Shock Acceleration Model with Postshock Turbulence for Radio Relics

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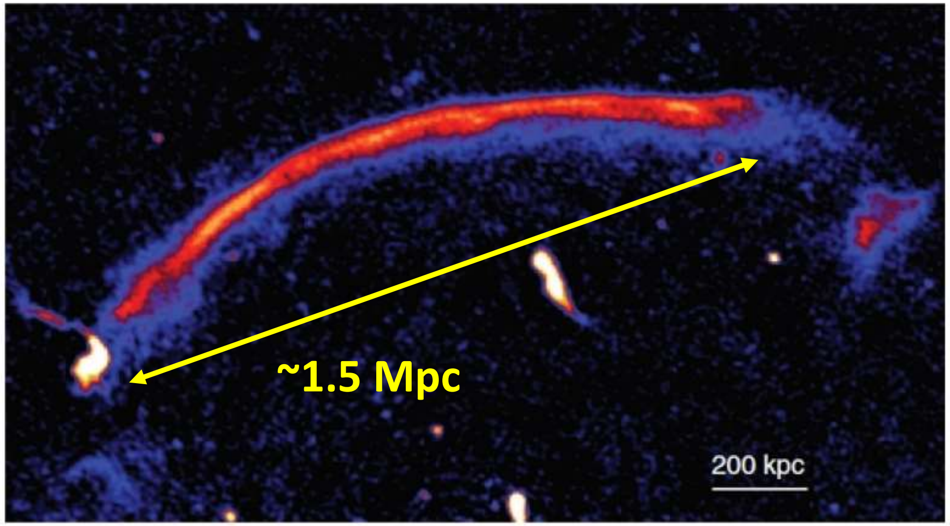
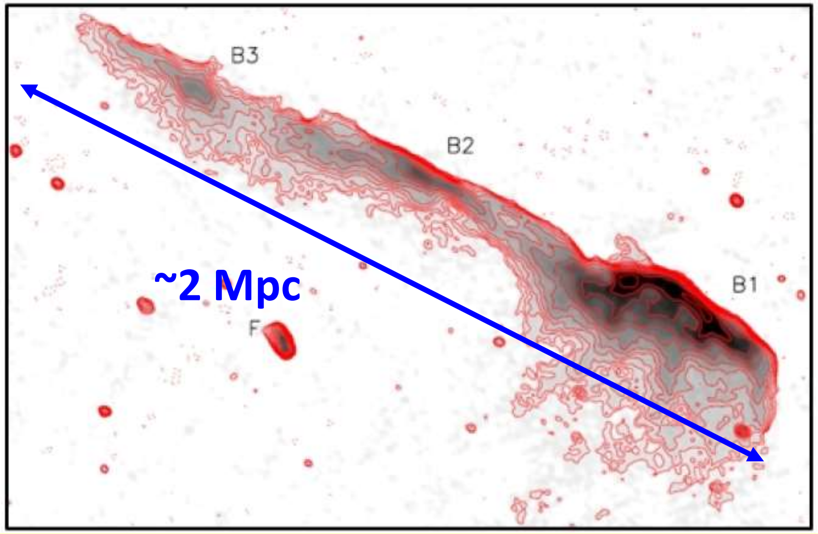
Kang, Ryu, Jones, 2017, ApJ

Sausage Relic in CIZA J2242.8+5301

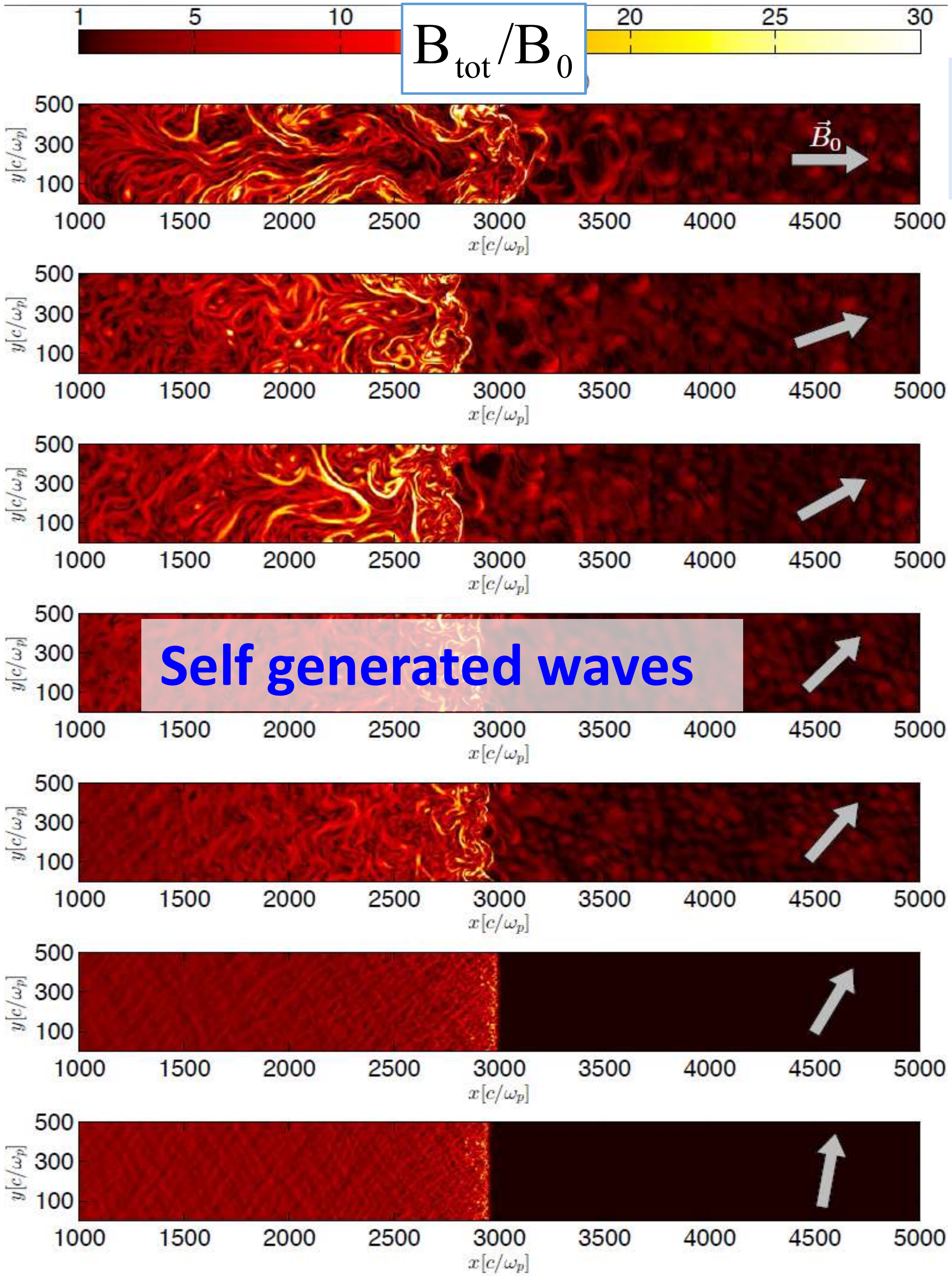


Toothbrush Relic in 1RXS J0603.3+4214



Diffuse radio sources on Mpc scales detected in the outskirts of galaxy clusters: synchrotron radiation emitted by ~GeV electrons accelerated at structure formation shocks via DSA (Fermi I) process.

