# Re-acceleration Model for Radio Relics in Galaxy Clusters

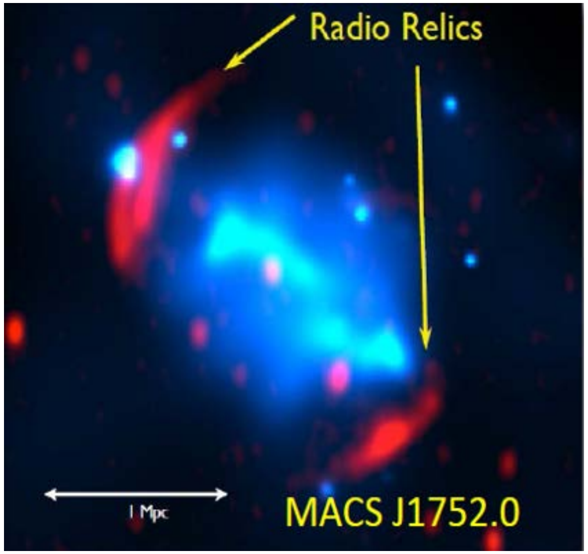
## + turbulent acceleration in the postshock region

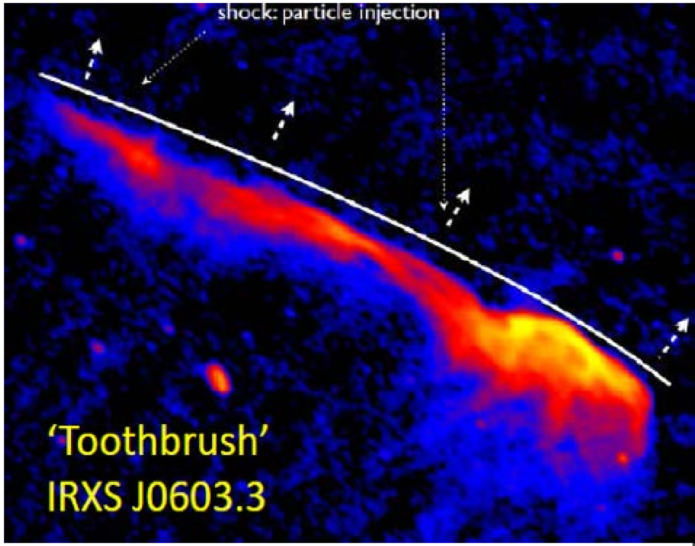
**Hyesung Kang**
Pusan National Univ., Korea

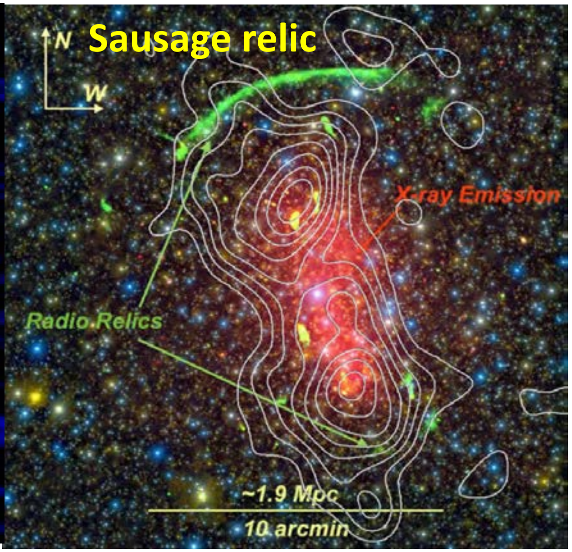
**Dongsu Ryu**
UNIST (Ulsan National Institute of Science & Technology), Korea

**T. W. Jones**
University of Minnesota

# **Radio relics**: diffuse radio sources found mainly in merging clusters





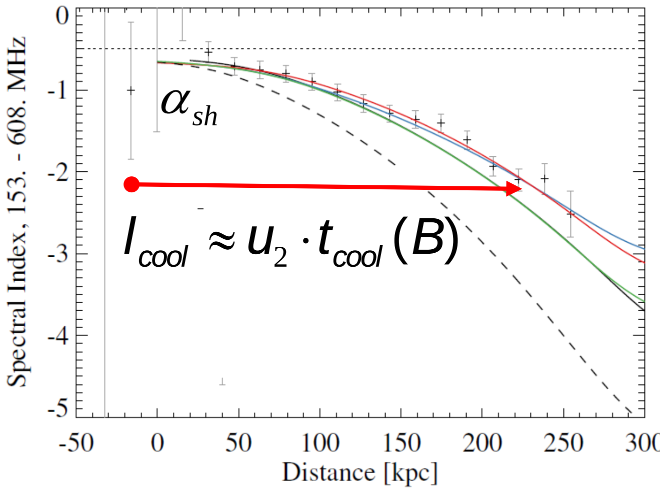


- **elongated morphology**
- **spectral aging behind the shock (due to radiative cooling)**
- **power-law like integrated radio spectrum**
- **high polarization up to 50 % (B field compression)**

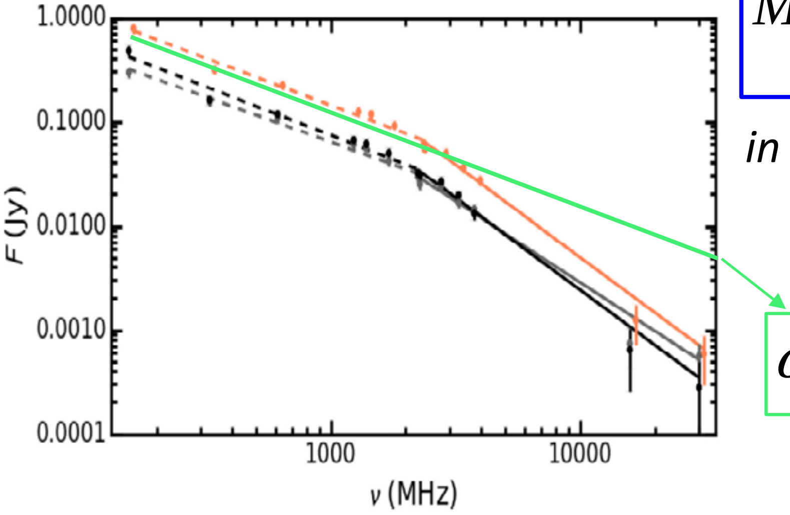
**→synchrotron radiation emitted by ~GeV electrons accelerated at structure formation shocks**

