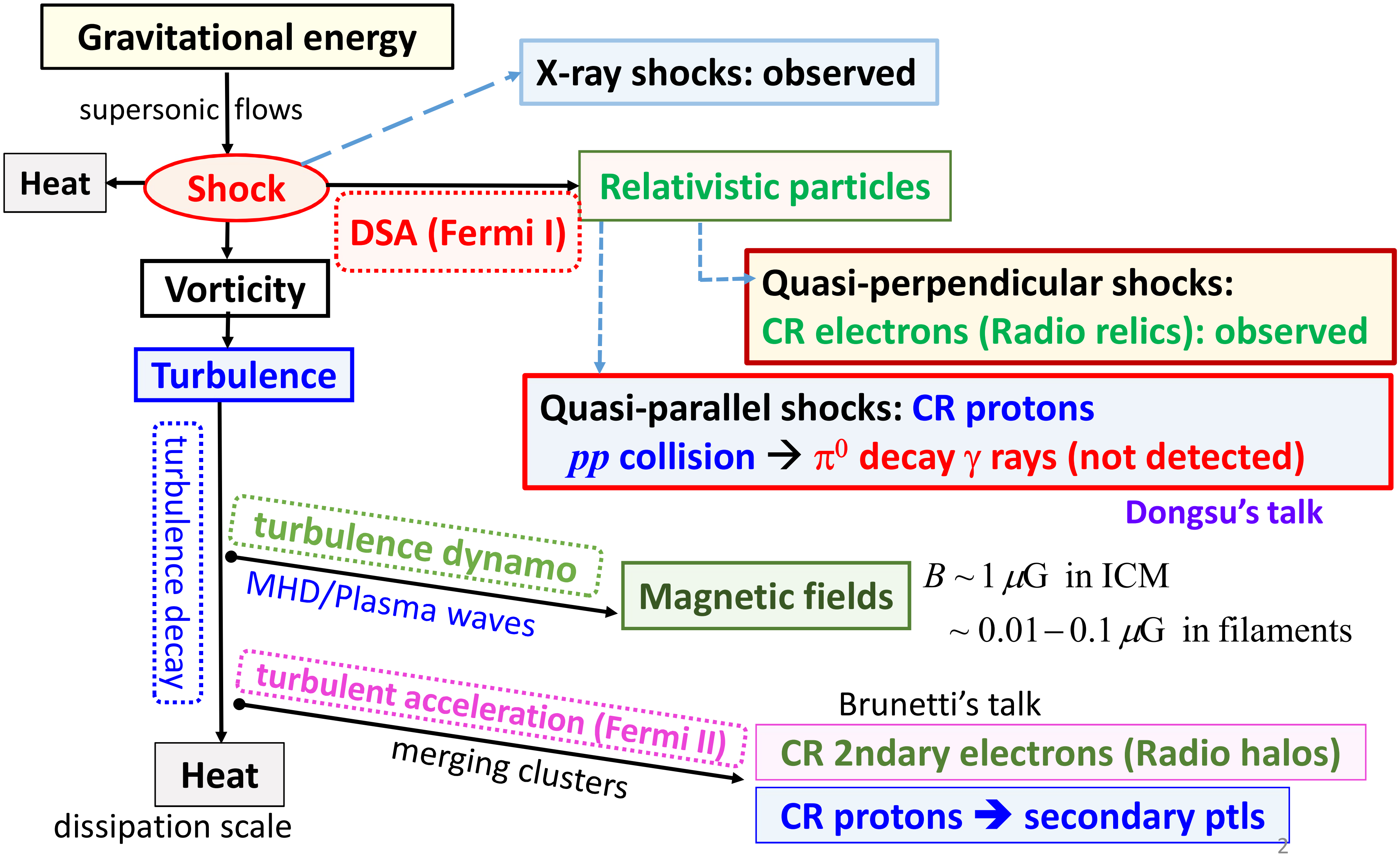
Key Physical Processes in ICM: shocks, turbulence, magnetic fields, & particle acceleration ➔ nonthermal radiation



Gravitational energy

supersonic flows

Heat

Shock

X-ray shocks: observed

Relativistic particles

DSA (Fermi I)

Vorticity

Quasi-perpendicular shocks:
CR electrons (Radio relics): observed

Turbulence

Quasi-parallel shocks: CR protons
pp **collision → π^0 decay γ rays (not detected)**

Dongsu's talk

turbulence decay

turbulence dynamo

MHD/Plasma waves

Magnetic fields

$B \sim 1\ \mu\mathrm{G}$ in ICM

$\sim 0.01 - 0.1\ \mu\mathrm{G}$ in filaments

turbulent acceleration (Fermi II)

merging clusters

Brunetti's talk

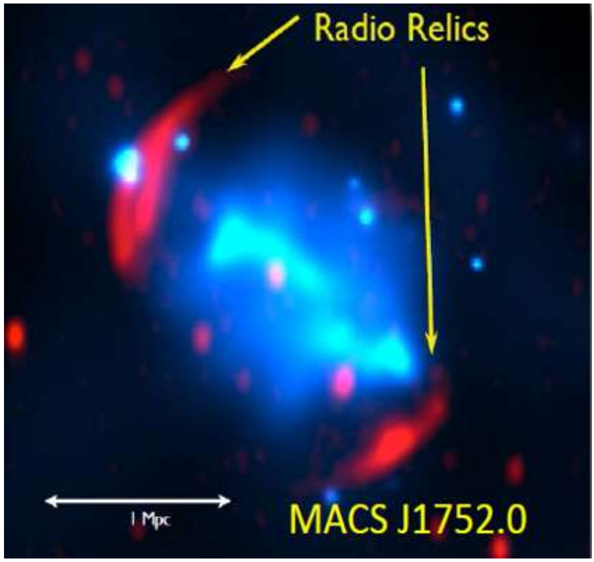
CR 2ndary electrons (Radio halos)

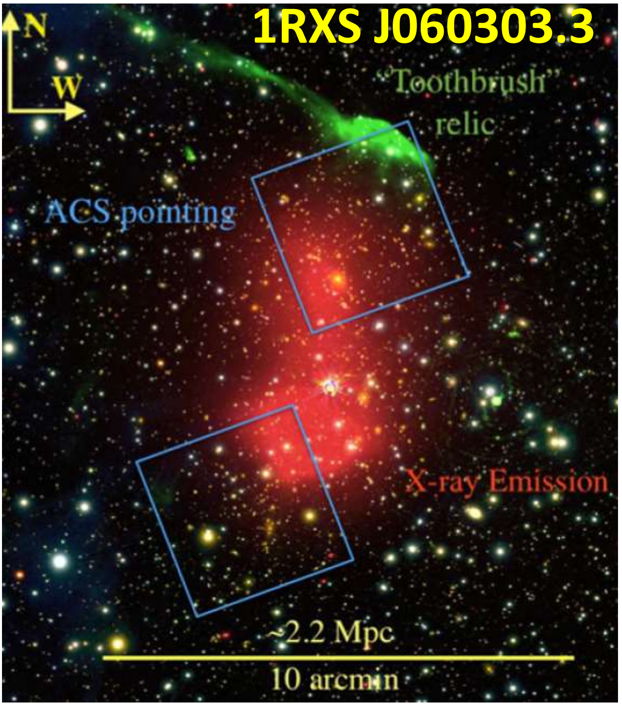
CR protons ➔ secondary ptls

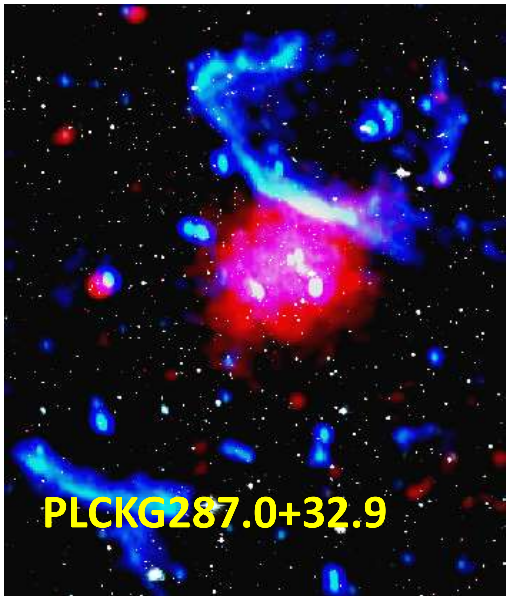
Heat

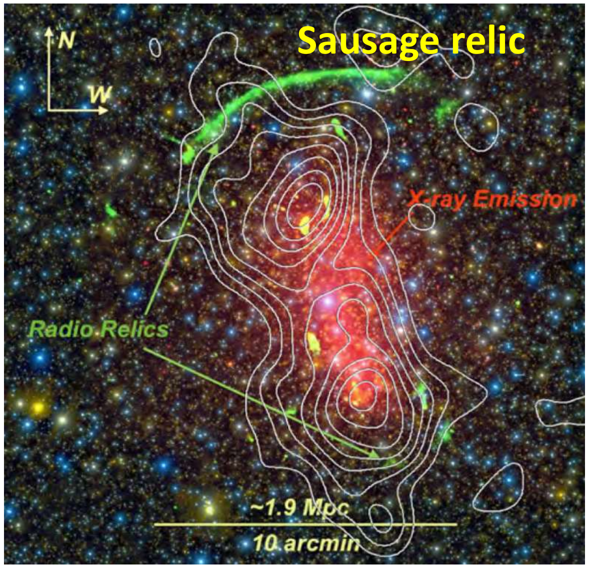
dissipation scale

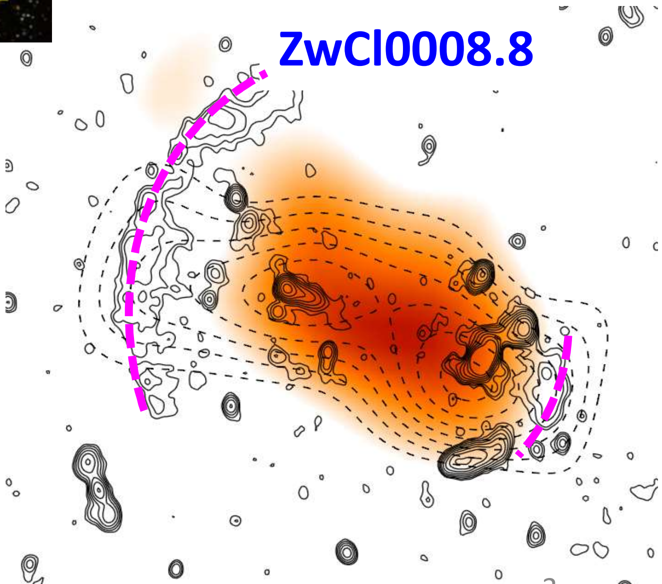
Radio relics: diffuse radio sources found mainly in merging clusters