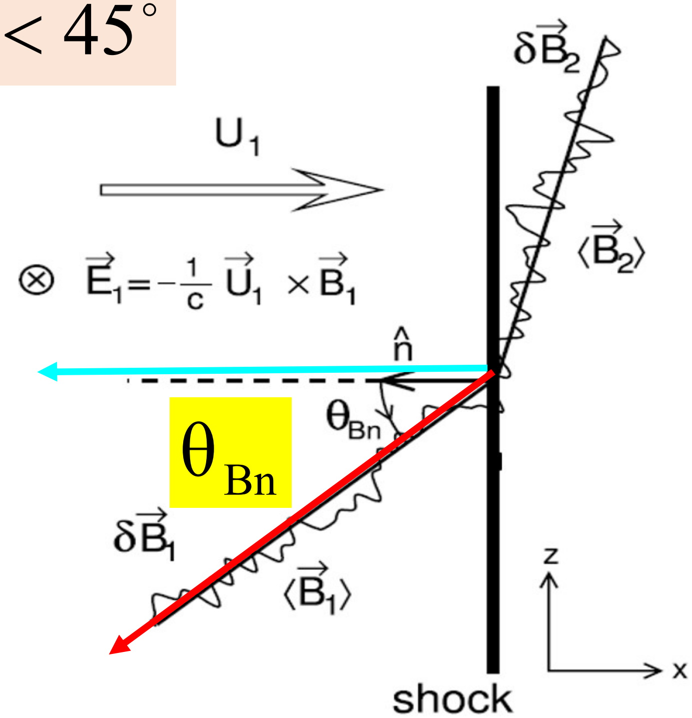
Characteristics of collisionless shocks depend on B field direction



Hybrid simulations by Caprioli & Sptikovsky 2014

Quasi-parallel= Q-par

$$\theta_{Bn} < 45^\circ$$



Quasi-perpendicular= Q-perp

$$\theta_{Bn} > 45^\circ$$

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	40	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	-
$M_A = u_s/v_A$	13	100	11	-

IPM =InterPlanetary Medium

ISM =InterStellar Medium

ICM =IntraCluster Medium

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

$$\alpha_p = \frac{\omega_{p,e}}{\Omega_{c,e}} \propto \frac{\sqrt{n_e}}{B}$$

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

θ_{Bn} : obliquity angle

ICM (cluster shocks) vs ISM (SNR shocks)

higher β_p : B pressure is dynamically less important in ICM

lower α_p : wave-part. interactions and stochastic acceleration more significant in ICM

particle acceleration at collisionless shocks depend on M_s, M_A, θ_{Bn}, β_p, α_p

Particle Acceleration Processes at collisionless shocks

(1) Diffusive Shock Acceleration (DSA): Fermi 1st order process

- effective at **quasi-parallel (Q-par)** shocks
- scattering off MHD waves in the upstream and downstream region

(2) Shock Drift Acceleration (SDA)

- effective at **quasi-perpendicular (Q-perp)** shocks
- drifting along the convective E field (grad B) at the shock front

$$\vec{E}_{conv} = -\frac{1}{c}\vec{V} \times \vec{B}_0$$

(3) Shock Surfing Acceleration (SSA)

- effective at **quasi-perpendicular (Q-perp)** shocks
- reflected by shock potential, scattered by upstream waves
- moving along the convective E field, while being trapped at the shock foot

at oblique shock

(4) Turbulent Acceleration (TA): Fermi 2nd order, stochastic acceleration

- much less efficient than Fermi I
- could be important in turbulent plasmas

(5) Turbulent Reconnection (TR) of Magnetic Fields

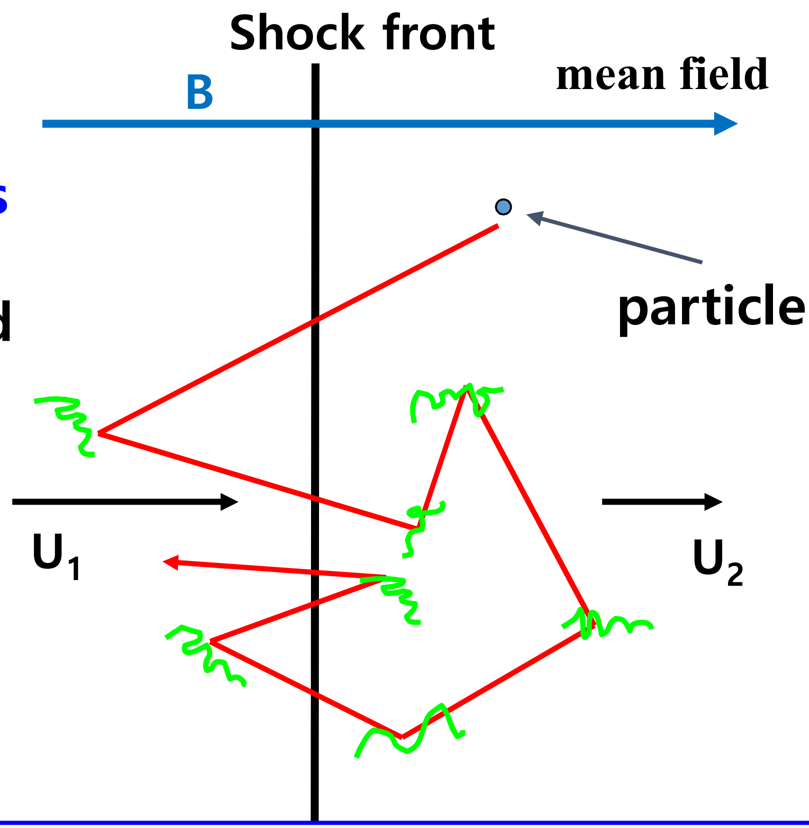
Essential ingredients: $\vec{B}_0$ & $\delta\vec{B}$

