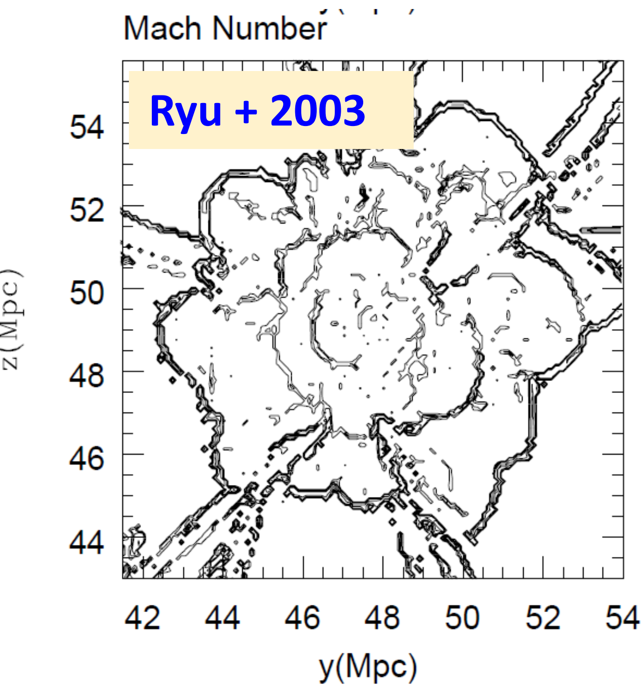
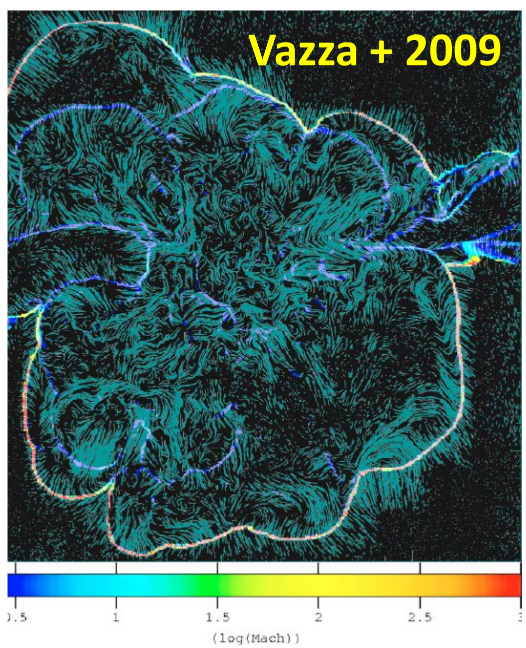
Particle Acceleration at Structure Formation Shocks

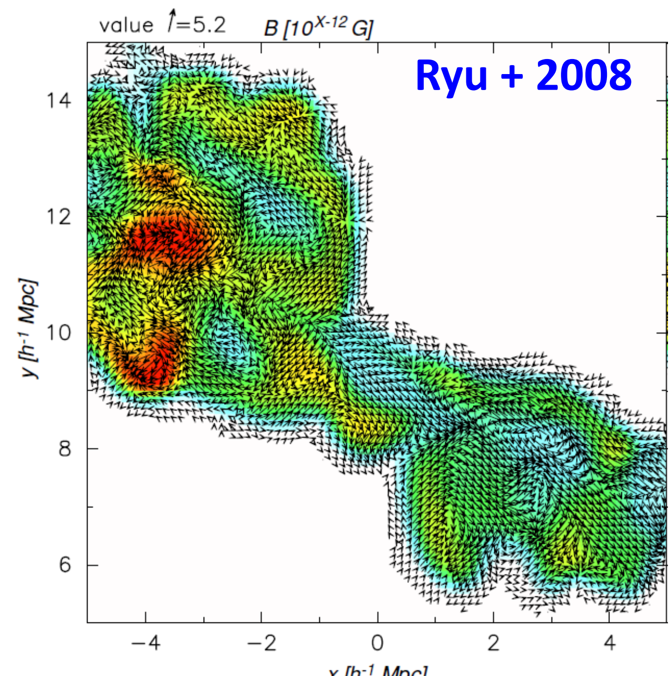
Hyesung Kang (Pusan National University)
Dongsu Ryu (UNIST, Korea)
T. W. Jones (Univ. of Minnesota)



Shocks



Turbulence



Magnetic Fields

Size limited E_{max} for acceleration sites: Hillas Diagram

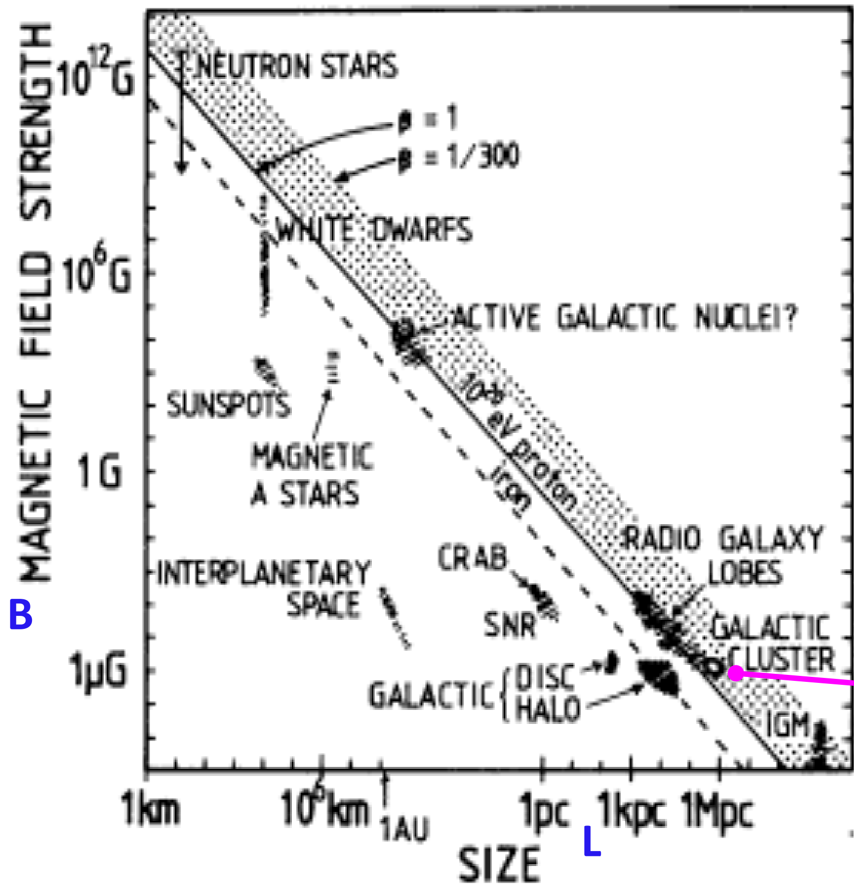


Figure 1 Size and magnetic field strength of possible sites of particle acceleration. Objects below the diagonal line cannot accelerate protons to 10^{20} eV.

THE ORIGIN OF ULTRA-HIGH-ENERGY COSMIC RAYS

A. M. Hillas **ARAA 1984**

$$B_{\mu G} L_{pc} > \frac{E_{15}}{Z\beta_a}$$

$$\beta_a = V_a / c$$

galaxy clusters :

$$B \sim 1\mu\text{G}, \quad L \sim 100\text{kpc}$$

$$\beta \sim 0.01, \quad E_{max} \sim 10^{18}\ \text{eV}$$

Bow shocks of galaxies in ICM, rather than structure formation shocks such as accretion shocks.

THE ORIGIN OF COSMIC RAYS ABOVE $10^{18.5}$ eV

COLIN A. NORMAN,[1,2,3] DONALD B. MELROSE,[3] AND ABRAHAM ACHTERBERG[4]

Received 1994 August 8; accepted 1995 June 1

MAXIMUM ENERGIES

Norman et al. 1995

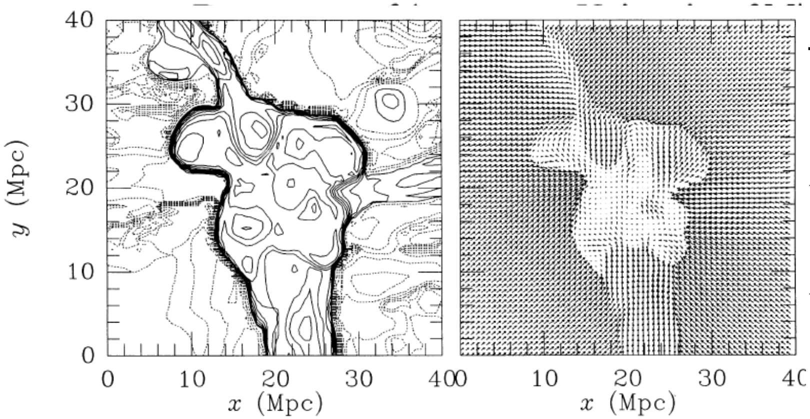
Source	E_m	D_{max}	$\langle n \rangle D^3_{max}$
AGN	10^{16} eV	~3 Gpc	10^5
Jets	10^{20} eV	200 Mpc	~10
Cocoons	5×10^{19} eV	500 Mpc	~100
Clusters	10^{19} eV	1 Gpc	~10^4
Superclusters	5×10^{19} eV	500 Mpc	~100

Cosmic shocks, formed as structure develops in the gravitational collapse of primordial perturbations as seen in the standard cosmological models such as in pancake-like structures, and in the collisions of hierarchical merging subunits, are also possible sites for the UHECR acceleration up to $10^{19.5}$ eV, provided there is a primordial field of $\gtrsim 10^{-9}$ G or if microgauss fields can be self-generated in shocks.

CLUSTER ACCRETION SHOCKS AS POSSIBLE ACCELERATION SITES FOR ULTRA–HIGH-ENERGY PROTONS BELOW THE GREISEN CUTOFF

HYESUNG KANG
Department of Earth Sciences, Pusan National University, Pusan 609-735, Korea; kang@astrophys.es.pusan.ac.kr
DONGSU RYU
Department of Astronomy & Space Science, Chungnam National University, Daejeon 305-764, Korea; ryu@sirius.chungnam.ac.kr
AND
T. W. JONES

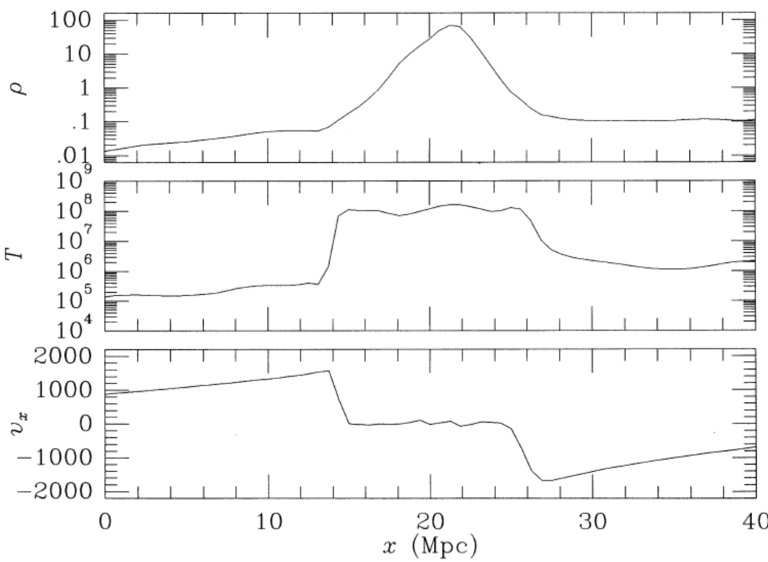
Kang, Ryu & Jones 1996



for $\kappa_{Bohm}(p) = \kappa^* \cdot p \cdot (\frac{\rho_0}{\rho})$

$\tau_{acc}(p) \approx \frac{3}{u_1 - u_2}(\frac{\kappa_1(p)}{u_1} + \frac{\kappa_2(p)}{u_2})$: mean accel. time for DSA

$\tau_{pp} \sim 5 \times 10^9$ years: photo-pair loss time at 10^{19} eV



$\tau_{acc} \sim \tau_{pp} \Rightarrow$ $$p_{\max} \simeq \frac{E_{\max}}{m_p c^2} \simeq 1.4 \times 10^{10} \left(\frac{u_s}{1500 \text{ km s}^{-1}}\right)^2 B_\mu$$

Accretion shocks, proton acceleration

for $u_s = 3000$ km/s, $B = 1\mu$G

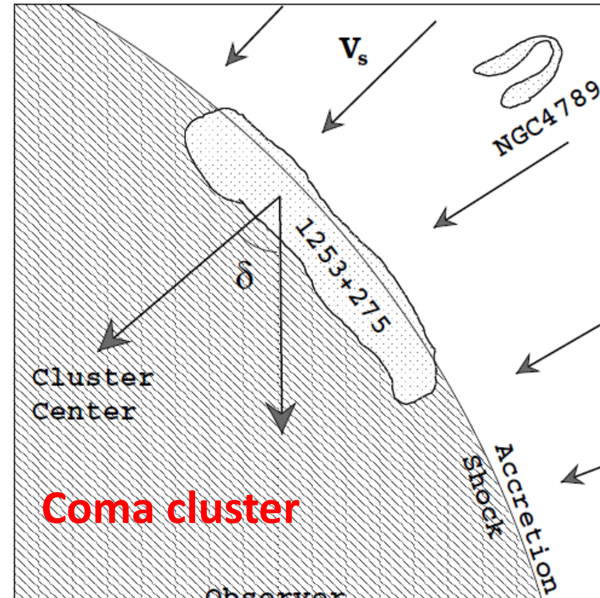
$E_{\max} \sim 6 \times 10^{19}$ eV

Cluster radio relics as a tracer of shock waves of the large-scale structure formation

Ensslin et al. 1998

Torsten A. Enßlin[1], Peter L. Biermann[1], Ulrich Klein[2], and Sven Kohle[2]

Observational evidence for structure formation shocks =radio relics : diffuse synchrotron emission from re-energized fossil electrons by accretion shock in the cluster outskirts.



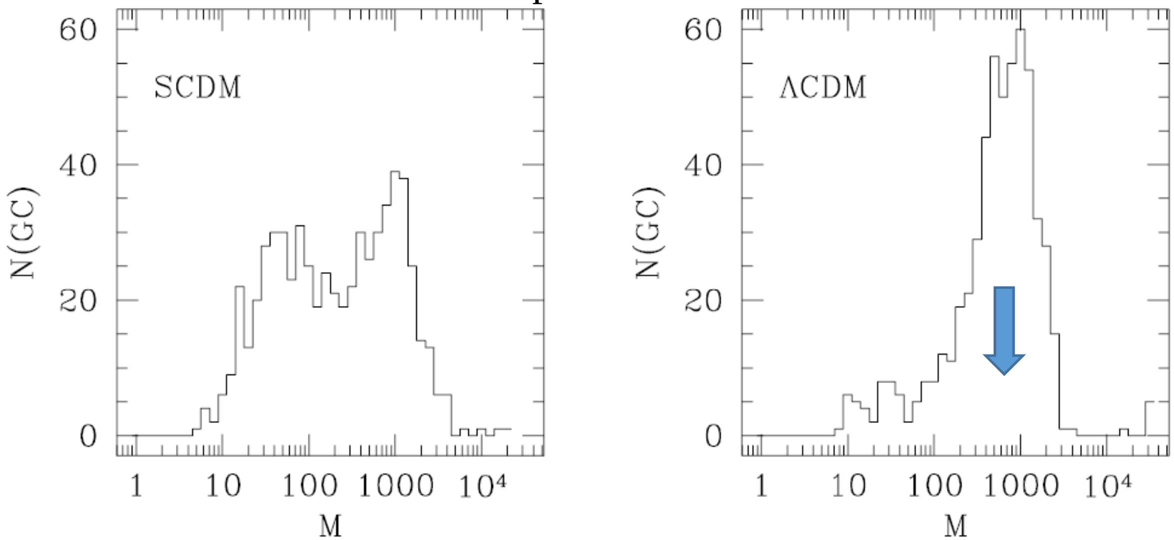
Cluster Relic		References	A85 0038-096	A786 0917+75	A1367 1140+203	Coma 1253+275	A2255 1712+64	A2256 1706+78	A3667 2006-56	S753 1401-33
z		fovffffn	0.0559	0.125	0.0216	0.0233	0.0824	0.0824	0.0566	0.0142
$kT_{\rm obs}$	keV	e–dbddrf	6.2	—	3.7	8.2	7.3	7.3	6.3	$2.5^{(6)}$
$n_{\rm e,o}$	$10^{-3}\,{\rm cm}^{-3}\,h_{50}^{1/2}$	p–pbhpr–	5.5	—	0.95	3	1.8	2.5	1	—
$r_{\rm core}$	kpc h_{50}^{-1}	p–pbhar–	225	—	430	400	579	352	286	—
β		e–pbhar–	0.62	—	0.52	0.75	0.74	0.76	0.54	—
$r_{\rm projected}$	Mpc h_{50}^{-1}	soilhtmn	0.64	5	1.09	2.9	1.25	0.74	2.95	0.911
α		gojlhtun	$>1.5^{(1)}$	1.1	1.9	1.18	1.4	$0.8^{(2)}$	1.1	1.4
P	%	–ol–ht—	—	54	—	27	<2	20	—	—
$B_{2,\rm eq}$	μG $h_{50}^{2/7}$	gojlhtmn	<1.4	0.5	2	0.7	0.6	2.7	1.6	0.4

PROPERTIES OF COSMIC SHOCK WAVES IN LARGE-SCALE STRUCTURE FORMATION

FRANCESCO MINIATI,[1] DONGSU RYU,[2] HYESUNG KANG,[3] T. W. JONES,[1] RENYUE CEN,[4] AND JEREMIAH P. OSTRIKER[4]

Miniati et al. 2000

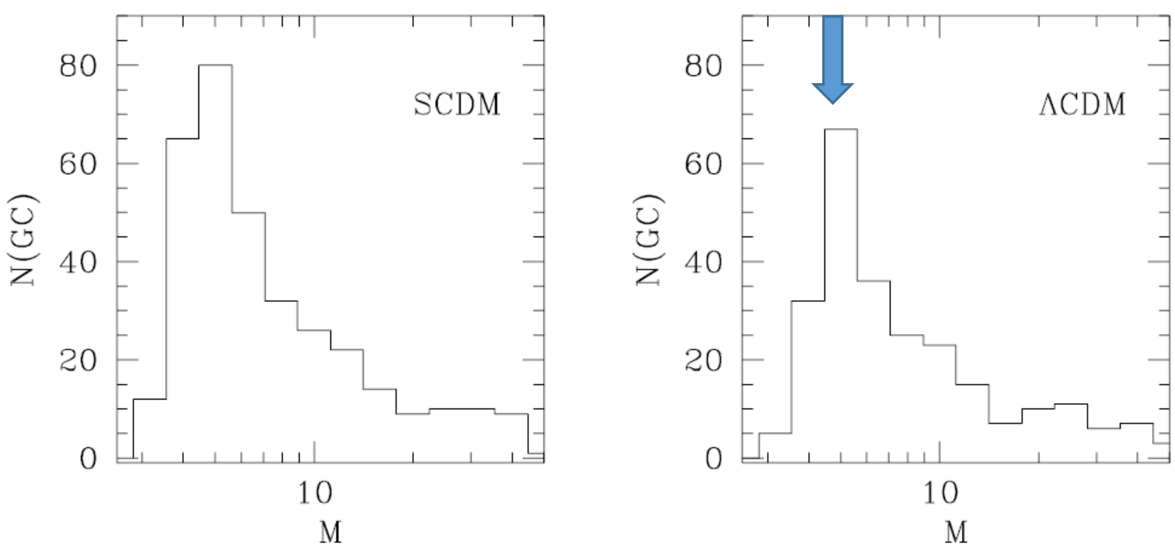
External shocks: $r > 0.5h^{-1}\mathrm{Mpc}$