# Radio vs. X-ray Observations of Radio Relics

**Spectral index profile**



**Integrated radio spectrum**

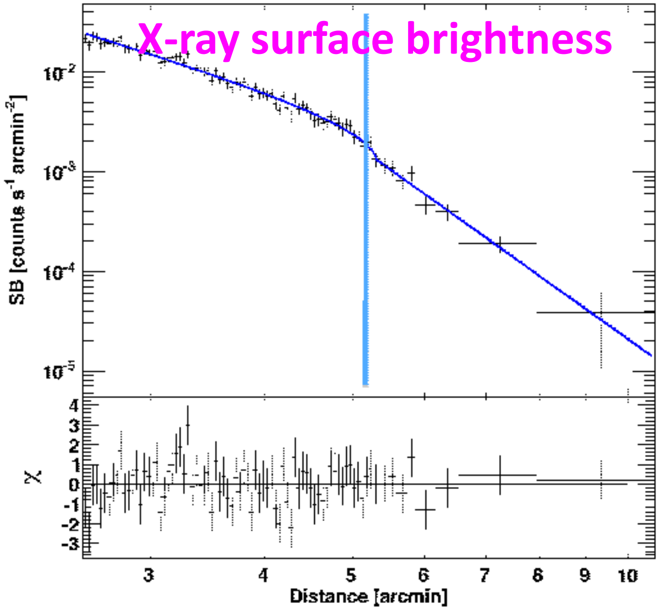


$$M_{radio}^2 = \frac{(3+2\alpha_{sh})}{(2\alpha_{sh}-1)}$$

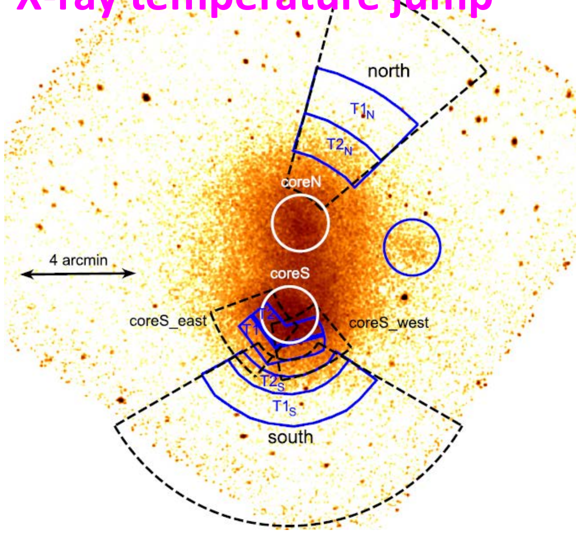
*in situ* injection model

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

**X-ray surface brightness**



**X-ray temperature jump**



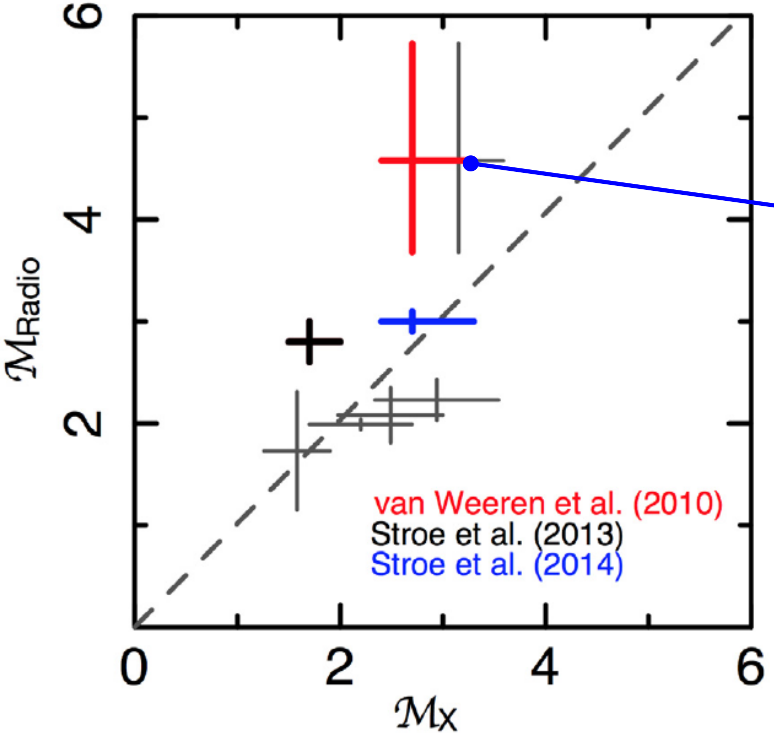
$$\frac{T_2}{T_1} = \frac{(M_X^2+3)(5M_X^2-1)}{16M_X^2}$$

$c_{s,1}$ = sound speed

$V_s$ = shock speed

*** Projection effects**

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



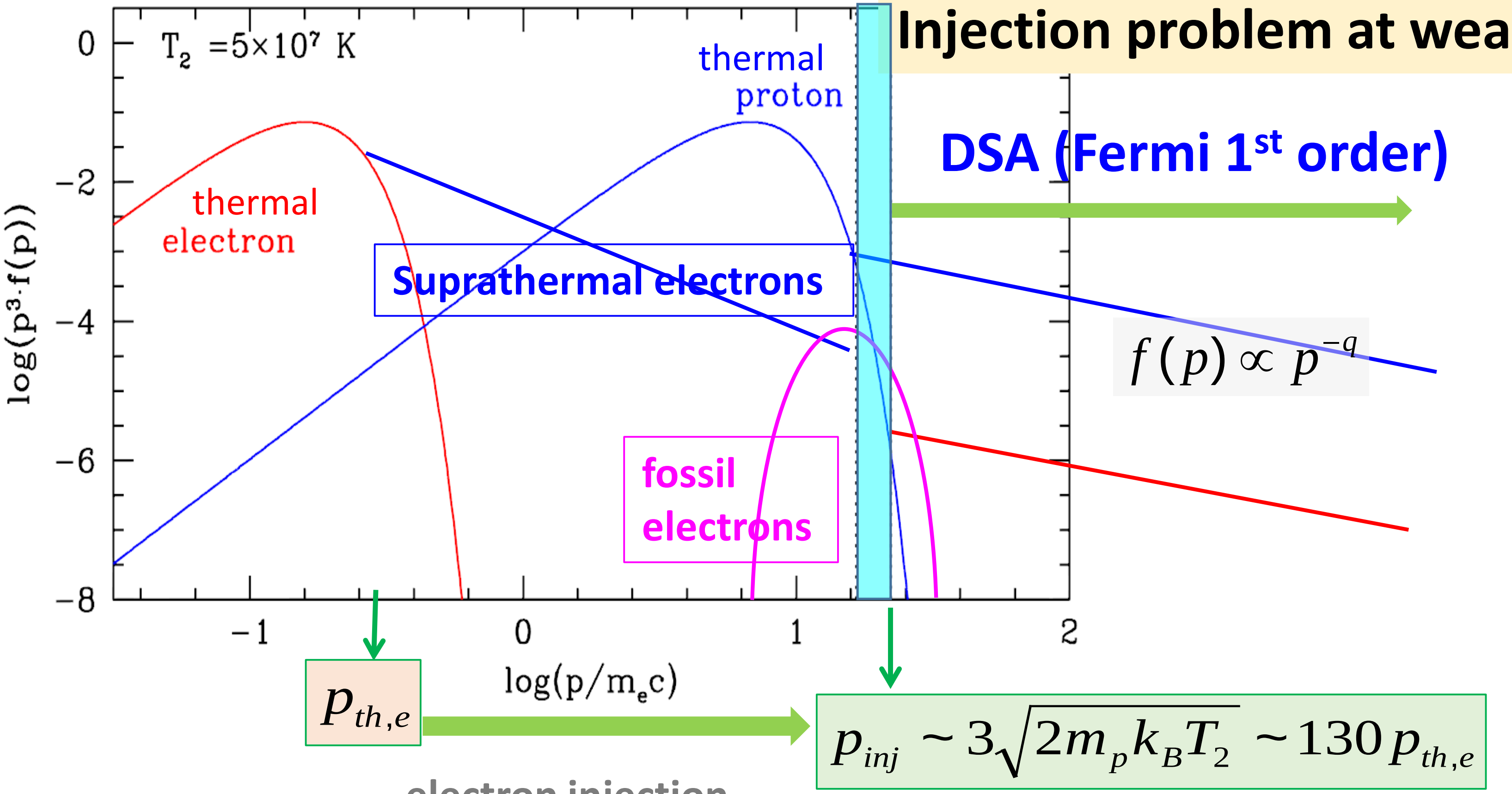
**Akamatsu et al. 2015**

**(1) For some radio relics,** $M_{radio} > M_X$

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

**(2) Low injection/acceleration efficiency expected for weak shocks that form in ICM** $(M < 3)$

# Injection problem at weak shocks



**DSA (Fermi 1st order)**

**Suprathermal electrons**

**fossil electrons**

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

$p_{th,e}$

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

**electron injection**

(pre-acceleration)

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

Electrons need to be pre-accelerated to $p_{inj}$ in order to get injected into DSA process