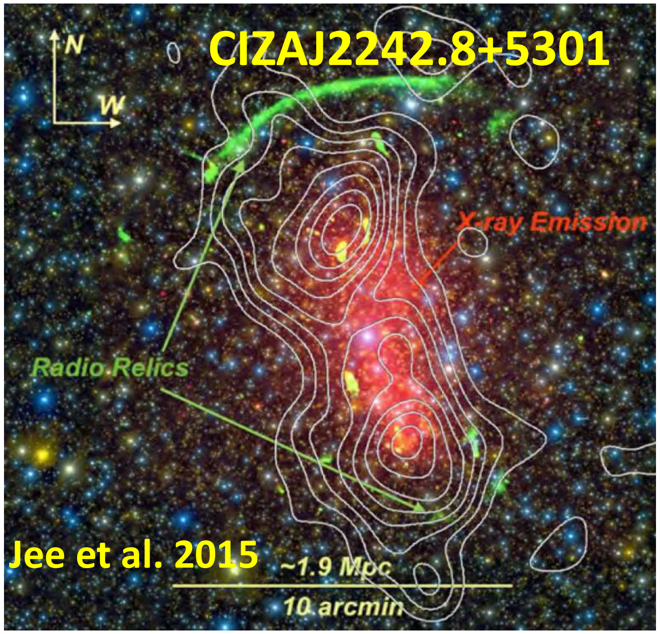




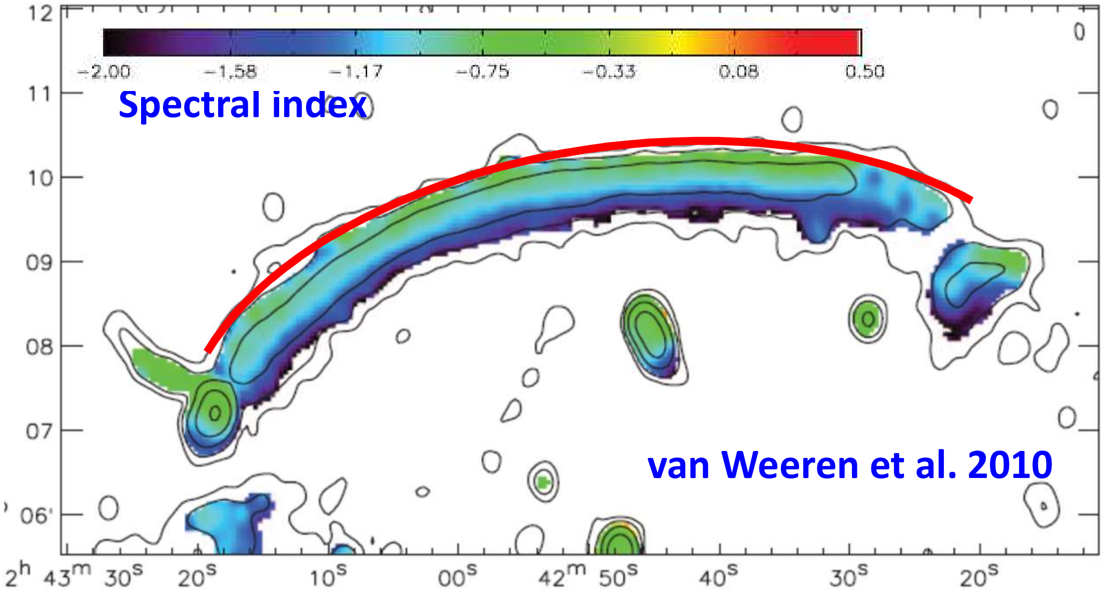




Sausage Relic



Jee et al. 2015



van Weeren et al. 2010

$$M_{\text{radio}}^{2} = \frac{(3+2\alpha_{\text{sh}})}{(2\alpha_{\text{sh}}-1)}$$

$$\Rightarrow M_{\text{radio}} \approx 2.7$$

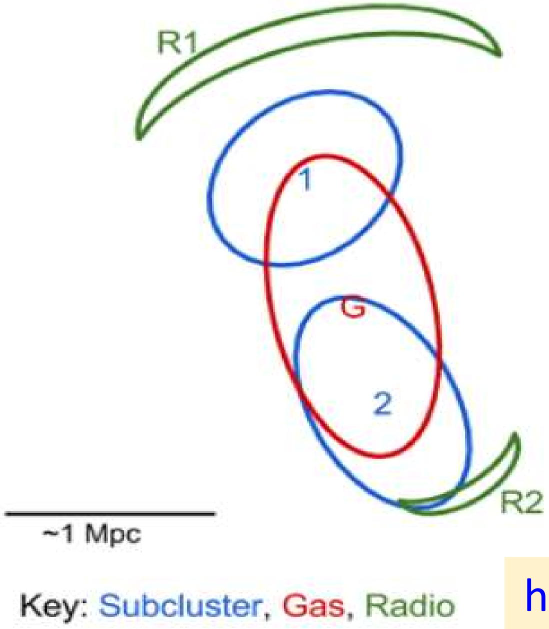
(Hoang + 2017)

$$\frac{T_2}{T_1} = \frac{(M_X^2+3)(5M_X^2-1)}{16M_X^2}$$

$$\Rightarrow M_X \approx 2.7$$

(Akamatsu + 2015)

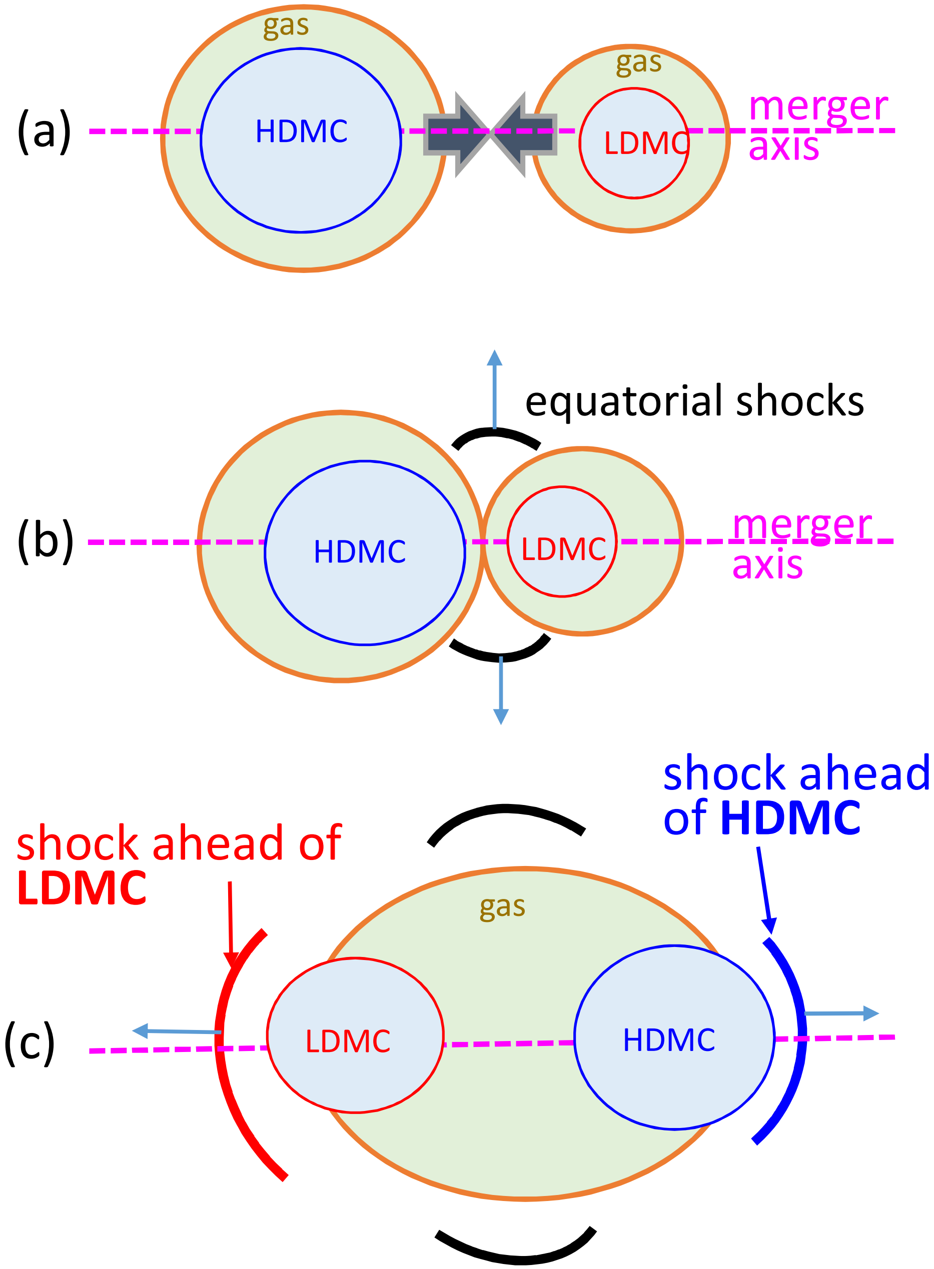
double radio relics (RN + RS) in a merging cluster: acceleration or re-energization CR electrons by merger-driven shocks.



http://www.mergingclustercollaboration.org/

cartoon picture for **Simple binary major merger**

LDMC – light dark matter core
HDMC – heavy dark matter core



Two clumps are approaching.

‘Equatorial Shocks’ are launched first perp. to the merger axis.

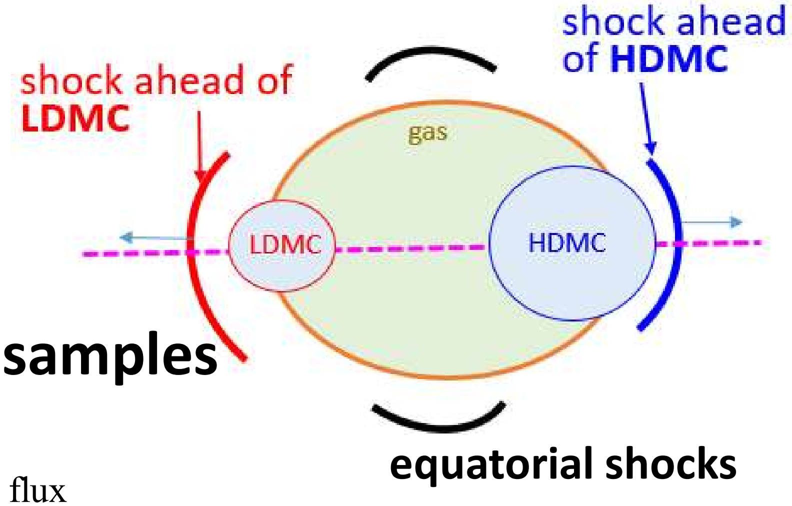
DM core passage

Two ‘axial shocks’ form and propagate along the merger axis.
(➔form double radio relics)

Evolution of merger shocks in simulated merging clusters

Ha, Ryu, & Kang 2017

1. Performed several LCDM cosmological simulations with 1024^3 grids on 50 h^{-1} Mpc box
2. Identify merging clusters going through almost head-on collision with ~ 2:1 mass ratio & kT_x ~ 5 KeV ➔ 5 sample clusters
3. Identify three types of shocks associated with each merging cluster: equatorial shocks + 2 axial shocks



equatorial shocks

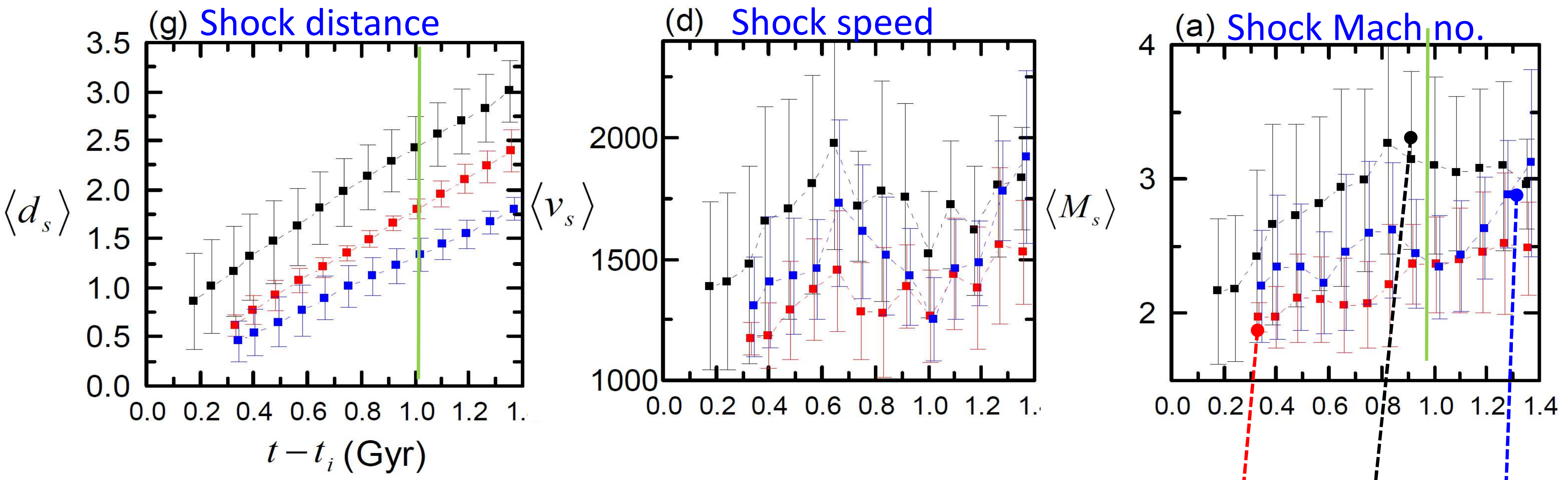
4. Calculate shock properties such as

$$d_s,\ u_s,\ M_s,\ F_{\rm kin} = \rho_1 u_s^3/2,\ F_{\rm CR}$$

5. Calculate statistics over many shock samples

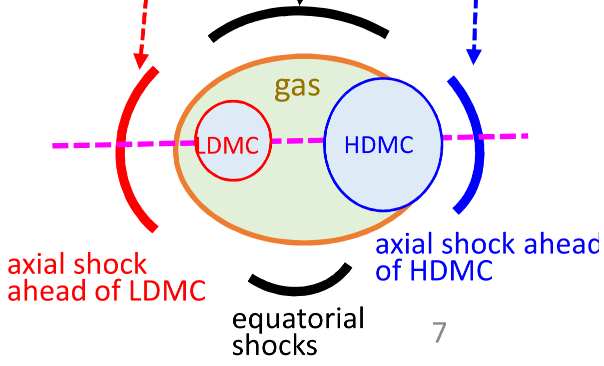
$$\langle d_s(t)\rangle,\ \langle u_s(t)\rangle,\ \langle M_s(t)\rangle,\ \langle M_s(t)\rangle_{\rm CR\_flux}$$