DSA: Fermi first order process

MHD waves in a converging flow act as converging mirrors

→ particles are scattered & isotropized by waves in local fluid frame
→ cross the shock many times

$$\frac{\Delta p}{p} \sim \frac{u_1 - u_2}{v} \text{ at each shock crossing}$$



test - particle limit solution

$$f_{\text{test}}(p) \propto p^{-q_{\text{test}}} \quad : \text{power - law}$$

$$q_{\text{test}} = \frac{3u_1}{(u_1 - u_2)} = \frac{4M_s^2}{M_s^2 - 1}$$

→

radio synchrotron emission

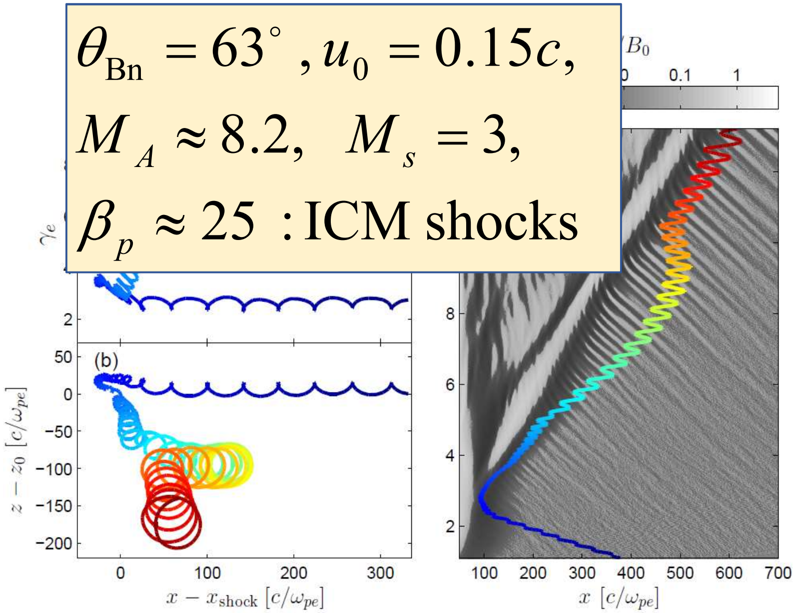
$$j_\nu \propto \nu^{-\alpha}$$

$$\alpha = \frac{q-3}{2} = \frac{M_s^2 + 3}{2(M_s^2 - 1)}$$

PIC simulations of Q-perp shocks (high β)

Guo, Sironi, & Narayan 2014

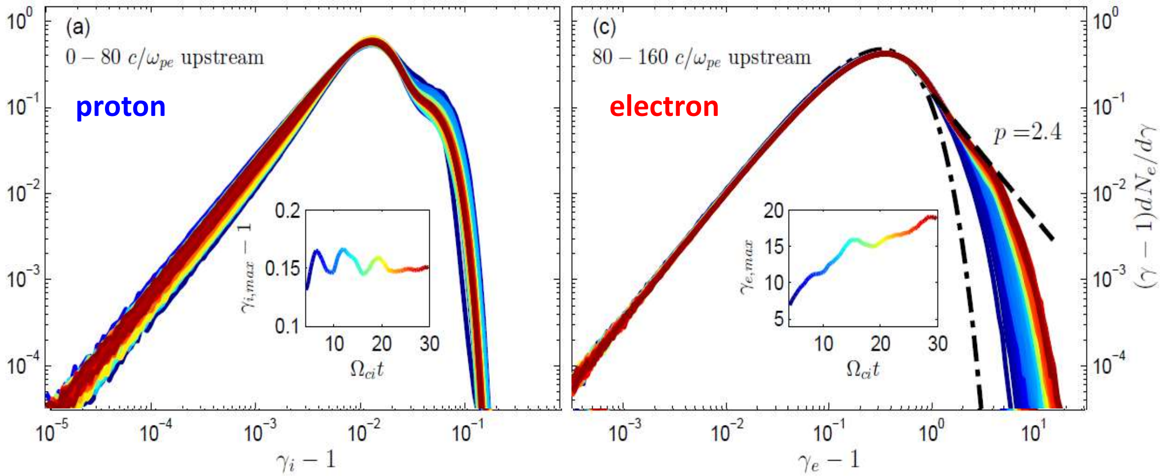
$$\theta_{\rm Bn} = 63^\circ, u_0 = 0.15c,$$
$$M_A \approx 8.2, \quad M_s = 3,$$
$$\beta_p \approx 25 \ : \text{ICM shocks}$$



Evolution of an electron undergoing multiple SDA

Reflection of some electrons
due to Magnetic mirror at shock $T_{\parallel,e} > T_{\perp,e}$

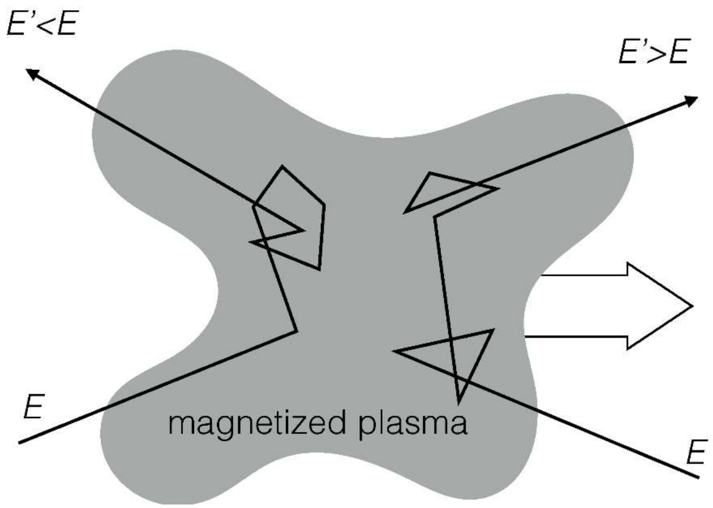
➔ Induce temperature anisotropy in the upstream
➔ firehose instability excites waves
➔ Reflected electrons are scattered back to the shock downstream by the waves
➔ Undergo multiple SDA cycles



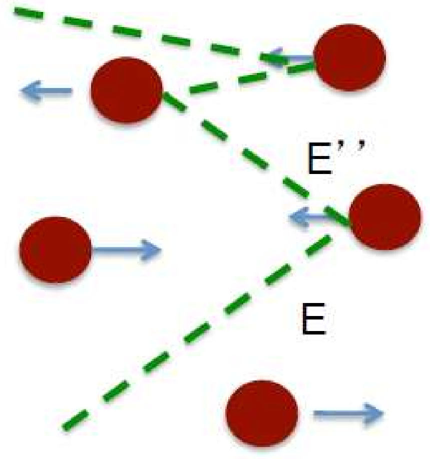
Energy spectrum

Multiple SDA for electrons
→suprathermal tail
→Pre-acceleration for DSA
→ injected to Fermi I

Fermi 2nd order process= Turbulent acceleration



$$\frac{\Delta E}{E} \sim \left(\frac{V}{c}\right)^2$$



Scatterings by turbulence (randomly moving clouds)