External shocks = accretion shocks with high Mach numbers

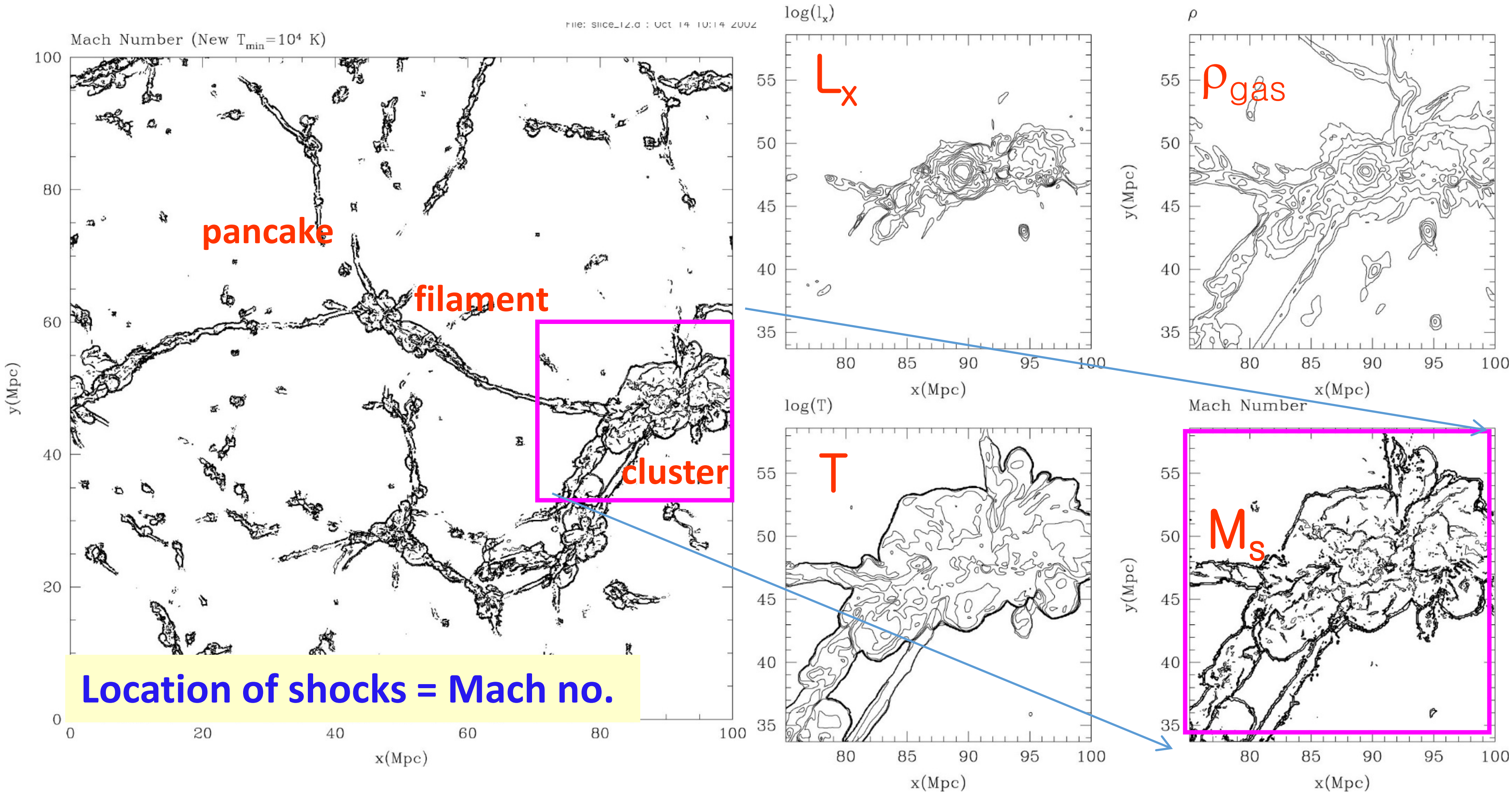
Possible acceleration sites for UHECRs

Internal shocks: $r < 0.5h^{-1}\mathrm{Mpc}$



Internal shocks = merger shocks, flow shocks with low Mach numbers

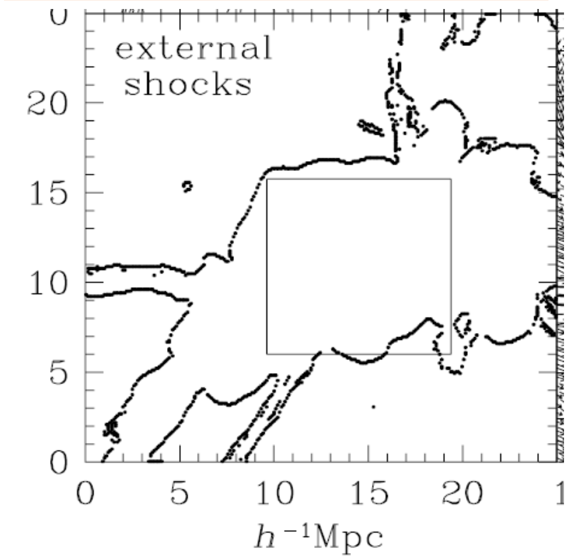
Shocks in Structure Formation Simulations



Miniati et al. 2000; Keshet et al. 2003; Ryu et al. 2003; Pfrommer et al. 2006; Kang et al. 2007; Skillman et al. 2008; Hoeft et al. 2008; Vazza et al. 2009; Pinzke et al. 2013; + many Later papers by these authors and others

Shocks in Structure Formation Simulations (Ryu et al 2003)

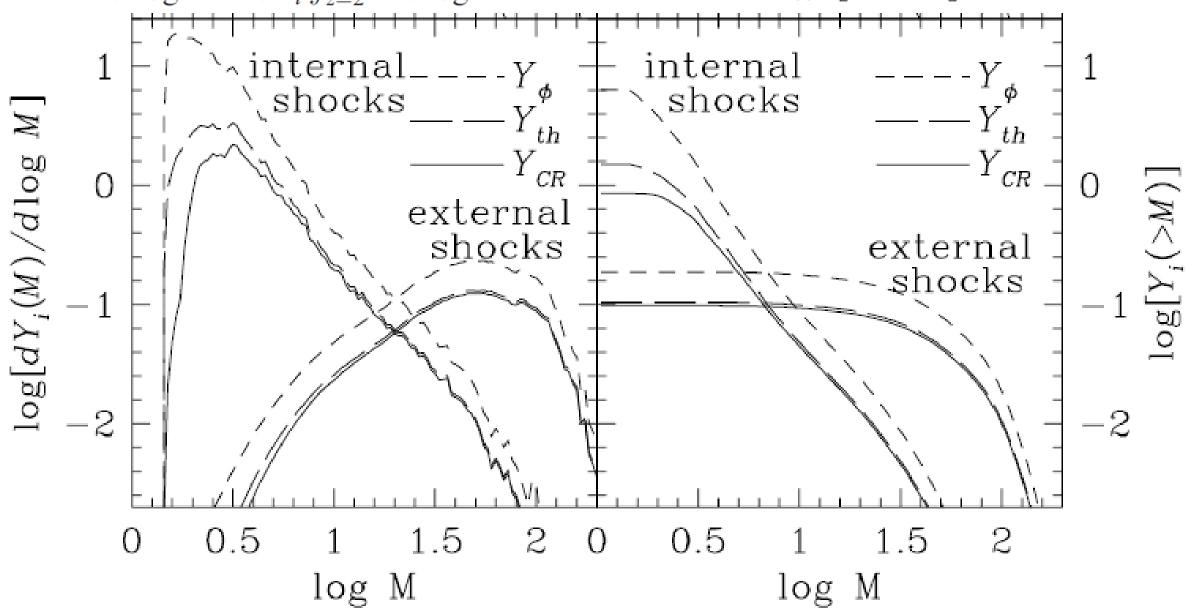
Accretion Shocks



At **Strong accretion shocks** with Vs~1000-3000 km/s M~10-100 DSA efficiency could be high as in SNRs.

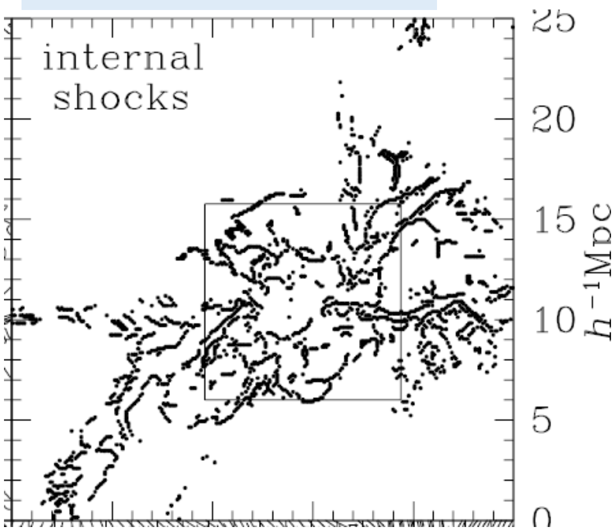
Energy generation function: $Y_i(M)$

$$\frac{dY_i(M)}{d\log M} = \frac{1}{\mathcal{N}_i}\int_{z=2}^{z=0} \frac{dF_i(M,\ z)}{d\log M}\,dt \qquad Y_i(>M) = \int_{\infty}^{M}\left[\frac{dY_i(M)}{d\log M}\right] d\log M$$



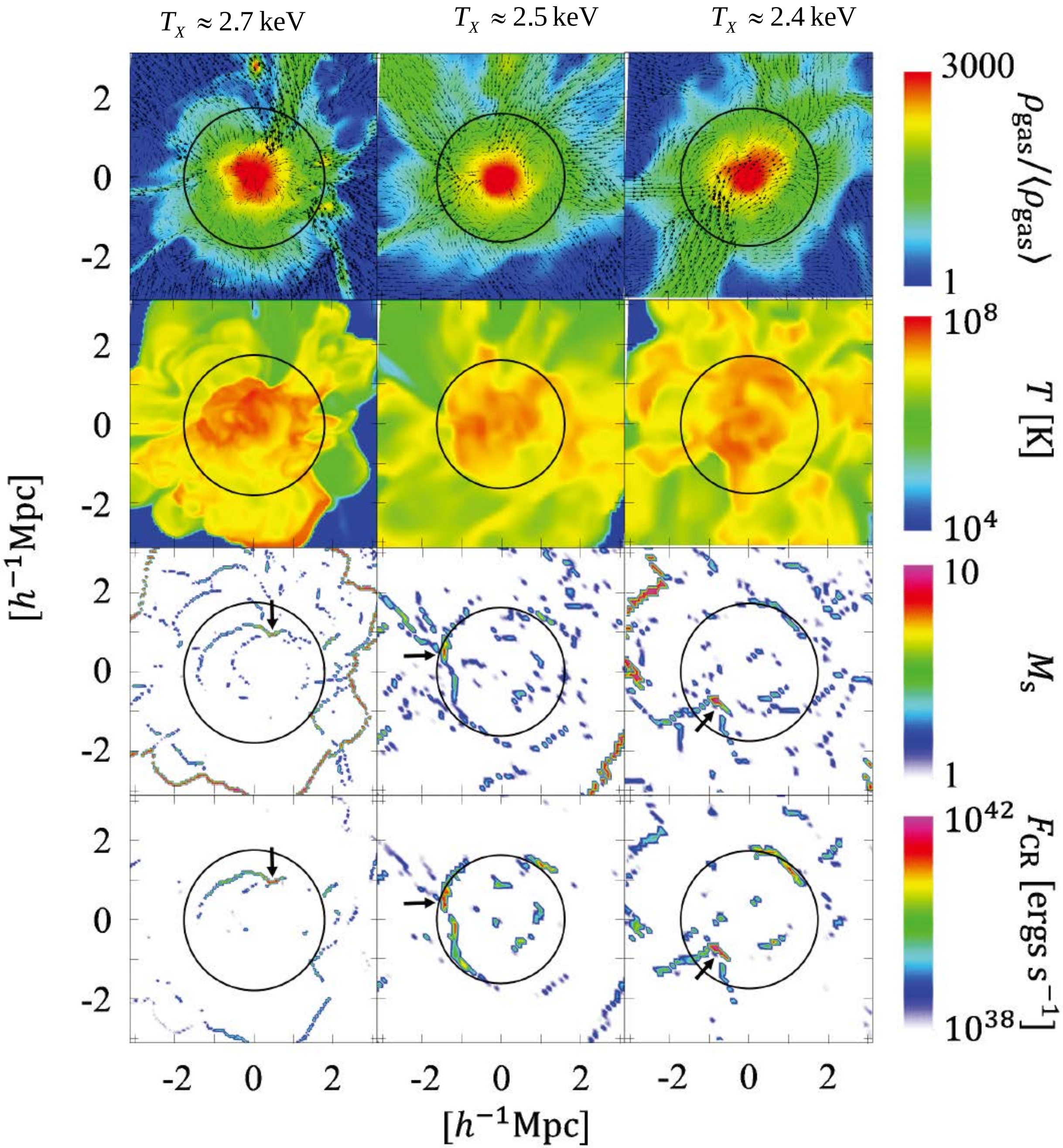
ϕ = kinetic energy, th = thermal energy, CR = cosmic ray energy

Shocks in ICM



Weak internal shocks with M<3 are dominant inside ICM and energetically important.

Shock Waves in the Outskirts of simulated clusters: filament accretion



- infalls of high ρ, low T filament gas
- penetrate deep in to ICM

Energetic Accretion Shocks

- $3 < M_s < 10$

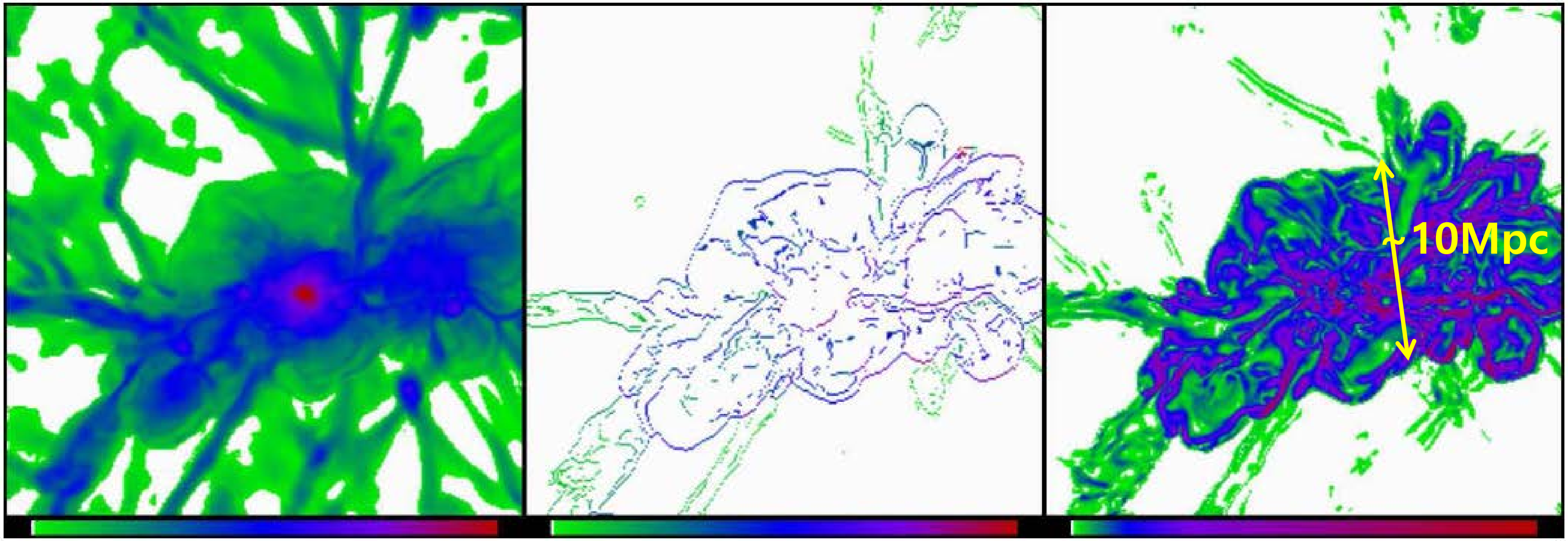
- Thin elongated arc-like morphology similar to radio relics.
- Mach number varies along the connected shocked zones.

$$-\ f_{CR} > 10^{42}\ \text{erg/s/}(h^{-1}\text{Mpc})^2$$

Hong, Ryu, Kang 2014

B fields in LSS

gravitational collapse → cosmological shocks → vorticy & turbulence → B field amplification via turbulence dynamo



gas density $(25h^{-1}\text{Mpc})^2$

shock locations: color coded with V_{shock}

vorticity

Ryu et al 2008

-Λ **cold dark matter cosmology**

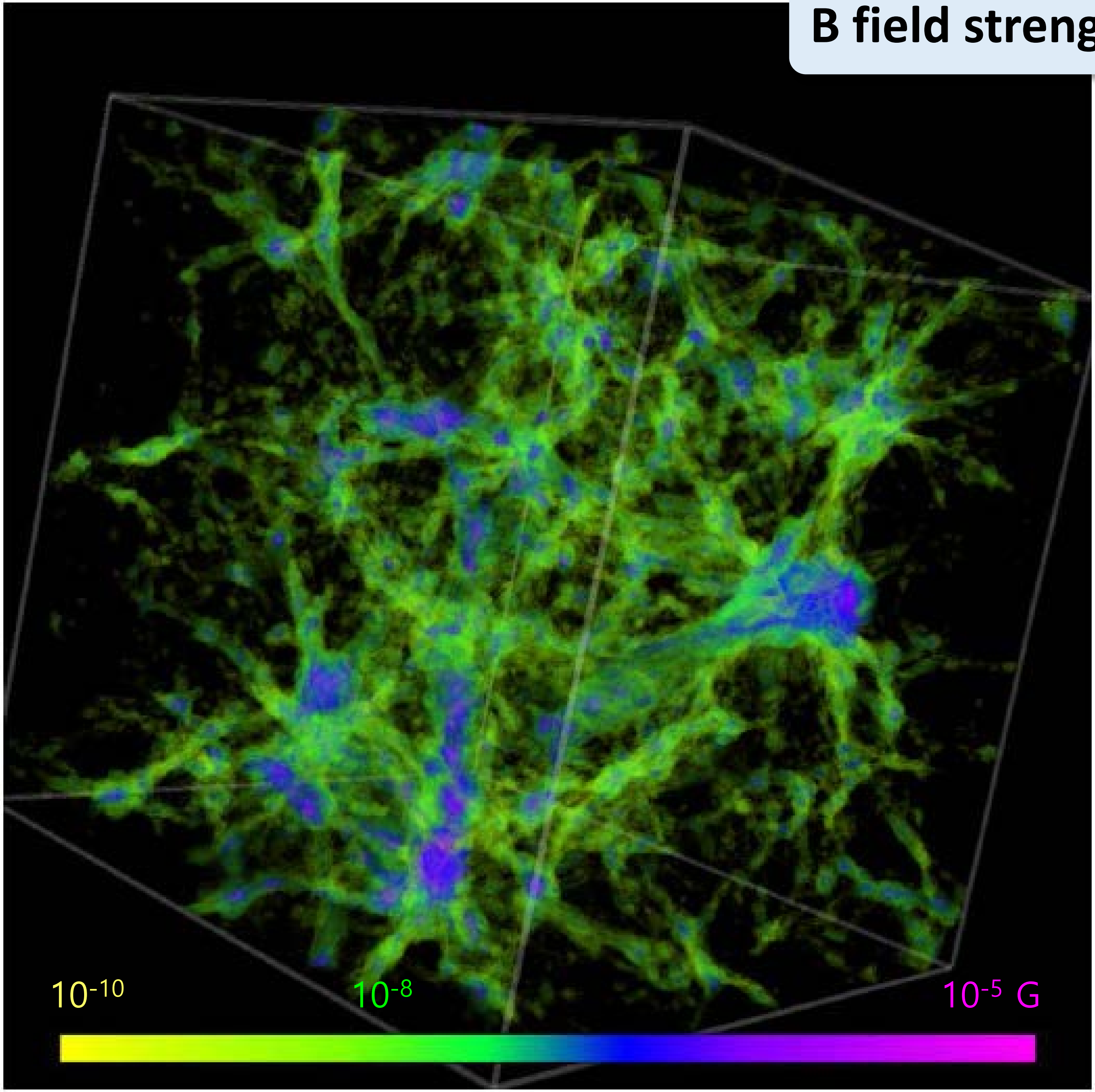
$\Omega_\Lambda = 0.73$, $\Omega_{DM} = 0.23$, $\Omega_{gas} = 0.043$, $h=0.7$, $n = 1$, $\sigma_8 = 0.8$