**In-situ injection** at the shock from **thermal electrons** is **very inefficient at weak shocks.**

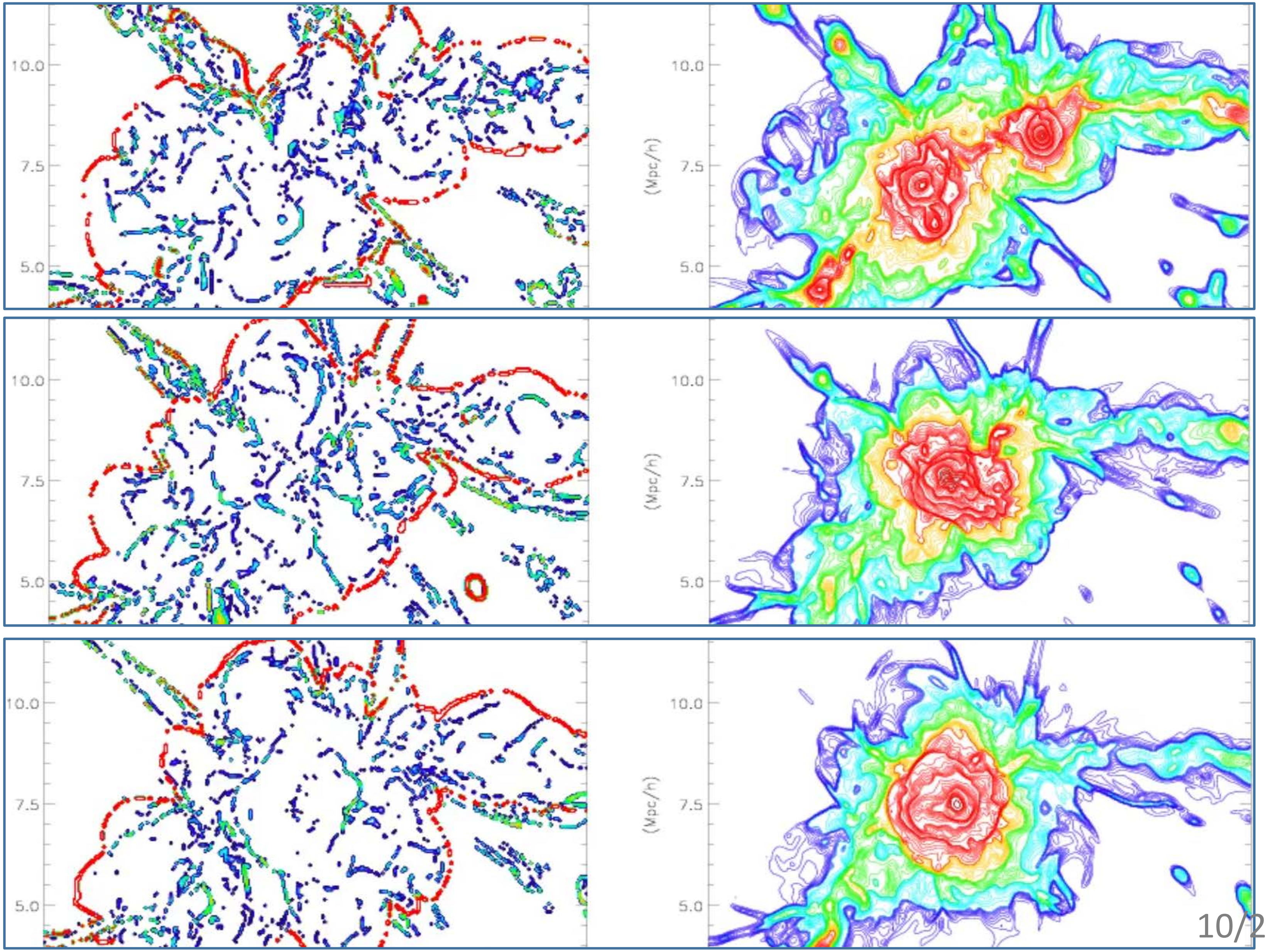
**If there are suprathermal/fossil electrons in the preshock region**

➔ **enhance injection into DSA**

# Ubiquitous presence of structure formation shocks in ICM

Shock distribution by Mach number

X-ray emissivity



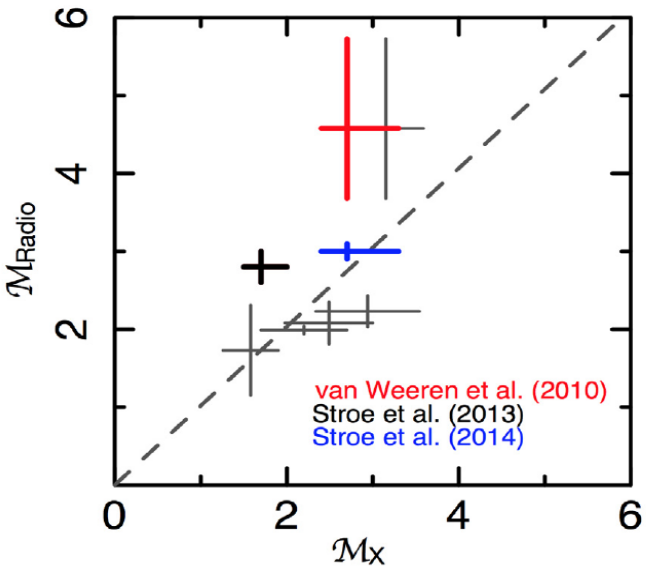
Z=0.65

Z=0.30

Z=0.22

Ha, Ryu, & Kang 2016

# Some puzzles with *in situ* injection model



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

(2) Low acceleration efficiency of weak shocks $(M < 3)$

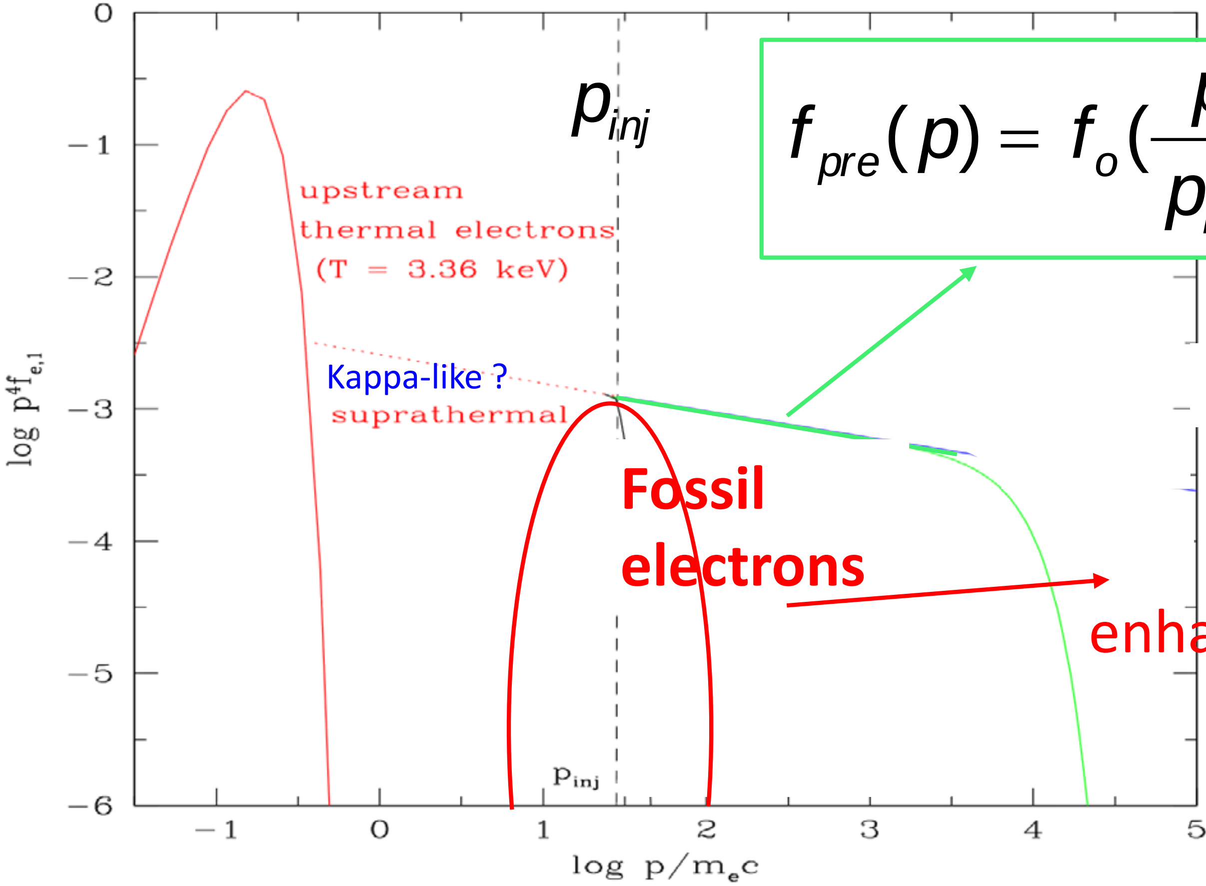
**(3) Only ~10 % of merging clusters host radio relics, while numerous shocks are expected to form in ICM.**

**(4) Some X-ray shocks without associated radio relics**

**(3) & (4) ➔ Not all shock can accelerate electrons and become radio relics.**

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

# Pre-existing electrons: fossil or live (radio-bright)



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

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

**live** radio bright electrons

**Fossil electrons**

enhance injection efficiency

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

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

# Diffusion-Convection Equation for electron distribution function

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} = \frac{p}{3}\frac{\partial u}{\partial x}\frac{\partial f}{\partial p} + \frac{\partial}{\partial x}\left(\kappa\frac{\partial f}{\partial x}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\dot{p}f\right)$$

spatial diffusion= Fermi 1st order acc.