Fermi 1949

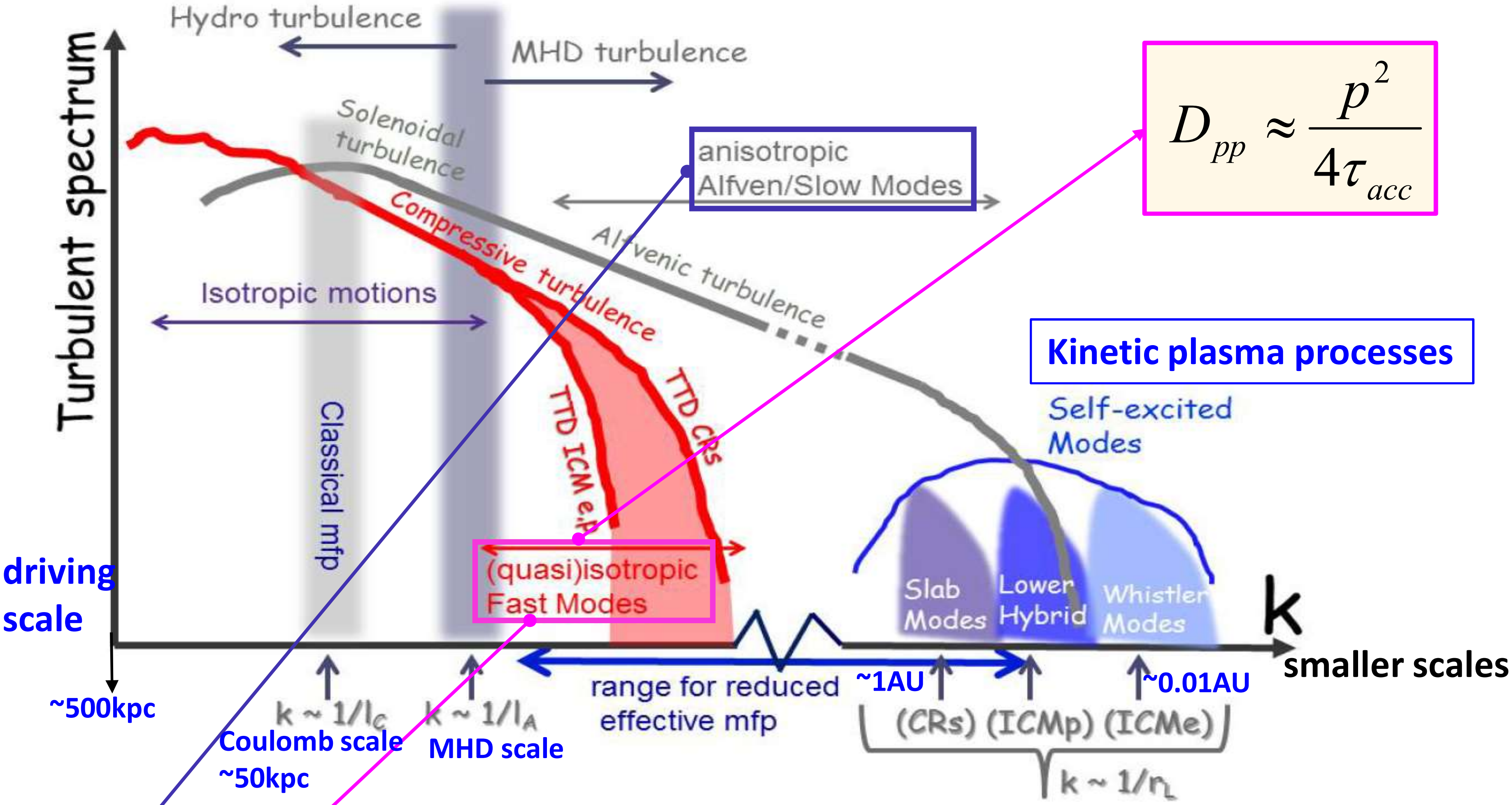
Stochastic energy gain in collisions with MHD/plasma waves (head-on collisions are more frequent than over-taking collisions)
➔ 2nd order in energy gain (slow and inefficient)

CR particles (protons + electrons) could be accelerated via Fermi II acceleration by turbulence in ICM.

Power-spectrum of Turbulence in the ICM

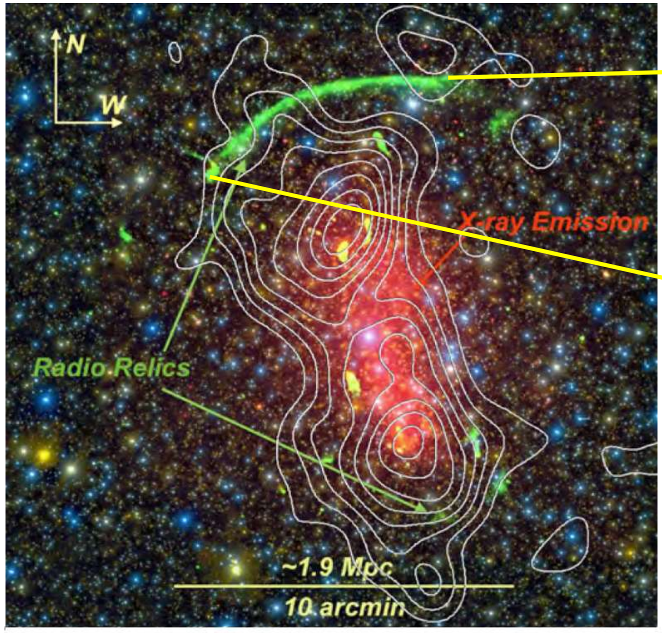
Brunetti & Lazarian 2011
Brunetti & Jones 2014

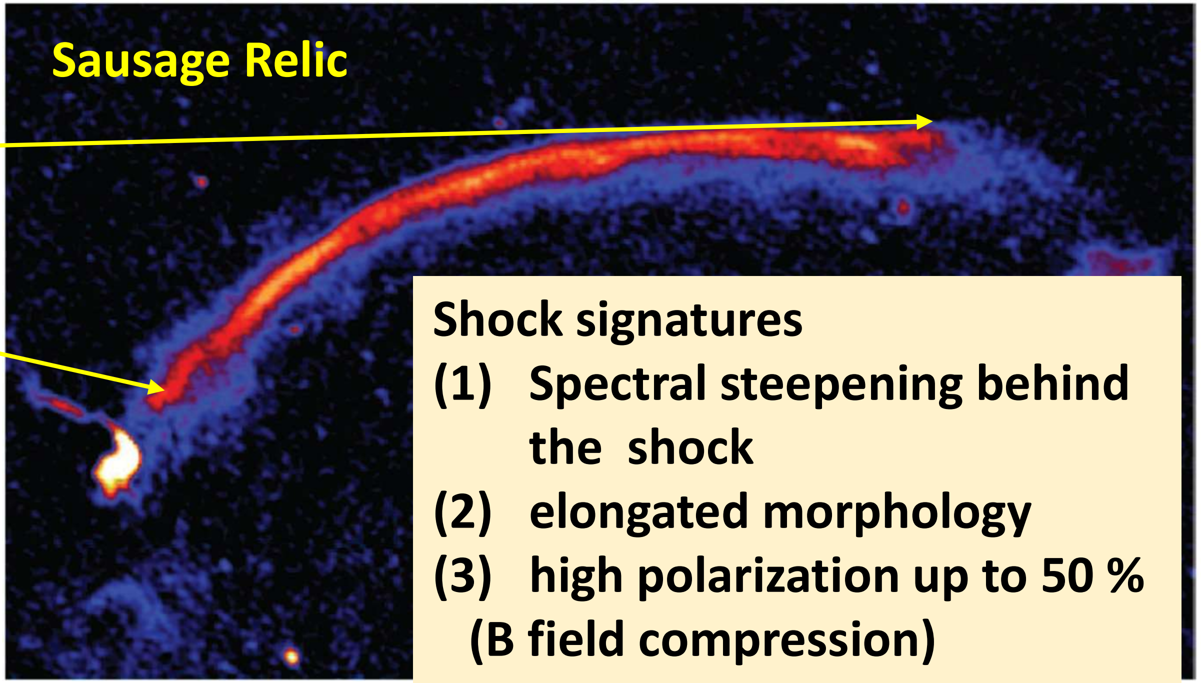
$$D_{pp} \approx \frac{p^2}{4\tau_{acc}}$$