-computational box: (143 Mpc)^3 : grid-based Eulerian TVD code: Hydrodynamic Sim

With passively evolving B field: B=0 initially, generated at shocks via Biermann Battery and amplified by flow motions

Magnitude of B based on turbulence dynamo: vorticity & E_{turb} → E_B

B field strength in the cosmic web



Color code:

Blue: clusters, 1μG

Green: filaments, 10nG

at each grid point

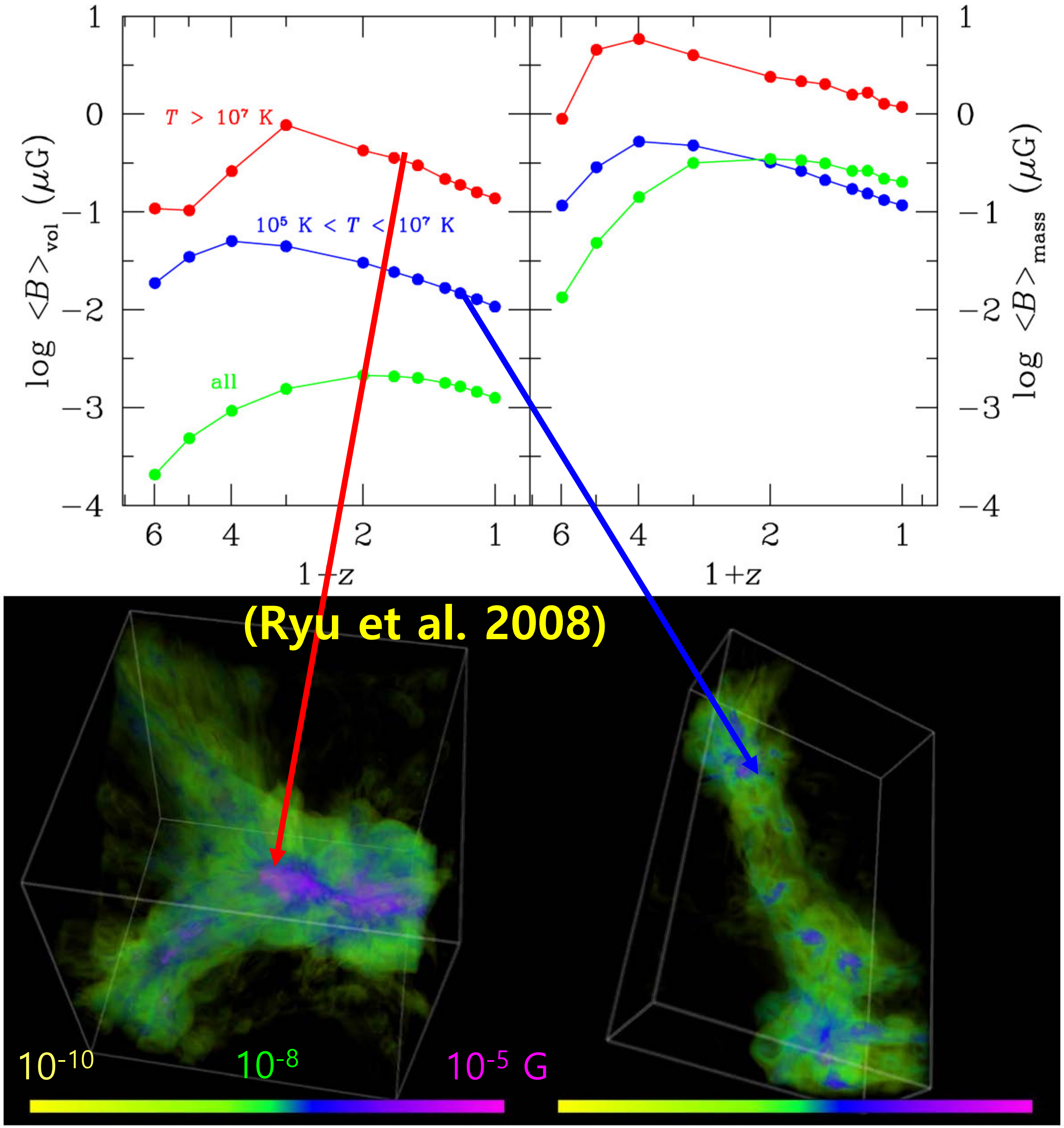
$$\vec{\omega} = \vec{\nabla} \times \vec{\upsilon}$$

$$E_{turb} = \frac{1}{2} \rho \ \upsilon_{curl}^2$$

$$\Rightarrow E_{mag} = \phi(\omega t) \cdot E_{turb}$$

$$= \frac{B^2}{8\pi}$$

Ryu et al 2008



magnetic field strength via turbulent dynamo

-in & around clusters :

$<B>_{vol} \sim 0.1\ \mu G$

-in filaments:

$<B>_{vol} \sim 10\ nG$

Many studies since then:

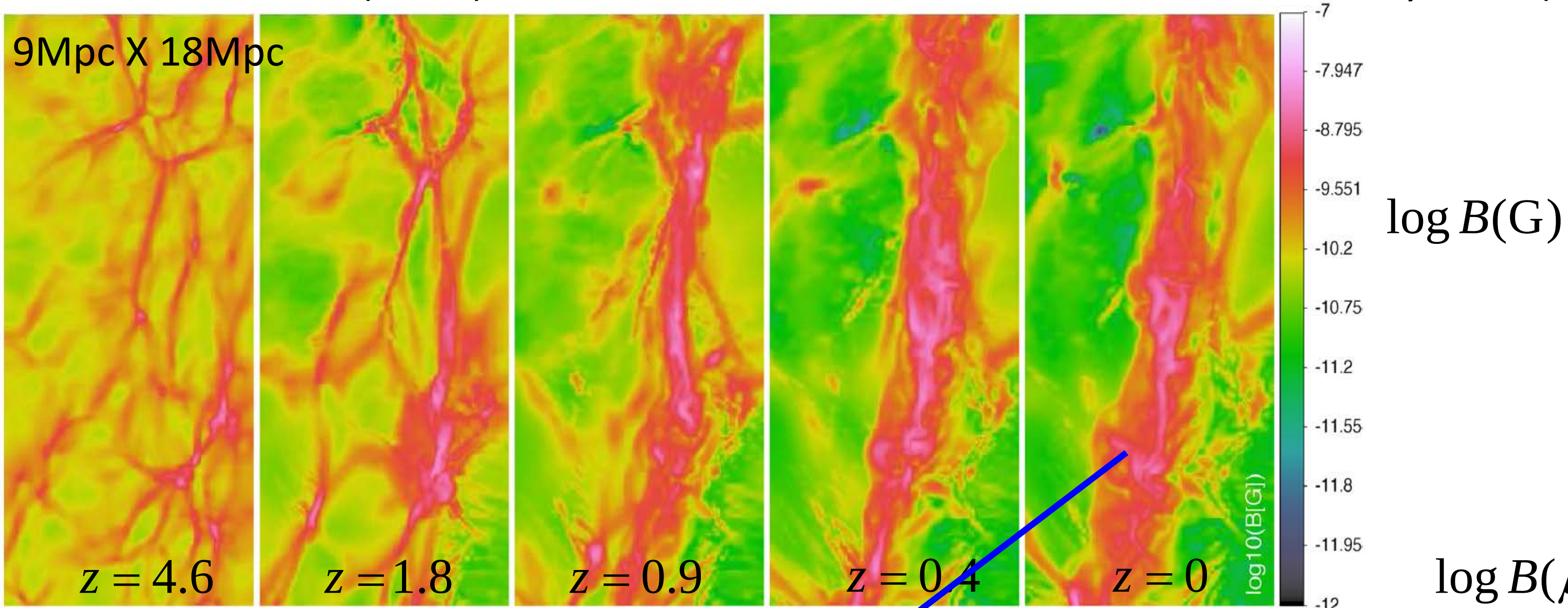
Vazza et al 2011 - 2016

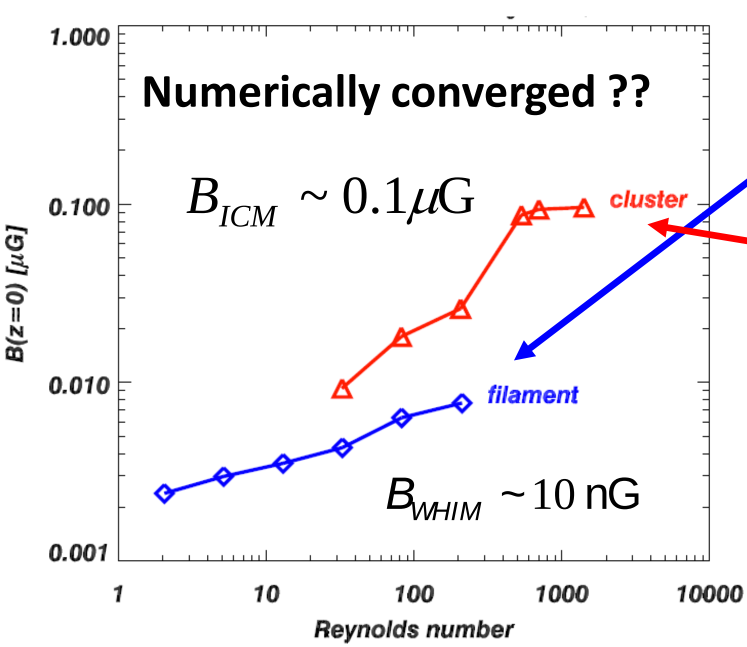
Cho 2014

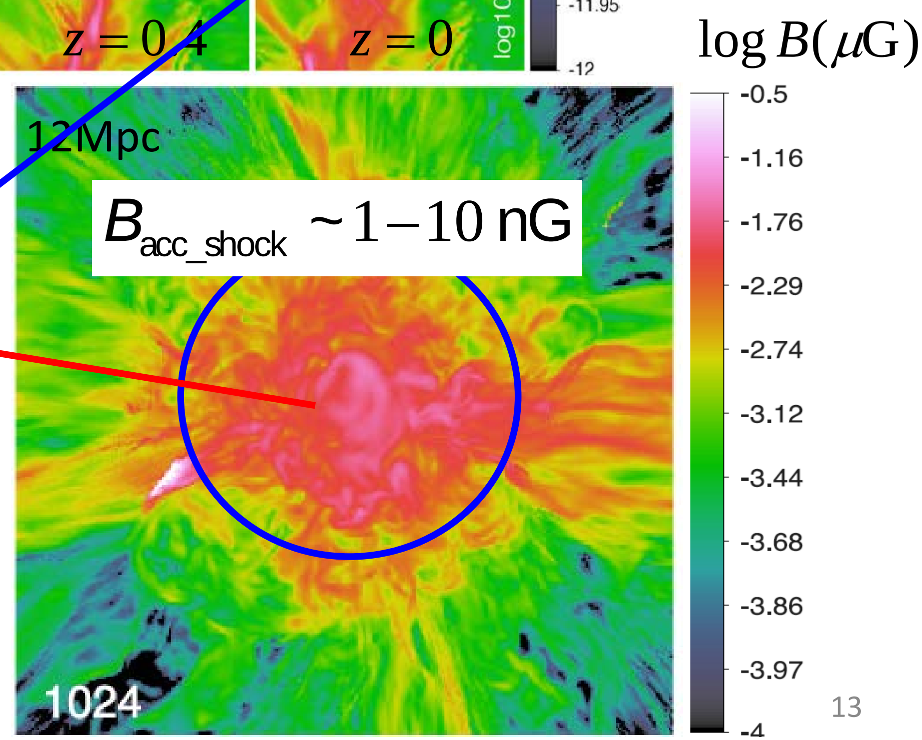
Miniati 2014, 2015

Beresnyak & Miniati 2016

MHD simulations (ENZO): **Vazza et el 2014** ➔ to see small-scale turbulent dynamo (?)

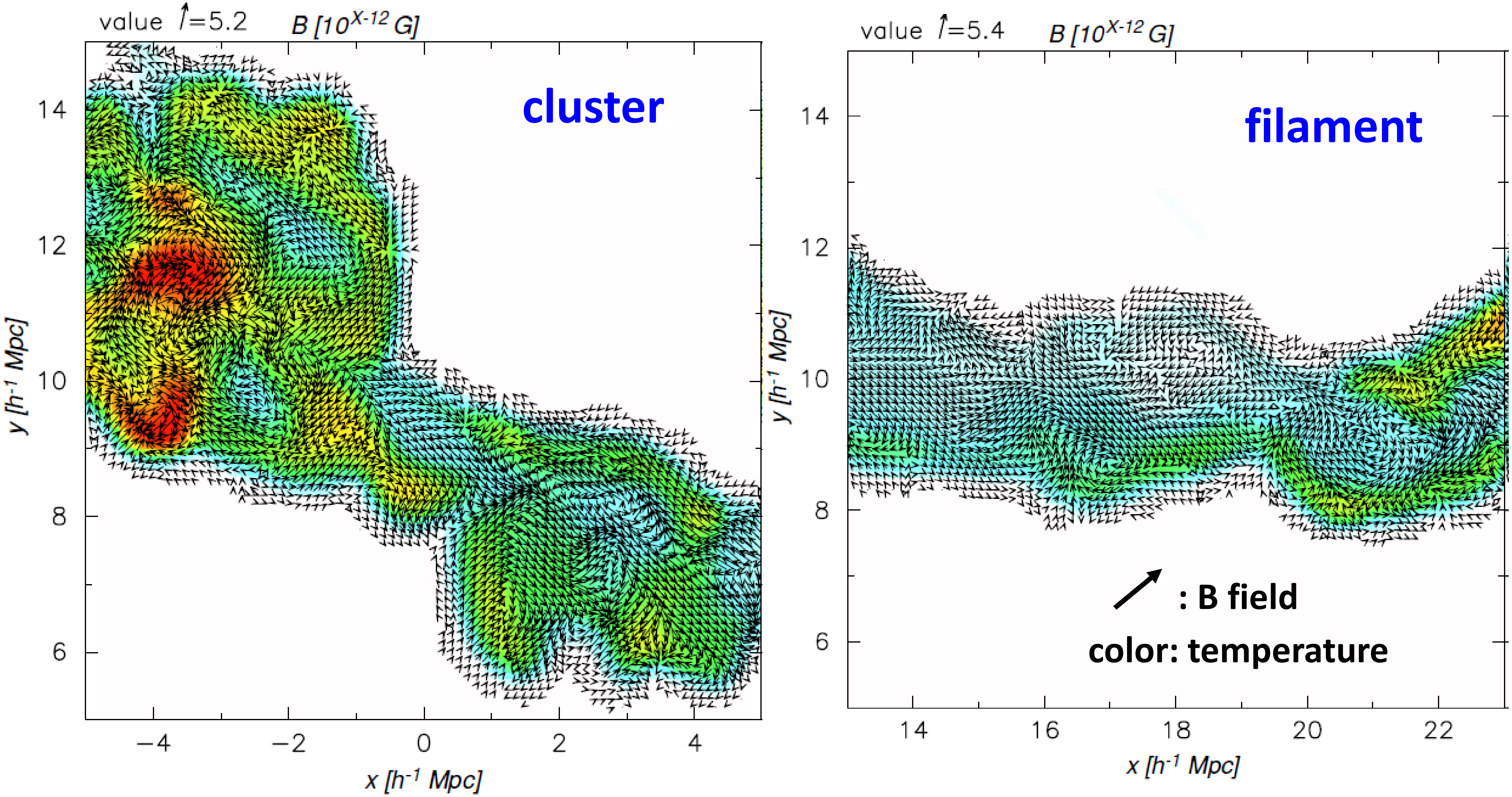






B fields in LSS

Akahori & Ryu 2010

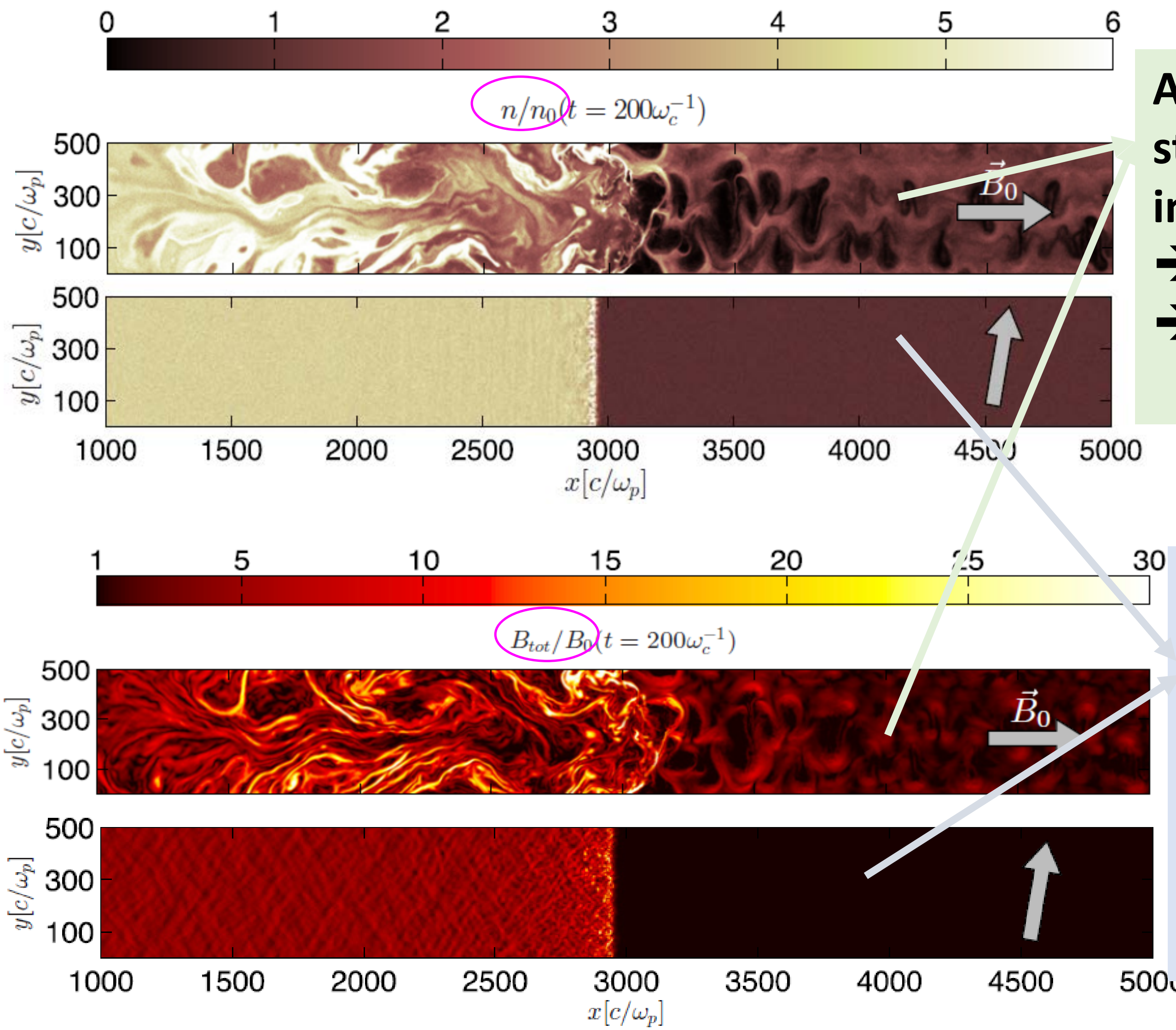


- -Accretion shocks encompass the outer surface of clusters and filaments.
- -Magnetic field vectors are random with coherent length of 100-130 kpc.
- -PDF of obliquity angle: $P(\theta) \propto \sin\theta$ for random orientation of B
- -Q-perp shocks (70%) are preferred over Q-par shocks (30%)