Evolution of Shock Properties in simulated merging clusters

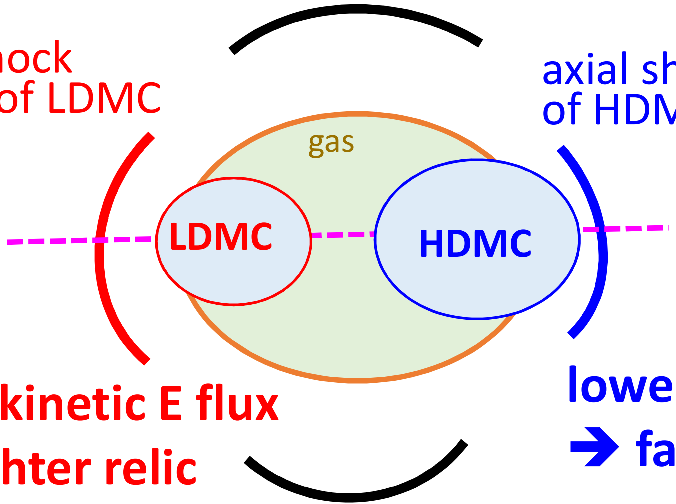


- Merger shocks are observed as X-ray shocks and radio relics **at d~ 1 - 2 Mpc at t~1Gyrs after DM core passage** with Mach number **M_s ~ 2 – 4**
- M_s increases slightly as shocks move out due to lower **T,** while v_s tends fluctuate in the outskirt.

acceleration of CR electrons at these shocks
➔ consistent with observations of Radio relics



*** note that variances are large.**



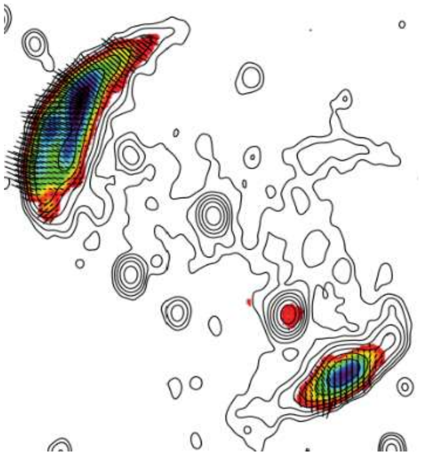
axial shock ahead of LDMC

axial shock ahead of HDMC

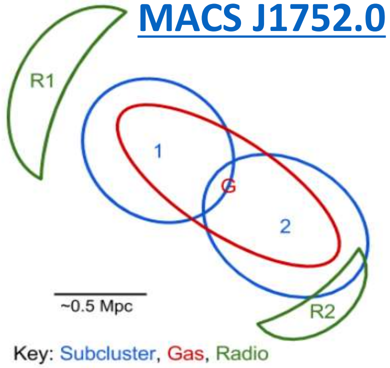
higher kinetic E flux
➔ brighter relic

lower kinetic E flux
➔ fainter relic

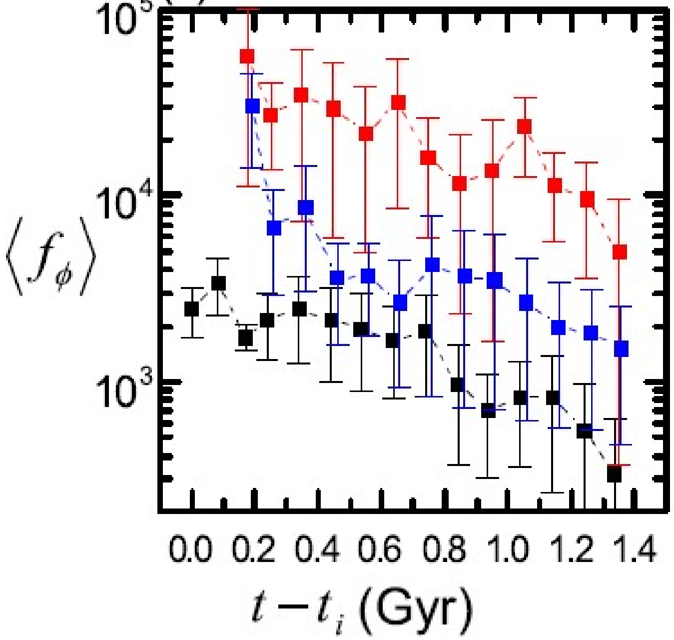
equatorial shocks



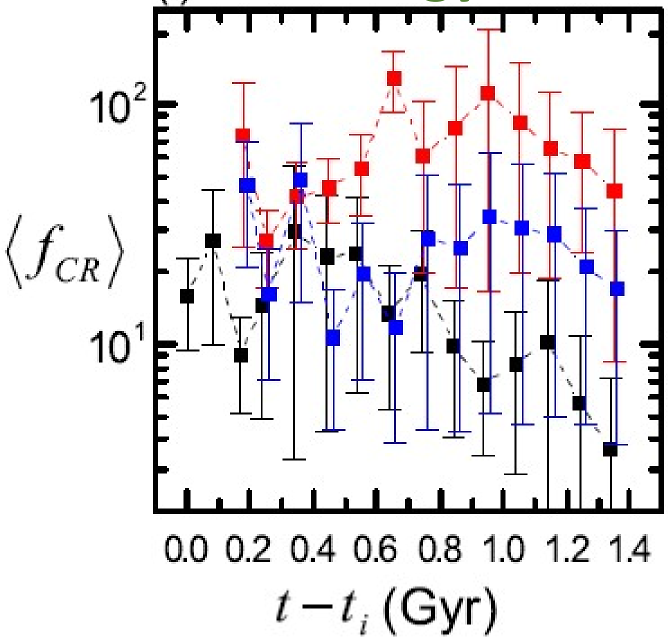
MACS J1752.0



Shock kinetic E flux

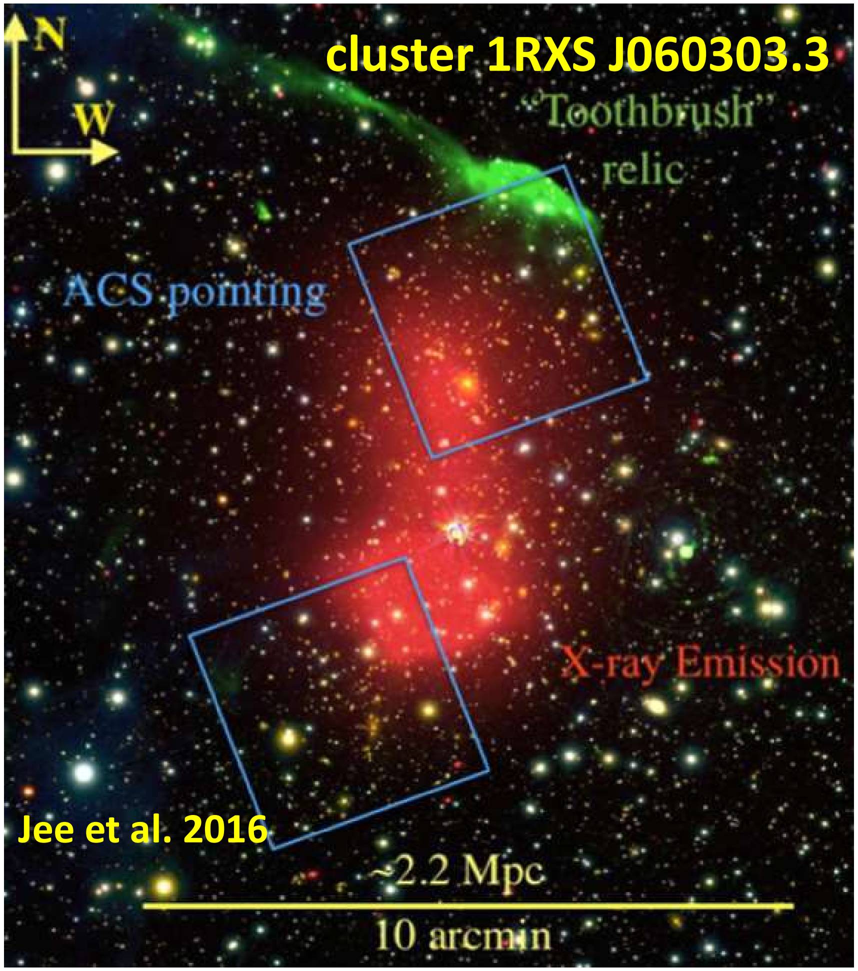


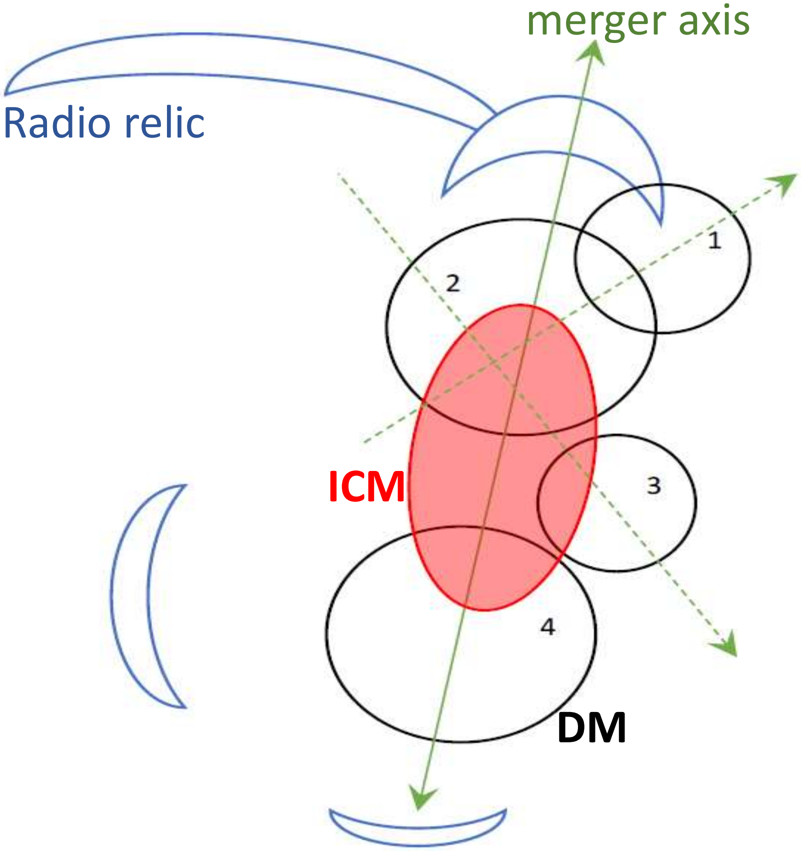
CR energy flux



Ha, Ryu, & Kang 2017

Toothbrush Relic: halo + radio galaxies + radio relics





MERGING CLUSTER COLLABORATION:
A PANCHROMATIC ATLAS OF RADIO RELIC MERGERS

$$\text{B1 relic: } M^2_{\text{radio}} = \frac{(3+2\alpha_{sh})}{(2\alpha_{sh}-1)} \Rightarrow M_{radio} \approx 2.8 \ \text{ but } M_X \approx 1.5$$

van Weeren + 2016

Some puzzles in DSA model with *in situ* injection only

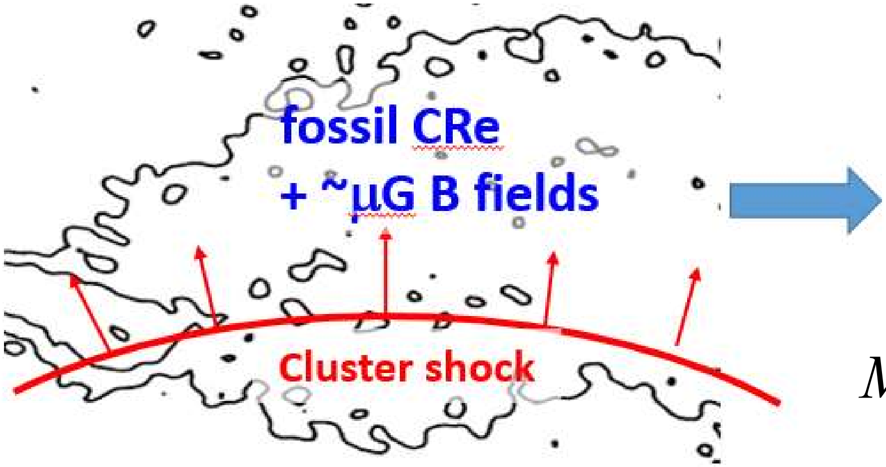
(1) For some radio relics, $M_{\rm radio} > M_{\rm X}$

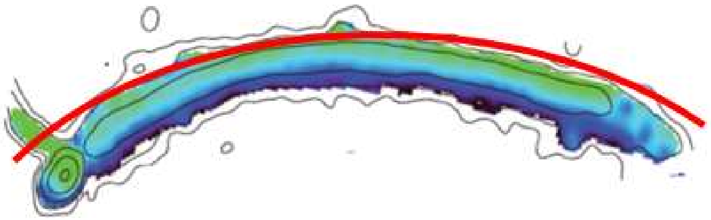
(2) Only ~10 % of merging clusters host radio relics, while numerous shocks are expected to form in ICM.