-Alfven and slow modes become anisotropic at small scales, so scattering by Alfvenic turbulence becomes inefficient. (Cho & Lazarian 2003)
-But fast mode remains isotropic at small scales, so Transit Time Damping (TTD) with fast modes is dominant in ICM (Brunetti & Lazarian 2007)

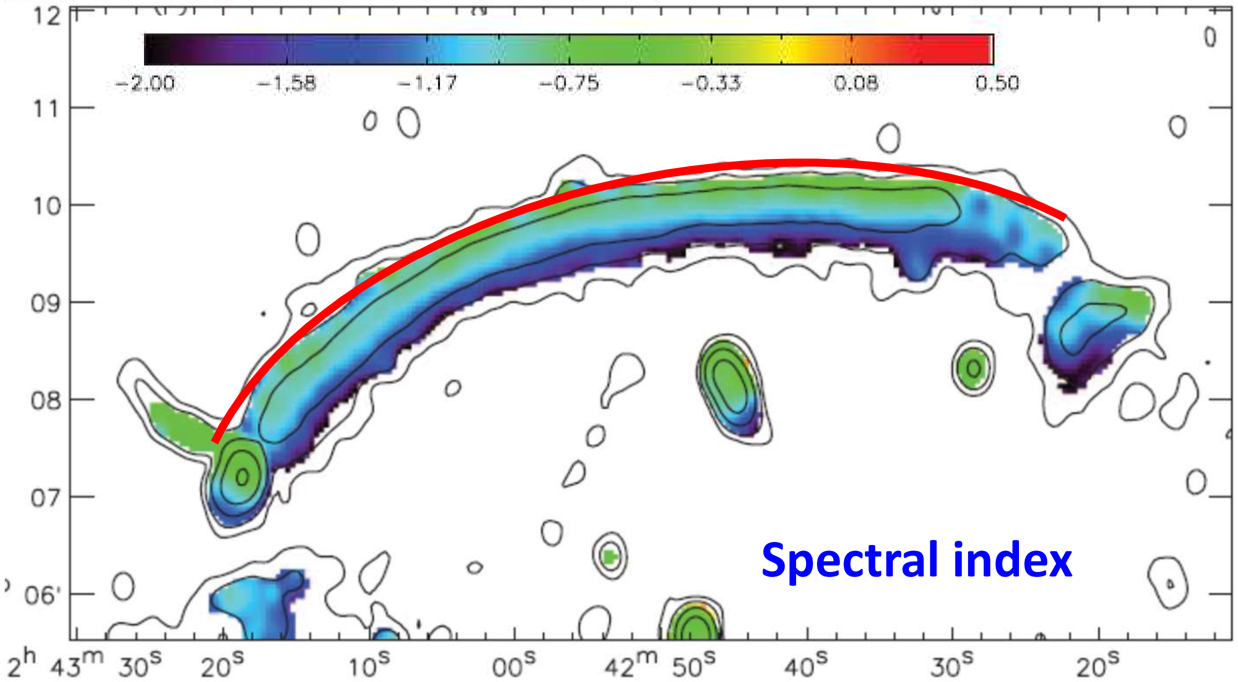
cluster CIZAJ2242.8+5301





Shock signatures

1. (1) Spectral steepening behind the shock
2. (2) elongated morphology
3. (3) high polarization up to 50 % (B field compression)



$$F_\nu \propto \nu^{-\alpha}$$

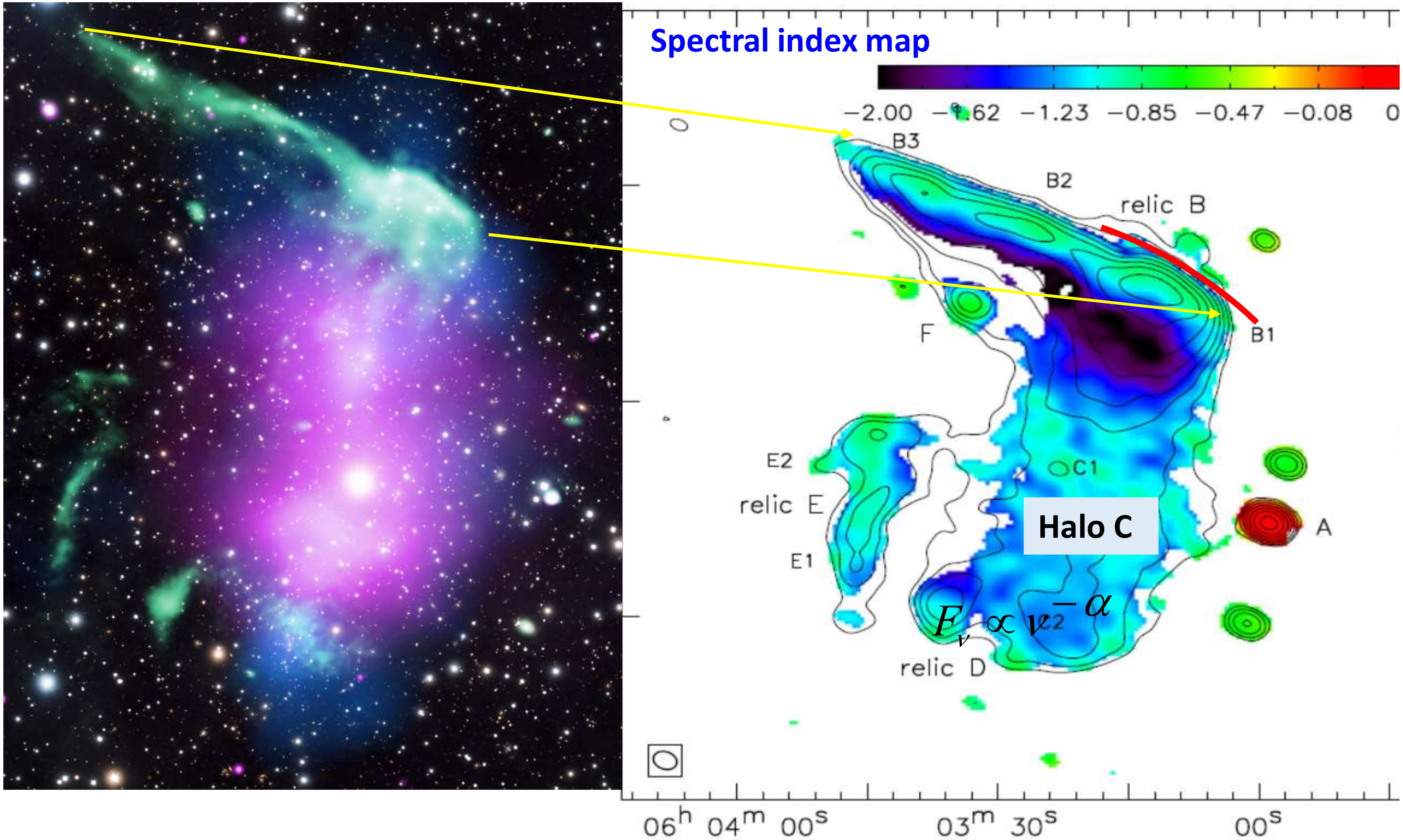
$$M^2_{radio} = \frac{(3+2\alpha_{sh})}{(2\alpha_{sh}-1)}$$