DSA Obliquity Dependence: 2D Hybrid Simulations (CRp)

$M = 20$ shock

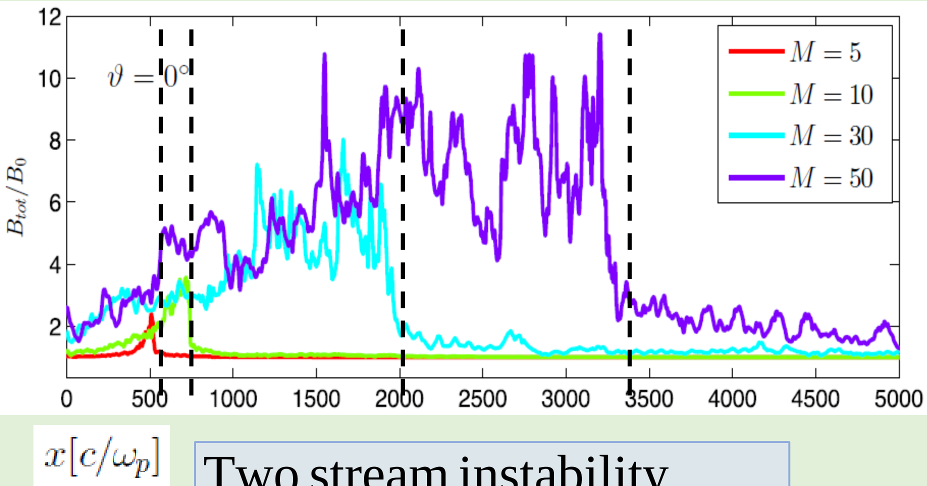
Caprioli & Sptikovsky 2014



At parallel shocks
stream of accelerated ions into upstream
➔ self-generated waves
➔ Turbulent B amplification

At Q-perp shocks
No accelerated ions into upstream
➔ No turbulent waves
➔ No turbulent B field amplification except shock compression

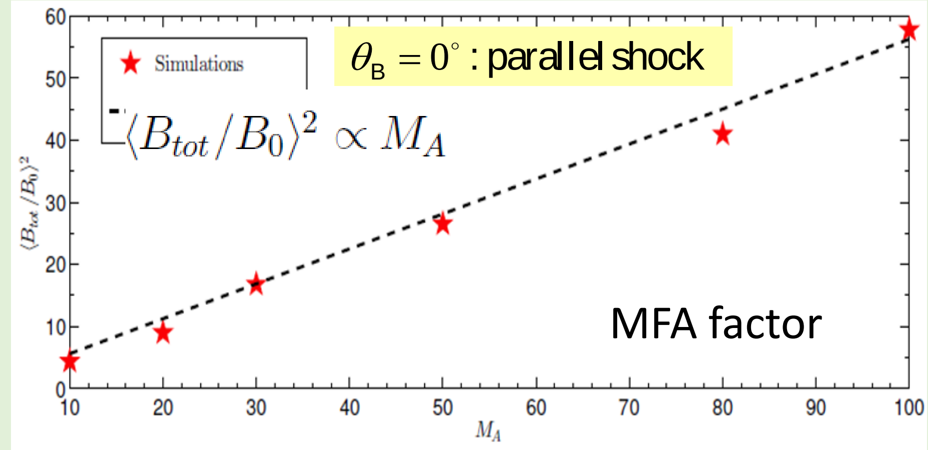
Parallel shock

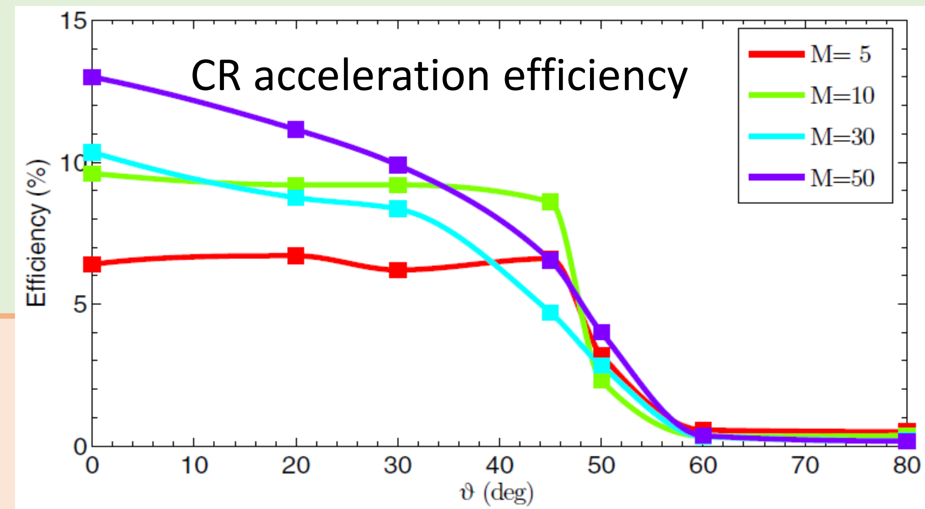


Two stream instability

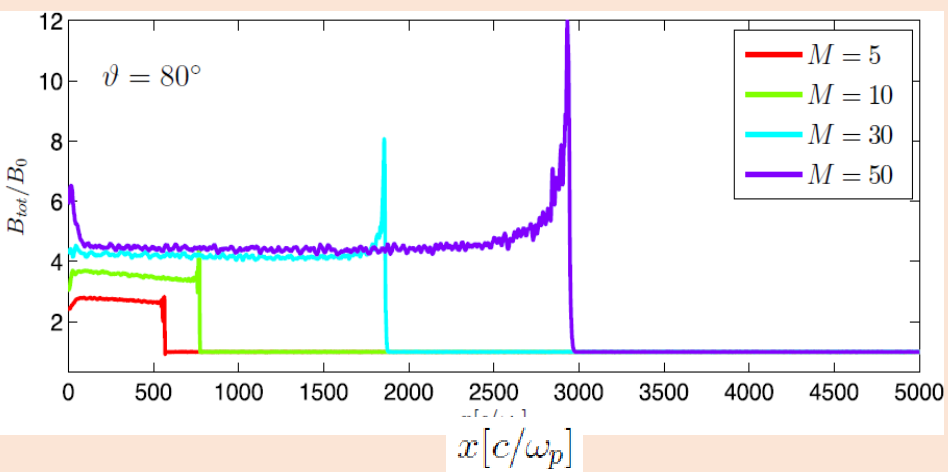
$\Rightarrow$ self - generated waves

$\Rightarrow$ amplification of B fields





Quasi-perp shock



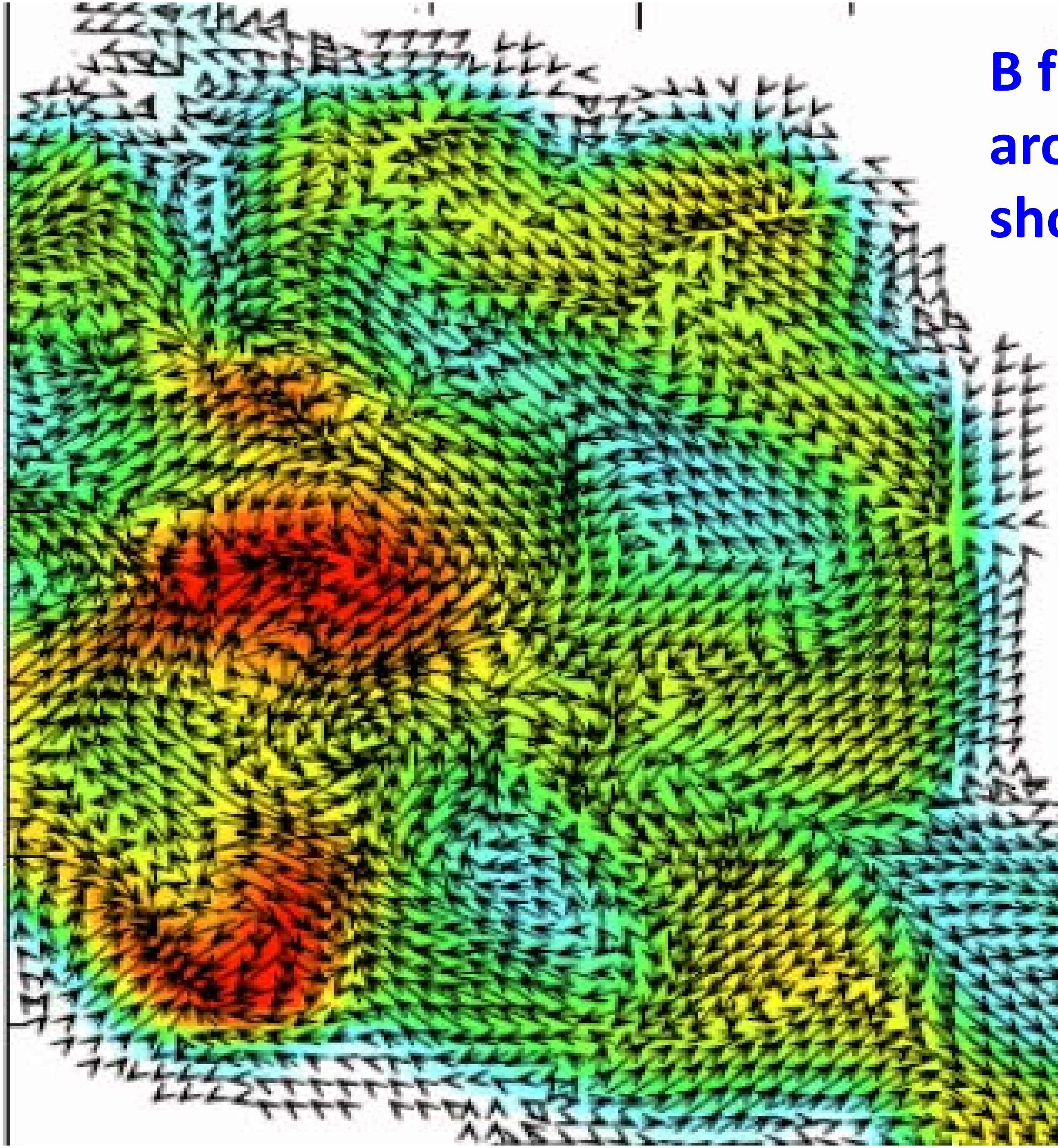
$B_2 = B_0(\rho_2 / \rho_1)$

only compression at the shock

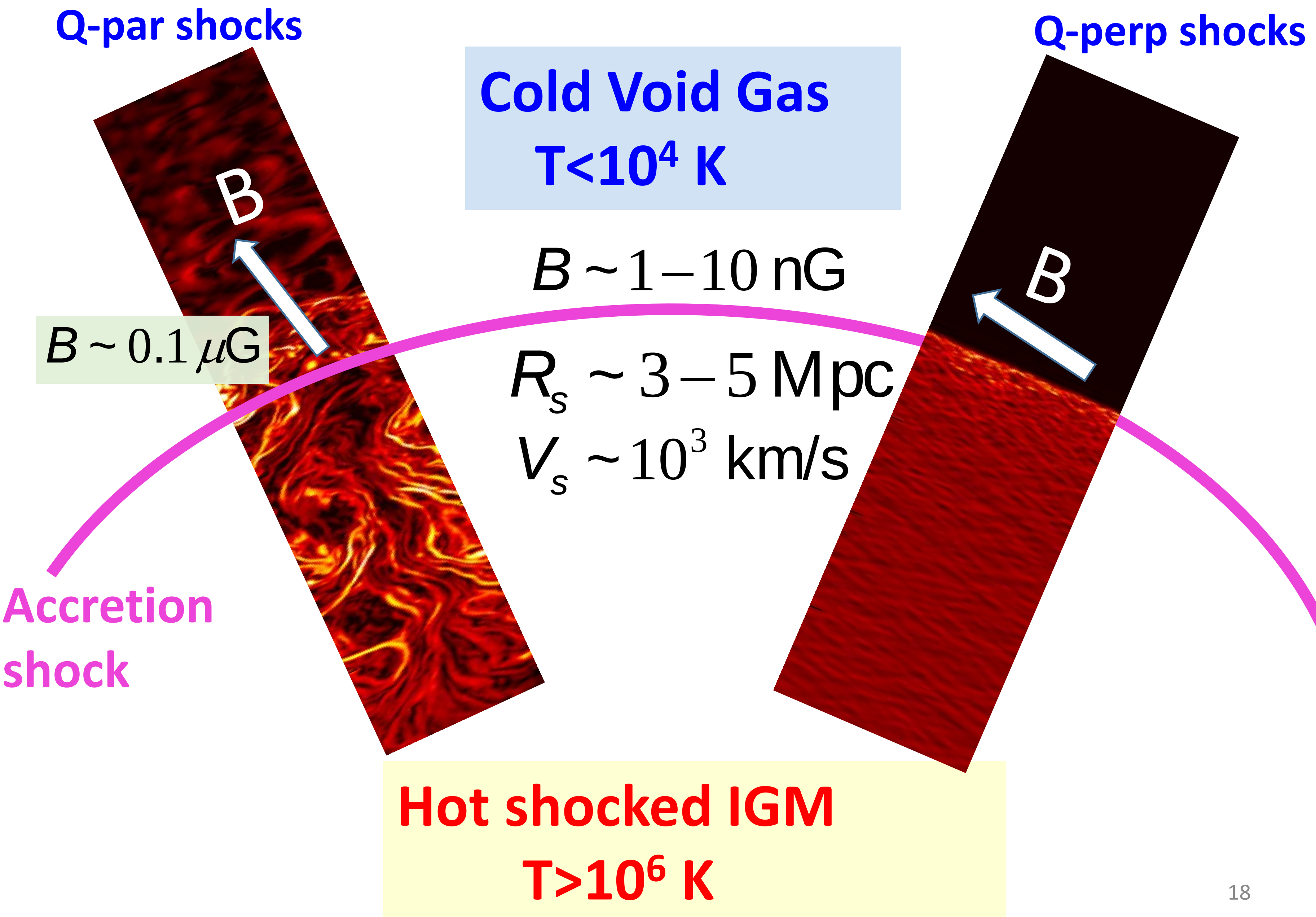
No self - generated waves

No amplification

Caprioli & Sptikovsky 2014



B field directions around accretion shocks: random

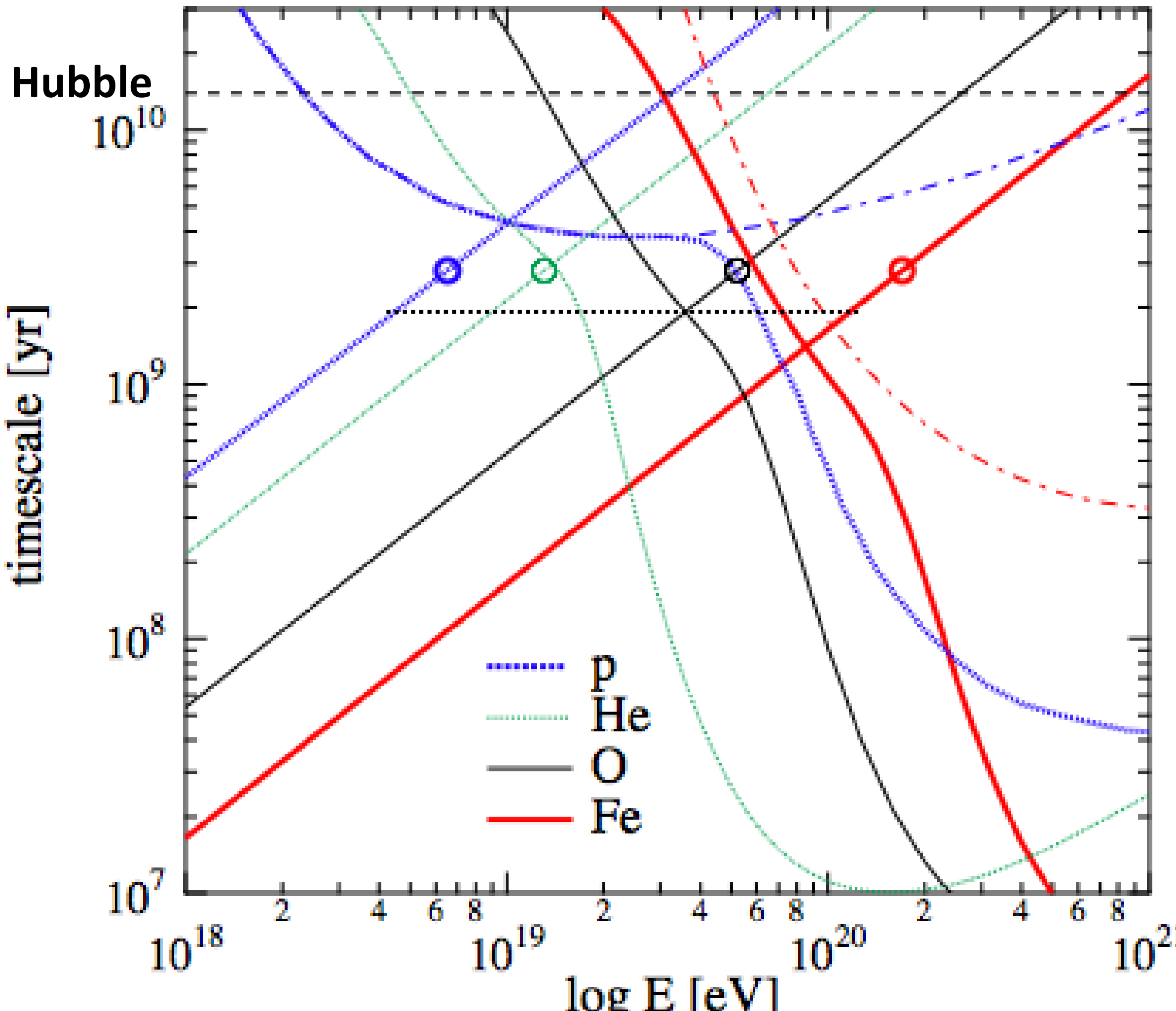

Q-par shocks
Q-perp shocks
Cold Void Gas
$T<10^4$ K
B
B
$B \sim 1-10$ nG
$B \sim 0.1\,\mu$G
$R_s \sim 3-5$ Mpc
$V_s \sim 10^3$ km/s
Accretion shock
Hot shocked IGM
$T>10^6$ K