(3) Some X-ray shocks do not have associated radio relics.

(4) Injection of thermal electrons to DSA may be inefficient.

Possible solution is Re-acceleration model:
a radio relic forms when a weak shock encounters the ICM plasma with pre-existing fossil electrons.





$$M_s = 3.0 \Rightarrow q_{\rm DSA} \approx 4.5 \Rightarrow \alpha_{\rm sh} \approx 0.75$$

DSA (Fermi-I) model parameters for giant radio relics

shock properties

$M_s(t) \sim 3,\ M_A \sim 20,$

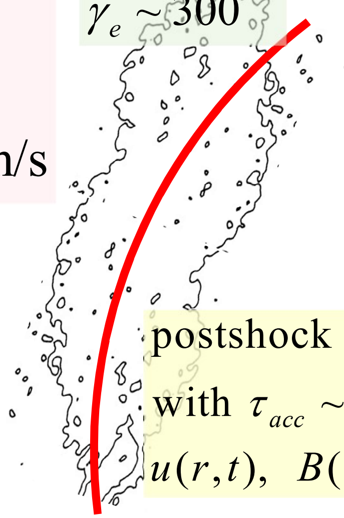
$u_s(t) \sim 2.5-3\times10^3$ km/s

background plasma

$B_1 \sim 1\mu$G

$n_{H,1} \sim 10^{-4}\,\mathrm{cm}^{-3}$

$kT_1 \sim 2-3\,\mathrm{keV}$



fossil CRe

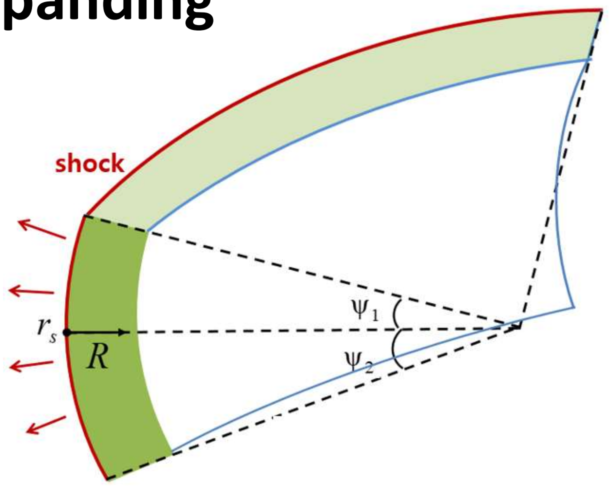
$\gamma_e \sim 300$

postshock turbulence

with $\tau_{acc} \sim 10^8$ yr

$u(r,t),\ \ B(r,t)$

spherically expanding shock surface



geometry of shock surface in 3D

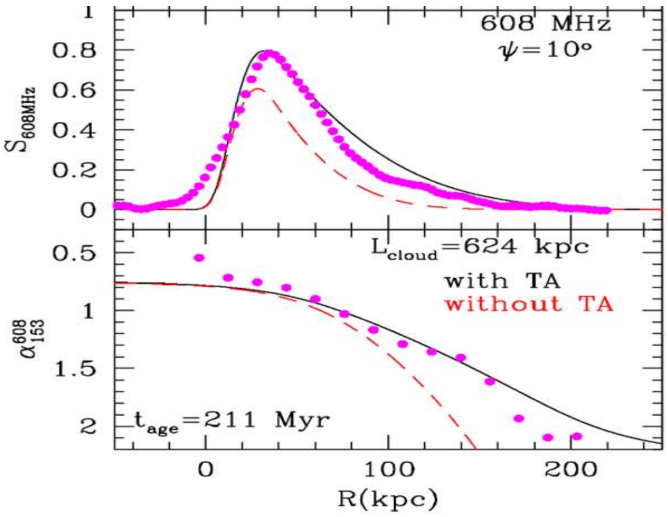
Observational Test

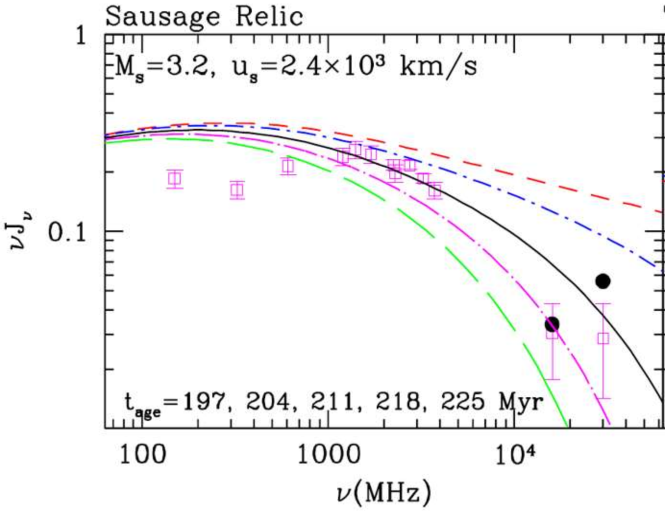
observables

$S_\nu(R)$

$\alpha_\nu(R)$

$\nu\cdot J_\nu$



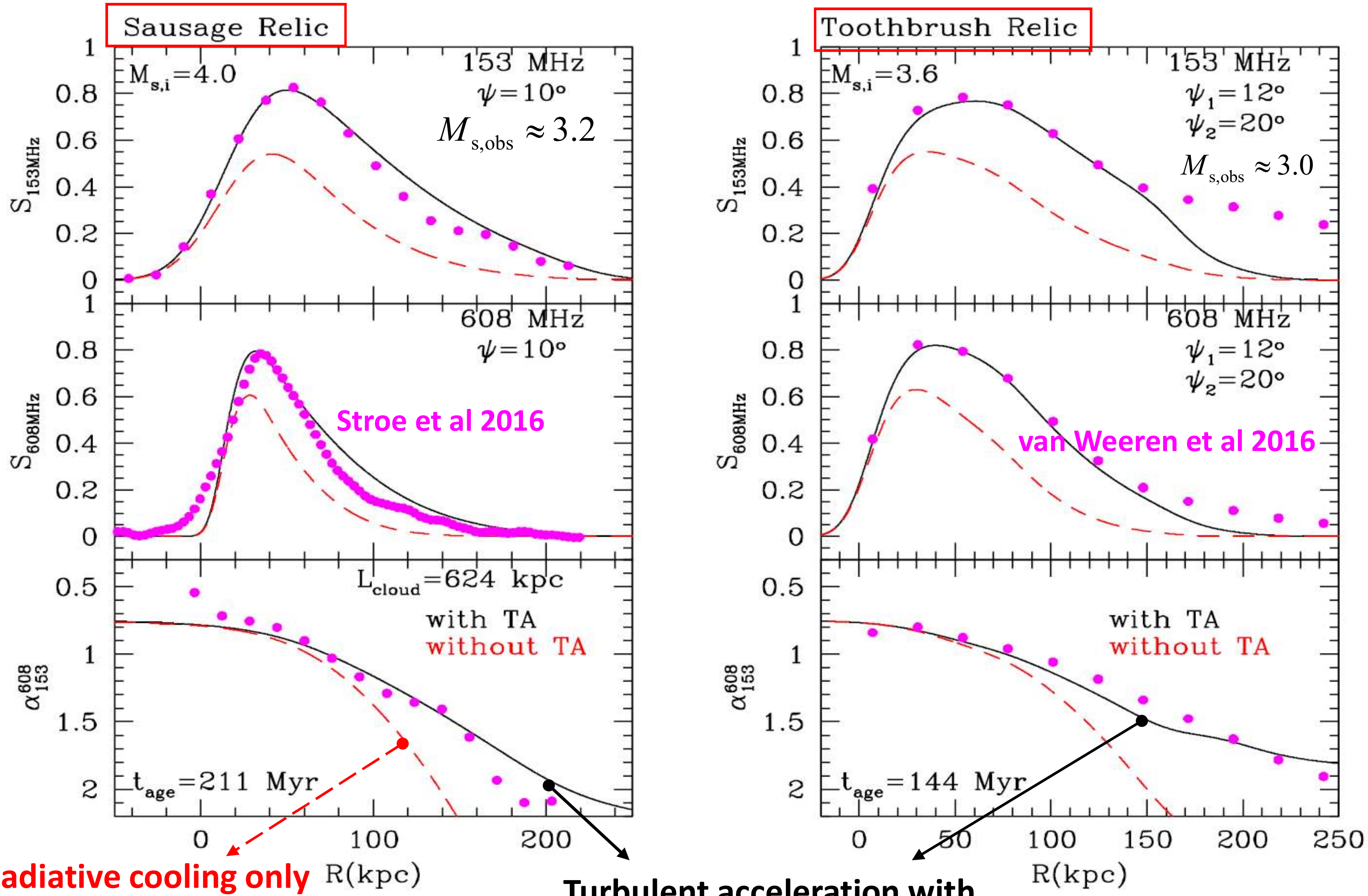


-Fitting S_ν, α_ν, & $\nu\ J_\nu$ simultaneously is necessary.

-Many free parameters in DSA modeling

Kang & Ryu 2015

Model Fitting of Radio Flux & Spectral index Profiles



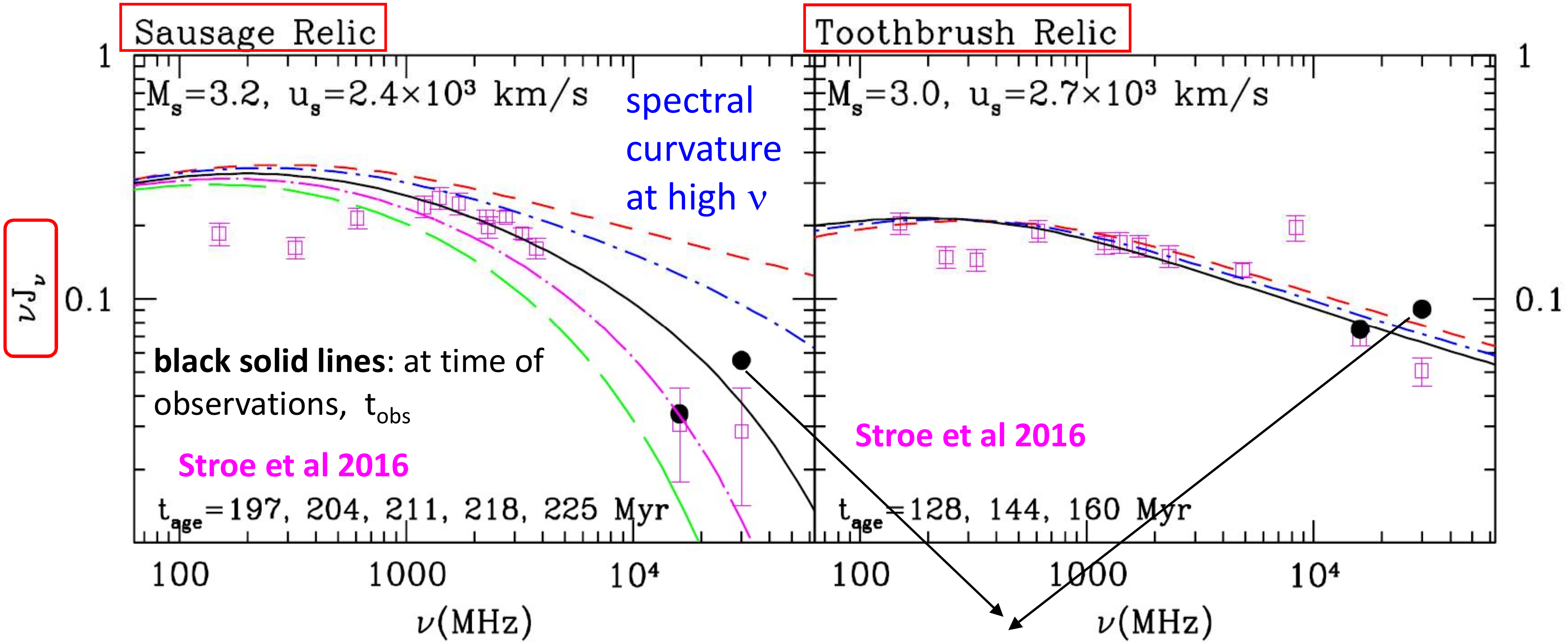
Radiative cooling only

Turbulent acceleration with

$$D_{pp} \approx \frac{p^2}{4\tau_{acc}}, \quad \tau_{acc} \approx 10^8 \text{ yr}$$