$M_{radio} \approx 4.6$

but $M_X \approx 2.7$ from

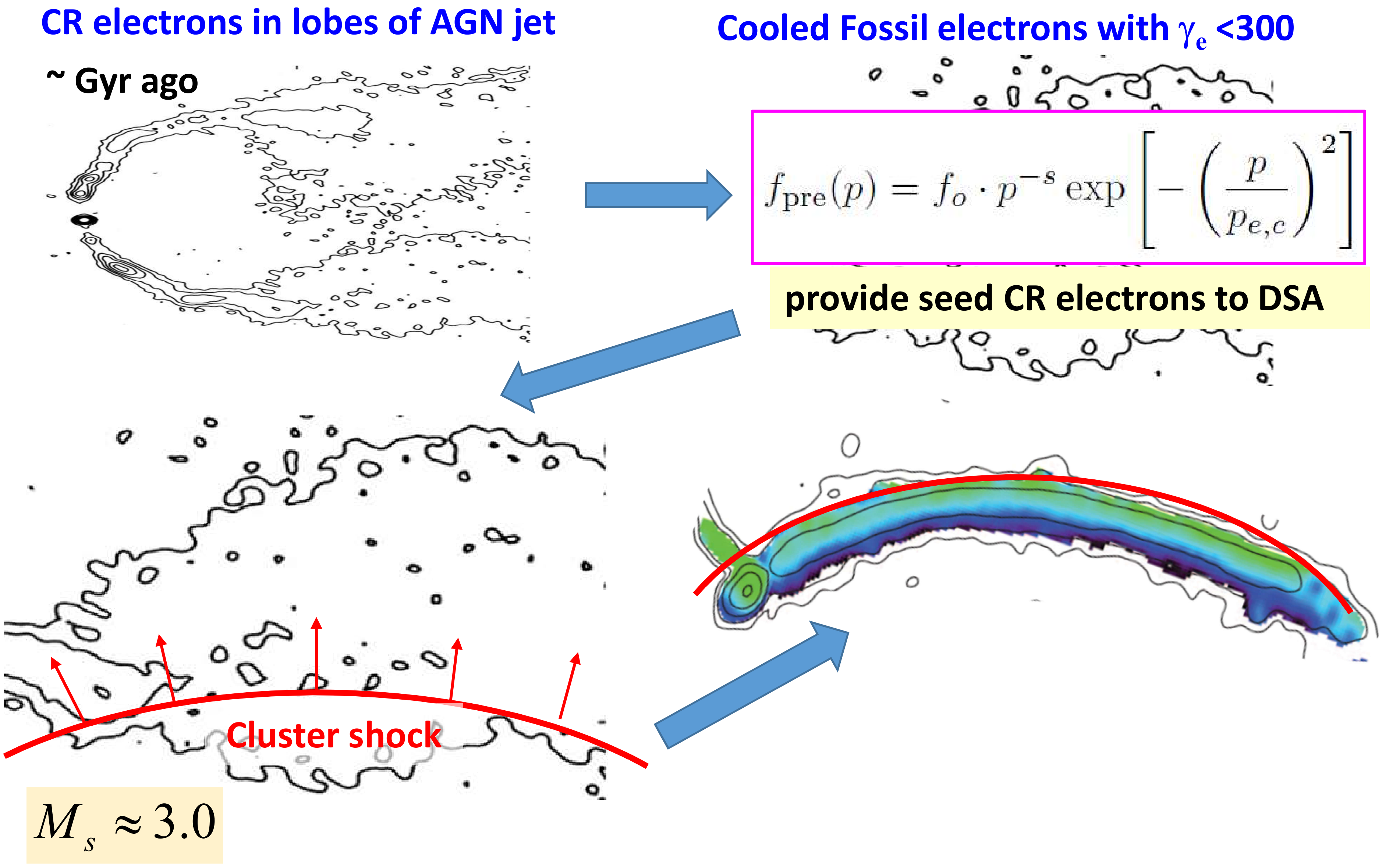
$$\frac{T_2}{T_1} = \frac{(M_X^2+3)(5M_X^2-1)}{16M_X^2}$$

cluster 1RXS J060303.3 Toothbrush Relic



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

Reacceleration Model for Formation of Giant Radio Relics



DSA simulations in test-particle limit

in a co-expanding frame which expands with 1D spherical shock.

ordinary gasdynamic Eqs (high beta)

$$\frac{\partial\tilde{\rho}}{\partial t}+\frac{1}{a}\frac{\partial(\upsilon\tilde{\rho})}{\partial x}=-\frac{2}{ax}\tilde{\rho}\upsilon$$

$$\frac{\partial(\tilde{\rho}\upsilon)}{\partial t}+\frac{1}{a}\frac{\partial(\tilde{\rho}\upsilon^2+\tilde{P}_g)}{\partial x}=-\frac{2}{ax}\tilde{\rho}\upsilon^2-\frac{\dot{a}}{a}\tilde{\rho}\upsilon-\ddot{a}x\tilde{\rho}$$

$$\frac{\partial(\tilde{\rho}\tilde{e}_g)}{\partial t}+\frac{1}{a}\frac{\partial(\tilde{\rho}\tilde{e}_g\upsilon+\tilde{P}_g\upsilon)}{\partial x}=-\frac{2}{ax}(\tilde{\rho}\tilde{e}_g\upsilon+\tilde{P}_g\upsilon)-2\frac{\dot{a}}{a}\tilde{\rho}\tilde{e}_g-\ddot{a}x\tilde{\rho}\upsilon-\tilde{L}(x,t)$$