CR Nuclei from cluster accretion shocks

$$\tau_{acc} \sim \tau_{pp} \Rightarrow E_{max}$$

Inoue, Sigl, Miniati & Armengaud (ICRC2007)

acceleration vs CMB losses



R_s~3.2 Mpc
V_s~2200 km/s
B_s~ 1 μG

In the cluster outskirts

B ~ 1- 10 nG

At Q-par shocks

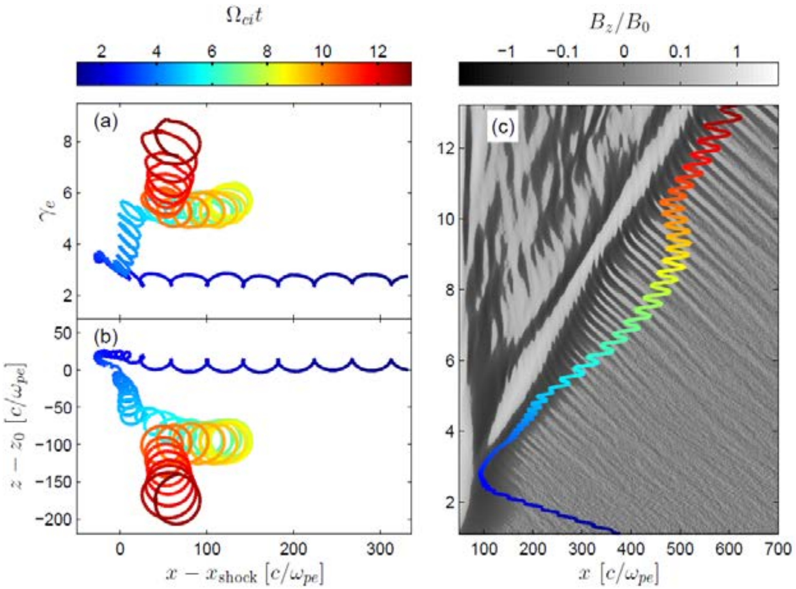
B_{shock} ~ 0.01- 0.1 μG

➔ $E_{p,\,max}$~10^{18} eV

Electron acceleration at Q-perp shocks : PIC

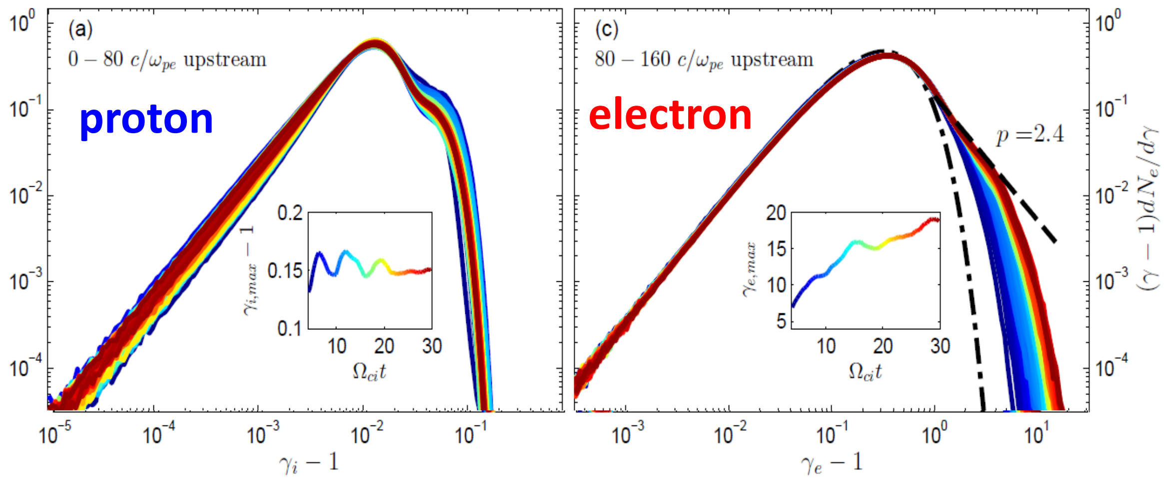
Guo, Sironi, & Narayan 2014

$\theta_{BN} = 63^\circ, \quad M_A \approx 8.2, \quad M_s = 3, \quad u_0 = 0.15c, \quad \beta_p \approx 25$: ICM shocks



Evolution of an electron undergoing multiple SDA

Magnetic field compressed at the Q-perp shock
- ➔ Reflection of some electrons
- ➔ Induce temperature anisotropy in the upstream
- ➔ firehose instability excites waves
- ➔ Reflected electrons are scattered by the waves back to the shock downstream
- ➔ Undergo multiple SDA cycles



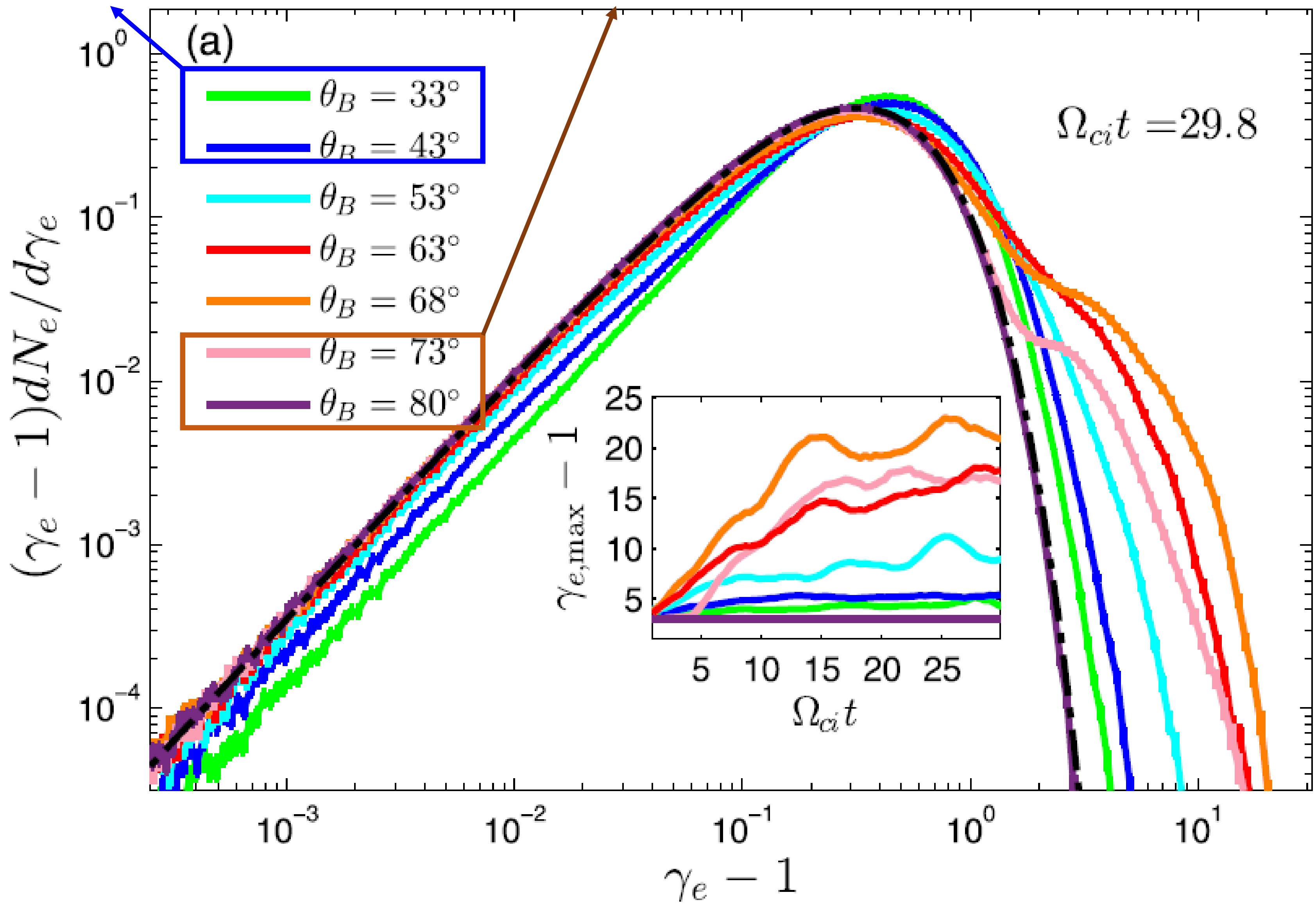
Minimal SDA for protons
→ No acceleration
Multiple SDA for electrons
→suprathermal tail
→Pre-acceleration for DSA
But Not yet full Fermi 1st order

DSA Obliquity Dependence: PIC Simulations (CRe)

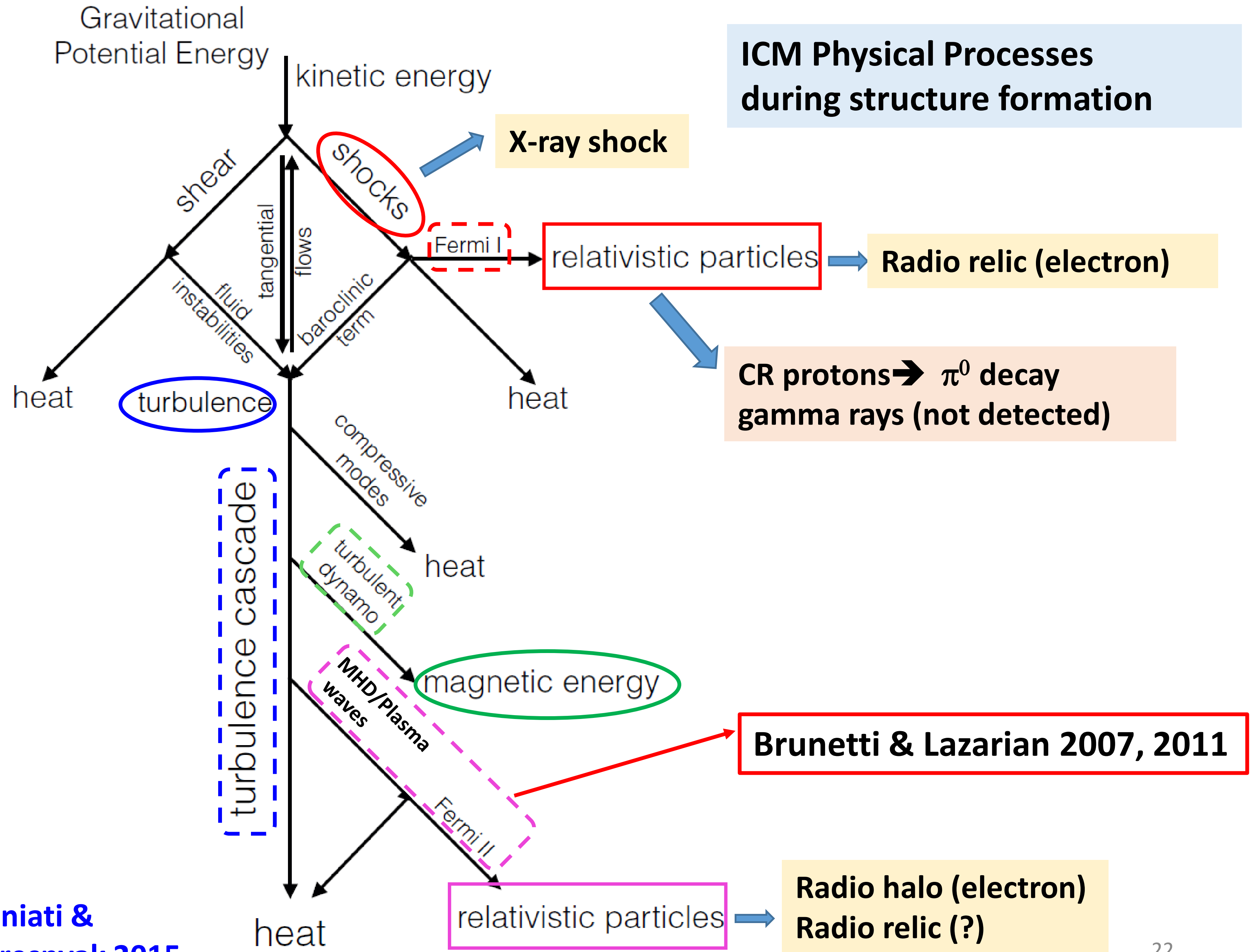
Guo, Sironi, & Narayan 2014

Slow acceleration of Fermi-I at Q-par shocks

Inefficient reflection at superluminal Perp shocks

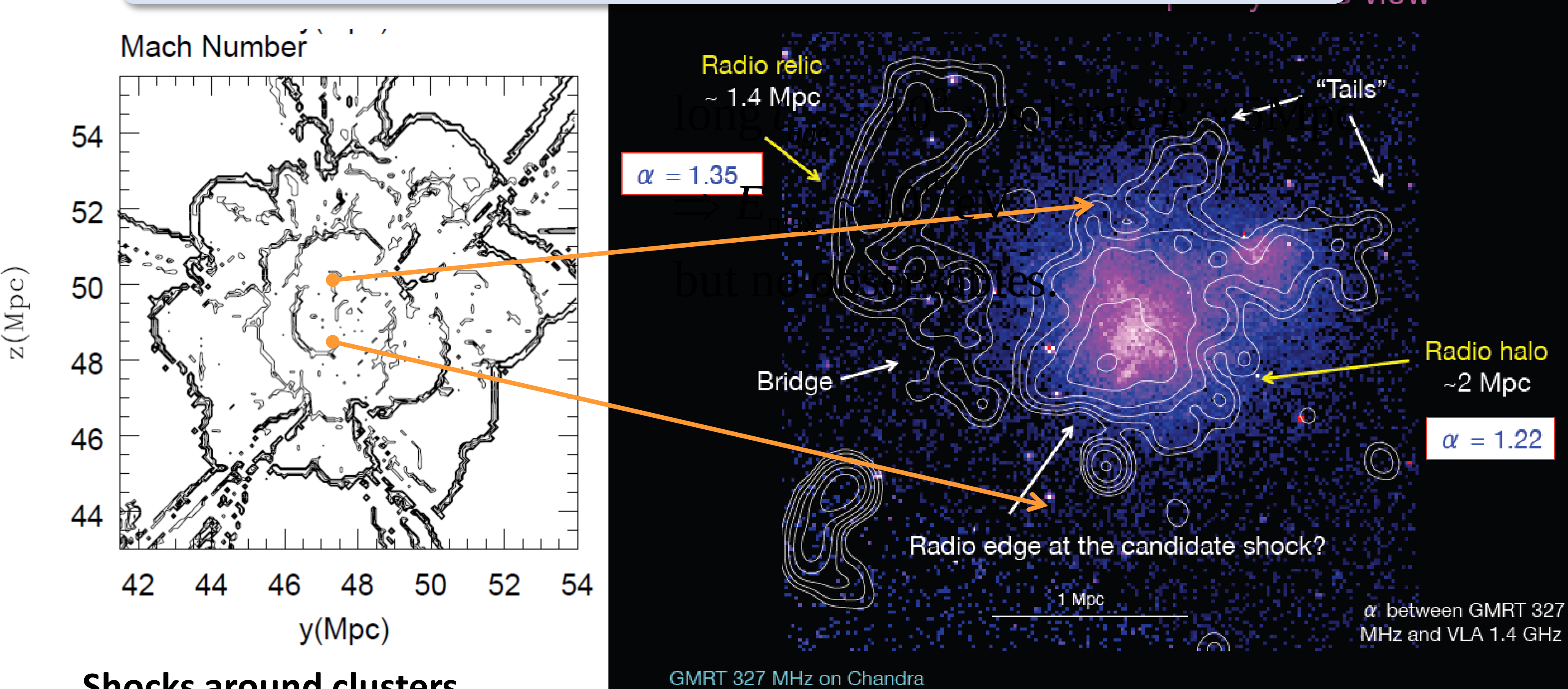


ICM Physical Processes during structure formation



Miniati & Beresnyak 2015

Cosmological Shocks: Observational Tests



Shocks around clusters

X-ray halo hot ICM gas → X-ray shocks

Radio halos: 2ndry electrons reaccelerated by turbulence (Brunetti +)

Radio relics: primary electrons (re)accelerated by shocks

Magnetic field: turbulent dynamo, shock amplification

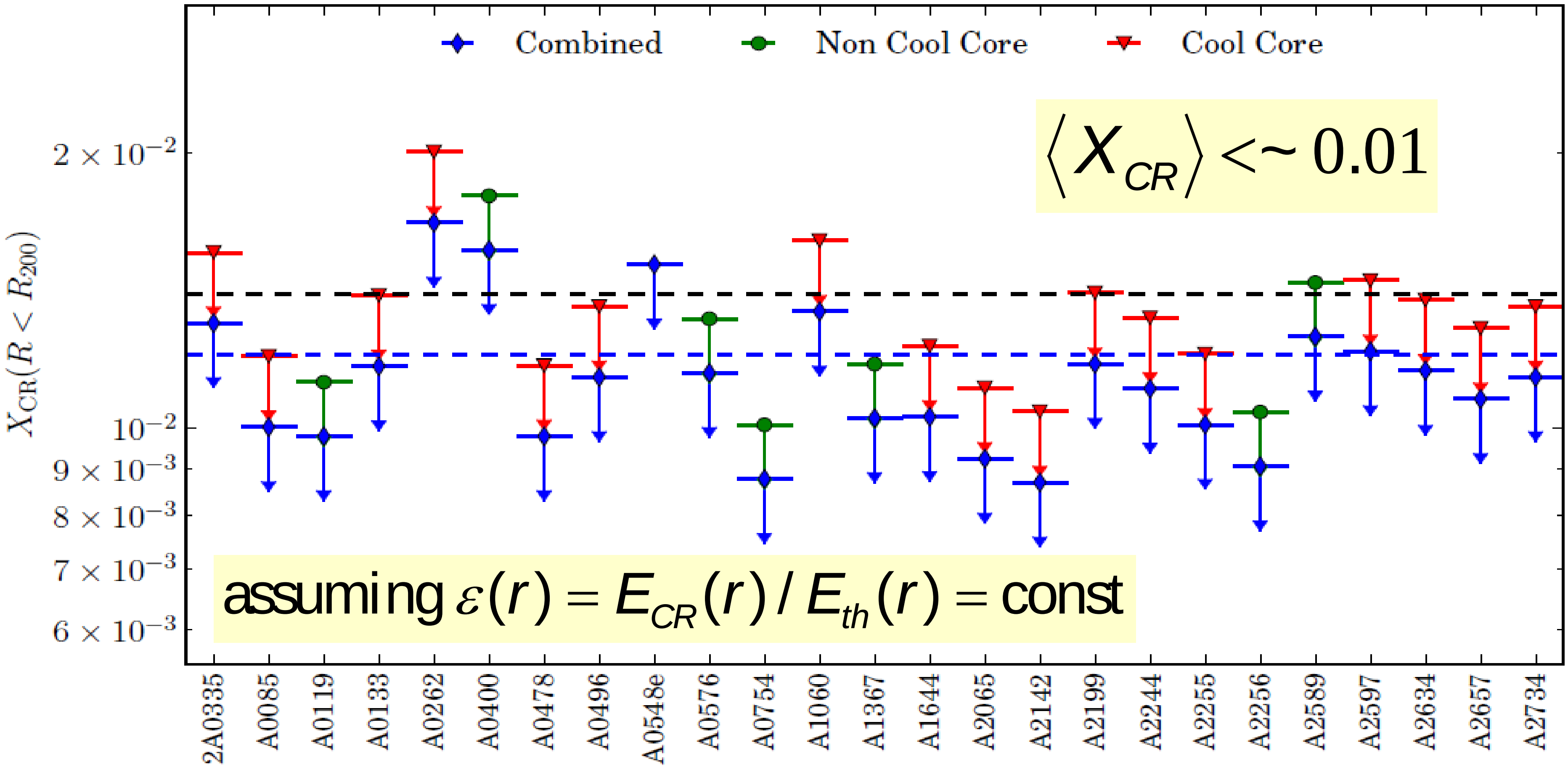
γ-ray emission: π^0 decay (hadronic CRs) : not detected