**Momentum diffusion = stochastic acceleration**

**Coulomb/ Synchrotron/iC losses**

$$\text{momentum diffusion due to TTD}: \quad D_{pp} \approx \frac{p^2}{4\tau_{acc}} \cdot \exp\left(-\frac{R}{R_{\text{decay}}}\right)$$

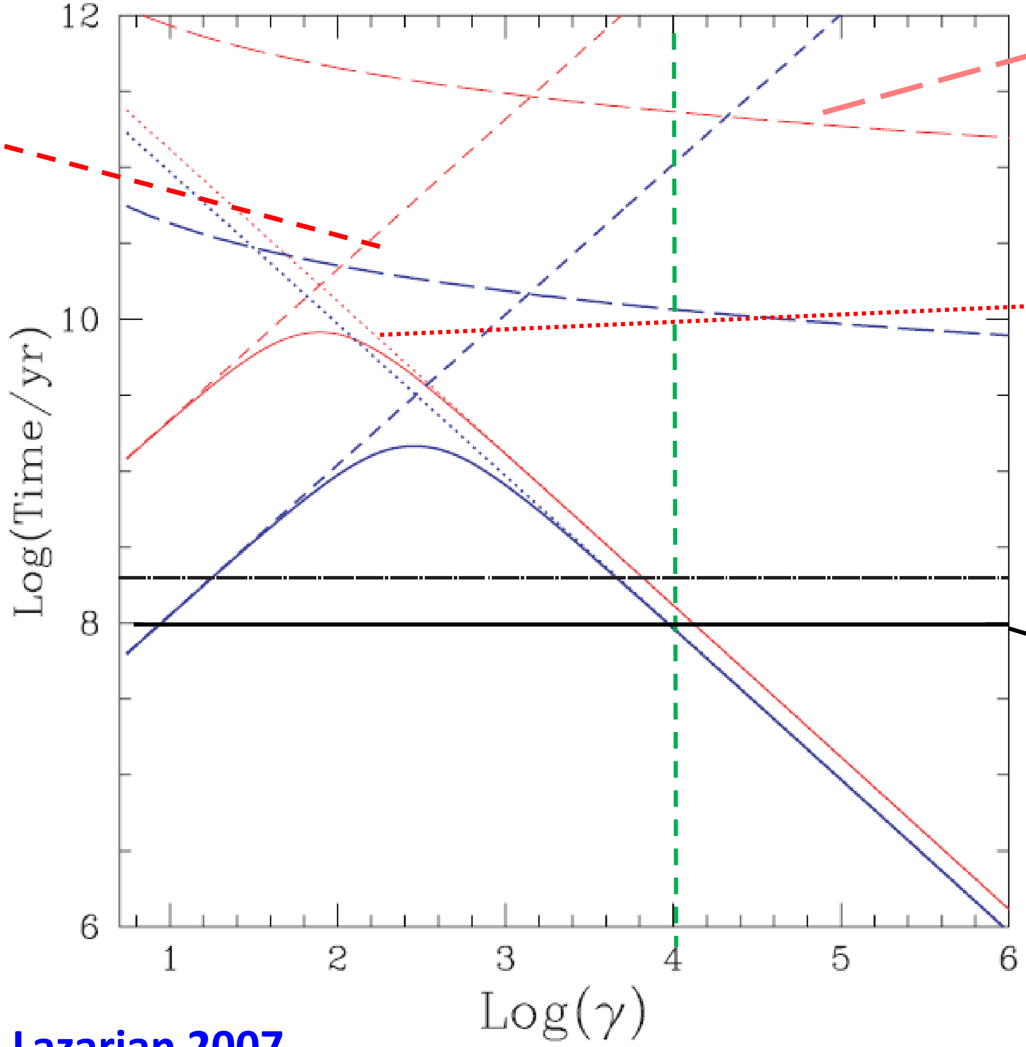
$$\text{where } \tau_{acc} \sim 10^8\, yr : \text{systematic acceleration time}$$

**Brunetti & Lazarian 2007, 2011**

$$\text{simple model for decay of turbulence with } R_{\text{decay}} \sim 100\ \text{kpc}$$

Kang, Ryu, & Jones 2016 (in preparation)