$x=r/a$: co-moving coordinate, $a=$ expansion factor

CR transport Equation for electron distribution function

$$\frac{\partial g_e}{\partial t}+u\frac{\partial g_e}{\partial r}=\frac{1}{3r^2}\frac{\partial(r^2u)}{\partial r}\left(\frac{\partial g_e}{\partial y}-4g_e\right)$$
$$+\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\kappa(r,p)\frac{\partial g_e}{\partial r}\right]+p\frac{\partial}{\partial y}\left[\frac{D_{pp}}{p^3}\left(\frac{\partial g_e}{\partial y}-4g_e\right)\right]+p\frac{\partial}{\partial y}\left(\frac{b}{p^2}g_e\right)$$

$g_e=f_e\cdot p^4,\ y=\ln(p/m_ec)$

Spatial diffusion = Fermi I

Momentum diffusion = Fermi II

Coulomb/ Synchrotron/iC losses

Table 1. Parameters for Model Spherical Shocks

Model	M_X	M_{radio}	$M_{s,i}$	kT_1 (keV)	B_1 (μG)	t_{obs} (Myr)	$M_{s,obs}$	$kT_{2,obs}$ (keV)	$u_{s,obs}$ (km s^{-1})	N (10^{-4})
Sausage	2.7	4.6	4.0	2.1	1	211	3.21	8.6	2.4×10^3	1.2
Toothbrush	1.5	2.8	3.6	3.0	1	144	3.03	11.2	2.7×10^3	5.0

M_X: Mach number inferred from X-ray observations

M_{radio}: Mach number estimated from observed radio spectral index at the relic edge

$M_{s,i}$: initial shock Mach number at the onset of the simulations ($t_{age} = 0$)

kT_1: gas temperature in the preshock ICM

B_1: magnetic field strength in the preshock ICM

t_{obs}: shock age when the simulated results match the observations

$M_{s,obs}$: shock Mach number at t_{obs}

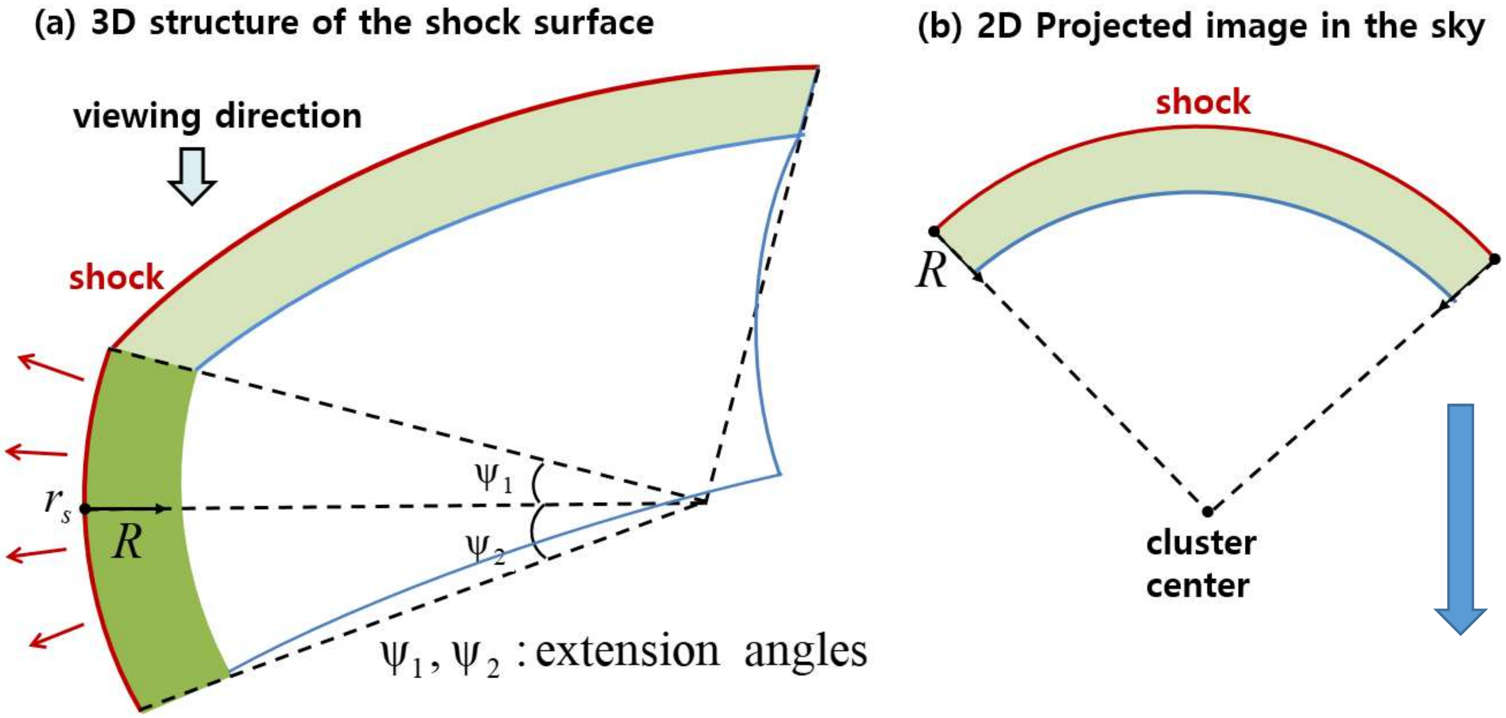
$kT_{2,obs}$: postshock temperature at t_{obs}

$u_{s,obs}$: shock speed at t_{obs}

$N = P_{CRe}/P_g$: the ratio of seed CR electron pressure to gas pressure in the preshock region

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

The spherical shock slows down and its Mach number decreases in time.