Accretion shocks: not detectable

Search for cosmic-ray induced γ-ray emission in Galaxy Clusters

The *Fermi*-LAT Collaboration: **Ackermann et al. 2013**

the volume-averaged CR-to-thermal pressure $\langle X_{\mathrm{CR}} \rangle$

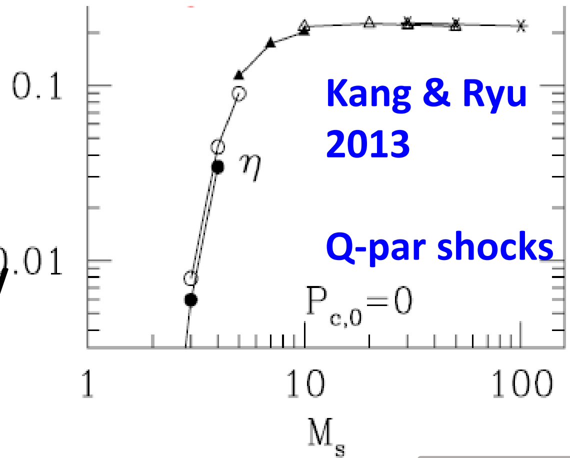


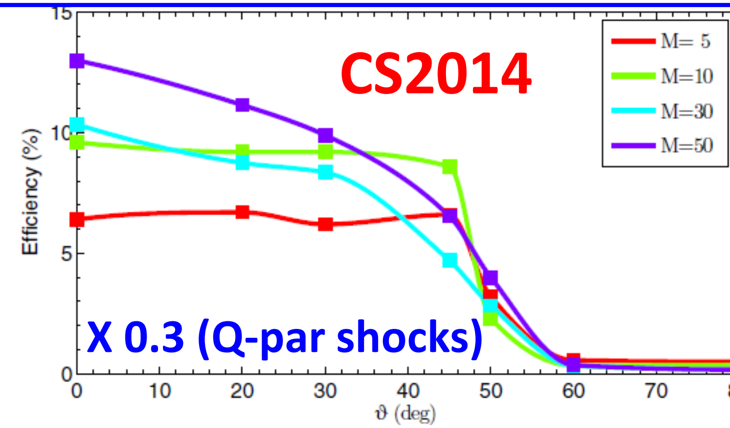
50 Galaxy Clusters in 4 years of Fermi LAT data

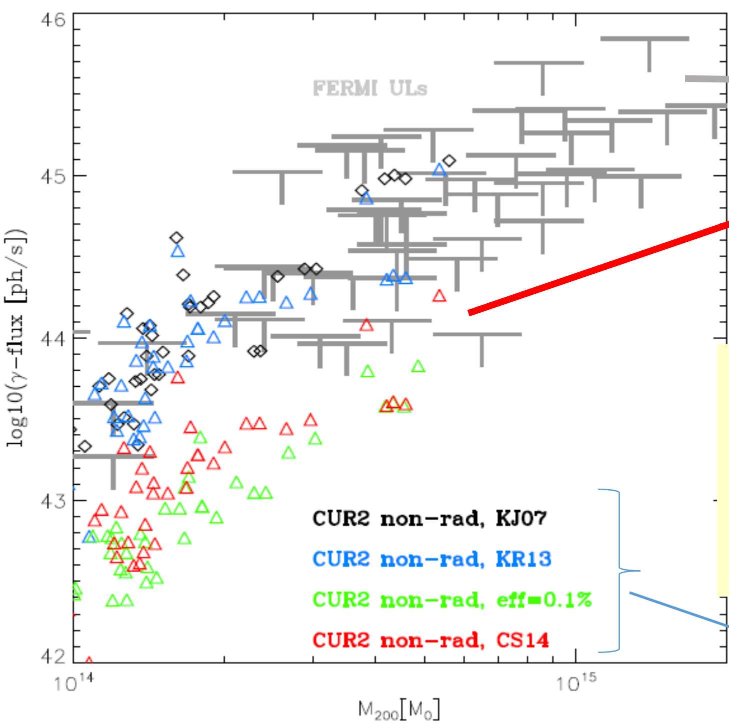
Constraining the efficiency of cosmic ray acceleration by cluster shocks

F. Vazza,[1★] M. Brüggen,[1] D. Wittor,[1] C. Gheller,[2] D. Eckert[3] and M. Stubbe **2016**

Adopting CR proton acceleration efficiency based on DSA models, Estimate gamma-ray flux







Fermi LAT upper limits on gamma-ray flux from individual clusters

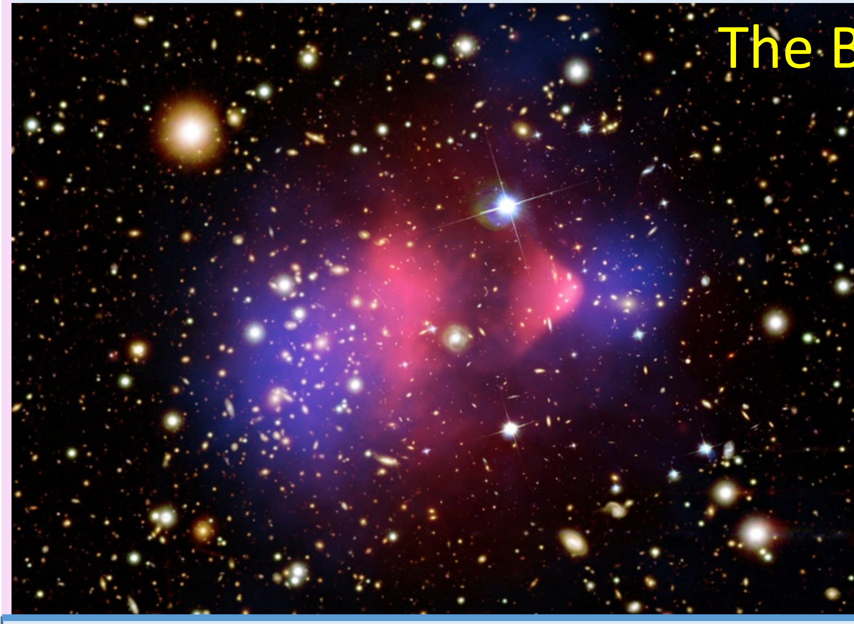
Gamma-ray flux of simulated clusters based on CS2014 DSA efficiency models

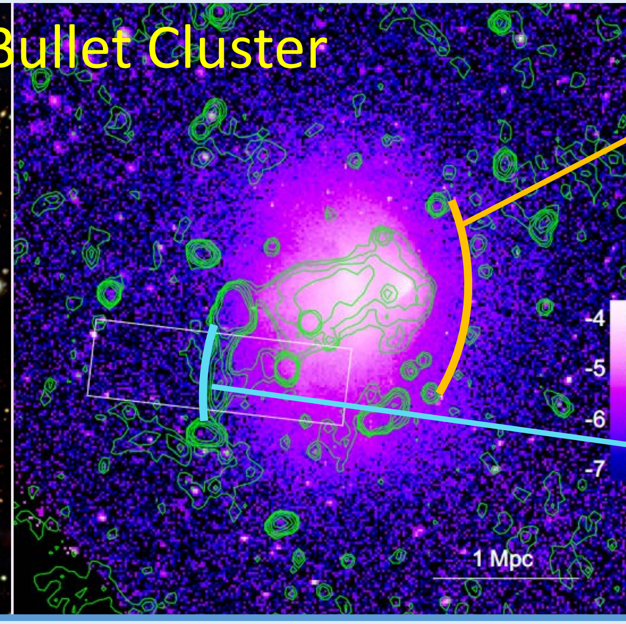
To be compatible with Fermi upper limits, the CR proton acceleration efficiency should be less than 10^{-3} for 2<M<5 shocks.

Different DSA efficiency models

Signatures of shocks in ICM : X-ray observations

The Bullet Cluster





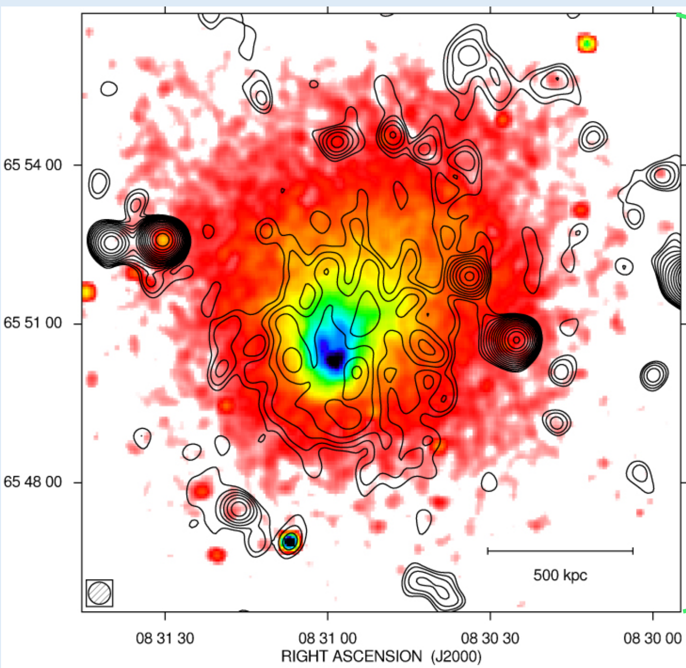
$M_X \approx 3.0$

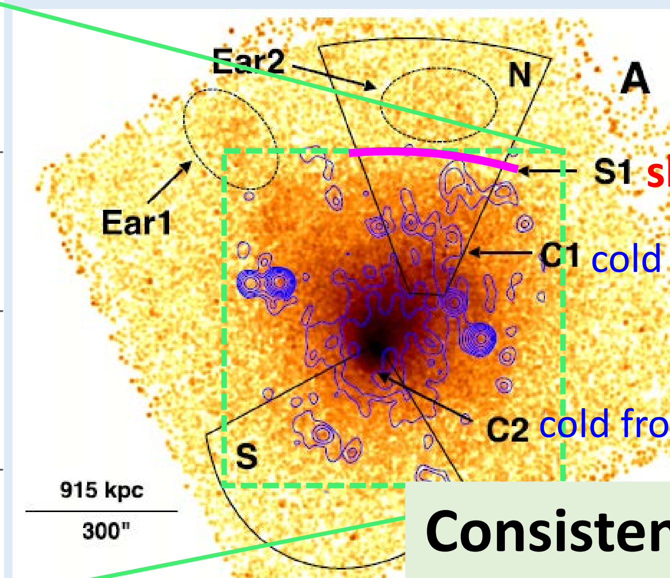
(no associated radio relic)

Markevitch 2006

$M_X \approx 2.5$

Shimwell et al. 2015





Cluster A665

S1 shock $M_X = 3 \pm 0.6$

(no associated radio relic)

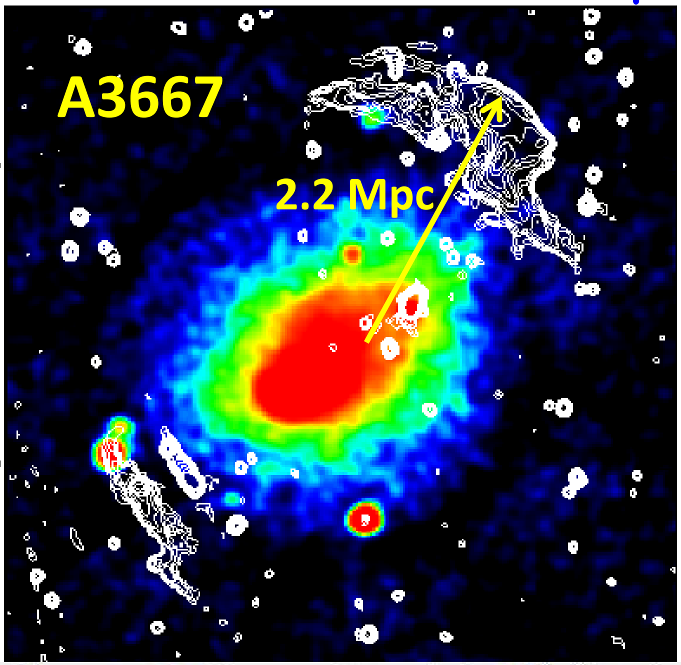
C1 cold front

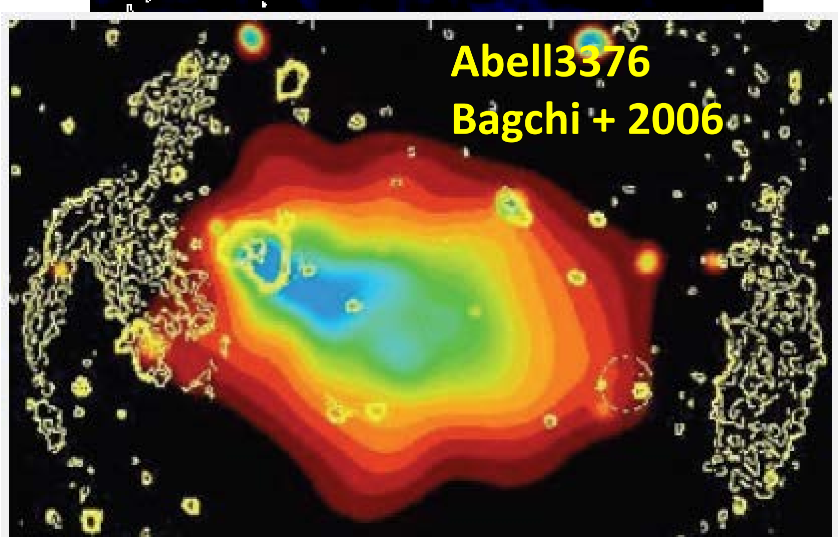
C2 cold front

Dasadia et al. 2016

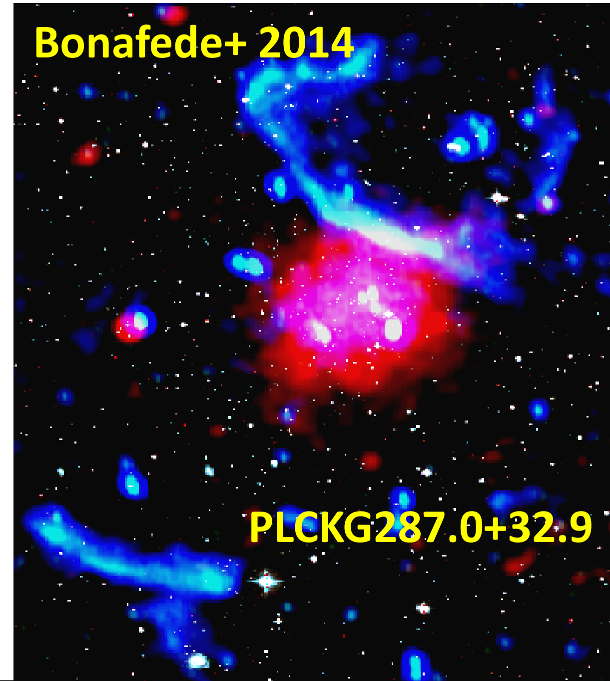
Consistent with theoretical predictions

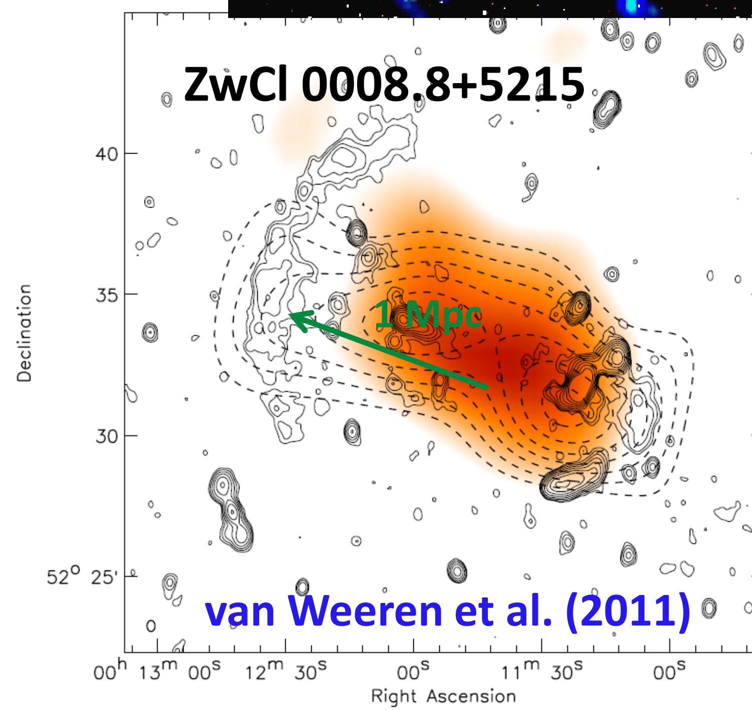
~50 Radio Relics : diffuse synchrotron radiation from GeV electrons in μG B fields



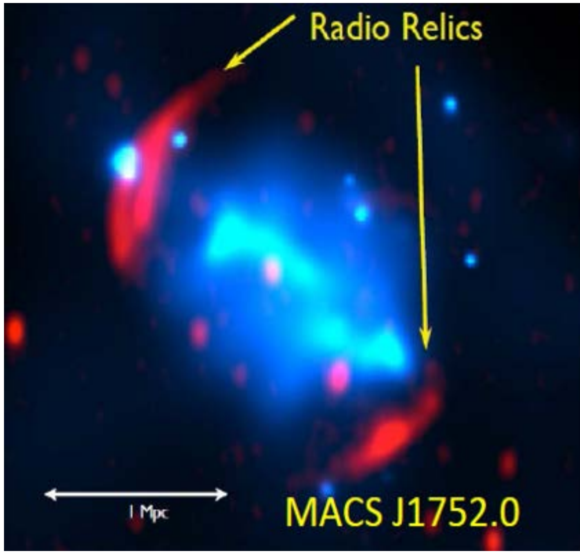


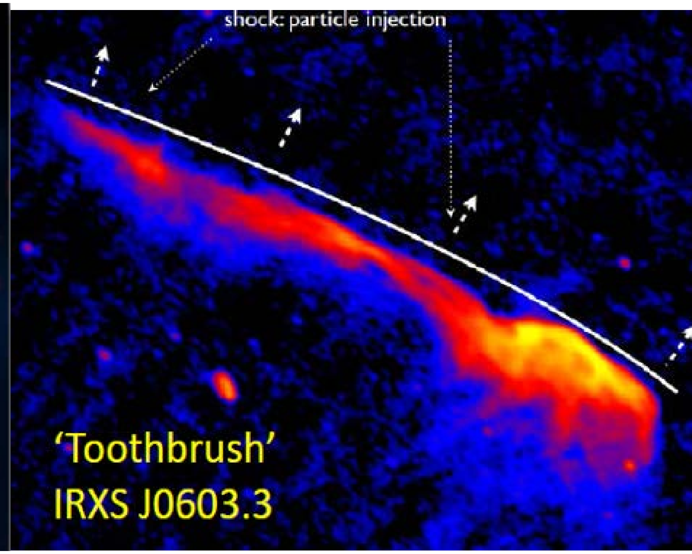
Found in merging clusters.