# Electron lifetime in the ICM : $B \approx 0.5\mu\mathrm{G},\ \mathrm{n_H} \approx 10^{-4}\ \mathrm{cm^{-3}}$



Coulomb cooling

Bremsstrahlung

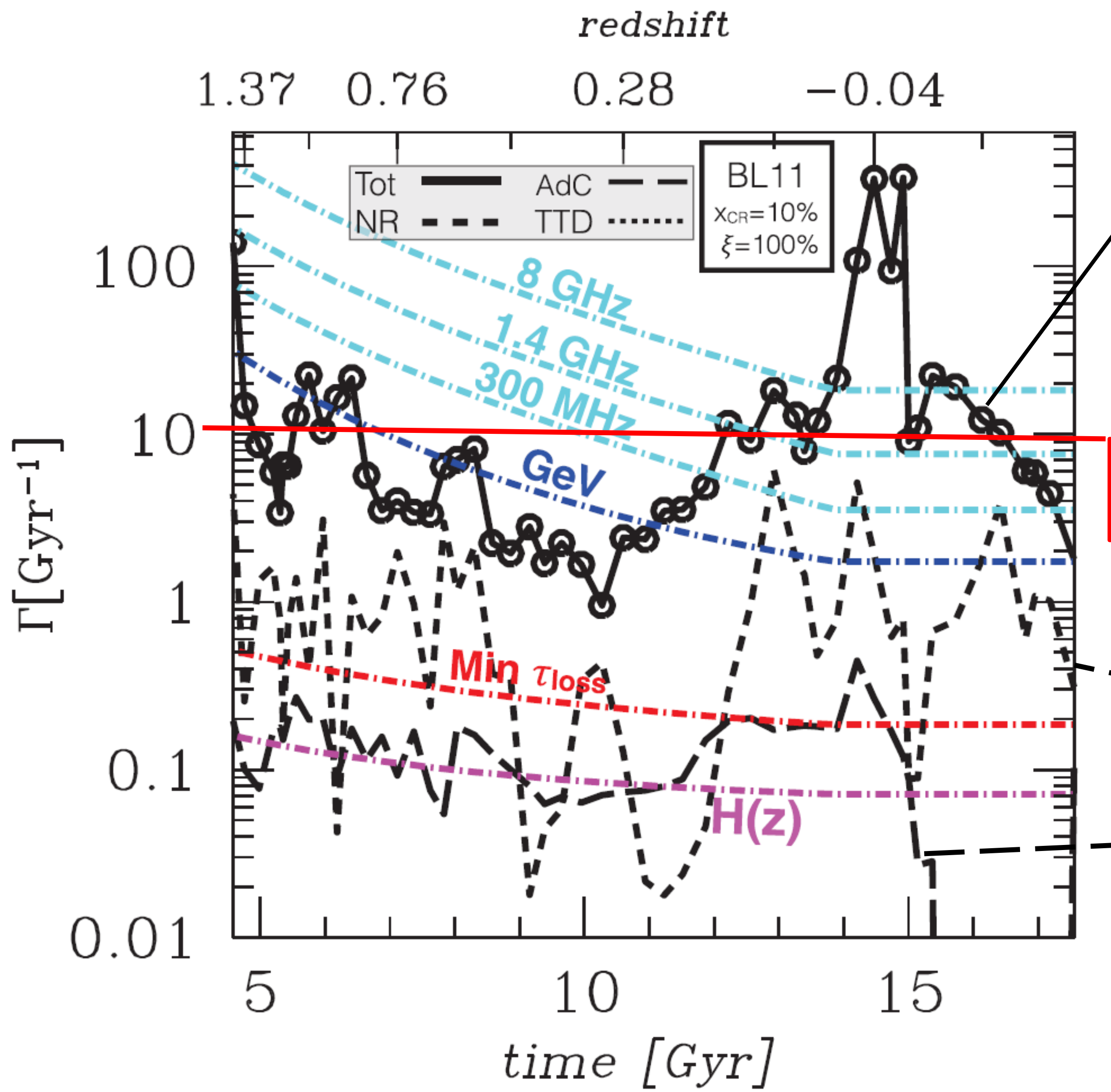
Sync/IC cooling

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

due to TDD resonance of ICM turbulence in merging clusters

Brunetti & Lazarian 2007

# Acceleration Rate due to ICM Turbulence based on Brunetti & Lazarian 2011



**Miniati 2015**

$\Gamma = 1/\tau_{acc}$

due to TDD resonance

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

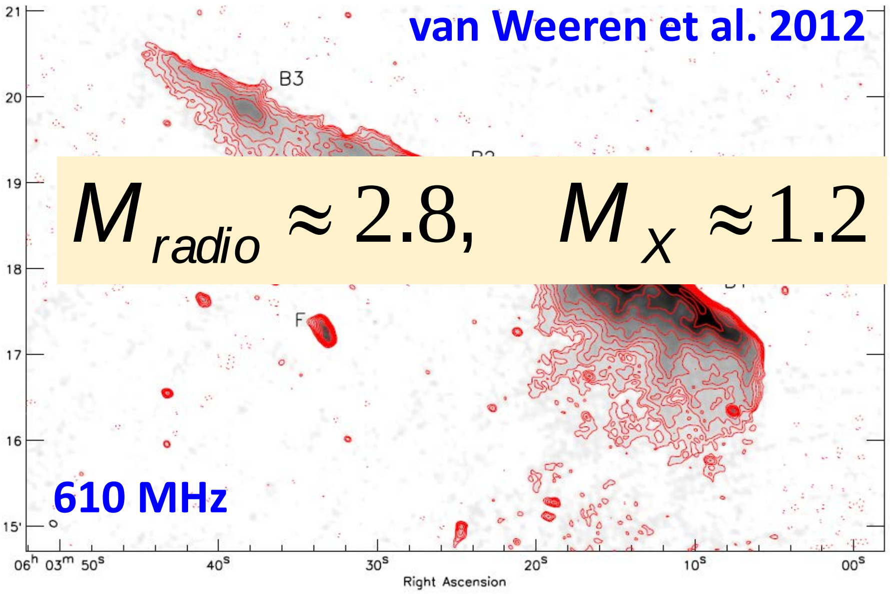
$\tau_{acc} \sim 10^8\, yr$

Non-resonant acceleration

Adiabatic Compression

**Structure formation simulations → Turbulence in ICM → Turbulence Acceleration rate**

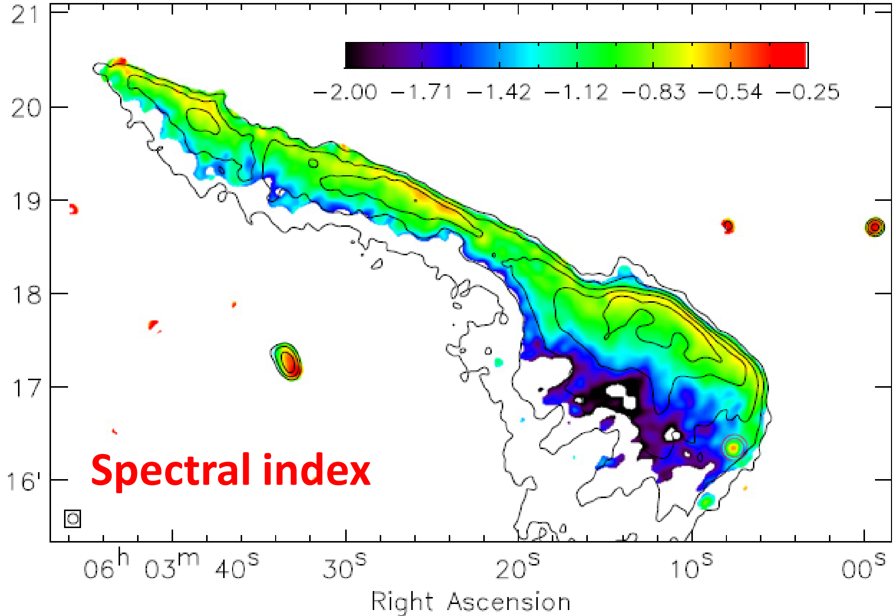
# **Toothbrush relic in** RX J0603.3



**van Weeren et al. 2012**

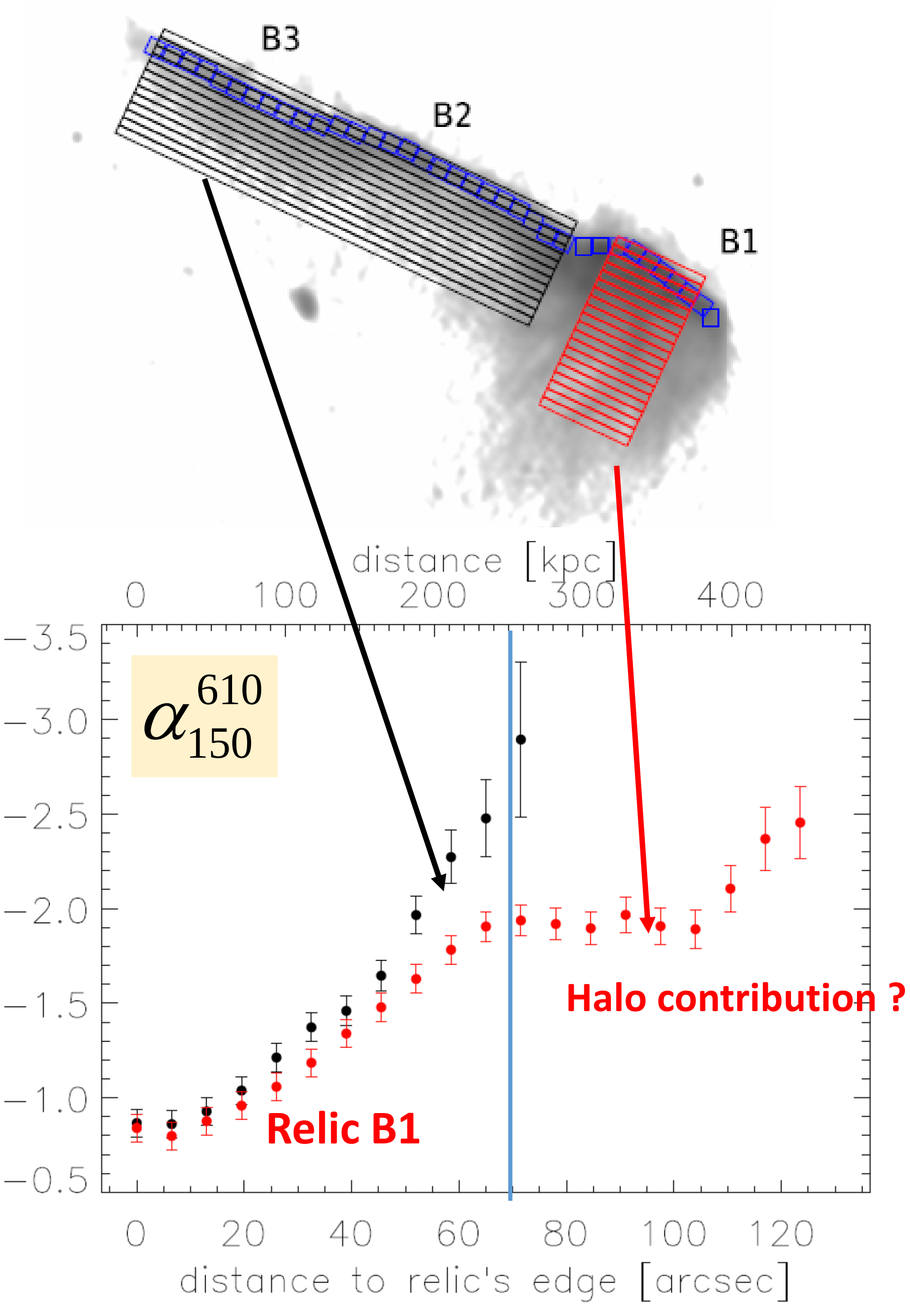
$$M_{radio} \approx 2.8, \quad M_X \approx 1.2$$

**610 MHz**



**Spectral index**

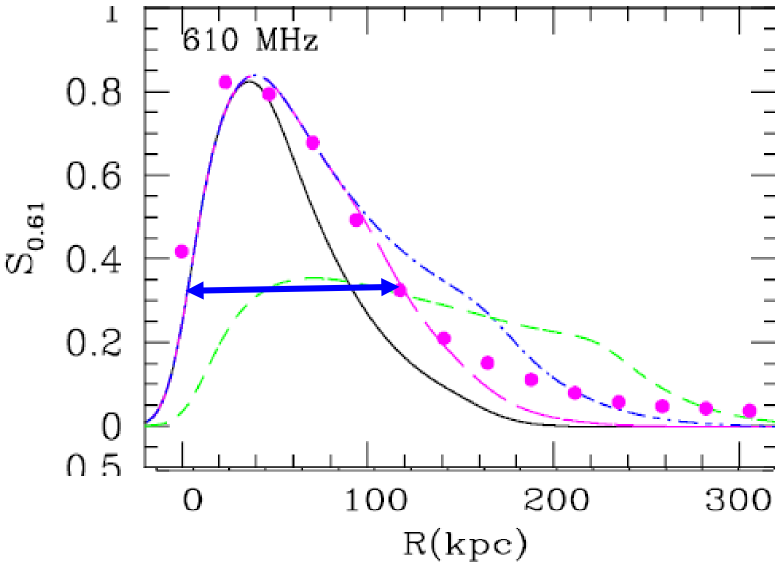
**van Weeren et al. 2016**



$$\alpha_{150}^{610}$$

**Relic B1**

**Halo contribution ?**



## Shock Parameters

$M_s \approx 1.4,\ kT_1 = 6.9\,\text{keV},$

$u_s \approx 1.8 \times 10^3$ km/s

radio flux profile at 610 MHz,

$\Delta l \sim 100$ kpc

**Relic Width at a given frequency ~ cooling length of electrons**

$$l_{cool} \approx u_2 \cdot t_{cool}(B,z) \approx 100\text{kpc} \cdot W_h \cdot u_{2,3} \cdot Q(B,z) \cdot \left[\frac{\nu_{obs}(1+z)}{0.63\text{GHz}}\right]^{-1/2}$$