Kang, Ryu, Jones 2017, Kang 2017

Modeling Fitting of Radio Integrated Spectra



spectral curvature at high ν

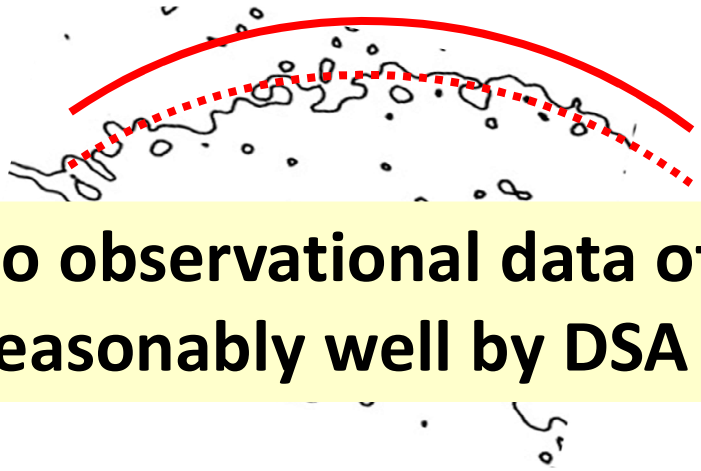
black solid lines: at time of observations, t_{obs}

Stroe et al 2016

Stroe et al 2016

SZ corrected flux by Basu et al. 2016

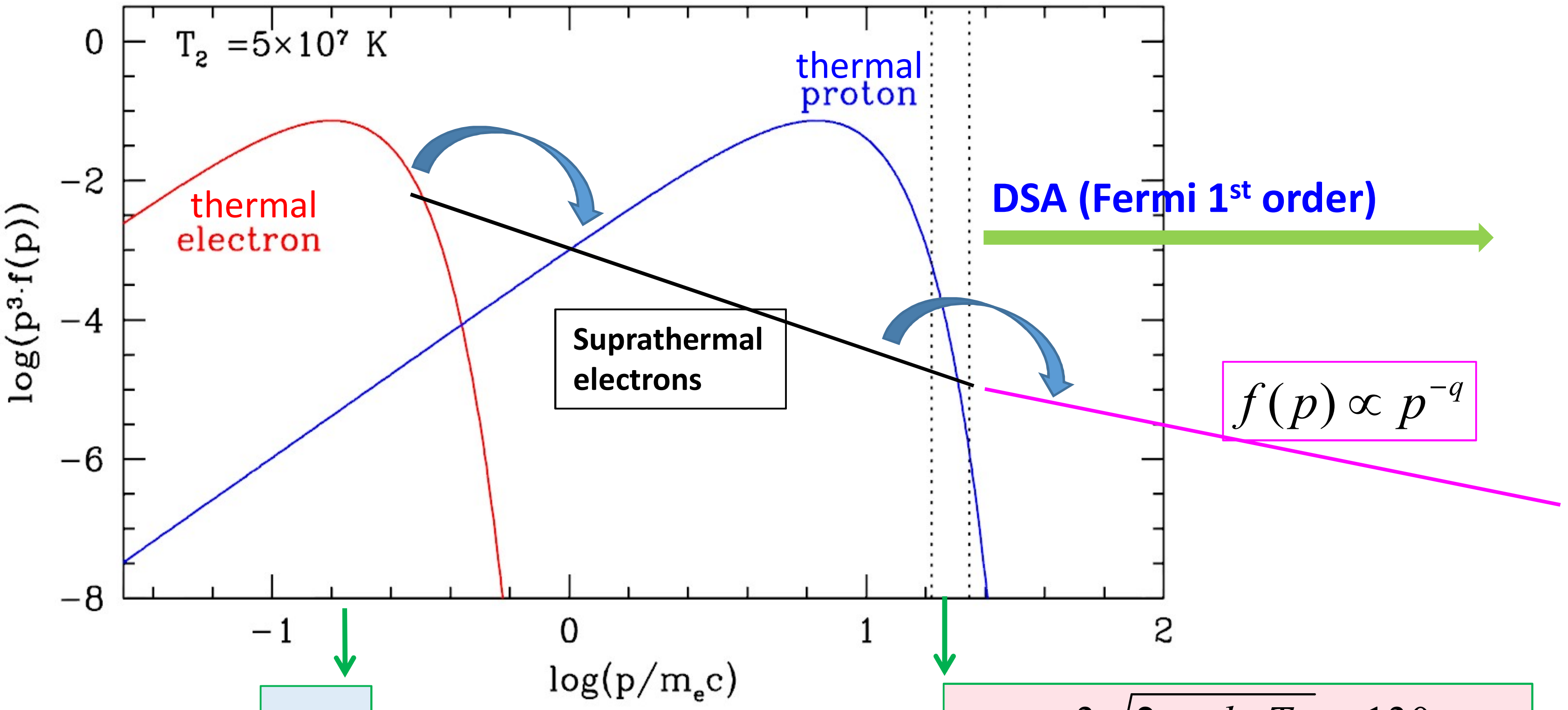
The shock has run out of fossil CRe.



The shock is inside the cloud of fossil CRe.

So observational data of radio relics can be reproduced reasonably well by DSA models.

Electron pre-acceleration to be injected to DSA ?



DSA (Fermi 1st order)

Suprathermal electrons

$f(p) \propto p^{-q}$

$p_{th,e}$ → **electron pre-acceleration** → $p_{inj} \sim 3\sqrt{2m_p k_B T_2} \sim 130\ p_{th,e}$

$\lambda_{mpf} \geq 3r_g(p_{th,p}) \sim$ shock thickness

Electrons need to be pre-accelerated from $p_{th,e}$ to p_{inj} in order to get injected into DSA process.

Understanding kinetic processes in the shock front is important.

⇒ Plasma simulations

Properties of Astrophysical Plasmas

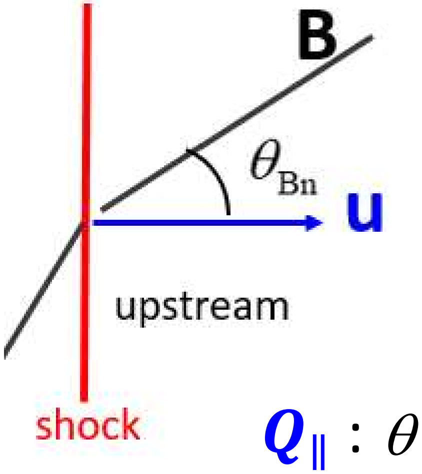
	solar wind (IPM)	ISM	ICM	solar flare
n_H (cm^{-3})	5	0.1	10^{-4}	10^{10}
T (°K)	10^5	10^4	5×10^7	10^5-10^6
B (μG)	50	5	1	10^8
c_s (km/s)	50	15	1000	50-150
v_A (km/s)	40	30	180	2000
$\beta_p = P_g/P_B$	1.6	0.3 - 1	50 - 100	0.01
$\alpha_p = \omega_{pe}/\Omega_e$	140	200	30	3
u_s (km/s)	500	3000	2000	-
$M_s = u_s/c_s$	10	200	2-3	
$M_A = u_s/v_A$	13	100	20-30	

$$M_A \approx \beta_p^{1/2} M_s$$

ICM: IntraCluster Medium

$$\beta_p = \frac{P_{gas}}{P_B} \propto \frac{n_H T}{B^2}$$

$\theta_{\rm Bn}$: obliquity angle



$Q_{\parallel}$: $\theta_{\rm Bn} \leq 45°$

$Q_{\perp}$: $\theta_{\rm Bn} \geq 45°$

particle acceleration at collisionless shocks depend on M_s, M_A, $\theta_{\rm Bn}$, $\beta_{\rm p}$, $\alpha_{\rm p}$

Previous studies on collisionless shocks focus mainly on low β (<1) plasma (e.g. solar wind & ISM). Physics of weak shocks in β=100 ICM could be quite different (e.g. various microinstabilities).

Electron pre-acceleration in weak Q-perp shocks in high beta ICM cf. Guo et al. 2014a, 2014b

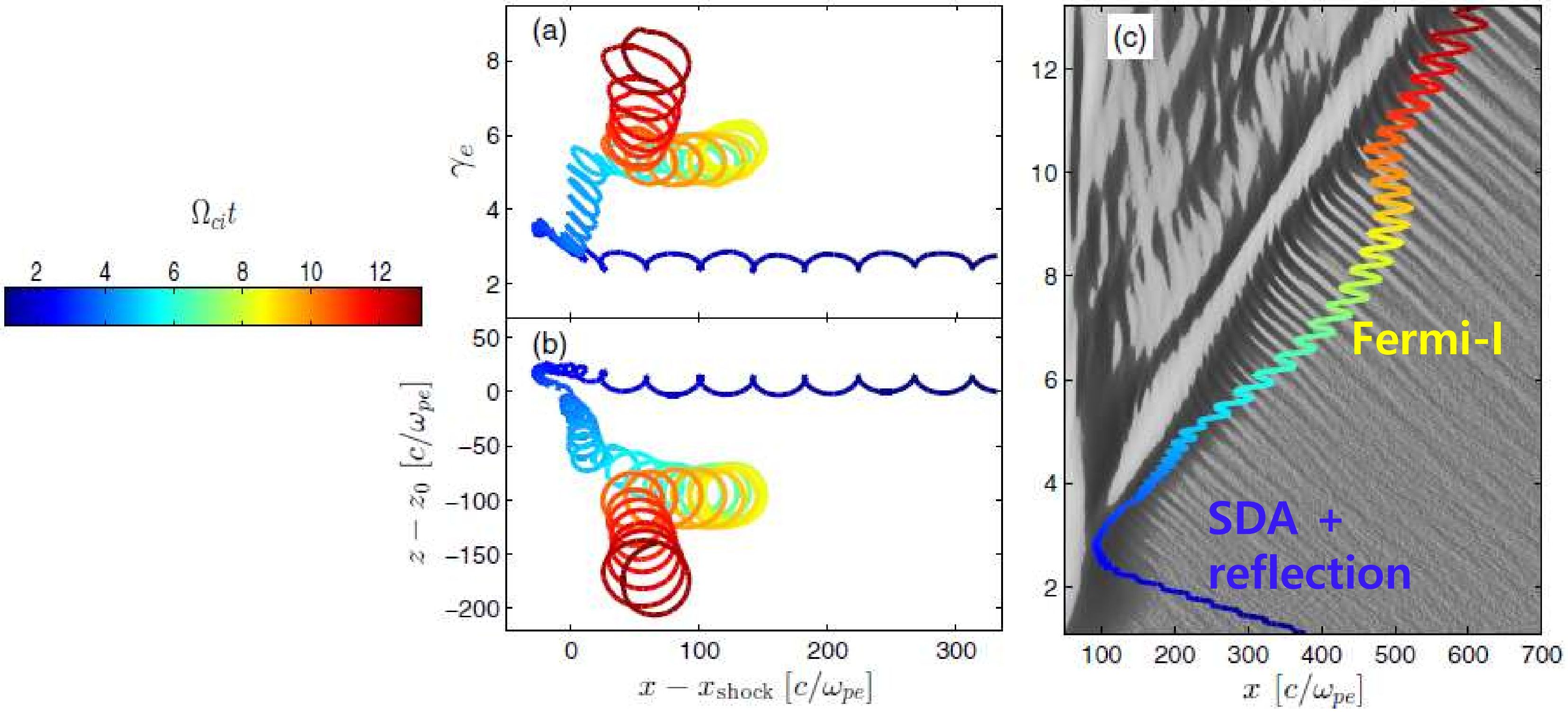
(1) **Reflection** by magnetic deflection (mirror) at the shock ramp