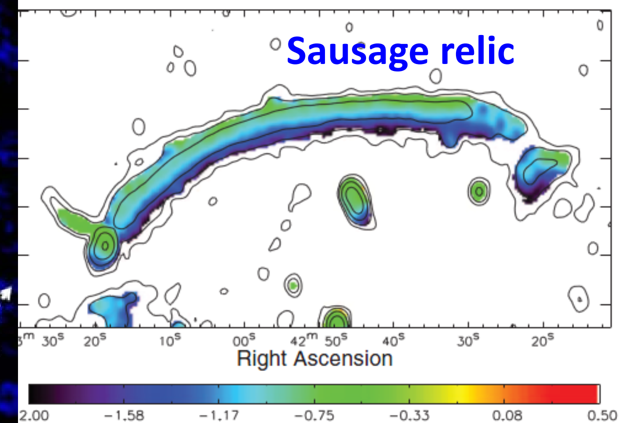




Radio relics: diffuse radio sources found mainly in merging clusters





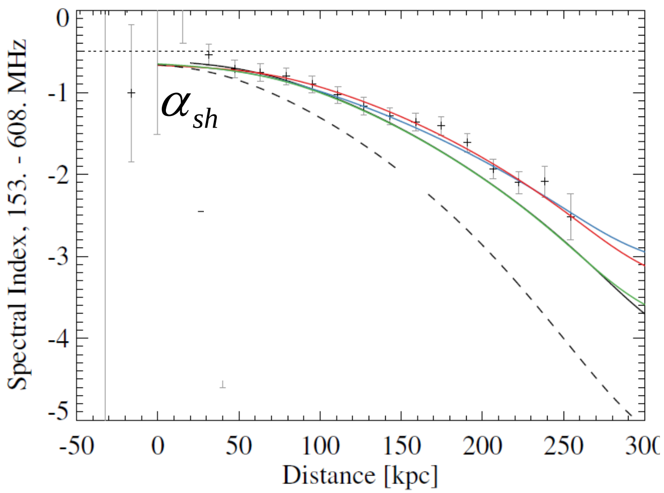


- elongated morphology
- spectral aging behind the shock (due to radiative cooling)
- power-law like integrated radio spectrum
- high polarization up to 50 % (B field compression across shock)

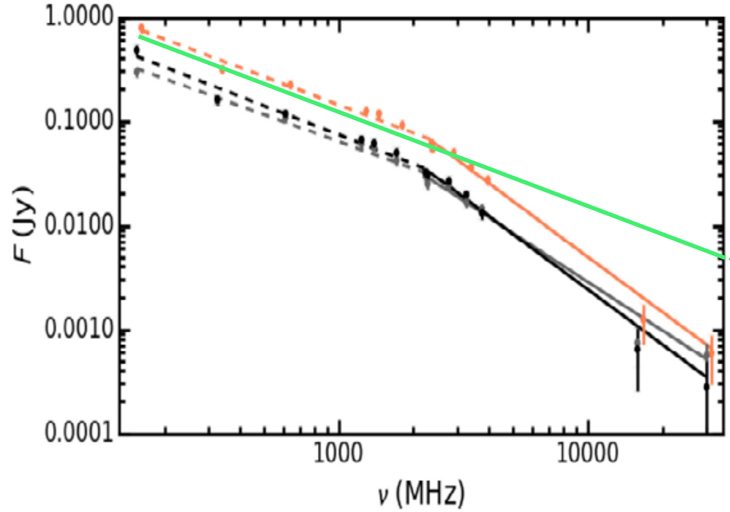
→synchrotron radiation emitted by ~GeV electrons accelerated at structure formation shocks

Radio vs. X-ray Observations of Radio Relics

Spectral index profile



Integrated radio spectrum

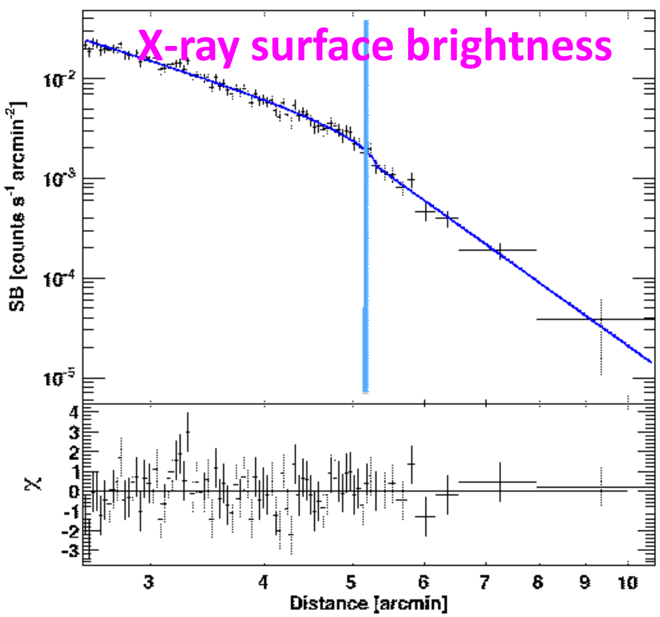


$$M_{radio}^2 = \frac{(3+2\alpha_{sh})}{(2\alpha_{sh}-1)}$$

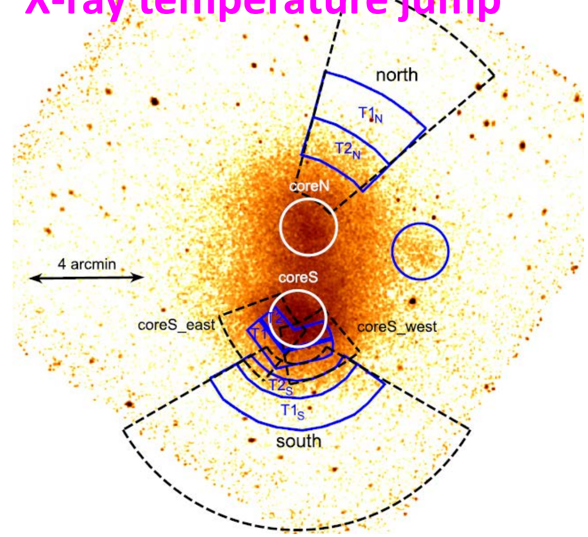
in situ injection model

$$\alpha_{\rm integ} \approx \alpha_{sh} + 0.5$$

X-ray surface brightness



X-ray temperature jump



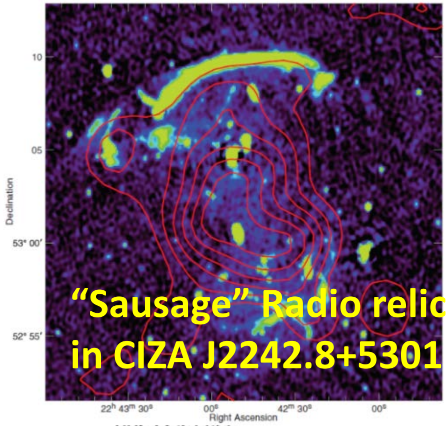
$$\frac{T_2}{T_1} = \frac{(M_X^2+3)(5M_X^2-1)}{16M_X^2}$$

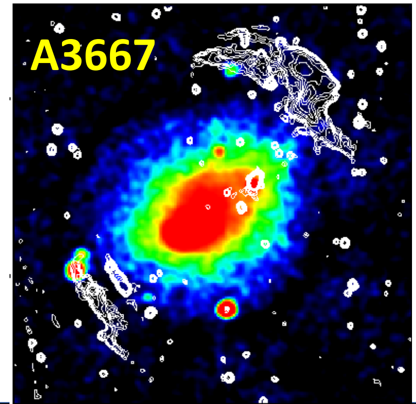
$c_{s,1}$ = sound speed

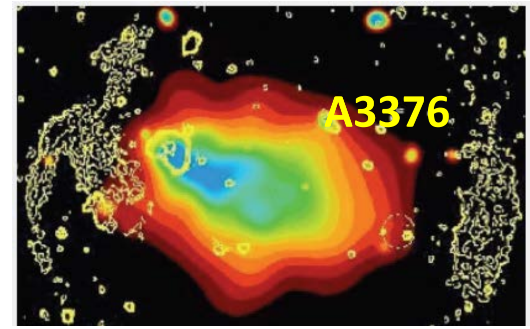
V_s = shock speed

* Projection effects

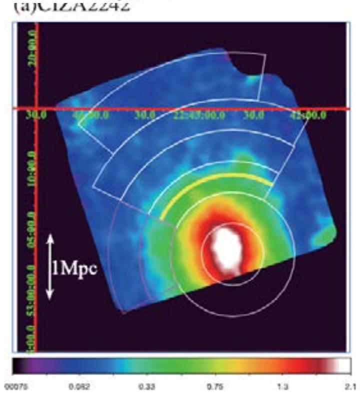
X-ray observations of radio relics: Akamatsu & Kawahara 2013



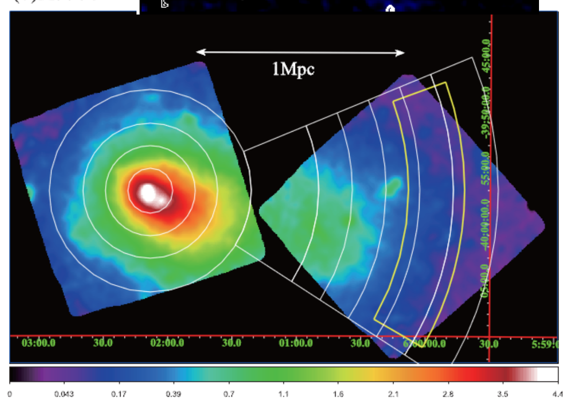




(a)CIZA2242



(b)A3376



(c)A3667

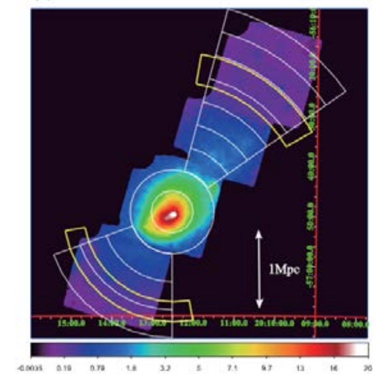
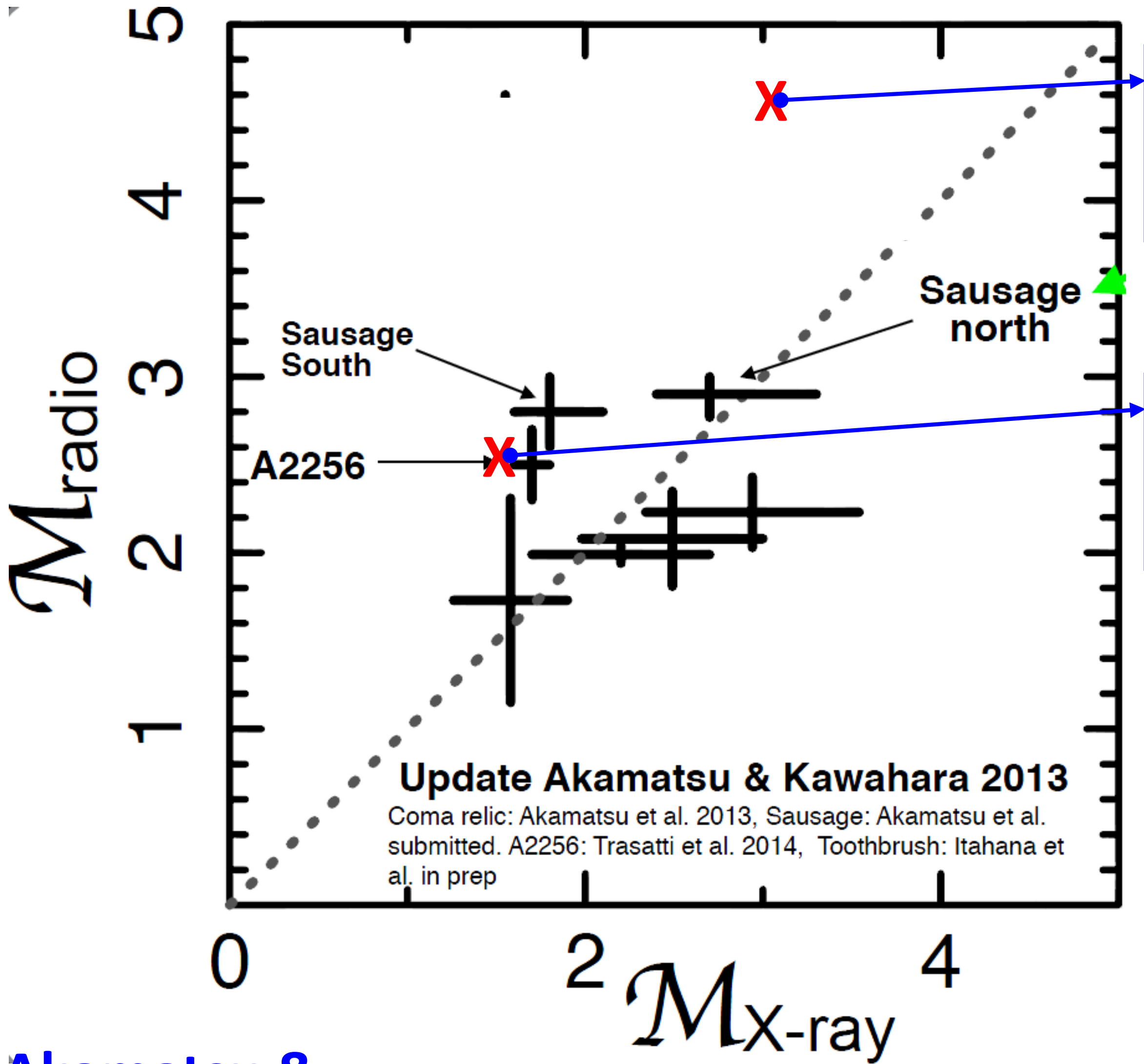


Table 4. Post- and pre-shock ICM quantities and Mach number derived from X-ray and radio observations.

	$kT_{\text{poste shock}}$ (keV)	$kT_{\text{pre shock}}$ (keV)	$\mathcal{M}_{X,kT}$	α	$\mathcal{M}_{\text{radio}}$
CIZA2242	$8.33 \pm 0.80 \pm 0.40^*$	$2.11 \pm 0.44^{+2.10}_{-0.20}*$	$3.15 \pm 0.52^{+0.40}_{-1.20}*$	-0.60 ± 0.05	4.58 ± 1.32
A 3376	4.81 ± 0.29	1.35 ± 0.35	2.94 ± 0.60	-1.00 ± 0.10	2.23 ± 0.20
A 3667 NW	5.52 ± 0.95	2.03 ± 0.34	2.41 ± 0.39	-1.10 ± 0.20	2.08 ± 0.37
A 3667 SE	6.34 ± 0.38	3.59 ± 0.28	1.75 ± 0.13	-1.50 ± 0.17	1.73 ± 0.58

Mach numbers from X-ray and Radio observations of Radio Relics

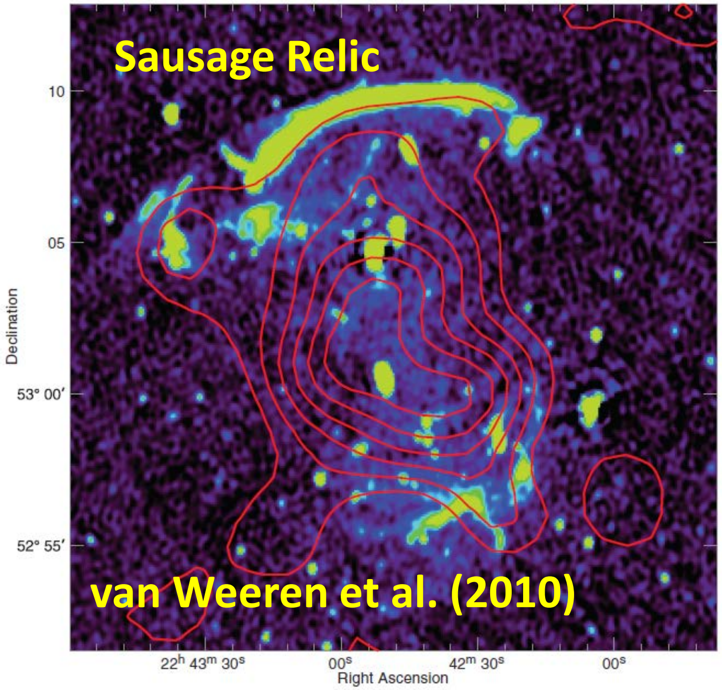


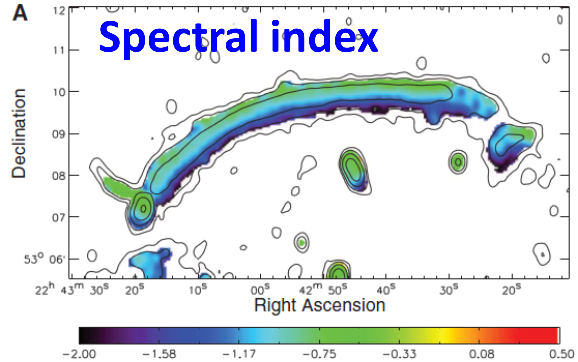
Sausage relic:
$M_{radio} \approx 4.6, \quad M_X \approx 3$

Toothbrush relic:
$M_{radio} \approx 2.8, \quad M_X \approx 1.2 - 1.5$

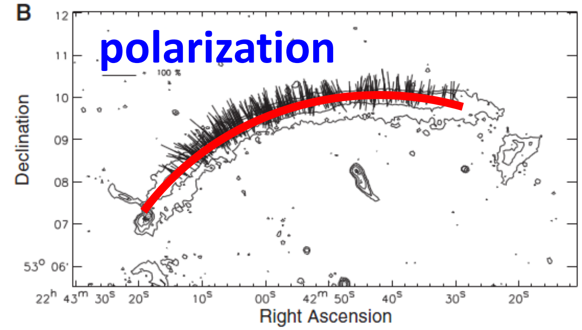
In some relics, X-ray Mach number is smaller than radio Mach number.

Akamatsu & Kawahara 2013

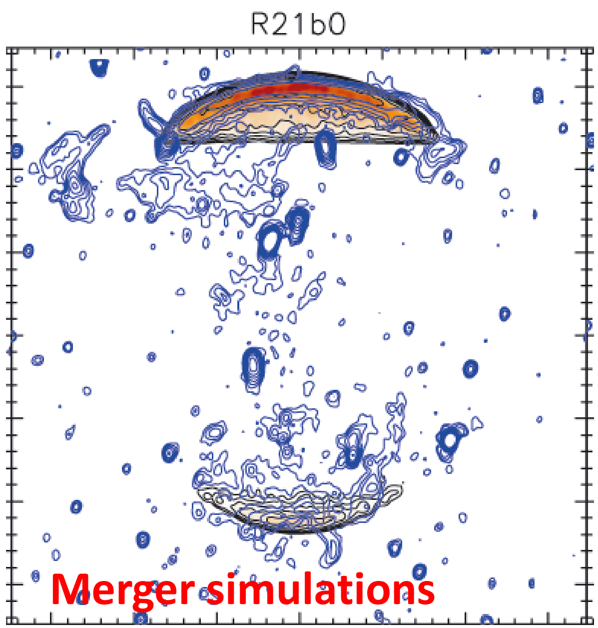




Radiative cooling behind the shock



B line along the relic
→Quasi-perp. shock



If the shock is a part of a spherical surface and if CR e are injected/ accelerated at shocks.

Q: Why are surface brightness and spectral index are uniform along the relic ?