**depends on the postshock flow speed and magnetic field strength**

$u_{2,3} = u_2 / 1000\text{km/s}, W_h \sim 1.3$

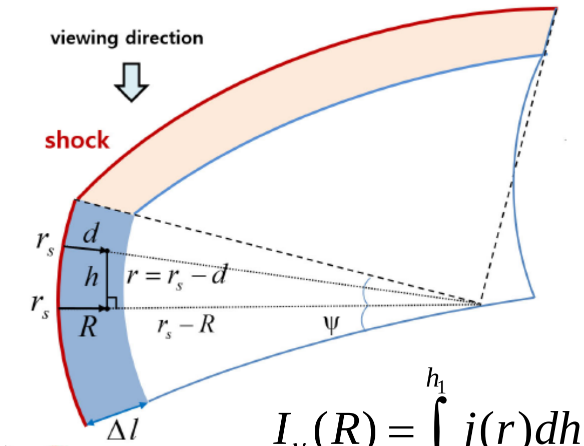
$Q_{\max}(z,B) \approx 0.6$ for $B_2 \approx 2.5\,\mu$G

**Assume pre-existing electrons**

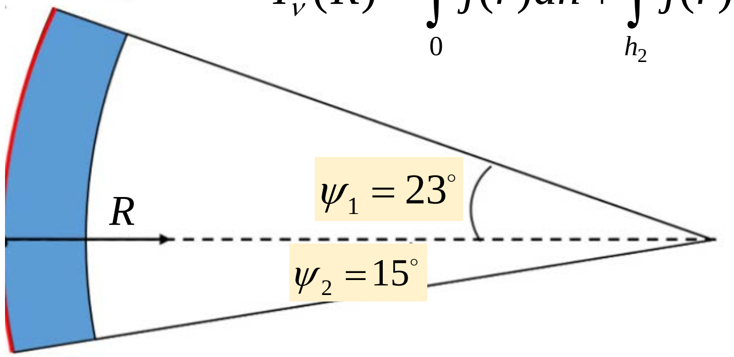
$$f_{pre}(p) = f_o\left(\frac{p}{p_{inj}}\right)^{-s} \exp\left[-\left(\frac{\gamma_e}{\gamma_{e,c}}\right)^2\right]$$

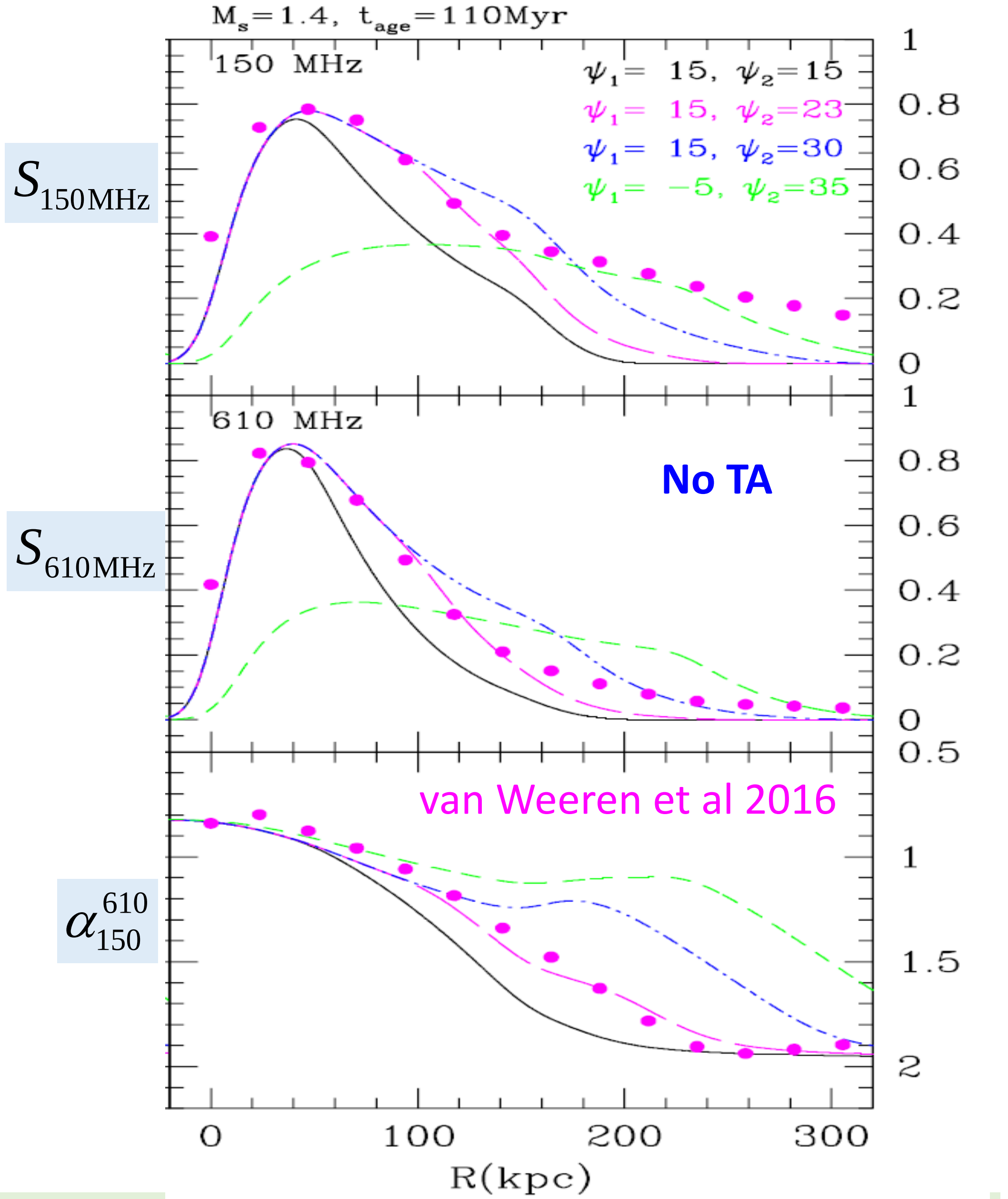
$s = 4.6, \quad \gamma_{e,c} = 7 \times 10^4$