(2) **Shock Drift Acceleration (SDA) along the shock surface**

(3) **Temperature anisotropy** ($T_{e_\parallel} > T_{e\perp}$) due to backstreaming electrons

(4) Generation of waves via the Electron Firehose Instability (**EFI**)

(5) **Fermi-like acceleration** bwt the shock and upstream waves



Fermi-I

SDA + reflection

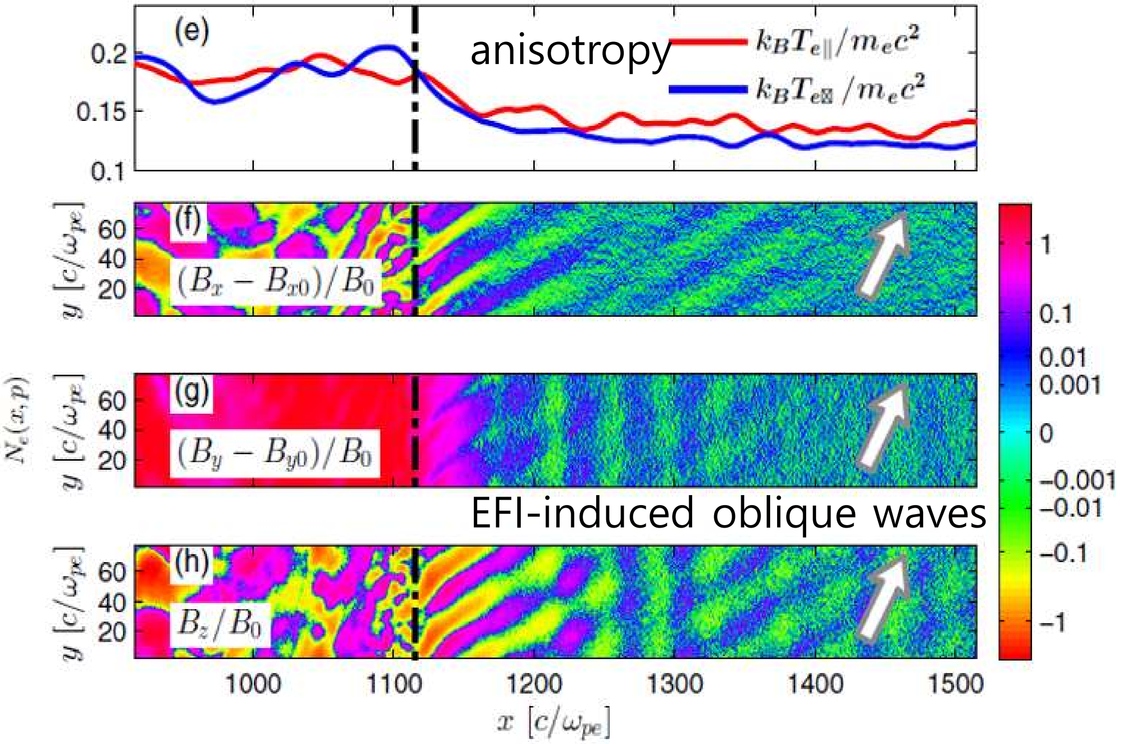
Electron pre-acceleration in weak ICM shock

Guo et al. 2014a, 2014b

2D PIC (TRISTAN-MP)

$$\frac{m_i}{m_e} = 100, \theta_{Bn} = 63^o, T = 10^9 K\ (86keV), M_s = 3\ (M_A \sim 12), \beta_p = 20$$

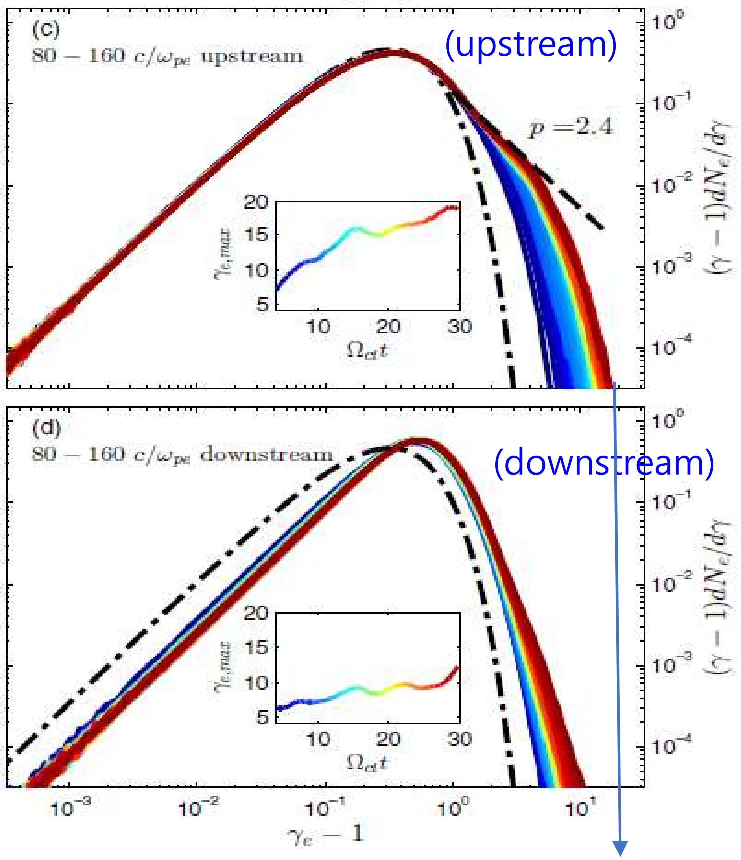
SDA+Fermi I



anisotropy

EFI-induced oblique waves

Electron Energy Spectra



(upstream)

(downstream)

$\gamma \sim 2$

- **Reflected electrons preferentially move along the upstream B**
- **EFI induced by electron T anisotropy.**
- **Upstream electrons are efficiently accelerated (SDA+Fermi-I process by upstream waves).**

2D PIC simulations for Q-pep shocks (electron acceleration)

Kang et al. 2019

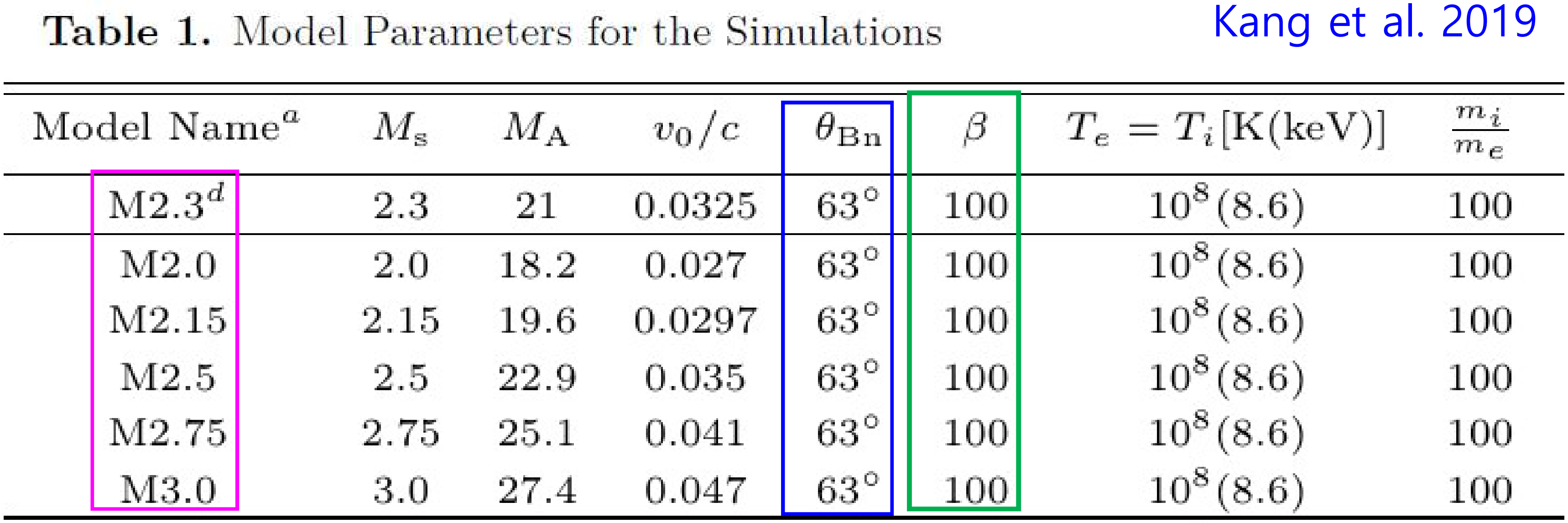


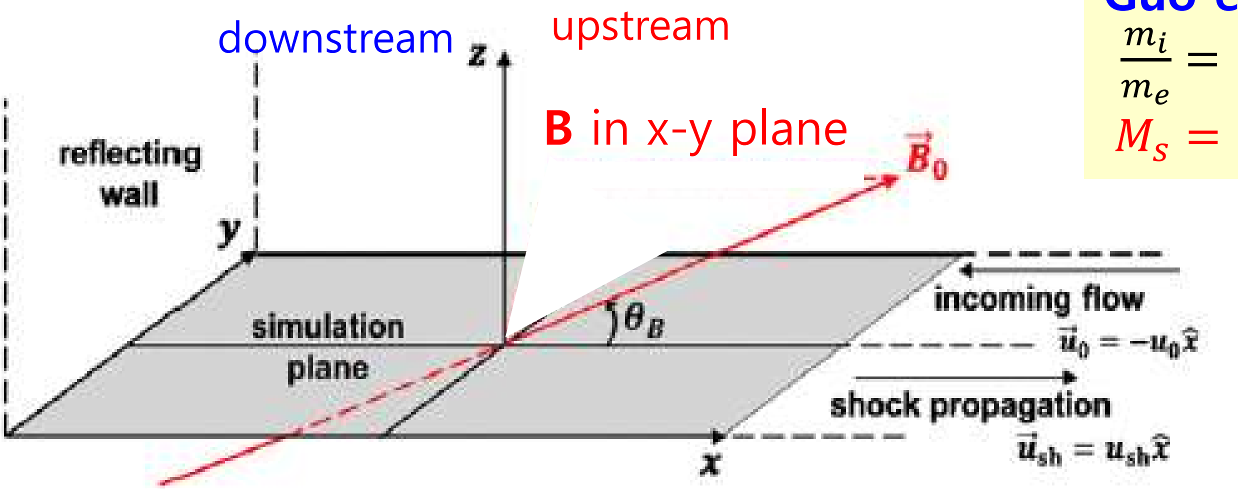
Table 1. Model Parameters for the Simulations

Model Name[a]	M_s	M_A	v_0/c	θ_{Bn}	β	$T_e = T_i$[K(keV)]	$\frac{m_i}{m_e}$
M2.3[d]	2.3	21	0.0325	63°	100	10^8(8.6)	100
M2.0	2.0	18.2	0.027	63°	100	10^8(8.6)	100
M2.15	2.15	19.6	0.0297	63°	100	10^8(8.6)	100
M2.5	2.5	22.9	0.035	63°	100	10^8(8.6)	100
M2.75	2.75	25.1	0.041	63°	100	10^8(8.6)	100
M3.0	3.0	27.4	0.047	63°	100	10^8(8.6)	100

Guo et al. 2014ab

$$\frac{m_i}{m_e} = 100, \theta_{Bn} = 63^o, T = 10^9 K,$$

$$M_s = 3\ (M_A \sim 12), \beta_p = 20$$



downstream

upstream

B in x-y plane

Figure 1. Simulation setup.