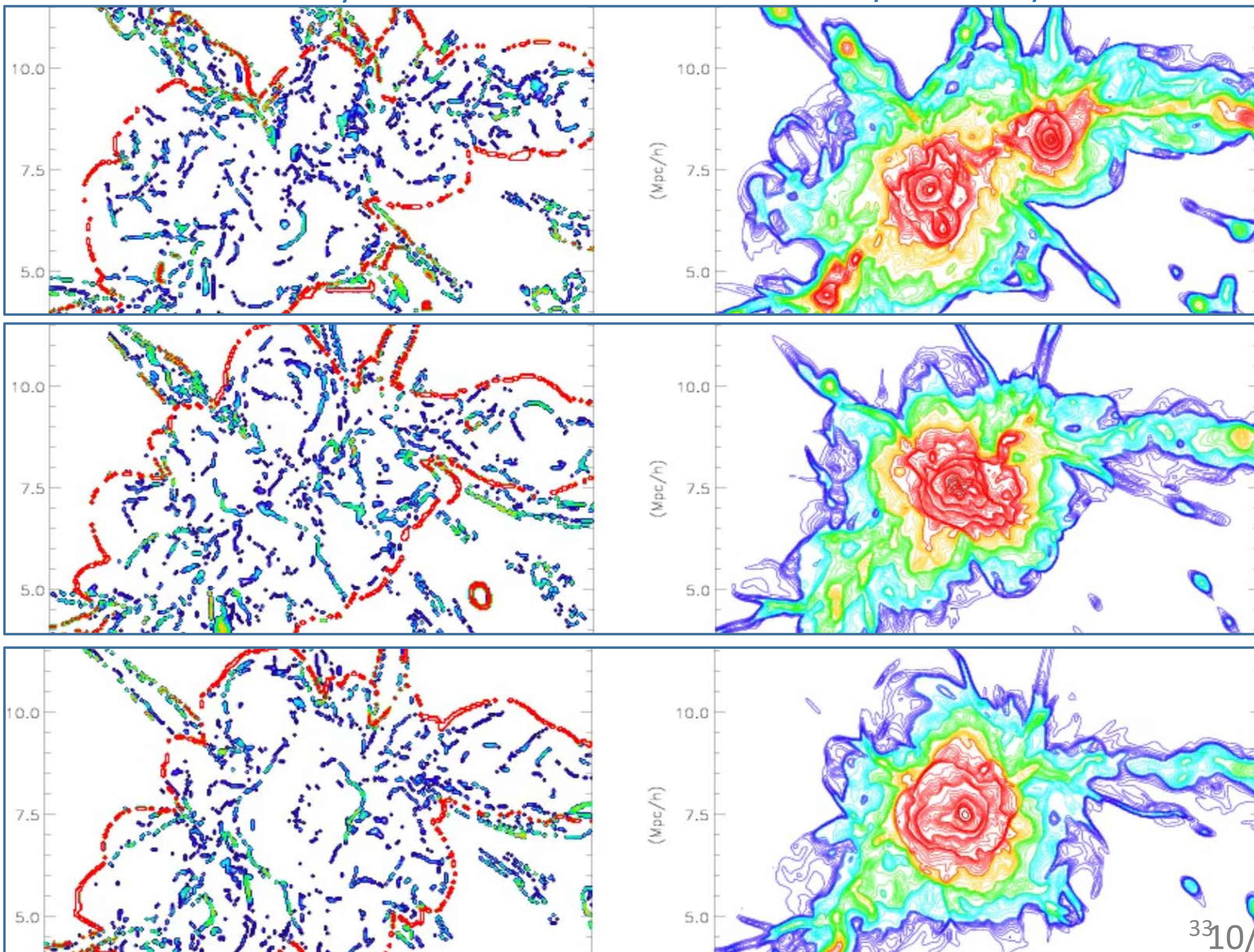
Ubiquitous presence of structure formation shocks in ICM

Shock distribution by Mach number | X-ray emissivity

Z=0.65

Z=0.30

Z=0.22



Ha, Ryu, & Kang 2016

Puzzles for *in situ* injection model

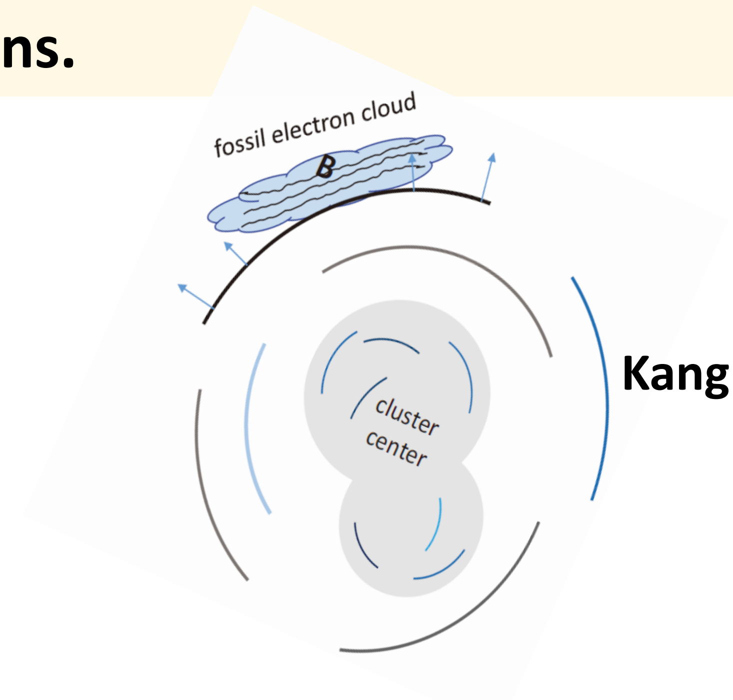
(1) Why for some radio relics, $M_{radio} > M_X$

(2) Low *in situ* injection and acceleration efficiency at weak shocks $(M < 3)$

(3) Why only ~10 % of merging clusters host radio relics, while numerous shocks are expected to form in ICM ?

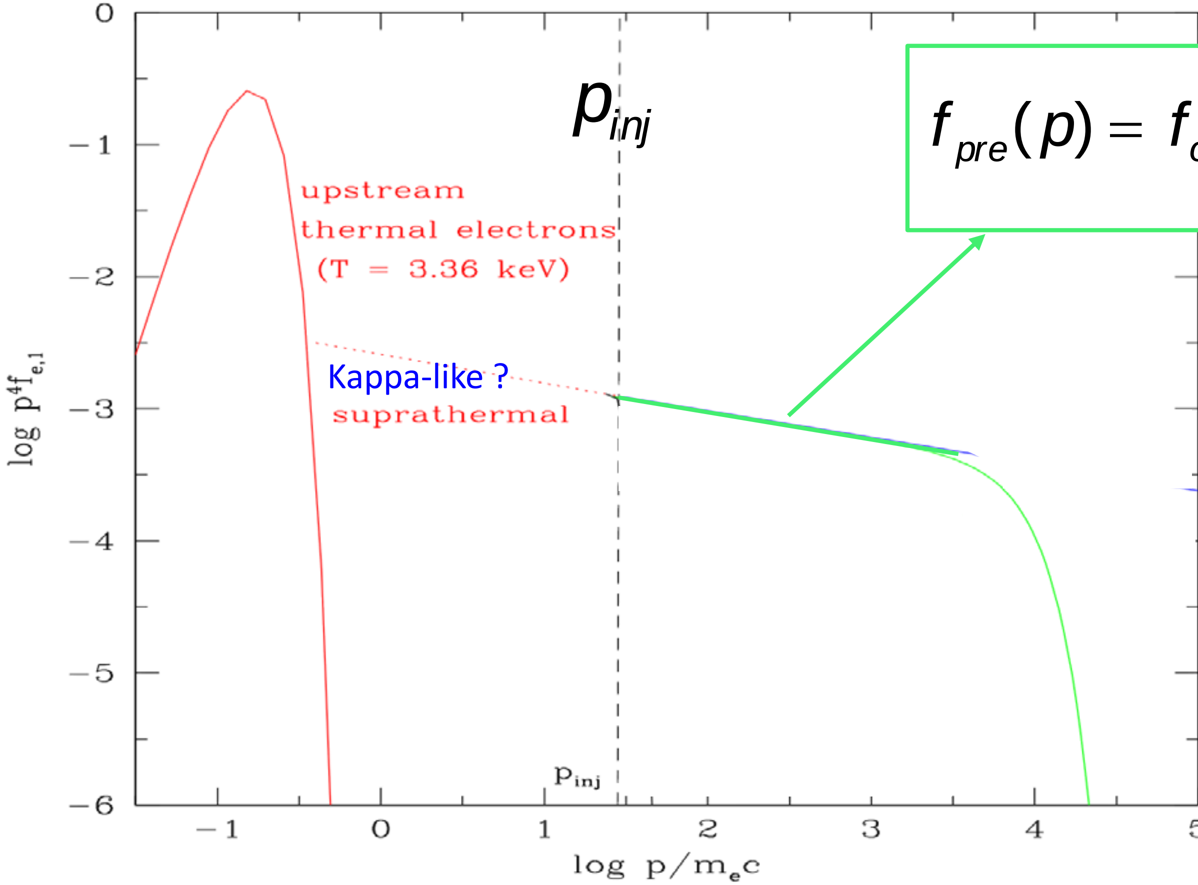
(4) Why some X-ray shocks do not have associated radio relics ?

Reacceleration model can solve these puzzles: a radio relic forms when a weak shock encounters the ICM plasma with pre-existing electrons.



Kang & Ryu (2015)

Solution: Re-acceleration of Pre-existing electrons



$$f_{pre}(p) = f_o\left(\frac{p}{p_{inj}}\right)^{-s} \exp\left[-\left(\frac{\gamma_e}{\gamma_{e,c}}\right)^2\right]$$

with $\gamma_{e,c} \sim 10^4$

radio spectral index α is determined by M_s, s, & $\gamma_{e,c}$

$\Rightarrow \quad M_{radio} \neq M_s$ or M_X (not necessarily)

Puzzles for *in situ* injection model

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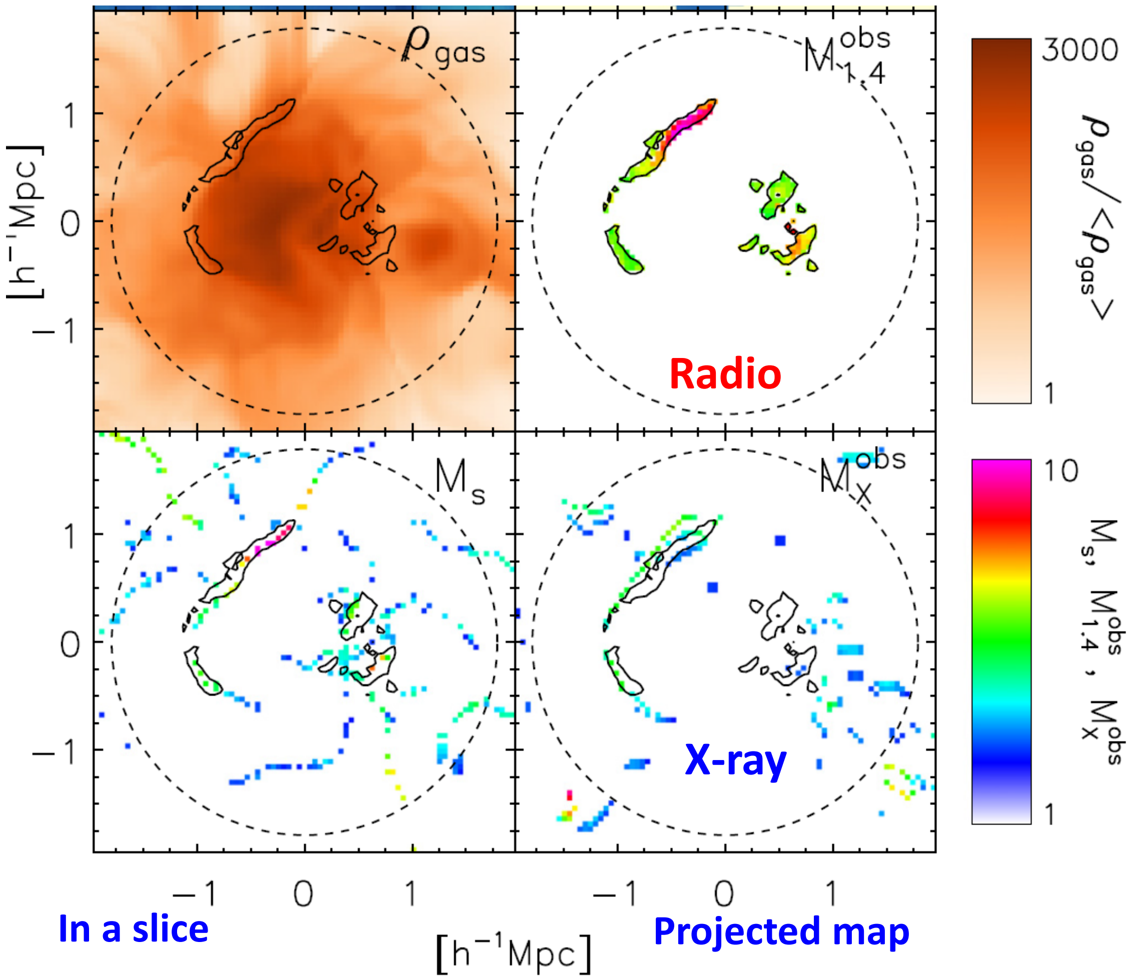
$\Rightarrow \quad M_{radio} \neq M_s$ or M_X (not necessarily)

(2) fossil electrons $\Rightarrow$ seed electrons to DSA

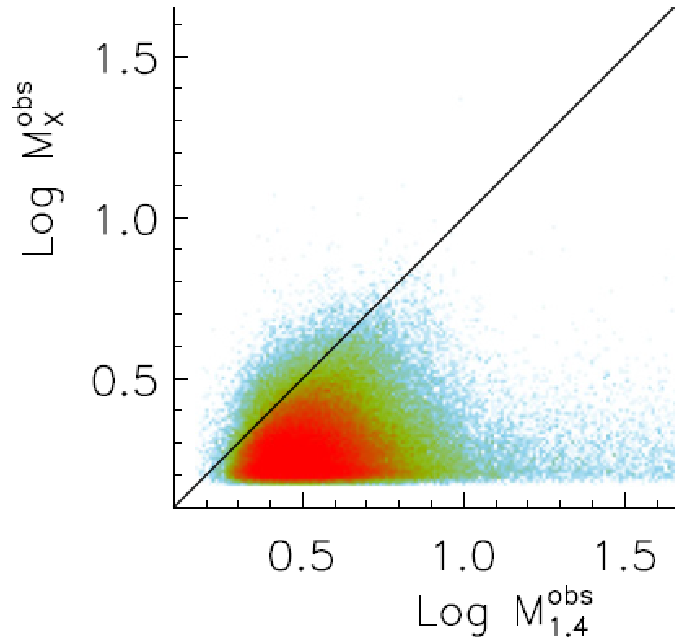
(3)(4) Not all shocks can accelerate electrons and become radio relics.

Mock observation of X-ray vs. Radio Shocks in the simulated clusters



Contour: 1.4 GHz radio flux

Radio vs. X-ray Shock Mach no.



$$M_X^{obs} < M_{radio}^{obs} \sim M_s$$

due to projection effects &
lack of spatial resolution

$M_{1.4}^{obs}$: derived from spectral index btw 140MHz and 1.4GHz

M_X^{obs} : derived from T_X jump across the shock

M_s : true shock Mach number

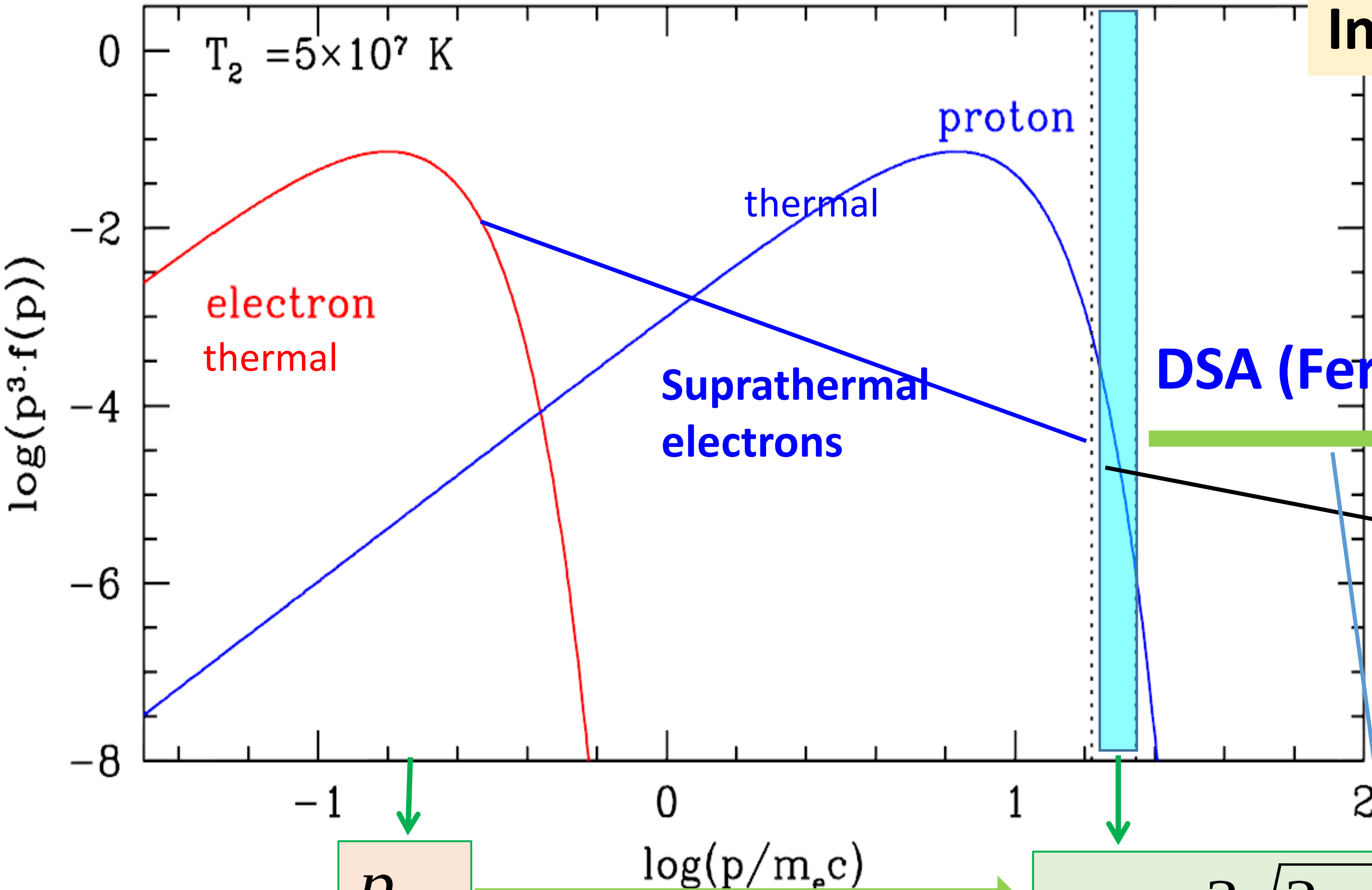
Hong, Kang & Ryu 2015

Going beyond the Standard Models ?

Need to go deeper into the Standard Models !

In particular, we need to understand Collisionless Shocks with low Mach numbers in high beta plasma.
e.g. Injection Problem is not a DSA problem.
It is a problem of plasma kinetic processes.

Injection problem



DSA (Fermi 1st order)

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

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

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

Plasma Kinetic processes:

wave-particle interactions

pre-heating due to instabilities

PIC/Hybrid simulations

MHD waves

Fokker-Planck Equation

DC equation

Summary

1. Shocks are abundant in and around galaxy clusters:

- external accretion shocks: $10 < M < 10^2$: **not detected (not detectable)**
- internal shocks driven by mergers and chaotic flow: $M < 3$ } **Radio relics**
- infall shocks induced by infalls along filaments: $3 < M < 10$ } **X-ray shocks**

2. Mean IGMF is 0.1-1 μG in ICM, while 1-10 nG in filaments and cluster outskirts

3. Cluster accretion shock may accelerate protons up to 10^{18} eV.

4. CR/Gas energy ratio in ICM constrained by γ-ray observations: $\langle X_{CR} \rangle <\sim 0.01$

5. Mock observations of simulated clusters in the projected maps:

➔ $M_{\mathrm{X-ray}} \leq M_{\mathrm{radio}}$ **due to projection effects**

6. Re-acceleration model can explain most of observed features of radio relics

7. DSA efficiency & MFA at shocks with 2<M<5 in high beta plasma need to be studied with plasma simulations: $\eta(M, \theta)$, B/B_0

Review Papers: Bruggen et al. 2012, Brunetti & Jones 2014, 2015, Ryu et al. 2012