# Reacceleration model for the Toothbrush Relic (Kang 2016, DSA + cooling only)



$$I_\nu(R) = \int_0^{h_1} j(r)dh + \int_{h_2}^{0} j(r)dh$$

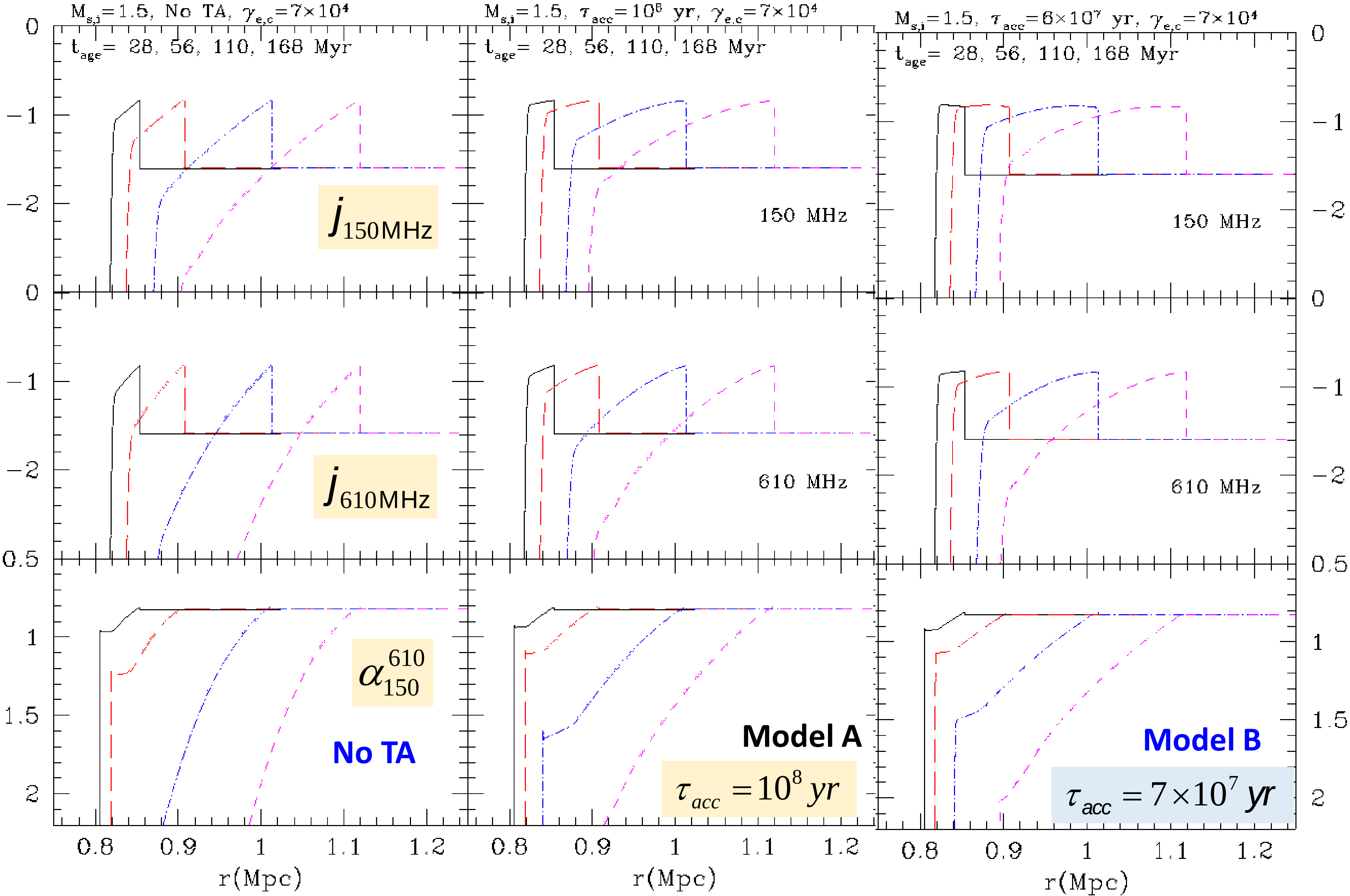




$$M_s \approx 1.4,\ kT_1 = 6.9\,\text{keV},\ kT_2 = 8.9\,\text{keV},\ u_s \approx 1.8\times10^3\ \text{km/s},\ B_1 = 2\mu\text{G},\ B_2 \approx 2.6\mu\text{G}$$

# Reacceleration model for the Toothbrush Relic: Test for Turbulence Acceleration

$$D_{pp} \approx \frac{p^2}{4\tau_{acc}} \cdot \exp\left(-\frac{R}{R_{\rm decay}}\right)$$



**No TA**

**Model A**

$\tau_{acc} = 10^8\ yr$

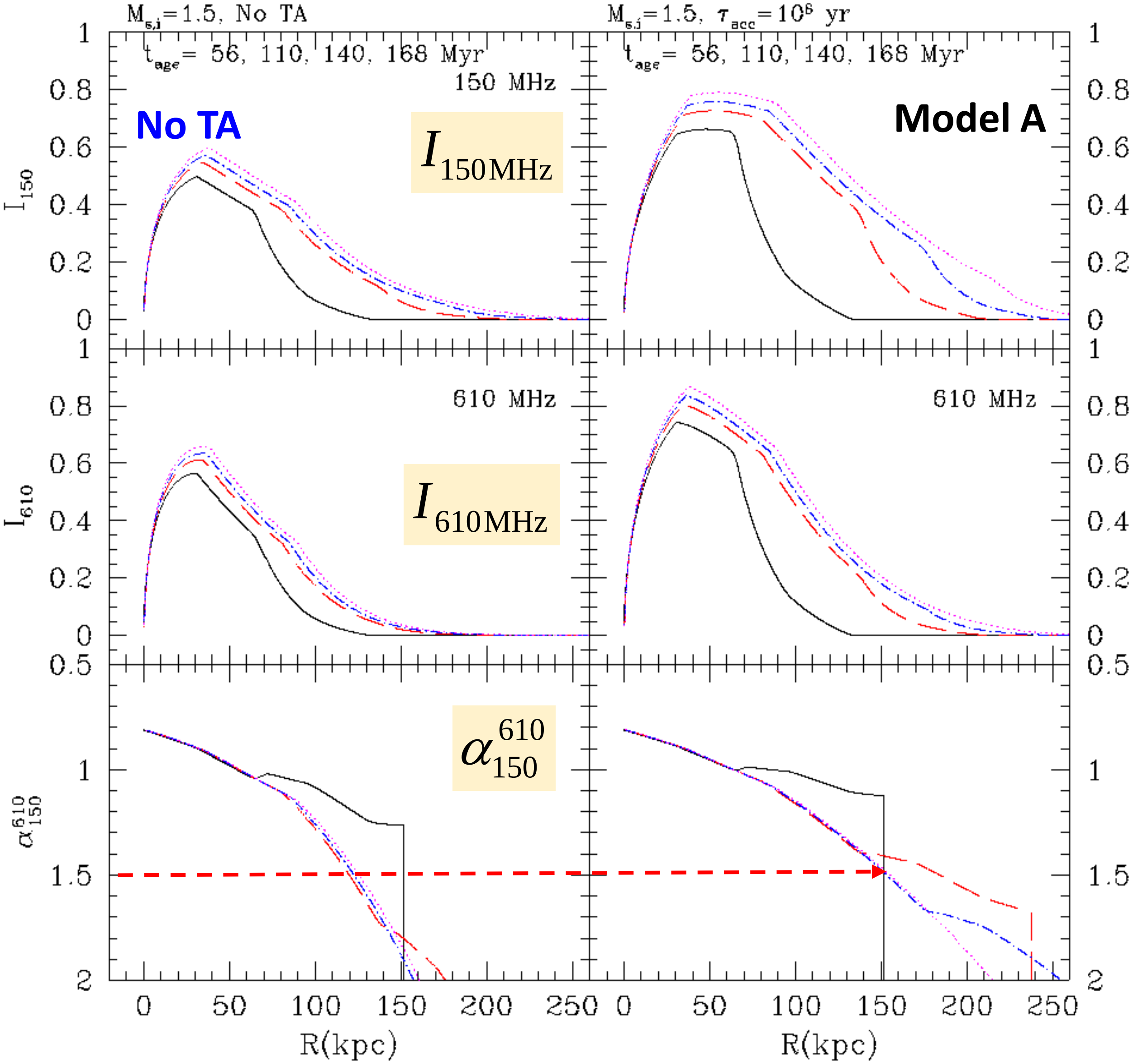
**Model B**

$\tau_{acc} = 7\times10^7\ yr$

# Toothbrush Relic Model

Coulomb/Sync/iC cooling

With Turbulent Acceleration



**DSA +**
**Coulomb/Sync/iC cooling**
**+ Turbulence Acceleration**

## Model A

$$D_{pp} \approx \frac{p^2}{4\tau_{acc}} \cdot \exp(-\frac{R}{R_{\text{decay}}})$$