Surface brightness profile

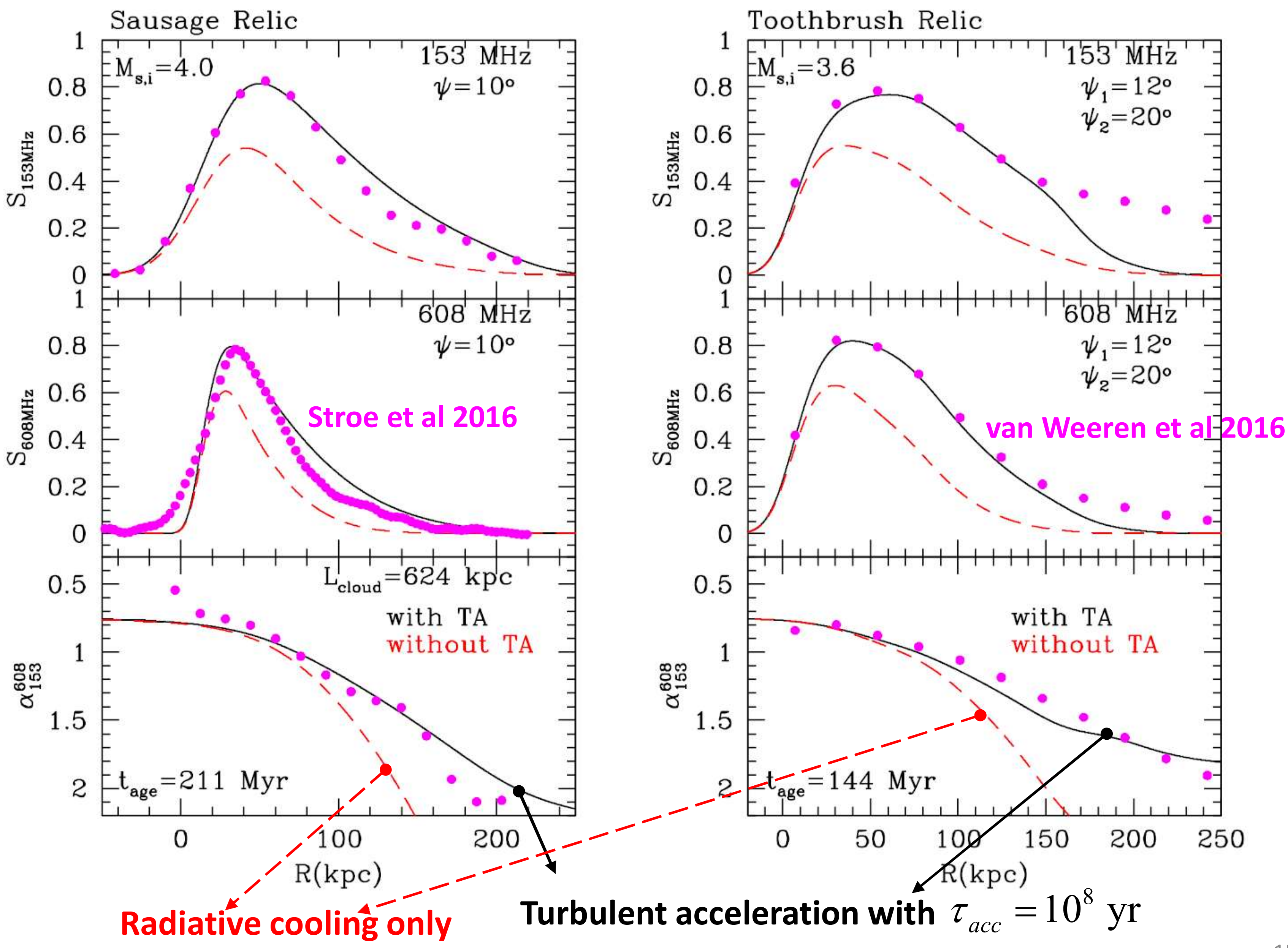
$$I_\nu(R) = \int_0^{h_{1,\max}} j_\nu(r)\,dh_1 + \int_0^{h_{2,\max}} j_\nu(r)\,dh_2$$

Radio flux density profile

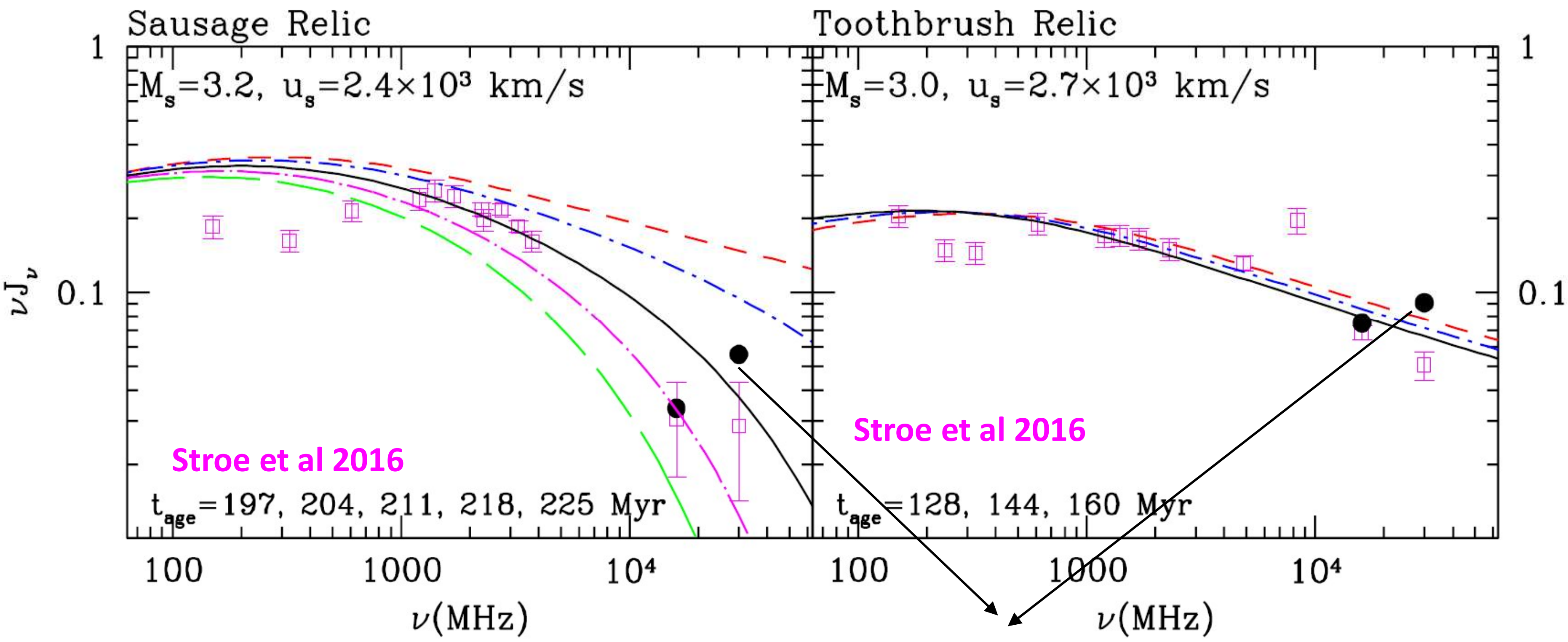
$$S_\nu(R) = \int_{beam} I_\nu(R)\,d\Omega$$

Smoothed over telescope beam

Fitting of Radio Flux Profiles



Fitting of Radio Integrated Spectra



SZ corrected flux by Basu et al. 2016

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

show reasonable agreement with observed data.

Summary

-Shock Acceleration model with M ~3 shock & postshock turbulence acceleration can reproduce observed profiles of radio flux $S_\nu(R)$ & integrated spectrum J_ν of the Sausage and the Toothbrush relic.

-need to understand better the properties of possible turbulence generated behind weak ICM shocks.

-need to study further collisionless shocks in β=100 plasma.

-These radio relics provide observational signatures of shocks in galaxy clusters.