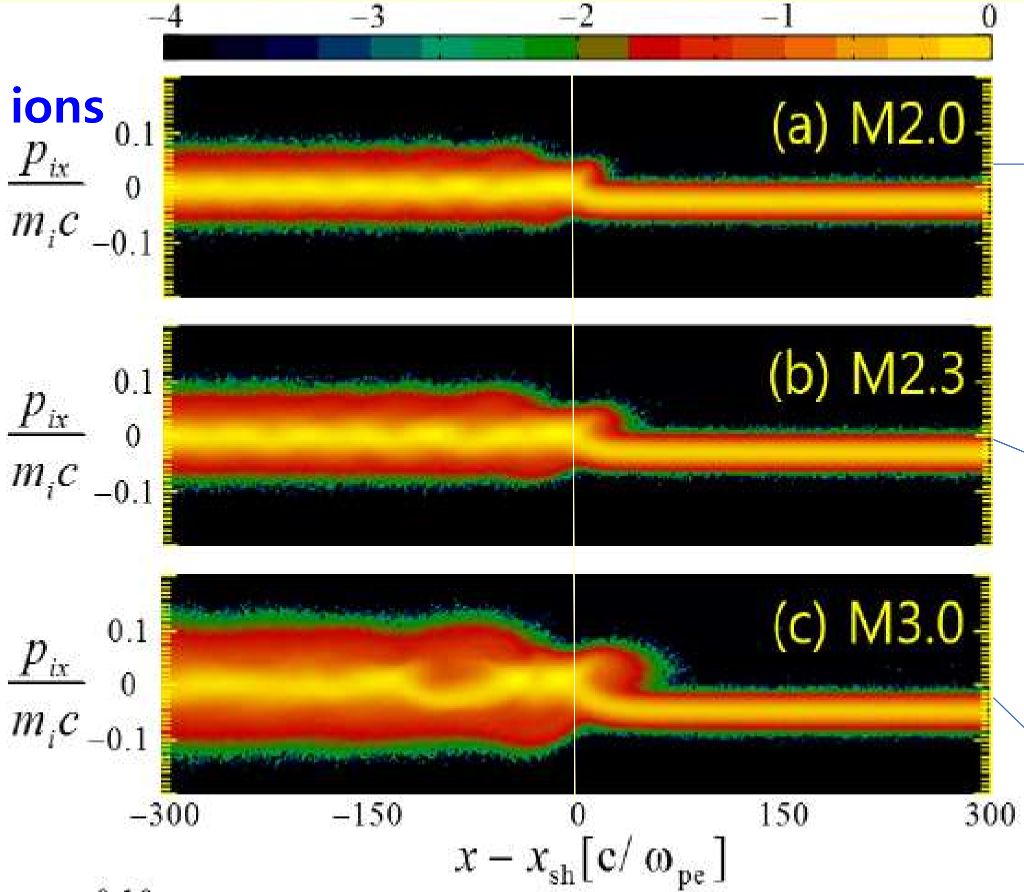
T = T$_i$ = T$_e$

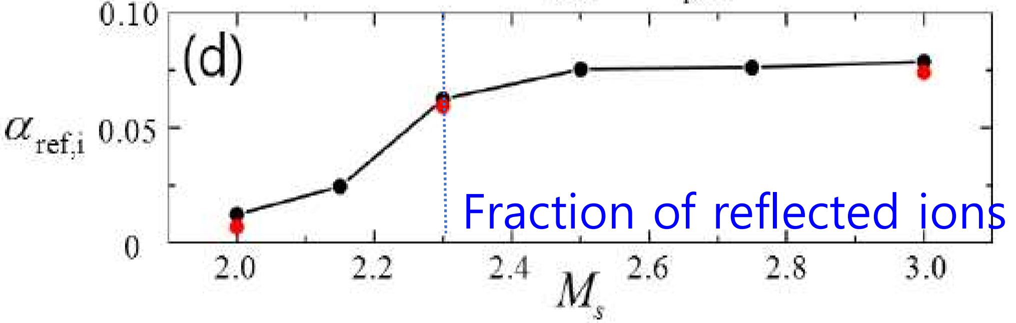
n = n$_i$ = n$_e$

$$\frac{m_i}{m_e} = 100$$

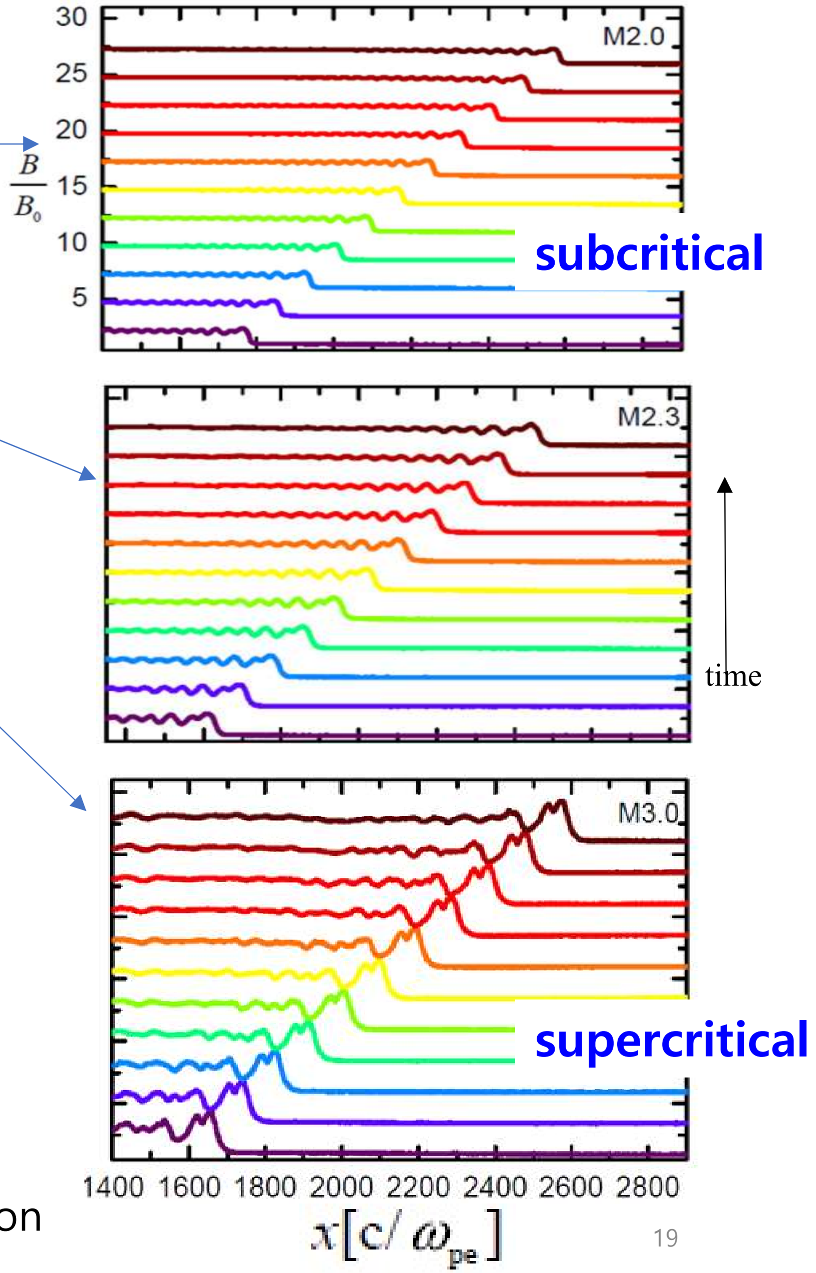
Shock structures governed by dynamics of reflected ions

ions





Fraction of reflected ions

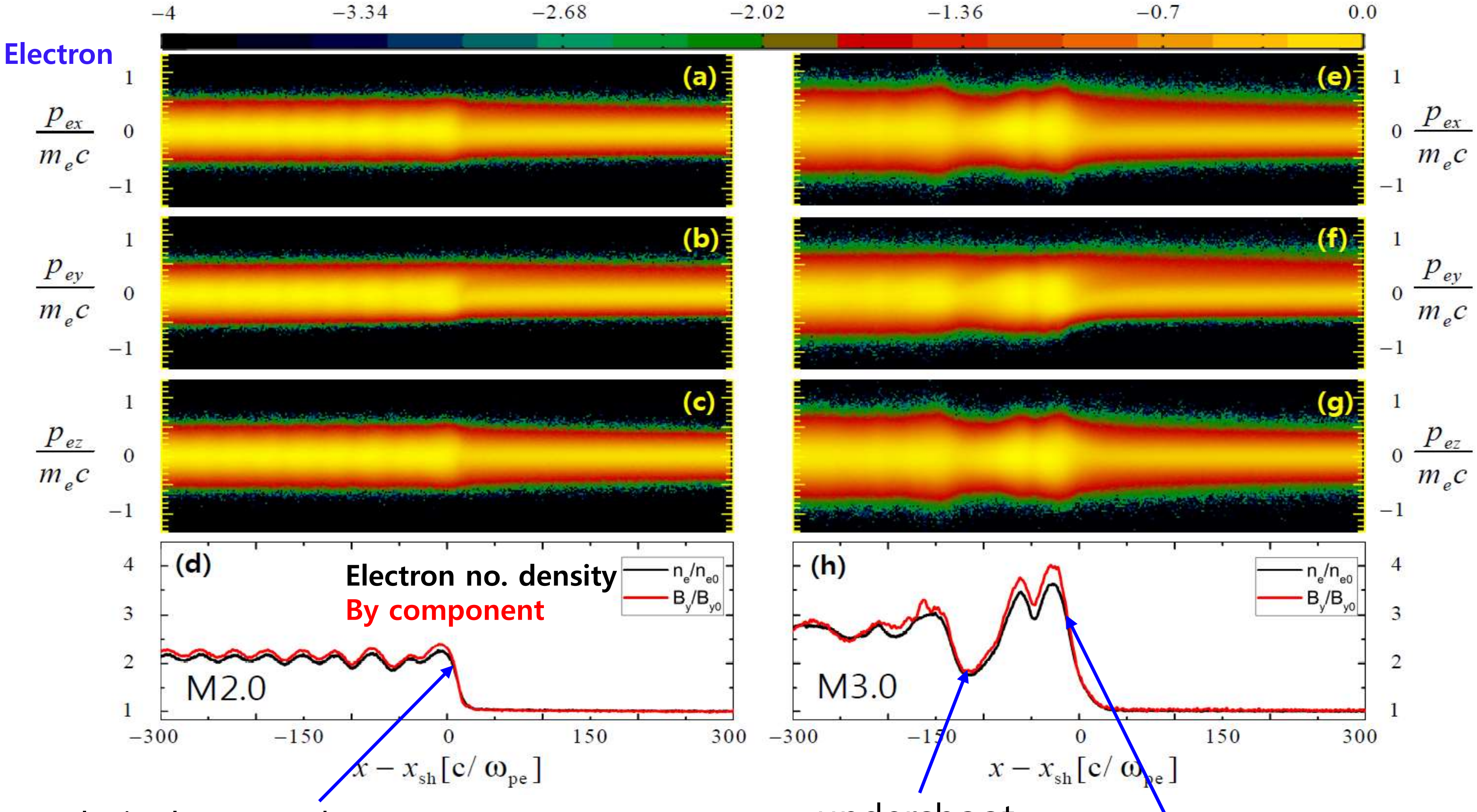


subcritical

supercritical

$M_f^* \sim 2.3$: First critical Mach number due to ion reflection

Ms = 2.0 (subcritical shock) **Ms = 3.0** (supercritical shock)



relatively smooth structure

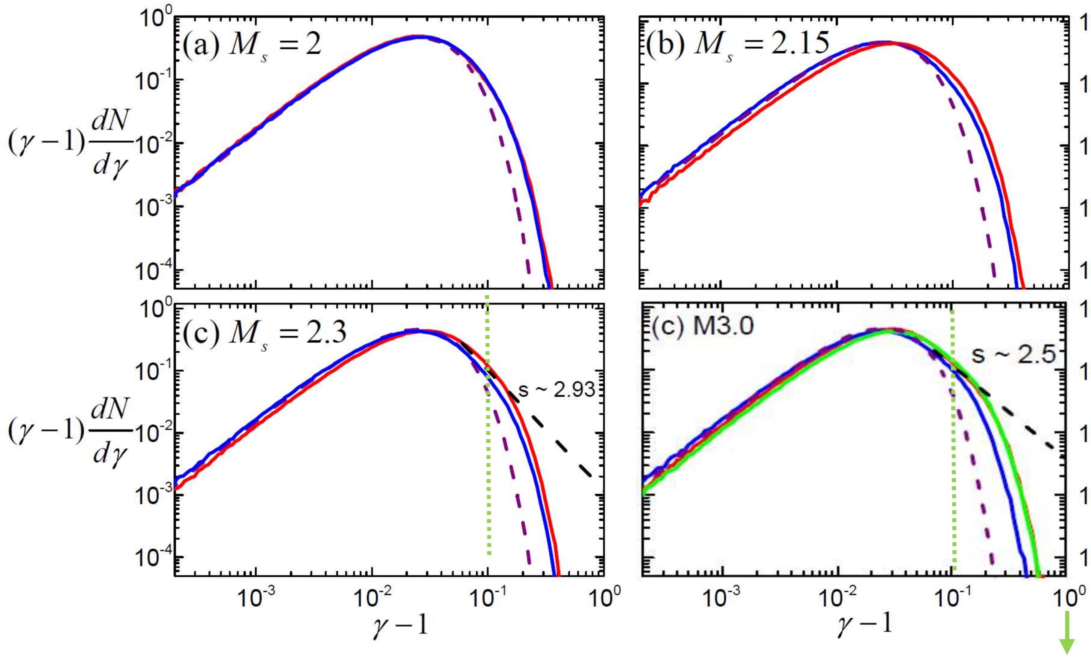
undershoot

overshoot

$M_f^* \sim 2.3$: First critical Mach number due to ion reflection

Evolution of upstream electron energy spectra

Blue: $\Omega_{ci}t = 10$, Red: $\Omega_{ci}t = 30$, Green: $\Omega_{ci}t = 60$



-Subcritical shocks: only SDA

-Supercritical shocks:

suprathermal tail via Fermi-like acceleration

-Pre-acceleration is saturated due to lack of power in longer λ

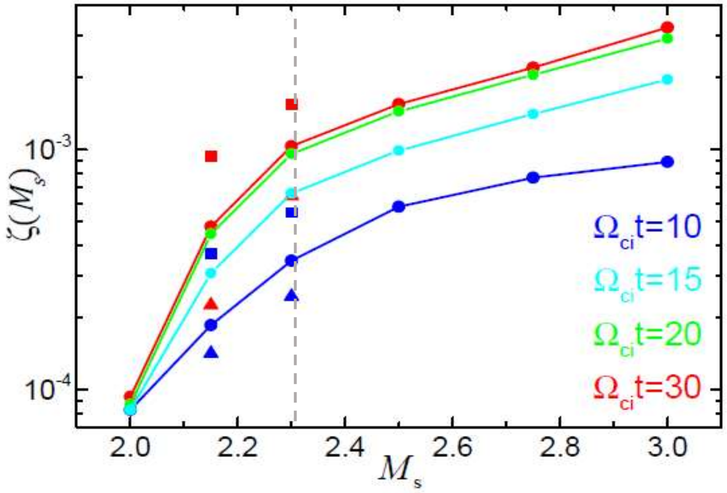
-Pre-acceleration may not go all the way to DSA

Suprathermal fraction

$$\zeta \equiv \frac{1}{n_2}\int_{p_{\rm spt}}^{p_{\rm max}} 4\pi \langle f(p,t)\rangle p^2 dp,$$

$p_{spt} \sim 3.3 p_{th,e}$: suprathermal

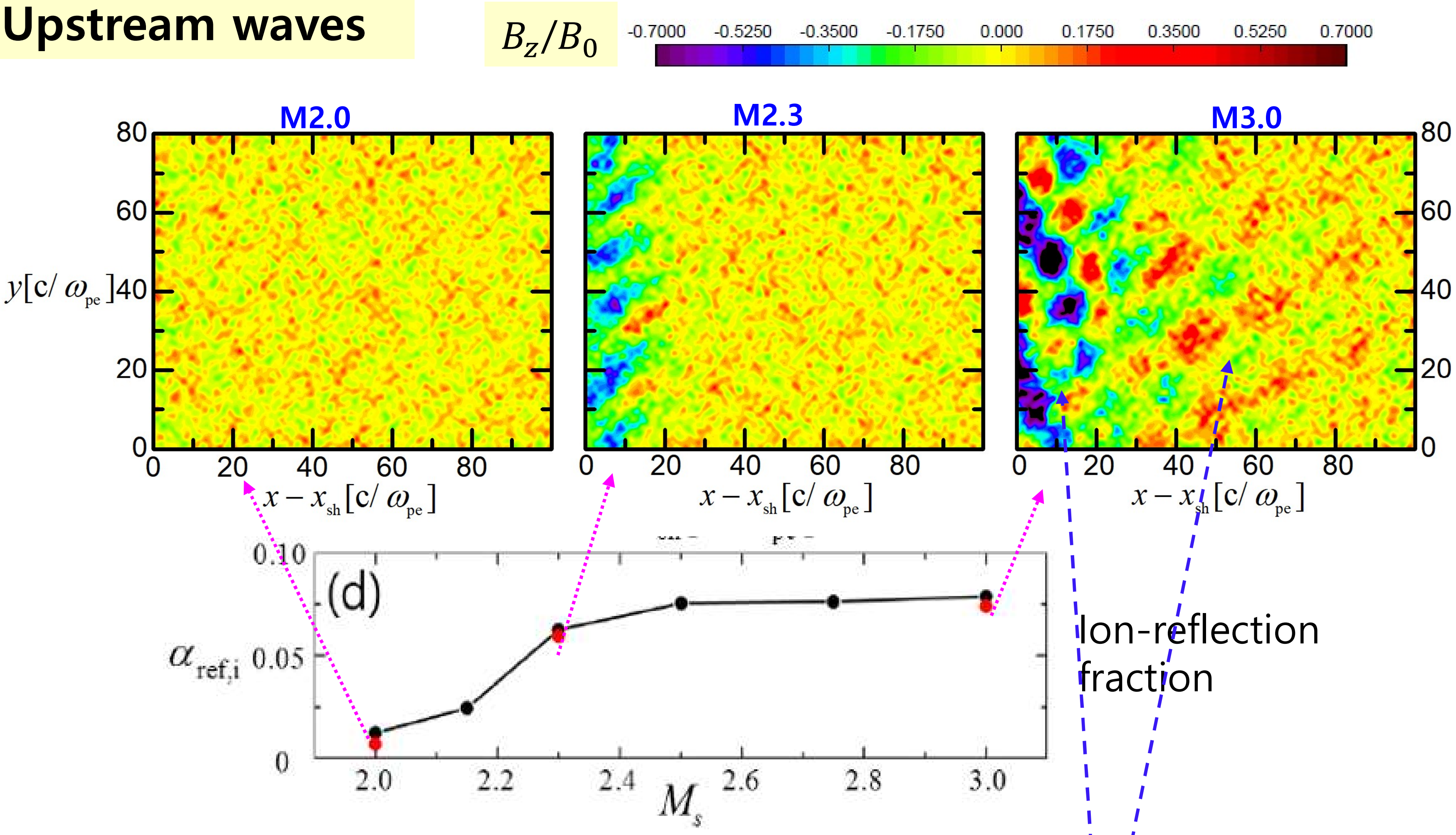
$p_{inj} \sim 3.3 p_{th,p}$: injection



- **suprathermal fraction increases with Ms**
- **saturates $\Omega_{ci}t>20$**

$M^*_{ef} \sim 2.3$

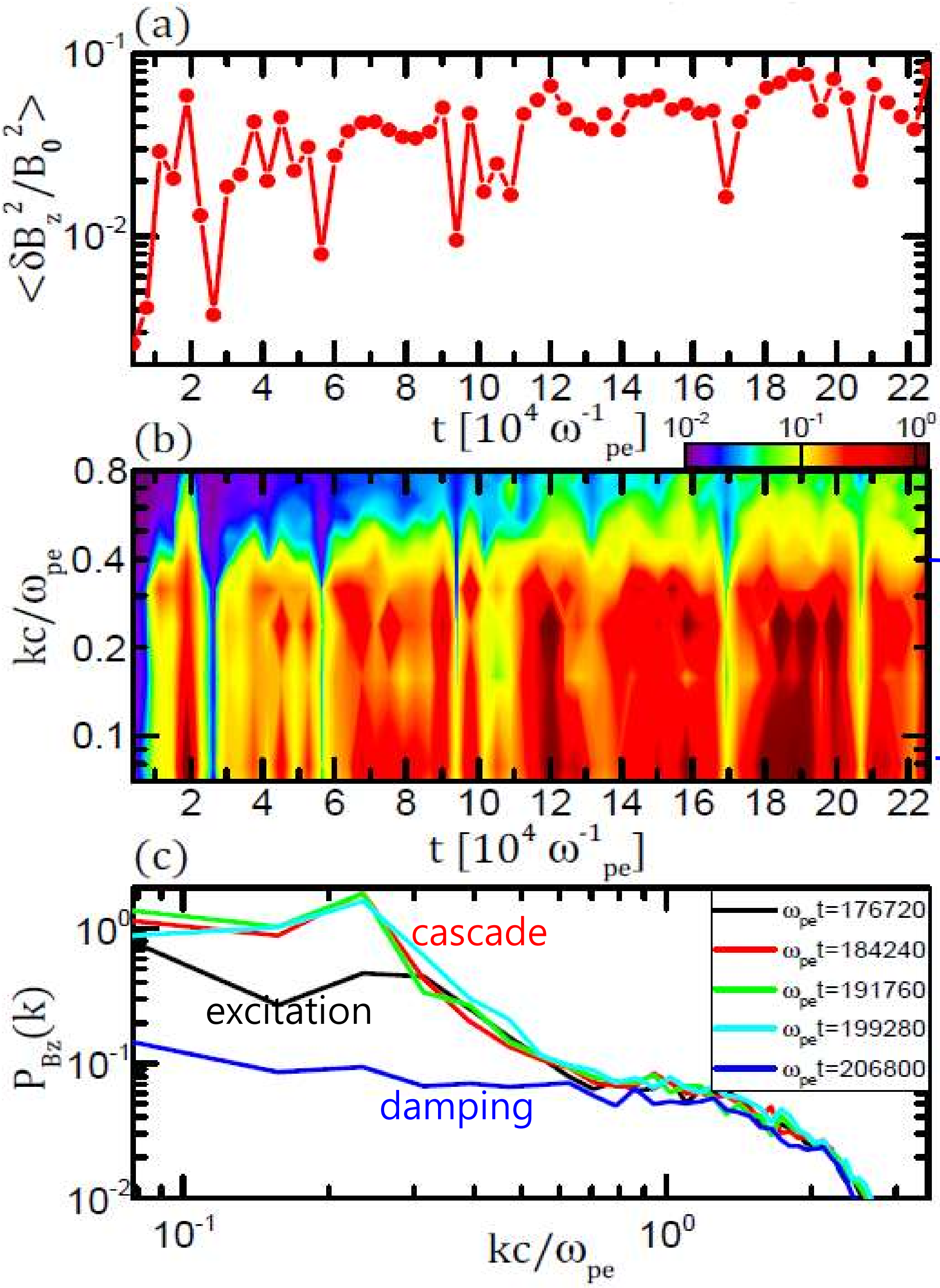
Upstream waves



Ion-reflection fraction

Three kinds of waves are expected:

1. phase-standing whistlers excited by reflected ions $kc/\omega_{pi} \sim 1$
2. Non-propagating $(\omega_r = 0)$ oblique waves by **EFI** $kc/\omega_{pe} \sim 0.4$
3. Propagating $(\omega_r \neq 0)$ oblique waves by **EFI : weak**



Quasi-periodic bursts of reflection:

$$t w_{\rm pe} \sim 2 \times 10^4 - 4 \times 10^4$$
$$t\Omega_{\rm ce} \sim 500 - 1000$$
$$t\Omega_{\rm ci} \sim 5 - 10$$

EFI-induced oblique waves

$$kc/\omega_{\rm pe} \sim 0.4$$

Whistlers induced by reflected ions $kc/\omega_{\rm pi} \sim 1$

Burst of reflection
→ Growth of T anisotropy
→ Excitation of the EFI
→ Growth of oblique waves
→ Inverse cascade to small k
→ Damping of waves

Summary

1. Radio relics observed in merging galaxy clusters are interpreted as quasi-perpendicular shocks with $M_s \sim 2-3$.

2. 2D PIC simulations to study electron pre-acceleration at weak Q-perp shocks by Shock Drift Acceleration (SDA) and Fermi-like acceleration due to upstream waves excited by the electron firehose instability (EFI)

3. First critical Mach number due to ion reflection: $M_f^* \sim 2.3$
   EFI critical Mach number for electron pre-acceleration: $M_{ef}^* \sim 2.3$
   Ion-reflection governs shock structure and affects electron-reflection

4. Pre-acceleration due to EFI may not be sufficient for electron to be injected to DSA, because the wave power at larger λ is small.