$$\tau_{acc} = 10^8\, yr$$

$$R_{\text{decay}} = 100\text{kpc}$$

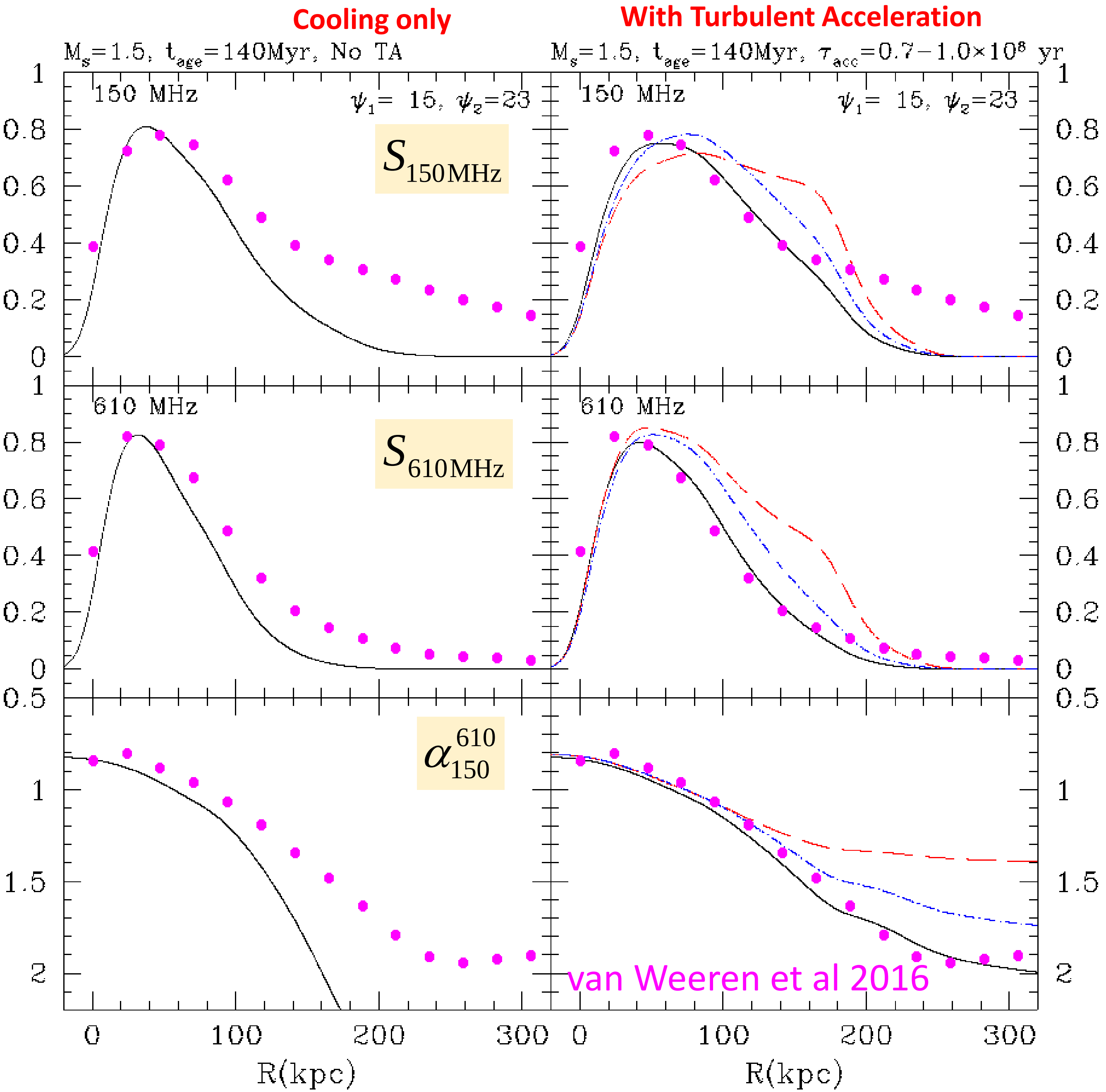
surface brightness

$$I_\nu(R) = \int_0^{h_1} j(r)dh + \int_{h_2}^{0} j(r)dh$$

$$M_s \approx 1.4,\ kT_1 = 6.9\text{ keV},\ kT_2 = 8.9\text{ keV},\ u_s \approx 1.8\times10^3\text{ km/s},\ B_1 = 2\mu\text{G},\ B_2 \approx 2.6\mu\text{G}$$

(Kang, Ryu, & Jones 2016)

# Beam convolved radio flux profile of the Toothbrush Relic



**Model A:**

$$D_{pp} \approx \frac{p^2}{4\tau_{acc}} \cdot \exp(-\frac{R}{R_{decay}})$$

$$\tau_{acc} = 10^8\, yr$$

**Model B:**

$$D_{pp} \approx \frac{p^2}{4\tau_{acc}} \cdot \exp(-\frac{R}{R_{decay}})$$

$$\tau_{acc} = 7 \times 10^7\, yr$$

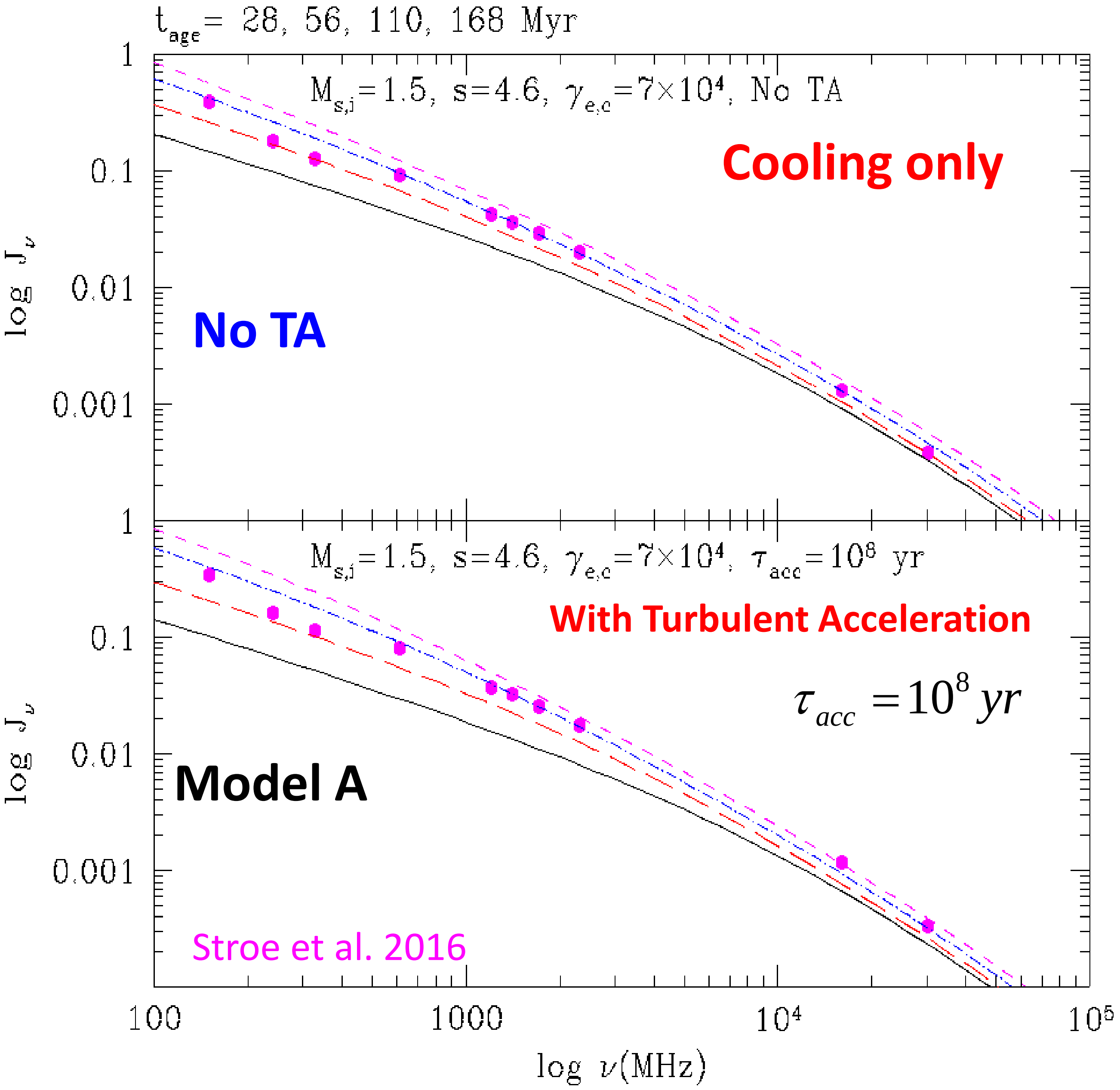
**Model C:**

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

$$\tau_{acc} = 10^8\, yr$$

Gaussian Smoothing with 23.5 kpc width

# Integrated Radio Spectrum of the Toothbrush relic



$$D_{pp} \approx \frac{p^2}{4\tau_{acc}} \cdot \exp\left(-\frac{R}{R_{decay}}\right)$$

$$\tau_{acc} = 10^8\,yr$$

$$R_{decay} = 100\mathrm{kpc}$$

# Summary

- **Re-acceleration model explains observed features of radio relics**

  (1) relative rareness, compared to the expected number of shocks in the ICM

  (2) radio spectral index $\alpha$ is determined by $M_s$, $s$, & $\gamma_{e,c}$ so $M_{radio} \neq M_X$

  (3) solves the low acceleration efficiency problem for weak shocks with $M < 3$

## -Turbulent acceleration by ICM turbulence

**due to TTD resonance with fast mode waves (Brunetti & Lazarian 2007, 2011)**

$$D_{pp} \approx \frac{p^2}{4\tau_{acc}} \cdot \exp\left(-\frac{R}{R_{\mathrm{decay}}}\right) \quad \text{with } \tau_{\mathrm{acc}} \sim 10^8 \text{ yrs}, \ R_{decay} \approx 100 \text{ kpc}$$

**The test results are consistent with the observational data of the Toothbrush and the Sausage relics.**